

Exhaust Aftertreatment in Diesel Engine

Luechen Wang

Rensselaer Polytechnic Institute

*Corresponding author. Email: wangl19@rpi.edu

ABSTRACT

As diesel engines are pervasively used in the transportation industry, the supervision and requirements on the exhaust emission from diesel engines are becoming stricter. Automobile manufacturers and exhaust designers are aiming at the development of diesel engines' exhausts to match the standard of environmental policies announced by governments from different countries as well as promote the innovation of technologies in the transportation sector. In this essay, the function of diesel engine exhausts is illustrated with the description of the development of aftertreatment of diesel engine exhausts. With the elaborate integration of analysis between emission laws from different areas the prediction on the current and future development of diesel engine exhausts, the article is providing insights from several perspectives.

Keywords: Diesel exhaust, Emission Standards, Nitrogen Oxide (NOx), Diesel Engine, Exhaust After-treatment.

1. INTRODUCTION

Nowadays transportation accounts for 14% of the global greenhouse gas emissions by the economic sector [1], and one of the primary power sources for transportation is diesel engines. In order to combat the pollution caused by the use of fossil fuels, engine makers and vehicle manufacturers had put the effort into developing exhaust aftertreatment systems in compliance with laws. In the era that the automobile industry and diesel engine systems have developed for decades, the principle and real functions of diesel engine exhausts have achieved significant progress to support the operation of countless machines powered by diesel engines. However, even the technologies within the diesel engine exhausts are getting more complicated and comprehensive, the newly announced laws are pushing the development of new research on exhausts to achieve the requirement of government policies. It is important to understand the essence of new laws for vehicle manufacturers to maintain their advantages in manufacturing costs and technologies in the market. Hence, the article is focusing on analyzing the development of diesel engine exhausts aftertreatment to provide appropriate prediction and insight on its future development.

2. WORKING PRINCIPLES

The diesel engine, a widely used engine type in the present automobile industry, is an internal- combustion engine that transfers diesel's chemical energy to mechanical energy to power the machines [2]. In the market, diesel engines are usually shown as the two-stroke diesel engines and the four-stroke diesel engine. Although two-stroke diesel engines have higher theoretical efficiencies, the worse emission conditions for two-stroke diesel engines make it mostly applied in small tools and machines, like the handhold chainsaw [3]. Although larger-sized machines, like transportation vehicles, are using four-stroke diesel engines, the working principle of diesel engines is different from that of gasoline engines that are commonly used in personal vehicles. The combustion of diesel in diesel engines causes by the extremely high temperature from high pressures instead of the ignition from spark plugs. It is necessary to consider the advantage of four-stroke engines when analyzing the emission and exhausts. When the strokes of intake, compression, power, and exhaust are separated in four cycles, the ratio of diesel that hasn't been combusted in the emission gas is significantly decreased. Hence, understanding the theory of diesel engines is necessary for developing exhaust aftertreatment technologies.

During the power cycle of an engine, oxygen reacts with fuel and nitrogen in the air, byproducts were also

generated during that process. Exhaust aftertreatment systems are installed to convert the harmful gases and substances to other safer substances. Modern day diesel exhaust aftertreatment systems usually contain the following stages: EGR – Exhaust Gas Recirculation, DOC – Diesel Oxidation Catalyst, DPF – Diesel Particulate Filter, and SCR – Selective Catalytic Reduction. One of the major harmful gases produced during the power cycle is oxides of nitrogen (NO_x).

When the air-fuel mixture in the cylinder combusts at a high temperature, NO_x was generated. The emission gas recirculation (EGR) system reduced the amount of NO_x generated by cooling and recirculating a portion of the exhaust gas back into the intake, due to the lower oxygen contents in the exhaust gas, the peak combustion temperature within the cylinder was lowered. Coming out from EGR, the exhaust gas will then pass-through diesel oxidation catalyst (DOC) which uses precious metal in a mesh shaped filter. Unburned fuel - hydrocarbon (HC), and carbon monoxide (CO) were oxidized to water vapor and carbon dioxide. Then exhaust gas flow through a diesel particulate filter (DPF). DPF has a similar structure to DOC, it captures soot (carbon) which is usually generated when the engine is running rich. Soot condenses onto DPF and then will be burned away either through continuous regeneration (275~360°) or forced regeneration (600°) depending on the load conditions of the engine[4]. The last stage is selective catalytic reduction (SCR). Even though EGR will reduce the level of NO_x compared with EGR non-equipped engines, the generated NO_x isn't being converted. SCR works in combination with a reducing agent. A constant supply of that agent is injected into the exhaust stream before entering the SCR. Inside the SCR the reducing agent will form ammonia, which reacts with the NO_x and converts them back to water vapor and nitrogen.

3. HISTORY OF EXHAUST AFTERTREATMENT

The earliest published paper on exhaust aftertreatment was by Ford in 1957 about a single cylinder oxidation catalyst [5]. The relevant technologies commonly used by diesel engines also came around shortly after. The first paper on DOC was published by Cummins in 1971, DPF by Esso in 1980, and SCR by Degussa in 1986. EGR was thought to be implemented around 1973 with no clear publication regarding that.

The earliest aftertreatment systems were usually constructed with putting precious metal pellets in a large can which results in very low efficiency and increased fuel consumption. As more studies were carried out, saw the grown in complexity in system design. For diesel engines, a single stage crude SCR was used first, then a combination of DOC and DPF was implemented, now the system consists of EGR, DOC, DPF, SCR, and some engines are also equipped with AOC (Ammonia Oxidation Catalyst).

4. CURRENT REGULATIONS REGARDING EMISSIONS

Although the development of the exhaust system started early, automobile manufacturers were considering more about decreasing the effect of smell and visual influence on people instead of eliminating the contamination from the emission gas. The original technologies were also primitive and the efficiency and function were limited. However, the present implementation of the exhaust aftertreatment systems closely relates to the current laws and regulations when governments from many countries realized the harm of emission gas and the importance of protecting the environment. As European Union puts in place the Euro I through Euro VI regulations from 1992 to 2012 [6] and US EPA mandates Tier I to Tier IV F from 1996 to 2015[7].

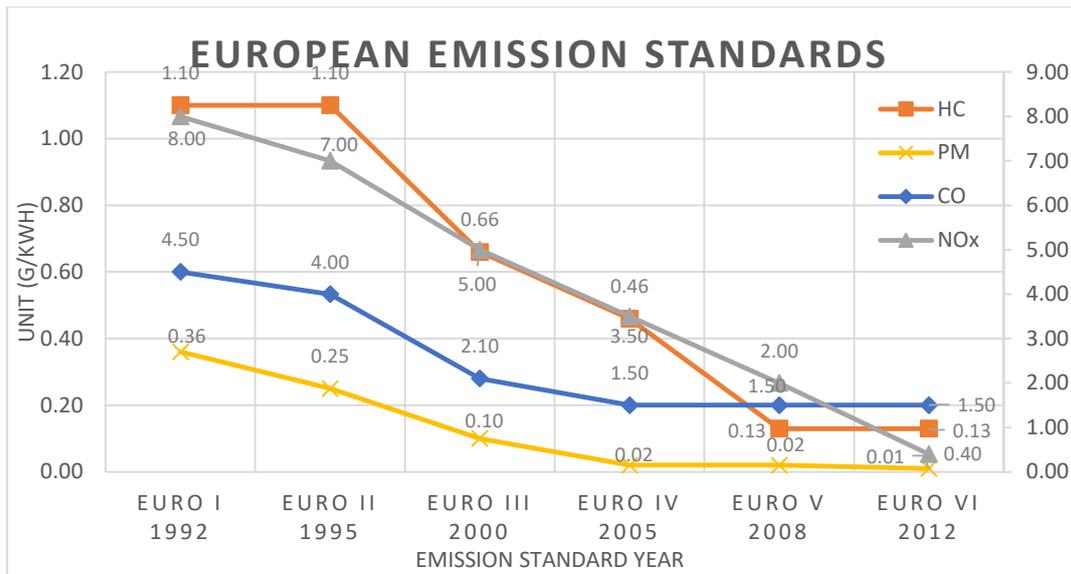


Figure 1 European Emission Standards

From 1992 to 2012, as shown in Figure 1, the emission standards had significantly changed to be stricter. In EURO VI Emission Standard, the allowance of HC in emission has dropped 88.18%, PM has dropped 97.22%, CO has dropped 66.67%, and NOx has dropped 95% compared to EURO I. Stringent regulations push automakers to develop better exhaust aftertreatment systems. It is evident that the policy of European Emission Standards would become stricter in every category of emission gases by analyzing the graph. The allowed number of different gases in every generation of policies may change the design of exhausting systems, because the method of controlling different gases and the technologies of aftertreatment is changing under various scenarios.

5. CONTROVERSIES ON AFTERTREATMENT SYSTEMS

The pros and cons of exhaust aftertreatment systems have always been a popular topic in the automobile industry. Its advantages, which are appreciated by many manufacturers, are the key points of why automakers are investing many resources in developing it. As the article illustrated above, the regulations on exhaust emissions are stricter presently, and they would be much tighter in the near future. With the implementation of exhaust aftertreatment systems, harmful particles produced by diesel engines had reduced by as much as 99% [8]. The design of the exhaust system is much complicated when plenty of working conditions are considered. Sophisticated design can significantly increase the cost of manufacturing and efficiency, as well as increase the cost of maintenance. The balance that the exhaust system achieves between efficiency and cost has direct influence on the competitiveness of the automaker in the market. Hence, investments in developing exhaust aftertreatment system are important for automobile manufacturers to

maintain their position in the industry under stricter laws. And indeed, the recent progress and performance report that the development of exhaust aftertreatment system achieve positive feedback and reactions in dealing with new emission policies. When the effectiveness and the cost are acceptable by the automaker, the development of this system is valuable.

On the other side, opposed opinions and unstable performance of exhaust aftertreatment systems also caused negative debates. Exhaust aftertreatment systems can significantly reduce the number of harmful byproducts of diesel engines, however, it's also causing reliability issues among users. DPF works by collecting soot and then burning it off later through regeneration. And it requires the engine to stay at a constant rpm higher than idling to generate the required amount of heat. It's usually done by taking the car on the highway for a period of time. When the vehicle owner was not able to take the car on highway drives, that usually could cause DPF to clog, and it could result in loss of power and worsen fuel economy. It usually takes about 200~300\$ to have it cleaned professionally at a shop or 1,000\$ to have it replaced if it's beyond repairable [9]. EGR system also has a reliability problem, since it's mounted directly by the cylinder, unprocessed exhaust constantly blows through it. In a similar fashion, soot could build up at the EGR valve which could cause the EGR system to be stuck on or stuck off. This would also cause the engine to run at lower fuel efficiency, loss of power and could even cause engine knocking. Truck owners have been complaining about the now rather fragile engines due to exhaust treatment systems compared with older engines without it. An experienced diesel truck mechanic shared his view on the system that there is no clear sign of failure of the EGR system when purchasing a secondhand truck, the system could fail at any moment and leave you stranded on the road. Manufacturers are also aware of this problem; the powertrain warranty could be 5 years

100,000 miles while the exhaust system warranty only covers 5 years 50,000 miles[10].

6. FUTURE FOR EXHAUST AFTERTREATMENT SYSTEMS

The future of exhaust aftertreatment closely relates to what the regulations are asking for. However, we can see from figure 1 that the requirement has been leveling off from Euro VI to Euro VI, similar situation also applies to EPA regulations. The latest regulation for both the European Union and US were put in place years ago. In the US, EPA hasn't started drafting the next Tier requirement. From that, we could understand it as they are encouraging automakers to stay at the current regulations and perfect their designs. However, EPA has been putting more pressure on aftermarket shops. EPA regulation states that if the engine is for off-road use, then it doesn't have to be Tier 4 compliant. Many shops have used this as a loophole to remove emission control to increase performance. There have been several cases where EPA penalized diesel mechanic shops for exploiting this loophole.

At the moment, the European Union is drafting the Euro VII standard which would be in effect in 2025. We could expect a stricter emission standard compared with Euro VI, thus pushing automakers for better aftertreatment systems. As alternative energy has become more available, the next round of laws may not be strictly limited to internal combustion engines.

7. CONCLUSION

The advancement of exhaust aftertreatment system is still demanding especially when the emission standards in many areas are continuously developing. It is beneficial that the promotion of laws stimulates the development of technologies. When the advancement of exhaust aftertreatment systems occurs independently of the establishment of regulations, government oversight should be thorough but precise in order to protect the healthy cycle of new technologies. The necessity of developing an exhaust aftertreatment system is still thriving, especially when it is one of the most effective methods to reduce the effect of emission problems in the automobile industry.

REFERENCES

- [1] US EPA. (2021, November). Global Greenhouse Gas Emissions Data. Retrieved from US EPA: <https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data>
- [2] Proctor, C. Lafayette and Armstrong, Lloyd Van Horn (2021, February 21). diesel engine. Encyclopedia Britannica. <https://www.britannica.com/technology/diesel-engine>
- [3] 2-Stroke And 4-Stroke Engines – Whats The Difference? (2016, January 13). LSU AgCenter.
- [4] Knight, B. (2017, August 9th). 3 Differences between DOC, DPF, and SCR filters. Retrieved from Hartridge: <http://www.hartridge.com/blog/3-differences-between-doc-dpf-and-scr-filters>
- [5] Keenan, M. (2017). Exhaust Emission Control: 60 Years of Innovation and Development. SAE Technical Paper, 24-0120. https://www.lsuagcenter.com/portals/communications/news/news_archive/2005/december/news%20you%20can%20use/2stroke-and-4stroke-engines--whats-the-difference
- [6] European Commission. (2021, November). Emissions in the automotive sector. Retrieved from Internal Market, Industry, Entrepreneurship and SMEs: https://ec.europa.eu/growth/sectors/automotive-industry/environmental-protection/emissions-automotive-sector_en
- [7] US EPA. (2021, November). All EPA Emission Standards. Retrieved from US EPA: <https://www.epa.gov/emission-standards-reference-guide/all-epa-emission-standards>
- [8] Steve Hansen(2012, February). In The Past 10 Years, Emissions From Diesel Trucks and Buses Have Been Reduced By 99% for NOx and 98% for Particulate Emissions. Retrieved from Diesel Technology Forum: <https://www.dieselforum.org/news/in-the-past-10-years-emissions-from-diesel-trucks-and-buses-have-been-reduced-by-99-for-nox-and-98-for-particulate-emissions>
- [9] Kevin. (2021, October 25th). 7 Symptoms of a Bad EGR Valve (and Replacement Cost in 2021). Retrieved from OARDS: <https://oards.com/egr-valve-symptoms-and-replacement-cost/>
- [10] Westen Champlin(2019, May). Buying A USED CUMMINS Diesel!! What I look for when BUYING. Retrieved from Youtube: <https://www.youtube.com/watch?v=4Aax2BCkWkM>