

ENVIRONMENTAL ASSESSMENT AND OPERATING WINDOW IDENTIFICATION FOR HYDROGEN-ASSISTED LEAN COMBUSTION CONTROL

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Hydrogen-assisted lean combustion represents a promising approach for improving the environmental performance of spark-ignition engines while maintaining high energy efficiency. This study presents an environmental assessment and operating window identification of a gasoline direct injection engine equipped with hydrogen port fuel injection under lean and ultra-lean operating conditions. Hydrogen energy shares ranging from 0% to 40% were investigated with respect to brake thermal efficiency, combustion stability expressed by the coefficient of variation of indicated mean effective pressure (COV IMEP), and gaseous emissions including carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). The results show that hydrogen enrichment improves thermal efficiency, significantly reduces CO and HC emissions, and extends the stable lean-burn operating range beyond $\lambda = 2.0$. Furthermore, ultra-lean operation contributed to the suppression of NO_x formation while maintaining stable combustion. An integrated environmental evaluation identified a favourable operating window corresponding to hydrogen energy shares of approximately 30–40%, where the best balance between efficiency, emission reduction, and combustion stability was achieved. The identified operating conditions provide a valuable basis for the future development of advanced combustion control and fuel injection management strategies aimed at minimizing environmental impacts.

KEYWORDS

hydrogen-assisted combustion, environmental assessment, operating window identification, lean-burn combustion, combustion control.

1 INTRODUCTION

Road transport remains one of the major contributors to environmental degradation worldwide. Besides greenhouse gas emissions, internal combustion engines generate a broad spectrum of environmental externalities, including gaseous pollutants that negatively affect both ecosystems and human health. While considerable attention has been devoted to reducing carbon dioxide emissions from the transport sector, increasing evidence suggests that sustainable mobility

strategies must also address local air pollution associated with vehicle operation.

Among the various technological pathways proposed for transport decarbonisation, hydrogen has attracted significant attention due to its carbon-free nature and favourable combustion properties [Ling-Chin 2020, Teoh 2023]. Hydrogen exhibits a wide flammability range, high laminar flame speed, low ignition energy, and high diffusivity, making it a promising combustion enhancer for spark-ignition engines [Purayil 2023, Pana 2023].

Previous studies have demonstrated that hydrogen addition can improve thermal efficiency, accelerate flame propagation, extend lean-burn operating limits, and reduce emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) [Niu 2022, Cakmak 2018, Park 2021]. Furthermore, hydrogen-assisted combustion enables stable engine operation under lean and ultra-lean conditions, contributing to lower fuel consumption and reduced carbon-related environmental impacts [Hosseini 2023, Niu 2022].

Current research on hydrogen-fuelled and hydrogen-assisted engines predominantly focuses on combustion efficiency, engine performance, and exhaust emissions [Park 2021, Niu 2022, Purayil 2023]. Although numerous studies have confirmed the beneficial effects of hydrogen enrichment on combustion characteristics, the identification of operating conditions that simultaneously maximize efficiency, ensure combustion stability, and minimize pollutant emissions remains an important research challenge [Rodriguez 2022].

The concept of environmental assessment provides a suitable framework for evaluating these interactions. In the context of transport systems, environmental externalities represent adverse effects imposed on society and the environment that are not directly reflected in the operational costs of a vehicle [Ling-Chin 2020, Teoh 2023]. For internal combustion engines, these externalities are primarily associated with atmospheric pollution and greenhouse gas emissions [Lamas 2011 & 2020]. Therefore, a comprehensive assessment of hydrogen-assisted combustion should consider both energy efficiency and pollutant formation in order to identify environmentally favourable operating conditions [Minchev 2023].

This study investigates the environmental performance of hydrogen-assisted lean combustion in a gasoline direct injection spark-ignition engine equipped with hydrogen multi-point port fuel injection. The engine was operated with hydrogen energy shares ranging from 0% to 40% under lean and ultra-lean conditions. The analysis focuses on combustion behaviour, brake thermal efficiency, combustion stability, and gaseous emissions including carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). The objective is to identify an operating window that provides a favourable balance between efficiency, emission reduction, and combustion stability, thereby supporting the development of environmentally sustainable combustion strategies.

2 MATERIALS AND METHODS

The experimental investigation was performed using a turbocharged four-cylinder spark-ignition engine originally equipped with a gasoline direct injection (DI) system. To enable dual-fuel operation, the engine was supplemented with an additional hydrogen port fuel injection (PFI) system supplying hydrogen into the intake manifold [Park 2021, Purayil 2023]. A simplified schematic representation of the experimental setup is shown in Figure 1. The engine was coupled to an eddy-current dynamometer used for load control and performance

measurements, while exhaust emissions were monitored using a multi-component exhaust gas analyzer [Puskar 2013 & 2017].

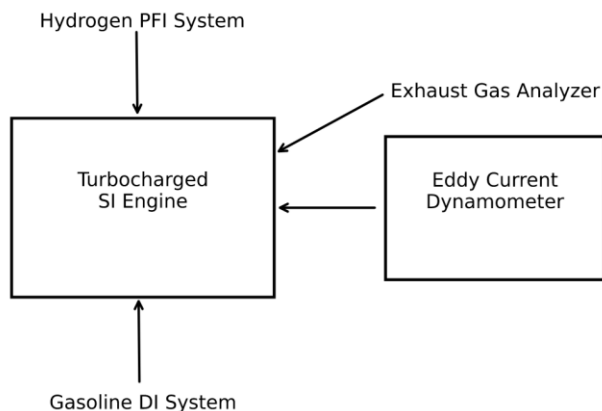


Figure 1. Simplified schematic representation of the experimental setup showing the turbocharged spark-ignition engine equipped with gasoline direct injection (DI), hydrogen port fuel injection (PFI), exhaust gas analysis, and dynamometer load control

The main specifications of the tested engine are summarized in Table 1.

Parameter	Value
Engine type	Turbocharged SI engine
Number of cylinders	4
Valvetrain	DOHC, 16 valves
Displacement	1498 cm ³
Compression ratio	12:1
Rated power	110 kW
Fuel system	Gasoline DI + Hydrogen PFI
Aspiration	Turbocharged

Table 1. Specifications of the tested engine

The tested engine had a displacement of 1498 cm³, a compression ratio of 12:1, and a rated power output of 110 kW. Hydrogen was supplied through a multi-point injection system integrated into the intake manifold, whereas gasoline was delivered using the original high-pressure direct injection system. The injection timing and duration of both fuels were controlled through an open electronic control unit, enabling adjustment of the hydrogen energy share and operating conditions [Cakmak 2021, Niu 2022].

Five operating fuel modes were investigated in order to evaluate the influence of hydrogen enrichment on combustion behaviour and environmental performance. The definition of the individual fuel modes is presented in Table 2.

Fuel mode	Gasoline energy share (%)	Hydrogen energy share (%)
G100	100	0
G9H1	90	10
G8H2	80	20
G7H3	70	30
G6H4	60	40

Table 2. Definition of fuel modes used in the study

As shown in Table 2, pure gasoline operation (G100) served as the reference condition, while four dual-fuel modes were established by gradually increasing the hydrogen energy share to 10% (G9H1), 20% (G8H2), 30% (G7H3), and 40% (G6H4). Throughout the study, the hydrogen proportion was expressed

as hydrogen energy share, defined as the fraction of the total lower heating value supplied by hydrogen. The upper hydrogen limit was selected to avoid excessive combustion instability and operational risks associated with higher hydrogen concentrations in port-injected systems [Purayil 2023, Pana 2023].

The engine was operated under lean and ultra-lean conditions with the air excess ratio ranging from $\lambda = 1.0$ to $\lambda = 2.6$. For each operating point, the combustion process was evaluated using brake thermal efficiency, in-cylinder pressure analysis, and the coefficient of variation of indicated mean effective pressure (COV IMEP). Combustion stability was assessed according to the commonly accepted criterion of COV IMEP below 5%, which was considered representative of stable engine operation [Niu 2022, Park 2021].

Environmental performance was evaluated through measurements of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). The measured emissions were analysed in relation to hydrogen energy share and air excess ratio in order to identify operating conditions that provide favourable environmental performance while maintaining stable combustion. Each operating point was measured repeatedly three times to ensure the reliability, repeatability, and statistical consistency of the experimental results.

3 ENVIRONMENTAL ASSESSMENT FRAMEWORK

The environmental performance of hydrogen-assisted lean combustion was evaluated using a set of indicators reflecting both energy utilization and pollutant formation. In the context of transport systems, environmental externalities represent adverse effects imposed on society and the environment that are not directly reflected in the operational costs of vehicle use [Ling-Chin 2020]. Among the most significant externalities associated with internal combustion engines are atmospheric pollution, greenhouse gas emissions, noise generation, and vibration-related impacts.

In the present study, environmental assessment was based on brake thermal efficiency (BTE), combustion stability expressed by the coefficient of variation of indicated mean effective pressure (COV IMEP), and gaseous emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). Brake thermal efficiency was considered an indirect environmental indicator because higher efficiency reduces fuel consumption and consequently lowers the overall environmental burden associated with fuel production and utilization [Ling-Chin 2020, Teoh 2023].

Carbon monoxide and unburned hydrocarbons were selected as indicators of incomplete combustion and local air pollution. Both pollutants contribute to deterioration of air quality and are associated with adverse impacts on human health. Nitrogen oxides represent one of the most important pollutants generated during high-temperature combustion processes, contributing to photochemical smog formation, acidification, and respiratory diseases [Cakmak 2021, Niu 2022, Hosseini 2023].

Combustion stability was included in the assessment because unstable combustion is commonly associated with increased fuel consumption, elevated pollutant emissions, and reduced overall engine efficiency. Consequently, improvements in combustion stability may provide environmental benefits beyond conventional performance indicators [Niu 2022, Park 2021, Pana 2023].

The environmental evaluation was performed by analysing the response of individual indicators to increasing hydrogen energy

share and air excess ratio. Particular attention was devoted to identifying operating conditions that simultaneously improve combustion stability, reduce pollutant emissions, and maintain favourable energy utilization characteristics. Such operating points may be considered environmentally preferable configurations for hydrogen-assisted lean combustion systems [Niu 2022, Purayil 2023].

4 RESULTS AND DISCUSSION

The results demonstrate that hydrogen enrichment significantly influences the environmental performance of the investigated spark-ignition engine operating under lean and ultra-lean combustion conditions. The environmental benefits are reflected not only in improved energy utilization but also in substantial reductions of pollutant emissions and enhanced combustion stability. The combined analysis of Figures 2–7 reveals a consistent trend indicating that increasing hydrogen energy share extends the environmentally favourable operating region of the engine.

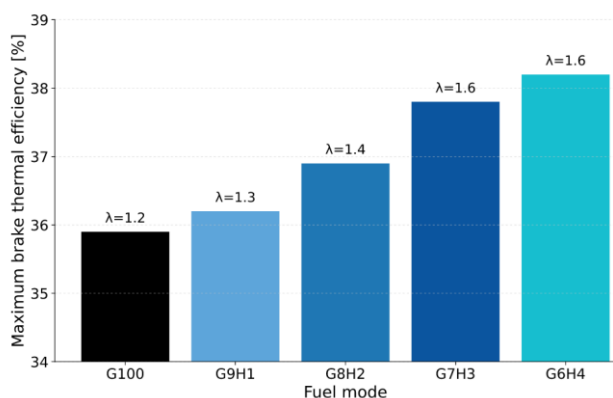


Figure 2. Maximum achievable brake thermal efficiency under lean operation for different hydrogen energy shares

The influence of hydrogen addition on brake thermal efficiency is illustrated in Figure 2. The results indicate a progressive increase in maximum achievable efficiency with increasing hydrogen energy share. While conventional gasoline operation (G100) achieved a maximum brake thermal efficiency of 35.9%, hydrogen enrichment increased this value to 38.2% at the highest investigated hydrogen share. The improvement can be attributed to the favourable combustion characteristics of hydrogen, including its high laminar flame speed, low ignition energy, and wide flammability range. These properties promote faster and more complete combustion, particularly under lean operating conditions. From an environmental perspective, improved thermal efficiency contributes directly to reduced fuel consumption and lower overall environmental burdens associated with fuel production, distribution, and utilization. The observed efficiency increase therefore represents an indirect but important environmental benefit of hydrogen-assisted combustion.

The environmental advantages of hydrogen enrichment become even more apparent when considering carbon monoxide emissions. As shown in Figure 3, the maximum reduction in carbon monoxide emissions increased progressively with hydrogen content, reaching approximately 45.5% for the G6H4 operating mode. Carbon monoxide is primarily generated during incomplete combustion processes; therefore, its reduction indicates improved oxidation efficiency and more complete fuel conversion. The observed decrease is consistent with the enhanced flame propagation characteristics of hydrogen, which improve combustion quality even under

highly diluted mixtures. Consequently, hydrogen-assisted lean combustion contributes to improved local air quality by reducing emissions of a pollutant known to adversely affect human health and urban environmental conditions.

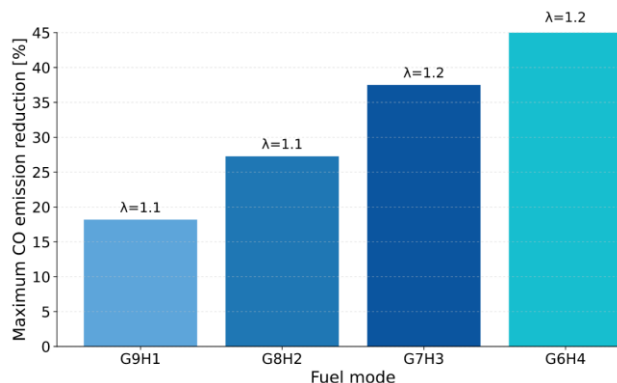


Figure 3. Maximum carbon monoxide emission reduction achieved under lean operation for different hydrogen energy shares relative to conventional gasoline operation (G100)

A similar trend was observed for hydrocarbon emissions. Figure 4 shows that the maximum hydrocarbon emission reduction increased continuously with hydrogen energy share. The greatest reduction was achieved for the highest hydrogen concentration, indicating that hydrogen effectively suppresses the formation of unburned fuel species. This behaviour is associated with improved flame stability and more complete combustion within crevice volumes and locally fuel-rich regions. Since unburned hydrocarbons contribute to photochemical smog formation and atmospheric pollution, their reduction represents another important environmental benefit of hydrogen-assisted combustion systems. The simultaneous reduction of both CO and HC emissions confirms that hydrogen enrichment substantially improves combustion completeness across a wide range of lean operating conditions.

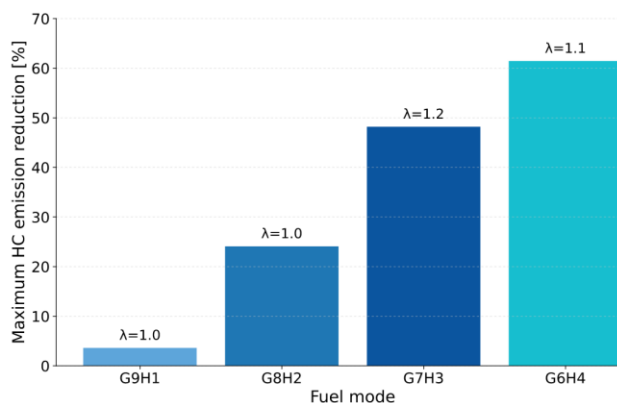


Figure 4. Maximum hydrocarbon emission reduction achieved under lean operation for different hydrogen energy shares relative to conventional gasoline operation (G100)

Nitrogen oxides exhibited a different behaviour compared to carbon-related pollutants. Figure 5 presents the minimum NO_x emissions achieved under ultra-lean operation. Although hydrogen enrichment is generally associated with increased combustion temperatures and potentially enhanced NO_x formation under moderately lean conditions, the results demonstrate that operation in the ultra-lean regime substantially suppresses thermal NO_x production. The minimum NO_x values remained low despite increasing hydrogen energy share, indicating that the beneficial effect of mixture dilution

outweighed the temperature increase associated with hydrogen combustion.

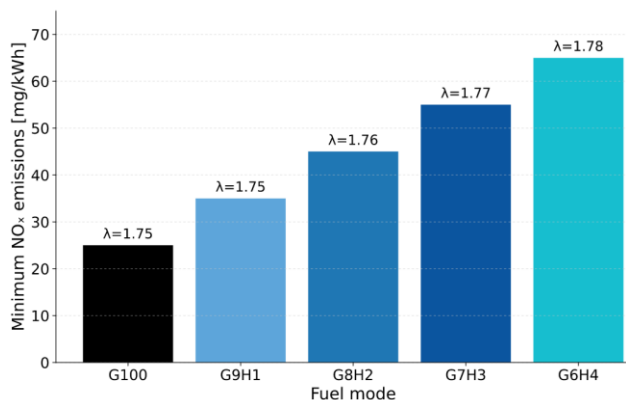


Figure 5. Minimum Nitrogen Oxides Emissions Achieved under Ultra-Lean Operation

These findings confirm that the environmental impact of hydrogen on NO_x emissions cannot be evaluated independently of the air excess ratio and that ultra-lean operation plays a critical role in achieving favourable emission performance.

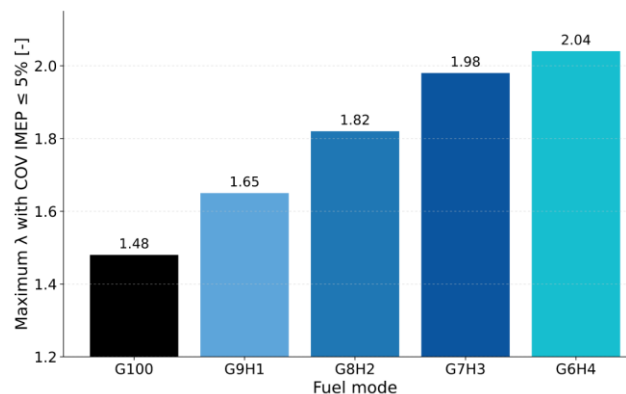


Figure 6. Maximum stable lean-burn operating range determined using the COV IMEP $\leq 5\%$ criterion for different hydrogen energy shares

Combustion stability represents another key environmental consideration because unstable combustion is often associated with increased fuel consumption, elevated emissions, and deteriorated engine performance. The results shown in Figure 6 demonstrate that hydrogen enrichment significantly extends the stable lean-burn operating range. The maximum air excess ratio satisfying the commonly accepted stability criterion of COV IMEP $\leq 5\%$ increased from approximately $\lambda = 1.48$ for conventional gasoline operation to values exceeding $\lambda = 2.0$ for hydrogen-enriched fuel modes. This improvement confirms the ability of hydrogen to stabilize combustion under highly diluted conditions where gasoline combustion would normally become unstable. From an environmental standpoint, the extension of the stable operating range is particularly important because it enables operation within ultra-lean regions characterized by reduced fuel consumption and lower pollutant emissions.

The combined environmental effects of hydrogen enrichment are summarized in Figure 7 through the Overall Environmental Performance Index. The index integrates thermal efficiency, combustion stability, carbon monoxide reduction, hydrocarbon reduction, and nitrogen oxide performance into a single comparative metric. The results clearly indicate a substantial improvement in overall environmental performance with increasing hydrogen energy share. The largest environmental gains were observed when the hydrogen proportion increased from 20% to 30%, suggesting the existence of a critical

transition region where the benefits of hydrogen-assisted combustion become particularly pronounced.

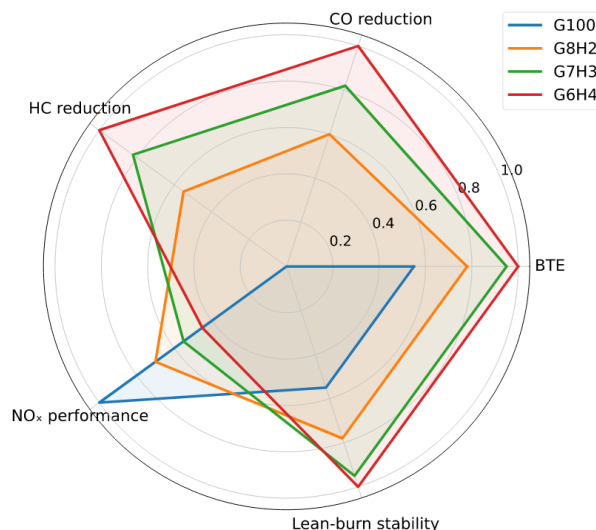


Figure 7. Overall Environmental Performance Index

While the highest index values were achieved for the G6H4 operating mode, the difference between the G7H3 and G6H4 configurations was relatively small compared with the increase in hydrogen consumption required to achieve the additional improvement.

Considering all evaluated indicators simultaneously, hydrogen energy shares between 30% and 40% appear to provide the most favourable balance between efficiency, emission reduction, and combustion stability. However, from a practical perspective, the 30% hydrogen energy share may represent the most attractive operating condition because it achieves environmental performance comparable to the highest hydrogen concentration while requiring a lower hydrogen supply rate. This finding is particularly relevant for future transportation applications where hydrogen availability, infrastructure requirements, and system costs remain important considerations.

Overall, the results demonstrate that hydrogen-assisted lean combustion offers significant potential for reducing the environmental externalities associated with spark-ignition engines. The simultaneous improvement of thermal efficiency, reduction of carbon-related emissions, suppression of nitrogen oxides under ultra-lean conditions, and extension of the stable operating range collectively indicate that hydrogen enrichment can contribute to more environmentally sustainable operation of internal combustion engines. The findings further suggest that environmental assessments of alternative fuels should incorporate multiple performance indicators simultaneously rather than relying solely on individual emission measurements, thereby providing a more comprehensive evaluation of their overall environmental impact.

5 CONCLUSION

This study presented an environmental assessment and operating window identification of hydrogen-assisted lean combustion in a turbocharged gasoline direct injection spark-ignition engine. Hydrogen energy shares ranging from 0% to 40% were evaluated under lean and ultra-lean operating conditions with respect to brake thermal efficiency, combustion stability, and gaseous emissions including carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). The results confirmed that hydrogen enrichment substantially improves the environmental performance of lean-burn

combustion systems. Increasing hydrogen energy share enhanced brake thermal efficiency, reduced carbon-related emissions, and significantly extended the stable operating range. The maximum air excess ratio satisfying the combustion stability criterion of COV IMEP $\leq 5\%$ increased from approximately $\lambda = 1.48$ for conventional gasoline operation to values exceeding $\lambda = 2.0$ for hydrogen-enriched fuel modes. This extended operating range enabled stable ultra-lean combustion associated with lower fuel consumption and reduced pollutant formation.

The environmental assessment further demonstrated that hydrogen enrichment contributes to significant reductions in carbon monoxide and hydrocarbon emissions, while ultra-lean operation effectively suppresses thermal NO_x formation. The integrated Environmental Performance Index revealed a progressive improvement in overall environmental performance with increasing hydrogen energy share. The most significant transition was observed between 20% and 30% hydrogen energy share, indicating the onset of a highly favourable operating region.

Based on the combined evaluation of efficiency, emissions, and combustion stability, hydrogen energy shares of approximately 30–40% were identified as the optimal environmental operating window for the investigated engine configuration. Within this range, the most advantageous balance between efficiency improvement, emission reduction, and stable operation was achieved.

The identified operating window provides a valuable foundation for the future development of advanced combustion control strategies and fuel injection management algorithms aimed at optimizing engine operation while minimizing environmental impacts. Future research should focus on real-time control implementation and validation under transient operating conditions [Krenicky 2018, Zidek 2024].

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