EFFECTS OF HYDROGEN ENHANCEMENT ON EFFICIENCY AND NO_X EMISSIONS OF LEAN AND EGR - DILUTED MIXTURES IN A SI ENGINE: A CLIMATE CHANGE PERSPECTIVE

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Abstract: The global climate crisis requires urgent reductions in greenhouse gas (GHG) emissions from the transportation sector, which contributes nearly a quarter of global CO_2 output. While electrification and hydrogen fuel cells represent long-term decarbonization pathways, improving the environmental performance of existing spark-ignition (SI) engines is critical in the short to medium term. This paper investigates the role of hydrogen enrichment in SI engines operating under lean and exhaust gas recirculation (EGR)-diluted conditions, reframing its implications within climate change mitigation. Hydrogen addition extends lean-burn limits, stabilizes EGR-diluted combustion, and enhances efficiency, thereby reducing fuel consumption and CO_2 emissions. However, the high flame temperature of hydrogen influences NO_x formation, raising a trade-off between efficiency gains and ozone-forming emissions. Results show that optimized hydrogen supplementation can achieve simultaneous improvements in efficiency and reductions in climate-relevant pollutants, positioning hydrogen enrichment as a transitional technology for decarbonizing the transport sector.

Index Terms - Hydrogen enrichment, Spark-ignition engine, Lean-burn, Exhaust gas recirculation, Climate change mitigation, NO_x emissions, Greenhouse gases

1. INTRODUCTION

Climate change, driven largely by anthropogenic CO_2 emissions, poses a critical challenge to global sustainability. The transportation sector alone contributes nearly 24% of global energy-related GHG emissions, with spark-ignition (SI) engines dominating passenger vehicle fleets. Although long-term solutions such as electrification and renewable hydrogen fuel cells are advancing, internal combustion engines (ICEs) will remain in use for decades, particularly in developing regions. Therefore, incremental improvements in their efficiency and emissions performance are essential for meeting near-term climate goals.

Hydrogen enhancement in SI engines has emerged as a promising technique to improve combustion. As a carbon-free fuel with high flame speed and wide flammability limits, hydrogen can stabilize lean and EGR-diluted mixtures. This enables higher efficiency and lower CO_2 emissions per unit of work. However, hydrogen's combustion properties also affect nitrogen oxides (NO_x), which—beyond their role as local air pollutants—act as precursors to tropospheric ozone, a short-lived climate forcer.

This paper reviews the role of hydrogen enhancement in SI engines under lean and EGR conditions, emphasizing the balance between improved efficiency, CO_2 reduction, and NO_x trade-offs, with direct implications for climate change mitigation.

2. HYDROGEN ENHANCEMENT AND CLIMATE MECHANISMS

Hydrogen enrichment affects several climate-relevant pathways:
Carbon dioxide reduction: Replacing part of the hydrocarbon fuel with hydrogen lowers the carbon intensity of combustion. Additionally, efficiency improvements translate into reduced overall CO_2 emissions [1].
Efficiency gains: Hydrogen enrichment increases flame propagation speed and reduces cyclic variability, resulting in higher thermal efficiency and lower CO_2 emissions per kilometer traveled.
- NO_x and climate trade-offs: Hydrogen raises local flame temperatures, increasing thermal NO_x formation. Although NO_x is not a direct GHG, it contributes to ozone formation, a strong short-lived climate forcer.
- Transitional role in decarbonization: Hydrogen enrichment in SI engines offers a bridge toward a hydrogen economy, enabling partial decarbonization without requiring fully new infrastructure.

3. LEAN-BURN SI ENGINES WITH HYDROGEN ENRICHMENT

Operating SI engines under lean-burn conditions reduces peak combustion temperatures, which lowers NO_x formation and improves efficiency. However, excessively lean mixtures cause combustion instability. Hydrogen enrichment counters this by expanding the lean limit, improving flame speed, and reducing misfire rates [2].
From a climate perspective, lean hydrogen-enriched combustion yields reduced CO_2 emissions due to lower hydrocarbon consumption, lower ozone-related warming through reduced NO_x under optimized conditions, and a viable near-term strategy for decarbonizing conventional SI fleets.
Figure 1 illustrates the effect of hydrogen fraction on engine efficiency and CO_2 reduction.

4. HYDROGEN IN EGR-DILUTED SI ENGINES

Exhaust gas recirculation (EGR) reduces oxygen concentration and peak temperatures, lowering NO_x emissions. However, high EGR levels destabilize combustion. Hydrogen enrichment addresses this by maintaining flame propagation under diluted conditions [4].
Figure 2 shows the NO_x response to hydrogen enrichment in EGR-diluted mixtures. Moderate hydrogen addition lowers NO_x emissions, while excessive enrichment increases them due to elevated local flame temperatures.

5. COMPARATIVE SUMMARY

Table 1 provides a consolidated view of the climate-relevant trade-offs of hydrogen enrichment in SI engines. The results demonstrate simultaneous CO_2 reduction and efficiency improvement with moderate hydrogen addition, while NO_x control requires careful management.

6. BROADER CLIMATE IMPLICATIONS

Hydrogen enrichment in SI engines aligns with global decarbonization strategies in several ways [5]:
- Short-term mitigation: Provides immediate reductions in CO_2 and ozone-forming NO_x emissions compared to baseline gasoline engines.
- Transition technology: Bridges the gap until renewable hydrogen infrastructure and electric vehicles achieve wider adoption.
- Integration with sustainable fuels: Pairing hydrogen with biofuels or synthetic e-fuels amplifies lifecycle GHG reductions.

However, to maximize climate benefits, hydrogen must increasingly be sourced from low-carbon pathways (green hydrogen).

7. CONCLUSION

Hydrogen enrichment of lean and EGR-diluted SI engine mixtures offers clear pathways to improve efficiency and reduce CO_2 emissions, directly contributing to climate change mitigation. While NO_x formation remains a challenge, optimized combinations of hydrogen fraction, EGR rates, and combustion control strategies allow for net reductions in climate-relevant pollutants [4].

As the transport sector transitions to zero-emission propulsion, hydrogen-enriched SI engines represent a valuable bridge technology, enabling meaningful near-term GHG reductions while supporting the long-term shift to renewable hydrogen and electrification.

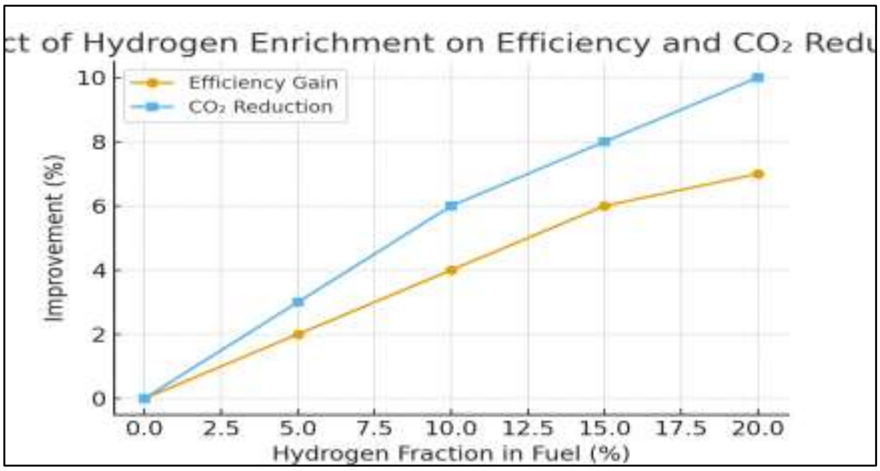

Figure 1. Effect of hydrogen enrichment on efficiency gains and CO_2 reduction in SI engines under lean-burn conditions

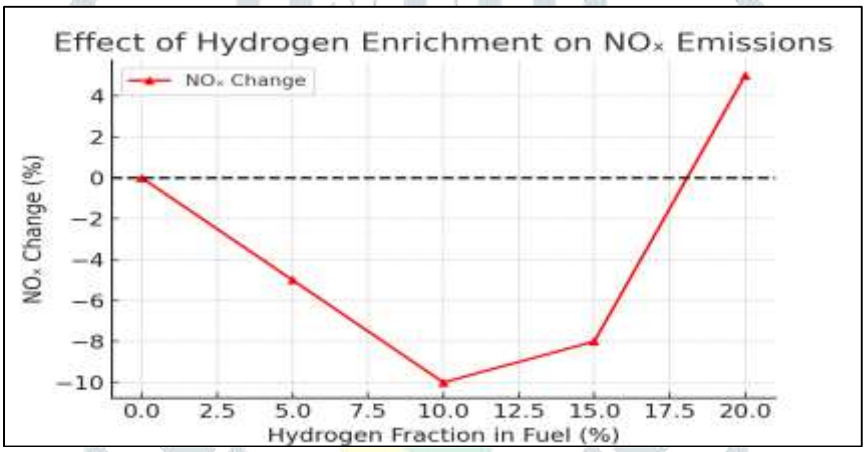

Figure 2. Effect of hydrogen enrichment on NO_x emissions in SI engines operating with EGR dilution.

Table 1. Illustrative impact of hydrogen enrichment on efficiency, CO_2, and NO_x emissions in SI engines.

Hydrogen Fraction (%)	Efficiency Gain (%)	CO2 Reduction (%)	NOx Change (%)
0	0	0	0
5	2	3	-5
10	4	6	-10
15	6	8	-8
20	7	10	5

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