



Compressed natural gas in aged internal combustion engines: performance, emissions, and challenges – a systematic review

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ABSTRACT

Compressed natural gas (CNG) offers significant emissions advantages over gasoline and diesel, yet most literature focuses on new or laboratory-optimized engines rather than the aged, retrofitted vehicles common in developing countries. With addition of other studies, the review followed PRISMA 2020 guidelines and a prospectively registered protocol (OSF) – <https://osf.io/c8u7f/>. Searches across Scopus, IEEE Xplore, and Google Scholar identified 816 records, of which 26 studies met inclusion criteria. CNG consistently lowered CO, HC, PM, and CO₂ emissions, but retrofitted SI engines experienced 10–20% losses in power and torque due to methane's low volumetric energy density and age-related declines in efficiency. High-mileage fleets showed methane-slip increases, catalyst deterioration, and lubricant oxidation, whereas optimized or dedicated CNG engines demonstrated improved thermal efficiency and fuel economy. Retrofit quality and calibration accuracy proved decisive in determining real-world outcomes. The findings highlight that CNG's environmental and efficiency benefits are achievable but depend on proper engine design, maintenance, and regulatory support, especially in regions dominated by older vehicle fleets. This review provides the first systematic synthesis focused on aged, high-mileage, and retrofitted spark ignition (SI) and compression ignition (CI) engines operating on CNG, integrating evidence on performance, emissions, combustion behavior, methane slip, lubricant degradation, and catalyst aging. By comparing retrofitted and dedicated CNG engines against real-world aged engine across diverse regions, it reveals how engine architecture, retrofit quality, and accumulated mileage shape CNG outcomes and identifies the operational challenges and research priorities needed for durable, efficient, and low-emission operation.

1. Introduction

Compressed natural gas (CNG) has gained attention as a cleaner alternative to gasoline in SI and CI engines because of its high-octane rating, lower carbon intensity, and naturally low particulate formation [1,2]. Numerous experimental and computational studies have shown that CNG can significantly reduce carbon monoxide (CO), unburned hydrocarbons (HC), and particulate emissions, while also supporting efficient lean-burn operation. These advantages make CNG an appealing transitional fuel for countries seeking to reduce transport-sector emissions and improve urban air quality.

Despite this promise, much of the existing research focuses on new, dedicated, or laboratory-optimized engines, which do not reflect the engines in which CNG is actually used in many developing regions. In real-world settings, CNG is commonly applied in aged, high-mileage

gasoline engines that have been retrofitted, often with non-original equipment manufacturer kits and limited calibration support [3,4]. These engines behave very differently from new test engines: their combustion characteristics, thermal loading, and degradation patterns are shaped by aging and wear, variable maintenance, and inconsistent operating conditions [1,5]. Issues such as calibration drift, valve-train wear, methane slip, lubricant oxidation and nitration, and catalyst deterioration become much more prominent in high-mileage fleets but remain underexplored in the published literature.

Previous reviews tend to examine performance, emissions, or durability as separate topics, which makes it difficult to understand how long-term aging, retrofit quality, and operating environment interact to influence CNG outcomes. A more integrated assessment is needed to describe how CNG truly performs under the everyday conditions in which it is most widely used.

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1.1. Novelty and contribution of this systematic review

To the best of the authors’ knowledge, this is the first PRISMA-guided systematic review to specifically synthesize evidence on aged and retrofitted SI and CI engines operating on CNG, integrating performance, emissions, and durability outcomes. It brings together evidence on performance, emissions, combustion behavior, and long-term durability, including detailed consideration of lubricant degradation mechanisms, methane slip, and catalyst aging. The topics seldom addressed together in previous reviews. The review also compares results across bi-fuel SI engines, dual-fuel CI engines, dedicated CNG research engines, and real-world aged vehicles, demonstrating how CNG performance varies with engine architecture, retrofit quality, and accumulated mileage. By drawing on studies from diverse geographical and operational contexts, the review connects engineering findings to broader energy-transition objectives, particularly in regions where retrofit-based CNG use continues to expand. The purpose of this systematic review is therefore to:

1. evaluate the long-term performance and emissions behavior of CNG in aged and retrofitted engines;
2. identify the operational challenges of CNG in aged and retrofitted engines that shape real-world outcomes; and
3. highlight the research gaps and engineering priorities needed to ensure durable, efficient, and low-emission CNG operation.

The conceptual framework of the systematic review, Fig. 1, showing the research motivation, review implementation, integrated analysis domains, key technical findings and engineering & policy contribution.

All extracted data, study-level appraisal, and figure mappings are reported in traceable tables and captions to ensure transparent linkage between synthesized outcomes and the included evidence base.

2. Methodology

This systematic review synthesizes empirical evidence on the performance, emissions, and operational characteristics of aged and retrofitted internal combustion engines operating on CNG. The review methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines and was conducted in accordance with a preregistered protocol on the Open Science Framework (OSF; <https://osf.io/c8u7f/>). The approach was designed to ensure methodological transparency, reproducibility, and suitability for the interdisciplinary nature of energy-conversion research.

1.1. Eligibility criteria

Studies were eligible for inclusion if they investigated internal combustion engines that met at least one of the following conditions: (i) aged or high-mileage engines with a documented service life of approximately 100,000 km or more; (ii) gasoline or diesel engines retrofitted to operate on CNG using aftermarket conversion kits; or (iii) dual-fuel compression-ignition engines utilizing diesel pilot injection with CNG as the primary fuel.

The intervention of interest was CNG operation, either as a full

substitute (bi-fuel/dedicated SI engines) or partial substitute (dual-fuel CI engines). Comparator fuels included gasoline, diesel, or baseline engine conditions prior to retrofit. Studies were required to report at least one of the following outcomes: The included studies evaluated outcomes in three closely connected areas. First, they assessed engine performance, focusing on brake power and torque, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and key combustion indicators such as ignition behavior, combustion phasing, and durability-related measures that reflect long-term operation. Second, they examined exhaust emissions, including regulated pollutants such as CO, HC, NOx, PM, and CO₂ as well as methane slip. Third, they reported operational and practical factors that determine real-world feasibility, such as lubricant degradation, retrofit quality, calibration stability, catalyst deterioration, valve and valvetrain wear, safety issues, and wider infrastructure or maintenance limitations.

Eligible designs included peer-reviewed experimental studies, field trials, simulation-supported experiments, and structured case-based investigations. Review articles and conference abstracts were screened only for contextual relevance. To reflect modern CNG technologies, only studies published in English from 1990 onward were included.

1.2. Information sources and search strategy

A comprehensive literature search was conducted in Scopus and IEEE Xplore, selected for their broad coverage of automotive, mechanical, and energy-engineering research. To capture field-based studies from developing regions, supplementary searches were also performed in Google Scholar. Reference lists of included studies were manually screened to identify additional relevant publications. The final search was completed on 20 August 2025.

1.3. Search strategy

Search strings were tailored to each database. The master search string combined key terms for fuel type, engine condition, and outcome variables: (“compressed natural gas” OR CNG) AND (“aged engine*” OR “high-mileage engine*” OR “retrofitted engine*” OR “old engine*” OR “used engine*” OR “internal combustion engine*”) AND (performance OR efficiency OR “engine output” OR “thermal efficiency” OR “fuel economy” OR emissions OR pollutants OR “air pollution” OR “greenhouse gas*” OR durability OR reliability OR wear OR “lubricant degradation” OR challenges OR limitations OR barriers).

Search performance was validated against a set of benchmark publications identified during protocol development. Reference lists from these key papers were further screened to ensure comprehensive coverage.

1.4. Study selection

The initial search produced 812 records (Scopus 374, IEEE 266, and Google Scholar 172) across all databases. Screening was managed using RAYYAN, which enabled automated duplicate removal, blinded decision-making, and transparent documentation of inclusion and

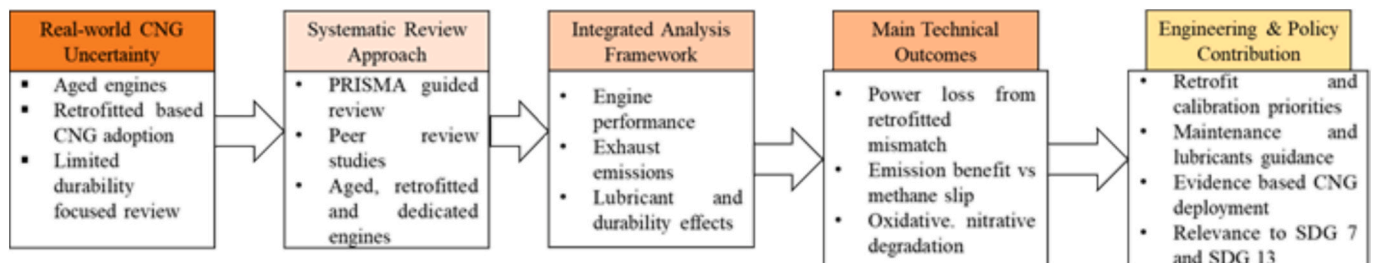


Fig. 1. Conceptual Framework of the Systematic Review.

exclusion decisions. After removing duplicate entries, 776 unique records were screened by title and abstract. A total of 652 articles were excluded for irrelevance to CNG combustion performance, emissions behavior, aging mechanisms, or internal combustion engine applications. The full texts of 124 articles were subsequently assessed against the predefined eligibility criteria.

Following detailed full-text evaluation, 98 studies were excluded due to insufficient methodological detail, lack of primary experimental data, non-engine-system focus, or failure to meet the defined scope criteria. Moreover, In response to reviewer feedback requesting broader representation of medium- and heavy-duty production CNG engines, four (4) additional peer-reviewed studies focusing on dedicated commercial truck platforms and advanced combustion architectures (e.g., MPFI heavy-duty engines, Miller/LIVC strategies, VCR concepts, and integrated system optimization) were incorporated after confirming eligibility under the same screening criteria. Ultimately, 26 studies met all inclusion requirements and were incorporated into the final synthesis.

Extracted variables included study metadata, engine class (light-duty, medium-duty, heavy-duty), technological generation (retrofit, transitional MPFI, contemporary production), accumulated mileage (where reported), retrofit specifications, combustion architecture, comparator fuels, measured performance parameters, emissions outcomes, and reported operational challenges. The full selection process is illustrated using the PRISMA flow diagram (Fig. 2).

1.5. Data extraction

Data extraction was performed independently by two reviewers using a standardized extraction form implemented in RAYYAN. Extracted information included:

- I. Study metadata: authorship, publication year, and country context.
- II. Study design: experimental setup, engine architecture, mileage, and retrofit specifications.

- III. Intervention details: type of CNG operation (bi-fuel, dedicated, dual-fuel), retrofit characteristics, and fuel-supply system.
- IV. Comparators: gasoline or diesel baselines, pre-retrofit conditions, or reference test cycles.
- V. Performance and emissions outcomes: power, torque, BTE, BSFC, regulated and unregulated emissions, and methane slip.
- VI. Operational indicators: lubricant degradation, maintenance issues, calibration drift, catalyst aging, and wear characteristics.
- VII. Methodological characteristics: sample size, test conditions, measurement protocols, and reproducibility.

Extracted information covered basic study details (author, year, and country), engine setup and operating conditions, fuel mode and retrofit features, comparator fuels, key performance and emission measures, and any reported operational challenges. After independent extraction, the reviewers cross-checked all fields to ensure accuracy and completeness. Any differences were addressed through a structured discussion and a re-check of the original full text until agreement was reached; unclear cases were settled through a third review in line with the registered protocol.

Formal inter-reviewer agreement statistics (e.g., Cohen's kappa) were not calculated because the extracted data involved continuous engineering variables and highly inconsistent reporting across studies. Instead, duplicate extraction and consensus reconciliation were used to reduce selection and extraction bias. Reviewers were not blinded to study identifiers (authors/journals), since technical details such as engine models, calibration approaches, test rigs, and instrumentation typically make study origins obvious and blinding is rarely practical in this research area.

1.6. Quality assessment

The methodological quality of included studies was evaluated using a hybrid appraisal approach adapted from the Critical Appraisal Skills Program (CASP) and Joanna Briggs Institute (JBI) tools, modified for

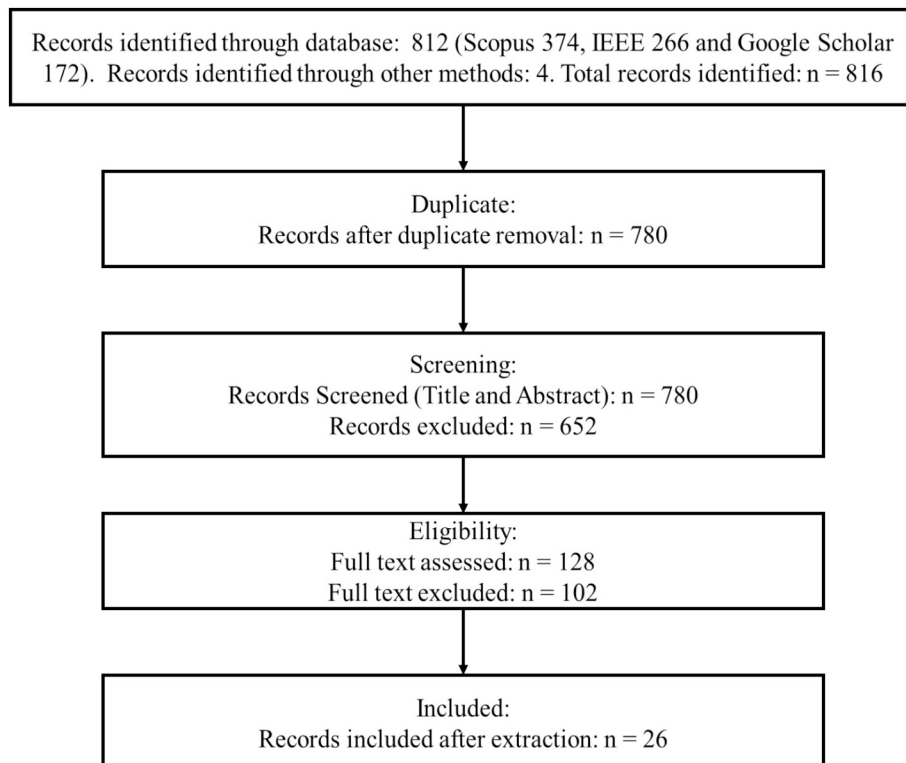


Fig. 2. PRISMA diagram summarizing the screening and inclusion process.

relevance to engineering and combustion research. Assessment criteria considered: clarity of research objectives, appropriateness of study design, adequacy of sample size and test matrix, reliability and calibration of instrumentation, validity of comparisons, transparency of reporting, and potential sources of bias. Quality assessments informed interpretation of findings, and sensitivity considerations were applied where methodological limitations were observed.

We assessed the quality of the included studies using a structured checklist adapted from established tools (CASP and JBI), and adjusted it to better fit engineering and energy-conversion research. Each study was reviewed across six key areas: (D1) whether the objectives were clear and the design was appropriate, (D2) how well the engine setup and operating conditions were reported, (D3) whether the comparator fuel and test protocol were valid, (D4) the reliability of measurements (instrumentation, calibration, and repeatability), (D5) the clarity and transparency of data presentation (figures, tables, statistics), and (D6) how representative the study was of real-world conditions, especially in terms of fleet relevance, engine aging, and retrofit realism.

Each area was rated “Yes,” “Partial,” or “No,” and an overall judgment was then assigned based on how consistently the study performed across the six domains. Studies were considered high quality when they met most criteria and showed strong measurement reliability and real-world relevance (especially D4 and D6). Moderate-quality studies typically had limitations in reporting completeness or representativeness, while low-quality studies had major gaps in key details, measurement validity, or comparator definition. The full appraisal results are presented in [Table S1](#).

Importantly, the quality assessment was used to guide interpretation, not to exclude studies. Evidence on real-world emissions compliance, methane slip, and long-term durability was therefore weighted more heavily toward higher-quality dynamometer and field-based studies. In contrast, findings from single-cylinder rigs, tribology-focused experiments, and simulation work were mainly used to support mechanistic explanations and explore how results change with calibration and operating conditions. This helped avoid overextending laboratory-optimized findings to the aging, retrofit-dominated fleets that matter most in practice.

1.7. Data synthesis

To make the evidence easier to compare despite differences across studies, we organized the findings using a predefined stratification framework based on engine type and how the engine is used in practice. The studies were grouped into four main categories: (i) retrofitted bi-fuel SI engines, (ii) dedicated SI engines designed to run on CNG, (iii) dual-fuel CI engines using a small diesel pilot with CNG substitution, and (iv) specialized or component-level studies such as marine engines and tribology-based durability tests.

We then synthesized the results mainly within each group to maintain fair comparisons, and only made cross-group comparisons when different studies showed the same directional trends and were supported by consistent underlying mechanisms. The extracted data were synthesized across three principal domains: engine performance, exhaust emissions, and operational challenges and degradation mechanisms.

Given the heterogeneity in test engines, retrofit specifications, and experimental conditions, the synthesis was primarily narrative. Comparative patterns were identified by examining engine type, mileage, retrofit quality, and test protocols. Missing or ambiguous data were clarified by contacting authors where possible; otherwise, such entries were excluded from pooled summaries. Qualitative findings related to maintenance burden, retrofit practices, or infrastructural barriers were synthesized thematically.

1.8. Publication bias assessment

Formal assessments such as funnel plots were not feasible due to

methodological and contextual heterogeneity across studies. However, to mitigate publication bias, the review incorporated: grey-literature searches via Google Scholar, manual screening of reference lists, and author contact for unpublished data when needed. These steps helped reduce selective reporting and ensured broader representation of real-world engine studies.

1.9. Data management and sharing

All extracted datasets, coding sheets, and synthesis outputs were compiled in CSV format. Analytical workflows (R scripts and Markdown documentation) were archived to support reproducibility. All materials will be made openly available in the OSF repository without embargo.

1.10. Summary of study selection

A total of 812 records were identified through database searches: Scopus (374), IEEE Xplore (266), and Google Scholar (172). After removing 36 duplicates, 776 unique records were screened. Title and abstract screening excluded 652 records, and 124 full-text articles were assessed for eligibility. Additionally, 4 studies were identified through other methods. Ultimately, 26 studies met the inclusion criteria and were incorporated into the review. The study selection process is depicted in the PRISMA flow diagram ([Fig. 2](#)).

While systematic data collection establishes the evidence base, the fundamental contribution of this review lies in the integrated analysis and interpretation of linking combustion thermodynamics, control strategy, and engine aging mechanisms to real-world CNG performance, emissions, and durability trends across engine categories.

Results

3.1. Overview of included studies

3.1.1. Classification of included case studies by engine class and technological generation

Following the expanded PRISMA screening, the dataset was extended to include recent medium- and heavy-duty production CNG engines in addition to retrofit-dominated light-duty platforms. This broader coverage enables clearer separation of fuel-related effects from combustion-architecture and technology-generation influences.

(A) Classification by engine application

Light-duty retrofitted SI engines

These studies examine gasoline engines converted to CNG using mixer-based or early MPFI systems while retaining original combustion chamber geometry and compression ratios.

Performance outcomes generally indicate modest reductions in brake power and torque (3–10%) attributable to methane’s lower volumetric energy density and volumetric efficiency penalties. Brake thermal efficiency (BTE) improvements are limited because compression ratio and valve timing remain unchanged. High-mileage engines exhibit increased cyclic variability and combustion phasing drift, further degrading efficiency.

Emissions trends show consistent reductions in CO and particulate matter relative to gasoline operation, but elevated unburned hydrocarbons (particularly methane slip). NO_x behavior varies with mixture control quality. Aging-related injector drift, catalyst deterioration, and valve seat wear are recurrent operational challenges.

Light-duty research and dedicated SI platforms

Controlled experimental engines demonstrate methane’s thermodynamic potential under optimized conditions. Variable compression ratio (up to 16:1), advanced ignition timing, and heat-release shaping yield measurable BTE improvements (3–8%) and improved knock tolerance. However, lean-burn strategies introduce stability limits near ultra-lean operation, with HC increases under misfire-prone conditions. These studies establish that methane efficiency gains are conditional on

combustion-system optimization rather than fuel substitution alone.

Dual-fuel CI-NG platforms

Heavy-duty diesel engines retrofitted for partial methane substitution show substantial soot reduction due to diffusion-flame suppression. Brake efficiency remains comparable to diesel at moderate substitution ratios but deteriorates at high substitution levels, particularly under low load. On the other hand, NOx sensitivity to substitution ratio and EGR calibration is pronounced, and methane slip increases under incomplete oxidation conditions. Combustion stability at low load remains a principal operational constraint.

Medium- and heavy-duty production CNG engines

The expanded dataset incorporates modern commercial truck and bus engines designed specifically for CNG operation. These engines employ electronically controlled MPFI, turbocharging and intercooling, stoichiometric combustion compatible with three-way catalysts, Miller/LIVC valve strategies, variable compression ratio (VCR), and, in some cases, waste heat recovery (WHR) [6–9].

Unlike retrofit systems, these platforms demonstrate system-level thermodynamic integration. Reported findings indicate: BTE improvements up to 5–6% via variable compression ratio (VCR) adaptation and optimized combustion phasing, pumping loss reduction through Miller-cycle/variable valve timing strategy – LIVC strategies, and competitive efficiency relative to diesel under optimized load regimes.

Effective NOx control through stoichiometric operation and three-way catalytic (TWC) compatibility While methane slip and catalyst thermal management remain challenges, performance penalties commonly reported in retrofit fleets are not observed when combustion architecture is purpose-designed.

(B) Classification by technological generation

Across engine classes, the included studies were further stratified into three technological generations. Early-generation retrofit systems were characterized by limited control authority, pronounced sensitivity to aging effects, progressive emissions drift, and elevated methane slip. Transitional electronically controlled MPFI systems demonstrated improved mixture homogeneity and combustion phasing stability, resulting in moderate efficiency gains and more consistent emissions behavior. In contrast, contemporary production engines incorporate architecture-level thermodynamic integration including VCR, variable valve actuation (VVA), turbocharging, and WHR enabling competitive brake thermal efficiency and more durable, stable emissions control under real-world operating conditions.

3.3.1.2. Geographical distribution of the studies. The studies originated from Asia, Africa, the Middle East, South America, and Eastern Europe, with the majority coming from countries where CNG is operationally significant. India, Bangladesh, Vietnam, and Malaysia contributed numerous studies focused on small SI engines and high-utilization urban fleets. In Africa, Tanzania provided valuable real-world evidence by analyzing high-mileage bi-fuel engines operating under everyday driving conditions.

In the Middle East, studies from Iran, Saudi Arabia, and Egypt examined both SI and dual-fuel CI engines, reflecting regional priorities related to energy diversification and emissions reduction. Argentina supplied long-distance durability data for retrofitted passenger vehicles, while research from Poland and Lithuania emphasized modeling accuracy, combustion optimization, and materials performance. Fig. 3 illustrates the geographic distribution of the included study, in which, each data point represents a distinct literature source. Aggregated ranges reflect reported operating conditions under comparable load and speed regimes. To account for differences in test protocols, results are expressed as relative changes with respect to the study-specific baseline fuel and engine configuration.

Where, A stands for India, B for Vietnam, C for Malaysia, D for Bangladesh, E for Iran, F for Tanzania, G for Argentine, H for Saudi/Egypt, I for Poland, J for Lithuania and K for Japan.

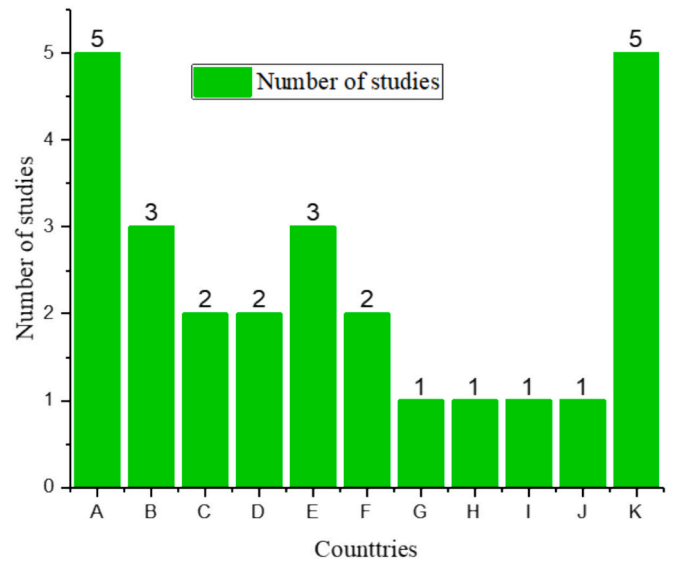


Fig. 3. Geographical distribution of the included studies.

Collectively, these geographical patterns reveal two distinct research orientations:

- I. Developing regions prioritize retrofit practicality, operational robustness, and aging-fleet behavior.
- II. Transitional or technologically advanced regions emphasize modeling, optimization, and component-level durability.

3.3.1.3. Study design and engine conditions. Most studies employed controlled experimental setups, typically using engine or chassis dynamometers with detailed combustion and emissions measurements. Single-cylinder rigs were commonly used for mechanistic investigations of ignition, combustion phasing, and mixture sensitivity; however, their results do not always translate directly to multi-cylinder fleet vehicles.

Several studies incorporated numerical simulation or machine-learning approaches, which enhanced predictive capability while reducing experimental burden. By contrast, field and real-vehicle studies from Bangladesh, Argentina, and Tanzania captured degradation trends that laboratory testing often overlooks, including oil oxidation, catalyst deterioration, calibration drift, and increasing emissions in aged

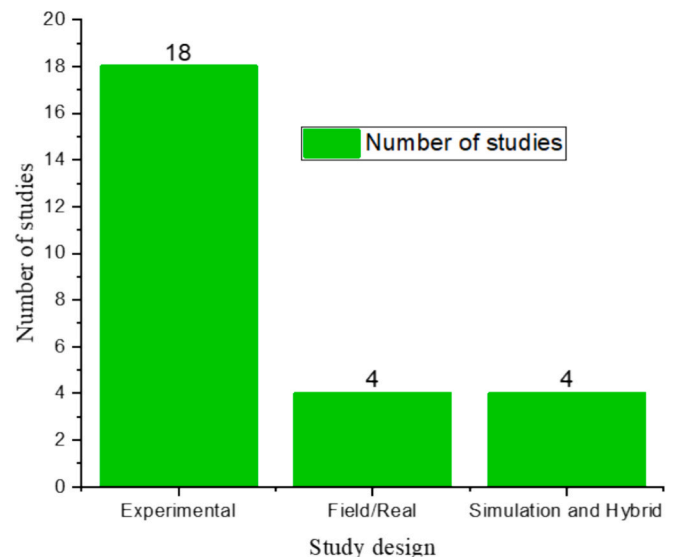


Fig. 4. Study design distribution among the included studies.

engines. Fig. 4 illustrates the study design distribution.

Distribution of the reviewed studies across engine and deployment strata. Retrofitted and bi-fuel SI fleet engines dominate the evidence base Aslam et al., 2006 [10,11]; Jahirul et al., 2010 [11]; Chauhan, 2014 [12,13]; Abedin et al., 2017 [12]; Ramasamy et al., 2017 [14]; Shamekhi et al., 2016 [15]; Duy et al., 2020 [16]; Kyando et al., 2025a,b [17,18]; Vassallo & Miró, 2023 [19]; Abdelghany et al., 2023 [12]; Vipartas et al., 2025 [20], followed by dedicated and research SI CNG engines optimized under controlled conditions Srivastava & Agarwal, 2018 [21]; Sahoo & Srivastava, 2021 [22]; Sahoo et al., 2022 [23]; Le et al., 2024 [24]. Fewer studies address dual-fuel CI engines (Bayat & Ghazikhani, 2020 [25], 2023 [26], while specialized and component-level investigations, including marine engines and tribology studies, remain limited (Machacon et al., 2000 [27]; Szczucka-Lasota et al., 2023 [5], Sok et al., 2023 [7], Sok & Kusaka 2025 [6], Sok et al., 2020 [8] Sok et al. 202 [9].

3.3.1.4. Summary of study metadata and key findings. Tables 1 and 2 summarize the study characteristics and outcomes. Table 1 provides metadata which include authorship, country, engine type, and study design highlighting the diversity of platforms and methodologies. Table 2 presents the primary findings, covering performance changes, emissions behavior, and reported operational challenges. Together, the tables offer a structured foundation for comparing results and interpreting cross-study patterns.

Across the studies summarized in Table 2, three clear trends stand out. First, retrofitted spark-ignition engines often show a drop in performance, mainly due to reduced volumetric efficiency and wear-related aging effects. Second, CNG delivers the most consistent emissions improvements for CO, non-methane hydrocarbons, particulate matter, and CO₂, but these gains can be increasingly reduced in high-mileage vehicles by methane slip. Third, long-term durability is shaped less by the fuel itself and more by retrofit quality, calibration stability, and the condition of the aftertreatment system.

3.2. Stratified evidence synthesis by engine/platform class

To allow fair and meaningful interpretation across different engine types and test setups, we synthesized the CNG performance evidence using a predefined stratification framework (Fig. 5). The included studies were organized into four groups based on both engine design and real-world application: (A) retrofitted bi-fuel SI engines, (B) dedicated or research-based SI CNG engines, (C) dual-fuel CI engines using a small diesel pilot with CNG substitution, and (D) specialized or component-level studies such as marine engines and tribology-focused durability investigations.

The evidence (in Fig. 5) base is dominated by retrofitted SI fleet engines (A), followed by dedicated/research SI engines (B), dual-fuel CI engines (C), specialized studies (D) and Medium- and heavy-duty CNG engines.

3.2.1. Retrofitted bi-fuel SI fleet engines

Most of the included studies examined retrofitted multi-cylinder SI engines operating in either bi-fuel or dedicated CNG modes, which reflects the most common route of CNG adoption in many developing regions [10,11,13]. Across this stratum, studies consistently reported a performance drop, with brake power and torque reductions largely explained by methane's lower volumetric energy density and charge-displacement effects in port-injected retrofit configurations [13,16]. Importantly, these losses were not purely fuel-driven. In many cases, they were worsened by retrofit-system constraints such as non-optimized ignition timing, delayed regulator-injector response, and incomplete exploitation of methane's knock resistance [10,11]. In high-mileage retrofitted vehicles, deterioration further amplified performance losses through reduced volumetric efficiency, combustion

Table 1

Summary of study metadata included in the review.

S/ No	Author(s)	Country	Engine Type	Study Design
1	Duy et al., 2020 [16]	Vietnam	Gasoline engine retrofitted to CNG – spark ignition (SI), 4-cyl, (multiport injection (MPI)	Experimental
2	Srivastava et al. 2018 [21]	India	Single-cylinder diesel engine modified to SI, operated on CNG with laser ignition	Experimental
3	Abedin et al. 2017 [12]	Bangladesh	Retrofitted gasoline car engines (CNG vs Octane)	Experimental (real vehicles, multiple samples, gas analyzer)
4	Chauhan 2014 [13]	India	Maruti multiport fuel injection (MPFI), 3-cylinder, 4-stroke, retrofitted gasoline-to-CNG	Experimental (spark advance study at 2000 rpm)
5	Kyando et al. 2025 [18]	Tanzania	Aged retrofitted Toyota 1NZ-FE, 4-cyl, 1.5 L, electronic fuel injection (EFI), bi-fuel (gasoline & CNG), 161,000 km	Experimental (mileage-based emissions tracking at 1000–5000 rpm)
6	Vipartas et al. 2025 [20]	Lithuania	Nissan HR16DE, 4-cyl, 1.6 L, port injection, SI engine – gasoline & natural gas (NG)	Experimental + numerical modeling (AVL BOOST™, BURN, dyno at 2000–3000 rpm, BMEP 0.31–0.79 MPa)
7	Kyando et al. 2025 [4]	Tanzania	Retrofitted Toyota 1NZ-FE, 4-cyl, 1.5 L, EFI, bi-fuel, 162,908 km	Experimental (oil analysis at 2000 rpm, 100 h gasoline + 100 h CNG)
8	Le et al. 2024 [24]	Vietnam	Retrofitted direct injection (DI) diesel into SI CNG (single-cylinder, port injection), piston-top geometries (concentric vs eccentric bowl), compression ratio (CR) = 11.5:1 & 12.5:1	Experimental and Simulation (AVL Boost, full-load 1000–2000 rpm)
9	Abdelghany et al. 2023 [28]	Saudi Arabia / Egypt	BYD-F3, 4-cyl, 1.6 L, MPFI, bi-fuel (gasoline & CNG)	Experimental (bi-fuel engine with modified exhaust muffler with 30 TEMs for TEG, dynamometer, brake specific fuel consumption (BSFC) & fuel combustion efficiency (FCE) analysis
10	Bayat et al. 2023 [25]	Iran	Perkins 4.108, 4-cyl, 1.76 L, naturally aspirated indirect ignition (IDI) diesel engine	Experimental (dynamometer, 81 test cases at 1200–3000 rpm, 25–75% load, exhaust gas

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Table 1 (continued)

S/ No	Author(s)	Country	Engine Type	Study Design
11	Vassallo et al. 2023 [19]	Argentina	retrofitted for dual-fuel (diesel and CNG) 2007 VW Vento, 5-cyl, 2.48 L, MPFI Otto cycle, bi-fuel (gasoline & CNG), EURO 3	recirculation (EGR) 0–10%, CNG substitution 0–20%) Experimental (chassis dynamometer under NEDC/EUDC cycles, >117,000 km durability, with three-way catalytic (TWC) replacement and CNG kit recalibration)
12	Szczucka-Lasota et al. 2023 [5]	Poland	Focus: valve seat materials in CNG/LNG-fueled engines (no specific engine, lab-based tribology tests)	Experimental (T-11 pin-on-disc tester, Stellite 6 vs Fe3Al coatings, S235JR steel counter-sample, room temp, 30 min tests)
13	Sahoo et al. 2022 [23]	India	Single-cylinder, 4-stroke, 661 cc, water-cooled SI research engine (dedicated CNG, variable CR up to 16:1)	Experimental and multilinear (ML) modeling (Polynomial regression, ANN, SVM; 144 data points across load 2–7 bar indicated mean effective pressure (IMEP), speed 900–1500 rpm, CR 9–16)
14	Sahoo et al. 2021 [22]	India	Single-cylinder, 4-stroke, 661 cc, port fuel injection SI engine (bi-fuel gasoline/CNG, variable CR 9–16)	Experimental (dynamometer, stoichiometric AFR, MBT ignition, CR 9–12 for gasoline, 9–16 for CNG, 900–1500 rpm at 7 bar IMEP)
15	Bayat et al. 2020 [26]	Iran	Perkins 4.108, 4-cyl, 1.76 L, naturally aspirated, IDI diesel engine, dual-fuel (diesel and CNG)	Experimental (81 test cases; 1200–3000 rpm; 25–75% load; 0–10% EGR; 0–40% CNG substitution)
16	Duy et al. 2020 [16]	Vietnam	Toyota 1NZ-FE, 4-cyl, 1.5 L, MPFI gasoline engine retrofitted to CNG with Maz 100 additive supply system	Experimental (dynamometer, AVL emission analyzers, full & partial load tests, 1000–4000 rpm)
17	Srivastava et al. 2018 [21]	India	Single-cylinder diesel engine modified to SI, operated on CNG, variable compression ratio (CR) (9.9, 10.8, 11.8), laser-plasma ignition	Experimental (1500 rpm, $\lambda = 0.9$ –2.0, fixed ignition timing 25° BTDC, in-cylinder pressure heat release rate (HRR) and emissions analysis)
18	Ramasamy et al. 2017 [29]	Malaysia	K3-VE, 1.3 L, 4-cyl, double overhead camshaft (DOHC), dual variable valve timing (DVVT), EFI gasoline engine retrofitted with dual fuel injection	Experimental (dynamometer, baseline gasoline & CNG vs mixtures G15–G45; in-cylinder pressure, HRR, emissions analyzer; torque, power, BSFC, efficiency,

Table 1 (continued)

S/ No	Author(s)	Country	Engine Type	Study Design
19	Jahirul et al. 2010 [11]	Malaysia (UM), Australia (CQU), Bangladesh (CUET)	(gasoline and CNG blends) 1.6 L, 4-cyl SI petrol engine retrofitted to bi-fuel system (gasoline/CNG), CR 9.5:1	combustion phasing) Experimental (dyno test, 50% & 80% throttle, 1500–5500 rpm, emission analyzers)
20	Shamekhi, Abazar; Khatibzadeh, ... 2016 [30]	Iran	Mazda B2000i, 2.0 L, 4-cyl SI, retrofitted to bi-fuel (gasoline and CNG), CR 8.6	Experimental (steady-state full & part load, 1500–5500 rpm, ISO-1585, dyno, gas analyzer, electronic control unit (ECU) monitoring)
21	Aslam et al. 2006 [10]	Malaysia	Proton Magma, 1.5 L, 4-cyl, carbureted gasoline engine retrofitted with Tartarini CNG bi-fuel kit	Experimental (dyno, steady-state, wide open throttle (WOT) 1500–5500 rpm and partial load 25–65%, emission analyzers, PC-based data acquisition)
22	Machacon et al. 2000 [27]	Japan	Yamato 202, 2-stroke, 2-cyl, 397 cc marine racing SI engine, CR varied 8.6–14.5	Experimental (WOT & part load, 4500–6950 rpm, varied CR, intake/exhaust throttling, self-ignition tests)
23	Sok et al. 2025 [6]	Japan	6-cylinder 9.8 L CNG engine. Medium/heavy-duty dedicated CNG SI, turbocharged MPFI, stoichiometric	Experimental dynamometer benchmarking. Electronically controlled multi-port fuel injection (MPFI).
24	Sok et al. 2023 [7]	Japan/China	Heavy-duty CNG SI with integrated WHR	Experimental system-level efficiency study
25	Sok et al. 2020 [8]	Japan	Modern heavy-duty CNG engine. 6-cylinder turbocharged SI engine fueled by city gas 13A. Miller/LIVC, turbocharged MPFI	Experimental system-level efficiency study
26	Sok et al. 2022 [9]	Japan	Heavy-duty CNG SI, VCR, turbocharged	Experimental compression ratio parametric study

instability, and calibration drift, underscoring that long-term CNG performance in this stratum is strongly shaped by engine wear state and retrofit quality rather than fuel properties alone [18,19].

3.3.2.2. Dedicated and research SI CNG engines. Dedicated or research-focused SI engines provided more mechanistic evidence under controlled conditions and showed that efficiency penalties are not inherent to CNG when combustion phasing and compression ratio are properly optimized [22,23]. In this stratum, operation at higher compression ratios enabled by methane's high knock resistance, together with improved ignition strategies increased BTE and reduced BSFC compared with baseline gasoline operation [21,22]. These trends align with Otto-cycle expectations, where increased compression ratio and improved heat-release phasing enhance the conversion of fuel

Table 2
Summary of findings on engine performance, exhaust emissions, and operational challenges in the included studies.

S/ No	Author(s)	Performance Parameters	Exhaust Emissions	Challenges
1	Duy et al., 2020 [16]	BP decreased for 19% with CNG; improved with 6.75% with Maz 100. BSFC decreased for 6.49% (full load), 3.53% (partial load); up to 7.6% at 4000 rpm. In-cylinder Pressure decreased to 57 bar with additive vs 50.6 bar without.	CNG operation reduced CO by 18–36% and HC by 35–37% under full and partial loads. NOx increased at low engine speeds but decreased by about 21–23% at 3000–4000 rpm, while CO ₂ increased slightly by 4–4.5%.	CNG operation increases engine oil thermal stress, requiring optimized ignition timing, higher compression ratios, and intake modifications, while limited refueling infrastructure and the high cost of direct injection systems constrain retrofit feasibility.
2	Srivastava et al. 2018 [21]	BP max at $\lambda = 1.05$; increased with compression ratio (CR) (9.9 to 11.8). Brake Thermal Efficiency (BTE) increased with CR ($\lambda = 1.0$: 27.4% to 28.5%). BSFC decreased with CR, up to 20% at $\lambda = 1.65$. In-cylinder Pressure increased from 26.15 bar (CR 9.9) to 37.3 bar (CR 11.8).	NOx increased with compression ratio (up to 300 ppm), HC peaked at moderate λ and declined under lean conditions, CO rose only in rich mixtures, and CO ₂ increased to 15–17%.	Laser ignition extends the lean limit ($\lambda = 1.76$ vs. 1.62 for spark plugs) but introduces higher cost, durability, and infrastructure challenges.
3	Abedin et al. 2017 [12]	CNG obtained with higher exhaust gas temperature vs Octane. No BP/BSFC data.	Laser ignition extends the lean limit ($\lambda = 1.76$ vs. 1.62 for spark plugs) but introduces higher cost, durability, and infrastructure challenges.	CNG reduces oil dilution and deposits, improving durability, but lower flame speed affects stability and poses fueling and storage challenges.
4	Chauhan 2014 [13]	Brake thermal efficiency (BTE) (%): Gasoline from 28@20° to 25@25° to 23@30°. CNG from 26@20° to 27@25° to 27@30°. BSFC (kg/kWh) Gasoline from 0.31@20° to 0.36@25° to 0.39@30°. CNG from 0.38@20° to 0.34@25° to 0.33@30°. BP (kW@2000 rpm): Gasoline 6.5, CNG 6.0. A/F: Gasoline from about 14, CNG 16–17.	Compared with gasoline, CNG reduced CO (0.6% – 0.2%), HC (220 to 140 ppm), NOx (300—180 ppm), and CO ₂ (14–15% to 12–13%).	Engine oil: Higher in-cylinder temps with CNG to oxidative stress. Maintenance: Knock risk at 30° BTDC (gasoline). Infrastructure: Needs reliable kit and fueling.
5	Kyando et al. 2025 [18]	Max. Power: 81 kW@6000 rpm, Torque: 143 Nm@4000 rpm. A/F: 14.6 to 13.5 (1000–5000 rpm). Combustion phasing: 13° to 31° BTDC. No BSFC/BTE, efficiency inferred from CO ₂ trend.	Compared with gasoline, CNG showed much lower CO and HC, lower CO ₂ , but higher peak NOx, in some cases exceeding Euro IV limits.	Engine oil: Mileage reduces viscosity to blow-by. Maintenance: Oil/filter changes, catalyst degrades. Infrastructure: Dependent on gas supply & retrofitting equipment.
6	Vipartas et al. 2025 [20]	BSFC decreased from 18 to 20% with NG vs gasoline. BTE increased from 3 to 6%. Ignition delay shorter by 1.3–7.3% (2000 rpm), up to 33% (3000 rpm low load). Late valve closing (LIVC) (59° BDC) increased BTE by 3%. Max torque: 156 Nm@4400 rpm, Power: 84 kW@6000 rpm.	With natural gas, CO ₂ fell by 20–26%, CO by 22–33%, and NOx by 20–38%, though delayed intake valve closing increased CO and could raise NOx up to 2.4×; methane slip rose by 10–30%.	Optimized intake valve closing improved BTE but late IVC increased CO, HC, and NOx, requiring advanced ECU control and integrated NG fueling systems.
7	Kyando et al. 2025 [4]	No BP/BSFC measured. Focus: oil degradation. Gasoline viscosity @40°C: 53.9 to 53.3 mm ² /s; CNG: 53.9 to 53.7. Fe: Gasoline 0 to 21 ppm, CNG 0 to 11. Si: Gasoline 0 to 13 ppm, CNG 0 to 4 ppm.	No exhaust data. Indirect: CNG cleaner (lower oil contaminants, lower dilution).	Engine oil: CNG slowed TBN decrease (11.6 to 9.5 vs gasoline 11.6 to 9.4). TAN: Gasoline increased by 2.99, CNG increased by 2.8. Maintenance: Oil retains quality longer on CNG. Infrastructure: Needs reliable sequential CNG kit.
8	Le et al. 2024 [24]	BP & torque highest with PS1 (concentric bowl, CR 11.5). BSFC lowest for PS1 decreased from (0.56–8.3% vs PS2/PS3). In-cylinder pressure highest in PS2 (CR 12.5 concentric), lowest in PS3 (eccentric). HRR faster for concentric bowls; eccentric retards HRR.	No direct emission data. Inferred: concentric bowls to higher efficiency, lower CO/HC; higher CR increases NOx.	Engine oil effects were not evaluated; optimal spark plug placement and ignition timing are required, while diesel-to-SI CNG retrofits demand piston redesign, ECU recalibration, and precise fuel metering.
9	Abdelghany et al. 2023 [28]	Compared with gasoline, CNG showed lower exhaust temperature at 40% load but higher at 80% load, reduced BSFC by 11–15%, and increased fuel combustion efficiency to 33–36%. With TEG integration, CNG delivered higher power output (178 W vs 164 W) and efficiency (9.6% vs 8.2%), with an additional BSFC reduction of 2.7%.	CNG yields higher NOx (higher exhaust temps) but better CO ₂ reduction with TEG due to lower BSFC. Future work on direct emissions characterization.	CNG reduced BSFC by 11–15% and improved combustion efficiency (33–36%), with lower exhaust temperature at low load. With TEG, CNG achieved higher power (178 W), efficiency (9.6%), and an additional 2.7% BSFC reduction.
10	Bayat et al. 2023 [25]	Max power: 38 kW, torque: 89 Nm (baseline diesel). At 20% CNG, exhaust total exergy ↑217% (1200 rpm), increased by 145% (2000 rpm), increased by 114% (3000 rpm). Exhaust chemical exergy decreased up to 11.7% at 3000 rpm, 25% torque, 10% exhaust gas recirculation (EGR). Second-law efficiency decreased by 4.5% (3000 rpm, 25% torque, 10% EGR).	NOx and soot decreased with CNG substitution, while CO and HC increased. For example, at 1200 rpm and 25% load with 20% CNG, NOx dropped from 221 to 187 ppm and soot from 58 to 34 mg/m ³ , whereas CO rose from 0.02% to 0.125% and HC from 9 to 145 ppm.	Engine oil: Not studied. Maintenance: Needs optimized EGR and dual-fuel calibration to balance exergy and emissions. Infrastructure: IDI diesel-to-dual-fuel retrofitting requires pressurized CNG supply and mixing system.
11	Vassallo et al. 2023 [19]	Fuel consumption: Gasoline 8.7–9.3 L/100 km, CNG 9.3–10.9 m ³ /100 km. No brake power/torque directly reported (focus on emissions/fuel use).	Gasoline vehicles with new three-way catalysts initially met EURO 3 limits but exceeded CO and NOx standards after 100,000 km. CNG vehicles showed high THC	Engine oil: Not analyzed. Maintenance: TWC lost efficiency after 60–80 k km; recalibration issues (miscalibration at 160 k km to CH ₄ emissions increased by 360%). Injector ramp replacement needed at 198 k

(continued on next page)

Table 2 (continued)

S/ No	Author(s)	Performance Parameters	Exhaust Emissions	Challenges
			due to methane and NOx often above EURO 3, while CO varied widely. CNG reduced CO ₂ emissions by 18%, but its GHG advantage dropped to 12% (100-year GWP) and 1% (20-year GWP) when methane was included.	km. Infrastructure: Generic CNG kits plus gasoline-optimized TWCs unsuitable long-term; selective catalysts required for CH ₄ /NOx.
12	Szczucka-Lasota et al. 2023 [5]	Coefficient of friction: Stellite 6 = 0.69; Fe3Al = 0.64 (decreased by 7%). Contact temperature: Stellite 6 = 48°C, Fe3Al = 44.5°C. Wear intensity: Stellite 6 = 1560 mg/m ³ ; Fe3Al = 1463 mg/m ³ (decreased by 6%). Surface: Stellite 6 to plastic deformation; Fe3Al to minor scratches, better wear resistance.	No direct exhaust gas data. Indirect evidence showed that degraded valve seats led to methane leakage into the exhaust system and increased CH ₄ emissions.	Engine oil was not analyzed. CNG/LNG engines showed accelerated valve seat wear; Fe ₃ Al outperformed Stellite 6, though further development and high-temperature validation are needed for practical application.
13	Sahoo et al. 2022 [23]	ITE increased (up to 35.86% at CR16, 7 bar), while ISFC decreased to a minimum of 0.20 kg/kWh. Peak pressure rose from 30.4 bar (CR9) to 50.6 bar (CR16). Maximum pressure rise rate reached 2.4 bar/deg. Flame development angle and combustion duration decreased with higher load and CR, but increased with speed.	CO and HC emissions decreased with higher load, compression ratio, and speed, while CO ₂ decreased with load but increased with compression ratio and speed. Overall, higher compression ratio reduced CO and HC but raised CO ₂ .	Engine oil and maintenance were not analyzed. ANN and SVM models proved effective for predictive engine control, reducing experimental effort.
14	Sahoo et al. 2021 [22]	Gasoline knocked at CR ≥ 12, while CNG remained knock-free up to CR16. CNG achieved higher ITE (35.85%) and greater ISFC reduction than gasoline. Increasing CR reduced FDA and combustion duration and raised peak pressure; gasoline showed knock-induced instability, while CNG remained stable.	CNG reduced CO and HC by 60% and CO ₂ by 20% compared to gasoline. Emissions decreased with higher compression ratio, giving cleaner and more stable combustion.	Engine oil: Not analyzed. Maintenance: Requires CR optimization gasoline limited by knock, CNG tolerant to high CR. Infrastructure: Variable CR and precise Electronic control unit (ECU) calibration needed for bi-fuel engines.
15	Bayat et al. 2020 [26]	BSFC decreased up to 15% (2000 rpm, 75% torque, 5% EGR, 40% CNG; from 233 to 198 g/kWh). Average BSFC decreased 4% with 40% CNG. Output power increased slightly. Exhaust temperature increased slightly with CNG.	With CNG substitution, NOx fell by up to 54% and soot by up to 74%. On average, 40% CNG with 10% EGR reduced NOx by 62% and soot by 35% compared to diesel-only operation.	Engine oil was not analyzed. Dual-fuel conversion is feasible but needs EGR control, and large-scale use requires CNG fueling infrastructure.
16	Duy et al. 2020 [16]	Relative to gasoline, CNG increased brake power by 19%, while CNG + Maz 100 raised it by 6.75% at full load. BSFC fell by up to 7.6%, and peak cylinder pressure dropped from 62 bar to 50.6 bar (CNG) and 57 bar (with Maz 100), with in-cylinder temperature reduced by ~ 55 K.	CO and HC decreased by ~ 18–37% on average, with maximum reductions of 52% (CO) and 62% (HC). NOx slightly increased at low rpm but decreased by 21–23% at higher speeds, while CO ₂ increased by 4–4.5% due to more complete combustion.	Engine oil: Higher combustion temps could accelerate oxidation. Maintenance: Requires additive supply, ignition timing advance, intake mods. Infrastructure: Additive logistics and fueling/distribution; direct injection more effective but costly.
17	Srivastava et al. 2018 [21]	Increasing CR improved BP and BTE, with peak BP at λ = 1.05. BTE rose to 28.5% (λ = 1.0) and 25.5% (λ = 1.65), while BSFC decreased by up to 20%. Pmax increased from 26.2 to 37.3 bar, and combustion stability improved, extending the lean limit from λ = 1.62 to 1.76.	NOx increased with compression ratio, peaking near λ = 1.15–1.2; HC peaked around λ = 1.57 then declined lean. CO was stable lean but rose rich at high compression ratio, while CO ₂ likely increased with efficiency.	Engine oil not analyzed; laser ignition extends lean limit (λ = 1.76) and eliminates spark plug wear but requires costly, robust optical hardware for practical deployment.
18	Ramasamy et al. 2017 [29]	Compared with CNG, gasoline blending increased torque/power up to 10.5% (G45), accelerated combustion, and shifted peak pressure toward TDC; efficiency improved only at G45, while G35 offered the best overall trade-off between performance, efficiency, and emissions.	HC and CO increased vs CNG but remained below gasoline levels; NOx decreased (≤1000 ppm), while CO ₂ was implied stable.	Engine oil: Not analyzed. Maintenance: Dual injection requires ECU and injector control integration, no major hardware mods. Infrastructure: Practical for taxis/retrofits, but high gasoline share (≥45%) risks excess CO.
19	Jahirul et al. 2010 [11]	Compared with gasoline, CNG reduced brake power (11–19%) but lowered BSFC (15%) and slightly improved BTE, while exhaust temperature increased by 6–24%.	With CNG, HC, CO, CO ₂ , and O ₂ decreased (22–73%), while NOx increased (38–41%) across both throttle conditions.	Oil not analyzed; retrofit kit worked but high exhaust temperatures limited full-throttle CNG, requiring proper fueling regulation and thermal management.
20	Shamekhi, Abazar; Khatibzadeh, ... 2016 [30]	With CNG, volumetric efficiency, torque, power, and BMEP decreased (10–14%), while BSFC dropped (15–24%) and thermal efficiency increased markedly (22–33%).	With CNG, CO, CO ₂ , and HC decreased (up to 89%, 11%, and 58%), while NOx increased due to hotter, leaner combustion and advanced ignition.	Cleaner CNG combustion suggests better oil durability, but ECU miscalibration limited gasoline operation; heavy high-pressure tanks remain a challenge, with ANG as a potential alternative.
21	Aslam et al. 2006 [10]	Compared with gasoline, CNG reduced BMEP (16%) but lowered BSFC (17–18%) and BSEC, while fuel conversion efficiency increased by 3%.	With CNG, CO, CO ₂ , and HC decreased (80%, 20%, 50%), while NOx increased (33%) due to hotter, lean combustion.	Oil not analyzed; retrofit required spark advance, with heavy tanks and limited fueling infrastructure as key constraints.
22	Machacon et al. 2000 [27]	Higher compression enabled self-ignition with low BSFC (285 g/kWh), increased IMEP, and reduced cyclic variability, extending the λ operating range, while BMEP gains were limited by friction losses.	HC: Slight decreased with self-ignition combustion. NOx: Low (≤100 ppm), unaffected by self-ignition, governed mainly by residual gas fraction.	2-stroke CNG required forced lubrication to avoid scuffing; high compression increased wear risk, and operation depended on specialized CNG fueling infrastructure.

(continued on next page)

Table 2 (continued)

S/ No	Author(s)	Performance Parameters	Exhaust Emissions	Challenges
23	Sok et al. 2025 [6]	Competitive brake thermal efficiency under medium-to-high load; improved torque stability; reduced cyclic variability compared with mixer-based systems	Significant PM reduction vs. diesel baseline; NOx sensitive to λ -control and combustion temperature; methane slip influenced by catalyst light-off	Precise equivalence ratio control required; catalyst temperature management under transient duty cycles; knock margin management at high compression ratios
24	Sok et al. 2023 [7]	Baseline: Peak BTE 34.2% at 2400 rpm (full load); brake power 102.1 kW; $\frac{1}{3}$ of fuel energy lost via exhaust. Gross power 0.009–2.423 kW; effective 0.027–1.168 kW. At peak condition, BTE improved by 0.56–0.79% with effective power gain of 1.15–1.8 kW. 0.5% exhaust loss reduction; no significant brake power penalty; no combustion modification required.	Operates under stoichiometric CNG enabling TWC compatibility for NOx control. No direct emissions measurements reported. Recovered electrical power may support faster catalyst light-off and improved aftertreatment efficiency (e.g., hybrid support), potentially reducing cold-start NOx and CH ₄ . Backpressure and aftertreatment impacts not experimentally quantified.	TEG integration increases exhaust backpressure and pumping losses; net efficiency gains depend on balancing heat recovery and pressure drop. Performance is sensitive to module density and flow characteristics, with diminishing returns at high packing. Low conversion efficiency (<5%) limits overall gains (<1%), and backpressure–aftertreatment interactions remain insufficiently assessed.
25	Sok et al. 2020 [8]	Improved expansion ratio; reduced pumping losses; enhanced part-load efficiency; diesel-competitive efficiency under specific duty cycles	Reduced PM; NOx dependent on EGR calibration; methane slip influenced by lean-burn operation	Turbocharger matching complexity; balancing EGR and boost pressure; aftertreatment durability under lean exhaust
26	Sok et al. 2022 [9]	Competitive BTE under optimized calibration; power comparable to gasoline baseline; knock-limited at high load; efficiency sensitive to spark timing, EGR, and mixture control.	Substantial PM reduction; NOx highly dependent on equivalence ratio and EGR; methane slips significant at low load; stoichiometric operation enables TWC compatibility.	Knock constraint at high load; catalyst temperature sensitivity; calibration robustness required; lean stability limitations; system-level integration essential.

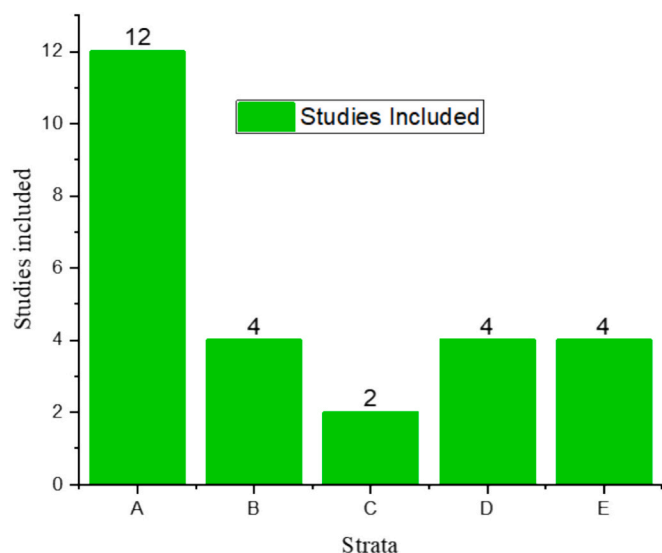


Fig. 5. Stratification of included studies by engine platform and study focus ($n = 26$). Results include both factory and retrofit CNG configurations. Baseline comparisons correspond to pre-retrofit gasoline or diesel operation of the same engine, unless explicitly noted. Variability across studies reflects differences in calibration strategy, aftertreatment presence, and engine age.

energy into useful work. However, because these studies are typically conducted under stable and controlled conditions, their findings cannot be directly transferred to real-world fleets where transient loads, hardware variability, and aging-related deterioration dominate retrofit performance. Nonetheless, this stratum provides an important benchmark by demonstrating the achievable performance potential of CNG under optimized combustion design and control. [23,24].

3.3.2.3. Dual-fuel CI engines. Dual-fuel CI studies showed a different performance trade-off structure compared with SI retrofits because combustion is governed by diesel pilot ignition and the premixed methane burn fraction, rather than spark-driven flame propagation [25,26]. In this stratum, performance depended strongly on substitution ratio, load, and EGR level, where benefits were often linked to reduced diffusion-driven combustion and soot suppression, while efficiency and stability remained sensitive to pilot quantity and combustion phasing.

Overall, the evidence suggests that dual-fuel CI systems can deliver meaningful particulate-related benefits, but require careful control of air–fuel mixing and pilot injection to avoid incomplete oxidation and efficiency losses, particularly under low-load conditions. This indicates that performance in dual-fuel CI engines is shaped more by ignition management and mixture preparation than by the volumetric energy constraints commonly emphasized in SI retrofit platforms [25].

3.3.2.4. Specialized and component-level evidence. A smaller subset of studies extended the evidence base beyond road passenger platforms by A smaller subset of studies extended the evidence base beyond road passenger applications, including work on high-speed SI marine engines and component-level durability under gaseous fuels [5,27]. Marine engine studies provide insight into combustion feasibility at elevated speeds and wide-open-throttle operation, but represent specialized regimes that are not directly transferable to urban fleet CNG applications [27]. Similarly, tribology-focused investigations of valve-seat materials provide important evidence on durability risks, particularly under the thermal loading and lubrication conditions associated with gaseous fuels. However, they do not yield system-level performance metrics comparable with vehicle-based studies. Therefore, these works were interpreted primarily as mechanistic evidence supporting durability and material-selection considerations rather than as direct benchmarks for fleet performance comparison [5].

Overall, the stratified synthesis confirms that CNG performance outcomes are highly dependent on engine design, and are strongly refuted by retrofit quality, calibration strategy, and aging effects. Retrofitted fleet SI engines are the most likely to exhibit power losses and deterioration sensitivity, whereas optimized research SI platforms show that efficiency gains are achievable when combustion phasing and compression ratio are tuned for methane. Dual-fuel CI systems follow a distinct trade-off structure controlled by pilot ignition and substitution dynamics, while specialized and component-level studies mainly provide mechanistic durability context rather than directly comparable performance outcomes.

3.4. Engine performance

3.3.3.1. Power, torque, and combustion characteristics

The power and torque changes shown in Figs. 6 and 7 are illustrative and represent percentage differences reported at representative operating conditions in the respective studies, typically at mid-to-high load

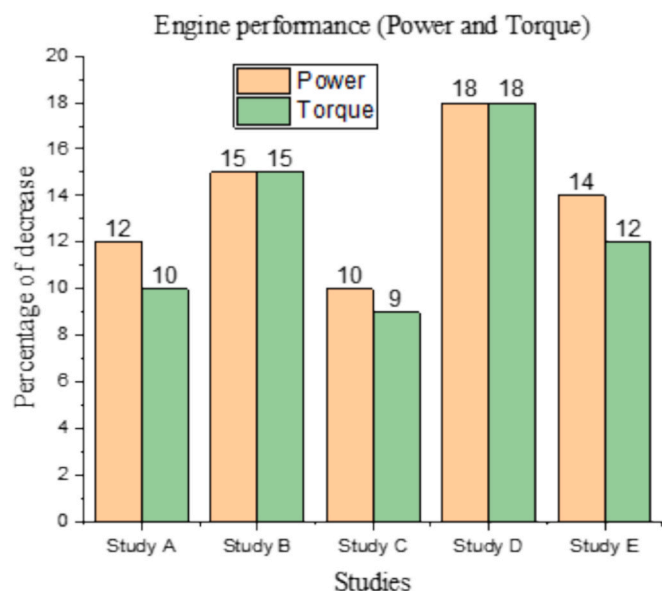


Fig. 6. Reductions in brake power and torque across representative retrofit and aged-engine studies. Where, Study A: Chauhan 2014 [13]; Study B: Duy et al. 2020 [16]; Study C: Abedin et al. 2017 [12]; Study D: Ramasamy et al. 2017 [14]; Study E: Aslam et al. 2006 [10].

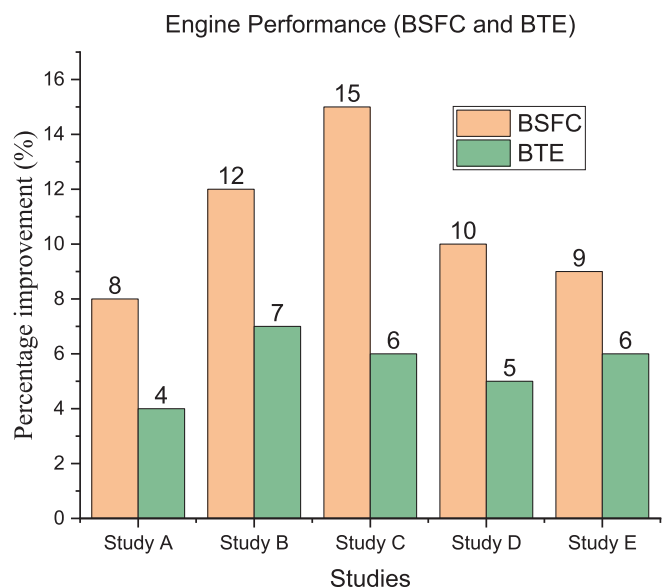


Fig. 7. Improvements in BSFC and BTE under optimized combustion conditions. In which, Study A stands for Chauhan 2014 [13]; Study B stands for Duy et al. 2020 [16]; Study C for Abedin et al. (2017) [12]; Study D for Ramasamy et al. 2017 [14]; Study E for Aslam et al. 2006 [10].

or near-rated engine speeds, as defined by each experimental protocol. Because the reviewed studies employed different engines, test speeds, and load conditions, the values are presented as normalized percentage changes rather than absolute outputs.

Across the 26 studies, CNG operation consistently resulted in lower brake power and torque typically by 10–20% relative to gasoline or diesel baselines. This reduction was evident in both retrofitted SI engines [13,16] and dual-fuel CI engines [25,26] – Fig. 6. The decline is primarily linked to methane’s lower volumetric energy density, which reduces the energy available per cycle, and to wear-related volumetric-efficiency losses in high-mileage engines.

Despite these reductions, several studies demonstrated that CNG

efficiency disadvantages are not inherent but contingent on engine calibration. Optimized ignition timing and higher compression ratios (CR 12–16) produced 5–10% increases in BTE and 15–20% reductions in BSFC [20,22]. Methane’s high-octane rating permitted advanced spark timing and elevated peak cylinder pressures without knocking [21,31]. Fig. 7 illustrates BSFC and BTE under optimized combustion conditions. In this regard, efficiency and fuel-consumption values are reported relative to baseline conventional-fuel operation in the same engine. Metrics are presented as brake thermal efficiency or brake-specific fuel consumption, as defined in the source studies. When absolute values differed in reporting basis, results were normalized as relative (%) changes to ensure consistency across the aggregated literature.

Combustion-phasing studies showed that retrofitted engines typically exhibited slower flame development and longer combustion duration [11]. In contrast, dedicated CNG engines demonstrated shorter ignition delays, steeper heat-release rates, and improved cyclic stability, attributed to optimized combustion-chamber geometry and ignition strategy [24,32].

3.3.3.2. High-mileage engine behavior

Studies of engines above 100,000 km revealed characteristic deterioration patterns, including increased blow-by, injector fatigue, valve-train wear, and catalyst aging contributing to delayed combustion, increased cyclic variability, and reduced peak pressures [17,33]. Field tests from Tanzania and Argentina found that suboptimal retrofit kits and calibration drift further compounded performance losses [19,34]. These results underscore the importance of maintenance, calibration accuracy, and retrofit quality in sustaining CNG performance.

3.5. Exhaust emissions

3.3.4.1. Carbon monoxide and hydrocarbons

CNG operation consistently reduced CO and HC emissions, often by 20–80% compared with gasoline [12,35]. These reductions stem from methane’s simple molecular structure, higher hydrogen-to-carbon ratio, and low aromatic content, which collectively promote cleaner combustion and minimal carbonaceous residue. Dual-fuel CI engines exhibited similar HC reductions at moderate substitution ratios [26,29].

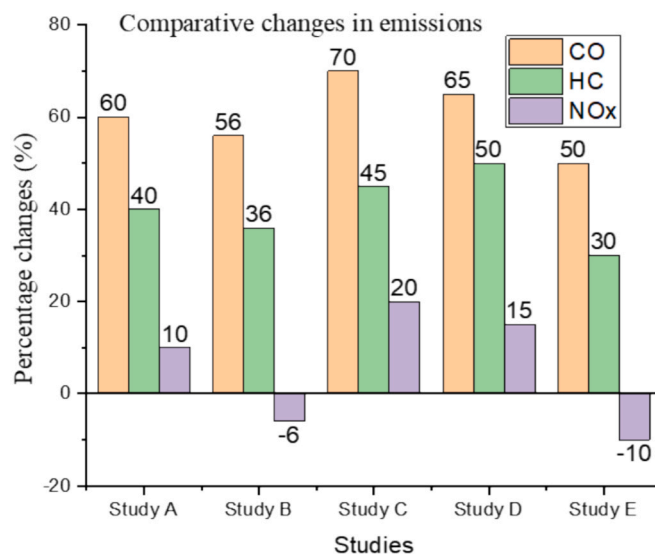


Fig. 8. Comparative changes in CO, HC, and NOx emissions under CNG operation. Studies A–E represent selected, representative investigations from the reviewed literature covering retrofitted SI engines, dedicated CNG engines, aged high-mileage vehicles, and dual-fuel CI engines; respectively. Values are shown as percentage changes relative to the respective baseline fuels reported in each study.

However, some studies reported elevated unburned methane under conditions of incomplete oxidation [36]. Fig. 8 – Unless otherwise stated, reported values represent changes relative to the baseline conventional fuel (gasoline for spark-ignition engines and diesel for compression-ignition engines) within the same engine configuration. Emissions are expressed on a brake-specific or distance-based basis (g/kWh or g/km), as reported in the original studies. Where necessary, results were harmonized using percentage change relative to the baseline to enable cross-study comparison.

Taken together, the emissions results indicate that while CNG consistently reduces carbon-based pollutants and soot, its real-world greenhouse gas benefit is increasingly governed by methane slip and NOx control. These effects intensify with engine aging and calibration drift, underscoring the need for CNG-specific aftertreatment and adaptive control strategies.

3.3.4.2. Methane slip and total hydrocarbon emissions

Because emission standards are cycle-based (typically reported in g/km) and vary by vehicle class and test procedure, compliance implications are discussed qualitatively unless the original study reported emissions in standard-relevant units.

Methane slip emerged as a major limitation in aged and retrofitted SI engines (Fig. 9.) Worn injectors, degraded catalysts, and calibration drift often caused methane increased substantially in aged retrofitted vehicles, indicating a potential risk to hydrocarbon compliance under regulatory test cycles, particularly when catalyst performance deteriorates [19]. Some vehicles demonstrated 300–360% increases in CH₄ emissions due to after-treatment deterioration [18,19].

3.3.4.3. Nitrogen oxides (NOx)

The NOx trends reported in the reviewed studies are strongly influenced by the calibration strategy set at installation and by how much adaptive control the engine can apply during real operation. In many retrofitted spark-ignition and dual-fuel CI engines, key parameters such as ignition timing, air–fuel ratio, and EGR are governed by fixed (or only weakly adaptive) calibration maps. As the engine ages and operating conditions shift, these static settings often fail to compensate for changes in combustion phasing, thermal loading, and sensor drift, which can lead to higher NOx formation. In contrast, systems with more advanced adaptive control, typically original equipment manufacturer (OEM)-calibrated or dedicated CNG platforms can continuously fine-tune ignition timing, mixture strength, and dilution based on feedback signals. This allows them to better stabilize in-cylinder temperatures and

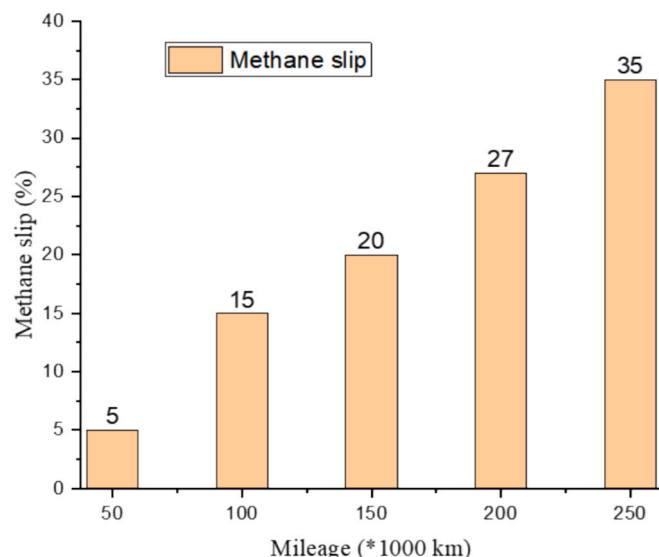


Fig. 9. Increase in methane slip with accumulated engine mileage.

maintain more consistent NOx control across a wider range of driving and load conditions. NOx behavior varied considerably across engine platforms:

- I. Retrofitted SI engines frequently showed increased NOx at high load or lean operation due to elevated in-cylinder temperatures [13,16].
- II. Dedicated CNG engines exhibited stable or reduced NOx when optimized chamber geometry moderated thermal loading [24,35].
- III. Dual-fuel CI engines often achieved 20–60% reductions in NOx, particularly under low-load or moderate substitution conditions [37,38].

These results highlight the strong sensitivity of NOx formation to combustion phasing, air–fuel ratio, load, and calibration strategy.

In the reviewed dual-fuel CI engines, CNG was typically introduced as a supplementary fuel while retaining the original diesel exhaust aftertreatment configuration, such as diesel oxidation catalysts (DOC) or baseline emission control systems. Dedicated CNG-specific catalytic converters were generally not implemented, and in several cases, emissions were reported under engine-out or minimally treated exhaust conditions. As a result, reported emission trends primarily reflect changes in in-cylinder combustion behavior rather than optimized aftertreatment performance.

3.3.4.4. Carbon dioxide (CO₂) and soot

Most studies reported 10–25% lower CO₂ emissions per unit fuel energy under CNG combustion [39,40]. Per-kilometer reductions were smaller (5–20%) but remained positive despite reduced power output [11]. In dual-fuel CI engines, CNG significantly lowered soot emissions ranging from 50 to 70% due to the absence of heavy hydrocarbons and the elimination of diesel-diffusion flames [25,29].

3.6. Operational, lubrication, and durability challenges

3.3.5.1. Lubricant degradation and wear behavior

Findings across ten studies revealed a dual effect of CNG on lubricant behavior (Fig. 9): positive effects; Reduced wear metals (Fe, Al, Si), lower soot loading and reduced fuel dilution, cleaner combustion, reducing abrasive wear [4,41]; negative effects: Increased oxidation, nitration, viscosity breakdown, higher thermal loads and NOx-driven oxidative stress [33,42]. These trends indicate that CNG can extend oil life only when engine sealing, injector condition, and combustion phasing are well maintained.

3.3.5.2. Retrofit and calibration issues

Retrofit quality was one of the strongest determinants of operational outcomes. Common problems included:

- I. Misfiring and idle instability in mixer-type systems.
- II. Incorrect ignition maps leading to higher NOx and reduced efficiency [22,31].
- III. Injector fouling, regulator wear, and sensor drift in aged fleets [19].
- IV. Calibration drift was particularly problematic; several engines that were emissions-compliant at installation became non-compliant after 60,000–100,000 km due to catalyst and sensor aging [18,19].

Infrastructure and safety considerations

Several studies highlighted non-engine constraints that influence CNG system viability – Fig. 10, these include: Limited refueling infrastructure [34,43]; high cylinder weight and installation costs [44]; safety issues linked to low-quality aftermarket components [34,45]. These challenges are especially relevant in developing countries with

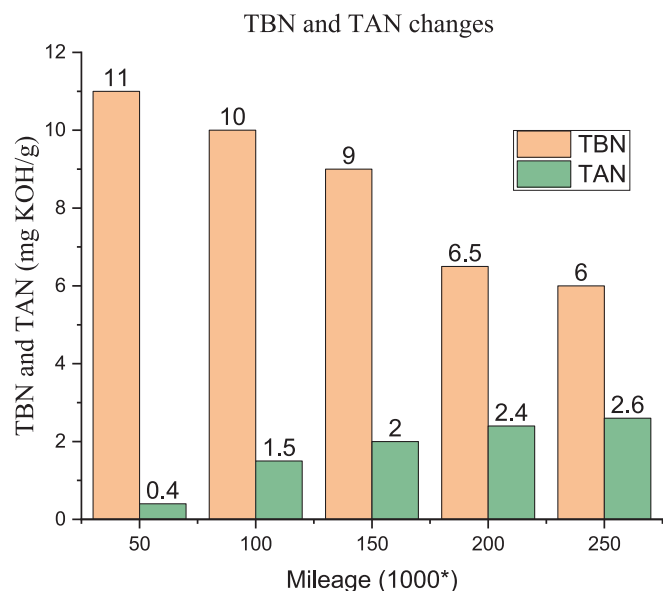


Fig. 10. TBN and TAN changes associated with oxidative–nitrate lubricant degradation.

growing CNG fleets.

3.3.5.3. Summary of findings

Across diverse platforms and regions, CNG consistently reduced CO, HC, particulate matter, and CO₂ emissions. However, trade-offs included lower power output, methane slip, variable NO_x behavior, and lubricant oxidation. Engine condition, retrofit quality, calibration stability, and after-treatment performance emerged as the dominant factors determining whether the theoretical benefits of CNG are realized in real-world high-mileage fleets [4,19,34].

6. Discussion

4.2. Study overview

The Discussion prioritizes interpretation of observed trends, linking combustion thermodynamics, control strategy, and engine aging mechanisms to real-world CNG performance.

4.1.1. Engine types used in the included studies

The range of engine types represented in the included studies has a direct influence on how CNG performance, emissions, and operational challenges should be interpreted. Most investigations focused on retrofitted multi-cylinder spark-ignition engines, reflecting conditions in many developing countries where aging gasoline vehicles are converted for CNG use. Because these engines were not originally designed for gaseous fuel, their combustion-chamber geometry, injector layout, and control strategies are often poorly matched to methane's slow flame speed and lean-burn capability. This mismatch helps explain the frequently reported moderate power and torque losses, increased NO_x under certain operating conditions, and accelerated lubricant oxidation, particularly in high-mileage engines.

By contrast, single-cylinder research engines provided valuable mechanistic insight by enabling precise control of compression ratio, ignition timing, and mixture strength. These configurations clarified how methane behaves during combustion, but their simplified design cannot fully replicate real-world wear, thermal interactions, multi-cylinder mixture distribution, or component degradation. Their findings are therefore foundational but not fully representative of aging, retrofit-heavy fleets.

A smaller subset of studies examined dual-fuel engines, illustrating

growing interest in supplementing compression-ignition engines with gaseous fuel. These systems consistently reduced soot but introduced new challenges in managing NO_x and CO, emphasizing the importance of optimized pilot injection, EGR strategy, and combustion control.

Overall, the diversity of engine platforms demonstrates that CNG performance is highly dependent on engine architecture, calibration, and condition. As a result, modelling approaches, regulatory limits, and policy decisions must reflect the actual engine types present in local fleets, rather than relying solely on data from idealized or laboratory-optimized engines.

4.1.2. Geographical distribution of included studies

The geographical distribution of the reviewed studies reveals clear regional patterns that shape both the technical focus and policy relevance of CNG research. A substantial portion of the evidence originates from South and Southeast Asia, where countries such as India, Bangladesh, Malaysia, and Vietnam rely heavily on retrofitted taxis, minibuses, and small passenger vehicles. Work from these regions therefore concentrates on bi-fuel SI engines, urban driving conditions, and low-cost retrofit solutions, providing contextually relevant insights for rapidly growing and resource-constrained transport systems.

In Africa, studies from Tanzania provide rare data on high-mileage CNG and bi-fuel engines, documenting long-term issues such as calibration drift, catalyst deterioration, and emissions non-compliance in aging fleets [18,34]. These findings are particularly important for regions where regulatory oversight is limited and vehicle lifetimes are extended.

Research from the Middle East, notably Iran, Saudi Arabia, and Egypt reflects a different strategic context, where CNG is closely linked to energy diversification and utilization of domestic gas reserves. These studies emphasize dual-fuel CI engines, high-load operation, and substitution strategies, providing a complementary contrast to the SI-dominated work from Asia [26,28].

Meanwhile, contributions from Eastern Europe and Japan focus more heavily on modeling, optimization, and materials durability, treating CNG as a platform for technological innovation rather than primarily a fuel-transition measure [5,20,27]. Taken together, these regional tendencies show that CNG research closely tracks local priorities, and its conclusions must be interpreted within each region's socio-economic conditions, fleet characteristics, fuel policies, and infrastructure constraints.

4.1.3. Study design and engine conditions

The diversity of study designs ranging from controlled laboratory experiments to numerical simulations and full-scale field trials provides a multidimensional basis for interpreting CNG engine behavior. Laboratory dynamometer studies dominate the evidence base and allow precise variation of ignition timing, equivalence ratio, compression ratio, and load. Such controlled conditions are well suited for isolating thermodynamic and combustion phenomena, but they cannot fully capture the transient loading, thermal cycles, variable fuel quality, and mechanical deterioration that characterize real-world operation.

Single-cylinder research engines offer additional mechanistic clarity by enabling systematic variation of key combustion parameters without the complexities of multi-cylinder interactions. However, their simplified geometry and operating conditions limit their ability to represent mixture distribution, heat rejection, frictional losses, and durability processes in production engines.

Simulation-based studies, including AVL BOOST™ modelling and machine-learning approaches, further extend the evidence base by supporting parametric optimization and prediction, but they remain constrained by model assumptions, boundary conditions, and the quality of input data [20,23].

In contrast, field studies from Bangladesh, Argentina, and Tanzania provide the long-term perspective often missing from laboratory work. [4,12,19]. These investigations document progressive lubricant

oxidation and nitration, blow-by escalation, catalyst aging, and calibration drift phenomena that directly affect emissions compliance, efficiency degradation, and maintenance requirements over extended service life.

In the other hand, the most reviewed dual-fuel CI studies, CNG was introduced while retaining the original diesel aftertreatment configuration, such as baseline diesel oxidation catalysts. Dedicated CNG-specific catalytic systems were rarely implemented, and across multiple categories, a consistent pattern emerges engine-out emissions. Only a limited number of investigations explicitly documented aftertreatment modification, restricting direct comparison of catalyst-optimized outcomes.

Collectively, these complementary methodologies show that short-duration laboratory findings must be interpreted with caution. Real-world CNG engines are subject to cumulative wear, fuel-quality variability, and control-system drift that significantly modify their operational and environmental performance over time. This underscores the need to integrate laboratory insights, simulation outputs, and long-term field evidence when evaluating the practical viability of CNG technologies.

4.3. Interpretation of engine performance outcomes under CNG

The stratified evidence base shows that CNG performance outcomes are not universal, but depend strongly on engine architecture, combustion mode, and the level of optimization achieved in practice. In retrofit-heavy fleets, the commonly reported reductions in brake power and torque are best explained by methane's lower volumetric energy density, charge displacement in port-injected systems, and non-optimized combustion phasing, rather than an inherent limitation of CNG itself [10,11,16]. In many aftermarket conversions, ignition and fueling strategies remain constrained by gasoline/diesel-oriented calibration, which limits spark advance and prevents effective use of methane's high knock resistance. As a result, combustion may occur later in the expansion stroke, reducing peak effective pressure and lowering brake work output.

4.2.1. Retrofitted bi-fuel SI fleet engines

In aged, high-mileage retrofit fleets, these limitations are further amplified by deterioration mechanisms such as reduced volumetric efficiency, blow-by, valve sealing losses, and injector or sensor drift, which increase cyclic variability and sensitivity to calibration errors [18,19]. Under these conditions, performance loss becomes coupled with instability: partial burns and occasional misfire can reduce torque while simultaneously increasing unburned methane emissions. This explains why real-world performance deterioration often exceeds what would be expected from charge-energy effects alone.

4.2.2. Dedicated or research SI engines

By contrast, dedicated and research SI engines show that CNG can achieve equal or better efficiency when combustion is optimized, particularly through higher compression ratio and improved ignition control [21–24]. These results align with Otto-cycle expectations, where higher compression and improved combustion phasing increase thermal efficiency, and methane's knock resistance enables advance without knock-limited spark retard. However, this evidence represents mechanistic potential rather than direct fleet prediction, since controlled platforms typically do not capture aging, transient operation, and multi-cylinder maldistribution effects that dominate retrofit outcomes.

4.2.3. Dual fuel CI engines

Dual-fuel CI engines operate under a different regime, where combustion is governed by diesel pilot ignition and the balance between premixed methane burning and diffusion-controlled diesel combustion [25]. Here, CNG substitution usually suppresses soot formation by reducing diffusion flames, but stability and oxidation limits can appear

at low loads due to methane's higher ignition temperature and slower oxidation kinetics. Performance and efficiency therefore depend mainly on substitution ratio, pilot quantity, and EGR strategy, which control ignition delay, heat-release phasing, and combustion completeness. Unlike SI retrofits, dual-fuel CI trade-offs are dominated by ignition management and mixing-controlled oxidation rather than volumetric energy constraints.

4.2.4. Specialized and component-level evidence

Specialized and component-level studies provide important durability context but should not be directly compared with fleet performance results. Marine engine investigations reflect high-speed, high-load conditions that differ from typical road operation [27], while tribology-focused work mainly informs wear mechanisms and material compatibility rather than brake-level outcomes [5]. Their primary value is in supporting explanations of durability risks, such as valve-seat wear and surface-coating performance, rather than benchmarking fleet efficiency.

Overall, this stratified interpretation reinforces that the key determinant of CNG performance is not fuel selection alone, but how effectively the engine system is calibrated and designed to exploit methane combustion. Retrofitted SI fleets are most prone to power loss and aging-driven deterioration, whereas optimized SI platforms demonstrate the achievable efficiency ceiling under improved combustion phasing and compression ratio. Dual-fuel CI systems follow a distinct benefit structure shaped by pilot ignition and substitution dynamics, while specialized studies provide mechanistic durability support. These distinctions highlight the importance of reporting CNG outcomes within compatible strata and avoiding generalized conclusions that overlook architecture-specific constraints.

4.2.5. Overall IC engines performance with CNG

The findings of this review indicate that the performance of CNG-fueled engines is governed by a combination of combustion characteristics, original engine design, calibration strategy, and accumulated mechanical degradation. Although CNG offers several intrinsic advantages, including a high-octane number, cleaner premixed combustion, and a high hydrogen-to-carbon ratio, these properties do not automatically yield superior real-world performance. Their impact strongly depends on whether the engine is purpose-built for CNG, retrofitted from gasoline or diesel, or significantly aged.

In retrofitted SI engines, the commonly reported decreases in brake power and torque arise mainly from methane's lower volumetric energy density, which reduces charge energy and peak cylinder pressures, particularly when manifold and combustion-chamber designs are inherited from gasoline operation [13,16,26]. As engines age, additional factors such as valve leakage, piston-ring wear, and injector fatigue further reduce volumetric efficiency and increase cyclic variability, amplifying performance losses [4,19].

By contrast, evidence from optimized and dedicated CNG engines demonstrates that these performance drops are not inherent to the fuel. Engines designed or recalibrated for gaseous combustion with higher compression ratios, advanced ignition control, and appropriately shaped combustion chambers showed significant gains in brake thermal efficiency and reductions in BSFC [20,22]. Methane's high knock resistance permits more advanced spark timing and higher peak pressures, in line with thermodynamic expectations from the Otto cycle [20,21]. Dedicated CNG engines also exhibited faster ignition, steeper heat-release rates, and more stable cycles Le et al., 2024 and Melaika et al., 2021 [24,35], emphasizing the importance of matched combustion-chamber geometry, valve timing, and control strategies.

Generally, the performance evidence suggests that much of the apparent disadvantage of CNG in aging retrofitted engines reflects design and degradation constraints, rather than fundamental fuel limitations. Purpose-built or thoroughly optimized engines can leverage CNG's properties to deliver competitive or superior efficiency outcomes.

4.4. Interpretation of emissions outcomes under CNG

The stratified evidence base shows that emission outcomes under CNG are strongly shaped by combustion mode, calibration strategy, aftertreatment condition, and engine aging. Although many studies report consistent reductions in CO, total HC, PM, and CO₂ compared with gasoline or diesel, the size and durability of these benefits vary across engine strata. In particular, outcomes differ depending on whether the engine is a retrofit fleet platform, an optimized research engine, or a dual-fuel CI system [11,12,19,26]. It is also important to note that emissions standards are defined under prescribed test cycles and are commonly expressed in distance-based units (g/km); therefore, compliance implications are discussed qualitatively unless studies reported emissions in standard-relevant metrics.

4.3.1. Retrofitted bi-fuel SI fleet engines

Among retrofitted SI fleet vehicles, the most consistent finding is a reduction in CO and non-methane hydrocarbon species relative to gasoline operation. This aligns with methane's simpler molecular structure, lack of aromatics, and cleaner premixed combustion behavior [10–12]. However, this stratum also provides the clearest evidence of a critical limitation: methane slip, especially under lean operation, low exhaust temperatures, and aging aftertreatment systems. Unlike gasoline-derived HC, methane is inherently difficult to oxidize and requires higher catalyst activity and light-off temperatures for effective conversion. As a result, high-mileage retrofit fleets frequently show rising unburned CH₄ emissions over time as catalyst performance degrades and calibration drift develops [18,19]. This helps explain why some fleet studies report large increases in total hydrocarbon output under CNG even when CO declines, indicating that the emissions advantage of CNG becomes conditional on stable mixture control, proper lambda regulation, and sustained three-way catalyst efficiency.

NOx trends in retrofit SI fleets are more variable, reflecting strong sensitivity to flame temperature, excess-air ratio, and combustion phasing. Engines operating lean or at high load may show increased NOx because higher combustion temperatures promote thermal NO formation and extend residence time [13,16]. In contrast, stoichiometric operation with a functional three-way catalyst can substantially reduce tailpipe NOx, showing that NOx outcomes in SI retrofits depend heavily on both calibration quality and aftertreatment effectiveness, not only on in-cylinder chemistry.

4.3.2. Dedicated and research SI CNG engines

In dedicated and research SI systems, emissions behavior is more tightly linked to controllable parameters such as equivalence ratio, spark timing, compression ratio, and combustion phasing [21–24]. CO and HC reductions remain common due to improved oxidation completeness under optimized combustion control, while NOx responses follow the expected trade-off between higher efficiency (and thus higher temperature) and dilution strategies that limit peak thermal conditions. When compression ratio and combustion phasing are optimized for maximum efficiency, NOx may rise unless countered through lean-burn operation, cooled EGR, or other temperature-moderating approaches. Conversely, improved phasing that shortens combustion duration and reduces late burning can suppress CO and HC formation while keeping NOx within acceptable ranges.

A key distinction in this stratum is that methane slip is usually lower than in aged retrofit fleets not because methane is inherently easier to oxidize, but because research engines tend to operate under stable calibration, controlled mixture preparation, and consistent thermal conditions that reduce incomplete oxidation at the exhaust.

4.3.3. Dual-fuel CI engines

Dual-fuel CI engines exhibit a fundamentally different emissions structure, and in this stratum the most consistent advantage is the strong reduction in soot/PM. This is largely driven by reduced diffusion-

controlled diesel combustion and the absence of aromatics in the methane fraction [25]. As substitution increases, diffusion-flame intensity is reduced, lowering soot precursors and particulate formation pathways. However, dual-fuel CI emissions are highly sensitive to pilot quantity, substitution ratio, and operating load. Under low-load conditions, combustion temperatures can be insufficient for complete methane oxidation, leading to increases in CO and unburned HC. This behavior is consistent with methane's slow oxidation kinetics and the reduced presence of high-temperature diffusion flames that would normally promote burnout.

NOx behavior in dual-fuel CI is often improved under moderate substitution and optimized EGR strategies, but outcomes depend strongly on heat-release phasing and in-cylinder temperature history. Studies that applied EGR show that NOx can be reduced by lowering oxygen concentration and peak combustion temperature, although excessive dilution may raise CO and HC by weakening oxidation completeness [25]. Overall, these findings highlight that dual-fuel CI systems can deliver strong particulate benefits but require careful management of both ignition and oxidation environments, particularly when aftertreatment systems are limited.

4.3.4. Specialized and component-level evidence

Specialized studies, including marine engines, provide useful boundary evidence but are not directly comparable to road-fleet emissions outcomes because of differences in speed range, load regimes, and combustion strategy [27]. Component-level tribology studies do not measure regulated emissions directly, but they support durability-linked emissions mechanisms by showing that valve-seat wear and material degradation can worsen sealing, increase blow-by, and destabilize combustion during long-term gaseous operation [5]. This reinforces the broader conclusion that emissions outcomes under CNG are often durability-coupled, particularly in retrofit fleets where aging accelerates catalyst performance loss and calibration drift.

Overall, the stratified synthesis indicates that CNG delivers its most consistent emissions benefits through CO reduction and soot suppression, while the most persistent risks arise from methane slip in aged and retrofitted SI fleets and from oxidation limitations (CO/HC) under low-load dual-fuel CI operation. NOx responses remain highly strategy-dependent across all strata and are governed by combustion temperature, mixture control, EGR use, and catalyst effectiveness. These patterns emphasize that sustained emissions improvements under CNG require not only fuel substitution but also robust calibration control, thermally appropriate operating conditions, and durable aftertreatment performance over the intended service life.

4.3.5. Overall exhaust-emission trends in CNG-fueled IC engines

The emission patterns observed across the included studies highlight the dual nature of CNG as a low-carbon but methane-rich fuel. On one hand, CNG consistently reduces CO, HC (excluding CH₄), particulate matter, and CO₂ relative to gasoline or diesel operation [11,12,26,29]. These benefits arise from methane's simple chemical structure, absence of aromatics, and strong tendency toward clean premixed combustion, which minimize soot precursor formation.

On the other hand, methane slip emerges as a critical challenge, particularly in retrofitted or high-mileage SI engines. Methane's high activation temperature and the degradation of three-way catalysts through wash-coat sintering, poisoning, or oxygen-storage loss limit oxidation efficiency at typical exhaust temperatures. As a result, some high-mileage fleets exhibit 300–360% increases in CH₄ emissions [19]. These outcomes significantly erode the apparent hydrocarbon benefits of CNG and have non-trivial implications for greenhouse-gas impact, given methane's high global warming potential. The findings reinforce that effective methane control requires healthy catalysts, robust lambda control, and accurate calibration throughout the engine's service life.

As methane slip emerges as an operational limitation of retrofitted CNG systems, this is because methane oxidation requires higher light-off

temperatures than those typically sustained in aged three-way catalysts. As catalyst oxygen-storage capacity degrades and lambda control accuracy declines with mileage, oxidation efficiency deteriorates, leading to inconsistent increases in CH₄ emissions despite otherwise reduced CO and non-methane HC.

NO_x trends are similarly context-dependent. Retrofitted SI engines, especially those operating lean or at high load, often show increased NO_x emissions due to elevated in-cylinder temperatures and longer thermal residence times [13,16]. In contrast, dedicated CNG engines with optimized combustion chambers or carefully controlled mixture strengths can moderate peak temperatures and lower NO_x [24,35]. Dual-fuel CI engines frequently achieve 20–60% NO_x reductions, because CNG displaces portions of diesel that would otherwise burn in high-temperature diffusion flames [37,38]. These patterns confirm that NO_x behavior is governed as much by combustion mode, EGR management, and equivalence ratio as by the fuel itself. These findings indicate that NO_x outcomes under CNG operation are governed not only by fuel chemistry, but also by the interaction between calibration strategy and the system's ability to adapt dynamically during long-term operation.

In summary, CNG offers clear advantages in CO, non-methane HC, soot, and CO₂ emissions, but these gains are conditional on effective control of methane slip and NO_x, especially in aged or poorly maintained systems. Meanwhile, the absence of CNG-optimized aftertreatment in most dual-fuel CI studies likely influences reported NO_x and hydrocarbon trends, indicating that further emissions reductions may be achievable through tailored catalyst integration in future dual-fuel engine designs.

Most retrofitted engines reviewed employed fixed or weakly adaptive control strategies, typically limited to short-term air–fuel ratio correction based on lambda feedback. Long-term adaptive learning capable of compensating for component aging, fuel variability, or calibration drift was generally absent or not reported. In contrast, dedicated or OEM-calibrated CNG engines incorporated both short- and long-term adaptive corrections, contributing to more stable combustion and emissions behavior over extended operation.

4.5. Engine durability, lubrication, and operational challenges under CNG

Durability, lubrication response, and operational reliability under CNG are strongly influenced by engine architecture, thermal management, retrofit quality, and the accumulated degradation state of the engine. Across the included evidence, durability emerges as one of the clearest factors separating laboratory-based evaluations from the long-term behavior of retrofit-dominated fleets. The stratified synthesis further shows that many operational challenges associated with CNG are not purely fuel-driven. Instead, they arise from the combined effects of methane combustion characteristics, limitations in control strategies, and progressive wear mechanisms that become increasingly important at high mileage [17,19,33].

4.4.1. Retrofitted bi-fuel SI fleet engines

In retrofitted SI fleet vehicles, long-term stability is often constrained by the mismatch between aftermarket conversion systems and the original gasoline-engine design envelope. Several studies report that durability outcomes depend strongly on mixture preparation quality, ignition calibration, and sealing integrity, with deterioration frequently appearing as unstable idle, misfire, and progressive calibration drift [10,16,34]. Because many retrofit kits rely on simplified fueling strategies and limited adaptive control, gradual sensor drift, regulator wear, injector degradation, and declining volumetric efficiency can shift equivalence ratio and combustion phasing over time. This increases cyclic variability and reduces combustion completeness at certain operating points, producing coupled consequences such as rising methane slip, reduced drivability, and the need for periodic recalibration to maintain emissions performance and acceptable fuel economy

[18,19].

Lubrication trends in high-mileage retrofit fleets show a distinct “dual effect” under CNG operation. Cleaner combustion typically reduces soot contamination and fuel dilution, which can lower abrasive wear and reduce the accumulation of some wear metals [4,41]. However, elevated combustion temperatures and increased NO_x exposure under some operating modes promote oxidative and nitrative stress in the lubricant, accelerating alkalinity depletion (TBN reduction), increasing acidity (TAN increase), and driving viscosity shifts associated with oil aging and degradation [33,42]. These effects become more severe when sealing is compromised, blow-by increases, or cooling performance deteriorates, because crankcase exposure to hot gases and reactive nitrogen species intensifies. Therefore, while CNG can reduce contamination-driven oil degradation, extended oil life in retrofit fleets cannot be assumed without appropriate oil formulation and disciplined maintenance control [17,33].

4.4.2. Dedicated and research SI CNG engines

Dedicated SI platforms generally exhibit fewer operational disturbances because fueling and ignition are deliberately stabilized and optimized for methane combustion. This stratum provides mechanistic insight into how compression ratio, combustion phasing, and mixture strategy influence thermal loading and long-term durability stress [22–24]. Under well-controlled calibration, CNG can reduce deposit formation and limit carbon-related wear pathways. At the same time, research findings also highlight that efficiency-oriented strategies such as higher compression ratio and more advanced combustion phasing can increase peak pressure and thermal gradients, potentially increasing tribological loading at valve seats, rings, and piston surfaces if materials and lubrication robustness are not matched to the operating regime. This indicates that efficiency gains in optimized CNG engines must be balanced against thermal and material durability requirements, particularly under sustained high-load operation.

4.4.3. Dual-fuel CI engines

In dual-fuel CI engines, durability and operational behavior are driven more by mixture preparation and oxidation limitations than by spark-stability constraints. By displacing part of diesel diffusion combustion with methane-containing premixed burning, these systems often reduce soot formation and soot-related oil contamination, which can improve lubricant cleanliness and reduce abrasive wear pathways [25]. However, dual-fuel CI operation introduces sensitivity to pilot injection strategy, substitution ratio, and EGR control. At low loads, combustion temperatures may be insufficient for complete oxidation, promoting higher CO/HC emissions and potentially increasing deposit formation in intake or exhaust pathways. Excessive EGR can further weaken oxidation environments, increasing the risk of incomplete combustion. These trends suggest that durability in CI dual-fuel systems depends on maintaining robust control of pilot timing, pilot quantity, and dilution levels to avoid prolonged partial-combustion regimes that may accelerate fouling or aftertreatment deterioration [25,26].

4.4.4. Specialized and component-level evidence

Specialized and component-level studies provide valuable boundary evidence that may not be captured in short-duration engine performance testing. Marine engine investigations demonstrate gaseous operation feasibility under high-speed and unique load regimes but represent specialized conditions that are not directly representative of aging road-fleet behavior [27]. Tribology-focused studies strengthen durability interpretation by showing that gaseous fueling can increase valve-seat wear risk under certain contact conditions, aligning with field evidence of sealing degradation and progressive performance and emissions drift in high-mileage engines [5]. Although such component tests do not provide full-system durability rates, they improve mechanistic traceability by isolating material response under representative stress conditions and highlighting the importance of surface engineering and

material selection in long-term gaseous operation.

Across all strata, a consistent operational conclusion is that long-term durability under CNG depends heavily on control-system robustness and maintenance infrastructure. In retrofit fleets, limited diagnostic capability, inconsistent conversion-kit quality, and weak inspection enforcement can accelerate degradation pathways and erode CNG's real-world emissions benefits. Infrastructure constraints such as limited refueling access, cylinder mass and packaging penalties, and safety risks associated with poor-quality components further limit sustainable deployment, particularly in developing-country contexts where retrofitting is common but technical oversight is inconsistent [34,43,44]. Overall, the stratified synthesis indicates that durable and low-emission CNG operation requires not only favorable fuel chemistry, but also fleet-appropriate calibration control, oxidation-resistant lubrication strategies, retained aftertreatment efficiency, and enforceable retrofit and maintenance standards throughout the service life.

4.4.5. Overall operational and durability challenges in CNG-fueled engines

CNG's impact on lubrication and long-term engine durability also exhibits a dual character. On the positive side, CNG operation reduces soot contamination, fuel dilution, and metal wear particles such as Fe, Al, and Si, resulting in cleaner oil and lower abrasive wear [33,41]. This reflects the absence of heavy hydrocarbons and the reduced tendency to form carbonaceous deposits.

Conversely, the higher combustion temperatures and elevated NO_x typical of some CNG operating regimes increase oxidation, nitration, and viscosity breakdown in lubricants, particularly when engines suffer from worn rings, poor sealing, or insufficient cooling [33,42]. In high-mileage engines, rapid TBN depletion and viscosity loss were commonly reported, indicating that CNG's potential durability benefits cannot be realized without adequate mechanical condition and lubricant formulation tailored to high-temperature, low-soot operation.

The review also shows that retrofit quality and calibration accuracy are central to long-term performance and emissions. Poorly configured mixer-type retrofits and non-optimized ignition maps led to frequent misfires, unstable idle, elevated NO_x, and increased methane slip [10,22,31]. Over time, injector wear, regulator degradation, and sensor drift shift the effective calibration, causing engines that were initially compliant to exceed emissions limits after 60,000 to 100,000 km [19,34]. These findings highlight the necessity of periodic recalibration, catalyst inspection, and maintenance of fuel-system components for sustained energy-conversion efficiency. Operational challenges in retrofitted engines commonly included misfiring and idle instability in mixer-type systems, incorrect ignition maps that elevated NO_x and reduced efficiency, and progressive injector fouling and sensor drift in high-mileage fleets.

A small number of studies on low-speed marine CI engines suggest that converting these platforms to CNG may not deliver the same performance and emissions benefits seen in road vehicles. At speeds below about 1500 rpm, in-cylinder turbulence is typically weaker and combustion lasts longer, which makes methane harder to burn efficiently and consistently. As a result, combustion stability and efficiency can deteriorate rather than improve. These findings indicate that the favorable CNG trends reported for automotive and medium-speed engines should not be directly assumed for low-speed marine applications.

Beyond purely technical issues, several non-technical barriers strongly influence the practical adoption of CNG. Limited refueling infrastructure, the high initial cost and weight of onboard CNG storage, and safety risks from low-quality retrofit components were repeatedly identified as constraints, particularly in developing-country fleets [34,43–45]. Together, these results make it clear that although CNG offers strong theoretical and experimentally demonstrated advantages, its real-world success depends on coordinated improvements in engine condition, retrofit quality, maintenance practices, and broader policy and infrastructure support.

4.4.6. Engine aging-related mechanisms influencing combustion, efficiency, and emissions under CNG

Although the fundamental chemistry of combustion and emissions does not change as an internal combustion engine ages, long-term operation gradually alters the conditions under which these processes take place. The literature reviewed in this study shows that many of the performance and emissions trends observed in aged or high-mileage engines operating on CNG are not driven by fuel properties alone and more by wear- and degradation-related effects that accumulate over time [39,45].

One of the most influential factors is mechanical wear at the piston–ring–liner interface. As engines accumulate mileage, increased wear leads to higher blow-by and a reduction in effective compression. This, in turn, lowers the trapped charge mass and promotes incomplete combustion, particularly under low-load and transient conditions. Several studies on high-mileage SI and CI engines reviewed in this work report corresponding increase in unburned hydrocarbons and methane emissions. Wear-induced reductions in volumetric efficiency and greater cyclic variability further affect combustion stability and heat-release timing, trends that have been documented in both gasoline- and CNG-fueled engines operating in retrofit configurations [5,19].

Changes in lubrication with age also play a critical role. While CNG combustion generally reduces soot formation and fuel dilution compared with gasoline or diesel operation, multiple studies included in this review report accelerated oxidative and nitrative degradation of engine oil. This behavior is often linked to higher combustion temperatures and extended oil drain intervals commonly adopted for gaseous-fuel engines. As lubricant properties degrade and oil consumption increases, deposits tend to form on piston crowns, ring packs, intake valves, and combustion chamber surfaces. Such deposits, reported in several aged CNG and LNG engine studies, can alter local heat transfer, mixture preparation, and flame development, increasing cycle-to-cycle variability and the likelihood of incomplete combustion [18,33,46].

Frictional losses associated with component wear impose an additional penalty on efficiency. Experimental investigations of aged engines summarized in this review indicate that increased friction in the piston assembly, valve train, and auxiliary systems reduces the fraction of indicated work converted into brake work. As a result, the decline in brake thermal efficiency commonly observed in high-mileage CNG engines is amplified. This effect is particularly pronounced in retrofit configurations, where volumetric efficiency is often already compromised, making incremental friction losses more impactful than in newer or purpose-designed engines [28].

Aging effects are further compounded by limitations in engine control systems. Several retrofit-focused studies reviewed here show that sensor drift, injector wear, regulator aging, and limited adaptive control capability progressively shift ignition timing and air–fuel ratio away from optimal values. These deviations influence combustion temperature, NO_x formation, and oxidation completeness, especially in systems relying on fixed or weakly adaptive calibration maps. As a result, emissions deterioration in aged CNG engines frequently exceeds levels that would be expected based on fuel substitution effects alone [12,19].

Overall, this synthesis highlights that the impact of aging on CNG engine performance and emissions is best understood as a systems-level phenomenon. While the underlying combustion principles remain unchanged, wear, lubrication degradation, friction, deposit formation, and control-system drift increasingly govern real-world outcomes as engines accumulate service life. This reinforces the need to treat aged and high-mileage engines as a distinct analytical category in assessments of CNG performance and emissions.

4.6. Implications and future directions

The findings of this systematic review carry direct implications for the design, calibration, maintenance, and regulation of CNG technologies, particularly in developing-country fleets where aged and

retrofitted vehicles dominate. Although CNG consistently offers reductions in CO, HC, PM, and CO₂ emissions, these benefits are not automatically sustained over long service life. Instead, real-world outcomes depend on whether engines are appropriately configured for methane combustion, whether calibration remains stable as components age, and whether aftertreatment systems retain conversion efficiency under realistic operating conditions [18,19,33]. The evidence therefore supports a shift from short-term performance assessments toward durability-informed evaluation, where emissions performance is interpreted as a function of both combustion optimization and degradation mechanisms.

From an engineering perspective, the review highlights that retrofitted SI engines frequently operate under combustion-system constraints that limit the exploitation of methane's high-octane tolerance. The observed power drop and NO_x variability in retrofit-heavy fleets indicate that improved outcomes require CNG-specific calibration strategies. This would include optimized spark advance, robust closed-loop mixture control, and in applicable platforms compression ratio adaptation or combustion-chamber redesign to improve combustion phasing and thermal efficiency [22,24,35]. In dual-fuel CI systems, practical deployment depends on control strategies that stabilize pilot ignition and manage substitution dynamics across load ranges. This is due to emissions trade-offs (notably soot–NO_x and CO/HC oxidation) are highly sensitive to EGR fraction, pilot quantity, and heat-release phasing [25]. Across both SI and CI strata, these findings emphasize that CNG transition strategies must be supported by calibration approaches designed for methane kinetics and real-world transient operation, rather than relying on generic aftermarket conversions.

Operationally, the durability evidence indicates that sustained CNG benefits require active management of deterioration pathways. High-mileage fleets repeatedly exhibit progressive methane slip, catalyst aging, and calibration drift, which can erode hydrocarbon-control advantages and increase long-term emissions despite initially favorable results [18,19]. The lubrication findings further suggest that CNG introduces a distinctive oil-degradation profile: reduced soot and fuel dilution can lower abrasive wear trends, yet increased oxidation and nitration risk under higher thermal loading can accelerate base depletion and viscosity change if oil formulation and service intervals are not adapted to gaseous operation [41,42]. These trends support the need for CNG-appropriate lubricant specifications with stronger oxidation stability and total base TBN retention, alongside condition-based maintenance supported by oil monitoring and diagnostic feedback where feasible.

At the policy and implementation level, this review shows that technical performance improvements alone are insufficient without supporting infrastructure and enforceable quality control. Many long-term challenges originate from inconsistent retrofit workmanship, variable conversion-kit quality, limited technician training, and weak inspection regimes, particularly in settings where retrofitting is the primary route to CNG adoption [34,43,44]. Strengthening certification standards for retrofit systems, enforcing periodic emissions testing (including catalyst efficiency checks), and requiring recalibration after defined mileage intervals would improve emissions durability and operational reliability. In parallel, infrastructure limitations such as refueling availability, storage-cylinder mass and packaging, and safety risks associated with low-quality components remain practical constraints that shape real-world feasibility for commercial fleets [34,44]. Moreover, because methane is itself a potent greenhouse gas, sustaining climate benefits also requires attention to upstream leakage control across the natural-gas supply chain [39,40].

Future research should prioritize (i) long-term fleet studies that quantify degradation trajectories in methane slip, catalyst conversion efficiency, and calibration stability over mileage; (ii) harmonized reporting of emissions using cycle-relevant metrics and consistent baselines to improve cross-study comparability; (iii) integrated thermo-lubrication analyses that link combustion phasing, NO_x exposure, and

oil oxidation/nitration kinetics under realistic duty cycles; and (iv) retrofit-focused control strategies, including adaptive ignition/mixing control and diagnostics capable of maintaining performance as components age. Collectively, these directions support a more durable deployment pathway in which CNG can function as an effective transitional fuel. Therefore, delivering sustained air-quality benefits and realistic greenhouse-gas reductions only when engine technology, maintenance systems, and regulatory frameworks evolve together in line with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Actions).

4.6.1. Modern medium- and Heavy-Duty production CNG Engines: Technological context

The inclusion of recent medium- and heavy-duty production CNG engines extends the analytical scope of this review beyond retrofit-dominated light-duty platforms and provides an essential technological benchmark. The expanded dataset indicates that many of the efficiency penalties and emissions instabilities reported in aged conversion fleets are not intrinsic to methane combustion, but instead arise from architectural and control-system limitations [6–9].

Modern heavy-duty CNG engines are designed as integrated combustion systems rather than fuel-substitution modifications. Contemporary platforms typically employ electronically controlled multi-port fuel injection (MPFI), optimized combustion chamber geometry, turbocharging, and closed-loop stoichiometric control compatible with three-way catalyst (TWC) aftertreatment. Under these configurations, cylinder-to-cylinder mixture homogeneity is improved, cyclic variability is reduced, and combustion phasing can be maintained closer to minimum spark advance for best torque (MBT) across a wide load range.

From a thermodynamic perspective, recent heavy-duty investigations demonstrate that methane's high knock resistance can be exploited through elevated effective compression ratios and advanced valve timing strategies, including Miller-cycle or late intake valve closing (LIVC). Variable compression ratio (VCR) concepts have been shown to improve brake thermal efficiency by enabling load-dependent optimization of expansion work recovery while limiting knock intensity at high load. Reported efficiency gains (up to 6% under simulated drive-cycle conditions) are achieved through expansion-ratio management and pumping-loss reduction rather than through enrichment or excessive spark retard.

System-level integration further differentiates production engines from retrofit platforms. Turbocharger matching, EGR calibration, and aftertreatment thermal management are co-optimized to maintain stable NO_x control while preserving efficiency. In contrast, retrofit systems typically modify only the fuel delivery subsystem while retaining baseline compression ratio, valve timing, and combustion chamber design. As a result, retrofit engines often operate under volumetric-efficiency limitations and calibration sensitivity that are absent in purpose-designed heavy-duty platforms.

Emissions behavior reflects this distinction. While particulate matter is consistently reduced relative to diesel baselines in heavy-duty CNG engines, NO_x formation remains sensitive to combustion temperature control and catalyst light-off management. Dual-fuel CI–NG systems exhibit strong dependence on substitution ratio and EGR strategy, confirming that emissions outcomes are governed primarily by control architecture rather than fuel chemistry alone.

Taken together, these findings clarify that performance degradation, methane slip, and emissions drift observed in high-mileage retrofit fleets represent aging- and calibration-driven phenomena rather than fundamental thermodynamic constraints of CNG. The expanded inclusion of medium- and heavy-duty production engines therefore strengthens the generalizability of the review by separating fuel-specific effects from technology-generation effects.

Strength and limitations

The synthesis was guided by study-level quality appraisal (Table S1). Field and high-mileage vehicle studies were prioritized when discussing durability, methane slip escalation, and catalyst aging, whereas controlled single-cylinder experiments and simulations were emphasized for mechanistic interpretation of combustion phasing, compression ratio effects, and NOx sensitivity. Accordingly, quantitative generalizations were avoided where study heterogeneity or limited reporting reduced confidence. Where conclusions depend on long-term durability and compliance, greater weight was placed on high-quality field and high-mileage studies than on short-duration laboratory tests.

7. Conclusion

The stratified synthesis confirms that CNG outcomes are strongly platform-dependent. Retrofitted and aged SI fleet engines commonly exhibit power penalties, calibration sensitivity, and increasing methane slip as components age, whereas dedicated SI CNG platforms demonstrate that efficiency gains are achievable when compression ratio and combustion phasing are optimized. Dual-fuel CI engines follow a distinct trade-off structure dominated by pilot ignition and substitution dynamics, delivering robust soot reductions but requiring careful control of CO/HC and NOx. Specialized marine and component-level studies mainly provide mechanistic durability insight and should not be directly cross-compared with road-fleet performance results.

The review demonstrates that the performance, emissions, and durability outcomes of CNG-fueled engines are highly sensitive to engine architecture, operational context, and evaluation methodology. In developing regions, where retrofitted and aged spark-ignition engines dominate the long-term behavior of CNG systems is shaped by aging components, calibration drift, and variable retrofit quality. In contrast, work from Europe and Japan emphasizes modeling, optimization, and component-level refinement, reflecting different technological priorities. When integrated, evidence from laboratory studies, simulations, and real-world fleet investigations shows that controlled thermodynamic gains frequently diverge from practical outcomes due to cumulative wear, fuel variability, and aftertreatment degradation. Therefore, meaningful assessments of CNG viability must incorporate the actual engine platforms, ambient conditions, and degradation mechanisms present in operating fleets.

Across the literature, CNG consistently reduced CO, HC, particulate matter, and CO₂ emissions because of its clean premixed combustion and favorable chemical structure [11,12,35]. However, persistent challenges, especially methane slip, NOx variability, and power deficits were most severe in retrofitted and heavily used engines, where injector wear, catalyst aging, and sensor drift compromised combustion and emissions control [18,19,33]. Crucially, these limitations reflect engineering and maintenance constraints, not shortcomings of the fuel itself.

Evidence from optimized and dedicated CNG engines highlights the fuel's potential: when equipped with higher compression ratios, improved ignition systems, and purpose-designed combustion chambers, CNG engines frequently outperform gasoline systems in thermal efficiency and fuel consumption [20,22]. In contrast, the performance penalties observed in many retrofitted engines arise from inadequate calibration, suboptimal conversion hardware, and accumulated mechanical wear that disrupts combustion phasing and aftertreatment efficiency [4,34].

The durability findings follow a similar dual pattern. CNG operation reduces soot formation and fuel dilution, thereby lowering wear-metal concentrations and slowing abrasive lubricant contamination. Yet elevated combustion temperatures and increased NOx exposure accelerate oil oxidation and nitration, especially in engines with weakened sealing or cooling systems [41,42]. Thus, realizing CNG's full durability benefits requires mechanically sound engines, appropriate lubricant formulations, and consistent calibration routines.

The integration of medium- and heavy-duty production CNG engines into the analytical framework further clarifies that the performance and emissions limitations frequently observed in aged retrofit fleets are not inherent to methane combustion. Contemporary commercial truck engines demonstrate that when CNG is implemented within purpose-designed combustion architectures, incorporating multi-port or direct injection, optimized valve timing strategies (e.g., Miller/LIVC), elevated effective compression ratios, turbocharging, and advanced electronic control, competitive brake thermal efficiencies and stable emissions performance can be achieved under real-world duty cycles.

This expanded evidence base reinforces a central distinction emerging from the review: efficiency losses, methane slip, and emissions drift in high-mileage conversion systems primarily reflect aging-related wear, lubrication degradation, and calibration sensitivity rather than intrinsic fuel limitations. Modern heavy-duty platforms illustrate that integrated thermodynamic optimization and durability-oriented engineering can mitigate these degradation pathways.

Accordingly, future research and policy assessments should explicitly differentiate between technology-generation effects and fuel-specific characteristics when evaluating CNG performance, particularly in the context of long-term fleet decarbonization strategies and commercial transport deployment.

Key quantitative outcomes and achievements of the review

Across retrofitted spark-ignition engines, CNG operation was associated with typical brake power and torque reductions of approximately 10–20%, primarily due to methane's lower volumetric energy density and calibration limitations in non-optimized engines.

When engines were optimized for gaseous combustion (e.g., higher compression ratios and advanced ignition control), brake thermal efficiency improved by approximately 5–10%, with brake specific fuel consumption reductions of 10–20% relative to gasoline operation.

CNG consistently reduced carbon monoxide and total hydrocarbon emissions by approximately 20–80%, and carbon dioxide emissions by 10–25% per unit energy, reflecting cleaner premixed combustion and a favorable hydrogen-to-carbon ratio.

In dual-fuel compression-ignition engines, partial diesel substitution with CNG resulted in soot reductions of approximately 50–70%, while NOx emissions varied depending on load, substitution ratio, and EGR strategy.

In aged engines (more than 100,000 km), methane slip increased substantially (ranges from 300 to 360%) in poorly maintained systems, highlighting the dominant role of catalyst degradation and calibration drift in long-term emissions performance.

Lubricant analyses showed a dual effect of CNG operation, with reduced wear-metal concentrations and soot contamination, but accelerated oxidation and nitration, emphasizing the need for CNG-specific lubricant formulations and maintenance strategies.

Modern medium- and heavy-duty production CNG engines achieve > 34% BTE with up to almost 6% gains from integrated optimization, confirming that performance limitations in aged retrofit fleets are technology-driven rather than fuel-intrinsic.

Collectively, these quantified outcomes demonstrate that while CNG offers substantial emissions benefits, its real-world performance is highly dependent on engine design, control strategy, retrofit quality, and long-term maintenance.

CRediT authorship contribution statement

Michael J. Kyando: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Justin W. Ntalikwa:** Writing – review & editing, Supervision, Methodology. **Thomas Kivevele:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to improve the language. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecmx.2026.101726>.

Data availability

Data will be made available on request.

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