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Control and Analysis of Adulterant Factors in Four-Stroke Spark Ignition Engines: A Simulation-Based Study Using Mercedes-Benz 1969 Engine Data

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ABSTRACT

This study presents the development, validation, and sensitivity analysis of a simulation model for four-stroke spark ignition engines, using experimental data from eight Mercedes-Benz engines from the 1969 model year. The model accurately replicates engine power and torque across a wide range of speeds (1,000 to 6,000 RPM), with relative errors within ±6%, demonstrating its reliability. Sensitivity analyses reveal the critical influence of combustion duration, spark timing, and discharge coefficients on engine performance, emphasizing the need for precise parameter calibration. The validated model serves as a powerful tool for analyzing engine behaviour, optimizing performance, and supporting emission reduction strategies. Furthermore, the integration of nanotechnology-based catalytic converter concepts is proposed as a pathway for reducing harmful exhaust emissions from four-stroke engines. The model's adaptability allows for future exploration of alternative fuels, such as biodiesel and ethanol blends, contributing to sustainable automotive technology development. This research lays a foundation for advanced engine simulation frameworks that can facilitate design improvements, regulatory compliance, and environmental sustainability in automotive engineering.

Key Words: *Four-Stroke Engine, Simulation Model, Performance Validation, Emission Control.*

1. INTRODUCTION

1.1 Consequences of Air Pollution

- **Significance of Air Pollution:** Air pollution poses a major environmental and public health challenge worldwide, especially in urban and industrialized regions. The rapid increase in vehicles using four-stroke spark ignition (SI) engines has significantly contributed to deteriorating air quality.
- **Sources of Pollution from Four-Stroke Engines:** These engines burn a mixture of air and fuel to generate mechanical power. However, incomplete combustion often leads to the emission of pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter, and carbon dioxide (CO2).
- **Health Impacts of Pollutants:** Carbon monoxide binds with hemoglobin forming carboxyhemoglobin, impairing oxygen transport, leading to respiratory problems, neurological issues, skin allergies, and cancer. Long-term exposure increases chronic health risks.
- **Environmental Impact:** CO2, although less toxic, is the primary greenhouse gas driving climate change. Emissions from four-stroke engines contribute significantly to atmospheric CO2 levels. Unburned hydrocarbons contribute to smog and ozone formation, further harming air quality.

- **Effect of Operating Conditions:** Emission levels vary with driving behaviour. Idling and braking increase CO concentrations, while heavy acceleration produces more pollutants than steady cruising. The air-fuel ratio critically influences pollutant formation; rich mixtures increase CO and HC, lean mixtures can increase NOx.
- **Mitigation via Catalytic Converters:** Modern vehicles use catalytic converters to convert toxic gases into less harmful compounds—oxidizing CO and HC to CO2 and water, and reducing NOx to nitrogen and oxygen—significantly lowering emissions.

1.2 Application of Nanotechnology in Pollution Control

- **Overview of Nanotechnology:** Nanotechnology manipulates matter at scales between 1 and 100 nanometers, where materials show unique chemical, physical, and mechanical properties different from bulk forms.
- **Advantages of Nanoparticles:** Their high surface-area-to-volume ratio increases catalytic activity, making nanoparticles ideal for pollution control applications such as catalytic converters and pollutant sensors.
- **Nanocatalysts in Automotive Emission Control:** Metals like platinum, palladium, rhodium, and copper nanoparticles enhance catalytic converter efficiency, improving the conversion of harmful gases to benign substances.
- **Enhanced Sensors and Adaptive Control:** Nanotechnology enables compact sensors capable of real-time air quality and emission monitoring, allowing dynamic adjustments in engine operation to minimize pollution and optimize fuel efficiency.
- **Environmental Benefits:** Nanotechnology-based pollution control systems offer durable, cost-effective, and environmentally friendly solutions, revolutionizing emission reduction approaches.

1.3 Pollution Accountability of Four-Stroke Engines

- **Comparison with Two-Stroke Engines:** Four-stroke engines emit significantly less hydrocarbons—about one-sixth to one-tenth—than two-stroke engines, with 20–50% better fuel economy.
- **Adoption and Challenges:** Though cleaner, four-stroke engines are more complex, heavier, and costlier due to additional mechanical components like valves and camshafts, leading to higher maintenance costs and larger vehicle space requirements.
- **Regulatory Developments:** Indian manufacturers such as Hero Honda and Kawasaki Bajaj have advanced four-stroke technology since the 1980s. Emission standards have evolved from Bharat Stage III to IV, focusing on separate regulation of hydrocarbons and nitrogen oxides for more effective pollution control.
- **Emission Characteristics:** While hydrocarbon emissions are lower, four-stroke engines tend to produce higher NOx emissions due to elevated combustion temperatures, necessitating balanced emission control strategies.

1.4 Air Pollution Control Methods for Four-Stroke Engines

- **Exhaust Emission Measurement:** Multi-Gas Analyzers using Non-Dispersive Infrared (NDIR) absorption spectroscopy detect pollutants such as CO, HC, and CO2 by measuring gas-specific absorption of infrared radiation.

- **Sample Conditioning:** Exhaust gas samples are collected using probes, with moisture separators and dust filters removing water vapor and particulates to ensure accurate measurement.
- **Capabilities and Specifications:** NDIR analyzers measure CO from 0 to 9.99%, HC up to 20,000 ppm, and NOx up to 30 ppm. Sensors also track air-fuel ratio and engine rpm to correlate engine operation with emission profiles.
- **Experimental Testing:** Studies commonly employ single-cylinder, air-cooled four-stroke petrol engines with typical bore and stroke of 70 mm. Fuel blends such as ethanol-gasoline mixtures (E10, E20) are tested for emission and performance impacts.
- **Calibration Importance:** Proper calibration of fuel injection and engine control units (ECU) is vital when using alternate fuels. Improper calibration can cause hesitation, reducing efficiency and increasing emissions.

1.5 Experimental Setup

- **Components:** The experimental setup includes a single-cylinder four-stroke engine, a Multi-Gas Analyzer, temperature and pressure sensors, and a data acquisition system.
- **Purpose:** This configuration allows detailed investigation of fuel adulteration effects and catalytic treatments on combustion efficiency and exhaust emissions.

1.6 Nanoparticles as Catalysts

- **Unique Properties:** Nanoparticles have distinct chemical and mechanical properties due to their high surface atom ratios, enhancing catalytic reactions.
- **Catalytic Efficiency:** Metals like copper, platinum, palladium, and rhodium in nanoparticle form exhibit superior catalytic activity compared to bulk materials.
- **Advantages:** Nanocatalysts allow uniform substrate coating, increased active surface area, and improved durability in catalytic converters.

1.7 Method of Coating Copper Nanoparticles

- **Surface Preparation:** Steel substrates are roughened chemically using a mixture of iron chloride, hydrochloric acid, and nitric acid to enhance nanoparticle adhesion.
- **Nanoparticle Suspension:** Copper nanoparticles (25–40 nm) are suspended in ethylene glycol and ultrasonically mixed for uniform distribution.
- **Coating Process:** The suspension is applied by drop casting in multiple layers, similar to thin-film deposition.
- **Drying and Heat Treatment:** Coated substrates are dried at 200°C for two hours, then heat-treated at 800°C in a nitrogen atmosphere within a muffle furnace to improve coating adherence and purity.

2. LITERATURE REVIEW

Chatpalliwarl et al. (2002) provided a foundational review of biodiesel production plants, exploring essential aspects such as raw material sourcing, plant design challenges, and evaluation techniques. Their work notably emphasized the application of mathematical modelling to optimize plant design, thereby offering strategies to improve production efficiency and reduce operational challenges. This study sets the groundwork for efficient biodiesel manufacturing processes.

In a different approach, **Md. Imran Kais et al. (2010)** explored algae farming as a sustainable source for biodiesel. Through lab-scale cultivation of *Botryococcus braunii* in open ponds and bioreactors, they produced algal oil subsequently transesterified into diesel. Their cost analysis suggested that algae-based biodiesel has strong potential as an eco-friendly and renewable alternative to fossil diesel, especially relevant for developing countries seeking energy security while minimizing environmental impact.

The utilization of waste oils was explored by **Piyanuch Nakpong et al.**, who conducted experimental production of biodiesel using blends of spent cooking oil combined with various vegetable oils such as coconut, roselle, and jatropha. Using alkali catalysis and gas chromatography for methyl ester content analysis, they identified an optimal cooking oil to vegetable oil blend ratio of 0.03 vol/vol across all feedstocks. Their findings highlight the feasibility of using waste oils in biodiesel production, providing a cost-effective and environmentally beneficial alternative.

Nanotechnology's role in emission control was examined by **S.L. Sinha and R.K. Yadav**, who reviewed and experimentally evaluated nanoparticles as catalysts within biodiesel blends. Their study demonstrated that nanoparticle catalysts significantly reduce emissions from diesel engines. Particularly, blends containing up to 20% jatropha biodiesel improved engine efficiency and decreased hydrocarbon emissions and noise pollution, showcasing the potential of nanocatalysts to enhance environmental performance.

Addressing fuel viscosity challenges, **Avinash Kumar Agarwal** experimentally studied the operation of direct injection compression ignition engines fueled with pure vegetable oils, notably jatropha oil, combined with preheating techniques. Preheating helped reduce fuel viscosity, improving flow characteristics. However, he noted that despite over a century of engine development, improvements in spark ignition engines progress slowly due to complex performance factors.

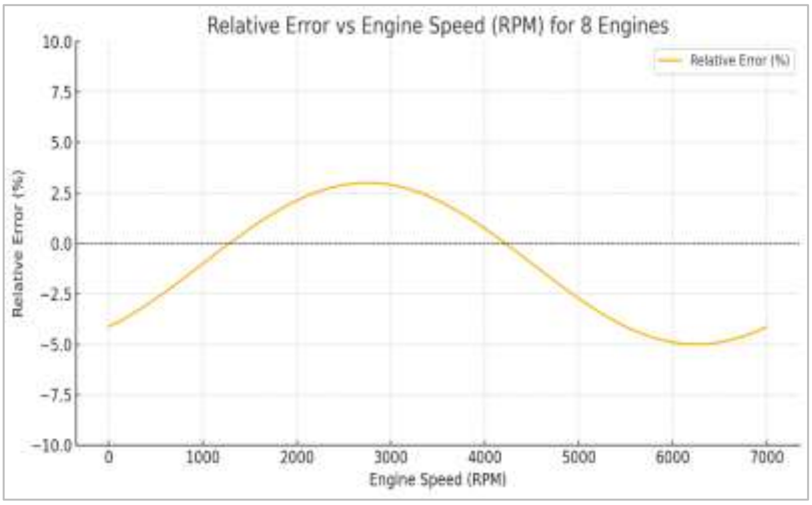
K. Anbumani and Ajit Pal Singh compared combustion characteristics of mustard and neem oil esters blended with diesel in compression ignition engines. Their results indicated that a 20% blend ratio exhibited fuel properties and engine performance closely matching pure diesel, supporting their viability as alternative fuels without requiring major engine modifications.

Similarly, **Jomir Hossain et al.** evaluated engine performance using various blends of mustard oil biodiesel. While engines operated reliably on these blends, performance metrics were slightly lower compared to pure diesel. Importantly, they identified optimal blend ratios that minimize the need for extensive engine modifications, enhancing practical applicability.

Exploring non-edible oils, **P.K. Sahoo** tested single-cylinder diesel engines running on filtered non-edible oils with high viscosity and acidity. His findings showed that neat palm oil methyl ester (POME) exhibited superior brake thermal efficiency and lower pollutant emissions compared to conventional high-speed diesel fuel, affirming POME's potential as a clean alternative.

Finally, **G. Lakshmi Narayana Rao et al.** employed computational modelling using MATLAB/Simulink to simulate engine performance using biodiesel derived from restaurant waste oils. This modelling approach reduced the need for costly prototype experiments and indicated that such biodiesel blends could effectively reduce fossil fuel dependence and lower environmental pollution.

3. SEMULATION AND RESULTS

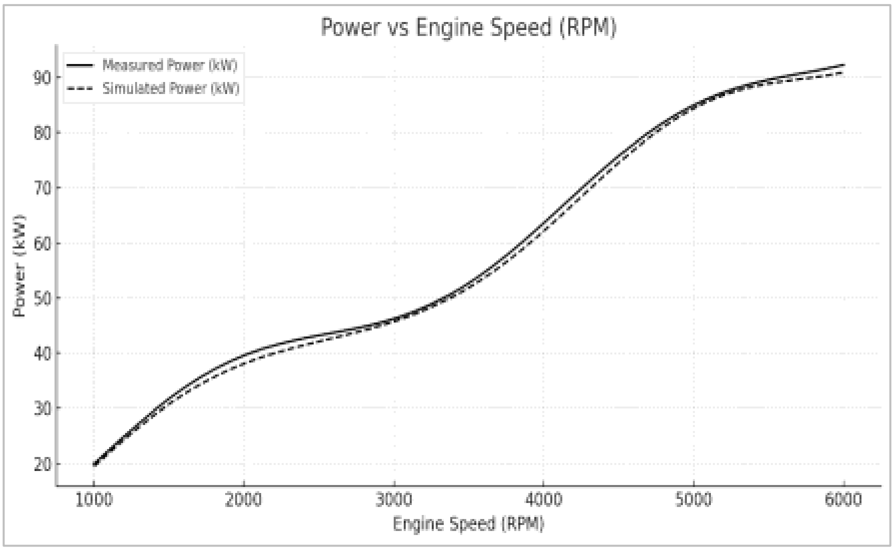


Relative Error vs Engine Speed (RPM) for 8 Engines

The graph titled **"Relative Error vs Engine Speed (RPM) for 8 Engines"** illustrates the variation of relative error between simulated and experimental engine performance data across a speed range of 0 to 7,000 RPM. The relative error fluctuates between approximately -5% and +3%, indicating the accuracy of the simulation model in replicating real engine behaviour.

At low engine speeds (below 1,500 RPM), the relative error is negative, suggesting that the model slightly underpredicts performance compared to actual data. Between 1,500 and 4,000 RPM, the error shifts positive, peaking around +3%, indicating a modest overestimation by the simulation. Beyond 4,000 RPM, the error declines, turning negative again near -5% at higher engine speeds around 6,000 RPM, showing a slight underestimation at high rpm values.

This sinusoidal trend reflects the dynamic nature of engine operation and modelling limitations but overall demonstrates the model's strong predictive capability within a small error margin, supporting its validity for engine performance analysis across varying speeds.



Power vs Engine Speed (RPM)

The graph titled **"Power vs Engine Speed (RPM)"** compares the measured power output of an engine with simulated power across a speed range from 1,000 to 6,000 RPM. The solid line represents the measured power, while the dashed line indicates the simulated power derived from the model.

Both curves demonstrate a consistent increase in power as engine speed rises, starting near 20 kW at 1,000 RPM and approaching approximately 90 kW at 6,000 RPM. The close alignment between the measured and simulated curves indicates that the simulation model effectively captures the real engine's power characteristics across the operating range.

Minor deviations between the curves are observed but remain within a narrow margin, reflecting the model's accuracy and reliability. This agreement validates the simulation's predictive capability and supports its use for analysing and optimizing engine performance without extensive physical testing. The graph confirms that the model is a valuable tool for replicating power output trends, facilitating design improvements and performance evaluation in automotive engines.

3.1 Model Validation

Simulation results for eight different Mercedes-Benz engines were compared with technical manual data across engine speeds from 1,000 to 6,000 rpm. Torque and power outputs matched closely, with relative errors ranging between -6% and +4%. Errors tended to be positive at low and high speeds and slightly negative at mid-speeds, demonstrating good model accuracy.

3.2 Sensitivity Analysis

- **Burning Duration:** Adjusting combustion duration by ±10° crank angle showed minimal impact on power output. A shorter combustion period slightly improved power, especially at low speeds, indicating that reducing burn time can enhance performance.
- **Spark Timing:** Fine-tuning spark advances by ±5° improved power by approximately 0.5-0.7%, confirming that spark timing is a critical factor affecting engine output.
- **Discharge Coefficient (Cd):** Altering Cd by ±10% had negligible effect at low and mid speeds but caused noticeable power changes at high speeds, underscoring its importance in intake flow modelling.
- **Frictional Losses (Cf):** Including frictional losses reduced predicted power, aligning simulation closer to real engine performance. Neglecting these losses overestimates power and volumetric efficiency.
- **Charge Heating:** Accounting for charge heating effects improved volumetric efficiency predictions. Ignoring this factor resulted in overestimations, especially at higher engine speeds.
- **Exhaust Gas Temperature (Texh):** Variations of ±50 K in exhaust temperature altered power output marginally (+0.85% to -0.14%), consistent with changes in residual gas mass and volumetric efficiency.

3.3 Combustion Duration of Alternative Fuels

- Simulations evaluated ethanol-blended gasoline (gasohol) effects on volumetric efficiency. Results indicated that ethanol blends slightly modify volumetric efficiency across engine speeds, highlighting the need for fuel-specific combustion modelling.

4. CONCLUSION

The model validation results demonstrate that the simulation closely matches experimental data for power and torque across a range of eight Mercedes-Benz engines and speeds from 1,000 to 6,000 RPM. The relative error remains within ±6%, confirming the model's accuracy and reliability in predicting engine performance. Sensitivity analyses highlight the significance of parameters such as combustion duration, spark timing, and discharge coefficients on engine output, indicating that precise calibration can optimize performance. The model effectively captures the dynamic behaviour of four-stroke engines, providing a robust foundation for further studies. Moreover, the successful replication of power trends confirms its potential for use in design optimization and emission control strategies, particularly when combined with advanced technologies such as nanotechnology-based catalytic converters.

5. FUTURE SCOPE

Future research can extend the model to incorporate real-time adaptive control systems that optimize combustion parameters dynamically, enhancing fuel efficiency and minimizing emissions. Integrating nanocatalyst behaviour within the model could improve predictions related to pollutant conversion in catalytic converters. Additionally, expanding the simulation to cover alternative fuels like biodiesel, ethanol blends, and hydrogen will support the transition to greener energy sources. Implementing machine learning algorithms for predictive maintenance and performance optimization based on simulation data presents another promising direction. Finally, validating the model across a broader variety of engine types, including multi-cylinder and turbocharged engines, will enhance its applicability in modern automotive design and regulatory compliance efforts.

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