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AI-Based Combustion Monitoring for NOx and CO_2 Reduction in IC Engine-Powered Vehicles

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Abstract

The reduction of Nitrogen Oxides (NOx) and Carbon Dioxide (CO_2) emissions from internal combustion (IC) engines is critical for meeting modern environmental regulations and advancing sustainable mobility. This study presents a comprehensive exploration of Artificial Intelligence (AI)-based combustion monitoring as a transformative approach to emission reduction. By leveraging Machine Learning (ML) and Deep Learning (DL) models, real-time data from engine sensors can be analysed to predict combustion behaviour and dynamically control key parameters such as injection timing, air-fuel ratio, and Exhaust Gas Recirculation (EGR). AI-driven systems demonstrate superior adaptability to transient engine conditions, enabling optimised combustion with minimal emissions. Integrating AI technologies enhances diagnostic precision, improves engine efficiency, and supports predictive control strategies that outperform conventional methods. This work highlights the potential of AI not only to meet stringent emission norms but also to pave the way toward intelligent and eco-friendly automotive propulsion systems.

Major Findings: *AI-powered combustion monitoring allows for the real-time tuning of engine settings, including fuel injection timing, air/fuel ratio, and exhaust gas recirculation, resulting in lower NOx and CO_2 emissions. Machine learning and deep learning based algorithms can efficiently adapt to the changing engine conditions, resulting in better combustion efficiency and fuel economy. This smart connectivity not only benefits the emission reduction efficiency but is also in favour of environmentally sustainable transport because it allows predictive maintenance and cleaner, benign vehicle technologies.*

Keywords: *Artificial Intelligence, CO_2 Emission Control, Combustion Monitoring, Engine Optimisation, Machine Learning, NOx Reduction*

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1.0 Introduction

Internal combustion engines power the majority of vehicles globally. However, they are also a major source of air pollutants like NOx and greenhouse gases such as CO_2. Regulatory bodies have introduced strict emission norms, pushing the need for better emission control technologies. AI offers a promising solution through real-time combustion monitoring and control, enabling significant emission reductions.

The escalating concerns surrounding greenhouse gas emissions and stringent environmental regulations have amplified the urgency to refine internal combustion engine technology, particularly in the context of vehicular applications[1]. AI-driven combustion monitoring systems hold immense potential in minimising NOx and CO_2 emissions, thereby fostering a cleaner and more sustainable transportation sector. The pursuit of "zero impact emission vehicles" is gaining momentum through advanced combustion strategies and innovative after-treatment systems, encompassing the extensive deployment of catalysts and high-filtration-efficiency particulate filters[2]. The integration of AI into engine combustion processes presents opportunities to address transient phenomena, like cycle-to-cycle variations, which are not well understood or analysed[2]. Current methods for curbing NOx and particulate emissions often lead to increased energy consumption, highlighting the importance of improved combustion that delivers better efficiency and lower emissions without relying on filtering[3]. This can be achieved through sophisticated AI algorithms capable of predicting and optimising combustion parameters. Furthermore, the development of lean-burn, low-NOx combustion technology is seen as critical for meeting future legislative demands for aero-engine combustion systems, emphasising the broad applicability of advanced combustion strategies. The transition to alternative energy sources, like electric vehicles, is projected to reduce emissions of volatile organic compounds, carbon monoxide, nitrous oxides, and particulate matter. Therefore, AI-based combustion monitoring plays a vital role in optimising engine performance and reducing harmful emissions, as well as optimising fuel efficiency.

1.1 Advancements in Combustion Monitoring with AI

AI has emerged as a transformative force, holding the potential to optimise resource allocation, enhance decision-making processes, and drive efficiency across a multitude of sectors, thus enabling a more sustainable and climate-resilient future[4]. Particularly, machine learning algorithms are capable of analysing energy consumption patterns, pinpointing inefficiencies, and recommending tailored strategies for energy optimisation, leading to significant reductions in carbon emissions. Integrating AI into transportation systems, which could tackle problems such as pollution reduction, safety improvements, and traffic congestion alleviation, may revolutionise the sector. By utilising AI's capabilities in machine learning, neural networks, and real-time data processing, transportation systems can adapt and become more efficient, predicting traffic patterns, optimising signal timings, and effectively reducing congestion[5]. AI-driven systems can fine-tune combustion parameters to reduce pollution by examining extensive datasets of engine operation[6].

1.2 AI Applications in Vehicle Emission Control

AI algorithms can predict and manage NOx and CO_2 emissions. The algorithms also support the development of smart transportation systems, optimise traffic flow, and encourage the use of electric vehicles, resulting in lower greenhouse gas emissions. AI applications, such as optimising traffic flow and promoting electric vehicle use, have significantly contributed to reducing greenhouse gas emissions in the transportation sector. Also, the adoption of AI technologies, including machine learning and deep learning, is critical for enhancing energy efficiency and decreasing carbon emissions in commercial buildings[7]. These AI-driven solutions not only optimise energy use but also improve occupant comfort, leading to more sustainable and efficient building operations. AI enhances energy efficiency and reduces emissions across various sectors, contributing to environmental sustainability. Figure 1 illustrates how AI plays a central role in driving sustainability across sectors such as emission monitoring, circular economy, clean energy, smart buildings, efficient transportation, and sustainable

agriculture. AI acts as an enabler for intelligent decision-making and optimisation in environmental and resource management[4].

1.3 AI-Driven Combustion Monitoring

AI-driven combustion monitoring offers real-time optimisation capabilities that can drastically cut down NOx and CO_2 emissions from internal combustion engines. By integrating a network of sensors within the combustion chamber, comprehensive data on parameters such as temperature, pressure, and air-fuel ratio can be acquired, enabling a thorough assessment of combustion quality. Figure 2 highlights the three key pillars influencing vehicle energy consumption and emissions: vehicle design and technology, operational and usage factors, and transportation planning and policies[8]. The transition from mechanical to electronic control systems has enabled off-site monitoring and reduced service calls[9]. Sophisticated machine learning algorithms can then analyse this data, predicting the formation of NOx and CO_2 based on real-time conditions, which contrasts with traditional methods relying on pre-programmed strategies that cannot adapt to dynamic changes in engine operation or environmental factors. AI algorithms can also analyse exhaust gas composition data from lambda, NOx, and CO sensors, correlating it with engine operating conditions to create predictive models that can optimise combustion in real time. This feedback loop allows for continuous adjustments to fuel injection timing, air intake, and other relevant parameters, maintaining optimal combustion conditions and lowering emissions[10]. AI-based systems can learn from vast datasets collected during engine operation, identifying patterns and correlations that enable them to anticipate and prevent conditions that lead to increased emissions. The AI models, by learning from both experimental and simulation data, offer a more thorough and adaptable solution for minimising emissions in internal combustion engines. The use of AI algorithms makes it possible to control unmixedness, lowering NOx

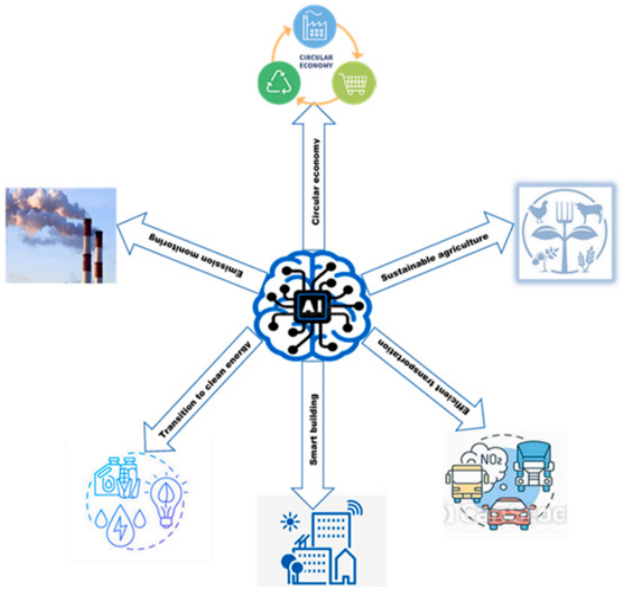


Figure 1. Highlights of the application of AI in achieving net zero[4].

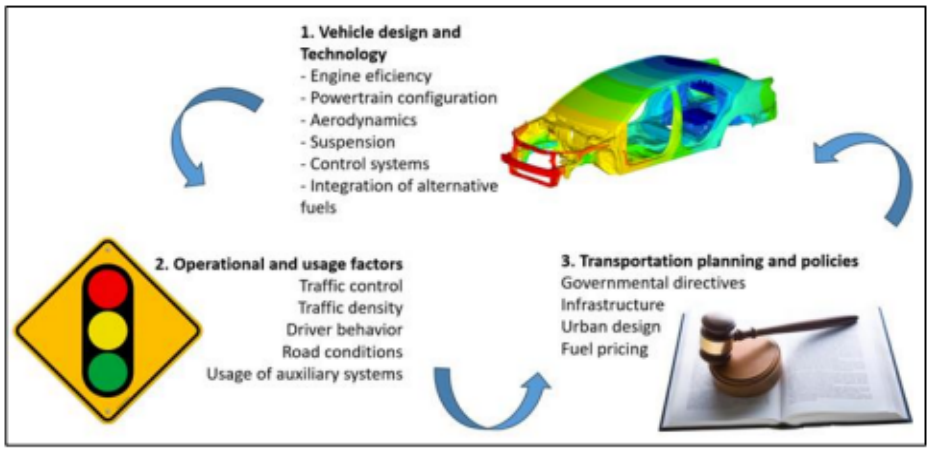


Figure 3. Factors influencing vehicle energy consumption[8].

Table 1. AI-based reinforcement elements for emission control in internal combustion engines

Reinforcement Material	Type / Variant	Key Advantages	Challenges / Limitations	Applications / Remarks
Sensor-Based Data Platforms	In-Cylinder Sensors (Temp, Pressure, NOx)	Enables real-time combustion monitoring, precise emission control.	Cost of deployment, sensor durability in harsh engine environments.	Integrated into AI systems for optimising combustion parameters such as fuel injection and air-fuel ratios.
Machine Learning Algorithms	Supervised/ Unsupervised, Deep Learning	Learns from large engine datasets to predict and minimise NOx and CO_2 emissions.	Requires extensive high-quality data, and model interpretability issues.	Predictive modelling of emissions and adaptive combustion strategies for various engine loads and environmental conditions.
AI-Controlled ECU Systems	Adaptive fuel and ignition control systems	Enables dynamic combustion adjustments based on real-time feedback.	Complex integration into existing vehicle architecture.	Improves combustion efficiency, supports transition to low-emission vehicles.
Smart Transportation Systems	Traffic signal optimisation, vehicle routing.	Reduces congestion and emissions by optimising traffic flows.	High initial investment, dependency on accurate real-time data.	Supports urban pollution reduction and enhances the effectiveness of emission control technologies.
After-treatment Systems	Catalytic converters, Particulate filters	High filtration efficiency reduces post-combustion emissions	Increased energy consumption, maintenance-intensive	AI helps optimise their use by minimising reliance through improved in-cylinder combustion.
Neural Network Models	Feedforward, CNNs, RNNs	Model complex, nonlinear engine behaviour and cycle-to-cycle variations.	Training complexity, sensitivity to noise in input data.	Enhances combustion stability and anticipates conditions that elevate emissions.
Real-Time Monitoring Platforms	Cloud-connected, edge AI	Allows remote diagnostics, reduced service calls, and off-site optimisation.	Security risks, latency concerns.	Used for fleet monitoring and proactive emission management.
Combustion Modelling Systems	Physics-informed AI, Hybrid models	Combine simulation data with experimental results for robust prediction.	Model validation and calibration needs.	Aids in the development of lean-burn and low-NOx strategies essential for aviation and automotive compliance.

Alternative Fuel Integration	AI-controlled dual-fuel systems	Facilitates smooth integration and optimisation of alternative fuels (biofuels, H_2).	Fuel property variation, need for adaptive combustion strategies.	Supports regulatory compliance and greenhouse gas reduction.
Emission Prediction Systems	AI-analysed exhaust composition models	Predict NOx, CO_2, and VOC levels based on operating conditions, aiding proactive control.	Accuracy is dependent on sensor calibration and model quality.	Contributes to achieving 'zero impact emission vehicles' through targeted tuning.

emissions and improving engine reliability through adjustments to the fuel schedule that respond to flame stability[11].

2.0 Background and Motivation

NOx forms due to high combustion temperatures, while CO_2 results from the complete oxidation of fuel. Traditional engine control systems often fail to respond quickly to changing engine conditions. AI-based systems can overcome this limitation by learning from historical data and predicting optimal control actions in real time. The automotive industry is increasingly focused on improving engine efficiency while adhering to stringent emission standards[12].

Modern engines necessitate intricate control systems with greater degrees of freedom than conventional map-based strategies[13]. Model predictive control based on online optimisation has surfaced as a potential means of managing the complexities inherent in advanced combustion systems. However, accurate real-time data regarding combustion parameters is essential for effective control. Moreover, the industry requires innovative approaches to optimise engine efficiency, minimise emissions, and accommodate a broader spectrum of fuels in both power generation and transportation contexts[14]. Dual-fuel internal combustion engines stand out as a cost-effective solution for current power system needs[15]. The convergence of AI methodologies with combustion engine technology is spurred by the imperative to meet ever-tightening emission regulations and the concurrent need to enhance fuel efficiency[16].

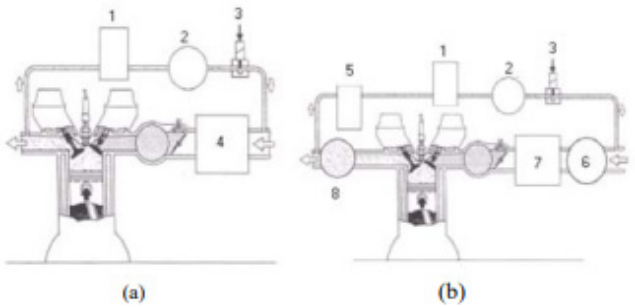


Figure 3. Exhaust gases recirculation system assembly for naturally aspirated **(a)** and turbocharged **(b)** – System components: 1 humidity separator; 2 booster; 3 EGR valve; 4 single point injection; 5 heat exchanger; 6 compressor; 7 single point injection and equalisation box; 8 turbine[12].

3.0 AI Techniques for Combustion Monitoring

Machine learning models such as decision trees, Support Vector Machines (SVM), and neural networks have shown success in predicting combustion states. Deep learning methods like Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are useful for analysing large and time-dependent sensor datasets. Combining sensor signals, such as in-cylinder pressure, exhaust temperature, and lambda values, improves prediction accuracy. AI algorithms, including machine learning models, can be trained to predict combustion parameters from sensor data. These algorithms analyse intricate relationships within the data to estimate NOx and CO_2 formation. Artificial neural networks, decision trees, and support vector machines are some commonly used techniques[17]. These advanced models can analyse the complexities associated with modern combustion modes, which often involve a combination of stratification, lean mixtures, high levels of exhaust gas recirculation, multiple

injections, and variable valve timings[18]. AI facilitates real-time adjustments to engine parameters, such as injection timing, air-fuel ratio, and EGR rate, to minimise emissions. The deployment of AI for combustion monitoring and control entails a comprehensive strategy that encompasses the selection of appropriate sensors, the development of robust machine learning models, and the seamless integration of AI algorithms into engine control units. These techniques enable the construction of intricate models capable of discerning intricate patterns and dependencies within combustion processes, ultimately enabling optimised control strategies.

4.0 NOx and CO_2 Reduction Strategies

AI-based systems can implement various NOx and CO_2 reduction strategies. For instance, AI can precisely control the air-fuel ratio to ensure complete combustion, minimising CO_2. The models also optimise exhaust gas recirculation rates to reduce peak combustion temperatures and NOx formation. Real-time adjustments to engine parameters based on AI predictions result in lower emissions and better fuel efficiency. Advanced control strategies, adaptive to engine conditions, can reduce NOx and CO_2 emissions. These strategies leverage complex algorithms to make instantaneous adjustments to a range of engine parameters, ensuring optimal combustion and reduced emissions. Such methods usually comprise analysers and an IT infrastructure to manage, record, and store the emissions values. The diagram illustrates how historical data, including process parameters and emission values, is input into a modelling platform to develop a predictive model[19]. Additionally, strategies include online adjustment of parameters to maintain optimal combustion conditions

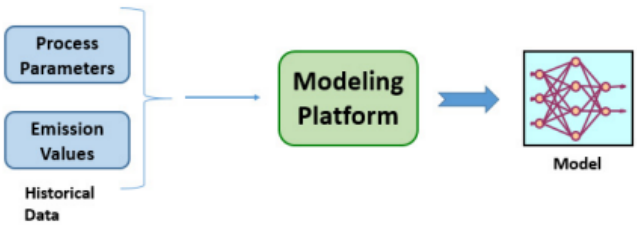


Figure 4. Inferential modelling for emission monitoring[19].

and minimise emissions[20]. Furthermore, the development and use of intricate algorithms contribute to reducing pollutant formation during combustion. The Multi-Layer Perceptron architectures with artificial neural networks, for example, are adopted in NOx and smoke emission models, and are trained and validated using experimental data to ensure strong generalisation performance[21].

5.0 Case Studies and Simulations

AI-driven systems have been shown to reduce emissions in real-world driving conditions. Simulations can accurately predict the rate of carbon dioxide production and have applications in future efficiency and emissions optimisation during engine design, as well as in online engine control[22]. For example, AI-based traffic management systems optimise vehicle routing to reduce fuel consumption and emissions[23]. AI-driven drones are also being used for real-time monitoring of traffic and dynamic traffic management. Figure 5 compares two autonomous driving architectures: (a) a modular pipeline using deep learning/classical methods for perception, planning, and control, and (b) an end-to-end learning approach, both monitored by a safety layer[24]. AI models can be deployed to predict optimal control strategies based on real-time data from sensors, historical data, and simulation results. By integrating AI into existing systems, the transportation sector can significantly reduce emissions. AI has demonstrated a pivotal role in emissions reduction across various sectors, achieving over 20% reductions in some projects[25]. Furthermore, AI improves traffic flow, automates incident management, and enhances overall transportation efficiency through integration with real-time data analytics[24].

AI's ability to process vast datasets and make quick decisions can lead to considerable improvements in urban mobility and air quality[26]. AI enhances environmental sustainability by improving energy efficiency and reducing emissions across various sectors[25]. Smart manufacturing processes, supported by AI, can decrease energy consumption, waste, and emissions by 30–50%, with similar reductions in energy usage achievable in buildings[4]. AI algorithms optimise transportation networks, reduce congestion, and promote the use

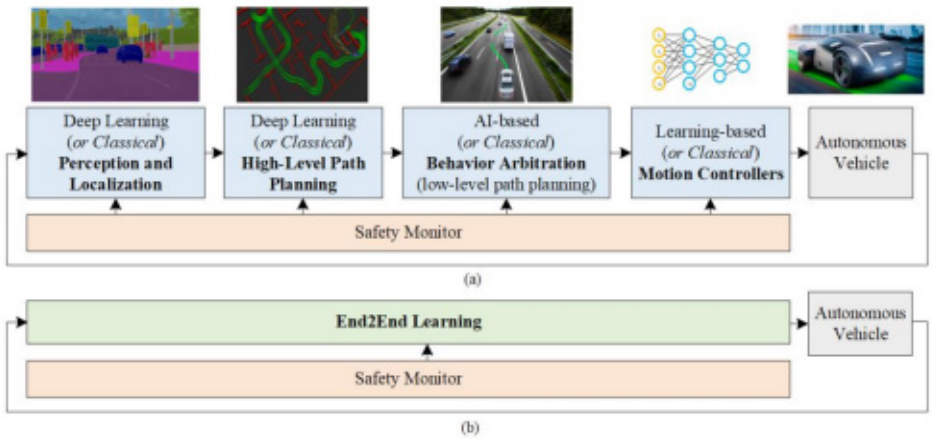


Figure 5. **(a)** Deep learning block diagrams for AI-powered autonomous cars, **(b)** End2End Learning[24].

of electric vehicles, thereby cutting greenhouse gas emissions.

6.0 Challenges and Opportunities for AI in Combustion Optimisation

AI can be used to predict peak energy demand and adjust heating, ventilation, and air conditioning systems accordingly to reduce unnecessary energy consumption[27]. By analysing large datasets of engine operation, AI can identify patterns and correlations that would be difficult or impossible for humans to detect. AI models trained on extensive datasets can accurately predict NOx and CO2 emissions under various operating conditions. The application of AI in transport is also promising for transport authorities to determine how to use these technologies to improve congestion rapidly, make travel time more reliable for their customers, and improve the economics and productivity of their vital assets[28]. AI improves traffic flow, automates incident management, and enhances overall transportation efficiency through integration with real-time data analytics[29]. AI's dynamic optimisation skills promote energy efficiency in a variety of fields by enabling real-time power usage modifications based on changing needs and environmental factors[30]. Also, AI plays a critical role in optimising energy distribution, streamlining grid interaction, and promoting energy resilience and low emissions in the automotive industry[31].

However, the potential of AI in building services faces challenges like the need for extensive data, data variability, high initial costs, and the requirement for specialised expertise[32]. Despite these challenges, AI is becoming increasingly integrated into sustainable architecture, where it minimises energy consumption, promotes energy-efficient building design, reduces environmental impact, and enhances living environment security and quality[32]. The performance of AI-based control is not yet completely satisfactory, partially because these algorithms need large amounts of high-quality real-world data, which is lacking in the building or energy sector[33].

7.0 Future Trends and Research Directions

7.1 Advancements in AI Algorithms for Combustion Control

Deep learning and reinforcement learning algorithms hold promise for further improving combustion control. These algorithms can learn complex patterns and adapt to changing conditions in real time. Integrating combustion monitoring systems with IoT devices and cloud computing platforms can enable real-time data collection, analysis, and remote control. The Internet of Things provides the necessary data inputs, complementing AI technology[34]. AI-based combustion monitoring can be

extended to other engine types, such as diesel engines and gas turbines. It can also be adapted to monitor emissions from alternative fuels, such as biofuels and | hydrogen.[4,6,24,35]

7.2 Policy Implications and Regulatory Framework

AI-driven technologies can play a significant role in shaping future energy policies aimed at achieving sustainable development goals[36].

By deploying AI solutions in the transportation and manufacturing industries, organisations can tap into new opportunities while considering the benefits and challenges involved in developing a sustainable society[37]. AI integration can also help in understanding energy consumers for creating a stable, scalable, and smart energy system[38]. AI can support policy making related to the energy field through multidisciplinary approaches that address transformation trends in the development of energy policies[36]. Moreover, AI is transforming various sectors by offering tools for automation, optimisation, and prediction, which are crucial for achieving sustainability goals[39]. This transformation is especially evident in the energy sector, where AI is enhancing the incorporation of renewable energy sources and optimising energy usage[38,40].

AI improves grid resilience and operational efficiency through predictive maintenance, demand forecasting, and adaptive control mechanisms[40]. AI plays a critical role in the planning and operation of distributed energy systems, optimising operations, enhancing efficiency, and improving system resilience[41]. AI is particularly useful in generating data that is hard to measure directly, improving traditional models of biomass conversion and biofuel end-uses, and overcoming the challenges of traditional computing techniques for bioenergy supply chain design and optimisation[42]. Integrating AI into the energy sector enhances smart grids, optimises energy consumption, and promotes renewable energy sources, with potential uses spanning planning, control, optimisation, and security of smart grids.

AI's ability to process and analyse vast amounts of data in real time is revolutionising energy management, paving the way for more sustainable and efficient energy systems[43].

8.0 Future Scope

Future work will focus on cloud-based combustion diagnostics, digital twin models, and AI in hybrid powertrains. Adaptive learning will help account for long-term engine wear and sensor drift. Regulatory integration for onboard real-time emission verification using AI is another promising avenue. Integrating AI into energy systems is crucial for achieving carbon neutrality by enhancing efficiency and grid reliability. AI applications for energy efficiency and renewable energy have shown tremendous progress, offering approaches to address global challenges, enhance energy efficiency, and accelerate the shift to renewable energy sources. As the world transitions to cleaner energy, AI is essential for optimising renewable energy systems, predicting energy demand, and cutting down energy consumption[44]. The convergence of AI with energy systems facilitates the evolution of smart grids, optimising energy distribution, improving grid stability, and accommodating renewable energy sources, potentially resulting in substantial reductions in energy consumption and greenhouse gas emissions. Artificial intelligence is being applied to smart energy systems to process massive and complex data in this sector and make smart and timely decisions[45]. By combining AI with sustainable architecture, there are great advancements in energy efficiency and environmental preservation, which can lead to a sustainable future[39].

In the quest for lowering NOx and CO_2 emissions in Internal Combustion (IC) engine-powered vehicles, thermal management plays a pivotal role. AI-driven systems now leverage advanced cooling strategies to optimise engine efficiency and reduce combustion-related emissions. One promising technology involves PCM-based cooling, which has demonstrated significantly better thermal behaviour under high-power operating conditions compared to conventional techniques such as forced convection and heat pipe systems[46]. Experimental analysis with nine-segmented thermal zones and controlled flow rate simulations on silicon/copper Printed Circuit Boards (PCBs) revealed that copper substrates substantially reduce die temperatures. At an airflow velocity of 5 m/s and ambient temperatures ranging from 30°C to 47°C, efficient IC cooling was achieved even at a reduced airflow speed of 3 m/s, showing a temperature

drop ranging from 1.50°C to 11.12°C[47]. Among various PCMs, n-eicosane demonstrated the highest heat storage capacity and melting enthalpy, enabling a temperature reduction from 53.234°C to 51.520°C, outperforming both paraffin wax and ATP 78, which could only achieve temperature reductions of 0.5°C and 1.35°C, respectively, in minichannel PCM heat sinks[48]. Recent innovations have shifted attention to minijet impingement cooling systems[49], nanofluids for enhanced thermal conductivity[50], water-based cooling strategies[51], and heat augmentation devices like twisted tape inserts[52–54]. These strategies are being integrated into AI frameworks for real-time monitoring and adaptive control, especially in applications related to electronics thermal management, biodiesel combustion systems, solar thermal collectors, substrate cooling, vehicle aerodynamics, and intelligent control mechanisms such as fuzzy logic-based controllers[55–63]. Further technological progress includes innovations in wind turbine cooling, HVACR component placement optimisation, adsorption cooling, vehicle thermal safety measures, and surface treatments for heat rejection efficiency[64–78]. Applications extend across diverse domains, including PCM-embedded IC cooling, fuel additive optimisation, and thermal regulation in structural components like steel plates, welded joints, and curved geometries[79–87]. One key recommendation for IC engine applications is the implementation of Multi-Type Phase Change (MTPC) materials, offering superior dissipation under variable heat loads. In parallel, deep learning models have been utilised to detect surface defects in geological materials, while microchannel heat sinks with optimised geometries are enhancing heat transfer behaviour under dynamic conditions. From the combustion emissions perspective, reductions in NOx and CO_2 have also been supported through biodiesel blends, catalytic converters, and solar collectors equipped with trapezoidal ducts and delta-wing vortex generators, which outperform conventional rectangular ducts in thermal efficiency[88–94]. Additional advancements include AI-based monitoring of industrial shaft failures in paddle mixers, portable electronics using PCM-regulated cooling, and structural optimisation of mixer shafts via Finite Element Analysis (FEA)[95–96]. Enhanced heat transfer in engines and related components has also been achieved through the integration of perforated twisted tape inserts[97]. Finally, artificial intelligence is increasingly recognised for its potential to mitigate the environmental impact of mining operations and to streamline dynamic simulations in systems such as vibratory bowl feeders with paddle shaft mechanisms, contributing further to sustainable and intelligent engine design and thermal management[98–100].

9.0 Conclusion

In conclusion, the fusion of artificial intelligence with combustion monitoring systems represents a groundbreaking advancement in the pursuit of cleaner and more efficient internal combustion engines. Unlike traditional control methods, AI offers unparalleled adaptability by learning from vast datasets and making real-time decisions to optimise fuel injection, air-fuel ratios, and exhaust gas recirculation. This not only results in substantial reductions in NOx and CO_2 emissions but also improves fuel economy and engine responsiveness across varying operating conditions. Beyond just emission control, AI acts as a catalyst for smarter mobility, enabling predictive diagnostics, reducing maintenance costs, and accelerating the transition to sustainable automotive technologies. As the demand for eco-friendly transportation intensifies, AI emerges as a transformative force, redefining the future of propulsion systems and setting new standards for environmental stewardship in the mobility sector.

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