Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

A Study of Exhaust Gas Recirculation in Diesel Engines

N. F. Khanyi[1], F.L. Inambao[2], R. Stopforth[3]

[1]*PG Scholar, Department of Mechanical, School of Engineering, University of KwaZulu-Natal, Durban 4041, South Africa.*

[2]*Professor, Department of Mechanical, School of Engineering, University of KwaZulu-Natal, Durban 4041, South Africa.*

[3]*Professor, Department of Mechanical, School of Engineering, University of KwaZulu-Natal, Durban 4041, South Africa.*

Abstract : This review provides a comprehensive evaluation of the impact of Exhaust Gas Recirculation (EGR) on performance parameters (BSFC, BMEP, and BTE) and emission characteristics (NO_x, CO_2, CO, THC, and smoke opacity) in diesel engines. By synthesizing existing literature, key findings regarding the effects of EGR on fuel consumption, power output, nitrogen oxide (NO_x) emissions, particulate matter, and other pollutants are highlighted. The review critically discusses the mechanisms through which EGR influences combustion processes, thermal efficiency, and exhaust gas composition, clarifying the balance between emission reduction and engine performance. Additionally, challenges and opportunities associated with EGR implementation, such as finding the optimum value of the EGR rate without affecting engine performance, are explored. Insights from this review paper offer valuable guidance for optimizing EGR strategies to achieve an equilibrium between meeting emission regulations and maintaining efficient diesel engine operation.

Keywords: Exhaust Gas Recirculation, diesel engines, smoke opacity, Nitrogen oxides, particulate matter, combustion, thermal efficiency, exhaust gas composition.

Nomenclature

EGR	Exhaust gas recirculation	λ	Excess air ratio
BSFC	Brake specific fuel consumption	αH2	Hydrogen energy fraction
BMEP	Brake mean effective pressure	EDir	Ethanol direct injection ratio
NO_x	Nitrogen oxides	SHC	Specific heat capacity
CO_2	Carbon dioxide	H_20	Water
CO	Carbon monoxide	UV	Ultraviolet
THC	Total hydrocarbon	HC	Hydrocarbon
DC	Donor-cylinder	WCME100	Waste cooking oil methyl ester
UHC	Unburned hydrocarbon	DMC	Carbonate additives
HPL	High pressure loop	CI	Compression ignition
LPL	Low pressure loop	HCCI	Homogeneous charge compression ignition
PB	30% palm biodiesel +70% diesel fuel	PBN	30% palm biodiesel +70% diesel fuel +25 ppm TiO_2

1 Introduction

Exhaust gas recirculation (EGR) technology implies that part of the exhaust gas from the engine is sent back to the intake manifold to enter the cylinder again together with the fresh mixture [1]. The technology was first applied to diesel engines, but EGR has been introduced to gasoline engines in recent years as emissions requirements for gasoline engines have increased. This technique plays a crucial role in modern diesel engines by helping to reduce harmful emissions and improve overall engine efficiency. The emissions from the engine exhaust comprise carbon monoxide (CO), unburned hydrocarbon (UHC) and nitrogen oxides (NO_x), and the mixture possesses higher specific heat compared to atmospheric air [2]. EGR is mixed with fresh air charge and then induced in the engine cylinder with carbon dioxide (CO_2) and water vapour in the exhaust manifold. Consequently, due to the involvement of less air, lower oxygen content is available for combustion. Thus, the air-fuel mixture tends to be lean [3, 4]. The significant lowering of the air-fuel ratio affects the emission concentration significantly. Moreover, the involvement of the EGR with fresh charge results in the rise of the specific heat of the induced charge. Therefore, the temperature of the flame gets reduced. The addition of lesser oxygen quantity in the fresh induced air as well as the lower flame temperature decreases the NO_x formation reaction rate [2, 5]. This further contributes to the cleaner and more environmentally friendly operation of IC engines.

As emissions standards become increasingly stringent worldwide, the quest to improve air quality and reduce greenhouse gas emissions has elevated the importance of EGR research [6]. Researchers focus on optimizing EGR systems to not only reduce emissions but also ensure optimal engine operation, combustion efficiency, and thermal management. The continual advancements in EGR technology, including innovative system designs, improved control strategies, and integration with other engine systems, highlight EGR as a pivotal area of research in the pursuit of cleaner and more efficient diesel engines. However, very few studies have made an effort to determine the optimal conditions for EGR deployment in different engine types, loads, and operating conditions to maximize emission reduction without compromising engine performance or fuel efficiency. Thus far, the challenge has been finding the balance between reducing emissions while ensuring that other performance parameters, such as BSFC, are not affected.

2 Overview of EGR systems

EGR systems can be categorised as either external or internal EGR systems. The internal EGR, often uncooled, pertains to the residual combustion product trapped within the cylinder and the counterflow of gas from the exhaust manifold or port back into the cylinder [7, 8]. Externally cooled EGR is typically more efficient than internally uncooled EGR in terms of reducing emissions and improving fuel economy [9]. However, the cooling system must be able to manage the heat dissipation in the external EGR system. The percentage of EGR is commonly calculated for the percentage at the exhaust manifold and is given by the following formula:

$$EGR\ (\%) = \frac{\%\ of\, CO_{2\ INTAKE}}{\%\ of\, CO_{2\ EXHAUST}} \times 100 \qquad (1)$$

The external EGR system can be classified into three types: high-pressure loop (HPL), low-pressure loop (LPL), and hybrid EGR (also known as dual-loop EGR, which combines HPL and LPL).

2.1 High-pressure loop

The term "classic" EGR architecture is used to describe high-pressure EGR in contrast to a low-pressure EGR system [10]. This design is highly prevalent and has been extensively utilised on diesel engines for many years. In a high pressure EGR system, the exhaust gas is extracted prior to the turbine and then reintroduced into the intake manifold after the compressor, as seen in Figure 1 [11]. This occurs within the high-pressure regions in both the exhaust and intake manifolds, which helps in reducing NO_x emissions.

2.2 Low-pressure loop

In a low-pressure EGR system, the gas is extracted from the exhaust after the turbine and then reintroduced into the intake manifold before the compressor as seen in Figure 1. This occurs in the low pressure areas of both the exhaust and intake manifolds, thus helping to reduce emissions and improve fuel efficiency [10, 11].

2.3 Hybrid (Combined)

This type combines high-pressure and low-pressure EGR systems (Figure 1) to optimize performance and emissions control. It offers the advantage of integrating the benefits of both low and high-pressure EGR systems, allowing for effortless transitioning between them based on the engine's operating conditions, such as speed and torque [9, 10, 12]. The hybrid EGR enables the turbocharger to function with optimal efficiency regardless of the diesel engine's operating conditions.

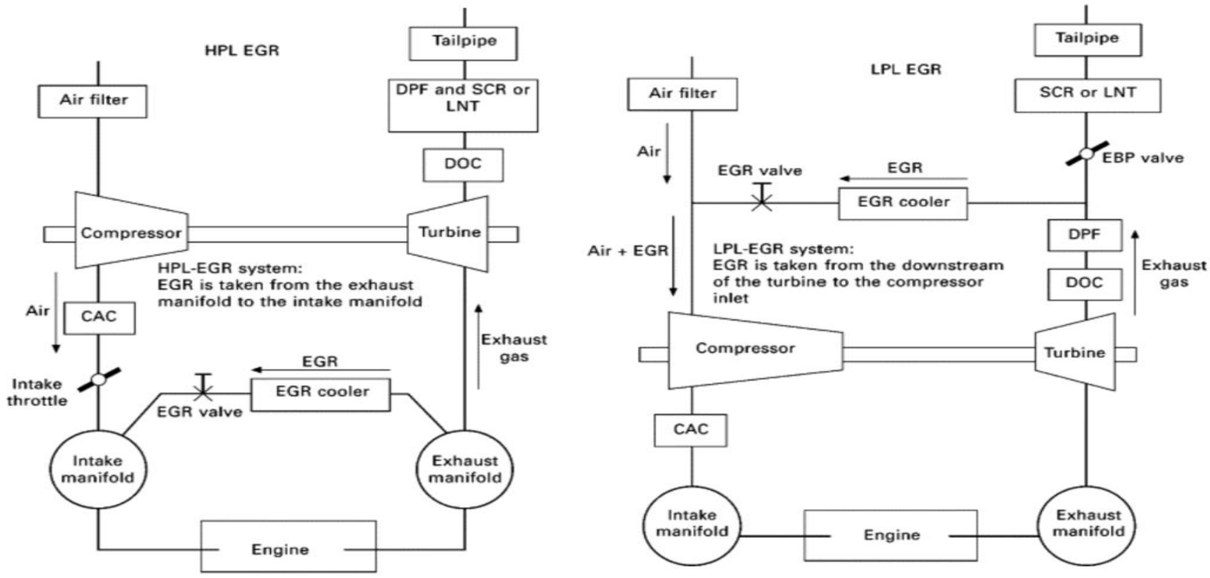

Figure 1: High-pressure (left) and low-pressure (right) EGR system mechanisms [11].

3 Effects on the performance parameters

3.1 Brake specific fuel consumption (BSFC)

Due to the more demanding pollution regulations for diesel engines, a higher rate of EGR is employed to decrease the levels of NO_x. Nevertheless, numerous studies have shown that an increased EGR rate negatively impacts BSFC. Hence, selecting an appropriate EGR pattern is crucial for achieving a balance between NO_x and BSFC. Seelam et al. [13] made a contribution where they demonstrated the BSFC variance at 75% engine load with EGR (Figure 2). They confirmed that the use of EGR has a detrimental impact on the BSFC. However, their study showed that an increase in the composition of EGR leads to an improvement in the BSFC. The combustion efficiency is reduced because the EGR replaces oxygen with water and CO_2, which in turn reduces the temperature inside the cylinder.

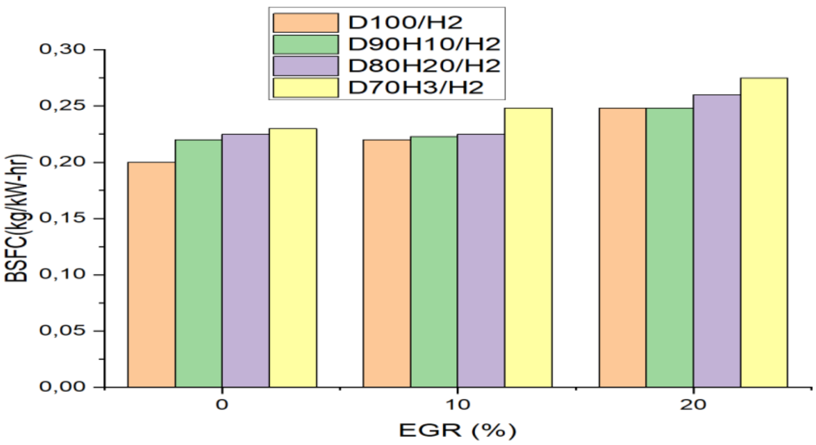

Figure 2: BSFC variation for different fuel blends at different EGR ratios.

Recent studies have suggested that the fuel blends used can also influence the correlation between EGR and BSFC [14, 15]. For instance, Venu, Subramani, and Raju [16] studied the effect of EGR rate on performance parameters, including BSFC, when using 30% palm biodiesel +70% diesel fuel (PB) and 30% palm biodiesel +70% diesel fuel +25 ppm TiO_2 (PBN). Based on Figure 3, it is observed that with increasing percentages of EGR in PB, there is an improvement in BSFC or reduction in thermal efficiency, which could be attributed to oxygen deficiency, followed by a higher level of air replacement by exhaust gases [16]. However, it is further observed that the engine load also plays a vital role in the increment of BSFC.

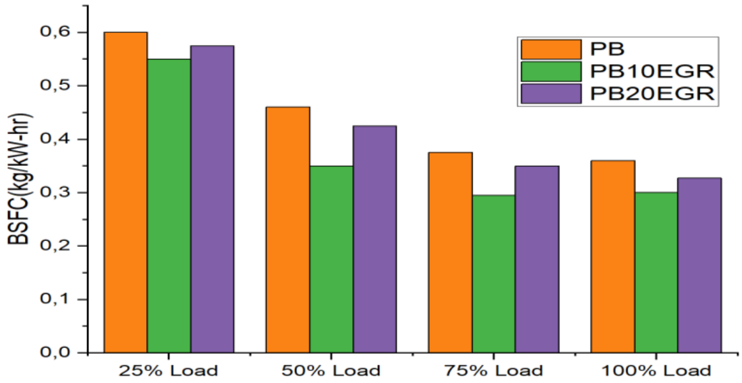

Figure 3: Variation of BSFC for engine load for PB-EGR.

These aforementioned studies are evidence that researchers have been exploring the impact of EGR on BSFC in diesel engines, focusing on the effects of varying EGR rates on BSFC. Nonetheless, a gap exists, as few studies have addressed the interaction of injection timing with EGR. Thus, studying the influence of combustion chamber design on BSFC under EGR conditions, examining the correlation between EGR and different fuel properties, and analyzing the trade-off between emission levels and BSFC optimization are all valuable avenues for further studies. These comprehensive studies would provide a more thorough understanding of how EGR affects BSFC in diesel engines and could contribute to enhancing engine efficiency and performance.

3.2 Brake mean effective pressure (BMEP)

Generally, BMEP is a measure of the average pressure exerted on the piston during the power stroke. It provides insights into the engine's performance capabilities. Several studies have demonstrated that the correlation between BMEP and EGR is often influenced by various factors, including EGR rates, engine operating conditions, and combustion strategies [17, 18]. Other scholars have suggested that employing modest rates of EGR might decrease the highest temperatures experienced during combustion, decrease the amount of NOx emissions, and potentially enhance thermal efficiency [19, 20]. Nevertheless, excessive amounts of EGR might result in combustion instability and decreased BMEP due to dilution effects. When EGR is introduced to the combustion process, it has an impact on the composition of the air-fuel mixture, the characteristics of combustion, and ultimately, the performance of the engine. Consequently, Sun et al. [21] demonstrated that the EGR effect on the engine at BMEP of 0.8 MPa is stronger than that at 0.4 MPa BMEP because the combustion is more sensitive to the oxygen content at a higher load.

Similarly, Mossa et al. [22] reported that BMEP decreases as the EGR rate increases. This suggests that the engine has less work to produce whenever the BMEP decreases. The decrease of BMEP due to an increase in EGR has been an ongoing challenge for researchers. Thus, Yu et al. [23] investigated the improvement afforded by the addition of hydrogen and the introduction of EGR for the original engine combustion and power. The combustion characteristics were examined at the conditions of excess air ratio $(\lambda) = 1.2$ and 1.4. They concluded that the addition of hydrogen and the introduction of EGR can increase the BMEP. At $\lambda = 1.2$, as the hydrogen energy fraction ($\alpha H2$) increases from 0% to 25%, the maximum BMEP value at each $\alpha H2$ condition increases by 9%, 12.70%, 16.50%, 11.30%, and 8.20%, respectively, compared with the value without EGR. The EGR rate that corresponds to the maximum BMEP value increases with increases in the $\alpha H2$.

Zhao et al. [24] conducted a comparable investigation wherein they compared the BMEP and EGR ratios for various ethanol direct injection ratio (EDIr) and excess air ratio (λ) values ranging from 0.9 to 1.2. It was noted that the BMEP exhibits its minimum overall value at λ = 1.2. This is since λ increases, both the total quantity of fuel and the heat discharge diminish. Simultaneously, the mixture thins, the velocity of flame propagation diminishes, and the constant volume combustion decreases; these factors contribute to a reduction in power capacity and BMEP. Thus, the authors concluded that 12%EGR+30%EDIr can effectively improve the BMEP and compensate for the loss of BMEP caused by the lean-burn condition. Other researchers have previously reported similar findings [22, 25, 26]. These studies are evidence that the effect of EGR on BMEP has a non-linear relationship and is strongly dependent on factors such as hydrogen, λ, EGR ratio, and fuel blend used. Studying the interaction between EGR and intake boost pressure to assess their combined effect on BMEP can provide insight into engine performance under varying operating conditions. Additionally, investigating the thermal effects of EGR on combustion characteristics and their subsequent impact on BMEP, as well as examining the potential interchange between emission reduction and BMEP optimization, are also crucial aspects to consider in further studies.

3.3 Brake thermal efficiency (BTE)

EGR can lower the oxygen concentration in the combustion chamber, potentially leading to incomplete combustion and higher particulate matter emissions [27]. This trade-off between NO_x reduced and increased particulate matter can impact the overall efficiency and emissions characteristics of a diesel engine. However, recent studies have suggested that engine calibration and control strategies play a crucial role in optimizing the EGR rate to achieve the best balance between emissions and fuel efficiency. Generally, the BTE of the engine decreases with an increase in EGR rates [28, 29]. This is because EGR displaces much of the necessary air for combustion, hence leading to a decrease in thermal efficiency.

Lou et al. [30] conducted a study that demonstrated that with EGR, BTE is adversely affected in the case of blended fuels. Seelam et al. [13] emphasized that the addition of EGR has a three-way effect on combustion. The exhaust gas increases the specific heat capacity (SHC) of the charge. It is composed of diluents such as CO_2 and water (H_20), removing the freshly induced oxygen component. An endothermic mechanism that worsens the combustion is the dissociation of H_20 and CO_2. All these effects have a detrimental effect on combustion, resulting in a decrease in BTE. A study by Mossa et al. [22] showed that BTE is also dependent on the engine speed. Figure 4, depicts their results, where it is shown that BTE is reduced when EGR is used. Additionally, the cylinder pressure reduces with increased EGR rates, hence affecting engine efficiency as a whole. Other scholars have observed that 30% EGR addition significantly reduces the BTE by 8 and 18% for conventional diesel and WCME100 fuelled engines, respectively. These studies are evidence that researchers have looked at the effects of varying EGR rates on BTE, and the impact of different engine operating conditions on this relationship. However, future studies could further explore advanced engine control strategies to enhance both BTE and EGR effectiveness.

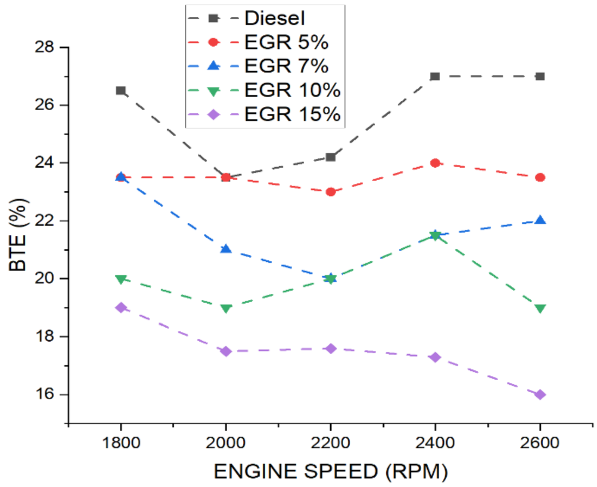

Figure 4: BTE at different engine speeds fuelled with diesel fuel with and without EGR.

3.4 Exhaust gas temperature (EGT)

Researchers often investigate how varying EGR rates influence EGT levels in diesel engines under different operating conditions. Understanding this correlation is crucial for optimizing engine performance, emissions control, and thermal management strategies. Most of the studies suggest that the EGT increases with an increase in engine loads for all operating modes. This is due to the increase in total energy input at high load following higher fuel consumption. Other scholars have demonstrated that an increase in the percentage of EGR results in a decrease in EGT.

A study by Mohd et al. [31] focused on the effects of the EGR technique and palm oil on the BSFC, performance, and emission levels. The experimental work used a multi-cylinder diesel engine at a constant engine speed of 2500 rpm under full load. The result showed that when using EGR, the NO_x emission level decreases along with the EGT but increases in BSFC and other emission levels. Additionally, Kuropyatnyk and Sagin [32] showed that the EGT of the diesel engine is decreased when the EGR system is used, while they observed the highest EGT when EGR was not used, which is in agreement with the study by Prakash, Prabhahar, and Kumar [33] demonstrating that when using EGR, the EGT was higher with biodiesel than normal diesel. According to Wei et al. [34], an engine equipped with hot EGR can utilise the high temperature of the exhaust gas to warm up the intake charge, resulting in enhanced combustion and fuel conversion efficiency. On the other hand, cooled EGR enhances the density of the intake, hence enhancing the volumetric efficiency of the engine. Few studies have addressed the interaction between EGR and turbocharger performance. This research work can provide insights into how boosting pressure levels affects EGT when EGR is introduced.

4 Emission characteristics

EGR is widely recognised as a highly effective technology for reducing NO_x emissions. However, it does have several disadvantages, including an increase in HC, CO, and smoke levels. Additionally, it leads to a rise in fuel consumption, resulting in a decrease in thermal efficiency [35, 36]. Nevertheless, this issue can be resolved by optimising the proportion of EGR supply. Some scholars have noticed that a 15% EGR rate is found to be effective in reducing NO_x emissions substantially without deteriorating engine performance in terms of thermal efficiency, SFC, and emissions [29, 37, 38]. This is evidence that EGR can be applied to diesel engine without sacrificing its efficiency or fuel economy, and NO_x reductions can thus be achieved. On the other hand, several researchers have focused on the influence of fuel blends on emission characteristics using the EGR technique [32, 39, 40]. Some of the results are summarised in Table 1 below.

Table 1: Emissions analysis on biodiesel-fueled engines with EGR technique [39].

Fuel used	Engine used	EGR rate and Load condition	Emission results	References
KB40	2C, DI, Diesel engine	15% EGR, 80% load	NO_x↓25.75%, HC↑17.5%, CO↑11.11%, Smoke ↑16.92%	(Pandian, Sivapirakasam, and Udayakumar, 2010)
JME20	4C, WC, IDI, Diesel engine	10% EGR	NO_x↓36%, Smoke↓31%	(Gomaa, Alimin, and Kamarudin, 2011)

RB100	1C, AC, DI, Diesel engine	20%EGR, IMEP = 6.1 bar	NO_x↓ 51.76%, HC↑15%, CO↑%, Smoke↑51.9%	(Tsolakis et al., 2007)
SOME20	2C, IDI, WC, Diesel engine.	15% EGR rate	NO_x↓ 25%, HC↓5%, CO↓10%, Smoke↑%	(Rajan and Senthilkumar ,2009)
SB100	4C, 16 valve Mercedes	27% EGR, Load = 68 Nm	NO_x↓87.7%, CO↑↑%, Smoke↑↑%	(Kassetal., 2009)
SME100	4C, 16 valve Mercedes	27% EGR, Load = 68 N/m	NO_x↓86%, CO↑%, CO2↑5.5%, PM↑%	(Kass et al., 2009)
JOB100	2C, 4S, WC, DI, Diesel engine,	12% EGR. 100% load	NO_x↓36%, HC↑%, CO↑%	(Saleh, 2009)
JB100	1C, 4S, DI, WC, Diesel engine	15%EGR (Hot), 100% load.	NO_x↓74.8%, HC↑%, CO↑%, Smoke↑%	(Pradeep and Sharma, 2007)
SB20	1C, 4S, DI, Diesel engine, CS,	15% EGR rate	NO_x↓55%, HC↑%, Smoke↑15%	(Can et al., 2016)
Diesel + H2	1C, 4S, HCCI, vertical, Diesel engine	20% EGR, 80% load	NO_x↓41.4%, HC↓12.3%, CO_2↓29.1%, Smoke↓8.3%	(Bose and Maji, 2009)

4.1 Nitrogen oxides (NO_x)

NO_x are the most significant pollutants produced by diesel engines, regardless of its kind, class, size, or design characteristics, in all operating conditions [41]. The NO_x in overall emissions make up 30 to 80% of the total weight and 60 to 95% of the comparable toxicity. NO_x, aerosols and chlororganic chemicals emitted into the atmosphere contribute to the depletion of the ozone layer, which is located at a height of 25 km and absorbs 99% of solar and Ultraviolet (UV) radiation [42, 43]. Researchers have proven that the use of fuel additives in biodiesel can reduce NO_x emissions [41, 44]. However, recent reports have suggested that EGR is the most appropriate and effective method for reducing the NO_x emissions from diesel engines [45, 46]. This technology contributes to ensuring compliance with international environmental protection requirements.

Several studies have proven that EGR is an effective method to reduce NO_x. For example, de Oliveira, Bernardes, and Ferreira [47] experimentally proved that utilising the EGR system will result in a reduction of NO_x emissions by 37.9 to 53.5%, which is contingent upon the engine's operating mode and the extent of EGR implementation. Tang et al. [48] examined the impact of high-pressure (HP) and donor-cylinder (DC) EGR on the fuel efficiency and emissions of marine diesel engines. Their findings indicate that as the load decreases, the NO_x emissions of HP-EGR and DC-EGR increase progressively. HP-EGR has greater levels of NO_x emissions at low and medium loads. When operating at a load of 25%, the NO_x emissions of the HP-EGR system are 3.46 g/kWh greater than those of the DC-EGR system. The greatest attainable EGR has a significant impact on NO_x

emissions. Similarly, Nag et al. [49] and Sharma et al. [50] found that a small decrease in NO_x levels were observed under lower loading limits of the engine.

In 2022, Lou et al. [51] demonstrated that as the diesel engine load drops, the maximum attainable EGR of HP-EGR and DC-EGR rapidly reduces. Saravanan et al. [52] experimentally proved that increasing the EGR level leads to a decrease in NO_x emissions under all engine load conditions. The use of EGR reduces emissions in diesel engines by lowering the oxygen concentration and flame temperatures in the combustible mixture [53]. Furthermore, other studies have shown that the EGR of the HP-EGR system is more responsive to changes in load, and its EGR level lowers more rapidly compared to the DC-EGR system. Most similar studies have suggested that the ideal level of EGR should fall between the approximate range of 5 to 15%, depending on the specific design and operational characteristics of a diesel engine, and this value must be found by experimental methods [52, 54, 55].

4.2 Carbon dioxide ($C0_2$) and carbon monoxide (CO)

Generally, EGR technology has a significant impact on exhaust gaseous emissions, inducing a significant reduction in NO_x and an increase in unburned hydrocarbons (UHC) and CO, which can affect the operation of the after treatment system [56]. Hoang and Pham [57] conducted a study on a solution to reduce emissions by using hydrogen as an alternative fuel for a diesel engine with integrated EGR. In their study, they compared the relationship between the volume concentration of CO and brake power at different values of enriched hydrogen with non-EGR cases, with 10% EGR, 20% EGR, and pure diesel fuel. The experimental results in Figure 5 show that CO emissions tend to decrease as the concentration of hydrogen fuel increases because the burning of hydrogen does not produce CO_2.

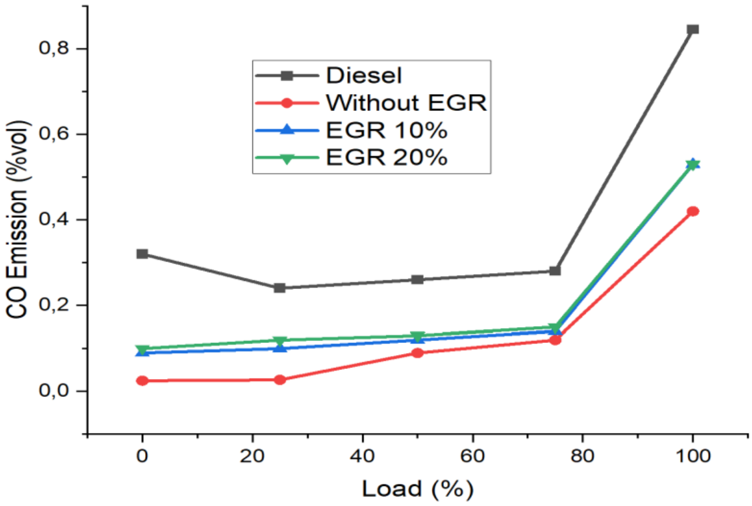

Figure 5: Different CO concentrations with power engines at various EGR levels.

De Serio, de Oliveira, and Sodré [58] examined the impact of the EGR rate on the efficiency and emissions of a diesel power generator running on B7 fuel. They noted that the emissions of CO_2, CO, and THC increase when EGR is used. The CO_2 trend shown in Figure 6 can be attributed to the fact that the fresh intake air has very small amounts of CO_2, whereas the EGR fraction has a significant amount of CO_2. This amount increases with a higher EGR flow rate and engine load [59]. Likhanov, Lopatin, and Yurlov [60] noted that when the diesel engine is running on natural gas with EGT, the content of CO_2 in the exhaust gases decreases by 43.2%, soot (C) by 5.6 times, CO_2 by 33.3%, and CO by 10.0%. This proves that further studies should look at using natural gas when aiming to improve the environmental performance of a diesel engine. Conversely, Nanthagopal et al. [61] observed that a 30% EGR rate substantially increases the CO and HC emissions for waste cooking oil methyl ester (WCME100) and conventional diesel fuels at maximum BMEP. Therefore, analyzing the impact of EGR on overall engine performance and fuel consumption to assess its indirect effects on CO_2 emissions could be crucial for further research. Additionally, investigating the optimal EGR strategies to concurrently minimize CO_2 and CO emissions without compromising engine efficiency is also essential.

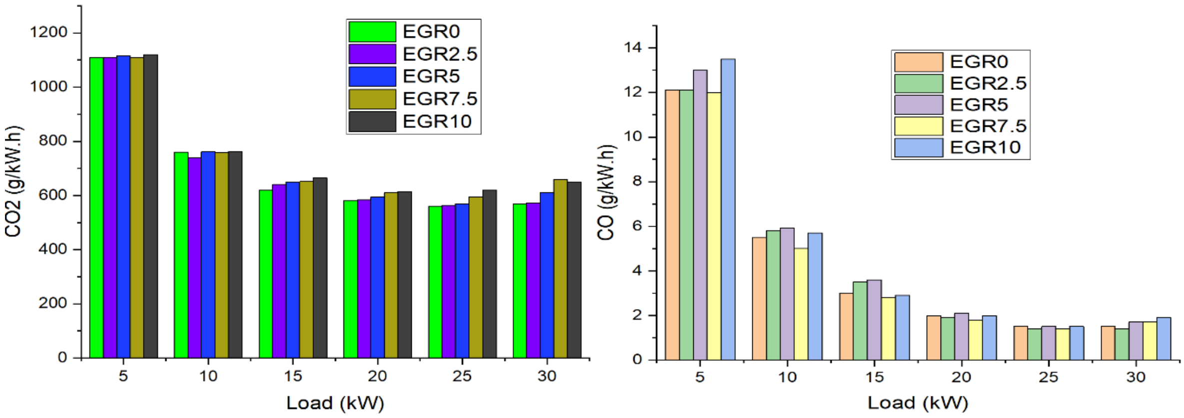

Figure 6: Variation of CO_2 (left) and CO (right) emissions with EGR rate and load.

4.3 Total hydrocarbon (THC)

Many studies have reported that the EGR rate in diesel engines can have an impact on various emissions, including THC [60, 62, 53]. Generally, an increase in EGR rate can lead to a decrease in combustion efficiency, potentially resulting in incomplete combustion and increased THC emissions. This is emphasized by several scholars, who have reported that the use of EGR commonly increases in CO_2, CO and THC emissions [64, 65]. However, the rate of increase depends on the load and EGR rate. Likewise, Ramesh et al. [66] compared the variants of hydrocarbon emissions under the influence of carbonate additives (DMC) and EGR with varying BMEPs of the test engine. They observed an increase in HC emissions with increasing engine BMEP and EGR in test mixes.

In contrast, Hussain et al. [67] studied the effect of EGR on the performance and emission of a compression ignition (CI) engine with staged combustion (insertion of UHC). They reported that HC and CO emissions increase with increasing EGR. Lower excess oxygen concentrations result in rich air-fuel mixtures at different locations inside the combustion chamber. This heterogeneous mixture does not combust completely and results in higher HC and CO emissions. This study was validated by Wang et al. [68] when they reported that EGR increases CO and HC emissions due to incomplete combustion and reduces the exhaust temperature in advance. Additionally, Abed et al. [69] stated that the increased percentage of palm biodiesel in the blends increases NOx emissions and decreases CO and HC emissions.

The optimum EGR rate for reducing THC emissions while maintaining good combustion efficiency can vary depending on the engine design, operating conditions, and emission control strategies employed. Researchers have been interested in testing and optimizing the EGR rate under different operating conditions, which can help achieve the best balance between emissions control and engine performance. Further studies should consider the overall engine system and emission control technologies when adjusting the EGR rate to achieve the desired balance between reducing NO_x and THC emissions.

4.4 Smoke opacity

In general, the presence of smoke in the exhaust of a diesel engine is a clear indication of an incomplete combustion process occurring during engine operation. Fayad [70] stated that increasing the EGR level results in an increase in smoke opacity emissions for all load conditions. This may be because the implementation of EGR reduces the availability of oxygen for the combustion of fuel, which results in relatively incomplete combustion and increased formation of particulate matter. Venu, Subramani, and Raju [71] concluded that the novel approach of the combined effect of nanoparticle blended palm biodiesel with EGR can lower all the major regulated emissions (HC, CO, and NO_x) simultaneously until part loads and reduce smoke throughout the engine load towards a sustainable green environment. Wu et al. [72] conducted a novelty study with the EGR system, aiming to reduce CO_2 exhaust. The injection timing was observed to advance by 33% of the decreased smoke density and increased NO_x emission level by 20%. The EGR result decreased by 63% with the NO_x emission level with the increase in smoke.

Nanthagopal et al. [61] were interested in the comparison of smoke absorption for diesel and 100% WCME100 fuel operations with and without EGR addition. They noted that the higher the BMEP, the higher the engine smoke absorption for all the tested fuels (Figure 7). Moreover, it was found that the introduction of 30% EGR shifted the curves above as compared to a fresh air charge mixture. These results are in agreement with the suggestion of many researchers that the WCME100-fuelled diesel engine emits low smoke emissions compared to conventional diesel fuel under all BMEPs. On the other hand, Rajasekar et al. [73] investigated the variation of smoke with EGR rate when the diesel engine is at 900 and 1500 r.p.m. conditions, where the load is 25%, 50%, and 75%. They observed that the diesel engine emits minimal variation in smoke under low-load conditions. As the load and EGR rate increase, the output of smoke also increases. Under the same speed setting, the high-smoke area of the diesel engine was shifted to the high-load and high EGR rate area. Other scholars, such as Syarifudin, Syaiful, and Yohana [74] and Reddy et al. [75], stated that EGR rates of 0% to 20% and addiction to DMC represent the proportionate amount of smoke drops with the rise in engine BMEP.

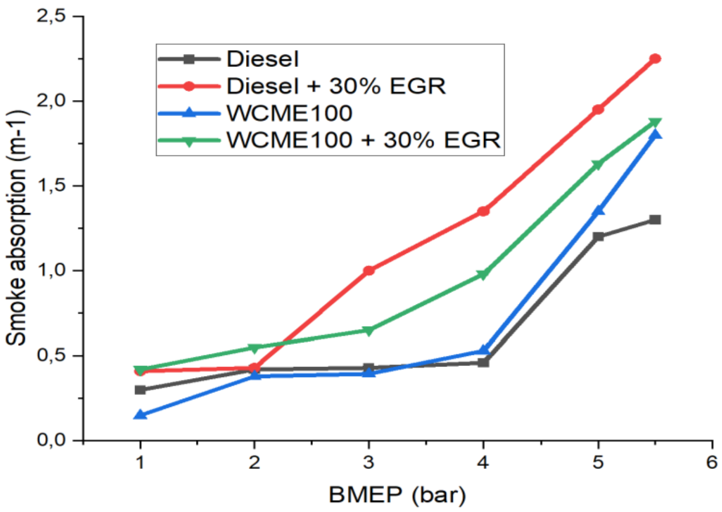

Figure 7: Comparison of smoke opacity with BMEP at 30% EGR.

5 Conclusion

This review paper examined the impact of EGR on performance parameters and emission characteristics of diesel engines. It has provided useful knowledge on the complex relationship between EGR and engine efficiency. It primarily focused on parameters such as BSFC, BMEP, and BTE and emission characteristics such as NO_x, O_2, CO, THC and smoke opacity. The main aim was to investigate the effect of EGR on all these aforementioned parameters and how this affects the performance of a diesel engine. According to the reviewed literature, EGR is thus the most effective method to reduce NO_x emissions, as it introduces a controlled portion of the exhaust gas back into the engine cylinders along with the intake air. While EGR effectively reduces NOx emissions, other studies have shown that there are some potential drawbacks to its use. Introducing exhaust gas can lower the oxygen concentration in the cylinder, potentially leading to incomplete combustion, increased particulate matter emissions, and reduced engine efficiency.

Existing studies have certainly focused on the immediate impact of EGR on fuel consumption, NO_x emissions, and other key parameters. However, there is a lack of research focusing on the durability and reliability aspects over extended periods of operation. In contrast, it is an ongoing challenge to balance the benefits of EGR technology with potential trade-offs in power output and smoke opacity to optimize engine performance. Having said that, researchers are required to find out the optimum value of the EGR rate without affecting the engine's performance.

References

[1] A. C. T. Malaquias, N. A. D. Netto, R. B. R. da Costa, and J. G. C. Baêta, "Combined effects of internal exhaust gas recirculation and tumble motion generation in a flex-fuel direct injection engine," *Energy Conversion and Management*, vol. 217, p. 113007, Aug. 2020, doi: https://doi.org/10.1016/j.enconman.2020.113007.

[2] L. Zhao, W. Qi, X. Wang, and X. Su, "Potentials of EGR and lean mixture for improving fuel consumption and reducing the emissions of high-proportion butanol-gasoline engines at light load," *Fuel*, vol. 266, pp. 116959–116959, Apr. 2020, doi: https://doi.org/10.1016/j.fuel.2019.116959.

[3] J. Cho, S. Park, and S. Song, "The effects of the air-fuel ratio on a stationary diesel engine under dual-fuel conditions and multi-objective optimization," *Energy*, vol. 187, p. 115884, Nov. 2019, doi: https://doi.org/10.1016/j.energy.2019.115884.

[4] A. P. Nigam and S. Sinha, "Techniques to control IC engine exhaust emissions through modification in fuel and intake air – a review," *International Journal of Ambient Energy*, pp. 1–13, Oct. 2020, doi: https://doi.org/10.1080/01430750.2020.1831591.

[5] B. Shi, J. Hu, H. Peng, and S. Ishizuka, "Effects of internal flue gas recirculation rate on the NO emission in a methane/air premixed flame," *Combustion and Flame*, vol. 188, pp. 199–211, Feb. 2018, doi: https://doi.org/10.1016/j.combustflame.2017.09.043.

[6] R. Y. Dahham, H. Wei, and J. Pan, "Improving Thermal Efficiency of Internal Combustion Engines: Recent Progress and Remaining Challenges," *Energies*, vol. 15, no. 17, p. 6222, Aug. 2022, doi: https://doi.org/10.3390/en15176222.

[7] Y. H. Teoh *et al.*, "A review on production and implementation of hydrogen as a green fuel in internal combustion engines," *Fuel*, vol. 333, p. 126525, Feb. 2023, doi: https://doi.org/10.1016/j.fuel.2022.126525.

[8] Y. Luo, B. Maldonado, S. Liu, C. Solbrig, D. Adair, and A. Stefanopoulou, "Portable In-Cylinder Pressure Measurement and Signal Processing System for Real-Time Combustion Analysis and Engine Control," *SAE International Journal of Advances and Current Practices in Mobility*, vol. 2, no. 6, pp. 3432–3441, Apr. 2020, doi: https://doi.org/10.4271/2020-01-1144.

[9] A. Reihani, J. Hoard, S. Klinkert, C.-K. Kuan, D. Styles, and G. McConville, "Experimental response surface study of the effects of low-pressure exhaust gas recirculation mixing on turbocharger compressor performance," *Applied Energy*, vol. 261, p. 114349, Mar. 2020, doi: https://doi.org/10.1016/j.apenergy.2019.114349.

[10] T. Kar, T. Fosudo, A. Marchese, B. Windom, and D. Olsen, "Effect of fuel composition and EGR on spark-ignited engine combustion with LPG fueling: Experimental and numerical investigation," *Fuel*, vol. 327, p. 125221, Nov. 2022, doi: https://doi.org/10.1016/j.fuel.2022.125221.

[11] H. Huang, Q. Wang, C. Shi, Q. Liu, and C. Zhou, "Comparative study of effects of pilot injection and fuel properties on low temperature combustion in diesel engine under a medium EGR rate," *Applied Energy*, vol. 179, pp. 1194–1208, Oct. 2016, doi: https://doi.org/10.1016/j.apenergy.2016.07.093.

[12] N. Shrivastava, S. N. Varma, and M. Pandey, "Experimental investigation of diesel engine using EGR and fuelled with Karanja oil methyl ester," *International Journal of Sustainable Engineering*, vol. 6, no. 4, pp. 307–315, Dec. 2013, doi: https://doi.org/10.1080/19397038.2012.749310.

[13] N. Seelam, S. K. Gugulothu, R. V. Reddy, and B. Burra, "Influence of hexanol/hydrogen additives with diesel fuel from CRDI diesel engine with exhaust gas recirculation technique: A special focus on performance, combustion, gaseous and emission species," *Journal of Cleaner Production*, vol. 340, p. 130854, Mar. 2022, doi: https://doi.org/10.1016/j.jclepro.2022.130854.

[14] Y. Wang, P. Ge, T. Liu, C. Gong, and D. Dong, "Quantitative Analysis of the Influence Saliency of VVA and EGR on the Fuel Economy and Mixture Combustion Characteristics of a Turbocharged Spark Ignition Engine," *ACS Omega*, vol. 6, no. 46, pp. 31017–31025, Nov. 2021, doi: https://doi.org/10.1021/acsomega.1c03962.

[15] S. K. M. Shanmugam, S. Muthusamy, R. K. Ramasamy, and A. Alagumalai, "Towards improved performance and lower exhaust emissions using exhaust gas recirculation coupled compression ignition

engine fuelled with nanofuel blends," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–17, Feb. 2022, doi: https://doi.org/10.1080/15567036.2022.2038734.

[16] H. Venu, L. Subramani, and V. D. Raju, "Emission reduction in a DI diesel engine using exhaust gas recirculation (EGR) of palm biodiesel blended with TiO2 nano additives," *Renewable Energy*, vol. 140, pp. 245–263, Sep. 2019, doi: https://doi.org/10.1016/j.renene.2019.03.078.

[17] J. Szybist, "Knock Mitigation Effectiveness of EGR across the Pressure-Temperature Domain," *SAE International Journal of Advances and Current Practices in Mobility*, vol. 3, no. 1, pp. 262–275, Sep. 2020, doi: https://doi.org/10.4271/2020-01-2053.

[18] Chandrakumar Pardhi, R. Prasad, C.P. Jawahar, Sanjay Chhalotre, and Z. Said, "Review on performance and emission of spark ignition engine using exhaust gas recirculation," *Energy Sources, Part A: Recovery, Utilization, And Environmental Effects*, vol. 45, no. 2, pp. 3692–3707, Apr. 2023, doi: https://doi.org/10.1080/15567036.2023.2196947.

[19] H. Huang, J. Tian, J. Li, and D. Tan, "Effects of Different Exhaust Gas Recirculation (EGR) Rates on Combustion and Emission Characteristics of Biodiesel–Diesel Blended Fuel Based on an Improved Chemical Mechanism," *Energies*, vol. 15, no. 11, p. 4153, Jun. 2022, doi: https://doi.org/10.3390/en15114153.

[20] S. Thangaraj and N. Govindan, "Investigating the pros and cons of browns gas and varying EGR on combustion, performance, and emission characteristics of diesel engine," *Environmental Science and Pollution Research International*, vol. 25, no. 1, pp. 422–435, Jan. 2018, doi: https://doi.org/10.1007/s11356-017-0369-4.

[21] C. Sun *et al.*, "Experimental study of effects of exhaust gas recirculation on combustion, performance, and emissions of DME-biodiesel fueled engine," *Energy*, vol. 197, pp. 117233–117233, Apr. 2020, doi: https://doi.org/10.1016/j.energy.2020.117233.

[22] A. Mossa, Abdul Aziz Hairuddin, Faieza Abdul Aziz, J. Zulkiple, and H. M. Tobib, "Effects of Hot Exhaust Gas Recirculation (EGR) on the Emission and Performance of a Single-Cylinder Diesel Engine," *International Journal of Automotive and Mechanical Engineering*, vol. 16, no. 2, pp. 6660–6674, Jul. 2019, doi: https://doi.org/10.15282/ijame.16.2.2019.14.0501.

[23] X. Yu *et al.*, "Experimental study on the effects of EGR on combustion and emission of an SI engine with gasoline port injection plus ethanol direct injection," *Fuel*, vol. 305, p. 121421, Dec. 2021, doi: https://doi.org/10.1016/j.fuel.2021.121421.

[24] Z. Zhao *et al.*, "Experimental study on combustion and emission of an SI engine with ethanol /gasoline combined injection and EGR," *Journal of Cleaner Production*, vol. 331, p. 129903, Jan. 2022, doi: https://doi.org/10.1016/j.jclepro.2021.129903.

[25] S. Victorovych Sagin and O. Andriiovych Kuropyatnyk, "The Use of Exhaust Gas Recirculation for Ensuring the Environmental Performance of Marine Diesel Engines," *Naše more*, vol. 65, no. 2, pp. 78–86, Jun. 2018, doi: https://doi.org/10.17818/nm/2018/2.3.

[26] A. Dubey, N. Ahmad Ansari, G. Kumar, A. Arora, and A. Sharma, "A Review on Performance and Emission of CI Engine using Exhaust gas recirculation (EGR)," *IOP Conference Series: Materials Science and Engineering*, vol. 691, no. 1, p. 012028, Nov. 2019, doi: https://doi.org/10.1088/1757-899x/691/1/012028.

[27] Medhat Elkelawy, E.A. El Shenawy, S. A. Mohamed, M. M. Elarabi, and Hagar Alm-Eldin Bastawissi, "Impacts of using EGR and different DI-fuels on RCCI engine emissions, performance, and combustion characteristics," *Energy Conversion and Management: X*, vol. 15, pp. 100236–100236, Aug. 2022, doi: https://doi.org/10.1016/j.ecmx.2022.100236.

[28] S. Park, K. Lee, and J. Park, "Parametric Study on EGR Cooler Fouling Mechanism Using Model Gas and Light-Duty Diesel Engine Exhaust Gas," *Energies*, vol. 11, no. 11, p. 3161, Nov. 2018, doi: https://doi.org/10.3390/en11113161.

[29] C. D. Rakopoulos, D. C. Rakopoulos, G. C. Mavropoulos, and G. M. Kosmadakis, "Investigating the EGR rate and temperature impact on diesel engine combustion and emissions under various injection timings and loads by comprehensive two-zone modeling," *Energy*, vol. 157, pp. 990–1014, Aug. 2018, doi: https://doi.org/10.1016/j.energy.2018.05.178.

[30] D. Lou, Y. Ren, Y. Zhang, and X. Sun, "Study on the Effects of EGR and Spark Timing on the Combustion, Performance, and Emissions of a Stoichiometric Natural Gas Engine," *ACS Omega*, vol. 5, no. 41, pp. 26763–26775, Oct. 2020, doi: https://doi.org/10.1021/acsomega.0c03859.

[31] M. H. M. Yasin *et al.*, "Study of a Diesel Engine Performance with Exhaust Gas Recirculation (EGR) System Fuelled with Palm Biodiesel," *Energy Procedia*, vol. 110, pp. 26–31, Mar. 2017, doi: https://doi.org/10.1016/j.egypro.2017.03.100.

[32] O. A. Kuropyatnyk and S. V. Sagin, "Exhaust Gas Recirculation as a Major Technique Designed to Reduce NOx Emissions from Marine Diesel Engines," *Naše more*, vol. 66, no. 1, pp. 1–9, Feb. 2019, doi: https://doi.org/10.17818/nm/2019/1.1.

[33] S. Prakash, M. Prabhahar, and M. Kumar, "Experimental analysis of diesel engine behaviours using biodiesel with different exhaust gas recirculation rates," *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 1508–1517, Jan. 2020, doi: https://doi.org/10.1080/01430750.2020.1712251.

[34] H. Wei, T. Zhu, G. Shu, L. Tan, and Y. Wang, "Gasoline engine exhaust gas recirculation – A review," *Applied Energy*, vol. 99, pp. 534–544, Nov. 2012, doi: https://doi.org/10.1016/j.apenergy.2012.05.011.

[35] X. Yin *et al.*, "Experimental analysis of the EGR rate and temperature impact on combustion and emissions characteristics in a heavy-duty NG engine," *Fuel*, vol. 310, p. 122394, Feb. 2022, doi: https://doi.org/10.1016/j.fuel.2021.122394.

[36] S. K. Pathak, A. Nayyar, and V. Goel, "Optimization of EGR effects on performance and emission parameters of a dual fuel (Diesel + CNG) CI engine: An experimental investigation," *Fuel*, vol. 291, p. 120183, May 2021, doi: https://doi.org/10.1016/j.fuel.2021.120183.

[37] K. Santhosh, G. N. Kumar, Radheshyam, and P. V. Sanjay, "Experimental analysis of performance and emission characteristics of CRDI diesel engine fueled with 1-pentanol/diesel blends with EGR technique," *Fuel*, vol. 267, p. 117187, May 2020, doi: https://doi.org/10.1016/j.fuel.2020.117187.

[38] M. Kumar, Varun Kumar Singh, A. Sharma, Naushad Ahmad Ansari, R. Gautam, and Y. Singh, "Effect of fuel injection pressure and EGR techniques on various engine performance and emission characteristics on a CRDI diesel engine when run with linseed oil methyl ester," *Energy & Environment*, vol. 33, no. 1, pp. 41–63, Jan. 2021, doi: https://doi.org/10.1177/0958305x20983477.

[39] P. Suresh Kumar, S. Joshi, N. Prasanthi Kumari, A. Sharma, S. Nair, and S. Chatterjee, "Reduction of emissions in a biodiesel-fueled compression ignition engine using exhaust gas recirculation and selective catalytic reduction techniques," *Heat Transfer*, vol. 49, no. 5, pp. 3119–3133, Apr. 2020, doi: https://doi.org/10.1002/htj.21765.

[40] T. Johnson and A. Joshi, "Review of Vehicle Engine Efficiency and Emissions," *SAE International Journal of Engines*, vol. 11, no. 6, pp. 1307–1330, Apr. 2018, doi: https://doi.org/10.4271/2018-01-0329.

[41] A. Joshi, "Review of Vehicle Engine Efficiency and Emissions," *SAE International Journal of Advances and Current Practices in Mobility*, vol. 2, no. 5, pp. 2479–2507, Apr. 2020, doi: https://doi.org/10.4271/2020-01-0352.

[42] T. Subramanian, E. G. Varuvel, S. Ganapathy, S. Vedharaj, and R. Vallinayagam, "Role of fuel additives on reduction of NOX emission from a diesel engine powered by camphor oil biofuel," *Environmental Science and Pollution Research International*, vol. 25, no. 16, pp. 15368–15377, Jun. 2018, doi: https://doi.org/10.1007/s11356-018-1745-4.

[43] Deepayan Priyadarshi, Kakoli Karar Paul, and S. Pradhan, "Impacts of Biodiesel, Fuel Additive, and Injection Pressure on Engine Emission and Performance," *Journal of Energy Engineering-asce*, vol. 145, no. 3, Jun. 2019, doi: https://doi.org/10.1061/(asce)ey.1943-7897.0000597.

[44] H. İ. Akolaş, A. Kaleli, and K. Bakirci, "Design and implementation of an autonomous EGR cooling system using deep neural network prediction to reduce NOx emission and fuel consumption of diesel engine," *Neural Computing and Applications*, vol. 33, no. 5, pp. 1655–1670, Jun. 2020, doi: https://doi.org/10.1007/s00521-020-05104-1.

[45] R. Sindhu, G. Amba Prasad Rao, and K. Madhu Murthy, "Effective reduction of NOx emissions from diesel engine using split injections," *Alexandria Engineering Journal*, vol. 57, no. 3, pp. 1379–1392, Sep. 2018, doi: https://doi.org/10.1016/j.aej.2017.06.009.

---

[46] A. J. Modi, D. C. Gosai, and C. M. Solanki, "Experimental Study of Effect of EGR Rates on NOx and Smoke Emission of LHR Diesel Engine Fueled with Blends of Diesel and Neem Biodiesel," *Journal of The Institution of Engineers (India): Series C*, vol. 99, no. 2, pp. 181–195, Oct. 2017, doi: https://doi.org/10.1007/s40032-017-0384-8.

[47] Alex de Oliveira, Alexandre Pinheiro Bernardes, and F. Ferreira, "Reduction of a diesel engine NO emissions using the exhaust gas recirculation technique," *SAE technical paper series*, Jan. 2020, doi: https://doi.org/10.4271/2019-36-0067.

[48] X. Tang, P. Wang, Z. Zhang, F. Zhang, L. Shi, and K. Deng, "Effects of high-pressure and donor-cylinder exhaust gas recirculation on fuel economy and emissions of marine diesel engines," *Fuel*, vol. 309, p. 122226, Feb. 2022, doi: https://doi.org/10.1016/j.fuel.2021.122226.

[49] S. Nag, P. Sharma, A. Gupta, and A. Dhar, "Experimental study of engine performance and emissions for hydrogen diesel dual fuel engine with exhaust gas recirculation," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 12163–12175, May 2019, doi: https://doi.org/10.1016/j.ijhydene.2019.03.120.

[50] A. Sharma, Y. Singh, N. Ahmad Ansari, A. Pal, and S. Lalhriatpuia, "Experimental investigation of the behaviour of a DI diesel engine fuelled with biodiesel/diesel blends having effect of raw biogas at different operating responses," *Fuel*, vol. 279, p. 118460, Nov. 2020, doi: https://doi.org/10.1016/j.fuel.2020.118460.

[51] D. Lou, L. Kang, Y. Zhang, L. Fang, and C. Luo, "Effect of Exhaust Gas Recirculation Combined with Selective Catalytic Reduction on NO_x Emission Characteristics and Their Matching Optimization of a Heavy-Duty Diesel Engine," *ACS Omega*, vol. 7, no. 26, pp. 22291–22302, Jun. 2022, doi: https://doi.org/10.1021/acsomega.2c01123.

[52] P. Saravanan, N. M. Kumar, M. Ettappan, R. Dhanagopal, and J. Vishnupriyan, "Effect of exhaust gas re-circulation on performance, emission and combustion characteristics of ethanol-fueled diesel engine," *Case Studies in Thermal Engineering*, p. 100643, Apr. 2020, doi: https://doi.org/10.1016/j.csite.2020.100643.

[53] P. Wang, X. Tang, L. Shi, X. Ni, Z.-L. Hu, and K. Deng, "Experimental investigation of the influences of Miller cycle combined with EGR on performance, energy and exergy characteristics of a four-stroke marine regulated two-stage turbocharged diesel engine," vol. 300, pp. 120940–120940, Sep. 2021, doi: https://doi.org/10.1016/j.fuel.2021.120940.

[54] Z. Wang, S. Zhou, Y. Feng, and Y. Zhu, "EGR modeling and fuzzy evaluation of Low-Speed Two-Stroke marine diesel engines," *Science of The Total Environment*, vol. 706, p. 135444, Mar. 2020, doi: https://doi.org/10.1016/j.scitotenv.2019.135444.

[55] X. Zu, C. Yang, H.-C. Wang, and Y. Wang, "Experimental study on diesel engine exhaust gas recirculation performance and optimum exhaust gas recirculation rate determination method," *Royal Society Open Science*, vol. 6, no. 6, p. 181907, Jun. 2019, doi: https://doi.org/10.1098/rsos.181907.

[56] S. Ravelli, "Thermodynamic Assessment of Exhaust Gas Recirculation in High-Volume Hydrogen Gas Turbines in Combined Cycle Mode," *Journal of Engineering for Gas Turbines and Power*, vol. 144, no. 11, Sep. 2022, doi: https://doi.org/10.1115/1.4055353.

[57] A. T. Hoang and V. V. Pham, "A study on a solution to reduce emissions by using hydrogen as an alternative fuel for a diesel engine integrated exhaust gas recirculation," *INTERNATIONAL CONFERENCE ON EMERGING APPLICATIONS IN MATERIAL SCIENCE AND TECHNOLOGY: ICEAMST 2020*, 2020, doi: https://doi.org/10.1063/5.0007492.

[58] D. De Serio, A. de Oliveira, and J. R. Sodré, "Effects of EGR rate on performance and emissions of a diesel power generator fueled by B7," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 39, no. 6, pp. 1919–1927, Apr. 2017, doi: https://doi.org/10.1007/s40430-017-0777-x.

[59] M. A. Fayad, W. K. Alani, H. A. Dhahad, and J. Zheng, "DIMINUTION OF AIR POLLUTION FROM NOX AND SMOKE/SOOT EMITTED FROM ALCOHOLS/DIESEL BLENDS IN DIESEL ENGINE AND INFLUENCE OF THE EXHAUST GAS RECIRCULATION (EGR)," *Journal of Environmental Engineering and Landscape Management*, vol. 31, no. 1, pp. 103–112, Apr. 2023, doi: https://doi.org/10.3846/jeelm.2023.17410.

[60] V. A. Likhanov, O. P. Lopatin, and A. S. Yurlov, "Study of the effective performance of the diesel engine

when working on methanol and methyl ether rapeseed oil," *Journal of Physics: Conference Series*, vol. 1399, no. 5, p. 055026, Dec. 2019, doi: https://doi.org/10.1088/1742-6596/1399/5/055026.

[61] K. Nanthagopal, K. Raj, B. Ashok, T. Elango, and S. Saravanan, "Influence of Exhaust Gas Recirculation on Combustion and Emission Characteristics of Diesel Engine Fuelled with 100% Waste Cooking Oil Methyl Ester," *Waste and Biomass Valorization*, vol. 10, no. 7, pp. 2001–2014, Jan. 2018, doi: https://doi.org/10.1007/s12649-018-0194-0.

[62] E. Öztürk and Ö. Can, "Effects of EGR, injection retardation and ethanol addition on combustion, performance and emissions of a DI diesel engine fueled with canola biodiesel/diesel fuel blend," *Energy*, vol. 244, p. 123129, Apr. 2022, doi: https://doi.org/10.1016/j.energy.2022.123129.

[63] K. A. Abed, A. K. El Morsi, M. M. Sayed, A. A. E. Shaib, and M. S. Gad, "Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine," *Egyptian Journal of Petroleum*, vol. 27, no. 4, pp. 985–989, Dec. 2018, doi: https://doi.org/10.1016/j.ejpe.2018.02.008.

[64] T. Sai, T. Karthikeya Sharma, K. Madhu Murthy, and A. Prasad, "Effect of reformed EGR on the performance and emissions of a diesel engine: A numerical study," vol. 57, no. 2, pp. 517–525, Jun. 2018, doi: https://doi.org/10.1016/j.aej.2017.01.008.

[65] Y. Park and C. Bae, "Experimental study on the effects of high/low pressure EGR proportion in a passenger car diesel engine," *Applied Energy*, vol. 133, pp. 308–316, Nov. 2014, doi: https://doi.org/10.1016/j.apenergy.2014.08.003.

[66] T. Ramesh, A. P. Sathiyagnanam, M. V. D. Poures, and P. Murugan, "A Comprehensive Study on the Effect of Dimethyl Carbonate Oxygenate and EGR on Emission Reduction, Combustion Analysis, and Performance Enhancement of a CRDI Diesel Engine Using a Blend of Diesel and Prosopis juliflora Biodiesel," *International Journal of Chemical Engineering*, vol. 2022, p. e5717362, May 2022, doi: https://doi.org/10.1155/2022/5717362.

[67] Hussain. J, Palaniradja. K, Alagumurthi. N, and Manimaran. R, "Effect of Exhaust Gas Recirculation (EGR) on Performance and Emission of a Compression Ignition Engine with Staged Combustion (Insertion of Unburned Hydrocarbon)," *International Journal of Energy Engineering*, vol. 2, no. 6, pp. 285–292, Dec. 2012, doi: https://doi.org/10.5923/j.ijee.20120206.03.

[68] N. Sunil Naik and B. Balakrishna, "Effects of EGR on performance and emissions of a diesel engine fuelled with balanites aegyptiaca/diesel blends," *International Journal of Sustainable Engineering*, vol. 11, no. 3, pp. 150–158, Oct. 2017, doi: https://doi.org/10.1080/19397038.2017.1386246.

[69] L. Wang, D. Liu, Z. Yang, H. Li, L. Wei, and Q. Li, "Effect of H2 addition on combustion and exhaust emissions in a heavy-duty diesel engine with EGR," *International Journal of Hydrogen Energy*, vol. 43, no. 50, pp. 22658–22668, Dec. 2018, doi: https://doi.org/10.1016/j.ijhydene.2018.10.104.

[70] M. E. Fayad, "Investigation of the impact of injection timing and pressure on emissions characteristics and smoke/soot emissions in diesel engine fuelling with soybean fuel," vol. 9, no. 2, May 2021, doi: https://doi.org/10.36909/jer.v9i2.9683.

[71] H. Venu, L. Subramani, and V. D. Raju, "Emission reduction in a DI diesel engine using exhaust gas recirculation (EGR) of palm biodiesel blended with TiO2 nano additives," *Renewable Energy*, vol. 140, pp. 245–263, Sep. 2019, doi: https://doi.org/10.1016/j.renene.2019.03.078.

[72] G. Wu, Jun Cong Ge, Min Soo Kim, and Nag Jung Choi, "NOx–Smoke Trade-off Characteristics in a Palm Oil-Fueled CRDI Diesel Engine under Various Injection Pressures and EGR Rates," *Applied sciences*, vol. 12, no. 3, pp. 1069–1069, Jan. 2022, doi: https://doi.org/10.3390/app12031069.

[73] Venkatesan Rajasekar, Varuvel Edwin Geo, Leenus Jesu Martin, and Beddhannan Nagalingam, "The combined effect of low viscous biofuel and EGR on NO-smoke tradeoff in a biodiesel engine—an experimental study," *Environmental Science and Pollution Research*, vol. 27, no. 15, pp. 17468–17480, May 2019, doi: https://doi.org/10.1007/s11356-019-05449-8.

[74] Syarifudin, Syaiful, and E. Yohana, "Effect of butanol on fuel consumption and smoke emission of direct injection diesel engine fueled by jatropha oil and diesel fuel blends with cold EGR system," *SHS Web of Conferences*, vol. 49, p. 02010, 2018, doi: https://doi.org/10.1051/shsconf/20184902010.

[75] S. Rami Reddy, G. Murali, A. Ahamad Shaik, V. Dhana Raju, and M. B. S. Sreekara Reddy, "Experimental evaluation of diesel engine powered with waste mango seed biodiesel at different injection

timings and EGR rates," *Fuel*, vol. 285, p. 119047, Feb. 2021, doi: https://doi.org/10.1016/j.fuel.2020.119047.