

Vehicle Emission-control Systems and the European Standards for Particulate (PM) Emission Legislations



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An assignment for the Emission Control & Diagnosis Module
March 2019.

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1. Introduction:

Many countries worldwide suffer from air pollution caused by vehicle-exhaust emission gases. This report focuses on the various systems developed to reduce and eliminate those harmful gases, systems studied are, Catalytic converter, EVAP, Exhaust-gas regeneration, Secondary air injection, Crank ventilation systems and GPF/DPF. Furthermore, a discussion of petrol's chemical structure has been covered along with the effect of Air/Fuel ratio on the overall emissions, engine efficiency and fuel economy. Particulate emissions and European regulation standards were studied in detail on the last section of this paper including the contribution of Hybrid-vehicles on the reduction of exhaust gases with a brief insight into the future trend of European legislation concerning emissions and efficiency.

2. Various emission control systems:

The concerns over air pollution has led to the introduction of the European emission regulations, Vehicle manufacturers have been since pushed to meet those standards and reduce the exhaust emissions going out from their engines. to overcome this issue, engineers and designers had to develop new devices which will be discussed separately in this section. There is a direct relation between the exhaust gases and the fuel burned inside the engine, therefore that last one need to be defined first to solve the emission gases issue. The most common fuels used in the automotive sector are, Petrol (or gasoline), Diesel, and LPG (Liquefied Petroleum Gas). This research though will mainly cover the emission gases caused by petrol engines including diesel for comparison reasons. Petrol is the most sold fuel type in the EU, the Pie-chart of market share on Figure-1 represent a statistic studies released in May 2018 by ACEA (Association des Constructeurs Europeens d'Automobiles) and it shows 55.5% of all new passenger cars in the EU ran on petrol, while 37.9% of cars ran on diesel (ACEA Article, 2018. [Online]).

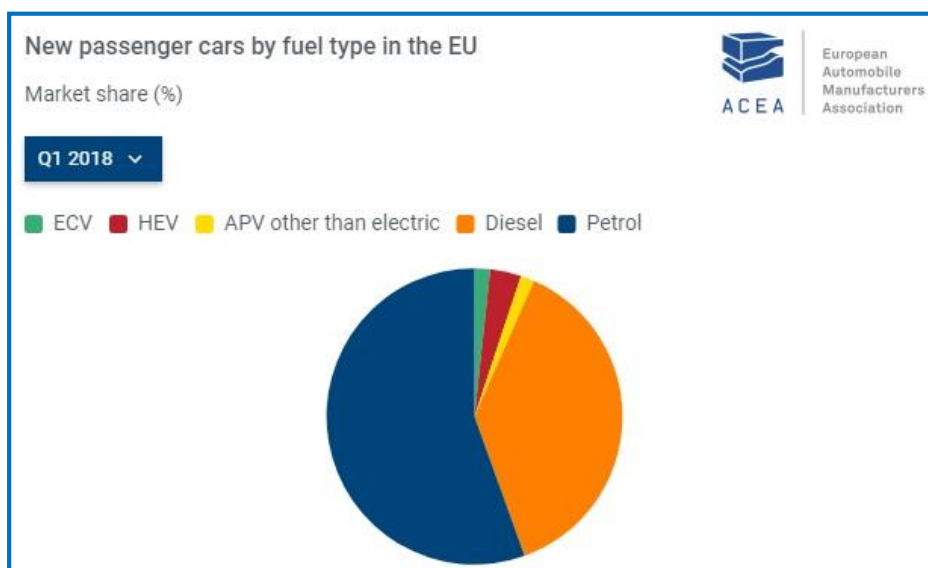


Figure 1 Passenger cars by fuel type in the EU

The petrol used in passengers/commercials vehicles is a complex blend of both straight and branched chain hydrocarbons, it is a mixture of various types of bunches of hydrogen and carbon and its chemical formula is C_8H_{17} (one molecule of gasoline

combines 8 carbon atoms and 17 hydrogen atoms bonded together) (Kevin S. [Online]). The two most important features of petrol are volatility and resistance to knock (octane), Octane number defines the gasoline's antilock quality (resistance to pre-ignition), the higher the octane number, the greater the resistance to engine knock. Most engines today are low compression engines and require a lower octane fuel (92). Volatility is a measurement of how easily the fuel vaporizes, if the petrol does not vaporize completely it will not burn properly (liquid fuel will not burn). The volatility of petrol has both upper and lower limits. They must contain an adequate proportion of highly volatile components to ensure reliable cold starting, but at the same time, volatility should not be so high as to lead to starting and performance problems during operation under high-temperature (vapor lock) (Bosch, 2014). When petrol mixed with oxygen and ignited inside the combustion chamber it burns, this chemically means a reorganization of hydrogen, carbon, and oxygen atoms. This reorganisation can form CO, CO₂, H₂O, NO, NO_x, and HC from some of the petrol which was left unburned.

2.1 Catalytic Converter / Temperature:

A catalytic converter consists of an inflow and outflow funnel, and a monolith. This last one is made up of high number (ranges between 400 and 1200 cpsi *cells per square inch*) of fine and parallel channels covered with an active catalytic coating. The monolith can be made either with metal or ceramic material (Bosch, 2007).

Three-Way dual bed catalytic converter is capable to convert and oxidize HC, CO and reduce NO_x, which arise during the combustion process, into harmless components (water vapour H₂O, carbon dioxide CO₂, nitrogen N₂). This type of catalytic converter requires a proper air/fuel mixture control and exhaust oxygen content for proper 3-way catalyst performance (Bosch, 2007). Dual bed catalyst has two separate chambers that allows NO_x reduction and CO & HC oxidation to occur at the same time. A catalyst cannot oxidise CO & HC efficiently unless there is enough oxygen in the exhaust, in contrast maximum efficiency of NO_x reduction cannot occur unless oxygen level is very low. To achieve low level of oxygen at the exhaust, the engine need to run slightly rich and that will allow max reduction of NO_x at the front bed of the converter. The rear bed is responsible on the oxidation of CO & HC and will use the oxygen generated during NO_x reduction process, however this amount of oxygen is not enough, therefore the system allows air to be injected in the middle of the catalyst (prior the second bed/half) to increase the level of oxygen content in the back half to achieve high efficiency oxidation of CO & HC. The injection of air in front of the rear bed allows both of oxidation and reduction to occur at maximum efficiency simultaneously (Bosch 2014. Et al., Kevin S. [Online]). An example of CO & HC oxidation equations and NO_x reduction equation has been described by Bosch in the latest automotive handbook version as following:

$2 \text{ CO} + \text{O}_2 \rightarrow 2 \text{ CO}_2$ (ending results of carbon monoxide oxidation is carbon dioxide).

$2 \text{ C}_2\text{H}_6 + 7 \text{ O}_2 \rightarrow 4 \text{ CO}_2 + 6 \text{ H}_2\text{O}$ (results of hydro carbon are carbon dioxide and water).

$2 \text{ NO}_2 + 2 \text{ CO} \rightarrow \text{N}_2 + 2 \text{ CO}_2 + \text{O}_2$ (ending results of nitrogen oxides is nitrogen, carbon dioxide and oxygen).

To ensure that the pollutant components HC, CO and NO_x are kept at its minimum, and the efficiency of the three-way cat-converter are as high as possible, the stoichiometric air/fuel ratio must be adhered to very precisely (mixture required $\lambda=1.0$). Therefore, a precise way to monitor the system and to evaluate its efficiency must be

followed up using lambda λ control loop as the accuracy of this system cannot be achieved only by controlling the metering of the fuel. Using λ control loop will allow the system to detect and correct the deviations of air/fuel ratio, detection start at λ oxygen sensor as this last one measure the residual oxygen content in the exhaust gas, then feedback to the ECU to correct the mixture ratio through the quantity of fuel injected (Bosch, 2014 Et al., Hillier, 2014). However, this control loop has been and still developing through the years as the technology advance and currently at the industry there are multiple control loop system including: Two-step λ control, Continuous λ control, Two-sensor λ control, and Three-sensor λ control. The last two systems are widely used by automotive manufacturers as they are the most efficient and advanced systems. The control system of cat-converter includes lambda sensor or also called oxygen sensor, it is mounted upstream the catalyst to monitors the flow of exhaust gases before they enter the converter. The engine control unit (ECU) will then allow the module to adjust its air/fuel ratio to increase or decrease the oxygen levels based on the information transmitted by the sensor, ensuring that the system stays within the stoichiometric point and still continues to make sure that enough oxygen is being supplied to burn off those unburnt hydrocarbons and carbon monoxides within the oxidation section of the catalyst (Hillier, 2014). In case of the Two-sensor λ control, the system includes an additional oxygen sensor mounted downstream of the cat-converter. As the first sensor is situated upstream the converter, it is heavily stressed by high temperature and untreated exhaust gas which causes a limitations in λ sensor accuracy. While the two-step λ sensor downstream of the catalyst is subjected to these influences on a much lesser extent. The voltage of that last sensor is compared with a setpoint value (e.g. 600mv), the control then evaluates the deviations from setpoint value and use that information to additionally alter over the controlled rich or lean shift of the first controlled loop of the upstream oxygen sensor (Bosch, 2014).

2.2 EVAP:

Petrol fuelled vehicle generate a large amount of fuel vapour from the fuel stored in the fuel tank, this fuel vapour is considered harmful for the environment and is added to the emission created by the vehicle's engine. Therefore, a system had to be designed to prevent this fuel vapours from entering the atmosphere, this system known as evaporative (EVAP) emission system and it comprises the following components: Two-way valve, Vapour separator, EVAP canister, Purge valve and Interconnecting vent pipes which links the system to the fuel tank by quick-release connectors (Hillier, 2014). The vapour separator separates the air-fuel mixture from the vapour and release it to the atmosphere as a fuel-free air, the fuel removed from that vapor is stored inside the canister. The carbon canister is connected to intake manifold through canister-purge valve to draw fresh air into the activated carbon when the purge valve opens during driving, the activated carbon absorbs the fuel vapor and when the fresh air enters the canister, it picks up the absorbed fuel and feeds it to the combustion process to burn it inside the engine. this is called purging the carbon canister (Bosch, 2014).

2.3 EGR:

Exhaust-Gas Recirculation operation start with removing hot exhaust gas and cool it in an exhaust-gas cooler, then mixed it with fresh air before returning it to the combustion chamber. The rate of this exhaust-gas is adjusted by a valve and it is used

in diesel engines and also increasingly in gasoline engines. EGR reduces NO_x emissions significantly in diesel engines, this has been achieved by lowering the peak temperature in the cylinder due to the recirculation of exhaust gas, which cause a decrease in the combustion velocity. In gasoline engines however, the idea is not to reduce NO_x directly, but the aim is primary to reduce the exhaust gas temperature in order to protect components linked to the exhaust systems which include catalytic converter and turbocharger (Bosch, 2014). Exhaust gas recirculation systems components include the EGR valve which meters the amount of recirculated gas, it can be found either at the exhaust manifold or at the intake air system, or it can be located at the exhaust-gas pipe which connects the exhaust manifold to the intake air system. Pneumatic EGR valves are actuated using vacuum taken from intake manifold or generated by vacuum pump via electromagnetic valves, on basic systems the pneumatic valve is actuated with an electric switchover which restrict the valve to only an open-close function. However, on systems provided with an electro-pneumatic pressure transducer (EPW), the valve is infinitely adjustable. Electric or electromotive EGR valves runs without vacuum or solenoid valve as they are directly actuated by the control unit (Pierburg, [Online]). Due to the high loads that the EGR valve has to withstand, it is considered one of the biggest source of faults. the oil in the intake air and soot from the exhaust emissions impede the valve, causing a reduction over time on the cross section of the valve opening until it completely closes up. this will lead to a steady reduction in the recirculated quantity of exhaust emissions which as a result reflected in the exhaust emission performance. In many cases the hose system for the vacuum is a cause of faults, the vacuum required for the EGR valve could be lost due to leaks and that will result to non-opening valve problem. If the valve is not functioning due to lack of vacuum, this can also be cause by a faulty pressure transducer or thermostatic valve that is not working properly (Hella, [Online]).

2.4 SAIR:

Emissions standards have become very strict when it comes to unburnt hydrocarbon, and since a significant amount of HC is emitted during cold start when the catalyst is not warmed up, it is vital to reduce those emissions along with decreasing catalyst warm-up duration during cold start (Bielaczyc P, Merkisz J, 1997). Various techniques have been proposed to reduce HC emissions and one of those solutions was the secondary air injection (SAI / SAIR). This system does not only help on reducing engine-out HC, but also aid on accelerating catalyst heating phase.

The advantages that SAI can provide is a significant reduction of HC through the oxidation and the acceleration of catalyst warm-up by the exothermic energy from the oxidation of HC and CO and H₂. Moreover, catalytic converter light-off temperature (temperature with 50% HC conversion), can be decreased as the oxygen concentration increases. A study has confirmed that the temperature decreased by over 50°C with increased oxygen concentration. The examination was carried by continuous SAI into the exhaust pipe, and the study reported that HC emission was reduced by 32% on a vehicle which does not use a three-way catalyst. Furthermore, when the test was performed on vehicle fitted with a three-way catalyst, HC emission decreased about 53% when the secondary air was injected into the exhaust valves directly (Kollmann K, Zahn W, 1994).

2.5 PCV:

During engine operation, some combustible mixture gas and exhaust gas can escape into the crankcase through piston rings (Hillier. 2014), this will cause a dilution to the engine oil because of the mixture of gas's coagulation. This mixture could also cause an increase in the crankcase's inner pressure and temperature and lead to engine oil seepage. The exhaust gas's high temperature, acidity substances and water vapor can also corrode engine component and alchemize (changing the chemical properties) engine oil, which will cause engine malfunction. Positive crankcase ventilation (PCV) system is function in a way that can protect the atmosphere by extracting the crankcase's mixture gas and exhaust gas and input fresh air as this will help engine air cylinder combustion. PCV operation can be surmised as following, the system abstracts the crankcase mixture gas and direct it into engine inlet pipe by mean of engine inlet pipe's vacuum performance (the timing of which the gas mixture enter inlet pipe is precisely controlled by the ECU), the mixture then will end-up inside the combustion chamber and burn (Gaoming Ding. 2011 Et al., Bosch, 2014). Using this system will protect the environment and almost all modern vehicles engines (light and heavy) have used PCV systems due to the strict emission legislation. Hill et al., Zimmerman et al., Gooch., have completed a deep study on diesel fuelled bus and reported that the use of diesel particulate filter (DPF) and ultra-low sulfur diesel fuel (ULSD) together contribute to the reduction of polycyclic aromatic hydrocarbons, black carbon and ultrafine particles to ambient levels inside the cabins of buses, however, a radical portion of PM_{2.5} mass was left (PM_{2.5} is particulates with a diameter of 2.5 microns or less). And they concluded that engine crankcase was the major contributor of that PM_{2.5} mass emissions inside passenger cabins, they continued with further studies and confirmed that closing the crankcase resulted in decreased PM_{2.5} mass. Similar study on school bus cabin PM levels have been completed by Ireson et al., Easter et al., Clark., where they discussed crankcase emissions separately in details.

2.6 GPF:

Gasoline particulate filter (GPF) is a system developed to reduce the PM emissions from Gasoline Direct Injection engines and like for wall-flow diesel particulate filter (DPF), the trapping mechanism include three types: interception, impaction, and diffusion. The interception and impaction mechanism are used for trapping larger particles, while smaller particles are trapped by diffusion. Therefore, smaller and bigger particles are all trapped, the lower filtration efficiency is for particles of around 200 nm in diameter. GPF coating also contributes to increase filtration efficiency (AECC. 2017).

3. The effect of air/fuel ration on overall emissions:

The most important variable which control engine-out pollutant emissions is the air/fuel ratio, or its inverse, fuel/air ratio of the carburetted mixture which directly affect the emissions concerning CO, NO, and unburned HC. Lean mixtures aid on reduction of CO and HC emissions. But in the other side cause an increase in NO_x emission as the combustion temperature rises due to the lean burn (Paul. 1995).

Optimum combustion occurs at 14.6:1 air/fuel ratio, a perfect combustion will occur if all the fuel vaporizes and burn inside the combustion chamber, which mean no NO_x formation [Perfect combustion: $\text{Air} + \text{Fuel} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$]. Unfortunately, as the

temperature goes up due to the increase on CO₂ gas, NO_x formation uses up the oxygen that is needed for CO₂ formation [Real world combustion: Air + Fuel → CO₂ + H₂O + NO_x + CO + Unburned HC, O₂ & N₂] (Bosch, 2007). NO_x emissions are at their highest between 14.6:1 and about 16.5:1 air/fuel ratio. HC emissions rises whenever the mixture is richer or leaner than about 14.6:1 air/fuel ratio, under lean mixture, the fuel charge sometimes fails to ignite and result in high HC emissions (this is known as lean-misfire). Under rich mixture, some of the fuel fails to burn because there is not enough oxygen. CO emissions increases under conditions richer than 14.6:1 air/fuel ratio. CO occurs at incomplete combustion and is essentially partially burned fuel. If the air/fuel mixture does not have enough oxygen during combustion, it will not burn completely as there is insufficient oxygen present to fully oxidize the carbon atoms into carbon dioxide CO₂. Thus, when carbon atoms bond with only one oxygen atom, carbon monoxide CO forms (Toyota, USA).

4. EU regulation on reducing Particulate emissions (PM) from passenger vehicles:

As the regulations concerning automobiles emission getting strict every year, engine and vehicle manufactures and designers are facing a technical difficulties in meeting those regulations. Ford, Jaguar, Lotus, and Rover sponsored a work on unburnt hydrocarbon (uHC) from petrol engines where the project was completed to achieve a deeper understanding of the mechanism contributing to the formation of uHC emissions. The project concentrated on cold-start emissions, i.e. prior to catalyst light-off and the majority of examination work was determined on test-bed engines undergoing repeated cold starts of 20°C. the results of this test revealed multiple aspects of engine fuel management that result in the creation of high level of uHC, in particular, the test highlighted the importance of fuelling and combustion performance on an individual engine-cycle basis if uHC levels are to be reduced without excessive cost penalties (Boam D, Finlay I, Biddulph T. 1994).

Emission legislation have been a worldwide concern for more than twenty-five years. Initially, the regulations mainly focused on exhaust pollutant gases of CO, HC, and NO_x. However, Hext P M., at el, Roger K O., at el, Paddle G M., has completed a studies in central toxicology laboratory (1999) and reported that particles emitted from vehicles and from other sources are now accepted as having a negative impact on human health and air quality. Several other studies also have been addressing the issue of particulate emission on human health. As a product of combustion and secondary atmospheric transformation, ambient Ultra-fine particulate (UFP_s) have various sources whose relative contributions to ambient concentrations vary with location, season, as well as time of the day. However, motor vehicle exhaust can be identified as the main contributor to UFP concentrations in urban areas, specifically in proximity to major roads (HEI. 2013). As a results of this studies, the European emissions legislation has set limits for the number of particulate emissions from vehicle powered with diesel engines since 1990, and their particulate mass (PM) limits were first introduced with Euro1 standards in 1992. Over the year, this limit has become progressively tighter, and in 2009 Euro 5 standards the number of PM reached 5 mg/km. Five years later, Euro 6 (2014) standards introduced even more tighter PM emissions limits of 4.5 mg/km. those limits along with the introduction of

clean fuels and advanced vehicle technology and after-treatment systems has significantly reduced automotive PM emissions as well as a substantial improvement in air quality (Joachim, Cecile., et al, Heather. 2017). When measuring PM emissions of port fuel injected (PFI) petrol engines, the numbers found to be very low, that because the fuel is well mixed with the inducted fresh air before the combustion occur. Therefore, research and legislations has remained focused much more on diesel engines which have historically proved to emit much higher PM emissions (Carbone R, Jorgensen A., et al. 2005). To improve the average fleet fuel economy, Gasoline Direct Injection (GDI) vehicles has increased significantly in the market share. GDI engines share some features with diesel engines as the fuel is injected directly inside the cylinder which mean that the fuel has less time to evaporate and mix before the combustion began, and this will lead to particulate formation (David K, Markus K. 2014). Particulate emissions limits now apply to GDI engines as well as Diesel engines, those limits have been introduced in both Euro 5 and Euro 6. As engine technology drastically advanced through the years, PM limits concerning petrol engines have so far met the Euro standards limits by engine modification and Gasoline Particulate Filter (GPF), where this last one has been proven to be a practical approach to meet future regulations as emission limits tighten further (Athanasios. 2011). Several papers and research studies showed the potential of GPF including previous studies determined by Dirk Bosteels who is a European Emissions Control Companies (AECC) member, the AECC and Concawe jointly commissioned the examination at an independent laboratory on a production Euro 6 GDI vehicle Equipped with a GPF where NEDC (new European driving cycle), WLTC (world harmonized light duty testing cycle), RDE (real driving emissions) tests has been conducted. the result reported at the end of this test was as mentioned in his studies summary “NO_x emissions on all cycles were less than half of the Euro 6 limits, PN emissions on all cycles were well below half of the Euro 6c limits, PN in RDE conditions was also well below the Euro 6c limits for all tests on the basis of both total test data and EMROAD evaluation” (Dirk. 2015). Another study has been completed where a petrol fuelled vehicle of Euro 6b was tested with and without GPF system, the vehicle was equipped with a 3-way catalyst for emissions control and an automatic gearbox to eliminate driver influence on gear shift strategy for the RDE tests. The results showed that GPF remarkably reduce PN emissions in GDI engines, and the vehicle met the Euro 6c limits of $6 \cdot 10^{11}$ particles/km on the regulatory test cycles NEDC and WLTC using the reference E5 fuel. PN emissions of the vehicle without GPF increased to $2 \cdot 10^{12}$ particles/km when vehicle accelerate, while with GPF, PN emissions were below $9 \cdot 10^{11}$ particles/km and that number is way below the Euro 6 limits. In the other hand, NO_x emissions were also below the Euro 6d NTE (not-to exceed) limits of 90 mg/km and further NO_x reduction was achieved with coated GPF during real-world driving. CO emissions were significantly below the Euro 6d limits and GPF also helped on lowering tailpipe CO emissions (Joachim, Cecile., et al, Heather. 2017).

Emissions legislation of PM level from Petrol engines also introduced challenges for the measurement techniques used. The effective method followed at Euro 5/6 level to measure PM emissions, is by collecting exhaust gas on a filter paper which is then weighed to determine the amount of particulate. However, this method cannot detect the small differences, which led to the development of new Particulate Number (PN) test. the PN test was developed through the European Particulate Measurement

Programme (PMP) over the past twelve years and introduced from Euro 5 for both GDI and Diesel engines (Joachim, Cecile., et al, Heather. 2017).

Gasoline-electric hybrid vehicles generally emit less emissions compared to their conventional counterparts, this have been achieved due to the reduction of fuel consumption. Internal combustion engine (ICE) operate efficiently in a narrow range of torque and speeds, but when supported with an electric motor and battery during hill climbing and acceleration, the ICE can be downsized and developed to run mainly at those points where it is most efficient (Martha, Deniz, at el., Lisa. 2007). Hybrid technology have been increasingly implemented in city bus markets, in china 2006, Eaton corporation and Beiqi Foton Motor Co. LTD., both developed two hybrid electric buses for city transport purposes. The Foton buses were field-tested in major Chinese cities by the China National Bus Quality Certification and Testing Centre, and the result found that buses reduced fuel consumption by 21% and 37% compared with equivalent conventional diesel buses with manual transmission (MT) and automatic transmission (AT) respectively over the standard Chinese city bus cycle (Haoran, Zhanjiang, Hanyun. 2009). Piotr, Jerzy, Jacek, and Joseph, recently completed a study in 2018 where two vehicles were tested under real driving conditions with gases exhaust emissions measured, the examination included a conventional vehicle which was powered with a spark ignition ICE, while the other vehicle featured a hybrid powertrain with a spark ignition ICE. Apart from the differences in the powertrain, both vehicles were similar size, weight and aerodynamic profile. The test route was mainly covering urban areas and the results was summarised as following: "Emissions of CO₂ and CO were much lower in the case of the hybrid vehicle, while HC and NO_x emissions were broadly comparable and very low. Emissions of CO₂ from hybrid vehicle were less than half those from the conventional vehicle".

Talking about light-duty vehicle future emission regulations, in Europe, the European commission's strategy for low-emission mobility aims to limit GHG emissions (Greenhouse Gas) by 2050 and the target limit is at least 60% lower than in 1990. Alongside the strategy, a legislation proposal has been adopted by the commission in late 2017, targeting reductions in average fleet CO₂ emissions from new LD vehicles by 15% in 2025 and 30% in 2030. Moreover, OEMs are continuously pushed to introduce zero and low emission vehicles with emissions less than 50g/km (Timothy J, Ameya J. 2018).

5. Conclusion:

The European regulations concerning Vehicle emissions has pushed the automotive industry to a new level of technology where various systems has been developed to reduce and eliminate exhaust gases. Those emission control systems which has been discussed during this essay, has proven their efficiency on reducing emissions and meeting Euro standards each year. However, the future insight of developing a clean zero emission vehicle, pushed the majority of car manufacturer to implement the Hybrid technology as this last one has been proved in comparison to conventional vehicle, that it is highly effective on relation to emission reduction and fuel economy.

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