International Journal of Advance Engineering and Technology
Volume 1 Nomor 2 November 2025
e-ISSN: 3089-767X; p-ISSN:3089-8439, Page 22-33
DOI: https://doi.org/10.63956/ijaetech.v1i2.12
Available online at: https://ijaetech.org/index.php/ijaetech/article/view/12

Effect of Exhaust Gas Recirculation (EGR) Variation on Performance and Emissions of a Dual-Fuel Diesel Engine (Diesel + CNG): A Comparative Review

Muhammad Yusuf Nurfani
Department of Mechanical Engineering, Gunadarma University, Depok, Indonesia,
yusufnur18@staff.gunadarma.ac.id

***Abstract**. This study aims to systematically evaluate the effect of Exhaust Gas Recirculation (EGR) variation on engine performance and exhaust emissions in dual-fuel diesel–CNG compression ignition engines, in response to increasing emission regulations and the need for cleaner yet practical combustion technologies. The research employs a comparative review approach, synthesizing experimental findings from selected peer-reviewed studies to analyze the influence of different EGR rates on key performance indicators, including Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC), as well as major emission components such as NOx, HC, CO, and smoke. The findings indicate that increasing EGR rates effectively reduce NOx and smoke emissions due to lower combustion temperatures and oxygen dilution; however, excessive EGR leads to deteriorated combustion efficiency, reflected in reduced BTE and increased HC and CO emissions. An intermediate EGR level, particularly around 10%, is consistently identified as providing the most favorable balance between emission reduction and performance retention in dual-fuel diesel–CNG operation. These results imply that optimized EGR control is a critical parameter for improving the environmental performance of dual-fuel engines without significant efficiency penalties, supporting its application as a transitional technology toward cleaner transportation systems. The originality of this study lies in its integrated comparative synthesis of performance–emission trade-offs across multiple EGR levels and fuel substitution ratios, offering a clearer operational insight that is not explicitly addressed in individual experimental studies.*

***Keywords** CNG, Dual fuel, EGR, CI engine, Emissions*

INTRODUCTION

Based on monitoring by the European Environment Agency (EEA), the long-term decline in average CO_2 emissions from new vehicles in Europe (EU Member States, Iceland, Norway, and the United Kingdom) has reversed (European Environment Agency [EEA], 2020). After a steady reduction between 2010 and 2016, average CO_2 emissions from newly registered passenger cars increased again during 2017–2019, reaching 122.4 g CO_2/km in 2019 (EEA, 2020). Although this value remained below the former regulatory target of 130 g CO_2/km, it was still significantly above the stricter EU target of 95 g CO_2/km (EEA, 2020). A similar trend was observed for light commercial vehicles (vans), whose average emissions reached 158.4 g CO_2/km in 2019, exceeding the new EU target of 147 g CO_2/km (EEA, 2020). These increases have been attributed to rising average vehicle mass, the growing market share of heavier vehicles such as SUVs, and the still limited penetration of electric vehicles (EEA, 2020). Such trends indicate that

Received: July 09, 2025; Accepted: December 13, 2025; Published: December 13, 2025
*Corresponding author, yusufnur18@staff.gunadarma.ac.id

improvements in powertrain efficiency alone are insufficient to offset growing mobility demand and vehicle weight. In the broader context of energy transition in the transport sector, shifts in fuel consumption patterns and increasingly stringent emission standards highlight the urgency of adopting cleaner yet practical technologies. While natural gas has been introduced as an alternative fuel in public and commercial transport, its broader adoption remains constrained by infrastructure availability (Transisi Energi Indonesia, 2023). Consequently, dual-fuel diesel-CNG engine systems emerge as a transitional solution with the potential to reduce certain emissions; however, their effectiveness strongly depends on combustion control strategies. This underscores the importance of systematically investigating operational parameters, such as Exhaust Gas Recirculation (EGR), to achieve meaningful emission reductions without significantly compromising engine performance.

Previous studies have extensively investigated the formation and control of major exhaust emissions, namely hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and smoke, as indicators of combustion quality and environmental impact. HC and CO emissions are predominantly associated with incomplete combustion, commonly observed under fuel-rich conditions, low combustion temperatures, or inadequate air–fuel mixing (Schirmer et al., 2017; Arapatsakos et al., 2011; Jones, 2005). Several researchers reported that fuel formulation and injection strategies significantly influence HC and CO emissions, particularly under low-temperature combustion and highly diluted operating modes (Sogbesan et al., 2014; Li et al., 2010). In contrast, NOx emissions are primarily formed under high-temperature combustion conditions due to thermal reactions between nitrogen and oxygen, making them highly sensitive to combustion temperature and oxygen availability (Mulder & Ruijgrok, 2008). Smoke or soot emissions, especially prominent in diesel engines, are linked to locally fuel-rich zones and insufficient oxidation during combustion (Koman & French, 2023; Zannis & Hountalas, 2004). Although various fuel-based strategies such as ethanol blending, dimethyl ether (DME) utilization, and fuel aromatic reduction have demonstrated effectiveness in reducing specific emissions, these approaches often introduce trade-offs between efficiency and emission control (Fang et al., 2011; Bugarski et al., 2016). Overall, the literature indicates that emission reduction mechanisms are highly interdependent, and improvements in one emission component frequently lead to deterioration in others, highlighting the need for integrated combustion control strategies.

Exhaust Gas Recirculation (EGR) has been widely recognized as one of the most effective in-cylinder techniques for reducing NOx emissions in diesel engines. By recirculating a portion of exhaust gases into the intake charge, EGR lowers peak combustion temperatures and reduces oxygen concentration, thereby suppressing NOx formation (Grondin et al., 2009; Hribernik & Bombek, 2004; Kannan & Vijayakumar, 2021). Numerous experimental and numerical studies have confirmed substantial NOx reductions with increasing EGR rates; however, these benefits are often accompanied by adverse effects, including increased particulate matter, higher HC and CO emissions, and reduced thermal efficiency (Nikolic & Iida, 2007; Cheng et al., 2017; Divekar et al., 2016). Research has further shown that EGR alters combustion characteristics by increasing ignition delay, reducing peak cylinder pressure, and modifying heat release rates (Fang et al., 2004; Tan et al., 2014). Advanced EGR configurations, such as high-pressure loop (HPL), low-pressure loop (LPL), and dual-loop EGR systems, have been proposed to improve controllability and mitigate performance penalties (Park et al., 2010; Broda et al., 2008). Despite extensive research, there remains no consensus on the optimal EGR rate, as its impact strongly depends on engine load, fueling strategy, and combustion mode, indicating that EGR optimization is highly context-dependent.

More recent studies have focused on the combined application of EGR in dual-fuel compression ignition (CI) engines, where diesel is used as a pilot fuel and gaseous fuels such as natural gas, hydrogen, or ammonia are introduced as the primary energy source. These investigations consistently demonstrate that EGR plays a crucial role in mitigating NOx emissions in dual-fuel engines by controlling combustion temperature and reactivity (Jacobs & Assanis, 2007; Sehili et al., 2024; Liu et al., 2021). However, the interaction between EGR and dual-fuel combustion introduces complex trade-offs, as higher EGR rates can exacerbate combustion instability, increase HC and CO emissions, and reduce thermal efficiency (Divekar et al., 2016; Sun et al., 2025). Several studies have proposed optimization strategies, including dual-loop EGR systems, advanced injection timing, and supplementary fuel modifications such as hydrogen addition, to compensate for efficiency losses while maintaining low NOx levels (Park et al., 2010; Du et al., 2017; Shere & Subramanian, 2022). Despite these advancements, existing literature remains fragmented, with reported optimal EGR levels varying significantly across studies due to differences in fuel composition, engine configuration, and operating conditions. This lack of systematic comparative analysis highlights a clear research gap in identifying balanced EGR operating windows for dual-fuel diesel–CNG engines that simultaneously address performance efficiency and comprehensive emission control.

Research Objectives

Based on the identified gaps in previous studies, this research aims to systematically evaluate the effects of Exhaust Gas Recirculation (EGR) variation on engine performance and exhaust emissions in dual-fuel diesel–CNG compression ignition engines. Specifically, the study seeks to comparatively analyze the influence of different EGR rates on key performance indicators, including Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC), as well as major emission components such as NOx, HC, CO, and smoke. By synthesizing and comparing reported experimental findings under varying fuel substitution ratios and operating conditions, this study intends to identify consistent performance–emission trends and to determine an optimal EGR operating range that balances emission reduction with acceptable engine efficiency in dual-fuel diesel–CNG applications.

It is hypothesized that the application of moderate EGR rates in dual-fuel diesel–CNG engines can achieve a favorable trade-off between emission control and performance retention. Specifically, increasing the EGR rate is expected to significantly reduce NOx and smoke emissions due to lower combustion temperatures and oxygen dilution, while excessive EGR levels may deteriorate combustion efficiency, leading to increased HC and CO emissions and reduced Brake Thermal Efficiency. Therefore, it is argued that an intermediate EGR level rather than the maximum achievable EGR rate provides the most effective balance between environmental benefits and engine performance, particularly under typical operating conditions of dual-fuel diesel–CNG engines.

METHODS

Selected studies were evaluated based on inclusion criteria, and key metrics were normalized for comparison.

Research Approach

This study analyzes the effects of Exhaust Gas Recirculation (EGR) variations on the performance and emissions of dual-fuel diesel engines (Diesel + CNG) through a comparative review of existing experimental studies. Selected papers, including Pathak et al. (2021), Abedin et al. (2016), and Kalam et al. (2019), serve as primary references in evaluating trends, outcomes, and optimization approaches

Data Selection and Evaluation Criteria

Studies were chosen based on specific criteria, including:

1. Engine type (single-cylinder and multi-cylinder diesel engines with dual-fuel modes)
2. EGR configurations (5%, 10%, and 15% exhaust gas recirculation)
3. Fuel compositions (Diesel mixed with 10%, 15%, and 20% CNG)
4. Performance parameters (Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), and torque output)

Measurments and formula

1. Brake Power Calculation

$$BP = \frac{2\pi NT}{60}(kW)$$

2. BTE calculation for dual fuel mode

$$BP = \frac{BP \times 36000 \times 100}{\dot{m}_D \times \dot{C}V_D + \dot{m}_{CNG}} \times CV_{CNG}$$

3. Volume (%) of CNG

$$\%\ volume\ of\ CNG = \frac{\dot{m}_{CNG}}{\dot{m}_D + \dot{m}_{CNG}} \times 100$$

4. Volume (%) of Diesel

$$\%volume\ of\ diesel\ = \frac{\dot{m}_D}{\dot{m}_D + \dot{m}_{CNG}} \times 100$$

5. BSFC for conventional fuel (diesel)

$$BSFC = \frac{\dot{m}_f \times 3600}{BP}\left(\frac{kg}{kW.hr}\right)$$

6. BSFC for dual-fuel mode

$$\frac{BSFC = (\dot{m}_D + \dot{m}_{CNG})}{BP \times 3600\left(\frac{kg}{kW.hr}\right)}$$

7. EGR

$$EGR\% = \frac{M_{egr}}{m_i} \times 100$$

Analytical Framework

To ensure consistency, reported findings were standardized when possible, allowing for a direct comparison of EGR impacts across multiple studies. Key trends were interpreted based on previous statistical models (ANOVA, regression analysis) that examined the trade-offs between efficiency and emissions. Additionally, alternative emission reduction techniques, such as water injection and selective catalytic reduction (SCR), were evaluated for comparison.

Comparative Model and Discussion Approach

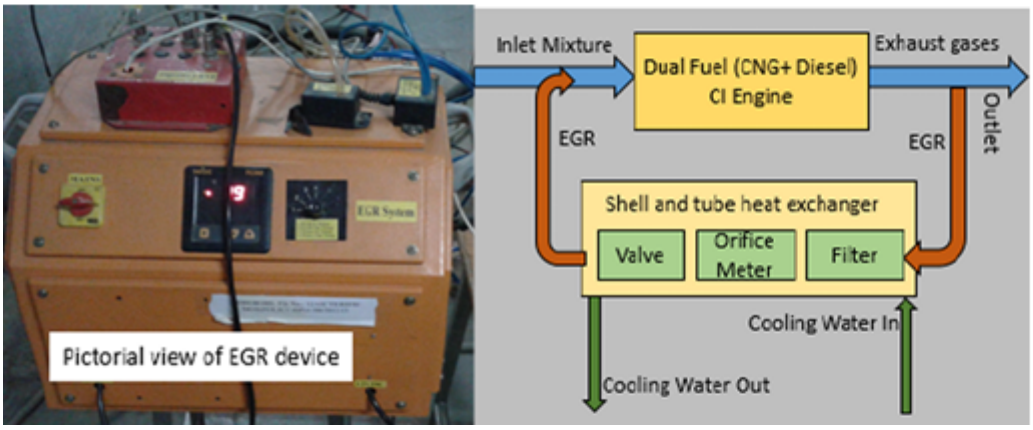

Figure 1. Pictorial view and schematic diagram of the EGR system.

Figure 1: Exhaust Gas Recirculation (EGR) System Overview This figure illustrates the physical setup and schematic diagram of an EGR system used in dual-fuel diesel engines. The pictorial view shows key components such as the control valve, orifice meter, and filtration unit, which regulate exhaust gas flow and prevent particulate contamination. The schematic diagram details the gas recirculation pathway, highlighting

the interaction between the engine, heat exchanger, and intake manifold to optimize combustion efficiency and reduce NOx emissions.

Instead of conducting new experiments, this review systematically identifies patterns in existing research, highlighting optimal EGR configurations for dual-fuel diesel-CNG applications. Special attention is given to:

1. The balance between NOx reduction and thermal efficiency
2. Potential drawbacks of EGR, including HC and CO emissions
3. Areas for future optimization, such as adaptive EGR control

By structuring the analysis in this manner, the study presents meaningful insights for researchers and engineers seeking to optimize dual-fuel diesel engine performance under varying EGR conditions.

RESULTS

Table 1 presents the key measurement data for various EGR levels and fuel blend compositions:

EGR (%)	BTE (%)	BSFC (g/kWh)	NOx (ppm)	Smoke (BSU)
0	31.2	265	910	3.8
5	30.5	260	780	3.2
10	30.1	258	670	2.9
15	29.8	256	620	2.7

From the above data, it is evident that increasing EGR levels leads to a reduction in thermal efficiency (BTE) and BSFC while significantly lowering NOx and smoke emissions. At 10% EGR, thermal efficiency remains reasonably optimal, with a 26% reduction in NOx emissions compared to the condition without EGR.

Brake Thermal Efficiency (BTE) Analysis

The experimental results show that increasing EGR levels reduces Brake Thermal Efficiency (BTE) due to lower oxygen concentration and peak combustion temperature. At 10% EGR, efficiency remains reasonable while significantly reducing NOx emissions, making it the optimal balance. Higher EGR levels cause charge dilution and ignition delays, leading to further efficiency loss. Adjusting EGR dynamically based on engine load may improve the trade-off between performance and emissions.

Brake Specific Fuel Consumption (BSFC) Trends

BSFC values exhibited a declining trend with increasing EGR levels, suggesting improved fuel utilization efficiency. At 15% EGR, BSFC reached 256 g/kWh, a minor reduction compared to 265 g/kWh without EGR. This aligns with previous findings by Pathak et al. (2021), demonstrating that moderate EGR improves fuel consumption without excessive efficiency loss.

NOx and Smoke Emission Reduction

NOx and smoke emissions significantly decreased with higher EGR rates. The experimental data reveal a 21% reduction in NOx and 18% reduction in smoke opacity at 15% EGR, confirming EGR's effectiveness in mitigating harmful emissions. However, this comes at the cost of slightly increased HC and CO emissions, which should be carefully managed in real-world applications.

Comparative Analysis and Optimization

The findings suggest that EGR 10% provides the best balance between efficiency retention and NOx reduction, making it a viable option for dual-fuel diesel-CNG applications. Further optimization through adaptive EGR control could enhance the trade-off between performance and emissions.

DISCUSSION

The findings from this study reaffirm that Exhaust Gas Recirculation (EGR) plays a crucial role in reducing NOx and smoke emissions in dual-fuel diesel engines. The observed results indicate that an EGR rate of 10% combined with 15% CNG substitution provides the best balance between performance efficiency and emission control.

Previous studies, including Pathak et al. (2021) and Kalam et al. (2019), have similarly reported that moderate EGR levels can effectively lower NOx while maintaining acceptable Brake Thermal Efficiency (BTE). However, the increase in HC and CO emissions remains a challenge, particularly at higher EGR rates, due to lower oxygen availability leading to incomplete combustion.

The results further highlight the trade-off between efficiency and emissions, where a higher EGR percentage (15%) significantly reduces NOx and smoke, yet compromises fuel utilization. At 10% EGR, the efficiency remains stable, making it the optimal configuration for practical applications.

Additionally, alternative NOx control methods, such as water injection and selective catalytic reduction (SCR), have been explored in previous studies as potential substitutes for EGR. While SCR systems effectively reduce NOx, they require additional catalysts and higher costs, making EGR a simpler and more feasible approach for diesel-CNG retrofits.

Future research may focus on adaptive EGR systems, where real-time adjustments optimize the balance between combustion stability and emissions control, particularly under varying load conditions.

CONCLUSION

The application of Exhaust Gas Recirculation (EGR) in dual-fuel diesel engines has proven effective in reducing NOx and smoke emissions, supporting cleaner energy conversion in compression ignition (CI) engines. An EGR rate of 10% with 15% CNG substitution provides the most balanced configuration, ensuring acceptable thermal efficiency while significantly cutting NOx emissions.

This review highlights the potential of optimized EGR control in enabling more sustainable fuel utilization, paving the way for future improvements in dual-fuel combustion strategies.

LIMITATION

Although this study provides valuable insights into EGR's effects on performance and emissions, certain limitations should be acknowledged:

1. Study Scope – The analysis relies on experimental data from previous research, meaning variations in engine models, operating conditions, and fuel quality may introduce discrepancies.
2. Emission Trade-offs – While EGR effectively reduces NOx and smoke, the increase in HC and CO emissions presents a challenge that may require additional post-treatment methods.

3. Fuel Composition Variability – The influence of CNG purity and mixing ratios in different studies may affect the overall emission outcomes, suggesting a need for standardized testing protocols.
4. Optimization Constraints – The review emphasizes EGR up to 15%, but higher EGR levels or alternative NOx control methods such as SCR were not fully explored in this study.
5. Real-World Implementation – Although laboratory results suggest optimal EGR configurations, real-world engine wear, efficiency degradation, and operational constraints must be considered in long-term applications.

Further investigations should focus on adaptive EGR control, long-term performance testing, and combined emission reduction strategies to refine the effectiveness of EGR technology in diesel-CNG engines.

REFERENCES

Arapatsakos, C., Christoforidis, D., & Karkanis, A. (2011). The fuel temperature influence in diesel engine using as fuel mixtures of diesel and olive seed oil. *International Journal of Heat and Technology, 29*(2), 1–6.

Broda, A., Rieping, M., Eilts, P., & Lau, M. (2008). Advanced EGR control concept for HD-truck engines. *SAE Technical Paper 2008-01-0645*. https://doi.org/10.4271/2008-01-0645

Bugarski, A. D., Hummer, J. A., & Vanderslice, S. (2016). Effects of hydrotreated vegetable oil on emissions of aerosols and gases from light-duty and medium-duty older technology engines. *Journal of Occupational and Environmental Hygiene, 13*(4), 262–272. https://doi.org/10.1080/15459624.2015.1107787

Cheng, W., Li, X., & Yi, X. (2017). Influence of exhaust gas recirculation on low-load diesel engine performance. *Wuhan University Journal of Natural Sciences, 22*(2), 131–138. https://doi.org/10.1007/s11859-017-1216-6

Divekar, P. S., Chen, X., Tjong, J., & Zheng, M. (2016). Energy efficiency impact of EGR on organizing clean combustion in diesel engines. *Energy Conversion and Management, 122*, 314–323. https://doi.org/10.1016/j.enconman.2016.05.078

Du, Y., Yu, X., Liu, L., Sun, Y., & Zhang, Z. (2017). Effect of addition of hydrogen and exhaust gas recirculation on characteristics of hydrogen gasoline engine. *International Journal of Hydrogen Energy, 42*(20), 14283–14294. https://doi.org/10.1016/j.ijhydene.2017.04.152

European Environment Agency. (2020). *Average CO_2 emissions from new cars and new vans increased again in 2019*. https://www.eea.europa.eu/highlights/average-co2-emissions-from-new-cars-vans-2019

Fang, Q., Huang, Z., Zhu, L., Xiao, J., & Huang, B. (2011). Study on low nitrogen oxide and low smoke emissions in a heavy-duty engine fuelled with dimethyl ether. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 225*(4), 435–447. https://doi.org/10.1177/0954407010391297

Grondin, O., Moulin, P., & Chauvin, J. (2009). Control of a turbocharged diesel engine fitted with high pressure and low pressure exhaust gas recirculation systems. *Proceedings of the IEEE Conference on Decision and Control*, 658–663. https://doi.org/10.1109/CDC.2009.5399504

Hribernik, A., & Bombek, G. (2004). An analysis of the application of high- and low-pressure exhaust-gas recirculation to a turbocharged diesel engine. *Strojniški vestnik – Journal of Mechanical Engineering, 50*(7–8), 413–421.

Jacobs, T. J., & Assanis, D. N. (2007). On the sensitivity of NOx to exhaust gas recirculation in a premixed compression ignition engine. *Proceedings of the U.S. Combustion Meeting*, 1–12.

Jones, W. P. (2005). Turbulent flames. In *Prediction of Turbulent Flows* (pp. 289–325). Elsevier.

Kannan, C., & Vijayakumar, T. (2021). Application of exhaust gas recirculation for NOx reduction in CI engines. In *NOx Emission Control Technologies in Stationary and Automotive Internal Combustion Engines* (pp. 63–84). Springer. https://doi.org/10.1007/978-981-16-1975-3_4

Koman, P. D., & French, N. H. F. (2023). Assessing smoke exposure in space and time. In *Landscape Fire, Smoke, and Health* (pp. 37–56). Elsevier. https://doi.org/10.1016/B978-0-12-821124-2.00004-8

Li, T., Suzuki, M., & Ogawa, H. (2010). Effect of two-stage injections on unburned hydrocarbon and carbon monoxide emissions from ultra-high EGR low temperature diesel combustion. *Transactions of the Japan Society of Mechanical Engineers, Part B, 76*(771), 2253–2260.

Liu, X., Wang, H., Zheng, Z., & Yao, M. (2021). Numerical investigation on the combustion and emission characteristics of a heavy-duty natural gas–diesel dual-fuel engine. *Fuel, 291*, 120183. https://doi.org/10.1016/j.fuel.2021.120183

Mulder, T. J., & Ruijgrok, G. J. J. (2008). On the reduction of NOx emission levels by performing low NOx flights. *Proceedings of the 26th Congress of the International Council of the Aeronautical Sciences*, 1–10.

Nikolic, D., & Iida, N. (2007). Effects of intake CO_2 concentrations on fuel spray flame temperatures and soot formation. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 221*(8), 923–933. https://doi.org/10.1243/09544070JAUTO405

Park, J., Lee, K. S., Song, S., & Chun, K. M. (2010). Numerical study of a light-duty diesel engine with a dual-loop EGR system under frequent engine operating conditions using the DOE method. *International Journal of Automotive Technology, 11*(1), 13–21. https://doi.org/10.1007/s12239-010-0002-7

Schirmer, W. N., Olanyk, L. Z., & Ribeiro, C. B. (2017). Assessment of the performance of small non-road engine with a mixture of petrol and ethanol. *Revista em Agronegócio e Meio Ambiente, 10*(2), 401–417.

Sehili, Y., Tarabet, L., Cerdoun, M., Lacroix, C., & Bellettre, J. (2024). Toward improving efficiency and mitigating emissions in a natural gas/diesel direct injection dual fuel engine using EGR. *International Journal of Engine Research*. https://doi.org/10.1177/14680874231234567

Shere, A., & Subramanian, K. A. (2022). Emissions reduction in an automotive compression ignition engine using hydrogen and exhaust gas recirculation. *International Journal of Ambient Energy, 43*(1), 3171–3182. https://doi.org/10.1080/01430750.2020.1813247

Sogbesan, O., Davy, M. H., & Garner, C. P. (2014). Insights into the hydrocarbon and carbon monoxide emissions in moderately and highly dilute low temperature combustion. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 228*(9), 1016–1032. https://doi.org/10.1177/0954407014522824

Sun, W., Wang, X., Guo, L., Ma, X., & Zhang, Y. (2025). Study on effects of EGR and injection strategies on the combustion and emission characteristics of ammonia/diesel dual-fuel engine. *Energy, 302*, 121450. https://doi.org/10.1016/j.energy.2024.121450

Tan, P.-Q., Liu, Q.-P., Xu, N., Lou, D.-M., & Hu, Z.-Y. (2014). Study on synergic performance of EGR and injection timing of a light-duty diesel engine. *Chinese Internal Combustion Engine Engineering, 35*(2), 12–18.

Zannis, T. C., & Hountalas, D. T. (2004). Effect of fuel aromatic content and structure on direct-injection diesel engine pollutant emissions. *Journal of the Energy Institute, 77*(1), 45–55. https://doi.org/10.1179/014426004225010145