Research on Issue of NO_x Emissions of Diesel Engine

Yiwei Gong *
School of Transport Studies, Chang' an University, Xi'an, China
* Corresponding Author Email: 2022905793@ids.chd.edu.cn

Abstract. Diesel engine shows higher thermal efficiency than gasoline engine. However, with the effect of emission of Nitrogen Oxide (NOx), diesel passenger vehicles are difficult to gain market share. The Volkswagen diesel emissions scandal that occurred in 2015 undoubtedly sent diesel vehicles to the bottom of the market. Just the issue of NOx emissions alone has plunged diesel vehicles into a crisis of trust. It indicates that the public has zero tolerance for NOx emissions. NOx emissions really have lots of harmful effects on human beings and environments. If diesel vehicles try to regain public favor, issue of NOx emissions must be solved. This article focuses on the specific hazards caused by NOx emissions from diesel vehicles. And give a brief introduction of principle of generation of NOx. Reducing the emission of nitrogen oxides is the key to solving the problem. Now, we need some feasible solutions to reduce the content of nitrogen oxides in the exhaust emissions from diesel vehicles. This article will introduce some potentially feasible solution, which were named as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR).

Keywords: Diesel engine, NOx emissions, SCR; SNCR.

1. Introduction

Diesel engine has been preferring to choose in heavy transportation and automobile industries because of its high-power output and efficiency [1]. Unlike the spark ignition of gasoline engine, diesel engine compression ignition. This helps diesel engine to gain higher compression ratio, which leads to higher thermal efficiency. Diesel engine can also output high torque to push heavy vehicles up the slope. These excellent properties made diesel vehicles gain considerable audiences in the early 2000s. However, the emission of NOx produced by diesel engine has become an enormous issue in recent years. In 2015, Volkswagen diesel emissions scandal was discovered. Volkswagen cheated in the test of NOx emission.

This is not an unfounded claim. In 2013, a Non-Governmental Organization discovered some evidence. They test two models of Volkswagen Group under real traffic conditions [2]. The organization found that the actual emission of NOx is much higher than legal standard. Specific numerical value can be observed in Fig. 1. The Volkswagen Jetta generated NOx emissions up to 38 times higher than the standard level allowed. The least emission was still about 15 times higher than standard. For Volkswagen Passat model, the NOx emission could get maximum 20 times higher than the U.S. limit. Volkswagen Passat model produced the lower limit 9 times higher than standard on the highway.

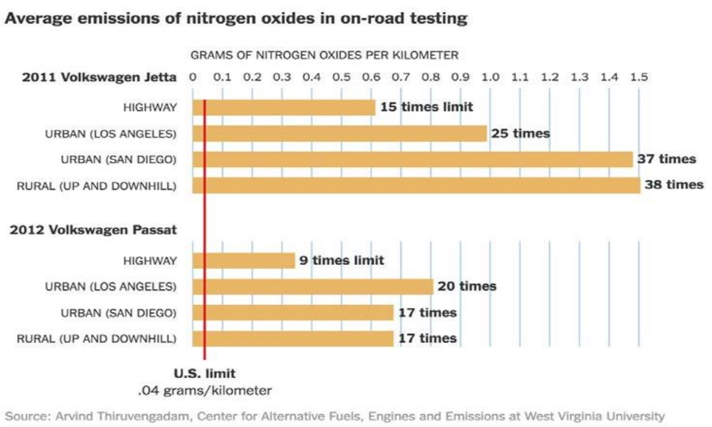

Fig 1. Average emissions of nitrogen oxides in on-road testing according to the study carried

The exposure of this scandal not only severely damaged the marketing efforts of Volkswagen Group but also caused significant damage to the public's reputation on diesel vehicles. Consumers avoid purchasing diesel vehicles, and more strict emission regulations were posed. Proportion of diesel vehicles in passenger vehicles decreased continuously over the years. Nowadays, it is hard to see diesel vehicles play the role of passenger vehicles. Diesel vehicles are still in use only on large trucks. If the diesel vehicles want to make a comeback, the emission problem must be solved first.

2. Principle of NOx Generation in Diesel Engine

The main source of nitrogen oxides in diesel engines is the thermal nitrogen oxide produced by nitrogen under high-temperature conditions with sufficient oxygen. For ammonia diesel engines, due to the nitrogen element contained in the fuel, N_2O and NOx are generated from the fuel. The combustion of ammonia generates a large amount of fuel nitric oxide, and in the later stages of the reaction, it reacts with nitrogen, oxygen and nitrogen elements to form nitrogen dioxide, nitrogen monoxide and nitrogen. Thermal nitrogen oxides are generated by the oxidation of nitrogen molecules and are further reduced to nitrogen oxides and nitrogen *oxides. When the energy ratio of ammonia increases from 20% to 60%, the proportion of nitric oxide in nitrogen oxide emissions decreases from 77.1% to 71.4%. The proportion of fuel nitric oxide increases from 35.2% to 58.8% [3]. The generation concentration of NOx is related to the following factors: 1) Temperature: High-temperature environment accelerates the reaction between nitrogen and oxygen; 2) Oxygen concentration: An oxygen-rich environment promotes the reaction; 3) Combustion chamber residence time: The longer the high-temperature duration, the more complete the reaction. The main reaction in diesel engines is as follows:

Phase 1: High-temperature cracking generates nitrogen monoxide

$$N_2(g) + O_2(g) \rightarrow 2NO(g)\ (\Delta H = +180.5\ kJ/mol) \tag{1}$$

Phase 2: Secondary oxidation produces nitrogen dioxide

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)\ (\Delta H = -114\ kJ/mol) \tag{2}$$

3. Brief Introduction of SCR and SNCR

Nitrogen oxides are produced in diesel engines and are released into the atmosphere through exhaust emissions. If these nitrogen oxide molecules are released into the air, they will contribute to the formation of acidic atmospheric precipitation. This precipitation results from changes in the acidity of the atmosphere and has significant impacts on surface water, forests, and human health. Specific nitrogen dioxide molecules can also damage the ozone layer in the atmosphere, thereby weakening the beneficial effects of the ozone layer. So many solutions were studied to reduce the emission of nitrogen oxides. This article will introduce two similar and highly feasible solutions, namely SCR and SNCR.

3.1. SCR

Diesel engine has four strokes: intake, compression, power, and exhaust. The combustion process happens in power stroke, and generation of nitrogen oxides occurs in exhaust stroke. SCR, which stands for Selective Catalytic Reduction, is a method for treating diesel engine exhaust. By optimizing the fuel injection and combustion processes, oxygen-nitrogen compounds formed under oxygen-rich conditions outside the engine are treated. Nitrogen oxides are promptly reduced through selective catalytic reduction using automotive urea (NH3), achieving the dual goals of energy conservation and emission reduction. The selective catalytic reduction (SCR) changes NOx with NH3 to harmless N2 and H2O proceeds by the overall reaction [4]

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \tag{3}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \quad (4)$$

In SCR technology, nitrogen oxides are reduced within a temperature range of 400 - 800 degrees Celsius, and its efficiency can reach 85% [5]. In SCR, ammonia and urea are used, and various metals (such as precious metals (Pt/Al2O3), catalysts containing alkaline metal oxides (vanadium), or metal ion-exchanged zeolites/crystalline silicates) are employed to promote efficient reactions.

Although the selective catalytic reduction (SCR) has been successfully applied in industry and transportation for almost 50 years, many fundamental details have long been debated. One is the precise control strategy for injecting the reducing agent into the SCR system relies on an accurate understanding of the original NOx emissions from diesel engines. Currently, due to the high cost of NOx sensors, the original NOx emission maps are mainly obtained through a large number of calibration tests, which is both time-consuming and require a significant investment [6]. Another is the urea deposits in the exhaust after-treatment system (ATS). Severe deposits can lead to ammonia leakage and exhaust pipe blockage, and they also increase back pressure, thereby reducing the conversion efficiency of nitrogen oxides [7]. Even though it has certain flaws, SCR is still regarded as one of the most promising methods for effectively reducing NOx emissions.

3.2. SNCR

SNCR is the abbreviation of "selective non-catalytic reduction". It refers to the process of injecting a reducing agent into the flue gas within the "temperature window" suitable for denitrification reactions, thereby reducing nitrogen oxides in the flue gas to harmless nitrogen and water. This technology typically uses ammonia, urea or hydrazine as reducing agents to reduce NOx in the flue gas. The reducing agent only reacts with NOx in the flue gas and generally does not react with oxygen. This technology does not use a catalyst, so it is called the selective non-catalytic reduction method (SNCR). Since this process does not use a catalyst, reducing agents must be added in the high-temperature zone.

Compared with SCR, this can be carried out at a higher temperature, but the required residence time is approximately one second. For efficient SNCR, the optimal temperature range is approximately between 1100 - 1300 degrees Celsius. When injecting the reducing agent below this temperature range, the reduction reaction of nitrogen oxides will not occur, and the reducing agent will remain in the exhaust gas. Above 1300 degrees Celsius, the reducing agent may burn, thereby generating more undesirable nitrogen oxides. Therefore, effective SNCR is the result of a delicate balance between high nitrogen oxide reduction and low reducing agent leakage. The best SNCR applied to industrial systems, with low NH_3 or urea leakage, can achieve up to 75% reduction in nitrogen oxides [5] The efficiency of SNCR is slightly lower than SCR, but it does not rely on catalysis, which is a significant advantage in terms of economy and maintenance. A reducing agent, such as ammonia or urea, is directly injected into the exhaust gas.

4. Hazard of NOx Emission

The public attaches great importance to NOx emissions, because the emission of NOx has numerous adverse effects. This is also the main reason why diesel vehicles are on the decline. The specific hazards of NOx emissions need to be analyzed so that solutions can be found to address them.

4.1. Health Impact of Nox Emission

NOx is the abbreviation of nitrogen oxides; it is composed of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). NO is a colorless, odorless gas and NO_2 is a reddish-brown gas with a characteristic sharp odor. NO can oxidize to form NO_2. NO_2 is a kind of strong oxidant. It can directly oxidize biomolecules. Besides, it also has undergone reactions to produce other highly reactive oxidants such as peroxynitrite (ONOO-) and nitric acid (HNO3) [8]. Exposure to nitrogen oxides can lead to oxidative stress, which occurs when the production of reactive oxygen and free radicals exceeds the inhibitory effect of the antioxidant defense mechanism, resulting in oxidative damage [9].

Nitrogen oxides (NOx) can aggravate asthma symptoms and trigger asthma attacks. NOx promotes airway inflammation and irritation in asthma patients, leading to wheezing, coughing and breathing difficulties. NOx has also been proven to cause asthma in young people. Long-term exposure to high concentrations of NOx increases the risk of developing chronic obstructive pulmonary disease (COPD), a chronic inflammatory lung disease that makes breathing even more difficult [10]. NOx may damage the lungs and cause two major diseases directly related to COPD - emphysema and chronic bronchitis.

Nitrosation is a kind of process where the nitro group (NO+) is transferred to specific molecules. For example, it attaches to amines and amides. Then they form the N-nitro compounds [10]. These N-nitro compounds are recognized as carcinogens, which can cause DNA damage and mutations, thereby increasing the risk of cancer. Nitrogen oxides can cause mutations in human DNA. Nitrogen oxides react with reactive nitrogen and oxygen atoms, resulting in DNA oxidation and the formation of DNA adducts, which may lead to mutations. Nitrogen oxides cause oxidative damage to DNA, thereby triggering a series of cellular reactions, which affects the regulation of the cell cycle as shown in Fig. 2 [11,12].

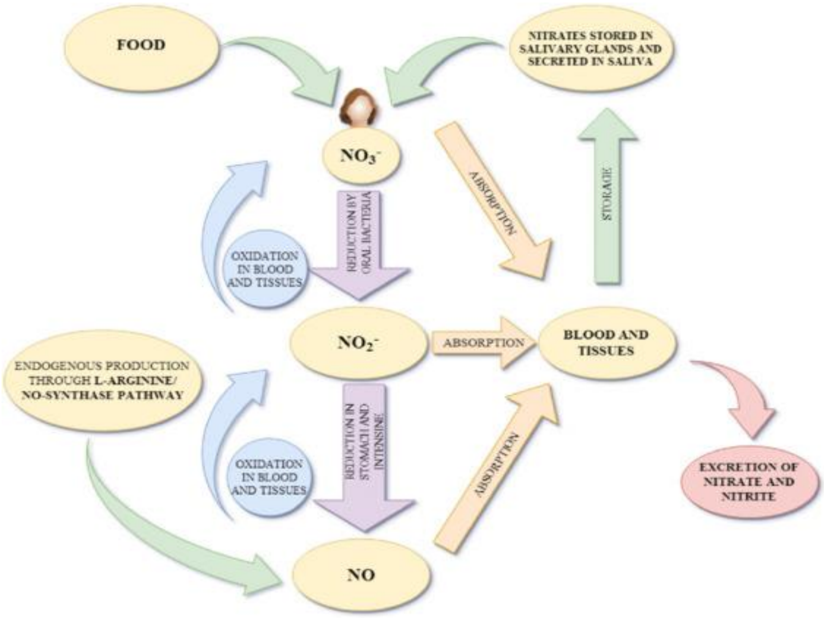

Fig 2. A summary of nitrite and nitric oxide metabolism in the body

4.2. The Impact of Nox Emissions on the Environment

Nitrogen oxides are main air pollutants in the atmosphere. They usually come from the combustion of fuels in all types of vehicles and from electricity generation. Diesel vehicles are one of the major sources of NOx emission.

After the combustion process of engine, the main pollutant emitted in the exhaust gas is nitrogen dioxide (NO). Then it is further oxidized into NO_2, and nitric acid can be formed from NO2. Nitric acid can react with vapor in the air to form the acid rain. Acid rain can disrupt the balance of aquatic ecosystems. At the same time, acid rain can also cause soil acidification, which affects the survival and activities of soil microorganisms, and subsequently influences the cycling of soil nutrients and the growth and development of plants. Besides, Acid rain has a strong corrosive effect on buildings, bridges and other structures. The acidic substances in acid rain react with concrete and stone on the surface of buildings, causing the surface to flake off, crack and even be damaged.

Nitrogen oxides also play a crucial role in the photochemical reactions in the troposphere, serving as precursor substance for tropospheric ozone (O_3) and nitrate aerosols [13]. The presence of tropospheric ozone not only affects the oxidizing capacity of the atmosphere, but also because of its strong oxidizing property, it can participate in the chemical transformation processes of various atmospheric pollutants, and cause harm to humans, ecosystems, and urban construction. Ozone is one of the main components of photochemical smog, which is particularly prevalent in regions with high temperatures and intense sunlight during summer. Photochemical smog can cause harm to plants, affect crop yields, and cause damage to the environment.

5. Conclusion

Based on the background of the Volkswagen diesel scandal, this article discusses the underlying issues behind the declining popularity of diesel vehicles, namely, the high NOx emissions of diesel vehicles and their inability to meet the increasingly strict emission regulations nowadays. This article describes the discovery process and evidence of the Volkswagen diesel scandal. And regarding the reasons why the public attaches importance to the issue of NOx emissions, it specifically lists the hazards caused by NOx emissions. From the perspectives of human health and environmental protection, it is elaborately explained that NOx emissions will cause tremendous harm to both. Besides, two efficient solutions that are currently feasible and can reduce NOx emissions have been introduced – SCR and SNCR. This article explains the basic operating principle of SCR and SNCR. Then some certain flaws that still exist in it. Although SCR or SNCR are not perfect, it is still very effective. It is believed that better solutions will emerge in the future, helping diesel vehicles to overcome the problem of NOx emissions and allowing them to regain their place in the public eye.

References

[1] Tan, Y.H. Engine performance and emissions characteristics of a diesel engine fueled with diesel-biodiesel-bioethanol emulsions. Energy Convers. Manag. 2017, 132, 54–64. [CrossRef]

[2] Dura, C. The Volkswagen Emission Scandal – Facts, Figures and Effects, mechanical engineering, 2019, 21, 35-48.

[3] Wu, B.Y. Generation mechanism and emission characteristics of N2O and NOx in ammonia-diesel dual-fuel engine, Energy, 2023, 284, 129291.

[4] Lai, J.K. A Perspective on the Selective Catalytic Reduction (SCR) of NO with NH3 by Supported V2O5–WO3/TiO2 Catalysts. ACS Catalysis, 2018, 8(7).

[5] Locci, C. Selective Non-Catalytic Reduction (SNCR) of Nitrogen Oxide Emissions: A Perspective from Numerical Modeling. Flow Turbulence Combust, 2018, 100, 301–340

[6] Shen, Q.Q. Prediction Model for Transient NOx Emission of Diesel Engine Based on CNN-LSTM Network. Energies (Basel), 2023, 16(14).

[7] Gao, W. Enhancement of SCR denitrification control strategy considering fluegas temperature fluctuation: Fundamental principle and performance evaluation. Fuel, 2024, 359, 130453.

[8] Amoatey, P. Indoor Air Pollution and Exposure Assessment of the Gulf Cooperation Council Countries: A Critical Review. Env. Int, 2018, 121(1), 491-506.

[9] Lee, G.H. Effects of Indoor Air Purifiers on Children with Asthma. Yonsei. Med. J, 2020, 61 (4), 310-316.

[10] Alrebei, O.F. CO_2-argon-steam oxy-fuel production for (CARSOXY) gas turbines. Energ. (Basel), 2019, 12 (18), 3580.

[11] Alrebei, O.F. Ammonia-hydrogen-air gas turbine cycle and control analyses. Int J. Hydrog. Energy, 2022, 47 (13), 8603-8620.

[12] Alrebei, O.F. Window-windcatcher for enhanced thermal comfort, natural ventilation and reduced COVID-19 transmission. Buildings, 2022, 12(6), 791.

[13] Filonchyk, M. Investigation of a NOx emission from coal power plants in Texas, United States and its impact on the environment. China Geology, 2025, 8(1), 107-116.