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# Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels - A review

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## HIGHLIGHTS

- Demonstrated EGR effectiveness on advanced diesel combustion and alternative fuels.
- Rendered a comprehensive outlook on EGR designs and measurement methods.
- Extensive classification and comparison of EGR configurations are carried out.
- Examined the engine combustion, emission characteristics with EGR from 0 to 70%.
- Adverse effects of EGR on engine wear and oil contamination are highlighted.

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## ABSTRACT

Ever since the establishment of the California Air Resources Board (CARB) in 1968 and Environmental Protection Agency (EPA) in 1970, significant strides have been made in diesel engine emission control technology. The diesel emission control is being achieved using strategies involving in-situ and after-treatment techniques and even with their effective combinations. Among these techniques, recirculation of the exhaust gases back to the engine inlet is an in-situ approach for Nitrogen Oxides ($NO_x$) control. Moreover, exhaust gas recirculation (EGR) has been used for controlling the onset of combustion process. In the current review, the importance of EGR for advanced diesel combustion like homogeneous charge compression ignition (HCCI) or low-temperature combustion (LTC) system and the requirement of EGR with the use of alternate fuels are discussed. In order to facilitate better understanding, the adverse effects of EGR, the impact of EGR on diesel engine wear and lube oil deterioration is also highlighted.


**Contents**



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**Nomenclature**

| | |
|---|---|
| ARC | Active Radical Combustion |
| ATAC | Active Thermo Atmospheric Combustion |
| CA | Crank Angle |
| CARB | California Air Resources Board |
| CFR | Co Operative Fuel Research |
| CI | Compression Ignition |
| CN | Cetane Number |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| COMF | Combustible Oxygen Mass Fraction |
| CRDI | Common Rail Direct Injection |
| CRT | Continuous Regeneration Trap |
| DME | Dimethyl Carbonate |
| DME | Dimethyl Ether |
| DOC | Diesel Oxidation Catalyst |
| DPF | Diesel Particulate Filter |
| DR | Dilution Ratio |
| EDAX | Energy Dispersive X Ray Analysis |
| EELS | Energy Electron Loss Spectroscopy |
| EGR | Exhaust Gas Recirculation |
| EMS | Electronic Mobility Spectrometer |
| EPA | Environmental Protection Agency |
| ESR | Electron Spin Resonance |
| FTP | Federal Test Procedure |
| $H_2O_{(v)}$ | Water Vapor |
| HC | Hydrocarbons |
| HCCI | Homogeneous Charge Compression Ignition |
| HPL | High Pressure Loop |
| HRTEM | High Resolution Electron Microscopy |
| HSDI | High speed Direct Injection |
| HVO | Hydrogenated Vegetable Oil |
| IEGR | Internal Exhaust Gas Recirculation |
| IMEP | Indicated Mean Effective Pressure |
| Lambda $\lambda$ | Excess Air Factor |
| LNT | Low $NO_x$ Trap |
| LPL | Low Pressure Loop |
| LTC | Low Temperature Combustion |
| MK | Modulated Kinetics |
| $NO_x$ | Nitrogen Oxides |
| NTU | Number of Transfer Units |
| PAH | Poly Aromatic Hydrocarbons |
| PCCI | Premixed Charge Compression Ignition |
| PCI | Premixed Combustion Ignition |
| PFI | Port Fuel Injection |
| PM | Particulate Matter |
| PPCCI | Partially Premixed Charge Compression Ignition |
| PSD | Particle Size Distribution |
| RME | Rapeseed Methyl Ester |
| SCR | Selective Catalytic Reduction |
| SEM | Scanning Electron Microscope |
| SI | Spark Ignition |
| SOI | Start of Injection |
| SVO | Straight Vegetable Oil |
| TDC | Top Dead Centre |
| TEM | Transmission Electron Microscope |
| VGT | Variable Geometry Turbocharging |
| VVT | Variable Valve Timing |

## 1. Introduction

Over the last five decades, the vehicle population across the globe has grown significantly. The concern over vehicular pollution increased steadily after 1960s Los Angeles episode. It is well-known that vehicular emissions vary with engine type, operating conditions and fuel utilized, and all these aspects need to be addressed simultaneously for their abatement. The severity of engine pollutant depends on their concentration and exposure time and severely affects human health. Owing to inherent fuel economy advantage, diesel engines have made inroads into automotive applications beside their usual stationary domain. However, the diesel fuel operated vehicles are the major source of $NO_x$ and particulate emissions and responsible for the deterioration of ambient air quality. Many countries like Brazil, China, Sri Lanka, Denmark and Paris are in the process of eliminating diesel vehicles and enforcing heavy taxes and levies on such vehicles. Recently, Indian government banned the registration of diesel-run private cars with capacity of 2000 CC and above in certain cities [1]. It is imperative that, the sustenance of diesel operated engines is possible with ultra-low emissions and lower fuel consumption. Numerous research works have been carried out on the influence of in-cylinder mixture formation and diesel combustion process [2–4]. The $NO_x$-PM trade-off in diesel engines is a classical challenge for developing emission control technology and hence stands at the forefront of diesel engine development. The $NO_x$/PM emission could be restricted through in-cylinder control measures well ahead of their formation, or through after-treatment control devices which involve the conversion of $NO_x$/PM emission to relatively benign compounds [5]. Achieving lower $NO_x$ and PM emissions, particularly in diesel engines, through in-cylinder technologies presents a formidable challenge, whilst developing after-treatment technologies to handle them individually is economically unattractive. A comprehensive summary of various strategies for controlling diesel $NO_x$ and PM emissions is provided in Fig. 1.

Among various strategies, recirculation of exhaust gases (EGR) is an established and effective technology for $NO_x$ inhibition in diesel engines [6,7]. In the diesel engines, even up to 50% or more of exhaust gas can be recycled. However, in the case of petrol engines, the maximum EGR is limited to 20% without affecting combustion stability [8]. Johnson [9] in a review highlighted that advanced engines will have significant amount of EGR to meet the stringent emission norms.

Abd-Alla [10] reviewed the $NO_x$ reduction potential of EGR in diesel, gasoline and dual fuelled engines. The author recommended that adding EGR along with the intake air of diesel engine has higher $NO_x$ reduction potential than the air displacement method. In the case of gasoline engines, substantial $NO_x$ reduction is reported with 10–25% EGR with a penalty in combustion stability. Simultaneous reduction of $NO_x$ and smoke is observed with EGR operated dual fuelled engine. Further, the author concluded that the usage of EGR is the most effective way in improving exhaust emissions. Zheng et al. [7] reviewed the various ways of implementing EGR and its threshold limits for $NO_x$ reduction. Further, the authors analysed the impact of EGR on diesel operations and proposed conceptual designs for EGR fuel reformer.

Thus, the future diesel vehicles demand engine modifications as well high quality fuels to adhere with stringent emission norms. It is inferred that, EGR has become an essential control strategy for both advanced combustion engines [11] and alternate fuelled engine applications [12,13]. Detailed discussions on the influence