



Internal Combustion Engines Emissions—A Review

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How to cite this paper: Mircea-Tudor Grapini, Nicolae Burnete. (2026) Internal Combustion Engines Emissions—A Review. *Engineering Advances*, 6(2), 105-120.

DOI: 10.26855/ea.2026.06.007

Received: April 8, 2026

Accepted: May 5, 2026

Published: June 3, 2026

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Abstract

Global ecosystems and public health face increasing risks from climate change, primarily driven by greenhouse gas emissions from fossil fuel combustion. The automotive sector accounts for more than 70% of greenhouse gas emissions within the transportation sector, marking it as a primary focus for environmental impact studies. This research examines the ecological consequences of internal combustion engines, which discharge a complex mixture of regulated pollutants—including carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter—alongside unregulated toxins such as nitrous oxide, hydrogen cyanide, and volatile organic compounds. These substances pose significant long-term threats to both human health and atmospheric integrity. Analysis highlights the vital role of stringent emission standards, including EURO regulations and modernized testing protocols like the Worldwide Harmonized Light Vehicles Test Procedure and Real Driving Emissions, in minimizing hazardous outputs. While advancements in engine architecture and aftertreatment technologies have been substantial, critical challenges persist regarding cold-start inefficiencies and the suppression of ultrafine particles. Simultaneously, the shift to low and zero-carbon fuels, such as hydrogen, ethanol, methanol, and biodiesel, is highlighted as a feasible route to sustainable mobility. When combined with lean-burn techniques and sophisticated engine designs, alternative fuels provide significant reductions in both regulated and unregulated emissions. They also have improved combustion characteristics and fewer adverse effects on the environment. The transportation industry can drastically lessen its environmental impact by combining alternative fuels, efficient combustion techniques, and strong emission control technologies with a supportive legislative framework. Achieving climate goals, enhancing urban air quality, and moving closer to a sustainable mobility future will all depend on these actions.

Keywords

Internal combustion engines; climate change; alternative fuels; regulated and unregulated emissions; emission control; hydrogen

1. Introduction

The planet's biosphere and human life are seriously threatened by climate change. Due to global warming, the Earth's surface temperature increased by an average of over 1 °C between 2011 and 2025 [1] compared to the late industrialization era and the period of oil and gas industries development. June 2023 was the warmest June ever recorded, with a worldwide temperature of 1.05 °C higher than the average for the 20th century, which was 15.5 °C. The increase of greenhouse gas (GHG) emissions into the Earth's atmosphere is the primary driver of climate change and global warming. Future projections (2021-2100) [2] of global surface temperature changes are presented for

various greenhouse gas emissions scenarios: very low (SSP1-1.9), low (SSP1-2.6), intermediate (SSP2-4.5), high (SSP3-7.0), and very high (SSP5-8.5) [2]. These projections are depicted as “climate stripes”, which illustrate the long-term human-induced trends in temperature while also accounting for ongoing natural variability. The patterns highlight the expected evolution of global surface temperatures under different emissions pathways (Figure 1 and see in Table 1 the explanation of the scenario terms). The transportation sector is a major contributor to global greenhouse gas emissions, accounting for nearly a quarter of energy-related emissions worldwide. Among transportation modes, road transportation is the largest source, responsible for over 70% of emissions, followed by marine transport at approximately 15% and aviation at around 10% (Figure 2), as well as the fossil fuels used for transportation, heating, and power generation contribute significantly to greenhouse gas emissions [1]. One of the most crucial objectives for determining future mobility that has no detrimental effects on the environment or human health is emission reduction.

Table 1. Relationship between emission scenarios and modelled pathways [5]

GHG Emissions Scenarios	Category description (SSP ¹ x-y in WGI and WGII ²)	RCPy ³ [W/m ²]
Very low (SSP1-1.0)	Limit warming to 1.5 °C with no or a limited exceeding of 1.5 °C by up to 0.1 °C-0.3 °C for up to several decades	-
Low (SSP1-2.6)	Limit warming to 2 °C	RCP2.6
Intermediate (SSP2-4.5)	Limit warming to 3 °C	RCP4.5
High (SSP3-7.0)	Limit warming to 4 °C	RCP6.0
Very high (SSP5-8.5)	Exceeding warming to 2 °C	RCP8.5

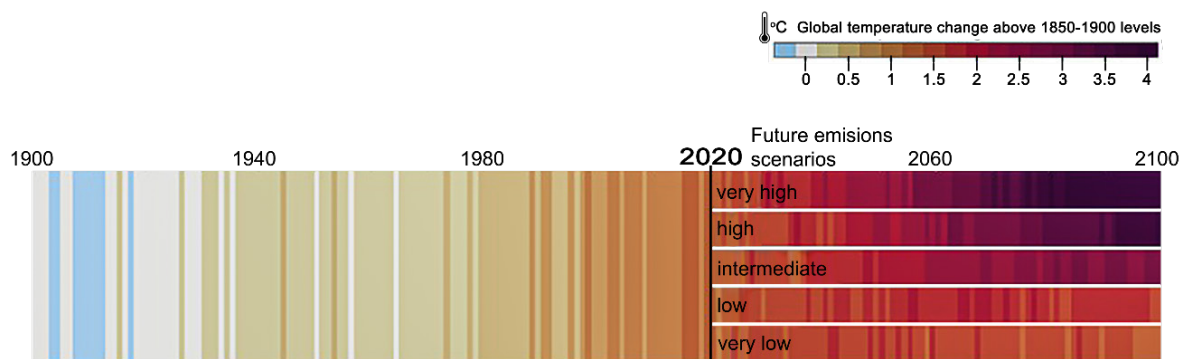


Figure 1. Predictions of the GHG emissions based on.

The world’s population is always increasing, as well as the increase in motorized individual mobility, facts that counteract the efforts to reduce worldwide emissions. Between 1990 and 2007, the global transportation sector alone had a 45% increase in CO₂ emissions, and by 2030, another 40% increase is anticipated [3]. The automotive industry is being forced to continuously create even more resilient powertrains, emission control, and exhaust gas aftertreatment systems due to the ongoing evolution of the carbon dioxide (CO₂) and pollutant emission limits [4]. Progress in lowering emission-related pollution is essential since it will result in waste management, a cleaner energy transition, and increased technological energy efficiency [5].

Most of the oil used in the transportation industry comes from carbon-based fuels like gasoline and diesel. In addition to CO₂, the exhaust of vehicles powered by gasoline and diesel contains several harmful contaminants. Within road transportation, the primary sources of emissions are light-duty vehicles, such as cars and trucks, which collectively dominate the sector’s environmental impact. This highlights the critical need for targeted strategies to

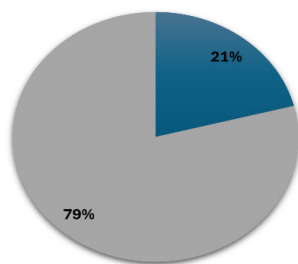
¹ SSPx refers to the shared socioeconomic pathway describing the socioeconomic trends and the “y” stands for the level of the radiative forcing.

² Working groups I and II refer to the physical science basis and the understating of the climate system and how it’s changing, respective impact, adaption and vulnerability.

³ RCPy are scenarios used in the climate science to display possible future greenhouse gas emissions, where the “y” stands for the level of the radiative forcing.

reduce emissions from road transport as part of broader efforts to address climate change [6]. Exposure to diesel and gasoline exhaust has been linked to negative health effects demonstrated in several previous investigations [7]. According to that research, breathing in particulate matter (PM10 and PM2.5) from diesel vehicle exhaust when stuck in traffic has an impact on the brain, heart, and lungs. Long-term exposure to fine particulate matter (PM2.5) has also been shown to increase the risk of heart failure and asthma [1]. There are two types of exhaust emissions from combustion engines: regulated emissions and unregulated emissions. Particulate matter (PM), nitrogen oxides (NOx), unburned hydrocarbons (HC), and carbon monoxide (CO) are all considered regulated emissions. Unregulated emissions that are harmful include nitrous oxide (N₂O), hydrogen cyanide (HCN), propene (C₃H₆), ethene (C₂H₄), and acetylene (C₂H₂) [8]. Acetylene inhalation can result in headaches, light-headedness, and unconsciousness [9]. Exposure to ethene causes similar symptoms, including headache, exhaustion, disorientation, and coma. Prolonged exposure to propene may cause liver damage and irregular heartbeats. Shock, irregular heartbeats, severely low blood pressure, and even cardiac arrest are among the severe cardiovascular effects caused by hydrogen cyanide, a highly toxic gas [1]. The transportation industry needs to investigate fuel substitutes. Low-carbon fuels, such as ethanol and methanol, and zero-carbon fuels, such as hydrogen, have the desirable qualities to take the place of conventional fuels.

Global Energy - Related emission \approx 42 GT CO₂



Transport emission \approx 9 GT CO₂

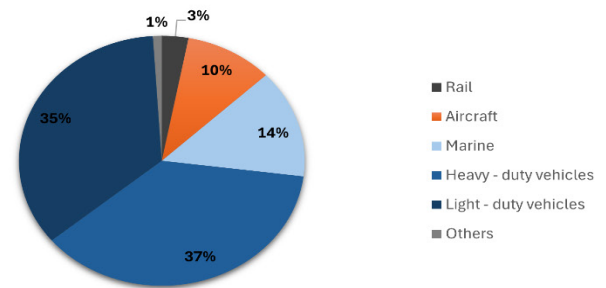


Figure 2. CO₂ emission representation (based on [6], [27], [26]).

In a broad sense, alternative fuels encompass both fossil-derived and renewable energy sources. These fuels are commonly categorized into two main types based on their physical state: gaseous fuels (e.g., liquefied petroleum gas [LPG], natural gas [NG]) and liquid fuels, including alcohols such as methanol and ethanol, as well as ethers like dimethyl ether (DME) and polyoxymethylene dimethyl ethers (PODEn). Biodiesel also represents a widely used renewable alternative. These fuels are increasingly employed in localized transportation systems and industrial applications as part of broader efforts to reduce environmental impact [10]. The transition to electric vehicles (EVs) is widely regarded as a promising long-term strategy for addressing the environmental challenges posed by conventional vehicle emissions. Although significant progress has been made in battery technology, electric drivetrains, and control electronics, two critical barriers remain. First, existing energy infrastructure often lacks the capacity to support large-scale vehicle electrification. Second, the reliability and availability of power supply may limit widespread EV adoption, especially in regions with underdeveloped grids. To mitigate harmful emissions, various strategies have been developed, including in-cylinder modifications, geometric and operational adjustments, and advanced exhaust gas aftertreatment technologies [11].

2. Formation of Exhaust Emissions

The process of converting thermal energy follows the fundamental principles of thermodynamics and can be systematically defined. Internal combustion engines and gas turbines serve as specialized energy conversion systems, where the chemical energy stored in fuel is transformed into mechanical energy, which is then converted into electrical energy by an electric motor. For large-scale electricity generation, stationary gas turbine plants are often used, either independently or in combination with steam turbines. Due to inherent conversion losses, the efficiency of these processes can be visually represented using a pyramid diagram (as shown in Figure 3), where the relative sizes reflect differences in conversion efficiency [11].

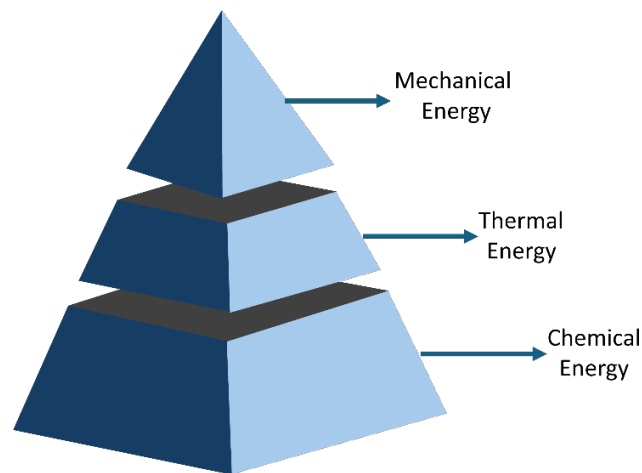


Figure 3. Energy conversion flow (based on [11]).

Exhaust pollutants generated during combustion processes can be categorized into harmless and harmful components. Those emissions that are subject to regulatory limits are referred to as regulated emissions, while others fall under the category of unregulated emissions. Air pollutants are further classified into primary and secondary pollutants. Primary air pollutants include particulate matter, sulfur dioxide, nitrogen oxides, hydrocarbons, volatile organic compounds, carbon monoxide, and ammonia. These pollutants are directly released into the atmosphere from sources such as vehicle emissions, the transportation sector (naval and air transport), industrial and construction activities ac. In contrast, secondary air pollutants are formed through chemical reactions involving primary pollutants or interactions with natural atmospheric components. Examples of secondary pollutants include ground-level ozone, formaldehyde, smog, and acid mist, which typically result from processes such as coagulation, condensation, or photochemical reactions.

Many primary pollutants, such as carbon monoxide, unburned hydrocarbons, sulfur oxides, and nitrogen oxides, are emitted in gaseous form and are often invisible. However, in addition to these gaseous pollutants, atmospheric pollution is significantly impacted by particulate matter, which has become a growing concern. The major sources of particulates include industrial combustion and other anthropogenic activities. Particulate matter consists of a mixture of solid particles and liquid droplets suspended in the air, with examples including smoke, fumes, and haze. Furthermore, gaseous pollutants such as NO_x , SO_2 , HC, VOCs, and NH_3 can undergo transformations in the atmosphere, ultimately contributing to the formation of particulate matter [11]. In order to determine the total exhaust mass and the individual contribution of each pollutant, the fundamental equation (2.1) of the combustion process gives a clear overview of such problems.

$$m_{ev} = m_{comb} + m_{air} = m_{comb} \left(1 + \frac{m_{air}}{m_{comb}} \right) = m_{comb} (1 + \lambda \cdot L_{min}) \quad (2.1)$$

where:

m_{ev} represent total mass of exhaust gases,

m_{comb} represent mass of the fuel combusted

m_{air} represent mass of air supplied

λ excess air coefficient (air-to-fuel ratio relative to stoichiometric)

L_{min} minimum air requirement per unit fuel mass (stoichiometric ratio)

A simple explanation is that the total mass of exhaust gases is increasing with the excess of the air-fuel ratio. At the stoichiometric ratio, the engine uses just enough air to completely burn the fuel, and once the ratio increases (a leaner combustion), then more air is added, which will lead to an increase in the amount of the exhaust emissions, even though the fuel remains constant (Figure 4).

The formation of toxic gases in automotive exhaust is influenced by several factors, including the combustion process, air-fuel ratio, engine power, compression ratio, flame temperature, and carburetor function. Complete fuel combustion requires a precise stoichiometric air-fuel ratio. In addition, the nature and quantity of pollutants depend on fuel quality, volatility, and the presence of minerals and contaminants. The release of highly toxic emissions from vehicles poses serious risks to human health and the environment. The severity of these effects is determined by the physical and chemical properties of the pollutants, their concentration, and the level of public exposure [12].

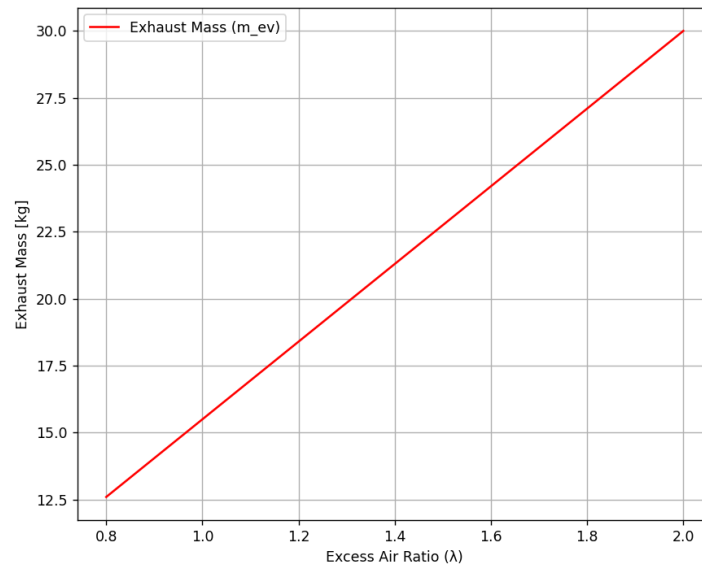


Figure 4. Gas mass on excess air ratio example.

2.1 NO_x Emissions

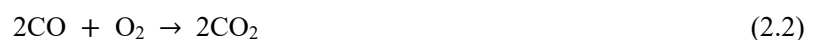
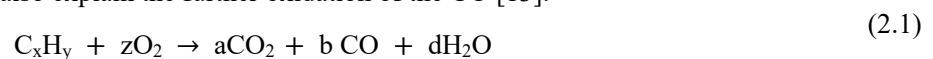
Nitrogen oxides, consisting mainly of nitric oxide and nitrogen dioxide, though N₂ makes up about 80% of the air around us and generally doesn't participate in chemical reactions, the scorching temperatures inside engines provide enough energy to split its strong molecular bonds. This thermal activation transforms the inert nitrogen into reactive NO, which accounts for most NO_x emissions from combustion sources. Later, some of this NO may oxidize further into NO₂, especially as exhaust gases cool [13]. The forward and reverse reaction rate constants found in the technical literature can be observed in Table 2, where the Zel'dovich emission formula describes how nitrogen oxides are formed from the nitrogen and oxygen naturally present in air under high temperature conditions (typically above 1800 K)

Table 2. Kinetic parameters for Zel'dovich mechanism reactions

Reaction	Forward rate constant [cm ³ /mol·s]	Temperature range [K]	Reverse rate constant [cm ³ /mol·s]	Temperature range [K]
N ₂ + O ↔ NO + N	$7.6 \times 10^{13} \exp(-38000/T)$	2000-5000	1.6×10^{13}	300-5000
N + O ₂ ↔ NO + O	$6.4 \times 10^9 \exp(-3,150/T)$	300-3000	$1.5 \times 10^9 \exp(-19,500/T)$	1000-3000
N + OH ↔ NO + H	4.1×10^{13}	300-2500	$2 \times 10^{14} \exp(-23,650/T)$	2200-4500

2.2 Carbon Monoxide

The production of carbon monoxide is similar to that of nitrogen oxide, which is primarily dictated by the fuel-air ratio within the engine's cylinder, a phenomenon observed across various fuel types. An enriched air-fuel ratio, characterized by an excess of fuel relative to the stoichiometric requirement, leads to incomplete combustion and a subsequent surge in CO emissions. Compression ignition engines, operating consistently with a lean AFR to ensure complete combustion, typically exhibit negligible CO output. Conversely, spark ignition engines pose a greater challenge in CO emission control. This disparity arises from their operational characteristics: at partial loads, SI engines function near stoichiometric conditions, while at higher loads, they often transition to a fuel-rich mixture. These fuel-rich conditions are particularly conducive to the formation of CO, necessitating robust emission management strategies. CO formation is one of the key reaction steps in the HC combustion reaction described by the following equation, which can also explain the further oxidation of the CO [13].





where $x = a + b$, $y = 2d$ and $z = a + b/2 + d/2$.

2.3 Particulate Matter

Particulate matter formation is intrinsically linked to fuel-rich zones within the combustion chamber, occurring at elevated temperatures around 1600 K and pressures approximating 100 bar. Under these conditions, the localized air-fuel mixture lacks sufficient oxygen for complete combustion, leading to the creation of particulate matter (as illustrated in Figure 5). Notably, diesel particulates typically exhibit larger particle sizes compared to those emitted by direct injection spark ignition engines. Port-fuel-injected gasoline engines, conversely, primarily generate particulates within the nucleation mode size range. It has been observed that significantly elevated injection pressures, exceeding 3000 bar, correlate with a reduction in both particulate mass and number. However, this decrease is suspected to be, at least partially, due to the resulting particle diameters falling below the detection threshold of measurement instruments [13].

Furthermore, nucleation mode particles can also form post-combustion, within the tailpipe's end region or immediately after exhaust expulsion, for both compression ignition (CI) and direct injection spark ignition (DI SI) engines. While these post-combustion particles constitute a minor fraction (single-digit percentage) of the total particulate mass, they dominate the particle number count, accounting for over 90% of the measured particles [13].

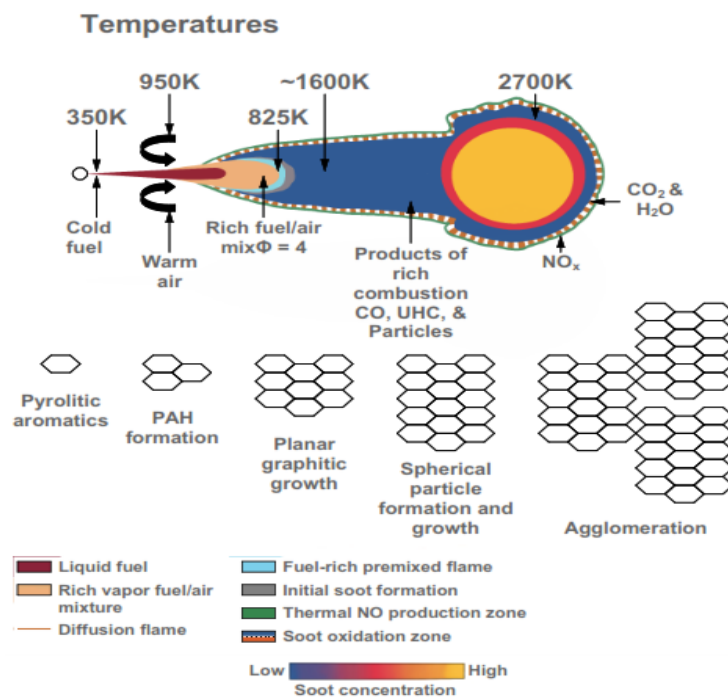


Figure 5. Particulate formation concept (based on [13]).

2.4 Hydrocarbon Emissions

Hydrocarbon emissions in engine exhaust are generated from various sources, with the main contributors being partially burned, recombined, or unburned fuel hydrocarbons. A smaller proportion of HC emissions can be traced to the lubricating oil, which may undergo partial oxidation or volatilization. Typically, the total hydrocarbons in the exhaust are reported as a collective measure, without distinguishing their individual sources. The concentration of total hydrocarbons in the exhaust serves as a useful indicator of combustion efficiency, with higher levels of those hydrocarbons signifying lower combustion efficiency [13]. Based on different studies, it was demonstrated that related to the speed of the vehicle, as the speed increases, the HC emissions decrease (Figure 6).

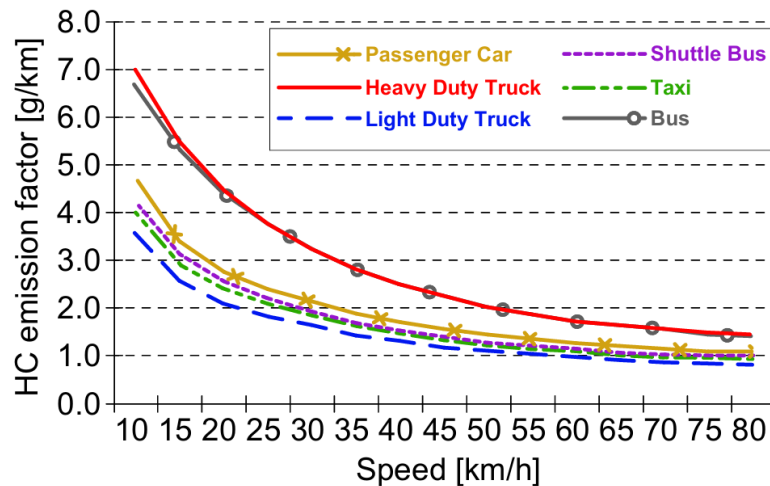


Figure 6. Evolution of speed vs HC emissions [28].

2.5 Emission Legislation

The primary goal of legislation updating emission regulations is to enhance air quality. For years, a key focus has been achieving zero-emission mobility in urban areas. However, significant differences between emissions measured in laboratories and those recorded using portable emissions measurement systems (PEMS) on the road have sparked public debate, legal disputes, and, in some cases, local bans on older vehicles. To address these discrepancies, the “worldwide harmonized light-duty vehicle test procedure” (WLTP) introduced real driving emissions (RDE) tests as part of the vehicle approval process, alongside traditional laboratory-based chassis dynamometer tests [4]. Further revisions to the regulations aim to establish fuel and technology-neutral emission standards. This means that uniform emission limits will likely apply to petrol, diesel, and hybrid vehicles. Additionally, it is expected that all commercially available fuels will be permitted for testing purposes.

Testing conditions for urban, rural, or highway profiles are considerably different, limiting the top speed, temperature, and altitude, and the separation into moderate and extended conditions restricts the potential test scenarios. As mentioned, different aspects should be taken into consideration during real driving test scenarios, but there are particular elements that can impact the exhaust emissions, such as whether the tests are performed on long or short trips, with or without cold starts, because cold starts can be affected by condensation when exhaust gas component temperatures fall below the dew point. Many approaches for future tests consider long-term goals such as test procedures that must monitor the vehicle cleanliness under all boundary conditions, or urban mobility must be emission-free, but the current short-term goals are more important because they will lead to the fulfillment of long-term goals:

- OEMs must ensure low emissions across the entire engine operating range through effective control mechanisms. In recent years, various studies—particularly on CO emissions from gasoline engines—have demonstrated the feasibility of achieving this goal;
- On-board diagnostics functionality must be validated under RDE conditions;
- The introduction of stricter and standardized emission limits for different propulsion technologies;
- New limits are being introduced for additional pollutants, including nitrogen dioxide, nitrous oxide, ammonia, formaldehyde, particle number (PN10) for solid particles larger than 10 nm, methane, and non-methane organic gases [14].

2.6 Marine Engines

The maritime industry is home to the largest internal combustion engines in operation. In 2018, over 50,000 commercial vessels—responsible for transporting approximately 75% of global trade—had a combined cargo capacity of around 1.4 billion tons. Although ship engines contribute a relatively modest share (5-7%) to global air pollution, the environmental standards for marine diesel engines are becoming increasingly strict [15]. This trend is driven by the immense total power output of ship engines, which in some cases exceeds 100 megawatts. In regions with high shipping density, such emissions can lead to significant local air quality concerns.

Efforts to regulate emissions from merchant ships began in 1973 with the International Maritime Organization, a United Nations agency, through the adoption of the MARPOL convention (ratified in 1978 as MARPOL 73/78). In 2005, this agreement was expanded to include emission limits for sulfur oxides, nitrogen oxides, particulate matter, and greenhouse gases [15].

Beyond global regulations, specific emission control areas have been designated to enforce even stricter emission limits. These emission control areas currently include the 200-nautical-mile zones off the coasts of the United States and Canada, as well as the North Sea, Baltic Sea, English Channel, Caribbean Sea, and other regions. The MARPOL limits have tightened over time: in 2010, the maximum allowable sulfur content in marine fuels was set at 1.0% in those regions and 4.5% elsewhere; by 2020, those limits dropped significantly to 0.1% and 0.5%, respectively [15].

To meet these more demanding standards, especially within emission control areas, the maritime sector is increasingly exploring alternative fuels—particularly combustible gas mixtures—as a viable solution. Among the most promising options are natural gas (primarily methane, CH₄) and liquefied petroleum gases, composed mainly of propane (C₃H₈) and butane (C₄H₁₀). Onboard storage of natural gas is typically in liquefied form at temperatures below -160°C in cryogenic tanks, while the liquefied form can be stored as a liquid at ambient temperature under 1.6 MPa pressure.

Switching to these gaseous fuels offers significant environmental benefits: they can virtually eliminate sulfur emissions, reduce NO_x emissions by up to 90%, and lower emissions of particulate matter and carbon dioxide (CO₂) by approximately 30% compared to conventional petroleum-based fuels [15].

3. Regulated Emissions

The automotive industry is among the most heavily regulated sectors in the European Union, as well as in other regions globally. Existing regulations addressing safety, environmental impact, vehicle type approval, and taxation have already substantially increased manufacturing expenses. With the European Commission proposed a range of new initiatives (such as updated CO₂ emission standards for the period beyond 2020), manufacturers are likely to face even greater cost pressures. These forthcoming measures, while aimed at advancing sustainability and innovation, are expected to further escalate production costs within the industry. For instance, by the year 2020, the average emissions from new passenger cars were reduced by 39% relative to their 2005 levels [16]. This target is notably more ambitious compared to the anticipated reductions in other sectors. Specifically, non-ETS sectors are expected to achieve a 10% reduction, while ETS sectors are projected to reduce emissions by 21% over the same period. This disparity highlights the particularly stringent requirements placed on the automotive industry in efforts to curb greenhouse gas emissions.

Vehicle emissions are regulated across global regions through various legislative frameworks, such as EU5, EU6, ULEV, LEV II, and others. These can be broadly categorized into three major regulatory clusters:

- The United States and parts of Central and South America primarily follow the U.S. federal test procedure or components derived from it [17];
- European countries and those aligned with EU standards transitioned in 2017 to the worldwide harmonized light vehicles test procedure (WLTP), alongside the real driving emissions (RDE) test to better reflect real-world conditions. Japan currently uses its own testing protocol but is shifting toward WLTP and considering the adoption of the RDE test [17];
- China employs a hybrid approach, integrating elements of both European (initially the NEDC, but moving toward WLTP and RDE) and U.S. regulatory frameworks [17].

Ongoing regulatory developments in Europe (Euro 7), the United States (particularly LEV 4 standards in California), and China (China 7) are focused on significantly tightening emission limits. These proposed regulations aim to sharply reduce nitrogen oxides and particle number emissions, including the measurement of ultrafine particles as small as 10 nanometers—a notable shift from the current 23 nm threshold. Additionally, new emissions targets are being proposed for substances such as ammonia (NH₃) and nitrous oxide (N₂O), which have not been previously regulated at this level [18].

Complying with these future standards will require advancements in both engine design and exhaust after-treatment technologies. At the same time, increasingly strict CO₂ regulations mean that any solution must avoid increasing system backpressure, as this could negatively affect fuel efficiency and performance. In stoichiometric gasoline engines, the primary tool for controlling gaseous emissions is the three-way catalyst, a well-established and highly effective technology. Once it reaches its operational “light-off” temperature, it can nearly completely convert harmful pollutants—NO_x, hydrocarbons, and carbon monoxide—into less harmful substances like carbon dioxide and water vapor [18].

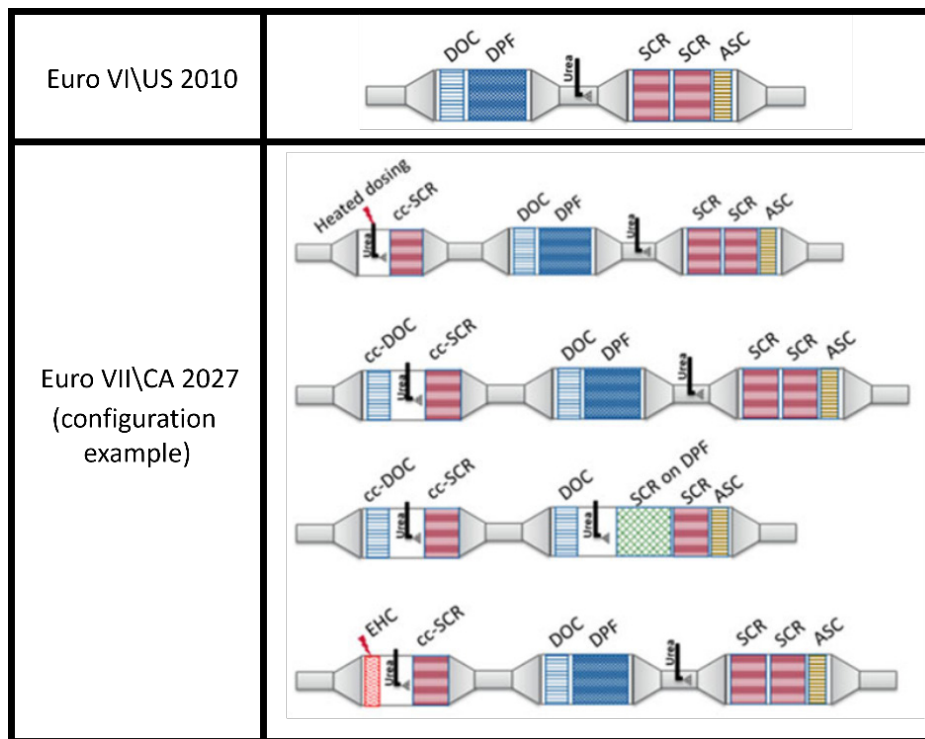


Figure 7. After treatment architecture for the future lows of NO_x requirements [18].

The main challenge that remains is mitigating “cold-start” emissions, which occur in the initial moments after engine start-up, before the catalyst reaches its effective temperature. Various system architectures are currently being developed to meet future emission standards more effectively (Figure 7). A common strategy involves integrating a selective catalytic reduction unit upstream of the diesel particulate filter (DPF). This configuration facilitates earlier catalyst activation and enhances NO_x reduction at lower exhaust temperature conditions commonly encountered during city driving and low-load operation.

3.1 Diesel Engines

In general, regulations and programs targeting diesel emissions can be categorized into the following groups:

- Tailpipe emission standards: emission standards for new engines and/or vehicles; In most jurisdictions, diesel regulated emissions focus on:
 - Particulate matter;
 - Nitrogen oxides (in some jurisdiction nitrogen oxide is regulated as greenhouse emission);
 - Hydrocarbons;
 - Carbon monoxide.
- Emission control retrofit programs for existing vehicles: equipping older vehicles with aftermarket treatment systems such as particulate filter, selective catalytic reduction;
- Inspection and maintenance programs.

Emissions are evaluated using an engine or vehicle test cycle, a critical component of every emission standard. These regulatory testing procedures are essential for verifying and ensuring compliance with established standards. Test cycles are designed to achieve two key objectives: they aim to provide consistent and repeatable conditions for measuring emissions, while also simulating real-world driving scenarios relevant to the specific application. This dual approach helps ensure that emission standards are both scientifically rigorous and reflective of actual operating conditions, thereby enhancing their effectiveness in reducing environmental and health impacts [19]. Test cycles can be categorized into two main types: steady-state cycles and transient cycles. In steady-state cycles, the engine operates at a series of fixed speed and load conditions, with emissions measured at each stabilized mode. These measurements are then averaged, often using specific weighting factors assigned to different modes to reflect their relative importance. In contrast, transient cycles involve simulating a dynamic driving pattern that includes accelerations, decelerations, and variations in speed and load. Emissions during transient cycles are typically calculated

either by integrating continuous, real-time measurements or by analyzing gas samples collected in sampling bags over the duration of the cycle. This distinction allows for a comprehensive evaluation of emissions under both controlled and realistic driving conditions. Among those test cycles, can be mentioned:

- US Heavy-Duty FTP Transient Cycle: used for testing the emissions of heavy-duty engines in United States;
- European stationary cycle or ACEA cycle: introduced for emission certification of heavy-duty diesel engines in Europe, introduced in the year 2000;
- World harmonized stationary cycle: a global emissions test cycle covering a hot start steady-state test cycle and a transient test cycle for both cold and hot start requirements;

3.2 Spark Ignition Engines

An evolution in the engineering process can be observed that from 1993, where approximately 9% of the fuel remained unburned during the main combustion process, which led to significant implications for engine performance and efficiency which resulted in a loss in the mean effective pressure and fuel conversion efficiency [20]. Recent studies show that the spark ignition engines can operate at higher compression ratios without abnormal combustion due to the high-octane number of NH₃. In order to speed up the flame speed is to use conventional fuel (gasoline) blended with faster-burning fuels (such as hydrogen) [21]. Another development brought in the field for the spark ignition engines are the use of multiple spark plugs, which ultimately increase the burning rate of the NH₃. Not only this, but this technique also allows multiple flame kernels to develop simultaneously, merge, and spread efficiently throughout the combustion chamber, leading to faster and more stable combustion. Research has shown that, compared to conventional single-spark ignition, the multi-spark strategy increases in-cylinder pressure, shortens combustion duration, and improves engine stability by enhancing the combustion rate of ammonia fuel. Notably, the coefficient of variation dropped significantly—from 19.58% with single-spark ignition to just 1.96% using multi-spark. Visual analysis using natural flame luminosity imaging also confirmed a substantial increase in both flame intensity and propagation area [21].

A variety of factors can interfere with the intended operation of the spark ignition engine, including the design of the combustion chamber, the chemical properties of the fuel, the buildup of deposits within the cylinder, and the specific conditions under which the engine operates. Among these, the most significant and concerning form of abnormal combustion is known as knock, a phenomenon that can lead to engine damage and reduced efficiency. Other issues related to abnormal combustion include surface ignition or preignition, where the fuel-air mixture ignites prematurely, and misfire, which disrupts the normal propagation of the flame within the cylinder. These challenges highlight the complexities of maintaining optimal combustion and the need for careful engineering to mitigate such issues [13].

Carbon monoxide and hydrocarbons are the primary pollutants found in the exhaust emissions of gasoline-powered vehicles. These emissions arise from the incomplete combustion of fuel during the engine's operation [22]. Conventional spark ignition engines often face difficulties in achieving an optimal balance between delivering high performance and maintaining low emissions [23]. In contemporary SI engines, reducing fuel consumption requires the integration of advanced technologies and strategies [24]. These include increasing boost pressure combined with downsizing the engine, as well as incorporating techniques such as water injection, nitrogen oxide reduction converters (de-NO_x), lean air-fuel mixtures, and exhaust gas recirculation to dilute the combustion mixture. These innovations aim to enhance fuel efficiency and reduce emissions, reflecting the ongoing effort to meet stringent environmental regulations while preserving engine power and performance.

In port-fuel-injected spark ignition engines, the air and fuel are mixed in the intake port before the mixture enters the cylinder. This intake charge then combines with any residual gases left in the cylinder from previous cycles. As a result, the air-fuel ratio and the concentration of diluents, such as those from EGR and residual gases, are ideally nearly uniform throughout the cylinder. During combustion, the portion of the mixture that ignites early is compressed to higher temperatures as cylinder pressures rise, while the portion that burns later remains mostly unburnt during compression and reaches lower temperatures. Consequently, the earlier-burning fractions of the fuel contribute significantly more to the formation of NO emissions compared to the later-burning fractions. The highest NO concentrations are typically found near the spark plug, where combustion initiates. This uneven temperature distribution and its impact on NO formation highlight the complex dynamics of in-cylinder combustion processes.

As mentioned above, spark ignition engines produce significant levels of CO emissions, which require careful management. This is primarily because SI engines typically operate at or near stoichiometric air-fuel ratios under part-load conditions and may run fuel-rich during high-load scenarios, creating ideal conditions for CO formation.

In premixed SI engines, CO concentrations rise rapidly within the flame zone, often exceeding the levels expected for adiabatic combustion under the same fuel-air conditions. Although CO concentrations decrease as the gases exit the cylinder, they remain higher than the equilibrium concentrations predicted for the exhaust temperature. This suggests that the formation and breakdown of CO are governed by kinetic processes rather than thermodynamic equilibrium, highlighting the complex chemical dynamics involved in CO emission control [13].

Hydrocarbon concentrations in the exhaust of SI engines are notably higher compared to those from compression ignition engines. Total hydrocarbon emissions tend to rise under two conditions: when the fuel-air mixture becomes richer than stoichiometric and when it is leaned out beyond the optimal ratio. Several mechanisms have been proposed to explain HC emissions in SI engines, including the following:

- The fuel-air charge was compacted within the crevice regions;
- The cylinder liner's oil film experienced absorption of fuel constituents;
- Incomplete burning resulted from flame quenching, liquid fuel, and exhaust valve leaks.

The incremental reactivity scale is widely utilized as a tool for assessing the environmental reactivity of HC mixtures. Recent data from a University of California-Riverside report submitted to the California Air Resources Board are presented in Table 3. Apart from methane, all HC species undergo chemical reactions over time in the atmosphere. As a result, it is often beneficial to categorize total HC concentrations into two groups: methane (CH₄) and non-methane organic gases. This distinction helps provide a more accurate understanding of the environmental impact of hydrocarbon emissions, as methane and NMOGs behave differently in terms of reactivity and their contributions to air quality issues [13].

Table 3. Hydrocarbons incremental reactivity [13]

Hydrocarbons type	Incremental reactivity [gO ₃ /gNMOG]
C ₁ –C ₄ alkanes	0.25-1
Benzene	0.4
Methanol	0.6
>C ₅ alkanes	1-2
Ethanol	1.3
Cyclic alkanes	1-2.5
Toluene	2.7
Olefins	4-10
Acetaldehyde	5.5
Aromatics	6-10
Formaldehyde	7.2
Ethylene	7.3
Diolefins	10

4. Unregulated Emissions

Emissions that fall outside the scope of the current regulatory system are called unregulated emissions [11]. These include all exhaust compounds other than those specifically targeted by existing regulations, such as carbon monoxide, total hydrocarbons, nitrogen oxides, and particulate matter. Despite the lack of regulations for these emissions, they continue to attract significant attention for several reasons. For instance, several countries are currently conducting trials to gather data on carbon dioxide emissions from vehicles, with the potential for future legislative action in mind. Moreover, in recent years, there has been growing interest in understanding and addressing these unregulated emissions due to their potential environmental and health impacts [25]. Certain emissions have diminished in significance as a result of technological advancements and regulatory measures. For instance, the formation of sulfur oxides in diesel oxidation catalysts is closely linked to particulate matter emissions. In response, countries such as the United States, Japan, and Europe have significantly reduced the sulfur content in fuels. This shift has led to the introduction of ultra-low sulfur diesel, with sulfur content decreasing from 0.05% by weight in traditional

diesel fuel to less than 0.005% by weight for specific urban applications. The adoption of low-sulfur fuels not only reduces harmful emissions but also helps preserve the effectiveness of catalytic converters over the lifespan of a vehicle, preventing catalyst poisoning and ensuring sustained performance [11].

Among the carcinogenic hydrocarbons of concern, polycyclic aromatic hydrocarbons stand out, particularly those with 3-, 4-, 5-, or 6-ring structures. Smaller PAHs, such as naphthalene and phenanthrene, exist in both vapor and particulate phases. One of the most potent carcinogens is Benzo(a)pyrene, a 5-ring compound that belongs to the group of particulate PAHs, which typically consist of four or more fused rings. Diesel engines are a major source of PAHs, and the carcinogenic nature of diesel particulate matter is largely attributed to the presence of these compounds. However, the harmful levels of PAHs can be significantly reduced through the use of oxidation catalysts, which help mitigate their impact on human health and the environment [11].

In summary, the exhaust emissions from vehicles burning hydrocarbon fuels can include a variety of concerning species. These encompass hydrocarbons, both saturated (e.g., alkanes) and unsaturated (e.g., C_2H_2 , C_2H_4 , C_3H_3), as well as aromatic compounds like benzene, toluene, and benzpyrene. Additionally, oxygenated hydrocarbons such as alcohols (e.g., CH_3OH , C_2H_5OH), aldehydes (e.g., formaldehyde, acetaldehyde), ketones, and ethers (e.g., $CH_3-CH_2-O-CH_2-CH_3$) may be present. Particulate matter, including soot and soluble organic fractions, is also a significant component. The sources of these compounds can be traced to several origins: intake air components (e.g., N_2 , O_2 , CO_2 , and H_2O), unburned fuel or fuel additives (e.g., MTBE, ETBE), products of complete combustion (e.g., CO_2 , H_2O), products of incomplete combustion (e.g., CO, hydrocarbons), and fuel contaminants (e.g., H_2O , NH_3). These emissions highlight the complex chemical processes involved in vehicle combustion and the importance of addressing their environmental and health impacts [11].

5. Alternative Fuels

There is a growing imperative to explore alternatives to conventional fuels within the transportation sector. Low-carbon fuels, such as ethanol and methanol, as well as zero-carbon fuels like hydrogen, exhibit properties that make them promising candidates to replace traditional fossil fuels. These alternatives offer the potential to significantly reduce greenhouse gas emissions and dependence on non-renewable energy sources. Table 4 provides a comparative analysis of key properties among gasoline, methanol, ethanol, and hydrogen, highlighting their respective advantages and challenges in terms of energy density, emissions, and compatibility with existing infrastructure. This comparison underscores the importance of transitioning to sustainable fuel options to address environmental and energy security concerns [1].

Table 4. Comparative properties of different fuels [1]

Properties	Gasoline	Ethanol	Methanol	Hydrogen
Number of carbon atoms	8	2	1	0
Molecular formula	C_8H_{18}	C_2H_5OH	CH_3OH	H_2
Mass weight of oxygen [%]	0	34.8	50	0
Molecular weight [g/mol]	114.62	46.068	32.041	2.016
Density [km/m^3]	700-800	778	792	0.084
Latent heat vaporization [kJ/kg]	317.7	837.4	1100	-
Stoichiometric air-fuel ratio	14.5:1	9:1	6.5:1	34:1
Flammability limit in air (% by volume of air)	1.1-6.0	3.3-19.0	6.0-36.5	4.0-75.0
Calorific volume [MJ/kg]	44.3	26.8	20.0	120.21
Laminar burning velocity at stoichiometric conditions (m/s)	0.46	0.47	0.50	2.6

Ethanol is a low-carbon fuel that offers several advantageous properties, including a higher-octane number and greater oxygen content compared to gasoline. Bioethanol, a type of ethanol, can be produced from lignocellulosic biomass, such as crop residues, wood chips, grasses, and sawdust. However, the production of bioethanol from lignocellulosic biomass faces several challenges, including high costs, waste disposal issues, and the toxicity of chemical reagents used in the process. Notably, the pretreatment of biomass alone accounts for over 20% of the total production cost of lignocellulosic bioethanol. Despite these hurdles, significant progress has been made toward commercializing this production method. According to different studies, the use of cost-effective raw materials,

efficient pretreatment methods, optimized bioprocess integration, improved recovery techniques, and strategies for minimizing energy use and waste can make the production of lignocellulosic bioethanol more economically viable [26]. These advancements are critical for making bioethanol a sustainable and competitive alternative to conventional fuels. Methanol is a low-carbon fuel that possesses several advantageous properties, making it a promising alternative to gasoline. It has a higher-octane number, which improves engine performance and efficiency, as well as a higher oxygen content, which promotes cleaner combustion. Additionally, methanol requires lower ignition energy and exhibits a higher laminar burning velocity compared to gasoline, enabling faster and more efficient combustion. These characteristics make methanol an attractive option for reducing emissions and enhancing fuel performance in the transportation sector [27]. Hydrogen is a zero-carbon fuel that offers numerous advantageous properties, making it a highly attractive alternative to gasoline. It has higher mass diffusivity in air, a wider flammability limit, and a higher-octane number, which contribute to improved engine performance and efficiency. Additionally, hydrogen requires lower ignition energy, has a higher heating value, and exhibits a faster laminar burning velocity compared to gasoline, enabling more efficient and cleaner combustion. Hydrogen can be produced from a wide range of sources, including both conventional and renewable energy systems, further enhancing its potential as a sustainable fuel for the future. These characteristics position hydrogen as a key candidate for reducing carbon emissions and advancing energy sustainability in the transportation sector [1].

In terms of efficiency, the thermal efficiency of engines using ethanol-gasoline blends remains largely comparable to that of pure gasoline under standard conditions. However, under lean operating conditions (where the air-fuel ratio, λ , exceeds 1.3), ethanol-blended fuels demonstrate significantly better thermal efficiency than gasoline. The peak efficiency for ethanol blends occurs at $\lambda = 1.3$, while for gasoline, it is achieved at $\lambda = 1.2$. A 3% improvement in efficiency can be attained by optimizing spark timing and reducing compression work. To fully understand this efficiency gain, it is important to examine the dynamics of the compression and combustion processes. During the compression stroke, the ongoing vaporization of the fuel lowers the temperature of the working charge, which reduces compression work. At the same time, the increased presence of fuel vapor in the working charge raises compression work. These competing effects highlight the complex interplay between fuel properties and engine performance [28]. Thermal efficiency is influenced in part by combustion efficiency, which varies depending on the air-fuel mixture. Combustion efficiency is highest under lean conditions (where the equivalence ratio is low) because there is sufficient oxygen to ensure complete combustion. In contrast, combustion efficiency decreases under rich conditions due to insufficient oxygen, leading to incomplete combustion. When ethanol is blended with gasoline, it introduces additional oxygen into the combustion process. This oxygen content in ethanol supports leaner combustion, enhancing the engine's ability to operate efficiently under lean conditions. As a result, ethanol-blended fuels can improve combustion efficiency and contribute to better overall thermal efficiency [28].

In terms of emissions, under slightly lean combustion conditions, where there is sufficient air to support oxidation reactions, burned hydrocarbons can participate in further oxidation, reducing hydrocarbon emissions. However, if the mixture becomes too lean, combustion becomes incomplete, leading to an increase in HC emissions. The introduction of ethanol as a fuel can help mitigate HC emissions. Ethanol molecules are polar, which makes them less likely to be absorbed by the non-polar molecules in the lubricating oil layer. This property of ethanol reduces the likelihood of HC emissions being produced, as it minimizes the interaction between fuel and oil that typically contributes to unburned hydrocarbon release. As a result, ethanol can play a significant role in lowering HC emissions and improving combustion efficiency. Inclusion of hydrogen to fuel mixtures can lead to higher flame temperatures, which typically increase NO_x emissions. However, when hydrogen is enriched with gases such as N_2 and CO_2 , the cooling and charge dilution effects of these gases can counteract the rise in NO_x emissions, even under stoichiometric combustion conditions [29]. This is because the presence of N_2 and CO_2 contributes to lowering peak combustion temperatures, reducing the formation of thermal NO_x . Lean combustion further contributes to this effect by lowering peak temperatures and inhibiting thermal NO_x mechanisms. On the other hand, the inclusion of CO_2 in hydrogen-enriched gas can lead to higher CO_2 emissions, particularly around stoichiometric conditions. This highlights the trade-offs involved in using hydrogen-enriched fuels, where benefits in NO_x reduction must be balanced against potential increases in CO_2 emissions [28].

In terms of unregulated emissions that came from the alternative fuels, studies show that methane emissions are significantly higher than in gasoline engines, and the explanation is that ethene interacts with methyl radicals during combustion, leading to the formation of methane as a byproduct. As a result, higher emissions of ethene, which are often observed when using ethanol as a fuel, contribute to increased methane emissions. In contrast, methane

emissions were found to be negligible when methanol or hydrogen was used as the fuel source. This difference highlights the varying chemical pathways and byproducts associated with different fuel types, emphasizing the importance of fuel composition in determining emission profiles. Those ones can also be extracted from the equation:



where CH_3 is the methyl radical, and C_2H_3 is the vinyl radical [1].

Also, in case of the ethanol use, due to the interaction of the hydrocarbons radical (CH_n) and atmospheric nitrogen (N_2) in the cylinder, will end with the result the hydrogen cyanide (HCN) (reaction 5.2 and 5.3), even though in past studies the emissions of HCN between ethanol and gasoline reported that the HCN emissions were low, nowadays studies show that those emissions tend to have similar values (2.4 to 2.5 ppm). But a significant 20% reduction in hydrogen cyanide emissions was observed when using hydrogen as a fuel compared to gasoline. Furthermore, hydrogen cyanide emissions were completely eliminated when methanol was used.



where N represents the nitrogen radical and NH the imidogen radical [1].

6. Conclusion and Future Perspectives

The purpose of this paper is to highlight the need to address the environmental and health impacts of transportation emissions, which remain a significant contributor to global greenhouse gas emissions and air pollution. These engines emit regulated pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter, as well as unregulated emissions like nitrous oxide and hydrogen cyanide, which pose severe risks to human health and the environment.

The transition to alternative fuels that are either low-carbon oriented, such as ethanol and methanol, or to zero-carbon oriented, such as hydrogen, represents a must in terms of methods to reduce emissions and achieve sustainable mobility. Prospects for this approach represent:

- Advanced techniques for the combustion process, which can optimise air-fuel mixing or lean-burn operation with respect to reducing the harmful common pollutants and the unregulated ones. More innovations in the components design can be included that can also minimize the unburned fuel and improve the fuel conversion efficiency.
- Adaptation of the alternative fuels that can improve the combustion properties by achieving higher oxygen contents compared to traditional fuels. Another key fuel that has been more and more analysed in recent years is hydrogen due to its capabilities of rapid combustion and high energy density, making it a valuable fuel for zero carbon emissions.
- Regulatory and technological advancements in the transportation industry, like EURO standards or real driving emissions tests, were also conceived with the purpose of reducing emissions and translating the virtual tests into real-world performance. Continued advancements in powertrains, exhaust aftertreatment systems, and onboard diagnostics will be essential for meeting stringent emission targets and improving air quality.

By embracing these strategies and perspectives, the transportation sector can significantly reduce its environmental footprint, contribute to global climate change mitigation efforts, and, as future perspectives can be mentioned:

- Focus on overcoming challenges associated with hydrogen, such as NOx emissions and infrastructure development, to unlock its full potential as a zero-carbon fuel. Explore the scalability and economic viability of alternative fuels production from renewable sources.
- Invest in infrastructure for hydrogen refueling, electric vehicle charging, and sustainable fuel distribution to facilitate widespread adoption.
- The transportation sector must adopt a holistic strategy that integrates alternative fuels, optimized combustion processes, and robust emission control technologies.
- Promote public awareness of the benefits of alternative fuels and sustainable transportation to drive consumer acceptance and demand.

References

- [1] Marwaha A, Subramanian K. Control of regulated and unregulated emissions of an automotive spark ignition engine with alternative fuels (methanol, ethanol and hydrogen). *Measurement: Energy*. 2025.
- [2] Intergovernmental Panel on Climate Change. *Climate Change 2023* [Internet]. 2023. Available from: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf. Accessed March 31, 2025.
- [3] Schneider A, Gkouliaveras V, Kalogiannidis S. Effects of Climate Change on Health and Health Systems: A Systematic Review of Preparedness, Resilience, and Challenges. *Int J Environ Res Public Health*. 2025;22(2):232.
- [4] Claßen J, Krysmón S, Dorscheidt F. Real Driving Emission Calibration-Review of Current Validation Methods against the Background of Future Emission Legislation. *Appl Sci*. 2021.
- [5] Ghosh BK, Mekhilef S, Ahmad S. A Review on Global Emissions by E-Products Based Waste: Technical Management for Reduced Effects and Achieving Sustainable Development Goals. *Sustainability*. 2022;14(7):4036.
- [6] Ashnani MHM, Miremadi T, Johari A. Environmental Impact of Alternative Fuels and Vehicle Technologies: A Life Cycle Assessment Perspective. *Environ Impact Assess Rev*. 2015;30:205-10.
- [7] Vallabani NV, Gruzjeva O, Elihn K. Toxicity and health effects of ultrafine particles: Towards an understanding of the relative impacts of different transport modes. *Environ Res*. 2023;231(2).
- [8] New Jersey Department of Health and Senior Services. Hazardous Substance Fact Sheet [Internet]. 2002 Aug. Available from: <https://nj.gov/health/eoh/rtkweb/documents/fs/0873.pdf>. Accessed February 20, 2025.
- [9] National Center for Biotechnology Information. PubChem Compound Summary for CID 6326 [Internet]. Available from: <https://pubchem.ncbi.nlm.nih.gov/compound/6326>. Accessed February 20, 2025.
- [10] Chen Y, Ma J, Han B. Emissions of automobiles fueled with alternative fuels based on engine technology: A review. *J Traffic Transp Eng*. 2018;5(4):318-34.
- [11] Prasad GA, Sharma TK. *Engine Emission Control Techniques: Design Modifications and Pollution Mitigation Techniques*. Apple Academic Press; 2020.
- [12] Dey S, Mehta NS. Automobile pollution control using catalysis. *Resour Environ Sustain*. 2020;2.
- [13] Strzelec A, Kasab J. *Automotive Emissions Regulations and Exhaust Aftertreatment Systems*. Pennsylvania: SAE International; 2020.
- [14] Consortium for Climate Change. *Study on Post EURO 6/VI Emission Standards in Europe (Part B): Presentation to the Advisory Group on Vehicle Emission Standards (AGVES)* [Internet]. 2020.
- [15] Bilousov I, Bulgakov M, Savchuk V. *Modern Marine Internal Combustion Engines A Technical and Historical Overview*. New Orleans: Springer; 2021.
- [16] Frontier Economics Consulting. *Regulation and Competitiveness of the EU Automotive Industry*. ACEA; 2015.
- [17] Continental Automotive GmbH. *Worldwide Emission Standards and Related Regulations*. 2019.
- [18] Kalghatgi G, Agarwal AK, Leach F, editors. *Engines and Fuels for Future Transportation*. Springer; 2022.
- [19] Majewski A, Jaaskelainen H. *Diesel Emissions and Their Control*. Second Edition. SAE International; 2023.
- [20] Cheng WK, Hamrin D, Heywood JB, et al. An Overview of Hydrocarbon Emissions Mechanisms in Spark-Ignition Engines. SAE Technical Paper 932708. 1993. doi:10.4271/932708
- [21] Menaca R, Silva M, Uddeen K, et al. Optical multi-spark ammonia combustion engine: numerical analysis and validation. *Front Mech Eng*. 2025;11.
- [22] Zhang R, Chen H, Xie P, et al. Exhaust Emissions from Gasoline Vehicles with Different Fuel Detergency and the Prediction Model Using Deep Learning. *Adv Sens Gas Monit*. 2023;23(17).
- [23] Ricci F, Avana M, Mariani F, et al. A Deep Learning Method for the Prediction of Pollutant Emissions from Internal Combustion Engines. *Appl Sci*. 2024;14(21).
- [24] Khurana S, Saxena S, Jain S, et al. Predictive modeling of engine emissions using machine learning: A review. *Mater Today: Proc*. 2021;38:280-4.
- [25] Bikomeye JC, Rublee CS, Beyer KM. Positive Externalities of Climate Change Mitigation and Adaptation for Human Health: A Review and Conceptual Framework for Public Health Research. *Int J Environ Res Public Health*. 2021;18(5):2481.
- [26] Pant S, Kuila A. Pretreatment of lignocellulosic biomass for bioethanol production. In: Srivastava N, Mishra PK, Upadhyay SN, editors. *Advanced Biofuel Technologies: Present Status, Challenges and Future Prospects*. Elsevier; 2022. p. 177-94.
- [27] Mohanty P, Singh PK, Pattnaik R, et al. A critical review on prospects and challenges in production of biomethanol from lignocellulose biomass. *Biomass Convers Biorefin*. 2022;12(5):1835-49.

- [28] Park C, Choi Y, Kim C. Performance and exhaust emission characteristics of a spark ignition engine using ethanol and ethanol-reformed gas. *Fuel*. 2010;89(8):2118-25.
- [29] Tunestål P, Christensen M, Einewall P, et al. Hydrogen Addition for Improved Lean Burn Capability of Slow and Fast Burning Natural Gas Combustion Chambers. In: *SAE Technical Papers*. Pittsburgh, PA, United States; 2002.
- [30] Reuters. Global CO2 emissions to hit record high in 2024 [Internet]. 2024 Nov 13. Available from: <https://www.reuters.com/business/environment/global-co2-emissions-hit-record-high-2024-report-says-2024-11-13/>. Accessed March 31, 2025.
- [31] United States Environmental Protection Agency. Transportation Sector Emissions [Internet]. Available from: <https://www.epa.gov/ghgemissions/transportation-sector-emissions>. Accessed March 31, 2025.
- [32] Kumar PG, Lekhana P. Effects of vehicular emissions on the urban environment—a state of the art. *Mater Today: Proc*. 2021;45:6314-20.