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The Scope for Improving the Pollution Impact of the Internal Combustion Engine

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Abstract
Internal combustion engines (ICEs) today drive 99.8% of worldwide transportation, while petroleum-based liquid fuels provide 95% of transportation energy. Many solutions are being studied, including battery electric cars (BEVs) and other fuels such as biofuels and hydrogen. However, all these choices start from a low point and face considerable barriers to indefinite expansion, so even by 2040, traditional liquid fuels powering combustion engines are estimated to account for 85-90% of transportation energy. Because of the huge number of vehicles on the road and the impact of emissions-related pollutants on human and ecological health, internal combustion engine research focuses on improving efficiency and lowering emissions. Nitrous oxides (NO_x), carbon dioxide, hydrocarbons, and particulate matter are some of the harmful components of engine exhaust gases. NO_x emissions have been linked to serious health consequences. When paired with other modern approaches, exhaust gas recirculation can minimize NO_x emissions while also improving engine efficiency. Rather, the residual quantity of the exhaust gas effect on the quality of engine lubrication that is cause of increasing the wear of piston. After examining the underlying concepts that regulate engine efficiency and the methods to minimize exhaust pollution, this paper discusses the review for such improvement. Consider the many practical ways now on the market to see how much room there is for improvement.

Keywords: Internal combustion engine, NO_x emissions, Water injection, Catalyst, Exhaust gas recirculation.

Nomenclature

CO	Carbon monoxide	iEGR	Internal exhaust gas recirculation
EGR	Exhaust gas recirculation	LDV	Light duty vehicle
eEGR	External exhaust gas recirculation	LPG	Liquid petroleum gas
GHG	Global greenhouse gas	NO_x	Nitrogen oxides
HC	Hydrocarbon	PM	Particulate matter
HGV	Heavy goods vehicle	WI	Water injection
ICE	Internal combustion engine		

1. Introduction

The internal combustion engine (ICE) is made to generate power from the energy stored in its fuel. More specifically, its fuel comprises chemical energy, which is burned with air to generate mechanical power. Petroleum, biofuels, and hydrogen are just a few of the fuel types that can be used in ICEs [1]. Transportation of products and persons accounts for over 25% of worldwide CO_2 emissions due to fossil fuel combustion [2]. However, when other factors such as methane are factored in, its contribution of global greenhouse gas (GHG) emissions is roughly 14% [3], which is equivalent to the share from livestock production [4]. In 2015, the globe possessed an estimated 1.1 billion light duty vehicles (LDVs), defined as cars weighing less than 8500 lb. (3860 kg), and 380 million heavy goods vehicles (HGVs) [5]; in 2018, worldwide LDV production was about 70 million, while commercial vehicle production was around 25 million. Vehicles are becoming more common, especially in developing nations, and by 2040, the global LDV population is predicted to reach 1.7 to 2 billion [5]– [7]. Currently, combustion engines power practically all modes of transportation (>99.8%), with reciprocating internal combustion engines (ICEs) dominating terrestrial and sea transport and jet engines dominating air transport. In addition to industry and electricity generation, combustion engines play a significant function.

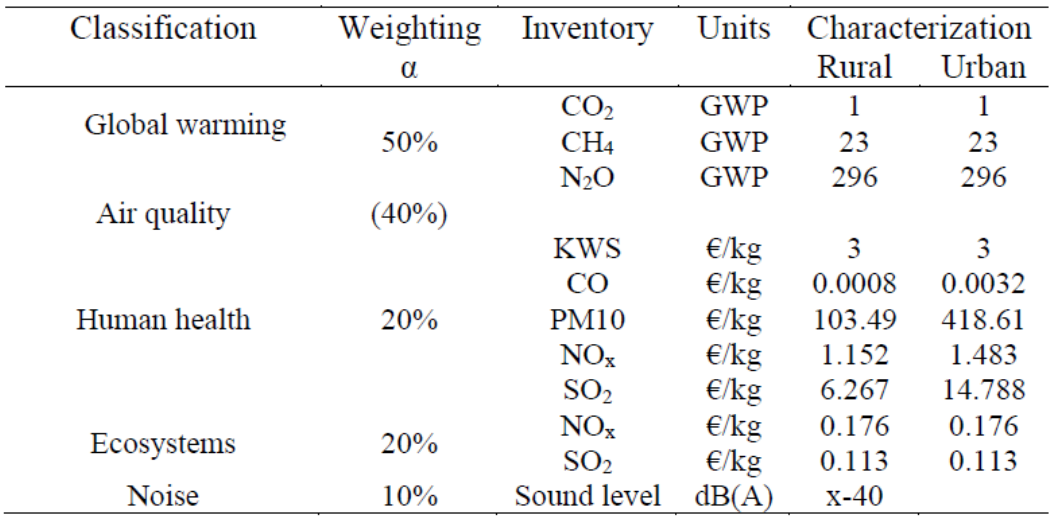
Because of their high energy density and ease of transport and storage, liquid fuels have become the preferred energy source for transportation. Gasoline, for example, has a volumetric energy density roughly 3100 times that of hydrogen and 800 times that of natural gas at normal temperatures and pressures. Over the last century or more, a large worldwide infrastructure for the manufacture and distribution of liquid fuels has been developed, which will be costly and difficult to replace or recreate. Transport and petroleum (crude oil) are inextricably intertwined; today, liquid fuels generated from petroleum provide over 95% of transport energy, and around 60% of crude oil is utilized to make transport fuels [6], [7].

Many efforts are ongoing throughout the world to develop alternatives to ICEs and petroleum-based conventional fuels, motivated by worries about climate change and local air pollution caused by CO_2, particulates, nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbon emissions (HC). Indeed, in many nations, criticism of ICEs is frequent in the mainstream media and among some politicians, leading to the idea that their abolition is desirable and imminent. Of course, in many countries, the goal for economic growth, energy independence, and energy security has a significant impact on transportation policy. The ICE might be replaced by a battery or a fuel cell, and biofuels, natural gas, hydrogen, synthetic fuels, electro-fuels, liquid petroleum gas (LPG), and methanol are all viable alternatives to conventional fuels [8], [9].

Nitrogen oxides [10] are one of the most harmful byproducts of diesel engines. They produce acids that irritate the bronchial airways and cause coughing in humans. People with asthma may be more vulnerable to NO_x. The effects on terrestrial and aquatic ecosystems are similarly harmful [11]. NO_x emitting locations have a larger photolytic source of OH, which stimulates O_3 generation and causes O_3 rich air and quality issues, but OH causes lower levels of O in ocean areas, which has a negative impact on climate regulation [12]. Radiative forcing agents include black smoke and black carbon. PM10 is a type of particulate matter that can linger in the air for hours or even days. Because they are bound to other toxic compounds, they enter the respiratory system and lungs, causing a slew of health issues [11], [12].

Table 1 summaries the characteristics utilized in the Eco-score approach, allowing for a better understanding of its impact and why pollution reduction is required.

Table 1: Overview of the Eco-score methodology characteristics [13].



Classification	Weighting α	Inventory	Units	Characterization Rural	Characterization Urban
Global warming	50%	CO_2	GWP	1	1
		CH_4	GWP	23	23
		N_2O	GWP	296	296
Air quality	(40%)				
Human health	20%	KWS	€/kg	3	3
		CO	€/kg	0.0008	0.0032
		PM10	€/kg	103.49	418.61
		NO_x	€/kg	1.152	1.483
		SO_2	€/kg	6.267	14.788
Ecosystems	20%	NO_x	€/kg	0.176	0.176
		SO_2	€/kg	0.113	0.113
Noise	10%	Sound level	dB(A)	x-40	

Following a review of the findings it is obvious that diesel engines have the greatest impact on human health, with the Eco-score methodology being driven mostly by the large number of particle matter (PM10), followed by NO_x and SO_2, which have an impact on both human health and ecosystems [11].

2. ICE Harmful Emissions Controlling and Efficiency Improving and

Optimal ignition timing [14]– [16], optimal injection timing [17]– [19], alternative fuels [20], [21], and turbocharger utilization [22], [23] are all efficient ways to increase internal combustion engine efficiency and reduce hazardous emissions. The peak firing temperature and oxygen concentration area have a considerable influence on the generation of NO_x in the combustion chamber [24], [25]. Reducing either of these factors may aid in the reduction of NO_x emissions. There are three approaches for reducing peak firing temperature and NO_x emissions that have been proven to work.

The first approach is water injection (WI): During the combustion stroke, water is pumped into the cylinder to lower the temperature of the hottest spot. This technique may also aid in the prevention of engine knock [26]– [30]. Water has a high latent heat of vaporization, thus as the liquid water vaporizes, it cools the charge air significantly. Furthermore, just like the cooled EGR gas, water vapor functions as a diluent in the combustion process, reducing NO_x emissions and minimizing knock reactions. Water cooling has long been used in ICEs, with the first effective use of WI for preventing combustion knock dating back to the early 1930s [31].

Water should first mingle with the airflow before evaporating, as this has a substantial impact on the engine's intake, compression, and subsequent combustion processes. Based on the fuel-air cycle, Hoppe et al. [32] separated the effects of specific heat and vaporization enthalpy of water on the in-cylinder compression temperature, showing that the charge cooling impact of WI is nearly completely attributable to the high latent heat of vaporization. As a result, the water evaporation process should be thoroughly studied, especially for the intake runner/port WI and the direct in cylinder WI, which are both dependent on not only the implementations stated above but also the engine operating conditions.

Nour et al. [33], [34] proposed introducing water into the exhaust manifold to use the enthalpy of exhaust gases to evaporate injected water, and then opening the exhaust valve during the intake stroke, the evaporated water and exhaust gases flow into the cylinder and participate in the combustion. As a result, WI's thermal effect is reduced, and other effects such as water vapor's chemical and dilution effects are expected to promote soot oxidation and reduce NO_x generation.

The second approach is using a catalyst: Before being released into the environment, engine exhaust gas passes through a catalyst. NO_x emissions are reported to be reduced by the catalyzers NH_3 and Mn-Ce/TiO_2 [35]– [37].

Composite vanadium-based oxide catalysts have been widely researched for selective catalytic reduction of NO_x with NH_3 throughout the last few decades. Ozkanet al. [38], [39], for example, investigated the catalytic efficacy of single V_2O_5. The results revealed that single V_2O_5's catalytic activity and temperature range were inferior and narrower. The composite oxide catalyst is an interesting topic because another metal can modify the catalytic properties of V_2O_5 in the polymetallic catalyst by both electronic and structural effects, and some researchers find that the vanadium-based bimetallic oxide can work well at low reaction temperatures and a wide range of operation temperatures.

The promoting effects of the doping elements are well established by numerous research groups following a detailed analysis of the catalytic activity of vanadium-based multiplex oxide catalysts. Zhao et al. [40], for example, created a unique $CeZrVO_4$ solid solution as a low-temperature NH_3-SCR catalyst, and the optimized catalysts demonstrated outstanding catalytic activity at low temperatures. Furthermore, Guan et al. [41] used the solution combustion approach to synthesize $CeTiVO_x$ nanocomposites serial catalysts, finding that the catalysts had good catalytic activity for NH3-SCR and more than 83 percent NO_x conversion at temperatures ranging from 150°C to 400°C. Kumar et al. [42] also used a homogeneous precipitation approach to make $CeSbVO_x$ catalysts and investigated their function in NH_3-SCR. Following the addition of Sb to NH_3-SCR, the conversion of NO_x was significantly boosted at both low and high temperatures, and the operation temperature window of the catalyst was dramatically widened. Over the $CeSbVO_x$ catalyst, above 80% NO_x conversion was achieved at temperatures ranging from 175°C to 400°C, with virtually 100% N_2 selectivity maintained throughout the temperature range.

The third approach is exhaust gas recirculation: When a portion of an engine's exhaust gas is recirculated back to the cylinders [43]– [46], the peak firing temperature and oxygen concentration area in the combustion chamber are reduced, and NO_x emissions are reduced. External exhaust gas recirculation (eEGR) [47], [48] and internal exhaust gas recirculation (iEGR) [49]–[51] are two types of exhaust gas recirculation.

After each exhaust stroke, remaining exhaust gases flow back into the combustion chamber through exhaust ports in iEGR. Premixing recirculated exhaust gases with a mixture of fresh air and fuel before the next combustion stroke can alter combustion stability, charge mass, flame speed, and the generation of hazardous compounds. The intake valve timing, exhaust valve timing, and valve overlap period can all be adjusted to manage the flow [52], [53].

The gas from the exhaust pipe is returned to the cylinder via the intake pipe in eEGR. Because up to 50% of the exhaust gases can be recirculated without impacting combustion stability, this is a helpful and more effective approach of lowering NO_x emissions in diesel engines [54]– [56]. However, to ensure combustion stability in gasoline engines, the eEGR rate should be kept below 20% [57]. The impacts of eEGR on diesel engine performance and emission parameters are summarized in Figure 1.

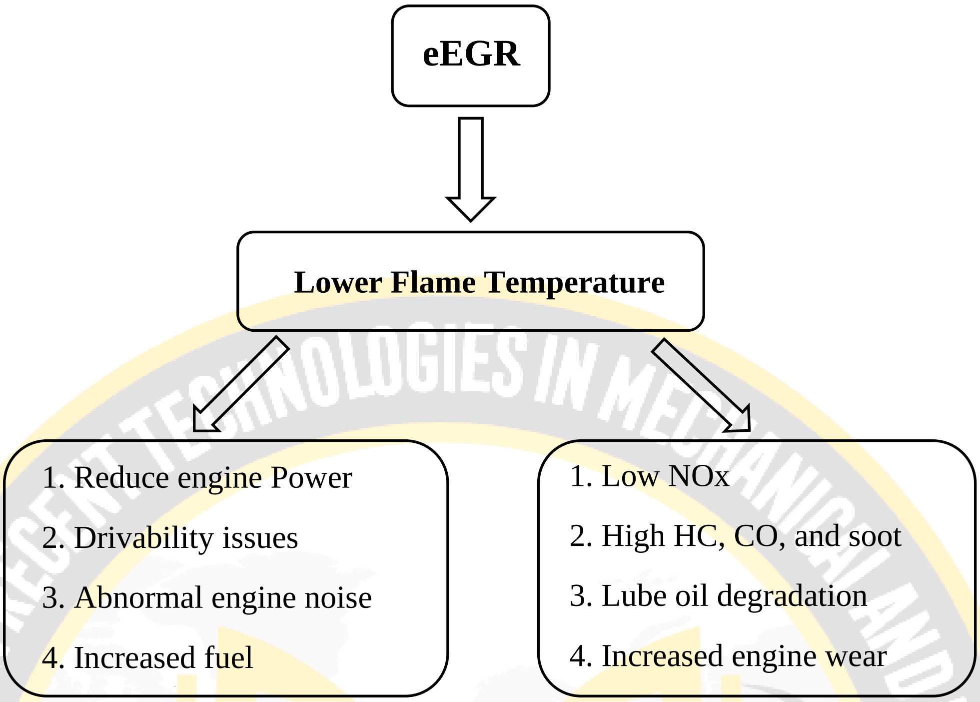
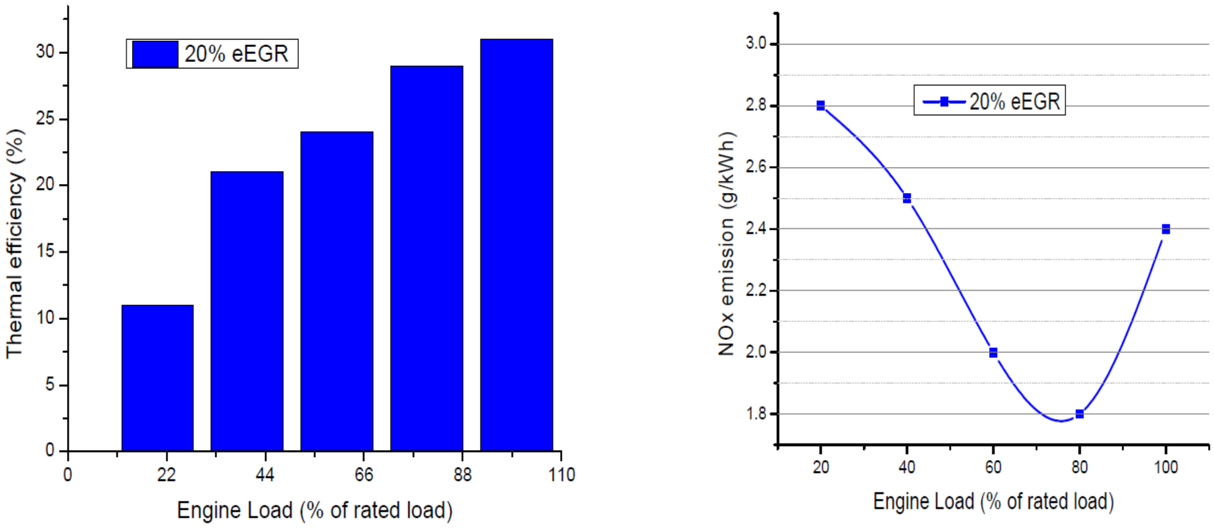


Figure 1: The impact of electronic exhaust gas recirculation (eEGR) on diesel engine performance and emissions.

The intake of air into the combustion chamber can be diluted by increasing the eEGR rate. eEGR enhances the heat capacity of the intake charge and the endothermic dissociation of CO_2 and H_2O at high temperatures. This explains why raising the eEGR rate lowers combustion quality and lowers the peak firing temperature. As a result, there is a reduction in NO_x emissions but a reduction in engine power, as well as high levels of hydrocarbons, CO, and soot. The effect of lubricating oil additives is negated by greater soot levels, which leads to increased engine wear.

Torregrosa et al. [58] investigated the effects of eEGR on heat transmission in the combustion chamber using a direct injection diesel engine. They discovered that eEGR has a significant impact on heat transfer, with higher levels lowering combustion wall temperatures and cylinder heat. The center of the cylinder head had the largest influence on heat flux. Temperature drops were linked to an 18% to 30% increase in eEGR. Torregrosa et al. also discovered that the reduction in NO_x emissions as a proportion of total emissions with eEGR was 10 times greater than the increase in CO_2 emissions as a percentage of total emissions.



(a) **(b)**

Figure 2: Impact of a 20% eEGR ratio on (a) engine thermal efficiency at various engine loads; (b) NO_x emissions at various engine loads.

eEGR was shown to have an influence on carbon deposits and engine wear in an agricultural diesel engine running at a constant speed [59]. At various engine loads, the influence of eEGR rates ranging from 0% to 20% on engine performance and emission characteristics was evaluated. At various engine loads, Figure 2 depicts the link between the eEGR rate, engine thermal efficiency, and NO_x emissions.

3. Discussions and recommendations

Currently, combustion engines power around 99.8% of transportation, while petroleum-based liquid fuels provide around 95% of transportation energy; any alternative starts from a low point and faces major impediments to indefinite expansion. As a result, even by 2040, conventional fuels powering combustion engines are estimated to contribute 85-90% of transportation energy. If existing greenhouse gas emission targets are to be met, the performance of such engines must be enhanced in terms of efficiency and exhaust pollutants. Such advancements, as detailed in this work, have a lot of room for development.

There are three approaches for reducing peak firing temperature and NO_x emissions that have been proven to work: using water injection, using a catalyst, and Exhaust gas recirculation. Water injection, which provides a good cooling effect on the in-cylinder combustion process, has gotten a lot of press in recent years because of the possible knock mitigation and NO_x reduction. It's also worth noting that water injection for commercial vehicles is still in its infancy. With respect to diverse water injection implementations and engine types, the fundamentals of both thermo-physical and chemical kinetic impacts of water addition on combustion phenomena and emissions need to be further researched. Furthermore, only a few studies on long-term water injection operation have been published, and friction analysis on piston rings and engine blocks, carbon deposit on water injectors, metal debris and water content in lubricating oil, and corrosion analysis must all be evaluated further before water injection can be commercialized.

Even though vanadium-based de-NO_x catalysts have made significant progress, some concerns still need to be investigated further. The following works may be taken into consideration further in order to develop precise vanadium-based catalysts for high catalytic activity and wide operating temperature windows in the reduction of NO_x with ammonia:

(1) Because the outstanding catalytic effectiveness of multi-metal and multi-support catalysts is based on cooperative action between multi-metal and multi-support, cooperative catalysis is a key factor to consider while designing a vanadium-based catalyst.

(2) In the vanadium-based catalyst, the synergistic mechanism between the active components and the assistants/ supports is not well understood, and it needs to be further investigated.

(3) Many parameters are linked to the catalytic processes of vanadium-based catalysts.

4. Conclusions

The impact of internal and exterior exhaust gas recirculation was thoroughly explored in this evaluation, and the gap in internal exhaust gas recirculation reviews was closed. The following are the key findings based on the review of iEGR and eEGR:

- Both iEGR and eEGR are extensively employed in modern internal combustion engines due to the benefits of reducing NO_x emissions and boosting ISFC and engine efficiency.
- Because the exhaust gas recirculation rate is lower with iEGR, it reduces NO_x emissions to a smaller amount than the eEGR approach. iEGR, on the other hand, has a lower starting cost, easier packing and retrofit potential, lower maintenance costs, improved dependability, and a higher tolerance for high-sulfur fuels. It improves cold engine start-up times and warm-up times.
- Control strategies for exhaust gas recirculation, as well as eEGR and iEGR determination equations, were also presented. For optimal efficiency, an appropriate combination of an exhaust gas recirculation control technique and determination equation should be adopted based on an engine's operating condition.
- Exhaust gas recirculation in internal combustion engines can minimize NO_x emissions by lowering combustion temperatures, cylinder head flow, and oxygen concentrations. Recirculation of exhaust gases, on the other hand, will increase hydrocarbon, CO, and soot emissions, as well as ignition delays and combustion duration. Increased carbon deposits produce a rise in soot output, which reduces the quality of lubricating engine oil and, as a result, causes an increase in engine wear. The greater heat loss transmission is responsible for the longer combustion duration.

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