Iran University of Science and Technology

Automotive Science and Engineering

Journal Homepage: ase.iust.ac.ir

ISSN: 2008-9899

Investigating the effects of the ozone gas injection process on the reduction of exhaust gas emissions

Alireza Goharian[1], Alireza Asadolahei[2*]

[1]Automotive Engineering Group, Technical and Vocational Training Organization, Alborz, Iran.

[2]Mechanical Engineering Group, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran.

ARTICLE INFO

Article history:

Received : 15 Sep 2024

Accepted: 15 Feb 2025

Published: 7 Mar 2025

Keywords:

Co Emission

Reduction of greenhouse gas emission

ozone injection

internal combustion engines

catalyst supplement

A B S T R A C T

This study investigates the effects of ozone gas injection on reducing exhaust emissions in internal combustion engines (ICEs). Ozone (O_3), a highly reactive oxidizing agent, has been widely utilized for air and water purification. Its ability to break down pollutants makes it a promising alternative or supplement to conventional catalytic converters, which require expensive materials and periodic recycling. In this research, ozone gas was generated using the corona discharge method and injected into the combustion system to evaluate its impact on carbon monoxide (CO) emissions. A low-power 12-volt compressor, capable of producing up to 10 bar pressure, was used to ensure proper injection. A five-gas analyzer was employed to measure emission changes before and after ozone injection. Results indicated an average CO reduction of 34–40% across seven tested vehicles, with the highest effectiveness observed at steady-state engine operation and moderate loads. Furthermore, an increase in lambda (λ) values suggested improved air-fuel combustion efficiency. Statistical analysis, including standard deviation (± 0.005) and a 95% confidence interval, confirmed the reliability of these findings. The results demonstrate that ozone injection can serve as a cost-effective method to supplement traditional emission control technologies, potentially reducing reliance on catalytic converters.

1. Introduction

Today, global warming and environmental pollution have created a serious problem for us. Not only human lives but also wildlife is at risk. Therefore, in the last few decades, various ways have been proposed to reduce environmental pollution. One of the types of environmental pollution is air pollution. This challenge is more serious in metropolis. In recent years, air pollution has been considered as a challenge, however, this issue is a major problem in developing countries. An excessive increase in the emission of harmful gases such as CO and NOx. If the emission of these gases is not prevented, these gases can cause irreparable damage. According to the mentioned cases, in order to reduce and in some cases prevent these pollutants, methods have been proposed. Currently, one of the useful ways in this field is the production and use of three-way catalysts for internal combustion engines. In gasoline engines, a Three-Way Catalyst (TWC) is used to simultaneously reduce CO, HC, and NOx emissions. In diesel engines, due to the higher production of PM and NOx, a combination of DOC, DPF, and SCR is required. Diesel catalytic systems are more complex than gasoline ones because they must handle a wider range of pollutants. Catalysts are composed of materials such as platinum, radium, iridium, gold, palladium and cadmium. In gasoline internal combustion engines, catalysts are most efficient

*Corresponding Author
Email Address: alireza4573@gmail.com
https://doi.org/10.22068/ase.2025.686

when the ratio of air to fuel (gasoline) is stoichiometric. The stoichiometric ratio, or air-to-fuel ratio, is about 14.7 to 1. This ratio means the mixture of air and fuel should be about 14.7 units of air to 1 unit of fuel [1]. In IC engines, the combustion of fuel takes place in the presence of air and not pure oxygen. Air contains many constituents, particularly oxygen, nitrogen, argon and other vapors and inert gases. Its volumetric composition is approximately 21% O2, 78% N2, and 1% argon. Since neither nitrogen nor argon enters into the chemical reaction, it is sufficiently accurate to assume that the volumetric air proportions are 21% oxygen and 79% nitrogen and that for 100 moles of air, there are 21 moles of oxygen and 79 moles of nitrogen. That is:

$$\frac{moles(N_2)}{moles(O_2)} = \frac{79}{21} = 3.76 \quad (1)$$

Therefore, for each mole of oxygen in air, there are 3.76 moles of nitrogen, the molecular weight of dry air is taken as 28.967 or 29. To account for argon, which is clubbed with nitrogen, the equivalent molecular weight of nitrogen is taken as 28.16 [2]. The general combustion equation in internal combustion engines is as follows:

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O + \Delta H\,(Energy) \quad (2)$$

Heat is represented as "Energy" on the products side of the equation, indicating that the reaction is exothermic. This means that energy is released in the form of heat generated by the combustion process. The above equation is in the perfect and ideal combustion state of the engine. Unfortunately, in real conditions, the above equation does not always occur and combustion in internal combustion engines occurs incompletely, and products such as CO, HC, NOx and soot may also be produced.

Anyway, depending on the intake air conditions, catalysts also have certain disadvantages. One major drawback is their high cost. The reason why catalysts are expensive is the use of expensive materials such as palladium and gold. Also, catalysts lose their effectiveness after about 60,000 to 80,000 km (depending on the quality of the fuel), which can harm the environment. In some cases, catalysts are destroyed earlier than their useful life. In such cases, the catalysts become toxic and no longer have the necessary efficiency. Among the cases of poisoning of catalysts, it can be mentioned phosphorus poisoning, lead poisoning and sulfur poisoning. Also, sometimes too much heat causes the catalysts to fail. Exhaust catalysts and catalytic converters are designed to withstand occasional high temperature operation. However, prolonged and repeated exposure to temperatures in excess of 1000 K leads to loss of noble metal surface area and even deterioration of the catalyst support [3].

Another way to reduce exhaust gas emissions is the exhaust gas recirculation (EGR). This system reduces the amount of NOx. EGR technique, as one of effective measures to reduce NOx formation, was firstly adopted in diesel engines. But with the growing energy and environment problems, EGR has been commonly used also in gasoline engines together with other advanced techniques [4]. In recent decades, various methods have been employed to enhance hygiene and purify materials and air. For example, chlorine has long been used in water treatment to improve quality and ensure purity. Similarly, ozone gas is utilized to reduce infectious contaminants and further enhance water quality. [5].

Today, ozone gas is used in various fields, including medicine and engineering, to purify and reduce environmental pollution. This gas can be widely used in important applications such as water purification and air disinfection. The use of electric discharge (creating the phenomenon of corona discharge) [6] and the passage of oxygen gas (air) through ultraviolet waves are two methods of producing ozone gas [7]. Ozone gas consists of three hydrogen atoms, which can help remove pollutants and reduce harmful gases such as CO or NOx. Ozone produces both in the Earth's upper atmosphere and at ground level. It can be good or bad, depending on where it is found. Called stratospheric ozone, good ozone occurs naturally in the upper atmosphere, where it forms a protective layer that shields us from the sun's harmful ultraviolet rays. This beneficial ozone has been partially destroyed by manmade chemicals, causing what is sometimes called a "hole in the ozone.

Ozone at ground level is a harmful air pollutant, because of its effects on people and the environment, and it is the main ingredient in “smog. Tropospheric, or ground level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC). This happens when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources chemically react in the presence of sunlight [8]. Of course,

[DOI: 10.22068/ase.2025.686]

the ozone produced by ozone generators is a useful type of ozone. In the past, ozone generators were bulky, but nowadays, portable devices are also used to produce ozone gas, which can be used in small spaces. In this research, using an ozone gas generator, the effect of this gas on the amount of CO gas and other comparative parameters in the exhaust gases was studied. One of the great advantages of using this method in order to reduce engine exhaust gas pollution is the lack of need for final disposal and recycling. In recent years, new models based on artificial intelligence have been developed to analyze heat release and other parameters of internal combustion engines, one of which is based on neural networks to calculate thermodynamic properties and combustion products [9]. By using this method and controlling the amount of ozone injection, it is possible to help reduce CO and other harmful gases in exhaust gases.

2. Equipment

As mentioned, to solve the disadvantages of common catalysts used in the automotive industry, a new and advanced method of using ozone gas and its proper configuration in cars can be used for this purpose. Of course, this method can also be used as a catalyst supplement. The half-life of this gas is limited and it cannot be stored, so it must be consumed in a relatively short period of time. Based on the investigations, there has not been much comprehensive research in this field, that's why we decided to design a comprehensive process to reduce the emissions of gasoline internal combustion engines by using the capacities and undeniable characteristics of ozone gas. In this research, in order to create proper mixing and reaction at the proper time, the chamber and the Fluid transfer system (compressible fluid) was designed and built. Also, to maintain the stability of the reaction and not cause disruption, proper sealing was applied during the process.

2.1. Ozone Generator

In this research, in order to produce ozone gas, a handy ozone generator used for this purpose. This device has shown in Figure 1. Also, this device is equipped with a 120 mm fan, which, due to forced ventilation, air enters from one side and ozone gas is released from the other side. According to the tests, we recognized that this ozone generator can completely cover a 9 square meter room. Also, this device is equipped with a timer that allows you to set the exact time of operation of the device.

Figure 1: Handy Ozone generator

2.2. Fluid Transfer System

The exhaust gas in internal combustion engines has a high pressure and this pressure changes between 1.5 and 3 bar depending on the engine speed. Due to this high pressure, the ozone generator alone is not able to inject gas into the mixing chamber, so we used an ozone transfer system. This system consists of a compressor and a mixing chamber and a fluid transfer pipe. In this process, a two-cylinder compressor was used to overcome the pressure of the exhaust gas. This compressor works with a voltage of 12 volts, so the power of this compressor can be supplied from the car battery. Also, this device was able to provide 10 bar pressures and the air flow rate of this compressor was about 35 cubic meters per hour.

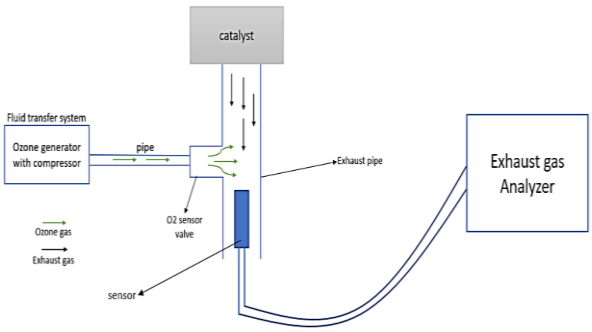

Figure 2: Schematic of CO reduction mechanism

3. Method

In the experimental test section, several cars were used to prove the useful function of this system in reducing CO. By using the ozone fluid transfer system chamber, it was produced and was transferred to the exhaust pipe with the appropriate pressure through the compressor. The transfer of fluid to mix with the exhaust gas is shown in Figure 1. As shown in the figure, the

[DOI: 10.22068/ase.2025.686]

pipe was connected from one side to the chamber and from the other side to the position of the second O_2 sensor.

An important part of this test is the exhaust gas analyzer. AIRREX HG-550 exhaust gas analyzer is able to determine the amount of HC, CO, CO_2, O_2, lambda, AFR, PEF and H/C. This device is also called 5 gas emission analyzer. But among all cases, the amount of Co gas changes in this experiment is very important. The experimental section comprises two distinct segments. In the first segment, the fluid transfer tank is saturated with ozone gas and this gas is directed to the exhaust outlet pipe by the compressor with the appropriate pressure and then reacts with the exhaust gases. In the second segment, After the reaction of ozone gas and exhaust gas, the result of this reaction is analyzed by the sensor and exhaust gas analyzer, and the result can be received both on the screen and in print form. Figure 3 shows the exhaust gas analyzer.

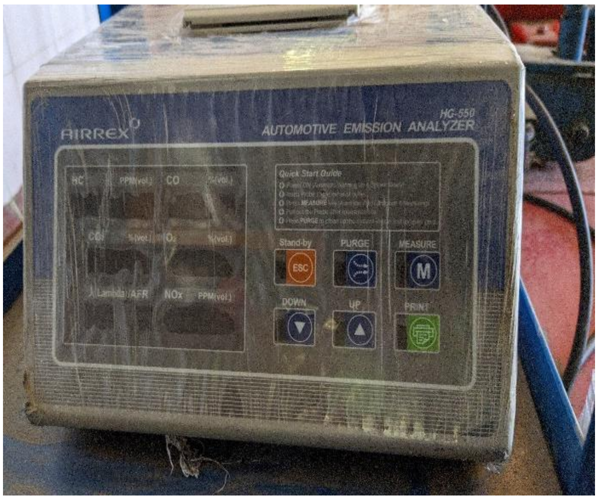

Figure 3:Exhaust gas analyzer

4. Results and Discussion

From the point of view of thermodynamic science, with the reaction of ozone gas with exhaust gases due to the instability of ozone, the bond of this gas is broken and finally this reaction causes a decrease in CO and an increase in O_2. This reaction is shown in Figure 4. In order to estimate the effect of ozone gas on CO reduction, in this research 7 vehicles were tested. After preparing the equipment, the engine was warmed up for a few minutes, then CO, CO_2, HC and Lambda (λ) values were measured with the

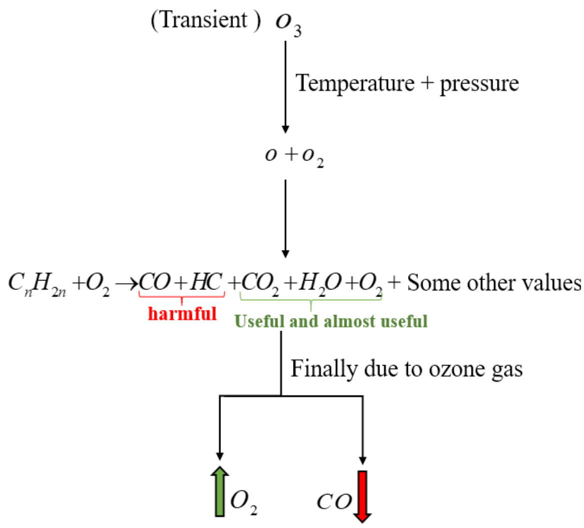

Figure 4: Schematic of the reaction between ozone and exhaust gas

exhaust gas analyzer was used in two methods, normal mode and after ozone gas injection. Finally, the mentioned gases values were printed as an output. Table 1 shows the tested vehicles along with their specifications. In an experiment, several samples with different characteristics are used to check the validity of the results. As a result, in this research, 7 samples were used to validate the results. One of the primary concerns regarding the validity of our findings is the variation in vehicle mileages across the sample. However, this variation does not significantly impact the accuracy of the results. The fundamental chemical mechanism through which ozone reduces carbon monoxide emissions remains unchanged regardless of the vehicle's age or mileage. The reaction between ozone and CO occurs in the exhaust system, and its effectiveness is not directly influenced by the vehicle's wear and tear. All vehicles in the study were tested under standardized conditions, ensuring that variables such as engine temperature, ambient conditions, and ozone injection dosage were consistent. This minimizes the impact of mileage differences on the results. While older or high-mileage vehicles may have more worn-out catalytic converters, the effect of ozone injection is still observed. The presence of ozone enhances oxidation reactions, compensating for the reduced efficiency of aging catalytic converters, further validating our findings. Instead of focusing on absolute emission levels, the study assesses the percentage reduction in CO emissions after ozone injection. This normalization ensures that the effectiveness of ozone is measured consistently across vehicles with different mileages.

[DOI: 10.22068/ase.2025.686]

Table 1: Characteristics of test items

Name of vehicles	Vehicle milage	Date of test
Renault Tondar 90 plus	51286	12/11/2023
Saipa Tiba(1st)	111451	12/14/2023
Peugeot 206(1st)	231000	12/8/2023
Saipa Tiba(2nd)	165300	12/10/2023
Ikco Roa	221015	12/17/2023
Peugeot 206(2nd)	321002	12/19/2023
Saipa Tiba 2	173441	12/20//2023

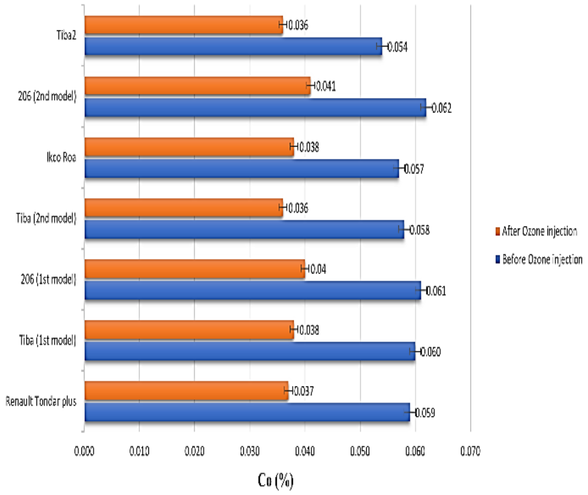

Figure 5: The amount of CO before and after ozone injection.

Figure 6: Ozone injection test in Renault Tondar 90 plus Automatic.

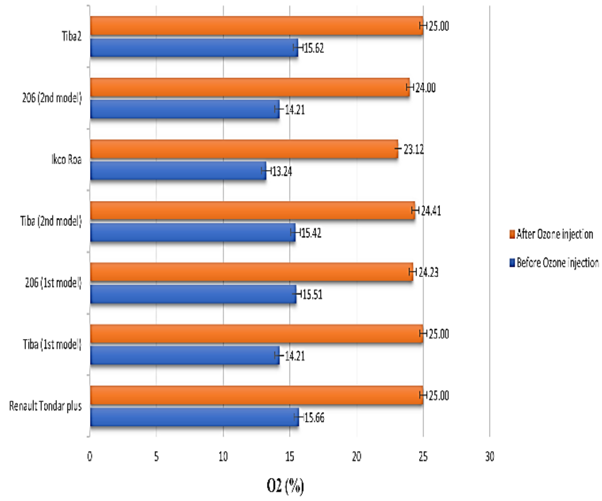

Figure 7: The amount of O_2 before and after ozone injection.

As shown in the graph related to the analysis of the amount of CO gas (Figure 5), after the injection of ozone gas in the exhaust pipe, the amount of CO gas in all vehicles has decreased significantly, which shows that this gas is effective in reducing CO. As mentioned before, ozone gas is composed of three oxygen atoms. When this gas reacts with CO, an atom combines with CO and this gas turns into CO_2 and finally ozone turns into O_2. For this reason, the amount of CO has decreased significantly. By comparing the samples, it can be concluded that the amount of CO has been reduced acceptably. For example, in the Renault Tondar 90 Plus with an automatic transmission, the CO percentage before ozone injection was equal to 0.059%, which after injection decreased to 0.037%. This process was repeated in the rest of the samples. After analyzing the amount of CO with the exhaust gas analyzer, the amount of O2 was also analyzed. As the amount of CO decreased, the amount of O2 also increased. The amount of oxygen in each sample is shown in Figure 7.

As mentioned, the lambda parameter is a parameter that plays an important role in engine ignition. Lambda is the air-fuel ratio of the engine in the non-ideal state compared to the air-fuel ratio in the stoichiometric state. The best value for lambda is 1. This amount of lambda shows that the ratio of air to fuel in the engine is equal to the stoichiometric state, which causes a significant reduction in CO. But achieving this number is very difficult and almost impossible in all stages of engine operation. The amount of lambda is defined in three general modes. If the lambda is greater than one ($\lambda > 1$), the air-to-fuel ratio is rich, and if it is less than one ($\lambda < 1$), the air-to-fuel ratio is lean. The best case of lambda is a number close to 1($\lambda \approx 1$). As shown in Figure 8, the amount of lambda increased significantly after the injection of ozone gas, which shows the effect of ozone gas on exhaust gases.

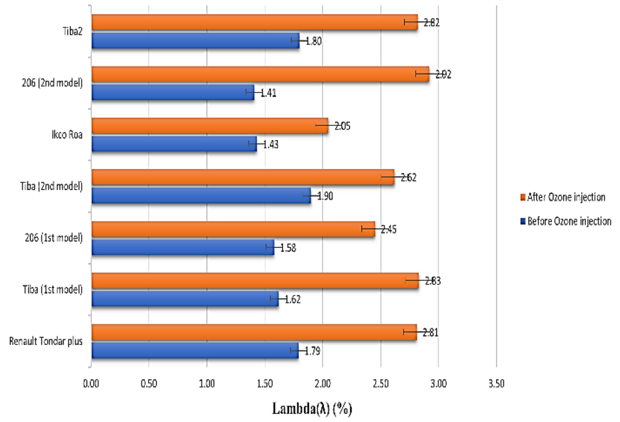

Figure 8: percentage of lambda changes (before and after injection)

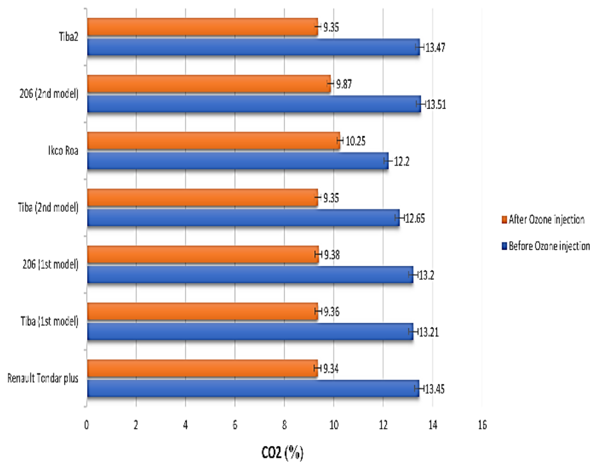

Figure 9: The amount of CO_2 before and after ozone injection

After analyzing and checking all the important parameters of this test, the amount of CO_2 gas was analyzed. According to the results obtained in recent years, this gas is considered one of the important factors in global warming. This gas is produced by many sources in nature. Plants and animals can produce this gas. As shown in Figure 9, the amount of CO_2 decreased significantly after the injection of ozone gas. The significant reduction of CO_2 gas after the injection of ozone gas is one of the advantages of this method compared to the use of a catalyst.

4.1. Statistical Analysis results

Using the provided CO reduction data from seven tested vehicles, we computed the following values:

1. Mean Co Reduction:

$$\bar{x} = \frac{\sum x_i}{n} \rightarrow \bar{x} = \frac{34.5+39.1+37.2+36.5+35.8+40.2+34.9}{7} = 36.89\% \quad (3)$$

2. Standard Deviation (SD):

$$SD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \quad (4)$$

Substituting the values:

$$SD = \sqrt{\frac{(5.72+4.88+0.1+0.15+1.19+11+3.97)}{7-1}} = 2.12 \quad (5)$$

To assess the statistical confidence of our findings, a 95% confidence interval (CI) was determined:

$$CI = \bar{x} \pm Z \times \frac{SD}{\sqrt{n}} \quad (6)$$

For a 95% confidence level, Z = 1.96. Substituting the values:

$$CI = 36.89 \pm 1.96 \times \frac{2.12}{\sqrt{7}} \quad (7)$$

$$CI = 36.89 \pm 1.57 \rightarrow CI = (35.32\%, 38.46\%) \quad (8)$$

4.2. Interpretation of Results

The results of the study show a significant reduction in CO emissions across all seven tested vehicles. The average CO reduction observed was 36.89%, with individual reductions ranging between 34.5% and 40.2%**.** This indicates that ozone injection was generally effective in reducing CO emissions, with some variation observed across different vehicles.

The calculated standard deviation of 2.12 reflects the variability in CO reduction among the tested vehicles. A standard deviation provides insight into how much individual data points differ from the mean. In this case, the SD suggests that the CO reduction percentages varied by an average of ±2.12% from the mean of 36.89%. This indicates that while the results show general effectiveness, there are differences between how the ozone injection affects different engines. For example, a higher standard deviation would suggest that the results are more spread out and less consistent, while a lower standard deviation would indicate more uniform results across all tested vehicles. The SD of 2.12 indicates moderate variability, which is typical when testing multiple vehicles under controlled conditions.

[DOI: 10.22068/ase.2025.686]

The 95% confidence interval for the CO reduction is (35.32% – 38.46%), meaning we can be 95% confident that the true average CO reduction for all vehicles falls within this range. The confidence interval is a statistical measure used to estimate the reliability of the mean value. A narrower CI would indicate a higher level of precision in estimating the true mean, while a wider CI suggests more uncertainty in the result. In this case, the CI range of 35.32% to 38.46% indicates that the ozone injection method is fairly consistent in its effectiveness, with a relatively small range of variation in the observed CO reductions. This reinforces the reliability of the ozone injection method in reducing CO emissions under controlled laboratory conditions.

5. Conclusions

Petrol combustion is a complex process that forms the backbones of the modern transportation. Despite its efficiency in powering vehicles, it has significant environmental implication due to its contributions to pollution and greenhouse gas emissions. As technology evolves, cleaner and more efficient alternatives are being developed to reduce the reliance on petrol-powered internal combustion engines, marking a shift toward more sustainable forms of transportation. CO_2 is one of the gases that causes global warming. One of the disadvantages of CO_2, which has been partially solved in this method. The economic feasibility of using ozone injection as a method to reduce carbon monoxide (CO) emissions in vehicles can be justified through several key aspects. Many countries impose environmental fines on vehicles that fail to meet emission standards. Non-compliant vehicles may also be restricted from entering low-emission zones. Implementing ozone injection can help vehicles meet the required emission thresholds, thereby reducing the financial burden associated with fines and regulatory penalties. Compliance with emission standards ensures continued operation without additional costs related to penalties. Conventional emission control systems, such as three-way catalytic converters, diesel particulate filters, and engine upgrades, require significant investment in hardware replacement and maintenance. In contrast, ozone injection offers a lower-cost solution that does not necessitate major modifications to the engine or exhaust system. This makes it a more viable option, particularly for older vehicles where retrofitting with newer emission control systems would be financially impractical. Studies indicate that a reduction in CO emissions can correlate with improved combustion efficiency. More complete combustion means less unburned fuel, which can lead to lower fuel consumption over time. Although ozone injection is primarily targeted at reducing pollutants, its potential to enhance combustion efficiency provides an economic advantage by lowering fuel expenses for vehicle owners. High levels of CO emissions are often associated with incomplete combustion, leading to carbon buildup in engine components and exhaust systems. By reducing CO emissions, ozone injection helps to minimize carbon deposits, which can extend the lifespan of the catalytic converter and engine components. This leads to reduced maintenance costs by lowering the frequency of expensive repairs and part replacements. The economic rationale for using ozone injection in vehicles is clear: it provides a cost-effective and efficient alternative to conventional emission control methods. By reducing regulatory fines, improving fuel efficiency, decreasing maintenance costs, and qualifying for government incentives, ozone injection offers a financially viable solution for reducing vehicular emissions. This method is particularly advantageous for fleet operators and owners of older vehicles who seek an affordable way to comply with environmental regulations. After all the experiments on the samples, the following results can be extracted:

1. By analyzing the exhaust gases with the exhaust gas analyzer, after the injection of ozone gas, the amount of CO decreased significantly.
2. This method can also be used as a supplement to car catalysts.
3. The average CO reduction observed was 36.89%. The standard deviation was 2.12, showing moderate variation in results. The 95% confidence interval was (35.32%, 38.46%), meaning we are 95% confident that the true mean CO reduction falls within this range.
4. This analysis statistically confirms that ozone injection significantly reduces CO emissions with high reliability.

Further Study Recommendations

To build upon the findings of this study and address potential limitations, we suggest the following areas for further research:

1. Investigating the difference in the effect of ozone gas in Carburetor and injector vehicles.
2. Studying the effect of ozone on 4, 6, 8-cylinder engines.

[DOI: 10.22068/ase.2025.686]

3. Investigating the extent of catalyst degradation over the traveled distance and its impact on the efficiency of pollutant reduction processes could be a subject for future studies to better evaluate its effect on the overall performance of the proposed reactions.
4. Long-Term Effects of Ozone Injection
5. Investigating whether prolonged exposure to ozone affects the engine or exhaust components over extended periods.
6. Studying potential interactions with catalytic converter longevity and efficiency.
7. Optimization of Ozone Dosage
8. Determining the most efficient concentration of ozone for different types of engines.
9. Exploring whether there is a threshold beyond which ozone injection becomes less effective or counterproductive.
10. Broader Vehicle Categories and Driving Conditions
11. Expanding the study to include diesel, hybrid, and electric vehicles.
12. Testing ozone injection under varying real-world driving conditions (e.g., city vs. highway driving).

Declaration of Conflicting Interests

The author declares that there is no conflict of interest such as financial or mandate from any particular organization.

Acknowledgements

Special thanks are extended to Technical and Vocational Training organization (Shahid Khodai Technical and Vocational Center) for their support such as exhaust gas analyzer device and 2-cylinder air compressor and some other equipments.

References

[1] Ntziachristos, L., & Samaras, Z. (2000). Speed-dependent representative emission factors for catalyst passenger cars and influencing parameters. Atmospheric Environment, 34(27), 4611–4619.

[2] H.N. Gupta. (2013). *fundamentals of internal combustion engines* (2nd edition).

[3] Taylor, K. C. (1984). Automobile Catalytic Converters (pp. 119–170).

[4] Wei, H., Zhu, T., Shu, G., Tan, L., & Wang, Y. (2012). Gasoline engine exhaust gas recirculation – A review. Applied Energy, 99, 534–544.

[5] Rice, R. G. (1996). Applications of ozone for industrial wastewater treatment — A review. *Ozone: Science & Engineering*, *18*(6), 477–515.

[6] Yao, S., Wu, Z., Han, J., Tang, X., Jiang, B., Lu, H., Yamamoto, S., & Kodama, S. (2015). Study of ozone generation in an atmospheric dielectric barrier discharge reactor. *Journal of Electrostatics*, *75*, 35–42.

[7] Claus, H. (2021). Ozone Generation by Ultraviolet Lamps. *Photochemistry and Photobiology*, *97*(3), 471–476.

[8] United states Environmental Protection Agency. https://www.epa.gov.

[9] Brusca S, Lanzafame R, & Messina M. (2005). *A Combustion Model for ICE.*