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Abstract

It was found that nitrogen oxides (NO_x) and carbon dioxide (CO_2) produced from the exhaust of a vehicle was significantly larger when the vehicle was put under real-time driving condition, recordings of NO_x produced were found to be five to six times above the type approval limit values. It was discovered that the largest production of NO_x occurs at a slightly lean fuel ratio of 16:1 while combined with a high combustion flame speed.

The emission control systems have improved significantly in the precision to control and monitor the emissions polluted, these include after treatment solutions after the combustion happens, but also methods applied during the combustion. Exhaust gas recirculation systems, lean burn technology and selective catalyst reduction are all found to aid in the reduction of NO_x .

Euro 7 predictions and speculations are in place, it is known that the emissions limits will be decreased from the Euro 6 limits, but the solutions manufacturers will take are still unknown. The option of downsizing the engines by replacing four-cylinder engines with three-cylinder engines has already been made, however there are options of applying a new architecture structure to the vehicles by introducing a 48-volt system which has been found to reduce the vehicles weight and decrease the CO_2 produced by up to fifteen percent by electrifying the drivetrain and ancillaries of the vehicle.

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2. Introduction

This report will provide an insight into what emission control systems manufacturers have previously used and what emission control systems they are currently applying to vehicles for Euro 6 to reduce emissions, including how they are monitored. The report will focus primarily on the pollution of nitrogen oxides, including methods applied to reduce the nitrogen oxides during and after the combustion process. With Euro 7 being introduced in 2020 there is a major concern regarding what emission limits will be applied for Euro 7, the introduction of new technology is almost certain, however what technology will be introduced. The possible solutions will be discussed including information sourced from technical reports regarding the speculations of what is to be expected with Euro 7.

3.0. Literature Review and Research

3.1. Oxides of nitrogen (NO_x)

The atmosphere consists of 78% nitrogen and 21% oxygen by volume, however the nitrogen is not used during the combustion process of an internal combustion engine, as confirmed by Hillier (2014). Nitrogen oxides (NO_x) are formed when the nitrogen and oxygen molecules separate, this happens when the temperature in the cylinder exceeds 1370.C during the combustion process, as confirmed by Haldreman (2015) and also Alcan (2019). However, this information was contested and expanded as it was found that the conversion of NO_x begins at an estimated 1000.C, as stated by Hsu (2002) and validated as 1093.C by Hillier (2014). Combustion temperatures above 1370.C increase the amount of NO_x produced significantly, and for every 100.C increment of temperature the rate that NO_x is formed at increases to over double, as confirmed by Hsu (2002).

The combination of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) form NO_x , NO_2 has been found to produce irritation of the respiratory system, as expressed by Adler (1985). Adler (1985, p. 16) quoted 'NO₂ destroys the lung tissue it is also detrimental to health when encountered in higher concentrations'. NO_x has been found to form a chemical smog in the atmosphere when combined with hydrocarbons (HC), it was found by Halderman (2015, p. 227) that quoted 'In the presence of sunlight, NO_x reacts with hydrocarbons in the atmosphere to form ozone (O_3) or photochemical smog, an air pollutant', which was also confirmed by Hillier (2014).

Euro 6 standards states that the NO_x limit for petrol cars is 0.06 g.kg⁻¹ and 0.08 g.kg⁻¹ for diesel cars, as confirmed by (Moody, 2017). However, it was found that the amount of NO_x produced during on-road testing of a novel Euro 6 diesel car was larger than the Euro 6 standards limit, resulting in an average of 0.21 g.kg⁻¹ ± 0.09 g.kg⁻¹, as discovered by Weiss et al (2012).

3.2. NO_x emitted during real-time driving tests

NO_x produced by diesel cars are found to be considerably higher than the euro emissions limit when the vehicle is tested under real-time driving conditions, as confirmed by Andersson et al (2014). Rexeis and Hausberger (2009, p. 4689) quoted 'The NO_x emission levels of recent modern diesel vehicle generations observed in several real-world driving conditions were observed to be clearly higher than demanded in the type approval procedure. Due to the growing number of modern diesel engine concepts equipped with coated catalytic exhaust after treatment, the fraction of NO_2 of the total tailpipe NO_x emissions is predicted to continue to increase in the next few years.'

The information was further confirmed by Moody (2017, p. 51) quoted 'Driving on-the-road has more frequent and prompt acceleration/decelerations than in the type-approval light-duty test conditions (NEDC), with Real Driving Emissions (RDE) of CO_2 and NO_x known to be considerably higher'.

Although CO₂ and NO_x are found to increase above the emission limits set in place during real-time driving it was found that CO, HC and PM do not exceed the limits as found by Ligterink et al. (2013, p. 8) who quoted ‘At ambient temperatures of 25 °C the real-world NO_x emission of diesel passenger cars are 400-500 mg/km (5-6 times of the type approval limit value). The CO, THC and PM real world test results do not exceed the type approval limit values’.

3.3. NO_x reduction methods

The maximum limit of NO_x produced from diesel light duty vehicles was drastically reduced by the government for Euro 3, as seen in table 1, and confirmed by (Hsu, 2002). Hsu (2002, p. 61) quoted ‘Besides smoke or particulate emissions, the major air-pollution problem for a modern diesel engine is controlling NO_x emissions’

3.3.1. Lean burn effect on NO_x

A lean mixture can simultaneously reduce CO, HC and NO_x, by altering the fuel ratio from a lambda reading of 1 to 1.4 the fuel consumption can be reduced by 7% and the amount of NO_x found in the emissions are reduced by 54% and a reduction of 85% of NO_x can be achieved by delaying the ignition timing, as found by Degobert (1995).

The largest production of NO_x within a combustion engine is found to be an air/fuel ratio of 16:1 combined with a high combustion flame speed, as confirmed by Hillier (2014). Hsu (2002, p. 62) quoted ‘maximum NO formation occurs slightly to the lean side of stoichiometry. This is because a lean air-fuel ratio has a higher oxygen concentration’. Hillier (2014, p. 233) quoted ‘An engine running weak mixtures with excess air will have lower combustion temperatures and lower NO_x production’. NO_x can be reduced by altering the ignition timing, this can be accomplished by reducing the amount the timing advances when the throttle is opened, this method assists in the reduction of NO_x by preventing any sudden increase of temperature within the cylinder, as confirmed by Hillier (2014).

3.3.2. NO_x storage catalyst

The NO_x storage catalyst is situated in the exhaust upstream of the catalytic convertor, its purpose is to store the NO_x produced when an engine is operating in the lean burn phase. When the engine operates at a rich burn phase or a stoichiometric ratio the stored NO_x are refused into nitrogen, this prevents NO_x emitting into the atmosphere from the exhaust, as expressed by Matsumoto (1996). The performance of the NO_x catalyst was shown to provide a 90% NO_x conversion efficiency between the ranges of 300-400.C, this was found by Matsumoto (1996).

3.4. Catalytic convertors

Catalytic convertors were introduced onto automotive vehicles in the 1970s to control and reduce the emissions produced from an internal combustion engine, as confirmed by Guillén Hurtado et al (2012).

The catalytic convertor is at its lowest efficiency at low temperatures (cold start), manufacturers try to fit the catalytic convertor as close to the exhaust manifold or engine as possible, this ensures that the temperature of the catalytic convertor is increased as quickly as possible. The faster the catalytic convertors temperature can be increased the duration that it is operating at low efficiency is decreased resulting in a decrease in the emissions produced.

3.4.1. Two-way catalyst

The two-way catalyst oxidises the HC and CO by using platinum and palladium, as confirmed by Hillier (2014). However, the two-way catalyst was not capable of reducing NO_x, therefore a three-way catalyst was introduced to assist in the reduction of NO_x to meet the emission standards, as expressed by Hillier (2014) and further confirmed by Amin and Rathod (2012).

3.4.2. Three-way catalyst

The three-way catalyst contains platinum and rhodium, its purpose is to reduce the three gases produced during the combustion process, these include HC, CO and NO_x. The gases are reduced by a chemical reaction caused by the catalyst by converting the NO_x, HC and CO into CO₂ and water as confirmed by Halderman (2015), Hillier (2014), Amin and Rathod (2012) and Guillén Hurtado et al (2012).

Galassi and Martini (2014, p. 9) quoted ‘Abatement of pollutants from gasoline engines is successfully accomplished by means of three-way catalysts which catalyses the reactions between oxidizing (O₂ and NO_x) and reducing (CO and HC) species present in the exhaust. The device takes its name from three simultaneous tasks fulfilled: reduction of nitrogen oxides to nitrogen and oxygen, oxidation of carbon monoxide to carbon dioxide, oxidation of unburnt hydrocarbons to carbon dioxide and water.’

To apply a three-way catalyst to a vehicle it must operate electronic fuel injection to provide a stoichiometric air and fuel ratio, an oxygen sensor within the exhaust to monitor the oxygen content (lambda), and a closed loop system, also known as a feedback-loop using the oxygen sensor signal feedback to the microprocessor. The signal received by the oxygen sensor is used by the microprocessor to determine the amount of fuel that must be injected under specific conditions to maintain the exhaust gas as close to the stoichiometric ratio as possible, as stated by Guillén Hurtado et al (2012).

3.4.3. Selective catalyst reduction (SCR)

The SCR’s purpose is to convert the NO_x, CO and HC into nitrogen, water and CO₂. This is done by injecting urea through a catalyst into a diesel engines exhaust before the SCR catalyst, the injected urea creates a chemical reaction that converts the nitrogen oxides into nitrogen, water and CO₂, SCR can achieve NO_x reductions up to 90 percent, as expressed by Johnson (2011) and confirmed by Andersson et al (2014). Johnson (2011, p. 148) quoted ‘injecting ammonia at 120°C instead of 200°C can drop NO_x ~60% on the NEDC test cycle (New European Drive Cycle)’.

3.4.4. Monitoring strategies

The use of two oxygen sensor is used to monitor the convertors efficiency, one is fitted before the catalytic convertor to monitor the emissions entering the convertor and the other oxygen sensor is fitted after the catalytic convertor to monitor the emissions exiting the convertor. The convertors efficiency is signalled to the control module to determine if the convertor is operating efficiently, as confirmed by Halderman (2015) and Hillier (2014).

3.5. Evaporative emission control

Gross (1994, p. 6) quoted 'engine evaporative emission control systems typically use a fuel vapor recovery canister to control the loss of fuel vapors from vehicle fuel tank'. This is to prevent the fuel vapour from venting to atmosphere, but instead to a charcoal canister, confirmed by Hillier (2014) and Halderman (2015). Reddy (2001, p. 1) quoted 'When a vehicle is parked in a warm environment during the daytime heating (...) the temperature in the fuel tank increases. The return of hot fuel from the engine also heats the contents of the fuel tank. The vapor pressure of the heated gasoline increases and fuel vapor will flow from any opening in the fuel tank. Normally, to prevent fuel Vapor loss into the atmosphere, the tank is vented through a conduit to a canister containing Suitable fuel adsorbent material. High Surface area activated carbon granules are widely used to temporarily adsorb the fuel vapor.'

3.6. Exhaust gas recirculation (EGR)

The EGR system was applied to vehicles to assist in passing the Euro 4 NO_x reduction limits, its purpose is to reduce the NO_x produced during high temperature combustions in petrol and diesel engines by recirculating a portion of the exhaust gas back into the combustion chamber, this effect decreases the flame speed during combustion enabling the combustion process to be slowed down under high load conditions, as confirmed by Hillier (2014), Amin and Rathod (2012) and Hountalas, Mavropoulos and Zannis (2007).

Studies have shown that although EGR aided in the decrease of NO_x, it had an increasing effect on the particulate matter and CO produced, as found by Hountalas, Mavropoulos and Zannis (2007) and confirmed by Hillier (2014) and Halderman (2015), this information is further validated by Degobert (1995, p. 294) who quoted 'recycling has a harmful effect on CO, particulate, and smoke emissions', in addition it also assists in the control of detonations, as expressed by Halderman (2015).

Amin and Rathod (2012, p. 1) quoted 'The exhaust gas, added to the fuel, oxygen, and combustion products, increases the specific heat capacity of the cylinder contents, which lowers the adiabatic flame temperature', and confirmed by Adler (1994). The maximum amount of exhaust gas allowed to be

recirculated in the combustion is limited to ensure that there is an adequate flame front during combustion to prevent misfires and partially burns, as expressed by Amin and Rathod (2012).

Euro 3/4 – The ECU monitors the operation of the EGR valve and determines that the EGR is functioning by the back EMF produced from the solenoid, however this does not determine that the EGR is opening and closing as it should be as it is only able to monitor and confirm that the EGR solenoid is producing a back EMF which isn't verification that the correct amount exhaust gas being introduced into the combustion process. Therefore, the ECU is unable to determine whether there is any carbon build up preventing the valve from closing or opening fully.

Ecotec Euro 4/5 – The EGR system used on the Ecotec engine released to meet the Euro 4 legislations is of the solenoid plunger type, the ECU operates the solenoid to lift the plunger which allows the exhaust gas to be entered into the combustion process to reduce the NO_x produced during high temperature produced during the combustion process when combined with oxygen, confirmed by Weiss et al (2012, p. 536) that quoted 'NO_x is generated under the condition of high-temperature and oxygen-rich environment'.

3.6.1. EGR valve position sensor

The EGR system can monitor the EGR valve position by using an EGR valve position sensor, this sensor is a linear potentiometer situated on the top of the EGR valve stem, the EGR valves position is signalled to the PCM, providing monitoring of the valve functioning, as confirmed by Halderman (2015).

3.6.2. OBD2 EGR monitoring procedures

The EGR system is monitored by the OBD2, the OBD2 alerts the driver if a fault is found with the EGR system by displaying a trouble code and illuminating the malfunction indication lamp as confirmed by Halderman (2015). Halderman (2015. p. 229) quoted 'The PCM monitors either the oxygen or MAP sensor for a change in signal voltage. If the EGR system fails, a diagnostic trouble code is set. If the system fails two consecutive times, the malfunction indicator lamp is lit'.

3.6.3. Monitoring strategies

Different vehicle manufacturers apply different strategies to monitor their EGR systems.

Oxygen sensor monitoring – Chrysler's strategy is to monitor the oxygen sensor voltage for any change as the EGR valve opens and closes. The oxygen in the exhaust increases when the valve is closed and decreases when it opens, as expressed by Halderman (2015).

Delta pressure feedback EGR sensor – Ford uses a delta pressure feedback EGR sensors (DPFE), the sensor measures the pressure difference either side of a metered orifice in the EGR tube situated between the EGR valves exhaust side and the exhaust. As the EGR valve opens the pressure between the EGR valve and orifice decreases, the DPFE sensor compares the pressure drop with the pressure found between the orifice and exhaust, then signals a value of the pressure difference to the PCM, as confirmed by Halderman (2015).

Map sensor monitoring – Many manufacturers monitor the manifold absolute pressure sensor (MAP) as the PCM signals the EGR valve to open, the signal received from the MAP sensor should change due to the EGR valve opening causing a change in the manifold pressure, or the change in the fuel trim caused by the oxygen sensor voltage. If the signal value from the MAP sensor falls out of the parameters programmed into the control module, then a trouble code will be stored and if the EGR fails for two consecutive times then the PCM illuminates the MIL to notify the driver that a fault has occurred, as confirmed by Halderman (2015).

Digital EGR valves – The digital EGR valves consists of three solenoids that are controlled by the PCM, each solenoid controls a different size orifice and the PCM controls the grounding of each solenoid individually, as confirmed by Halderman (2015). Halderman (2015, p. 330) quoted ‘it can produce any of seven different flow rates, using the solenoids to open the three valves in different combinations. The digital EGR valve offers precise control and using a swivel pintle design helps prevent carbon deposit problems.’

Linear EGR valves – A linear EGR valve uses a pulse width modulated solenoid to control the regulation of the exhaust gas, a feedback potentiometer is used to signal the position of the EGR valve to the PCM. Most General Motors and other vehicle manufacturers apply this to vehicles as confirmed by Halderman (2015).

3.7. Secondary air injection

Halderman (2015, p. 339) quoted ‘The secondary air-injection (SAI) system provides the air necessary for the oxidizing process either at the exhaust manifold or inside the catalytic convertor.’

Ford Euro 3/4 –The Ford Euro 3/4 engine operates a pulsed air SAI system, its method of function is that the ECU determines when the solenoid is pulsed, allowing the air to be drawn into the exhaust manifold, its purpose is to attempt to burn off HC. SAI aids in improving the efficiency of the catalytic convertor when the engine and catalytic convertor is cold and assists with heating up the lambda sensor quicker.

Euro 5 SAI - The SAI system moved away from the pulsed air type and to the electric pump type SAI. The electric pump operates during cranking and during cold engine operating temperatures, the operation of the fan results in the valve opening allowing the air to be drawn into the exhaust.

3.8. Positive crankcase ventilation (PCV)

During the compression stroke of a four stroke cycle a small amount of the gases produced during combustion escape past the piston, these gases contain approximately 70% HC which causes the engine oil to become diluted and contaminated, as expressed by Amin and Rathod (2012). As the engine speed is increased the gases that are blown passed the piston builds up pressure within the crankcase and can cause oil leaks, as confirmed by Amin and Rathod (2012).

The purpose of the PCV is to remove the gases from the crankcase and return them into the combustion process, as expressed by Amin and Rathod (2012). The PCV valve allows minimal flow of the gases into the combustion chamber during low engine speed and load, and maximum flow during high engine speed and load.

3.9. European emission standards

Table 1. European Emission standards

(Type approved) Year	#	Petrol NO _x g/km	Diesel NO _x g/km	HC Petrol g/km	HC Diesel g/km	Diesel PM g/km	CO Petrol g/km	CO Diesel g/km	Petrol PM g/km
1992	Euro 1	0.97	0.97	0.97	0.97	0.14	2.72	2.72	n/a
1996	Euro 2	0.5	0.9	0.5	0.7	0.1	2.2	1	n/a
2000	Euro 3	0.15	0.5	0.2	0.56	0.05	2.3	0.66	n/a
2005	Euro 4	0.08	0.25	0.1	0.3	0.025	1	0.5	n/a
2009	Euro 5	0.06	0.18	0.068	0.23	0.005	1	0.5	0.005
2014	Euro 6	0.06	0.08	0.068	0.17	0.0045	1	0.5	0.005

The Euro 6 emission standards was introduced in September 2014, as found by Moody (2017) and confirmed by Johnson (2011). The NO_x European emissions limit for diesel vehicles was reduced from 0.18g/km for Euro 5 to 0.08g/km for Euro 6. This strict reduction was implemented due to studies confirming that NO_x contributes towards respiratory complications. Johnson (2011, p. 6) quoted ‘In Europe, up to 80% deNO_x control is being planned to meet the Euro 6 NO_x regulations, with an emphasis on reducing CO₂’.

The emissions regulations for the Euro 5 diesel vehicle NO_x limits were 180mg/km, and the PM being 5mg/km. For Euro 6 the NO_x limit dropped significantly to 80mg/km, and the PM reducing to 4.5mg/km, all information confirmed by Johnson (2009) and can be seen in fig.1. This shows that there was a 56% reduction in the NO_x limit requirements set in place for Euro 6.

4.0 Analysis

4.1. Euro 7 predictions

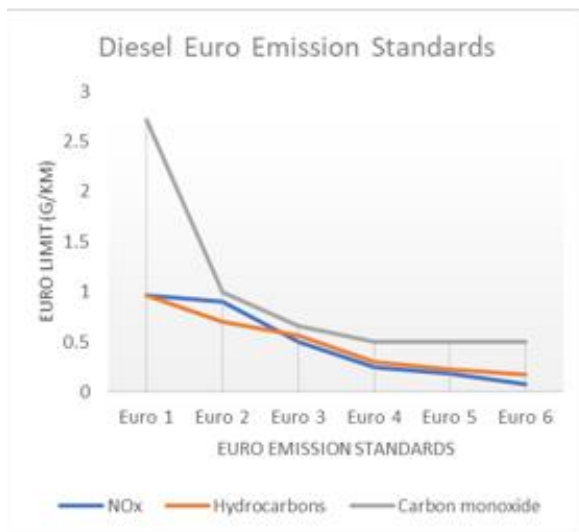


Fig. 1. Euro emission standards graph of NO_x, HC and CO.

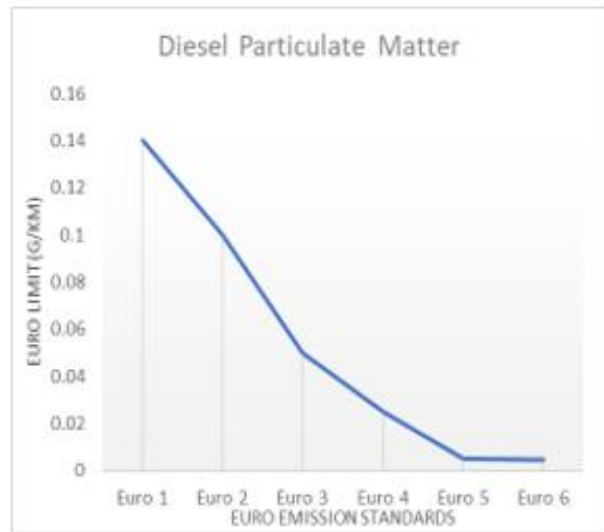


Fig. 2. Euro emissions standard graph of PM.

It is shown in table 1, fig 1 and 2 that the NO_x, HC and PM limits are decreasing every time there is a new European emission standard introduced. There is a high possibility that there will be a decrease in NO_x, HC and PM for Euro 7. Euro 7 emissions standards is expected to be implemented in 2020, with a CO₂ emission limit reducing from 130g/km to 95g/km, as researched by Frost (2019). CO₂ is produced from the burning of all fuel that contains carbon, as found by Degobert (1995). Frost and Sullivan (2019, p. 1) quoted ‘The majority of OEMs are working on lightening their powertrains as a 100 kg reduction in weight is expected to reduce CO₂ emission by 8.5 gm for every 100 km. This has resulted in most OEMs downsizing and electrifying their powertrain portfolio from their existing portfolio without reducing the drivability factor’.

4.2. 48-volt systems

The use of a 48V system to power a vehicles drivetrain and ancillaries has been found to decrease the CO₂ emissions produced by 12-15%, as found by Menon (2018) and confirmed by Milton et al (2017). By applying 48V system to a vehicle it is possible to reduce the mechanical loads produced from belt operated ancillaries by replacing them with electrified ancillaries, this is confirmed by Milton et al (2017). Melon (2018, p. 1) quoted ‘The use of higher voltage enables a cross section and weight reduction of the wiring harness, thereby contributing towards lighter vehicle architectures and emission reduction. Secondly, electrifying certain components means better performance in terms of instantaneous response, better power management, and the chance to recuperate energy while braking’.

4.4. Downsizing engines

There has been an increase from manufacturers of downsizing petrol engines from four cylinders to three cylinders, as confirmed by Frost and Sullivan (2016), this increases compression ratios with the use of turbochargers to meet the emission standards of Euro 6 and 7, although Euro 7 is an unknown there are predictions being made within the automotive industry. The increase in compression ratio increases the engines thermal efficiency, therefore increasing the performance and fuel consumption, as confirmed by Denton (2000). However, NO_x have been found to increase significantly as combustion temperature increases past 1370.C, as confirmed by Halderman (2015) and Alcan (2019).

5.0 Conclusion

Emission control systems have advanced significantly since Euro 1 was introduced in 1992. Since EOBD was applied to vehicles during Euro 3, all vehicle emission control systems must be able to monitor the emissions to notify the driver when there is a fault within the emission control and that the vehicle could be polluting above the legislation limits for that vehicles.

The motor industry will have to improve on the current technology applied to Euro 6 vehicles to meet the limits being applied for euro 7 in 2020, it is known that the emission limits applied for diesel and petrol vehicles for Euro 7 will be lowered compared to Euro 6.

The research found regarding what the automotive industry is predicting will happen for Euro 7 is that there will be a 35% decrease in the maximum limit of CO₂ polluted from the vehicle, going from 130g/km to 95g/km. A combination of reducing the weight of the vehicle, downsizing the engine and applying a 48V system to vehicles would assist in meeting the legislations put forward for Euro 7.

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