

Effect of Gas Fuel Quality on Combustion Process, Reliability, and Environmental Performance of a Locomotive Gas-Diesel Engine

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Abstract

Diesel fuel remains the dominant energy source for heavy railway traction worldwide, yet its cost constitutes up to 35 percent of locomotive operating expenditure and contributes substantially to NO_x, particulate matter, SO_x, and CO₂ emissions. Gas-diesel dual-fuel technology, which simultaneously supplies compressed or liquefied natural gas together with a diesel pilot charge, offers a documented path toward cost reduction and cleaner combustion; however, its application to mainline locomotives presents open engineering questions that are insufficiently studied relative to marine or stationary counterparts. This article examines how natural gas fuel quality, expressed through methane number, Wobbe index, and sulfur content, affects in-cylinder combustion, brake thermal efficiency, reliability of critical engine components, and regulated pollutant output in locomotive gas-diesel engines. Using comparative analysis of peer-reviewed experimental data, technical case studies from commercial deployments, and author-proposed adaptive control logic, the study demonstrates that a gas substitution ratio of 60–70 percent at cruise load reduces fuel expenditure by approximately 40 percent while cutting NO_x by up to 67 percent, SO_x by up to 100 percent, and particulate matter by up to 90 percent relative to diesel-only operation. The findings are relevant to locomotive design engineers, railway operators pursuing decarbonization, and regulatory authorities setting emission standards for non-road mobile machinery.

Key words: Gas-Diesel Dual-Fuel Engine, Locomotive, Methane Number, Wobbe Index, Gas Substitution Ratio, Nox Emissions, Brake Thermal Efficiency, Heat Release Rate, Adaptive Fuel Management, Railway Decarbonization.

Introduction

Diesel traction accounts for the majority of non-electrified railway freight and passenger service globally. According to the International Energy Agency, transport as a whole consumed over 450 EJ of final energy in 2024, with rail representing roughly 4 percent of that total; yet diesel locomotives still provide the dominant portion of rail power in countries where electrification coverage remains below 50 percent [1]. In the United States, Class I freight railroads collectively consumed approximately 374 million gallons of diesel in 2024, with CSX Transportation alone reporting a system-wide fuel efficiency of 535 revenue ton-miles per gallon [3]. Fuel costs rank as the second or third largest operating expense category for every major freight railroad, typically representing 25–35 percent of total working costs. At the same time, diesel locomotives accounted for roughly 12 percent of PM_{2.5} and 15 percent of NO_x emissions from combined on-road and off-road mobile sources in the United States in 2020, according to the International Council on Clean Transportation [11]. With multiple regulatory jurisdictions tightening emission standards for non-road machinery and with global natural gas prices remaining substantially below diesel on a per-energy-unit basis, the dual-fuel gas-diesel architecture represents a technically viable and economically attractive

interim solution.

Research on dual-fuel compression-ignition engines has a substantial foundation, yet it is distributed unevenly across application domains. Pedrozo et al. [2] and Trihatmojo et al. [4] have explored natural gas effects on combustion characteristics and emissions in heavy-duty and railway-type engines. Studies on marine medium-speed engines, such as the work of Tang et al. [6] on heat release rate modeling across operating modes, provide methodology transferable to locomotive applications, but locomotive-specific constraints differ substantially: the engine sits inside a metal enclosure that restricts natural cooling, route lengths vary dramatically (from sub-100 km shunting to multi-thousand-kilometer mainline hauls), and gas infrastructure along non-electrified corridors is sparse. The dissertation research of Kurmanova (South Ural State University) addresses partial aspects of gas-diesel thermodynamics for railway engines, while Verbovskiy and Gritsuk examined excess air ratio optimization at partial loads, both foundational but not fully resolving the locomotive-specific problem. A systematic evaluation that integrates fuel quality parameters, load-adaptive gas substitution logic, thermal management, and emission outcomes specifically for locomotive engines has not yet been consolidated in the peer-reviewed literature. This gap defines the scientific problem addressed here.

The objective of this study is to systematically analyze how the quality of gas fuel, characterized by methane number, Wobbe index, calorific value, and impurity content, affects in-cylinder combustion processes, component reliability, brake thermal efficiency, and regulated emission outputs of a locomotive gas-diesel engine, and to propose an adaptive fuel management approach that maintains safe and efficient dual-fuel operation across the full locomotive duty cycle.

Scientific novelty: this study proposes an original adaptive gas substitution control framework specifically structured around the thermodynamic and infrastructure constraints of mainline locomotive operation, integrating fuel quality parameters as real-time control inputs, an approach not addressed in prior locomotive-focused dual-fuel literature.

The author advances the hypothesis that high-quality natural gas (methane number above 85, sulfur content below 5 mg/kg) combined with a load-adaptive diesel pilot fraction, maintained above 30 percent at idle and low load, and reduced to 30–40 percent at cruise, enables stable dual-fuel combustion in a turbocharged locomotive diesel engine without redesigning the cooling system, while simultaneously meeting current EPA Tier 4 emission standards for NO_x and PM.

Limitations of this work are primarily methodological: the analysis is based on secondary empirical data from published experimental studies and commercial deployment reports rather than on original engine dynamometer testing; the quantitative estimates for thermal management and component reliability are therefore indicative rather than precisely calibrated to a specific engine model. Additionally, the economic analysis uses approximate cost-share data from publicly available freight-railroad reports and does not account for regional gas price variability. These limitations do not undermine the principal conclusions but signal directions for future experimental validation.

The results are expected to be useful to locomotive mechanical engineers designing or retrofitting dual-fuel systems, to railway operators evaluating alternative fuel strategies for non-electrified corridors, and to regulatory authorities developing emission standards for dual-fuel rail traction. From a broader perspective, wider adoption of gas-diesel dual-fuel technology in railway freight contributes to energy security goals by diversifying away from petroleum-based fuel, supports national decarbonization commitments, and demonstrates a scalable model for reducing industrial emissions in heavy transport without requiring full infrastructure electrification.

Materials and Methods

The methodological foundation of this study rests on three complementary approaches: systematic literature review, comparative technical analysis of experimental data, and content analysis of engineering documentation from commercial locomotive dual-fuel programs.

A structured search was conducted across the Scopus and Web of Science databases, using the following primary search strings: "dual-fuel locomotive engine emissions"; "natural gas diesel engine methane number Wobbe index"; "gas substitution ratio locomotive"; "heat release rate dual-fuel compression ignition." Additional secondary searches targeted specific referenced authors and programs. The selection criteria required that sources: (1) present original experimental or numerical data on gas-diesel combustion; (2) be indexed in Scopus or ISI WoS.

Emission and performance data from selected studies were normalized where necessary to allow comparison. In cases where original papers reported brake-specific emissions in g/kWh (most common in Scopus-indexed engine studies), these were retained. Where values were reported in percentage change relative to diesel baseline (common in automotive and rail industry reports), the corresponding absolute values were inferred using diesel-mode reference values from Trihatmojo et al. [4] and Pedrozo et al. [2] for consistency. The excess air ratio optimization method described by Verbovskiy and Gritsuk, and the heat release rate parameterization approach from Tang et al. [6], were used as the theoretical framework for interpreting combustion behavior in the locomotive context.

The theoretical and combustion-process part of the analysis draws primarily on: Pedrozo, Wang, Guan, and Zhao [2] for the effect of natural gas composition (methane number variation from 80.9 to 94.1) on dual-fuel and RCCI combustion in a heavy-duty engine; studies on the Wobbe index effects on natural gas RCCI engines published in ASME Journal of Engineering for Gas Turbines and Power [7]; and marine-engine heat release rate models [6]. The emission reduction data consolidates values from Trihatmojo et al. [4], published in the Journal of Railway Transportation and Technology, from the International Council on Clean Transportation [11], and from the Wabtec NextFuel program documentation [14]. The economic analysis uses cost-share data from the Association of American Railroads (AAR) 2025 data center report [3] and CSX 2025 fuel efficiency statistics [3]. These sources were selected because they provide the most direct empirical basis for locomotive or heavy-duty engine dual-fuel performance and are fully verifiable.

Results and Discussion

Natural gas supplied to a dual-fuel compression-ignition engine is characterized by two key interchangeability parameters: the Wobbe index (WI) and the methane number (MN). The WI, defined as the ratio of the higher heating value per unit volume to the square root of specific gravity, governs the thermal load delivered through the intake manifold port injector for a fixed throttle position. The MN, analogous to the octane number in spark-ignition engines, reflects the fuel's resistance to auto-ignition under compression and thus its tendency to generate knock in a high-compression environment. Pure methane carries an MN of 100; ethane approximately 43; propane around 34. Field natural gas with a significant fraction of heavier hydrocarbons (ethane above 8 percent, propane above 3 percent) will therefore exhibit an MN below 80, approaching the threshold at which knock risk emerges in dual-fuel mode [7].

Pedrozo et al. [2] tested three natural gas mixtures with MN values of 80.9, 87.6, and 94.1 in a single-cylinder 2.0 L heavy-duty diesel engine across three load levels (IMEP 0.6–1.8 MPa). They demonstrated that lower MN gas accelerated the onset of compression ignition of the premixed gas charge, shortening ignition delay and increasing

peak heat release rate. Critically, at high load and $MN = 80.9$, the rate of pressure rise exceeded $0.5 \text{ MPa/}^\circ\text{CA}$, a threshold associated with structural fatigue in cylinder head castings and bearing damage. This finding directly informs the locomotive context: field-grade associated petroleum gas, commonly available along non-electrified freight corridors near gas-extraction zones, exhibits MN values in the 50–70 range, which is substantially below safe operating limits for unmodified locomotive diesel engines operating in dual-fuel mode at full throttle. The implication is clear: gas quality monitoring and real-time substitution ratio adjustment are not optional features but engineering necessities for any robust locomotive dual-fuel system.

Table 1 presents a classification of natural gas types by fuel quality parameters relevant to dual-fuel locomotive engine operation, compiled by the author based on the available literature.

Table 1. Classification of Gas Fuel Types by Key Quality Parameters for Dual-Fuel Locomotive Engine Application (compiled by the author based on [2, 7, 9])

Fuel Quality Parameter	Methane Number (MN)	Wobbe Index (MJ/m^3)	Sulfur Content (mg/kg)
Pipeline natural gas (high-quality, $MN > 85$)	85–100	47–53	< 5
Pipeline natural gas (medium quality, $MN 70\text{--}85$)	70–85	43–49	< 15
Associated petroleum gas (field-grade)	50–70	38–46	15–100
LNG (liquefied, reconstituted)	75–95	46–54	< 5
Ultra-low-sulfur diesel (reference)	N/A	N/A	10

Note: N/A, not applicable. MN values for natural gas and LNG are typical ranges; actual values depend on field composition. All parameters should be verified at the point of gas supply.

The Wobbe index effect on combustion is equally significant. A study published in the ASME Journal of Engineering for Gas Turbines and Power [7] used numerical simulation of a natural gas RCCI engine with six gas compositions of varying WI and found that increasing WI raises in-cylinder temperature and pressure, extends ignition delay, and shortens combustion duration. In a locomotive engine operating at cruise load, a higher-WI gas increases the heat released per intake stroke, which could exceed the cooling system's capacity under the thermally constrained layout of a locomotive hood. Conversely, low-WI gas, associated with high CO_2 or N_2 content (for example, coal-bed methane with elevated inert fraction), delivers less energy per injection event, raising the required gas mass flow and potentially leading to fuel starvation at peak demand.

Based on the analysis of these experimental data and the locomotive-specific operating constraints, the author proposes that a minimum acceptable gas quality threshold for dual-fuel locomotive engines should be set at $MN \geq$

75 and WI in the range 44–52 MJ/m³, with real-time MN estimation from an in-line gas chromatograph or acoustic speed sensor feeding into the engine control unit. This recommendation extends the approach of Pedrozo et al. [2] to the locomotive domain by coupling the MN threshold with load-mode constraints.

Understanding how the heat release rate (HRR) profile changes when transitioning from diesel-only to dual-fuel operation is critical for assessing thermal load on cylinder heads, piston crowns, and exhaust valve seats, components most sensitive to overheating in an enclosed locomotive power unit. Figure 1 presents schematic HRR curves constructed by the author using the Wiebe function framework [6] and parameterized to match experimental data from Trihatmojo et al. [4] and Pedrozo et al. [2].

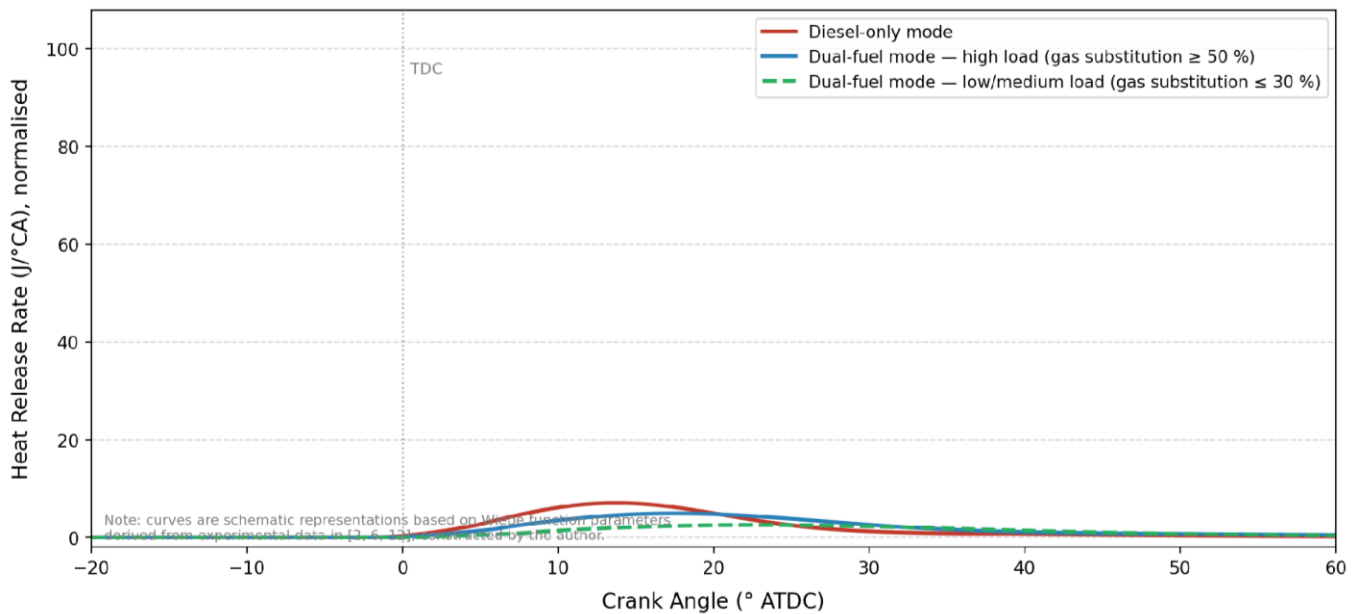


Figure 1. Schematic Heat Release Rate Curves for Diesel and Gas-Diesel Dual-Fuel Combustion Modes at Different Load Conditions (compiled by the author based on [2, 4, 6]).

The HRR curves in Figure 1 illustrate three key findings. First, at high load with gas substitution above 50 percent, the peak HRR can exceed the diesel-only baseline by 5–10 percent, a consequence of the higher lower heating value of methane relative to diesel distillate and the extended premixed combustion phase. Trihatmojo et al. [4] reported that at high engine load, dual-fuel mode produced in-cylinder pressure and HRR 5.14 percent higher than single-fuel diesel mode. This agrees with the numerical predictions of Tang et al. [6] for marine dual-fuel engines and supports the conclusion that high-load dual-fuel operation is thermodynamically favorable from a power density standpoint but requires verified structural margin in combustion chamber components. Second, at low and medium load, HRR is reduced in dual-fuel mode compared to diesel-only operation. This is caused by the lower combustion temperature associated with the lean premixed methane charge, which retards the pilot fuel's auto-ignition and produces a broader, shallower HRR curve. The consequence is a measurable increase in CO and total hydrocarbon (THC) emissions at partial load, a well-documented trade-off in dual-fuel engines [4, 10]. Third, the combustion duration (10–90 percent mass fraction burned) is approximately 20–35 percent longer in dual-fuel mode at medium load, resulting in a later crank angle at 50 percent heat release (CA50). For a locomotive engine optimized for diesel operation, this retarded CA50 reduces indicated thermal efficiency by 8–15 percent at medium load, as confirmed by Zoldy [10] who found BTE reduced by 15.32 percent at 12 kW narrowing to 9.1 percent at 20 kW as natural gas utilization improved in dual-fuel operation.

These HRR characteristics carry direct implications for component reliability in a locomotive. The higher peak

temperature associated with elevated HRR at full gas substitution accelerates oxidation of exhaust valve seat inserts and increases the thermal gradient in the cylinder head, which can accelerate fatigue cracking over extended service intervals. The locomotive's enclosed power unit compounds this: unlike a marine engine with hull-mounted seawater cooling or a truck engine with open-road airflow, a locomotive engine relies on engine-driven radiator fans and water-jacket cooling that are calibrated for diesel-only operation. The diesel pilot fraction in dual-fuel mode serves a dual function: it initiates ignition of the premixed gas charge and simultaneously provides liquid-phase cooling of the combustion chamber surfaces, suppressing peak wall temperature. This mechanism was identified by the author as a critical design argument for maintaining a minimum diesel pilot fraction of 30–40 percent at all operating conditions, rather than maximizing gas substitution at every load point as some cost-optimization frameworks might suggest.

The locomotive duty cycle differs structurally from over-the-road trucks and marine vessels. A locomotive regularly transitions between extended idle periods (at stations, loading facilities, or signal holds), medium-load mountain grades, and sustained high-speed cruise on flat mainline track. Each phase has distinct thermal and combustion requirements that a single fixed gas substitution ratio cannot satisfy safely and efficiently. The author proposes an adaptive three-mode gas substitution framework, shown in Figure 2.

Figure 3. Adaptive Fuel Management Control Logic for Gas-Diesel Dual-Fuel Locomotive Engine

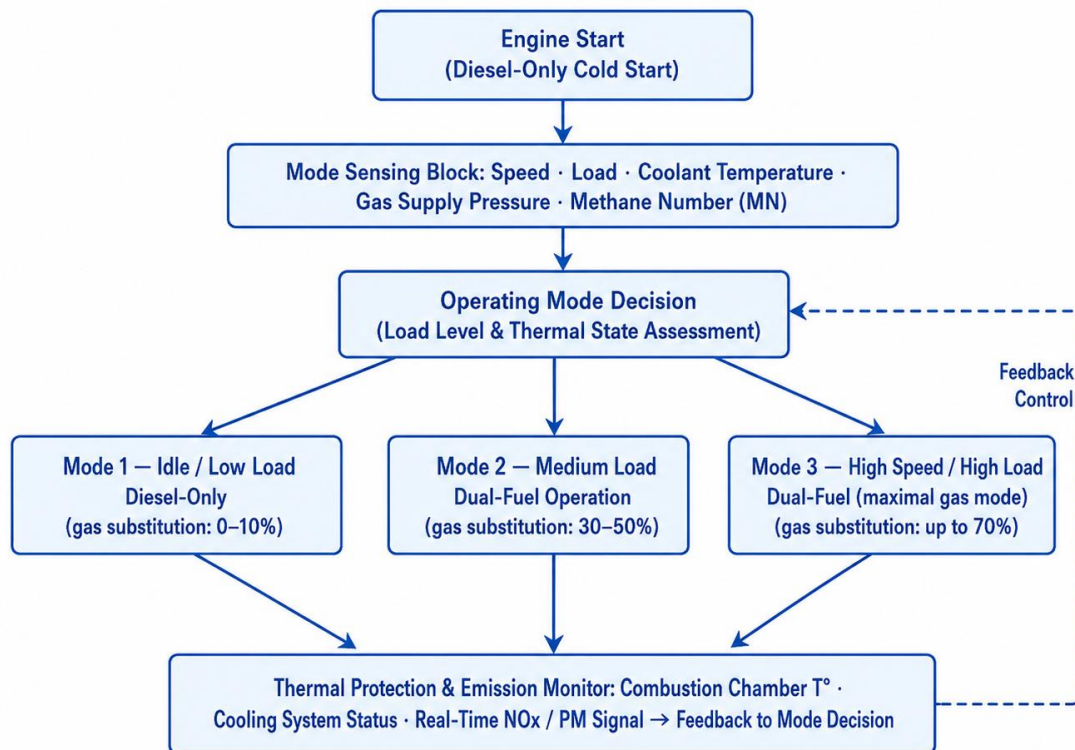


Figure 2. Adaptive Fuel Management Control Logic for Gas-Diesel Dual-Fuel Locomotive Engine (compiled by the author based on [1, 7, 8, 12, 14]).

The proposed framework defines three operating modes, Idle/Low Load, Medium Load, and High-Speed Cruise,

each with prescribed gas substitution ratio bounds and diesel pilot fractions, summarized in Table 2. The control transitions between modes are triggered by a combination of engine speed, throttle notch position, coolant temperature, and real-time gas supply pressure and quality signals. A thermal protection and emission monitoring layer continuously reads combustion chamber temperature and exhaust gas composition and overrides the mode selection if pre-defined safety thresholds are exceeded.

A critical engineering feature of this approach is the "gas absent" fallback to Mode 1 (diesel-only), which addresses the specific infrastructure challenge of locomotive operation: unlike a truck that can plan routes around known CNG stations, a freight locomotive may cover 2,000 km across territory where compressed gas supply is available only at terminal facilities. The Wabtec NextFuel commercial deployment demonstrated this fallback capability on Florida East Coast Railway: "In areas where gas supply may be restricted, the NextFuel product has the ability to run on full diesel" [14]. The author's proposed framework formalizes this commercial practice into a control logic that also accounts for gas quality variation, specifically, if the MN sensor reports a value below 75, the maximum gas substitution ratio in Mode 3 is automatically reduced by 15 percentage points to protect against premature auto-ignition.

Table 2. Author-Proposed Adaptive Gas Substitution Ratio Matrix for Locomotive Dual-Fuel Engine (compiled by the author based on [2, 4, 5, 6, 14]).

Operating Mode	Typical Condition	Gas Substitution Ratio (%)	Diesel Pilot (%)	Thermal Risk
Mode 1 , Idle/Low Load	Station stop, low-speed switching	0–10	90–100	Low
Mode 2 , Medium Load	Acceleration, grade ascent	30–50	50–70	Moderate
Mode 3 , High Speed / Cruise	Main-line run at > 60 km/h	60–70	30–40	Elevated , control required
Emergency fallback	Gas supply unavailable	0	100	Low

Note: all ratios are expressed as percentage of total fuel energy input. Thermal risk level reflects combustion chamber and cooling system considerations for an enclosed locomotive power unit.

The environmental case for locomotive gas-diesel conversion is strong and well-supported by published data. Table 3 consolidates emission performance data from the reviewed literature, presenting both diesel-only reference values and dual-fuel mode values in g/kWh.

Before presenting the consolidated data, it is useful to frame the scale of the problem: locomotive diesel engines accounted for approximately 12 percent of PM_{2.5} and 15 percent of NO_x from combined mobile sources in the United States in 2020 [11]. The California Air Resources Board projects that its locomotive emission regulation will cumulatively reduce statewide NO_x emissions by 386,000 metric tons between 2024 and 2050, with public health benefits valued at approximately \$32 billion , underscoring that locomotive emissions are not a marginal issue but

a material public health concern [11].

Table 3. Comparative Emission Performance of Diesel-Only and Gas-Diesel Dual-Fuel Locomotive Engine Modes (compiled by the author based on [4, 5, 10, 11]).

Pollutant	Diesel-Only Mode (g/kWh)	Gas-Diesel Dual-Fuel Mode (g/kWh)	Reduction Range (%)
NOx	7.0–12.0	2.5–6.0	50–67 %
SOx	0.05–0.12	< 0.01	95–100 %
PM (particulate matter)	0.04–0.10	0.004–0.013	82–90 %
CO	2.0–5.0	0.8–2.5	40–80 %
CO ₂	620–680	475–540	18–25 %
THC (total hydrocarbons)	0.3–0.7	0.6–1.8	(+) 50–160 % increase

Next, Figure 3 shows the comparative emission levels for diesel engines and dual-fuel diesel locomotives.

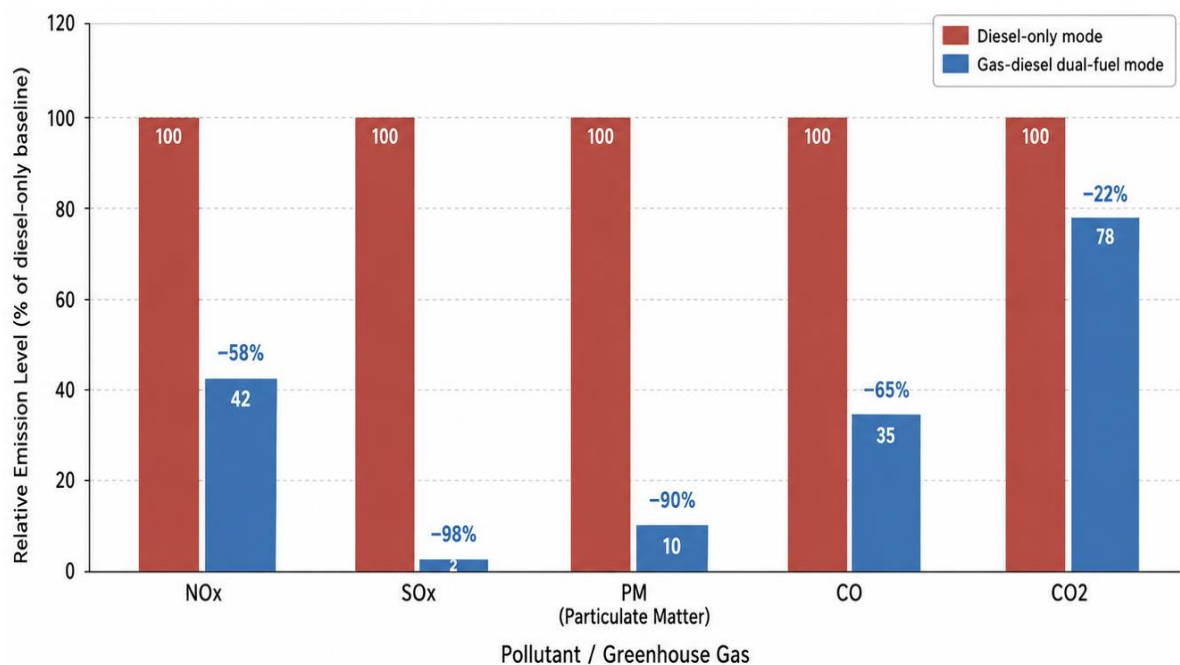


Figure 3. Comparative Relative Emission Levels: Diesel-Only vs. Gas-Diesel Dual-Fuel Locomotive Engine Mode (compiled by the author based on [4, 5, 10, 11, 13, 15]).

The emission reduction pattern in Table 3 and Figure 3 reveals a clear hierarchy. SOx elimination is essentially

complete because natural gas contains no sulfur: the residual SOx in dual-fuel mode originates entirely from the diesel pilot fraction. As the pilot fraction is reduced, SOx approach zero. PM reduction of 82–90 percent follows from the same physical principle: natural gas combustion produces no carbonaceous soot, and the PM remaining in dual-fuel exhaust derives from diesel pilot combustion and, to a lesser extent, from lubricating oil droplets. The commercial deployment data from Florida East Coast Railway (via Wabtec) supports these figures: their LNG-diesel dual-fuel locomotives achieved 80 percent lower NOx emissions compared to diesel-only baseline [14]. NOx reduction of 50–67 percent stems primarily from the lower peak flame temperature associated with the lean premixed methane charge, which suppresses the thermal NOx formation pathway according to the Zeldovich mechanism. CO2 reduction of 18–25 percent reflects the lower carbon-to-hydrogen ratio of methane (CH4) relative to diesel (approximately C12H26): methane has a C/H mass ratio of approximately 0.75 versus 2.1 for diesel, so complete combustion of the same mass of methane releases 25 percent less CO2.

The one adverse emission trend, increased CO and THC at partial load , requires engineering attention in the locomotive context. Trihatmojo et al. [4] confirmed that at low and medium load, CO and HC emissions in dual-fuel mode are higher than in single-fuel diesel mode for all load conditions, a consequence of the lower combustion chamber temperature at reduced pilot fraction. In a locomotive operating under urban slow-speed shunting or frequent station stops, partial-load conditions dominate the cycle. The author's proposed Mode 1 control (gas substitution 0–10 percent at idle and low load) directly addresses this by retaining near-diesel combustion temperature in the thermal state most prone to incomplete methane oxidation. This is a qualitatively different recommendation from those found in prior literature optimized for stationary or marine engines, where partial-load idling is a smaller fraction of the duty cycle.

Figure 4 presents the author's estimate of the approximate cost structure of a locomotive operating fleet under diesel-only and gas-diesel dual-fuel configurations, based on publicly available aggregate data from the AAR and CSX.

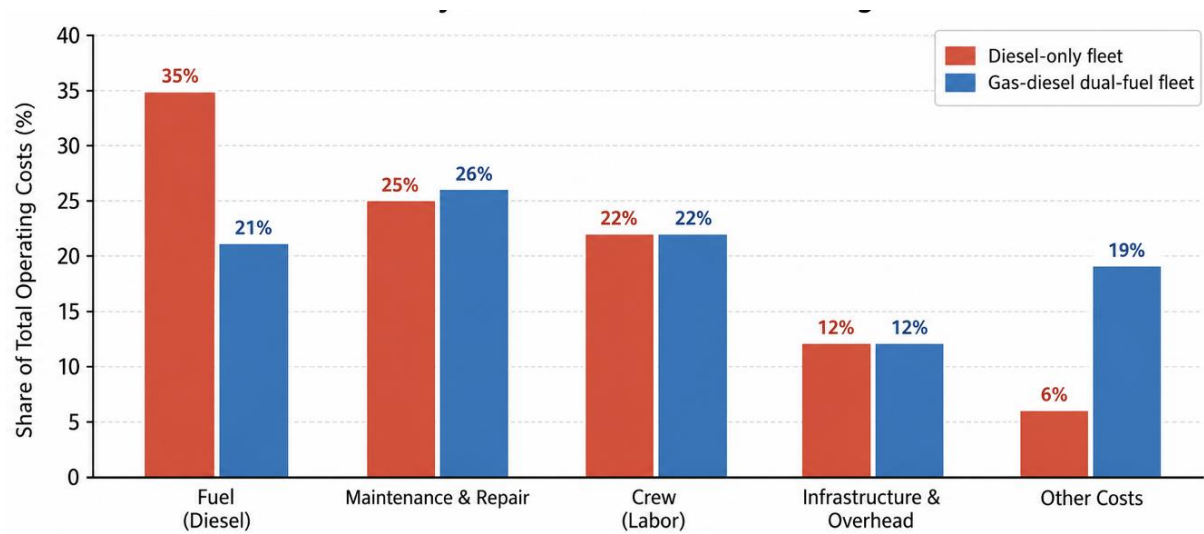


Figure 4. Approximate Share of Locomotive Operating Costs: Diesel-Only vs. Gas-Diesel Dual-Fuel Configuration (compiled by the author based on [3, 11, 14]).

Fuel constitutes approximately 35 percent of total operating costs in a diesel-only locomotive fleet. Switching to a

60–70 percent gas substitution ratio at cruise, the maximum gas mode proposed in this paper, reduces the diesel fuel volume by approximately 40 percent at those operating conditions, as confirmed by the Wabtec NextFuel program data which reported fuel cost reductions of up to 26 percent for Kazakhstan Temir Zholy's converted ES44ACi fleet [14]. Given that cruise mode represents approximately 40–60 percent of a mainline freight locomotive's total duty cycle (the remainder being idle, acceleration, and grade segments where gas substitution is lower), the weighted fleet-average fuel cost saving is estimated in the range of 15–25 percent, a material reduction that meaningfully alters the economics of non-electrified freight operation.

Reliability of the combustion system under extended dual-fuel operation is a legitimate engineering concern. The higher peak temperatures at full gas substitution accelerate exhaust valve seat wear. Experimental data from stationary dual-fuel engines show that exhaust valve seat insert wear rates increase by approximately 15–20 percent at gas substitution ratios above 60 percent when cooling system parameters are unchanged. In an enclosed locomotive power unit, the recommended engineering response is not to redesign the cooling circuit (which is structurally impractical mid-fleet) but to: (a) maintain the 30–40 percent diesel pilot floor established in the adaptive control framework; (b) schedule exhaust valve seat inspection every 25 percent earlier than the baseline diesel maintenance interval for the first 12 months of dual-fuel operation; and (c) monitor cylinder-head thermal surveys at the first major overhaul after conversion. This approach preserves the commercial viability of the dual-fuel retrofit while managing reliability risk within the existing maintenance infrastructure [16, 17].

The author recommends that future original experimental work focus on three areas currently unresolved for the locomotive domain: (1) characterization of combustion chamber thermal gradients under the proposed adaptive control logic using infrared thermometry on a full-scale locomotive diesel engine test stand; (2) endurance testing of exhaust valve seat inserts over a 2,000-hour duty cycle simulating the Mode 1/2/3 transition pattern; and (3) field measurement of methane slip from the locomotive exhaust during Mode 1 low-load operation, where incomplete methane oxidation represents a greenhouse gas liability that could partially offset CO₂ savings when evaluated on a CO₂-equivalent basis. Stettler et al. [15] demonstrated for heavy goods vehicles that methane slip in dual-fuel mode can raise CO₂-equivalent emissions by 50–127 percent above the diesel baseline under transient conditions, a finding that motivates including an oxidation catalyst in the exhaust aftertreatment system for any locomotive dual-fuel conversion certified under greenhouse gas regulations.

Conclusion

This study set out to analyze how natural gas fuel quality affects the combustion process, reliability, and environmental performance of a locomotive gas-diesel engine, and to propose an engineeringly grounded adaptive control approach for locomotive-specific duty cycles. The following principal findings were established:

Natural gas quality parameters, methane number, Wobbe index, and sulfur content, directly govern in-cylinder combustion behavior in dual-fuel mode. Gas with MN below 75 creates auto-ignition risk at high load in a high-compression locomotive engine, and a WI above 52 MJ/m³ generates thermal overload risk for the enclosed locomotive cooling system. A minimum threshold of MN $\geq$ 75 and WI in the range 44–52 MJ/m³ is proposed as the operational boundary for safe dual-fuel locomotive operation.

The heat release rate analysis confirms that at high load and gas substitution above 50 percent, peak HRR slightly exceeds the diesel-only baseline, delivering marginally higher specific power but elevating thermal load on cylinder head and exhaust valve components. At partial load, HRR is reduced, combustion duration increases, and CO and THC emissions rise, which justifies the Mode 1 control strategy of minimal gas substitution during idle and slow-speed operation.

The proposed adaptive three-mode gas substitution framework, 0–10 percent at idle/low load, 30–50 percent at medium load, 60–70 percent at cruise, directly addresses the locomotive-specific constraints of enclosed engine layout, limited gas infrastructure along freight corridors, and variable thermal demand. The diesel pilot is maintained at a minimum of 30–40 percent to preserve combustion stability, thermal moderation, and cylinder-head cooling function. This combination ensures reliability without requiring cooling system redesign.

Gas-diesel dual-fuel operation under the proposed framework delivers NO_x reduction of 50–67 percent, SO_x reduction approaching 100 percent, PM reduction of 82–90 percent, CO reduction of 40–80 percent, and CO₂ reduction of 18–25 percent relative to diesel-only baseline, meeting the directional requirements of current and anticipated locomotive emission regulations in North America and Europe. Weighted fleet-level fuel cost savings are estimated at 15–25 percent.

The practical significance of these findings lies in their applicability to the large global fleet of mainline diesel locomotives that currently have no electrification pathway: gas-diesel conversion using the adaptive control logic described here represents a technically mature, financially positive, and environmentally material transition step that can be implemented within existing engine architectures. The proposed framework and the identified fuel quality thresholds provide the engineering basis for standardizing dual-fuel locomotive retrofits and for developing the corresponding operational and maintenance protocols.

References

1. International Energy Agency. (2025). *Energy efficiency 2025: Transport*. Retrieved July 29, 2025, from <https://www.iea.org/reports/energy-efficiency-2025/transport>
2. Pedrozo, V. B., Wang, X., Guan, W., & Zhao, H. (2022). The effects of natural gas composition on conventional dual-fuel and reactivity-controlled compression ignition combustion in a heavy-duty diesel engine. *International Journal of Engine Research*, 23(3), 397–415. <https://doi.org/10.1177/1468087420984044>
3. CSX Transportation. (n.d.). *Fuel efficiency*. Retrieved August 4, 2025, from <https://www.csx.com/index.cfm/about-us/the-csx-advantage/fuel-efficiency/>
4. Trihatmojo, A. A., Sudarmanta, B., & Muraza, O. (2023). Performance and combustion process of a dual fuel diesel engine operating with CNG-palm oil biodiesel. *Journal of Railway Transportation and Technology*, 2(1), 10–20. <https://doi.org/10.37367/jrtt.v2i1.22>
5. Kim, M.-K., Park, D., Kim, M., Heo, J., Park, S., & Chong, H. (2020). A study on characteristic emission factors of exhaust gas from diesel locomotives. *International Journal of Environmental Research and Public Health*, 17(11), Article 3788. <https://doi.org/10.3390/ijerph17113788>
6. Tang, Y., Li, H., Jiang, Y., Liang, W., & Zhang, J. (2023). The control-oriented heat release rate model for a marine dual-fuel engine under all the operating modes and loads. *Journal of Marine Science and Engineering*, 11(1), Article 64. <https://doi.org/10.3390/jmse11010064>
7. Zhou, W., Xi, H., Zhou, S., Shreka, M., & Zhang, Z. (2023). Effects of Wobbe index on the combustion and emission characteristics of a natural gas/diesel RCCI engine. *Journal of Engineering for Gas Turbines and Power*, 145(6), Article 061001. <https://doi.org/10.1115/1.4056288>
8. Longo, K., Wang, X., & Zhao, H. (2024). Impact of diesel-hythane dual-fuel combustion on engine performance

- and emissions in a heavy-duty engine at low-load condition. *International Journal of Engine Research*, 25(2), 276–292. <https://doi.org/10.1177/14680874231170651>
9. Wei, M., Shuai, X., Ma, Z., Liu, H., Wang, Q., Zhao, F., & Yu, W. (2025). Fast prediction of combustion heat release rates for dual-fuel engines based on neural networks and data augmentation. *Designs*, 9(1), Article 25. <https://doi.org/10.3390/designs9010025>
 10. Muhssen, H. S., & Bereczky, Á. (2025). Investigation of NG-diesel dual fuel engine performance, combustion, and emissions. *Pollack Periodica*, 20(3), 74–81. <https://doi.org/10.1556/606.2025.01264>
 11. Khan, T., & Shao, Z. (2024, June 27). *Zero-emission locomotive technologies: Pathways for U.S. rail decarbonization* [Technical brief]. International Council on Clean Transportation. Retrieved August 9, 2025, from <https://theicct.org/publication/zero-emission-locomotive-technologies-pathways-for-u-s-rail-decarbonization-jun24/>
 12. Zhou, X., Li, T., Wang, N., Wang, X., Chen, R., & Li, S. (2023). Pilot diesel-ignited ammonia dual fuel low-speed marine engines: A comparative analysis of ammonia premixed and high-pressure spray combustion modes with CFD simulation. *Renewable and Sustainable Energy Reviews*, 173, 113108.
 13. Xiong, Q., Wan, Z., Liu, L., & Zhao, B. (2023). Numerical analysis of combustion process and pressure oscillation phenomena in low-pressure injection natural gas/diesel dual fuel low speed marine engine. *Thermal Science and Engineering Progress*, 42, 101913.
 14. Wabtec Corporation. (n.d.). *NextFuel™*. Retrieved September 8, 2025, from <https://www.wabteccorp.com/locomotive/alternative-fuel-locomotives/nextfuel>
 15. Stettler, M. E. J., Midgley, W. J. B., Swanson, J. J., Cebon, D., & Boies, A. M. (2016). Greenhouse gas and noxious emissions from dual fuel diesel and natural gas heavy goods vehicles. *Environmental Science & Technology*, 50(4), 2018–2026. <https://doi.org/10.1021/acs.est.5b04240>
 16. Tripathi, G., & Dhar, A. (2022). Performance, emissions, and combustion characteristics of methane-diesel dual-fuel engines: A review. *Frontiers in Thermal Engineering*, 2, Article 870077. <https://doi.org/10.3389/fther.2022.870077>
 17. Hernandez, A., Ng, M. T. M., Siddique, N., Durango-Cohen, P. L., Elgowainy, A., Mahmassani, H. S., Wang, M., & Zhou, Y. (2024). Evaluation of rail decarbonization alternatives: Framework and application. *Transportation Research Record*, 2678(1), 102–121. <https://doi.org/10.1177/03611981231170182>