

The Formation, Effects and Control of Oxides of Nitrogen in Diesel Engines

Maroia Semakula¹ and Prof Freddie Inambao²

^{1,2}University of Kwazulu-Natal Durban South-Africa.

Abstract

The transport service industry is a heavy user of diesel propelled engines as prime movers of goods and services. The diesel propelled engine is praised due to its high fuel efficiency, reliability and durability. However, the nitrogen emissions as a result of diesel fuel combustion characteristics raise major concerns for the manufacturing industry, environmentalists and health care researchers. The manner in which diesel engines combust their fuel is the main cause of the nitrogen oxide emission proportion. Although there are other sources of nitrogen oxide emission, this work will cover the sources of nitrogen oxides and their formation within the diesel engine, their routes of formation, identify the mechanisms under which the formations occur, identify their types and interactions, look at the various effects of the oxides of nitrogen on human health and the overall damage to the natural environment, and look critically at control systems.

Keywords: Nitrogen Oxides, Human Health, Formation Mechanisms, Durability.

NOMENCLATURE AND ABBREVIATIONS

A/F	Air-Fuel Ratio
ATDC	After Top Dead Centre
B	Cylinder Bore
BTDC	Before Bottom Dead Centre
CA	Crank Angle
CI	Compression Ignition
CN	Carbon of Nitrogen
CO	Carbon Oxide
DICI	Direct Injection Compression Ignition
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
F/A	Fuel-Air Ratio
HCCI	Homogeneous Charge Compression Ignition
HCN	Hydrogen Cyanide

HPL	High Pressure Loop EGR
IDICI	Indirect Injection Compression Ignition
L	Length or Piston Stroke
LPL	Low Pressure Loop EGR
M	Organic Residue
NG	Natural Gas
NO	Nitrogen Oxide
NO _x	Oxides of Nitrogen Excluding Nitrogen Trioxide Up
OH	Water or Hydroxide Radical
P	Pressure
PCCI	Pre-Mixed Charge Compression Ignition
PM	Particulate Matter
r _c	Compression Ratio
RCCI	Reactivity Charge Compression Ignition
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SO ₂	Sulphur Dioxide
SOI	Start of Injection
UV	Ultra-Violet Rays
V _c	Clearance Volume
V _d	Swept or Displaced Volume
λ	The Air Excess Factor Symbol Lambda

INTRODUCTION

The modern-day diesel engine, also known as the compression ignition engine, offers high fuel efficiency, low engine noise, reliability and durability during its life and service. However, diesel engines produce more oxides of nitrogen emissions than their counterparts, spark ignition (SI) engines. This collection of oxides of nitrogen emissions are collectively referred to as NO_x. Along with particulate matter emissions (PM), these

emissions have become major environmental and health concerns and have also become important themes in global discussions and forums.

Due to the ever increasingly stringent regulations on emissions by environmental protection agencies and governments, there has been development and improvement in design to accommodate and conform with the growing list of emission standards, especially developments in diesel fuel improvement [1] and [2]. Among the fuels for the 21st century being proposed as an alternative to diesel fuel is natural gas (NG), which is highly promising and attractive according to Abdelaal and Hegab (2012) [3]. The advantages of NG include availability, lower price, and reduction in CO emissions due the low carbon to hydrogen ratio. Further, because of its high octane number, NG has a high auto-ignition temperature characteristic which eliminates compression ignition (CI) engine knock such as it occurs during high compression ratios due to the low octane number of diesel fuel. Above all, it is eco-friendly with clean combustion compared to conventional diesel fuel engines. NO_x emissions are approximately 50% to 80% less, with zero smoke and PM emissions – something that is very hard to achieve in basic diesel propelled engines [3].

Besides the use of alternative fuels as a method of reducing NO_x emissions, the use of other control strategies and measures besides fuels has become equally important in mitigating the effects and impact of NO_x emissions. One of the techniques that has gained widespread use, although not as a standalone technology, is exhaust gas recirculation (EGR). This technique has been found to be an effective tool in reducing the emissions of NO_x [4, 5].

Although the combustion of biodiesels and its blends is different from conventional diesel and fossil fuel in compression ignition engines due to their physio-chemical fuel properties, they do also cause emission of NO_x, PM, CO and HC [6]. There has been a tremendous development in combustion technologies for biodiesel fuel combustion in diesel compression ignition engines, to accommodate the developments witnessed in the growth and expansion in alternative fuels, especially the biodiesels. Among the strategies that have been developed are: homogeneous charge controlled ignition (HCCI), pre-mixed charge controlled ignition (PCCI) and reactive charge controlled ignition (RCCI). These strategies have been extensively studied and found to significantly reduce NO_x and other emissions [7].

SOURCES OF OXIDES OF NITROGEN AND FORMATION

There are five mechanisms of NO_x formation in a diesel engine combustion process:

- Fenimore CN and HCN pathways.
- N₂O intermediate route or the Zeldovich mechanism.
- Due to super equilibrium concentrations of O and OH.
- Radicals in the extended Zeldovich mechanism reactions.
- The NNH route.

Prompt NO_x or The Fenimore Mechanism

Prompt NO_x, also known as Fenimore mechanism (named after the person who discovered it [8]), accounts for the smallest contribution to the quantity of NO_x. It is usually formed at the flame front especially in rich fuel-air ratio areas due to unavailability of oxygen, from the radicals of CH through their oxidation when they react with molecular nitrogen (N₂), leading to the formation of cyanhydric acid (HCN) and nitrogen oxide (NO) at the termination of the reactions. The general scheme of prompt NO_x causes hydrocarbon radicals to react with molecular nitrogen to form amines or cyano compounds which are then transferred and converted to intermediate compounds thus forming NO as can be shown in equation 1 and equation 2 below and expressed as:



Where equation 2 forms the primary path and becomes the rate limiting step in the reaction chain of the entire mechanism. However, it is vital to mention here that in the diesel engine combustion process, NO_x is generated through the Fenimore mechanism or prompt NO_x and the thermal mechanism or Zeldovich mechanism only. The conversion of hydrogen cyanide (HCN) to form NO takes the following path as expressed in the following equations as:



2.2 The Thermal NO_x (Zeldovich Mechanism)

The Zeldovich mechanism which takes the intermediate route is an important mechanism in lean fuels $\Phi < 0.8$ operating under low temperature conditions as can be seen in the three equations below with M as the organic residue [9] as:



The Zeldovich scheme mechanism consists of three main reaction chains as shown in the following equations and are coupled to fuel combustion chemistry through O₂, O and OH species [10] as follows:



The thermal NO_x formation of oxides of nitrogen depend on the following factors for their formation and propagation:

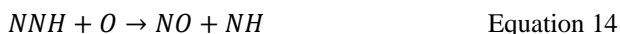
- Temperature especially in the reaction zone. Other than the disassociation process in the equation 2 of

oxygen, the reaction chain is inherently a temperature function as concluded by the studies conducted by Dangar and Rathod (2013) [11].

- The equivalence ratio or the air-fuel ratio in the reaction zone as it influences the atomic oxygen concentration within a combustion mixture. It has been observed that the NO_x emissions decrease with a decrease in the air-fuel ratio [12].
- The amount of time or duration of the reacting gases, also called retention time, spent in the reaction zone at maximum temperature determine the amount of NO_x formed. The shorter the time the smaller the quantity of NO_x and vice versa.

The NNH Mechanism

This is a recently discovered reaction pathway [13], with two major reaction mechanisms which has been shown to be important especially in the combustion of hydrogen [14, 15] and hydrocarbon fuels which have large carbon to hydrogen ratios [16]. The following two equations illustrate this route as follows:



The Fuel NO_x

Fuel NO_x can be defined as the reaction of fuel bound nitrogen from the compounds of N-H or N-C leading to the formation of ammonia (NH₃) and cyanhydric acid (HCN), which, when disassociated during the chain reaction, form NO. For lean fuel-air ratio mixtures almost two thirds of fuel bound nitrogen becomes converted to NO with the rest being converted to molecular nitrogen N₂ [17]. However, for rich mixtures (that is fuel-air ratios that have high fuel-to-air ratios), less NO is formed but more ammonia and cyanhydric acid (HCN) is produced, which, when released to the atmosphere, form NO through decomposition [18]. It is imperative to mention here that the NO formed from this mechanism and route cannot be optimized and controlled through combustion. The various forms of nitrogen bound fuel from different fuel sources are shown in Table 1.

Table 1: Forms of nitrogen bound fuel from different fuel sources [19]

FUEL TYPE	PERCENTAGE OF FUEL BOUND NITROGEN (WEIGHT%, DRY, ASH FREE BASIS)
COAL	0.5-2.0
BIOMASS (WOOD)	< 0.5
PEAT	1.5-2.5
FUEL OIL	0.0
NATURAL GAS	0.0
DERIVED GASES	0.1-1.0 (>>1 chemical sources)

Due to the fact that hydrocarbon fuel contains organic bonded nitrogen (organic nitrogenous compounds) some of the oxidized nitrogen will eventually be oxidized to be NO_x. The percentage amount of nitrogen going through this process depends on the nature of the combustion process. This is compounded by the fact that light distillate fuels contain 0.06 % by volume of organic hydrogen, while the heavy distillates contain 1.5 % or above. Thus, it can clearly be seen that depending on the amount of or percentage of nitrogen converted into fuel, NO_x can contain large portions of and percentages of total NO_x emissions [20].

The oxidation of the nitrogenous compounds is known to be less temperature dependent; thus, oxidation can even occur at low temperatures as the air excess ratio increases. However, during combustion a portion of the nitrogen fuel is changed to NO_x especially in fuel rich areas of combustion where thermally formed NO_x can be reduced to molecular nitrogen [21] as demonstrated by Figure 1 with the reactions taking the following forms:

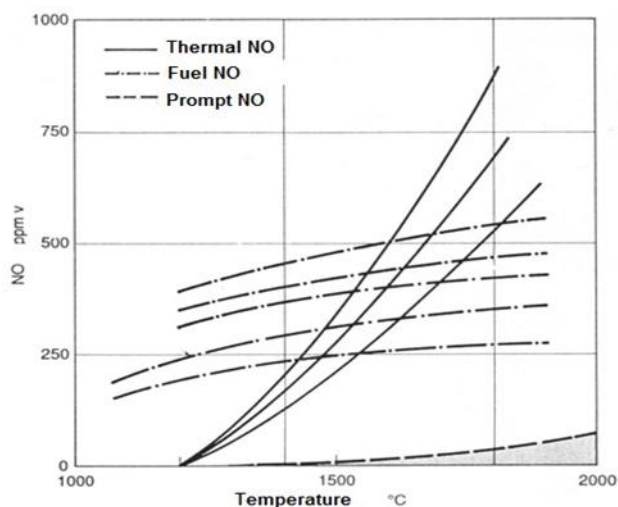
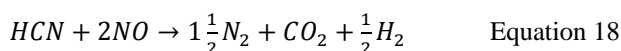


Figure 1: The relationship between temperature and NO_x formation, the air excess factor also known as the oxygen excess factor, and the parameters of thermal NO_x formation, fuel NO_x and prompt NO_x [22]

From Figure 1 we can see the relationship between combustion and the NO_x formation path. The figure shows a positive correlation between fuel and prompt NO_x with temperature that is almost linear with the amount or quantity of thermal NO_x increasing disproportionately with increasing combustion temperature. In addition, the figure shows that those areas where there is a rich fuel-air ratio naturally have reduced oxygen availability, thus making insufficient oxygen available

to react with the molecular nitrogen (N_2) in the combustion mixture, leading to reduced fuel conversion and thermal NO_x .

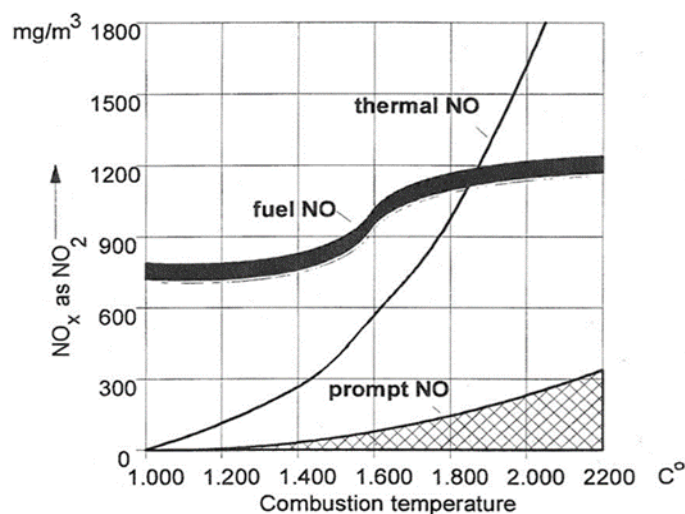


Figure 2: The relationship between the various types of NO_x formation under the influence of varying combustion temperature ranges

Figure 2 shows the relationship between the various types of NO_x formation under the influence of varying combustion temperature ranges where thermal NO_x , prompt NO_x and fuel NO_x set in, and the quantity of NO_x emissions produced under varying temperatures. A conversion mechanism of NO_x from fuel bound nitrogen shows the following trends and characteristics as can be seen in Figure 2 above as suggested by [23]:

- Conversion of fuel based nitrogen to NO_x is practically complete for fuel lean flames operating on low nitrogen concentrations of $< 0.5\%$ by weight ratio.
- Conversion increases slowly with increase in flame temperatures as indicated by all routes and mechanisms of NO_x formation in preceding sections and Figure 2.
- The composition of the nitrogen bearing compounds do not have any effect on the nitrogen bound fuel conversion rate percentage.

It is imperative to mention here that according to Figure 1, the temperature range at which fuel NO_x sets in is relatively higher than the prompt NO_x , but it is less than the thermal NO_x formation temperatures which kick in at temperatures exceeding $1800\text{ }^\circ\text{C}$. Table 1 shows that fuels with a high nitrogen content have a natural inclination to produce more NO_x emissions than those with a low nitrogen content. However, it is important to note that in diesel propelled engines NO_x formation from nitrogen fuel is strongly controlled and overlapped by thermal NO_x formation, therefore there is no guarantee that low nitrogen fuel content would not cause high production of NO_x emissions.

THE EFFECTS OF OXIDES OF NITROGEN

The oxides of nitrogen are recognised now as causing negative effects for human health and the natural environment. The harmful effects of oxides of nitrogen pollution do not necessarily take effect immediately after exposure, but after prolonged exposure. In the environment, oxides of nitrogen pollutants are known to cause destruction of the ozone layer, acid rain, poor visibility due to smog, poor air quality, and they contribute to the rise in earth surface temperatures leading to global warming. All these effects cause serious environmental degradation and poor human health, thereby increasing the rate of natural disasters and the global health burden, requiring billions of dollars for repair and reconstruction of the destroyed environment and of health.

Global Warming

Among the fundamental effects of oxides of nitrogen emission is global warming, although these are not the only emissions that contribute to global warming of the earth's surface. The stratosphere ozone layer is destroyed by oxides of nitrogen emissions therefore increased high energy ultra-violet rays (UV) warm up the earth's surface due to the decreased reflective capacity of the lower atmospheric layers.

The increase in earth's surface temperature has serious repercussions, shifting the climatic zones and thus shifting habitable regions of the earth leading to increase of the deserts and increasing the unpredictability of the weather patterns. For example, flooding and an increase in the intensity of typhoons have been witnessed in recent times or example in the USA (hurricane Katrina) and in the Philippines (typhoon Haiyan), leaving behind massive destruction of infrastructure, life and economies of the hit areas [24].

Smog and Visibility

Smog is a combination of smoke and fog and represents cloud formation from photochemical reactions of the sun with the hydrocarbons and oxides of nitrogen emission effluents from automobiles and stationary engines. Besides automobiles, smog can also be derived from other sources like coal emissions, industrial emissions, frost, agricultural fires and natural causes. Smog irritates eyes and the throat, and causes impairment to the lungs decreasing capacity, emphysema, bronchitis, asthma, inflammation of the breathing passages, shortness of breath, damages plants and crops, and destroys rubber products by cracking them through deterioration. One of the major impacts of smog has been poor visibility in cities such as Beijing (China), New Delhi (India), and London (United Kingdom) amongst others. Poor visibility is caused by nitrogen oxide absorbing the full visible spectrum of the light energy, thus leading to poor visibility even in the absence of particulate matter (PM) that would cause physical absorption of light.

The Ozone

The tremendous increase in the urbanization has seen an increase in energy consumption putting millions of cars on the road [25, 24]. As a consequence, many cities are feeling pressure from severe air pollution and air quality. The oxides of nitrogen are key to the formation of ozone and aerosols ($PM_{2.5}$) in the atmosphere which have a negative effect on air quality, acid deposition and the balance of atmospheric radiation [24].

The consequence of the anthropogenic pollutants like NO_x in decreasing the thermal layering of the stratosphere and increase of earth's surface temperatures cannot be over-emphasized. Animals, plants and humans are known to be sensitive to UV-B and UV-C rays of radiation which are richer in radiation energy. Exposure to a concentration level of $2500 \mu\text{m}/\text{m}^3$ of NO_x for one-hour decreases a human being's lung volume and maximum breathing thus impairing breathing and can lead to death, while exposure to ozone causes pulmonary haemorrhage with symptoms such as a dry throat, severe headache, disorientation and altered breathing patterns.

Toxicity

Nitrogen dioxide is a very toxic gas which irritates the entire pulmonary system. Though little is known by what mechanism it causes toxicity, high concentrations have been known to cause pulmonary oedema which is an abnormal accumulation of fluid in the pulmonary tissues [26]. In humans, oxides of nitrogen interact with vitamin B12 leading to selective inhibition of methionine synthase, with long exposure leading to megaloblastic bone marrow depression and other neurological diseases [27].

Acid Rain

The accumulation of oxides of nitrogen in the atmosphere increases acid deposition which tends to decrease ecosystem stability. Acid rain is caused by a chemical reaction which starts first with sulphur dioxide compounds reacting with oxides of nitrogen that have been released to the stratosphere [28]. Sulphur dioxide and oxides of nitrogen react and dissolve in water and can be transported by wind. Once they mix and react in the presence of moisture they form more pollutants with the result being acid rain [29]. Human activities, which release various chemicals into the air, are the main cause of acid.

The major contributors and sources of sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) are:

- Burning fossil fuels to generate power and electricity, producing two thirds of the sulphur dioxide and a quarter of oxides of nitrogen in the atmosphere.
- Heavy duty equipment and vehicles.

- From manufacturing industries, oil refineries and other industrial manufacturing processes.

There are two forms of acid deposition mechanisms – wet deposition and dry deposition. The former is where sulphuric acid and nitric acid in the atmosphere fall to the ground in the form of rain, snow, fog or hail, and the latter is when acidic particles and gases deposit on surfaces of water bodies, on vegetation and buildings in the absence of moisture but quickly react during atmospheric transportation to form particles that can harm human health. The dry mechanism largely depends on the amount of rainfall an area receives to cause maximum effect.

FACTORS OF NO_x EMISSIONS AND CONTROL

NO_x or oxides of nitrogen emissions control is the most difficult problem engineers and environmentalists have been grappling with since the discovery of the automobile, since most control methods tend to present additional problems in their own right. Most control systems will either increase fuel consumption or introduce new forms of emissions. However it is important to note that NO_x emissions can only be obtained by carefully considering air-fuel ratios, combustion and exhaust temperatures, design features that will reduce quench zones, fuel injection timing, fuel injection rate, compression ratios, catalytic reductants and convertors, exhaust gas recirculation systems, and advanced combustion control strategies. No single method can handle the issue of NO_x emissions efficiently, but by combining two or more of these methods, the objective of reducing NO_x emissions can be achieved. The following sections will endeavour to discuss some of the methods that have been developed to mitigate the emissions of NO_x and show that through a multiple approach this objective is achievable.

Injection Timing

Injection timing is one of the most influential factors in control of oxides of nitrogen emissions, especially in lean burn diesel engines, also known as direct injection compression ignition (DICI) engines, or their variant, indirect injection compression ignition (IDICI) engines. By retarding ignition or injection timing, significant reduction of oxides of nitrogen emissions can be achieved [30, 31] and as shown in Figure 3.

It is observed from Figure 3 that advancing the injection timing or the SOI causes an increase in NO_x emissions for all the test fuels covered by the study under multiple injection schemes. This can be explained by the fact that ignition and combustion then occur much earlier leading to early peak pressure as the piston approaches top dead centre (TDC), thus causing a rapid increase in combustion temperatures which promotes NO_x via the thermal mechanism also known as the Zeldovich mechanism.

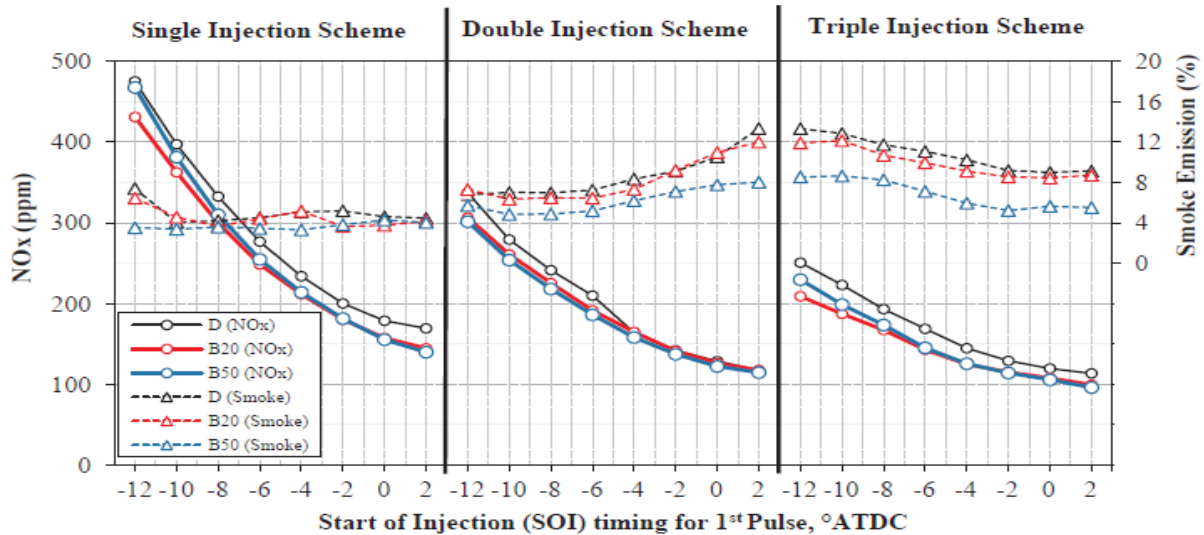


Figure 3: Effects and influence of start of injection (SOI) timings and injection timing strategies on NO_x and smoke emission reduction for various diesel fuel blends compared to conventional diesel [31].

Injection Rate

The rate of injection determines the level and quantity of emissions of oxides of nitrogen. This is due to an increase in the mixing time or ignition delay during the injection period which gives a very hot flame when combustion occurs, thus a greater quantity of NO_x emission are released to the environment [32]. Research conducted so far points to the successful reduction in the NO_x emissions by use of this strategy [33, 34].

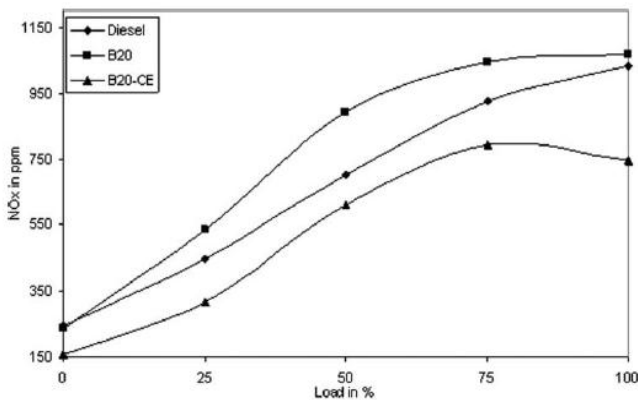


Figure 4: NO_x emissions at different engine loads of 25%, 50%, 75% and 100%, with application of EGR of 15% and injection pressure rate of 240 bar, with two diesel blends of B20, B20-CE and conventional diesel at normal operating conditions.

Considering the effects of oxides of nitrogen on the environment, it is important to note from Figure 4 above that diesel engines working to move goods and services normally operate at injection timings slightly retarded from the best fuel economy timing. Indirect injection (IDICI) engines have a

lower NO_x emission level due to the fact that their retarding is greater than direct injection (DICI) engines with common values for BTDC being 2⁰ and as late as 5⁰ ATDC without an effect on fuel economy. Continued retardation is observed to continue reducing NO_x emissions but creates more hydrocarbon emissions and particulate matter (PM) emissions.

The NO_x emissions in Figure 4 were observed to significantly reduce with the combined effect of EGR, injection pressure and injection timing, with reduced injection rate showing an increase in the NO_x emissions as compared to high injection pressure [35].

The Air-Fuel Ratio

Any change to the air-fuel ratio mixture affects the combustion temperature which in turn affects the formation of NO_x because it is a temperature dependent function as aforementioned. Therefore, an increase in air-fuel ratio achieved by decreasing the air amount in the mixture increases the amount of oxides of nitrogen. At higher fuel-air ratios the additional fuel has a tendency to cool the intake charge mixture temperatures, resulting in a drop in local peak temperatures within the combustion area, which decreases the NO_x concentrated emissions. However, IDICIs behave differently due to the presence of a pre-chamber unit where the pre-chamber tends to operate in rich fuel situations and conditions, thus producing less NO_x emissions [36, 37].

In diesel engines both air mass flow rate \dot{m}_a and the fuel mass flow rate \dot{m}_f are measured parameters, with most modern diesel engines running on an air-fuel ratio of lambda λ between 1.65 to 1.10, with the lowest fuel consumption occurring at $\lambda = 1.65$. This ratio of the flow rate is vital when defining engine operating conditions [18] as shown in these two equations:

$$\frac{A}{F} = \frac{\dot{m}_a}{\dot{m}_f} \text{ (air/fuel)} \quad \text{Equation 19}$$

$$F/A = \frac{\dot{m}_f}{\dot{m}_a} \text{ (fuel/air)} \quad \text{Equation 20}$$

The Compression Ratio

The compression ratio is defined as the ratio of the volume of the cylinder and of the combustion chamber of the cylinder head when the cylinder piston is at bottom dead centre (BDC) to the volume of the cylinder and of the combustion chamber of the cylinder head when the cylinder piston is at top dead centre (TDC), as shown on Figure 5 below.

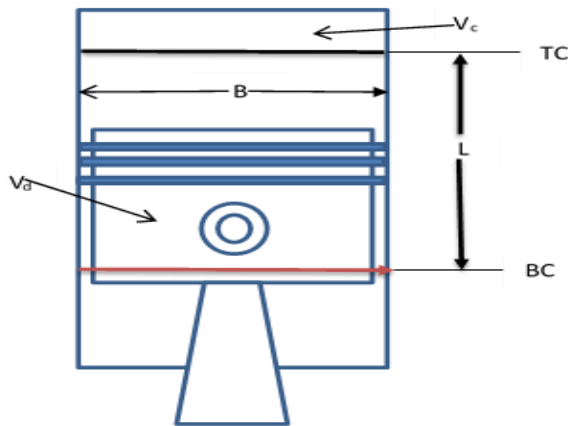


Figure 5: Schematic diagram of an engine theoretical cylinder and the cylinder head showing the definition of the compression ratio. Where TC is top dead centre, BC is bottom dead centre, V_c is clearance volume, B is the cylinder bore, L is the stroke and V_d is the swept or the displaced volume.

The compression ratio (r_c) thus can be expressed in equation form as:

$$r_c = \frac{V_d + V_c}{V_c} \quad \text{Equation 2}$$

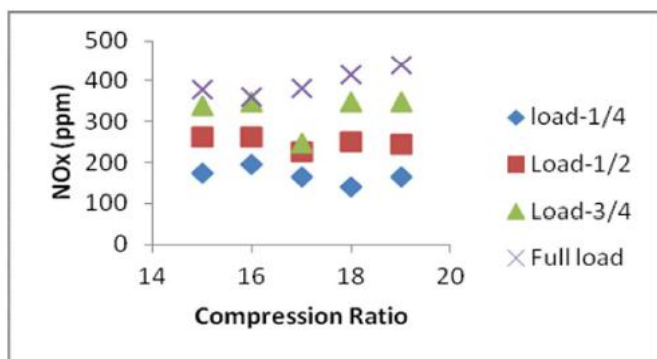


Figure 6: Effects of the compression ratio on NO_x formation, at different engine loads

The increase in the compression ratio in Figure 6 shows that the combustion duration also decreases by almost 2°CA to 3°CA, due to the decrease in ignition delay which is a crucial factor of compression ratio in compression ignition engines [38].

Increasing the compression ratio increases the power created by the higher thermal efficiency that accrues due to the increase in the compression ratio. However, it is noticed that a continued increase in the compression ratio increases NO_x emissions by increasing the cycle temperatures [39].

4.5 The Catalysts

As a means of reducing NO_x emissions in automobiles (both heavy and light duty) and stationary engines, several kinds of catalytic converters have been developed to reduce the NO_x emissions in the presence of oxygen within the normal operating conditions of diesel engines, achieving some very positive results especially when used in tandem with other NO_x control systems or in combination with themselves. Currently the most commonly used catalytic systems in diesel engines are selective catalyst reduction (SCR), diesel oxidation catalyst (DOC), and diesel particulate filter (DPF)

Their main function is to oxidize HC, CO and NO_x emissions through chemical reactions in the presence of oxygen thus rendering NO_x emissions ineffective and low or eliminating them altogether, or, in the case of the diesel particulate filter, clean particulate matter emissions. Figure 7 below shows how a diesel oxidation filter works in schematic diagram form.

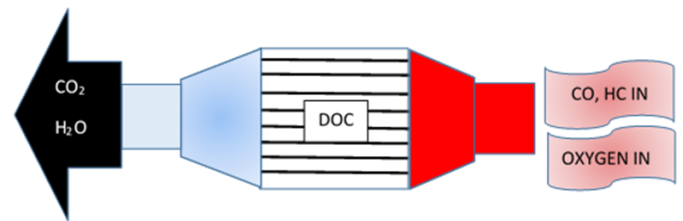


Figure 7: Schematic diagram of a diesel oxidation catalyst (DOC) and its operation in reducing emissions of CO and HC through the process of oxidation.

Exhaust Gas Recirculation (EGR)

EGR is a method of NO_x control that has increasingly become very effective and is widely used in the control and reduction of NO_x emissions in tandem with other NO_x control systems. The system works by recirculating a portion of the exhaust gases into the combustion chamber for reburning together with the fresh intake charge. Since NO_x is a temperature dependent function, EGR's main function therefore is to reduce the combustion temperatures gases for a given mass of fuel and oxygen that is burnt in the combustion chamber. However, while it is effective as a measure to control NO_x emissions, it has demerits because it tends to increase CO and PM emissions, thus limiting the extent to which it can be applied and recirculated, to about 30%.

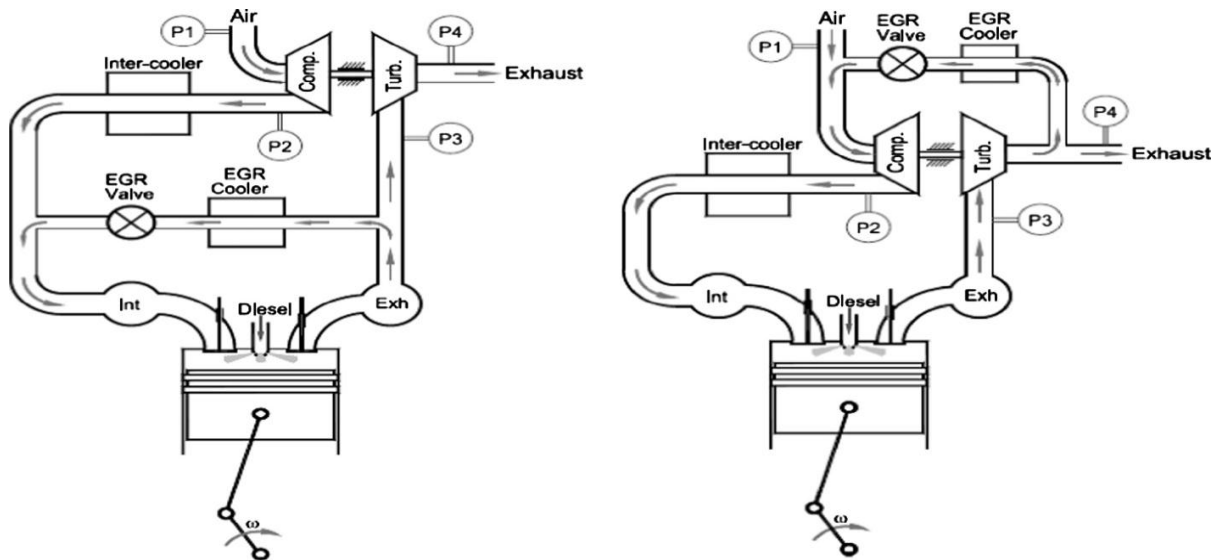


Figure 8: Two types of EGR systems in use today, where if $P_3 - P_2 > 0$ the delivery arrangement pipe is shorter hence the name short part (HPL)EGR, the long part arrangement (LPL)EGR is where the exhaust gases are taken from down stream of the compressor turbine and the pressure values $P_3 - P_2 < 0$ [40].

CONCLUSION

This work points out that human activities are the major source of oxides of nitrogen, especially from power generation and from power propulsion for the transport industry.

Although the effects of air pollution and environmental degradation on material, plants and animals can be measured and quantified, the effects of oxides of nitrogen emissions can only be estimated in humans from the epidemiological evidence which comes on later after exposure to high levels of NO_x concentrations.

The main significant oxides of nitrogen responsible for the pollution of the air, environmental degradation, human and animal health are nitric oxide and nitrogen dioxide.

All evidence available on the effects of NO_x emissions pollution so far provided indicate that high levels of NO_x concentrations are a threat to human and animal health, besides posing an immediate danger to the natural environment, therefore if measures are not implemented and attitudes changed, damage will continue and will increase.

The control measures discussed in the preceding sections cannot operate effectively and efficiently alone to deal with the problem of NO_x emissions but require to be included in a multifaceted approach rather than as standalone control mechanisms. Therefore, this calls for integration of all players in the transport, manufacturing, research and development, and the environmental protection agencies to harness their synergies in dealing with the problem of NO_x emission in the transport industry.

Adoption of the control measures discussed and highlighted in this work in sections 4.0 to section 4.6, will reduce and mitigate the effects of air pollution and general degradation of the natural environment.

More resources need to be allocated for research and development, so that continued studies can be conducted on those methods of NO_x control that have proved useful and efficient in dealing with the problem of emission, at the same time affording young researchers an opportunity to carry out experiments and collect data that can be useful in development of these methods and protecting the environment.

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