Environmental Effects of Liquefied Petroleum Gas in Spark Ignition Engines: A Technical Review

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Abstract **- Liquefied petroleum gas (LPG) is one of the most mature alternative fuels currently used in spark ignition engines because it combines commercial availability, well-established fuel infrastructure and favorable combustion characteristics. This paper presents a technical review of the environmental effects of LPG in spark ignition engines by analyzing and comparing the findings of more than twenty experimental and numerical studies published over the past two decades. The review discusses the physicochemical properties of LPG and examines their influence on the formation of carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC) and nitrogen oxides (NO_X). The collected literature demonstrates that LPG generally provides lower CO and HC emissions because of improved mixture homogeneity and more complete combustion, while CO_2 emissions are typically reduced owing to the lower carbon-to-hydrogen ratio of the fuel. In contrast, the effect on NO_X emissions remains dependent on engine operating conditions, combustion temperature, air–fuel ratio and engine calibration. The review further evaluates the influence of engine load, speed, ignition timing, fuel-delivery system and catalyst performance on the reported emission characteristics. The presented analysis summarizes the principal mechanisms governing pollutant formation and provides a comprehensive technical overview of the environmental performance of LPG-fueled spark ignition engines.**

Keywords **- liquefied petroleum gas; spark ignition engine; exhaust emissions; alternative gaseous fuel.**

1. INTRODUCTION

Spark ignition (SI) engines remain one of the most widely used power units for passenger cars, light commercial vehicles and small stationary power systems because of their relatively simple design, high reliability and low production cost. Despite the rapid development of hybrid and battery electric vehicles, gasoline-fueled engines continue to play an important role in the global transportation sector owing to their well-established technology, extensive fueling infrastructure and continuous improvements in fuel economy and emission control [1]. Consequently, considerable research efforts are still directed toward reducing the environmental impact of SI engines while maintaining their performance and operational reliability [2].

Road transport is one of the major contributors to atmospheric pollution, emitting significant quantities of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_X), particulate matter (PM) and carbon dioxide (CO_2). These pollutants adversely affect air quality, contribute to the formation of photochemical smog and greenhouse gases, and pose serious risks to human health. Although modern three-way catalytic converters have substantially reduced regulated emissions, increasingly stringent environmental regulations continue to encourage the development of cleaner combustion technologies and alternative fuels capable of further reducing pollutant formation.

Among the various alternative fuels available for spark ignition engines, liquefied petroleum gas (LPG) has become one of the most successful commercially implemented solutions. LPG has been used in automotive applications for several decades and is currently one of the most widely adopted alternative fuels worldwide. It consists primarily of propane (C_3H_8) and butane (C_4H_{10}), with their relative proportions varying according to regional fuel specifications, seasonal requirements and climatic conditions. The fuel is stored in liquid form under moderate pressure, allowing considerably higher energy density than compressed gaseous fuels while retaining many of the combustion advantages associated with gaseous fuel operation.

The physicochemical properties of LPG differ substantially from those of conventional gasoline and directly influence mixture formation, combustion development and exhaust emission characteristics. LPG possesses a high octane number, allowing efficient engine operation without knocking even at relatively high compression ratios. In addition, its gaseous state after pressure reduction promotes excellent mixture homogeneity and virtually eliminates fuel wall wetting, resulting in more uniform combustion. The lower carbon-to-hydrogen ratio of LPG, together with the absence of aromatic compounds and sulfur, creates favorable conditions for reducing carbon monoxide, unburned hydrocarbon and carbon dioxide emissions. However, the lower volumetric energy density of the gaseous fuel–air mixture, the absence of charge-cooling effects and the differences in flame propagation may also influence engine power output, combustion temperature and nitrogen oxide formation.

Unlike oxygenated alcohol fuels, whose environmental performance is largely associated with chemically bound oxygen, the emission characteristics of LPG are primarily governed by its hydrocarbon composition, gaseous mixture preparation and relatively high hydrogen-to-carbon ratio. Consequently, the mechanisms responsible for emission formation differ considerably from those observed for ethanol or isopropanol fuels and require separate technical evaluation.

Over the past three decades, numerous experimental investigations have examined the influence of LPG on

engine performance and exhaust emissions under various operating conditions, including different engine loads, compression ratios, ignition timings and fuel-system configurations. Nevertheless, the reported results are not always directly comparable because of differences in engine technology, fuel composition, conversion systems and experimental methodologies. A comprehensive technical assessment is therefore necessary to identify the principal trends reported in the literature and to explain the engineering mechanisms responsible for the observed emission characteristics.

The present paper provides a technical review of the available experimental studies concerning the application of liquefied petroleum gas in spark ignition engines, with particular emphasis on regulated exhaust emissions. The review discusses the influence of LPG on carbon monoxide, carbon dioxide, unburned hydrocarbons and nitrogen oxides, while relating the reported emission characteristics to the physicochemical properties of the fuel and the fundamental combustion processes occurring in spark ignition engines.

2. ANALYSIS

A. Carbon monoxide emissions

Carbon monoxide is formed as an intermediate product of hydrocarbon oxidation when the available oxygen, combustion temperature or residence time is insufficient for complete conversion of carbon into carbon dioxide. Its formation is therefore strongly influenced by the air–fuel ratio, mixture homogeneity, combustion stability and engine operating conditions. Rich mixtures generally promote CO formation because of oxygen deficiency, whereas operation near the stoichiometric or moderately lean condition favors the oxidation of CO into CO_2.

The reviewed literature consistently demonstrates that replacing gasoline with LPG generally reduces CO emissions [3] – [19]. This improvement is primarily attributed to the gaseous nature of LPG, which promotes superior fuel–air mixing, eliminates wall wetting and reduces locally rich combustion zones. In addition, the lower carbon-to-hydrogen ratio of propane and butane decreases the amount of carbon introduced into the cylinder, while the homogeneous mixture facilitates more complete oxidation. Numerical investigations by Bayraktar and Durgun and Obayes et al. likewise predicted lower CO formation for LPG than for gasoline under a wide range of operating conditions [9], [13].

The magnitude of the reported reduction varies considerably among the published studies. Çinar et al. measured a 5.3% decrease in CO emissions for gaseous LPG at stoichiometric operation, while Şimşek and Uslu reported a maximum reduction of 20.63% for pure LPG [5], [7]. Tasic et al. observed reductions of approximately 30% during urban driving and 10% during extra-urban operation [8]. Similar improvements were reported by Murillo et al., Mohammed and Abdulhaleem, Mustafa and Gitano-Briggs, Tukiman et al., Salhab et al. and Mohammed et al., confirming the general tendency toward lower CO emissions with LPG [4], [11], [12], [14], [15], [16].

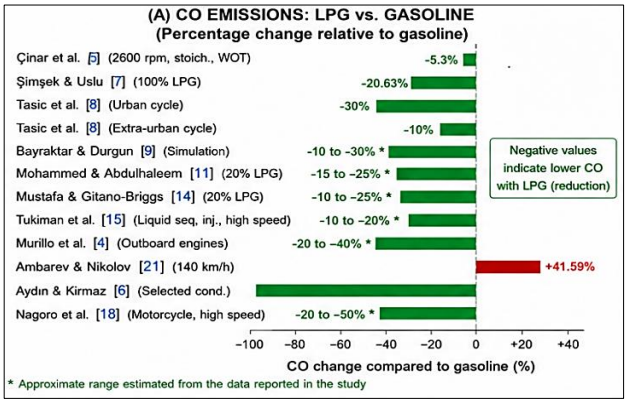
Engine operating conditions significantly influence the magnitude of the reduction. Operation close to the stoichiometric air–fuel ratio generally produces the lowest CO emissions, whereas rich mixtures increase CO because of oxygen deficiency and incomplete combustion. Under excessively lean conditions, slow flame propagation and partial burning may also increase CO despite the excess oxygen [3], [14], [16], [18], [20]. Engine load and speed have a similar influence. Moderate increases in load and speed generally improve combustion and promote CO oxidation, whereas high-load enrichment or very high engine speeds may increase CO because of shortened combustion time and oxygen deficiency [7] , [11], [14], [16], [18].

The LPG fuel-delivery system also affects carbon monoxide emissions. Conventional mixer systems generally provide lower CO than gasoline because of improved mixture homogeneity, while sequential gaseous injection further improves fuel metering and cylinder-to-cylinder distribution [10], [12]. Liquid-phase LPG injection may additionally improve volumetric efficiency through charge cooling, although its environmental benefit depends strongly on engine calibration. Tukiman et al. reported lower CO emissions for liquid sequential injection, whereas Mustaffa et al. measured higher CO under certain operating conditions because of suboptimal injection strategy and calibration [15], [17].

Although the overall trend is well established, several investigations reported increased CO emissions under specific conditions. Ambarev and Nikolov observed higher CO during high-speed operation owing to inappropriate LPG ECU calibration [21], while Mustaffa et al. attributed increased CO to unsuitable injection timing and locally rich combustion zones in liquid-injection systems [17]. Cold-start operation and delayed catalyst light-off may also increase cycle-integrated CO emissions despite favorable engine-out combustion characteristics.

Overall, the reviewed literature clearly demonstrates that LPG offers substantial potential for reducing carbon monoxide emissions in spark-ignition engines. The reduction is primarily associated with improved fuel–air mixing, lower carbon content and more complete combustion. However, the magnitude of the benefit depends on engine operating conditions, fuel-delivery system, ignition strategy, ECU calibration and catalyst temperature rather than on the LPG composition alone.

Summary of the influence of LPG on CO emissions in spark-ignition engines is presented in Fig. 1.



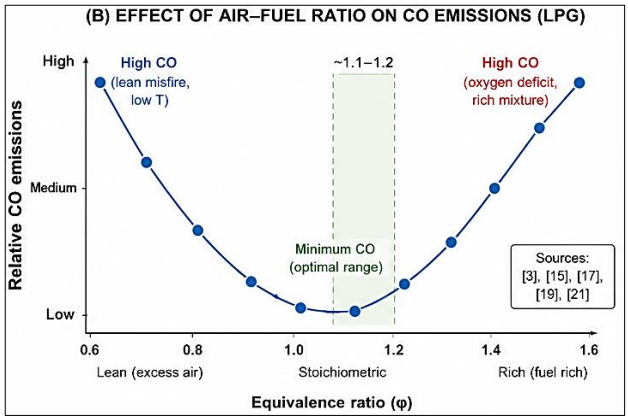


Fig. 1. Summary of the influence of LPG on CO emissions in spark-ignition engines [3] - [9], [11], [14] , [15], [17] – [19], [21].

B. Carbon dioxide emissions

Carbon dioxide is the final product of complete oxidation of the carbon contained in the fuel. Unlike CO, higher CO_2 concentrations in the exhaust do not necessarily indicate poorer environmental performance, since they often reflect more complete combustion. Therefore, the environmental effect of LPG should be evaluated together with fuel consumption and brake-specific CO_2 emissions rather than by exhaust concentration alone.

Most of the reviewed studies report lower CO_2 emissions for LPG compared with gasoline [5] – [8], [10] – [12], [14] – [17]. This tendency is mainly attributed to the lower carbon-to-hydrogen ratio of propane and butane, which results in less carbon being introduced into the cylinder for the same released energy. In addition, the homogeneous gaseous mixture and the high octane rating of LPG improve combustion efficiency and may reduce fuel consumption under optimized operating conditions.

Several investigations quantitatively confirm this trend. Şimşek and Uslu reported a maximum CO_2 reduction of 5.19% for pure LPG compared with gasoline, while Tasic et al. measured reductions of approximately 10% under urban and 11% under extra-urban driving conditions [7], [8]. Mohammed et al. observed an even greater reduction of 18.75%, which was associated with both the lower carbon content of LPG and improved thermal efficiency [16]. Similar reductions were reported by Çinar et al., Salhab et al., Mustafa and Gitano-Briggs, Mohammed and Abdulhaleem, Tukiman et al., and Aydın and Kirmaz, confirming the overall tendency toward lower CO_2 emissions with LPG [5], [6], [11], [12], [14], [15].

Nevertheless, not all investigations reported lower CO_2 emissions. Nagoro et al. measured higher exhaust CO_2 concentrations for LPG at high engine speed despite simultaneously observing significantly lower CO emissions [18]. This behaviour suggests that a greater proportion of carbon was completely oxidized to CO_2 owing to improved combustion. Likewise, Nisulescu et al. predicted higher accumulated CO_2 emissions during transient driving cycles because the LPG-powered vehicle required greater throttle opening to compensate for reduced engine performance [22]. These results indicate that exhaust CO_2 concentration alone cannot be regarded as a reliable indicator of greenhouse-gas emissions.

Engine operating conditions substantially influence CO_2 formation. Increasing engine load generally raises CO_2 because more fuel is consumed and combustion becomes more complete. Similarly, operation close to the stoichiometric air–fuel ratio promotes maximum carbon oxidation, whereas rich mixtures increase CO formation at the expense of CO_2. The fuel-delivery system also affects the results. Sequential gaseous injection and liquid-phase LPG systems generally provide better mixture control and lower brake-specific CO_2 emissions than conventional mixer systems, although the final outcome depends strongly on engine calibration.

Summary of the influence of LPG on CO_2 emissions in spark-ignition engines is presented in Fig. 2.

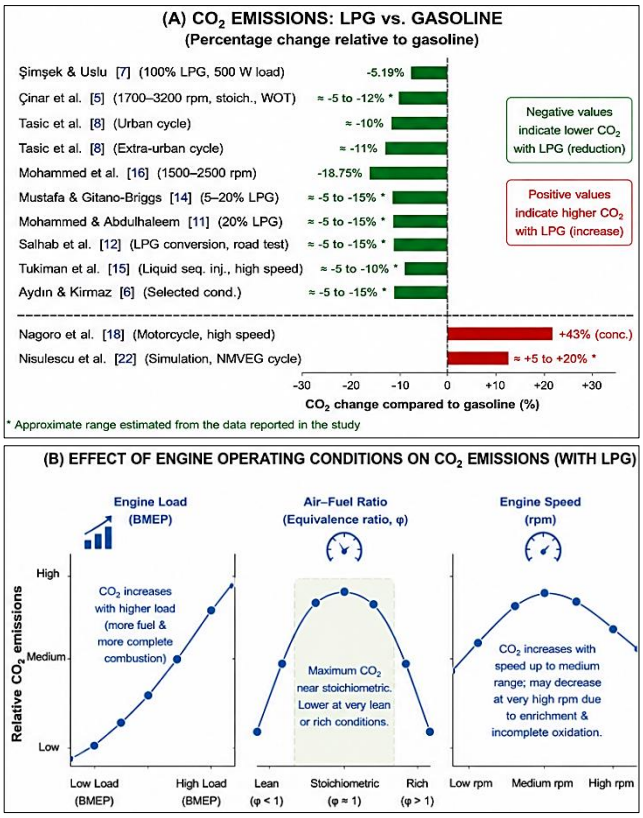


Fig. 2. Summary of the influence of LPG on CO_2 emissions in spark-ignition engines [5] – [8], [11], [12], [14] - [19], [22]

Overall, the reviewed literature demonstrates that LPG generally reduces carbon dioxide emissions from spark-ignition engines because of its lower carbon content and favorable combustion characteristics. However, the magnitude of the reduction depends on engine operating conditions, fuel-system configuration and the selected evaluation parameter. For this reason, brake-specific CO_2 emissions or mass emissions per kilometre represent more appropriate indicators of the environmental benefits of LPG than exhaust-gas concentration alone.

C. Unburned hydrocarbons

Unburned hydrocarbons are formed when a portion of the fuel escapes complete oxidation during the combustion process. Their formation is mainly associated with flame quenching near the combustion chamber walls, fuel trapped in crevice volumes, incomplete combustion of locally rich mixtures and misfire under unstable operating conditions. Consequently, HC emissions are strongly influenced by mixture preparation, combustion stability, air–fuel ratio, ignition timing and combustion temperature.

The reviewed literature consistently demonstrates that

LPG generally reduces HC emissions compared with conventional gasoline [3] – [18], [22]. This trend is considerably more uniform than that observed for CO_2 and NO_x emissions. The principal reason is the gaseous nature of LPG, which provides excellent fuel–air mixing before entering the combustion chamber. Unlike liquid gasoline, LPG does not produce liquid fuel films on the intake manifold or cylinder walls, thereby reducing wall wetting and the formation of locally rich regions that normally contribute to incomplete combustion. Furthermore, LPG consists mainly of simple hydrocarbons (propane and butane) that burn more readily than the complex mixture of gasoline hydrocarbons.

Several investigations quantified this reduction. Çinar et al. reported approximately 20% lower HC emissions for LPG compared with gasoline under stoichiometric conditions [5]. Şimşek and Uslu likewise observed a continuous decrease in HC emissions as the LPG fraction increased, with pure LPG producing the lowest values over the investigated load range [7]. Similar reductions were reported by Mohammed and Abdulhaleem, Mustafa and Gitano-Briggs, Salhab et al., Murillo et al., and Mohammed et al., all of whom concluded that replacing gasoline with LPG substantially improves combustion completeness and decreases the amount of unburned fuel leaving the cylinder [4], [11], [12], [14], [16].

Vehicle investigations confirm the same tendency under practical driving conditions. Tasic et al. measured lower HC emissions during both urban and extra-urban driving cycles for an LPG-converted passenger vehicle [8]. Bielaczyc et al. also demonstrated that modern sequential LPG systems equipped with closed-loop electronic control produce consistently lower HC emissions than gasoline under standardized emission cycles [10]. Similar conclusions were reported by Aydın and Kirmaz, who found that LPG operation reduced HC emissions throughout the investigated speed range despite changes in gear selection and engine operating conditions [6].

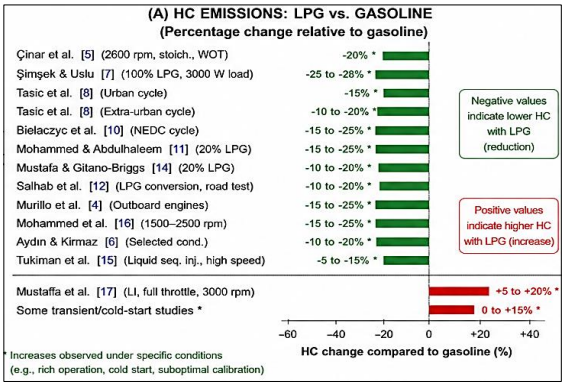
The reduction in HC emissions can be explained by several complementary mechanisms. First, the homogeneous gaseous mixture promotes more complete flame propagation throughout the combustion chamber. Second, the absence of liquid fuel droplets reduces fuel deposition on the intake ports and cylinder walls, minimizing quench-layer hydrocarbon formation. Third, LPG contains virtually no heavy aromatic compounds that are comparatively difficult to oxidize during the late stages of combustion. Finally, the high octane number of LPG permits optimized ignition timing and, in dedicated engines, higher compression ratios, both of which improve combustion efficiency and decrease the amount of unburned fuel.

Engine operating conditions significantly influence the magnitude of the observed reduction. Increasing engine load generally decreases HC emissions because the associated rise in in-cylinder temperature accelerates oxidation reactions and reduces flame quenching and partial combustion. Şimşek and Uslu observed a continuous decrease in HC emissions with increasing load for all investigated gasoline–LPG mixtures, with the lowest value obtained for pure LPG at the highest tested load [7]. However, this tendency is not universal, since mixture enrichment at high throttle opening may increase the amount of unburned fuel. Mustaffa et al., for example, measured increased HC emissions at full throttle, where the engine operated with a rich mixture [17]. The air–fuel ratio is similarly important: operation near stoichiometric or moderately lean conditions generally promotes complete combustion, whereas excessively lean mixtures may cause slow flame propagation, cyclic instability or misfire. Rich mixtures also increase HC emissions because of insufficient oxygen availability [4], [7], [17], [20], [23].

The LPG supply system also affects hydrocarbon emissions. Conventional mixer systems generally provide improved fuel–air homogeneity compared with gasoline, but their limited metering precision and the displacement of intake air by gaseous fuel may restrict their emission benefits. Sequential gaseous injection provides more accurate fuel metering and improved cylinder-to-cylinder distribution, which can reduce HC emissions when the system is properly calibrated [10], [12]. Liquid-phase LPG injection can additionally improve volumetric efficiency through charge cooling during vaporisation; however, its influence on HC is not uniformly favourable. Some investigations reported reduced HC because of rapid vaporisation and improved mixture formation, whereas others measured higher values owing to inappropriate injection duration, locally rich mixtures or insufficient optimization of ignition and injection parameters [15], [17]. Consequently, the final HC level depends strongly on fuel phase, injector position, injection timing, air–fuel-ratio control and ECU calibration.

Although the overall tendency is favourable, several studies reported higher or irregular HC emissions under specific operating conditions. Such results have been associated with rich operation at high throttle opening, unstable ultra-lean combustion, excessive EGR dilution, inappropriate ignition or injection settings, and fuel losses during the valve-overlap period [4], [17], [20], [23]. Cold-start operation is also important because delayed catalyst light-off reduces the oxidation of unburned hydrocarbons in the exhaust system. In bi-fuel vehicles, the initial gasoline operation and subsequent transition to LPG may further influence cycle-integrated emissions. Studies employing liquid LPG injection have shown that catalyst temperature and transient control strategy can substantially affect tailpipe HC results during standardized driving cycles, even when warmed steady-state operation demonstrates lower engine-out emissions [10], [17].

Summary of the influence of LPG on HC emissions in spark-ignition engines is presented in Fig. 3.



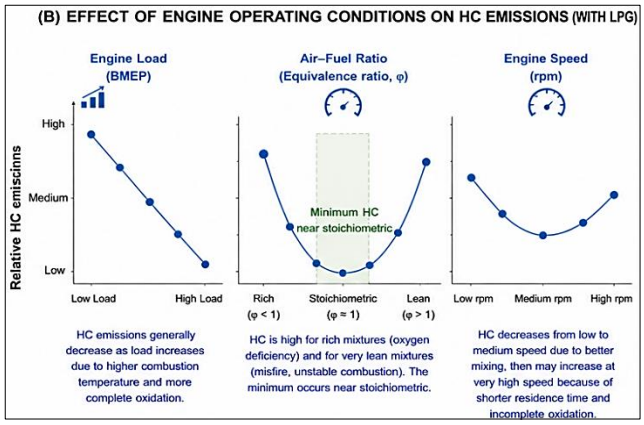


Fig. 3. Summary of the influence of LPG on CH emissions in spark-ignition engines [4] – [8], [10] - [17], [20], [23].

D. Nitrogen oxides

Nitrogen oxides are formed primarily through the thermal oxidation of atmospheric nitrogen at high combustion temperatures. Their formation depends mainly on peak in-cylinder temperature, oxygen availability and the residence time of combustion gases under high-temperature conditions. Consequently, NO_X emissions are influenced not only by fuel composition but also by ignition timing, compression ratio, engine load, air–fuel ratio, combustion duration and exhaust gas recirculation. Unlike CO and HC emissions, the influence of LPG on NO_X formation is not unidirectional, and the reviewed studies report both reductions and increases depending on engine design and operating conditions.

The majority of the reviewed investigations indicate that LPG generally reduces NO_X emissions compared with gasoline [4] – [8], [10], [11], [12], [14] – [17]. This tendency is commonly attributed to the lower flame temperature observed in many converted LPG engines, together with the absence of locally rich combustion zones and improved mixture homogeneity. In addition, the reduced volumetric efficiency of conventional gaseous-fuel systems often lowers peak combustion temperature, thereby suppressing thermal NO_X formation.

Several experimental investigations quantified this reduction. Çinar et al. reported approximately 8.7% lower NO_X emissions for LPG than for gasoline at 2600 min^{-1} under stoichiometric operation [5]. Şimşek and Uslu observed that NO_X emissions decreased progressively as the LPG proportion increased, reaching a maximum reduction of approximately 16% for pure LPG [7]. Mohammed et al. likewise measured reductions approaching 20%, while Salhab et al., Mustafa and Gitano-Briggs, Mohammed and Abdulhaleem, Murillo et al., and Bielaczyc et al. all reported lower NO_X emissions under most investigated operating conditions [4], [10], [11], [12], [14], [16]. These studies consistently attribute the reduction to lower combustion temperatures and more uniform combustion.

Engine operating conditions substantially influence NO_X formation. Increasing engine load generally raises combustion temperature and therefore promotes thermal NO_X formation regardless of fuel type. Similarly, operation close to the stoichiometric air–fuel ratio usually produces the highest NO_X emissions because both oxygen availability and combustion temperature are favorable for NO formation. Under lean operation, excess air lowers combustion temperature despite the increased oxygen concentration, resulting in lower NOx emissions. Rich mixtures also suppress NOx because oxygen deficiency limits nitrogen oxidation, although this is accompanied by increased CO and HC emissions [3], [5], [7], [17], [20], [23].

The LPG supply system also plays an important role. Conventional mixer systems generally reduce NO_X because the displacement of intake air by gaseous fuel slightly lowers volumetric efficiency and combustion temperature. Sequential gaseous injection offers more accurate fuel metering and allows optimization of ignition timing, producing stable combustion with relatively low NO_X emissions [10], [12]. Liquid-phase LPG injection presents a more complex behavior. The evaporation of liquid LPG inside the intake port or cylinder cools the charge and may reduce combustion temperature; however, the improved volumetric efficiency can increase cylinder pressure and combustion intensity. Consequently, liquid injection does not always produce lower NO_X emissions than gasoline, and the final outcome depends strongly on engine calibration, injection strategy and spark timing [15], [17].

Despite the predominant reduction tendency, several investigations reported increased NO_X emissions under specific operating conditions. Nagoro et al. observed higher NOx emissions for LPG at elevated engine speeds, which were associated with improved combustion efficiency and higher combustion temperatures [18]. Similar observations were reported in studies employing advanced ignition timing or high compression ratios, where the thermodynamic benefits of LPG resulted in increased peak cylinder temperatures. These results indicate that improved combustion quality may simultaneously decrease CO and HC emissions while increasing thermal NO_X formation.

Cold-start operation generally has a smaller influence on NO_X than on CO and HC because combustion temperatures remain relatively low before the engine reaches normal operating conditions. Nevertheless, catalyst temperature significantly affects tailpipe NO_X emissions. Before catalyst light-off, the three-way catalyst is unable to reduce nitrogen oxides effectively, whereas under fully warmed conditions its conversion efficiency increases considerably. Consequently, transient driving cycles may produce different NO_X trends compared with steady-state laboratory measurements [8], [10], [17].

Overall, the reviewed literature demonstrates that LPG generally produces lower NO_X emissions than gasoline in conventional spark-ignition engines. The reduction is mainly associated with lower combustion temperatures and improved mixture homogeneity. However, this advantage is not universal. Engine calibration, ignition timing, compression ratio, fuel-delivery system and operating conditions may increase combustion intensity sufficiently to promote thermal NO_X formation. Therefore, the influence of LPG on nitrogen oxide emissions should be evaluated as the result of the balance between combustion-temperature reduction and combustion-efficiency improvement rather than as an intrinsic property of the fuel itself.

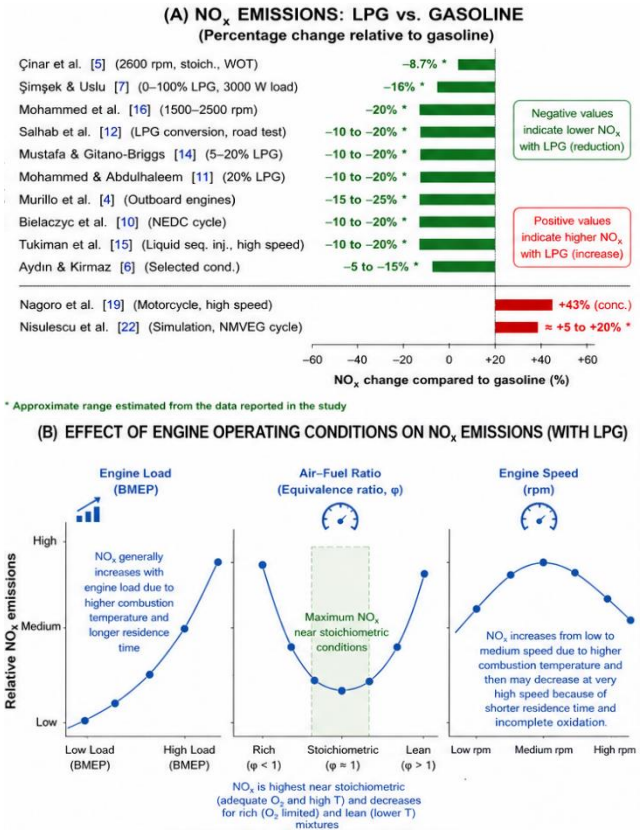


Fig. 4. Summary of the influence of LPG on NOX emissions in spark-ignition engines [4] – [8], [10] - [18], [20], [23].

3. CONCLUSION

The reviewed literature demonstrates that the environmental performance of LPG is primarily governed by its gaseous nature, lower carbon-to-hydrogen ratio, high octane number and favorable combustion characteristics.

The majority of the published studies consistently report lower carbon monoxide and unburned hydrocarbon emissions compared with conventional gasoline operation. These improvements are mainly attributed to superior air–fuel mixing, reduced wall wetting, improved combustion homogeneity and more complete oxidation of the fuel. The lower carbon content of LPG also contributes to reduced carbon dioxide emissions in most investigations, although the magnitude of the reduction depends on engine efficiency, fuel consumption and the parameter used for emission evaluation.

Unlike CO, HC and CO_2 emissions, no universal tendency can be established for NO_X emissions. Although most studies indicate a reduction in NO_X resulting from lower combustion temperatures and improved mixture preparation, several investigations report increased emissions under specific operating conditions. The final NO_X level depends on the balance between combustion-temperature reduction and combustion-efficiency improvement, as well as on engine load, air–fuel ratio, ignition timing, compression ratio, fuel-delivery system and electronic engine calibration.

The reviewed literature also demonstrates that engine operating conditions considerably influence the environmental benefits of LPG. Sequential gaseous injection and properly calibrated liquid-phase injection systems generally provide the most favorable emission characteristics, whereas inadequate fuel metering, unsuitable ignition settings and transient operating conditions may partially reduce the advantages of LPG. Consequently, the emission performance of LPG should be evaluated together with engine design and calibration rather than solely on the basis of fuel properties.

Overall, LPG represents one of the most mature and practically applicable alternative fuels for spark-ignition engines. It provides a favorable compromise between emission reduction, engine performance and technological maturity while requiring only relatively limited modifications to conventional gasoline engines. The findings presented in this review contribute to a better understanding of the mechanisms governing pollutant formation during LPG combustion and may support the development and optimization of future low-emission spark-ignition engines.

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