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# ASSESSING CATALYTIC CONVERTER DEGRADATION IN EMISSION REDUCTION: COMPARATIVE STUDY OF CO, THC, AND NOx ACROSS MILEAGE, ENGINE CAPACITY, AND TRANSMISSION TYPE

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**ABSTRACT.** *Environmental concerns have led to stricter global emission standards for combustion engine vehicles. This study evaluates the degradation patterns of catalytic converters in reducing CO, THC, and NOx emissions across 20 passenger vehicles with varying mileage (up to 100,000 km), engine capacities (1.2 - 1.5L), and transmission types (manual/automatic). Four catalytic converter designs (Types A-D) were assessed using the New European Driving Cycle (NEDC) methodology for compliance with Indonesian and EURO-4 standards. Results revealed that Type D converters maintained the best performance for CO (0.2 - 0.4 g/km) and THC emissions (0.02 - 0.04 g/km) with stable degradation across their lifespan. Conversely, Type B exhibited significant degradation (degradation factor 9.0) and higher emission levels overall. Statistical analysis showed significant differences in THC emissions between converter types ($p < 0.05$), while differences in CO and NOx were not statistically significant ($p > 0.05$). NOx emissions showed the highest degradation factor (5.78) across all converter types. This research demonstrates the critical relationship between catalytic converter design, vehicle operational parameters, and emission reduction effectiveness over time, providing insights for future catalyst material development and maintenance strategies to maintain long-term environmental compliance.*

## INTRODUCTION

Environmental pollution has become a significant global challenge alongside rapid industrialization and technological advancement. Urban populations increasingly fail to meet air quality standards set by the World Health Organization (WHO) (WHO, 2016a), and air pollution continues to rise globally (European Environment Agency, 2016), making it a recognized public health emergency (United States Environmental Protection Agency, 2024). The automotive transportation sector plays a major role in this issue by emitting harmful gases such as carbon monoxide (CO), total hydrocarbons (THC), and nitrogen oxides (NOx) from vehicle exhaust (Walsh, 2011; IEA, 2017; UNECE, 2023).

Governments worldwide have introduced regulations aimed at reducing automotive emissions and promoting environmentally friendly vehicles (Kholod & Evans, 2016; European Commission, 2019). These standards differ across countries based on policy readiness and infrastructure support. The

European Union has set $CO_2$ emission targets for new cars (Gaikindo, 2020), while Russia emphasizes black carbon reduction due to diesel transport (Kholod & Evans, 2016). Indonesia implemented Euro 4 emission standards in 2018, with permitted levels for CO max 1 g/km, THC max 0.1 g/km, and NOx 0.08 g/km (Republic of Indonesia, 2017), supported by regulations for compliance (UNCAS, 2019; Tempo, 2024) and a roadmap targeting Euro 5 adoption by 2027 (OECD, 2019). However, the success of such standards depends heavily on fuel availability and supporting distribution infrastructure (AEA Technology, 2021).

Emission standards such as Euro 4, 5, and 6 define permissible levels of CO, THC, NOx, and particulate matter (PM) (European Commission, 2007; ACEA, 2014). Euro 5 and Euro 6 introduce stricter limits, necessitating advancements in fuel quality and emission control technologies (ICCT, 2016; van Wee, 2019). Some countries also require an Air Pollution-Health Risk Assessment (AP-HRA) for policies affecting air quality (WHO, 2016b). To meet these regulations, manufacturers deploy catalytic converters that use oxidation and reduction catalysts to convert toxic gases into less harmful substances (Twigg, 2007; Heck *et al*., 2012; Ashok, 2021). These devices are designed to maintain emissions below regulated limits throughout a vehicle's lifespan (Johnson, 2015; Milku *et al*., 2024), but their performance can degrade due to mileage, wear, and varying operating conditions (Li *et al*., 2001; Abdolmaleki *et al*., 2020).

Although catalytic converters are widely used, long-term evaluations of their real-world performance remain limited (Giuliano *et al*., 2020; Barbier *et al.*, 2023). Efficiency loss over time can lead to increased emissions, reducing environmental compliance (Zotin *et al*., 2005). Research has shown that engine output, operating conditions, and fuel quality all influence emission levels. Kim *et al*. (2020) and Kim *et al*. (2021) observed increased PM and NOx with higher engine loads and high CO levels during start-up and acceleration. Other studies highlight the roles of fuel detergency and additives in reducing $CO_2$, CO, and HC emissions (Kean *et al*., 2003; Zhu *et al*., 2016; Zheng *et al*., 2017; Shabanov *et al*., 2020; Daud *et al*., 2022). Driving behaviour, such as acceleration and deceleration, and road gradient also significantly affect emission levels (André & Rapone, 2009; Pathak *et al*., 2016; Prakash & Bodisco, 2019; Jang *et al*., 2023). Emissions are particularly high during positive acceleration, contributing to increased particle counts (Pelkmans & Debal, 2006; Weiss *et al.*, 2013). Differences between Real Driving Emissions (RDE) and New European Driving Cycle (NEDC) testing further underscore the importance of accurate emission assessments (Fontaras *et al.*, 2014).

Life cycle studies show that emissions and fuel consumption from internal combustion engines significantly affect environmental load (Hawkins *et al*., 2013; Messagie *et al*., 2014; Wu *et al*., 2017; Bieker, 2021), with mileage and maintenance practices being key influencing factors (Sakno *et al.*, 2021). Previous research has established methodological approaches for studying catalytic converter degradation with varying sample sizes. Van der Schoot *et al*. (2001) conducted an experimental study of 24 catalysts (9 with lower mileage under 40,000 km and 15 with high mileage up to 80,000 km), concluding that degradation was primarily caused by thermal deterioration. de Almeida *et al.* (2014) analyzed a single vehicle's catalytic degradation over 30,000 km at 10,000 km intervals, finding degradation factors of 1.40 for CO and NOx emissions and 1.34 for MNHC emissions. Corvalán and Vargas (2003) utilized a database of 160 light-duty vehicles across 9 driving cycle categories, determining that deterioration depends on average speed and accumulated distance.

This study analyzes the degradation of catalytic converter performance in 20 Jakarta-based vehicles with varying engine capacities and transmission types. Using NEDC-based tests under Euro 4 conditions, emissions of CO, THC, and NOx were measured across a mileage range of almost 100,000 km. All vehicles received standard maintenance (European Commission, 2007; Toyota Motor Corporation Australia Limited, 2025), and the findings aim to inform catalytic design improvements and long-term emission reduction strategies (van der Schoot *et al.*, 2001). By examining the comparative performance of different catalytic converter types across multiple parameters, this research addresses a critical gap in understanding how these emission control technologies perform throughout their operational lifetime.

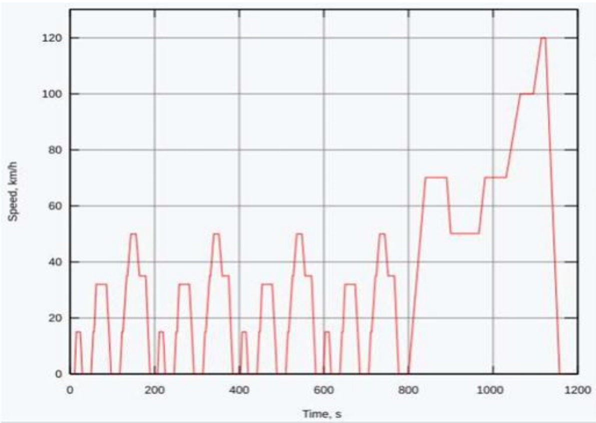
## METHODOLOGY

### Emission Data

Emission measurement data were collected from the laboratory certified by Vincotte Belgium, which conducted the Euro 4 emission tests. The total number of vehicles was 20 units from various models: AMPV, BMPV, SUV, and Van, consisting of different engine capacities and transmission types. Before conducting the test, it was important to ensure that each vehicle received maintenance treatment. The treatments included standard services such as changing the engine oil, fuel filter, and air filter, as well as draining the remaining fuel from the gasoline tank and replacing it with Euro 4 gasoline.

### Experimental Test

The New European Driving Cycle (NEDC) test mode was a driving pattern implemented to assess vehicle emissions and fuel economy, excluding light trucks and commercial vehicles. It is also referred to as the MVEG cycle (Motor Vehicle Emissions Group). It consists of four times ECE-15 urban driving cycles (UDC) and one time Extra-Urban driving cycle (EUDC). The NEDC, intended to represent typical car usage in Europe, has faced repeated criticism for often delivering unachievable economy figures. Some preparations were needed and conducted before the test. Figure 1 shows the test cycle process.




**NEDC Test**

| No | Activity |
|---|---|
| 1 | Setting vehicle to Chassis Dyno |
| 2 | Fit Exh tail to pipe CVS |
| 3 | Setting Cooling fan |
| 3 | Setting Operational vehicle data to VET System |
| 4 | Setting Road Load data at Chassis Dyno |
| 5 | Setting Test Mode Euro4 NEDC |
| 6 | Klik Start at PC control Chassis Dyno for Analysis |
| 7 | Run NEDC test for 20 Menit then idle rpm 5 menit |
| 8 | Evaluation Coasdown for 1 time run |

**Figure 1.** NEDC Test Mode, the ECE-15, Urban Driving Cycle (UDC), and Extra Urban Driving Cycle (EUDC) (Source: van der Schoot *et al.*, 2001).

### Data Collection and Analysis

Data collection in this study employed quantitative methods to analyse the performance of various vehicles with various catalytic converter types based on their service life. The research steps are as follows:

*Data Collection*

Emission measurement data is collected in a laboratory that adheres to the EURO 4 emission test measurement standard. Before conducting the test, the vehicle being evaluated has undergone general maintenance procedures, including the replacement of engine oil, oil filters, air filters, fuel filters, and refuelling with Euro 4 Gasoline. Emission content data collected during testing includes CO (Carbon monoxide), THC (Total hydrocarbons), and NOx (Nitrogen oxides). Testing was conducted on 25 vehicles. 5 vehicles for each catalyst type A, B, C, and D, as well as across a range of some period, driven on each catalyst type. Catalyst A, used for the 1.2-liter engine, the vehicle sample consists of 3 units with automatic transmission and 2 units were manual transmission. Catalyst B, used for 1.3 and 1.5-liter engines with all manual transmission types. Catalyst C is used for the 1.5-liter engine and consists of 4 units of automatic transmission and 1 unit was manual transmission. The last catalytic is D type, consists of 1,3 and 1,5 litres engines, and all of the vehicle samples were manual transmission.

*Analysis Procedure*

The output of the emission test data was the emission content of CO, THC, and NOx. Software MATLAB version R2024 was utilized to process the data to create the analysis of variance, correlation analysis, and regression. These statistical tests identified any significant differences in emissions among catalysts for CO, THC, and NOx levels. MATLAB was also used to assess and visualize the distribution and variability of emissions for each type of catalyst. The first analysis was an analysis of variance to visualize a graph showing each catalyst's effect on emission gases. The next was a correlation analysis of emission levels toward mileage and engine capacity, as well as a comparison between transmission types through a t-test. The analysis continued with the variance of transmission types and presented a graph to show the tendencies. Next, linear regression was used to analyze the data for each catalyst, and finally, analyses were conducted to examine the degradation of the catalyst through a first-order kinetic reaction equation and the second Arrhenius equation.

*Analysis Model*

First-order reaction kinetics models and second-Arrhenius-type models were employed to analyze the experimental data on CO, THC, and NOx emissions. By adopting these theoretical frameworks, the objective was to evaluate the degradation behaviour of each catalyst over time and the corresponding emission levels. For CO and THC emissions, a first-order reaction kinetics model was utilized (Ma *et al.*, 2009). This model is typically used to describe processes where the rate of change is proportional to the current value, such as a decline in catalyst efficiency resulting in increased emissions. We can assess how effectively each catalyst maintains low emission levels over the distance traveled by fitting the CO and THC emission data to an exponential model. The fitted models facilitate quantifying the rate of degradation in catalyst performance.

In the case of NOx emissions, an Arrhenius-type model was employed. The Arrhenius equation is commonly used to describe the relationship between chemical reaction rates and temperature; however, in this context, it has been adapted to model the variation in NOx emissions relative to the distance travelled. This approach offers valuable insights into the degradation behaviour of the catalyst, particularly in reducing NOx emissions over extended use. The fitted Arrhenius model enables us to comprehend each catalyst's efficiency decline, which subsequently affects NOx emissions (Wang *et al.*, 2016; Huang *et al.*, 2017).

The resulting graphs for each catalyst type display experimental data and the fitted model. First-order and Arrhenius fits are plotted to compare predicted emission trends over the distance travelled with the observed values. This analysis is conducted to assess the effectiveness of each catalyst type at each specified period. To obtain good analysis results, we use the regression equation in each plot, which helps us read the data on the relationship between distance travelled and emissions for each catalyst type. The graphs generated for each catalyst type include experimental data along with the fitted model. The first-order and Arrhenius fits are plotted to compare the predicted emission trends against mileage with the actual observed values. Regression equations are also presented in each plot, which helps interpret the model parameters and understand the relationship between travel distance and emissions for each catalyst type. This analysis aims to determine the effectiveness of each type of catalyst in minimizing emissions over time, providing valuable information to improve catalytic converter technology.

## RESULTS AND DISCUSSIONS

Samples of vehicle catalytic converters from around Jakarta city were obtained from one of the emission testing laboratories certified by the international body. The sample included several indicators: catalytic types, engine capacity, transmission, mileage, and emissions. The emission data presented in Table 1 comprehensively compare CO, THC, and NOx emissions across four different types of catalytic converters (types A, B, C, and D). Meanwhile, the degradation factor of the catalyst was defined by comparing emission concentration data after transitioning from used to new vehicle conditions. Results from previous and current studies are shown in Table 2.

**Table 1**. Catalytic converter performance test data.

| No. | Catalytic Type | Vehicle Data | | | Emissions (g/km) | | |
|---|---|---|---|---|---|---|---|
| | | **Engine Capacity (cc)** | **T/M Speck** | **Mileage (km)** | **CO** | **THC** | **NOx** |
| 1 | A | 1200 | AT | 19.792 | 0,235 | 0,059 | 0,015 |
| 2 | A | 1200 | MT | 23.796 | 0,386 | 0,055 | 0,018 |
| 3 | A | 1200 | MT | 36.106 | 0,408 | 0,047 | 0,012 |
| 4 | A | 1200 | MT | 51.617 | 0,493 | 0,061 | 0,018 |
| 5 | A | 1200 | AT | 72.319 | 0,502 | 0,066 | 0,021 |
| 6 | B | 1300 | MT | 24.749 | 0,332 | 0,048 | 0,014 |
| 7 | B | 1300 | MT | 75.068 | 0,411 | 0,062 | 0,027 |
| 8 | B | 1300 | MT | 91.751 | 0,697 | 0,066 | 0,052 |
| 9 | B | 1500 | MT | 34.700 | 0,513 | 0,048 | 0,022 |
| 10 | B | 1500 | MT | 91.702 | 0,437 | 0,047 | 0,024 |
| 11 | C | 1500 | MT | 918 | 0,371 | 0,037 | 0,007 |
| 12 | C | 1500 | AT | 8.853 | 0,489 | 0,050 | 0,015 |
| 13 | C | 1500 | AT | 37.095 | 0,277 | 0,062 | 0,023 |
| 14 | C | 1500 | AT | 50.317 | 0,316 | 0,059 | 0,028 |
| 15 | C | 1500 | AT | 60.152 | 0,259 | 0,057 | 0,027 |
| 16 | D | 1500 | MT | 19.491 | 0,354 | 0,028 | 0,023 |
| 17 | D | 1500 | MT | 20.215 | 0,283 | 0,025 | 0,034 |
| 18 | D | 1500 | MT | 62.795 | 0,303 | 0,030 | 0,027 |
| 19 | D | 1300 | MT | 21.156 | 0,497 | 0,041 | 0,015 |
| 20 | D | 1300 | MT | 40.164 | 0,384 | 0,035 | 0,015 |

**Table 2**. Comparison studies: Degradation Factor**.**

| Approach | Deterioration | | |
|---|---|---|---|
| | **THC** | **CO** | **NOx** |
| AP-42 | 1.17 | 1.40 | 1.10 |
| COPERT | 1.46 | 1.44 | 1.51 |
| Roberto M. | 3.23 | 1.72 | 3.04 |
| Rodriguez P. | 1.34*) | 1.40 | 1.40 |
| Present Study | 1.36 | 1.88 | 5.78 |

Note: *) MNHC

## Catalyst Performance

Figure 2A illustrates the distribution of carbon monoxide (CO) emissions. The Type B converter catalyst shows less than optimal results in reducing CO emissions, indicated by results between 0.4 to 0.6 g/km. This result is inversely proportional to the Type D catalyst, which shows the lowest CO emission level at 0.2 to 0.4 g/km. It also indicates that this converter is the most effective in minimizing CO compared to other types. Type A has moderate CO emissions, while Type C demonstrates a relatively narrow distribution with values lower than Type B but higher than Type D. These data take one test per vehicle after conducting maintenance treatments to refresh engine combustion performance as a standard, such as replacing engine oil, changing filters, and cleaning the combustion chamber.

Figure 2B focuses on total hydrocarbon (THC) emissions. Type D performs the best again, with emissions tightly clustered between 0.02 and 0.04 g/km and a significantly lower median value compared to other types. In contrast, Type A shows a moderately wide distribution, with THC emissions ranging from 0.04 to 0.06 g/km. Type B has a similar but slightly wider range of THC emissions, indicating inconsistent performance. Type C shows a moderate improvement over Types A and B, with emissions ranging from 0.03 to 0.05 g/km. Figure 2C presents the NOx emissions for each catalytic converter type. Type A converter catalysts show quite optimal results in reducing NOx emissions, indicated by a value between 0.01 to 0.03 g/km; the same occurs for Type D converter catalysts. However, unlike Type A and D catalysts, Type B catalysts show less favorable results, with the efficiency level of this catalyst on NOx emissions ranging from 0.02 to 0.04 g/km. Type C has a distribution similar to Type B, with a slightly higher median value, reflecting moderate but not exceptional performance.

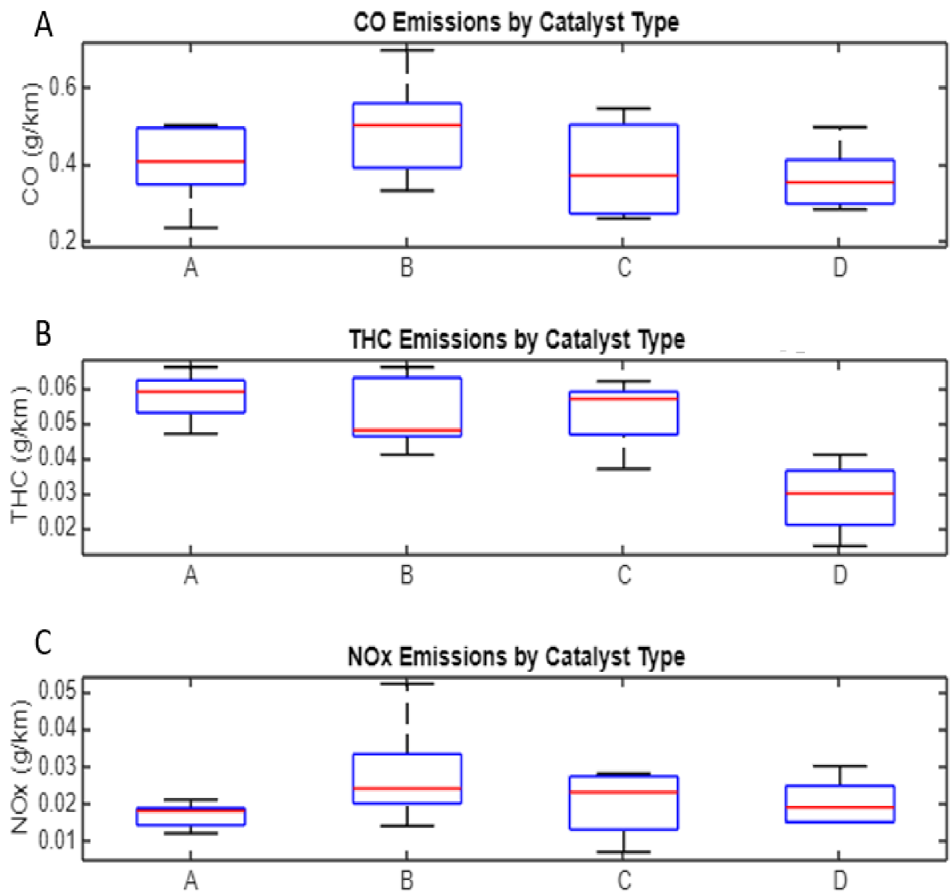



**Figure 2**. Performance of each type of catalyst: (A) against CO emissions; (B) against THC emissions; and (C) against NOx emissions.

### Emissions Trend as a Function of Vehicle Mileage

Figures 3A, 3B, and 3C illustrate the trends in CO, THC, and NOx emissions as a function of vehicle mileage. In Figure 3A, there is a positive but not statistically significant correlation between mileage and CO emissions, with a correlation coefficient (r) of 0.361 and a p-value of 0.118. This suggests a mild upward trend in CO emissions as mileage increases, but the relationship is not strong. Figure 3B shows different results, where a significant positive correlation between distance traveled and THC emissions, with r = 0.452 and p = 0.045, indicates that THC emissions tend to increase with longer distances. Figure 3C shows a strong and significant relationship between distance traveled and NOx emissions, with r = 0.632 and p = 0.003, indicating that NOx emissions increase significantly with greater distance.

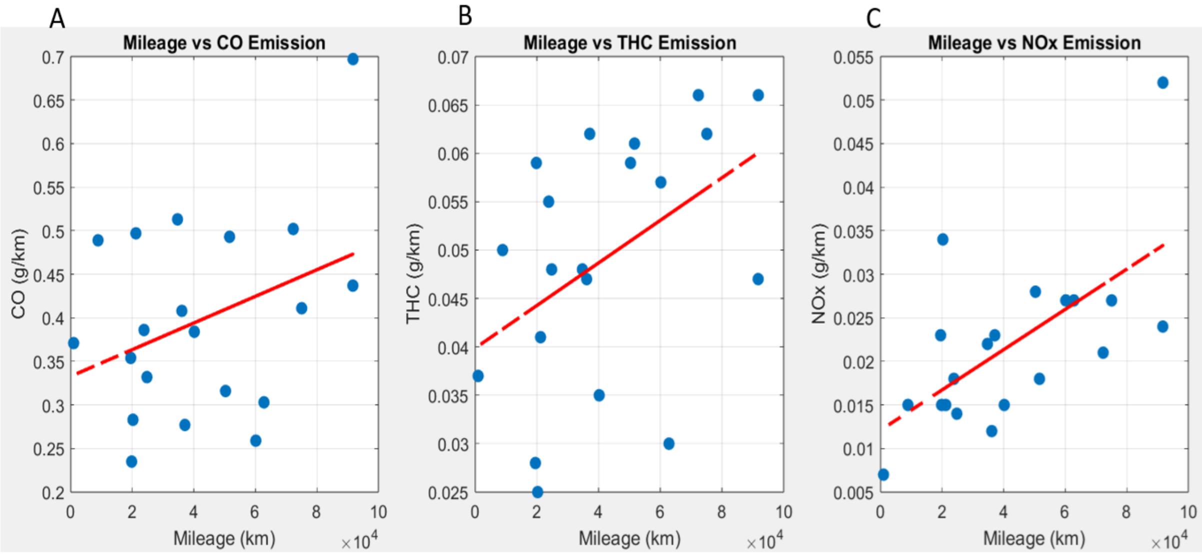



**Figure 3.** Illustration of emissions trend as a function of vehicle mileage: (A) against CO emissions; (B) against THC emissions; and (C) against NOx emissions.

As shown in Table 3, the correlation analysis between engine capacity and emissions reveals varying relationships. CO emissions have a negative correlation with engine capacity (r = -0.275) but are not statistically significant (p = 0.241). THC emissions also show a negative correlation with engine capacity (r = -0.427), with a p-value of 0.060, indicating a trend where larger engines might produce lower THC emissions, although this is only marginally significant. NOx emissions, however, have a weak positive correlation with engine capacity (r = 0.197) and are not statistically significant (p = 0.405). These results imply that engine capacity may not be a strong predictor of CO and NOx emissions, but could have a modest influence on THC emissions.

**Table 3.** Correlation of emissions against mileage and engine capacity.

| Relation | CO | | THC | | NOx | |
|---|---|---|---|---|---|---|
| | **r-value (correlation coefficient)** | **p-value** | **r-value (correlation coefficient)** | **p-value** | **r-value (correlation coefficient)** | **p-value** |
| Mileage | 0.361 | 0.118 | 0.452 | 0.045 | 0.632 | 0.003 |
| Engine Capacity | -0.275 | 0.241 | -0.427 | 0.060 | 0.197 | 0.405 |

## Emissions Trend as a Function of Engine Capacity

Figure 4A shows the relationship between engine capacity (measured in cubic centimeters, cc) and CO emissions. The graph line shows a negative correlation, meaning CO emissions tend to decrease with increasing engine capacity. Although the graph shows a relatively large spread of variability, this aligns with the correlation analysis, where a weak negative correlation was identified between engine capacity and CO emissions ($r = -0.275$, $p = 0.241$) (see Table 3). However, the downward slope of the graph line implies that vehicles with large engine capacities can emit lower levels of CO. In Figure 4B, the scatter plot shows the correlation between engine capacity and THC emissions. The trend line shows a negative correlation: THC emissions tend to decrease with increasing engine capacity. The data points show less variability than CO emissions, and the downward trend is more pronounced. This aligns with the correlation coefficient of -0.427 ($p = 0.060$) (see Table 3), which indicates a stronger negative relationship, although slightly significant, between engine capacity and THC emissions. These results confirm that vehicles with larger engines are more efficient in reducing THC emissions. Figure 4C illustrates the relationship between engine capacity and NOx emissions. The trend line in this scatter plot indicates a weak positive correlation, with NOx emissions slightly increasing as engine capacity grows. However, the distribution of data points is highly scattered, and the correlation is not statistically significant, as indicated by a correlation coefficient of 0.197 ($p = 0.405$) (see Table 3). This weak relationship suggests that engine capacity does not substantially impact NOx emissions.

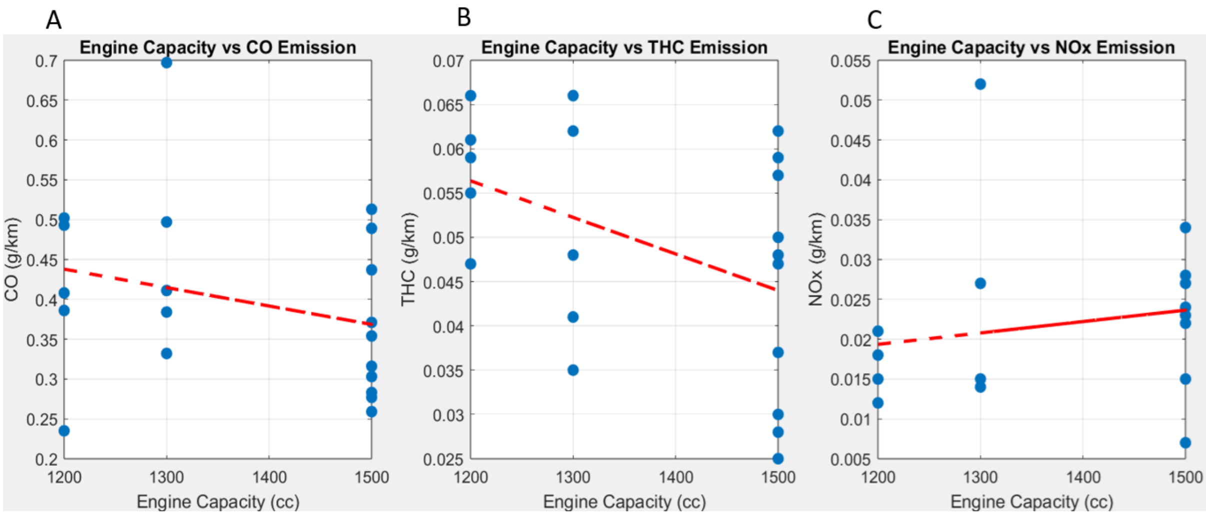



**Figure 4.** Illustration of emissions trend as a function of engine capacity: (A) against CO emissions; (B) against THC emissions; and (C) against NOx emissions.

## Emissions Trend as a Function of Transmission Type

The analysis of the impact of transmission type (AT vs. MT) on emissions shows notable differences. As shown in Table 4, the t-test results indicate that CO emissions are higher in manual transmission (MT) vehicles (mean: 0.419 g/km) compared to automatic transmission (AT) vehicles (mean: 0.346 g/km), though the difference is not statistically significant ($t = -1.361$, $p = 0.190$). For THC emissions, the t-test reveals a significant difference ($t = 2.482$, $p = 0.023$), with AT vehicles producing higher THC emissions (mean: 0.059 g/km) compared to MT vehicles (mean: 0.045 g/km). NOx emissions, however, show no significant difference between AT and MT transmissions, with identical means of 0.022 g/km and a t-value of -0.103 ($p = 0.919$).

Figure 5A shows the distribution of CO emissions for vehicles with AT and MT. The box plot reveals that cars with manual transmissions (MT) generally have higher CO emissions than those with automatic transmissions (AT). The median CO emission for MT vehicles is greater than that of AT vehicles, with a wider interquartile range, indicating more variability in CO emissions among MT vehicles. This observation supports the statistical analysis, which suggests a difference in emission performance based on transmission type, although it is not statistically significant for CO emissions ($t = -1.361$, $p = 0.190$). Figure 5B explains the THC emission picture for AT and MT transmission vehicles. The box plot highlights a significant difference: AT transmission vehicles show higher median THC emissions compared to MT transmission vehicles. The interquartile range for AT is narrower, indicating a less frequent emission distribution, while MT vehicles show a more spread-out THC emission distribution. The t-test confirms this difference as statistically significant ($t = 2.482$, $p = 0.023$), suggesting that AT vehicles are less effective in controlling THC emissions.

Figure 5C presents the NOx emission levels for AT and MT vehicles. Both transmission types display similar NOx emission values, with overlapping medians and comparable interquartile ranges. The distribution indicates minimal variability, and the t-test results confirm that there is no statistically significant difference between the two transmission types for NOx emissions ($t = -0.103$, $p = 0.919$).

**Table 4.** Relation transmission type against emission.

| **Transmission** | **Mean Value** | | |
|---|---|---|---|
| | **CO** | **THC** | **NOx** |
| AT | 0.346 | 0.059 | 0.022 |
| MT | 0.419 | 0.045 | 0.022 |
| Comparison AT vs MT [t-test result] | t = -1.361<br>p = 0.190 | t = 2.482<br>p = 0.023 | t = -0.103<br>p = 0.919 |

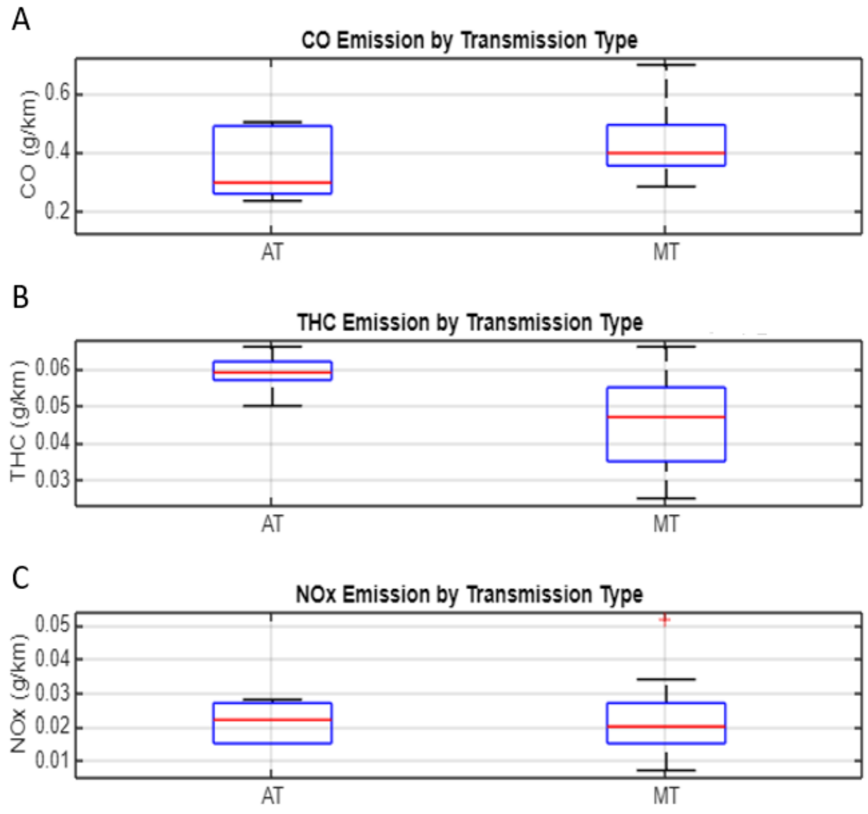



**Figure 5**. Distribution of emissions of each type of transmission: (A) CO emissions; (B) THC emissions; and (C) NOx emissions.

**CO Emissions as a Function of Catalytic Converter Type, Engine Capacity, and Vehicle Mileage**

Figures 6A, 6B, and 6C illustrate the analysis of carbon monoxide (CO) emissions concerning catalytic converter type, engine capacity, and vehicle mileage. Figure 6A examines the relationship between CO emissions and the type of catalytic converter. The trend line indicates a slight negative correlation, represented by the equation $y = -0.0257x + 0.022$, with an $R^2$ value of 0.0692. This low $R^2$ value suggests that the type of catalytic converter has a minimal impact on CO emissions, and changes in catalytic type do not powerfully explain the variation in CO emission levels. The negative slope indicates a trend where CO emissions decrease as the catalytic converter type improves, although the effect is relatively weak. Figure 6B shows the relationship between CO emissions and engine capacity. The linear regression line, represented by the equation $y = -0.0002x + 0.7152$, also suggests a weak negative correlation with an $R^2$ value of 0.0754. This indicates that as engine capacity increases, CO emissions slightly decrease. However, the low $R^2$ value indicates that engine capacity is not a significant predictor of CO emission levels. The scatter of data points suggests that other factors may influence CO emissions.

Figure 6C analyzes the relationship between CO emissions and vehicle mileage. The regression line $y = 0.0000x + 0.3330$ shows a positive correlation, with an $R^2$ value of 0.1300. While the correlation is slightly stronger compared to the other two analyses, the $R^2$ value remains low, indicating that mileage explains only a small portion of the variability in CO emissions. The positive slope implies that CO emissions increase as vehicle mileage rises, reflecting potential degradation in the vehicle's emission control systems over time.

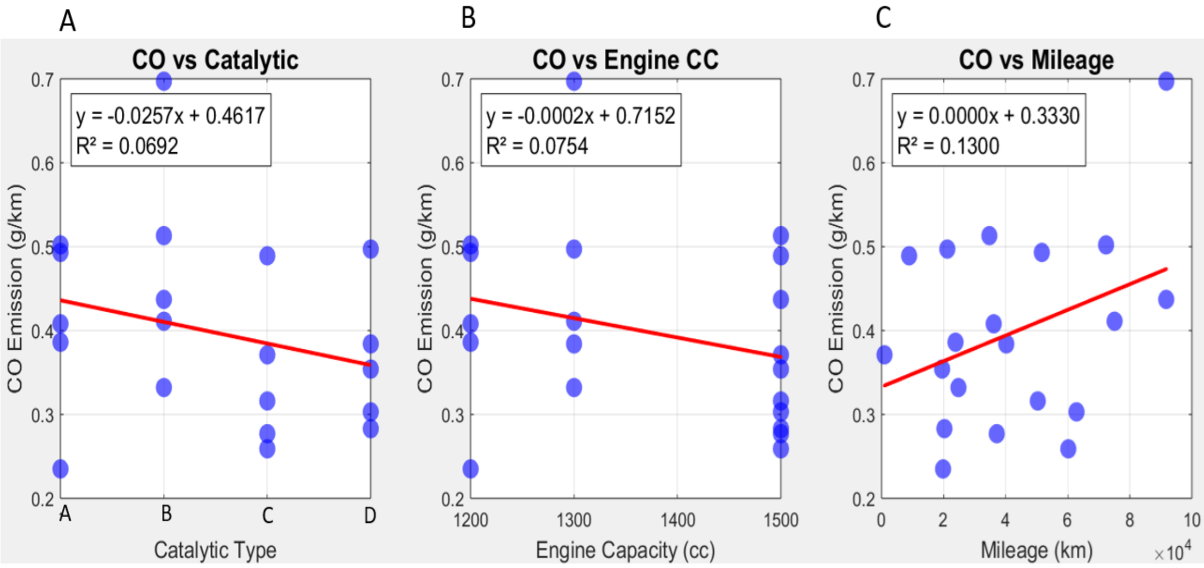



**Figure 6.** Illustration of CO emissions: (A) on catalytic type; (B) on engine capacity; and (C) on vehicle mileage.

**$NO_x$ Emissions as a Function of Catalytic Converter Type, Engine Capacity, and Vehicle Mileage**

Figures 7A, 7B, and 7C analyze nitrogen oxide (NOx) emissions concerning catalytic converter type, engine capacity, and vehicle mileage. Figure 7A illustrates the relationship between NOx emissions and the type of catalytic converter. The regression line equation $y = 0.0010x + 0.0193$ shows a slight positive correlation with an $R^2$ value of 0.0146. This very low $R^2$ value indicates that the catalytic converter type has an almost negligible impact on NOx emissions, and the variability in NOx emissions needs better explanation by changes in catalytic type. The slight upward trend suggests a minimal increase in NOx emissions as the catalytic type number increases, but the effect is statistically insignificant. Figure 7B examines the correlation between NOx emissions and engine capacity. The regression line $y = 0.0000x + 0.0222$ indicates a weak positive relationship, with an $R^2$ value of 0.0388. This suggests that NOx emissions increase slightly with larger engine capacities, but the relationship is not strong. The scatter of data points highlights the minimal impact of engine capacity on NOx emission levels, indicating the need for additional factors to explain the variability in NOx emissions.

Figure 7C presents the relationship between NOx emissions and vehicle mileage. The regression equation y = 0.0000x + 0.0121 reveals a more pronounced positive correlation, with an $R^2$ value of 0.3996. This indicates a moderate relationship, suggesting that NOx emissions increase as vehicle mileage accumulates. The $R^2$ value is considerably higher than in the previous analyses, indicating that mileage is a more significant factor influencing NOx emissions. The positive slope reflects the effect of wear and aging on the vehicle's emission control systems, contributing to higher NOx emissions over time.

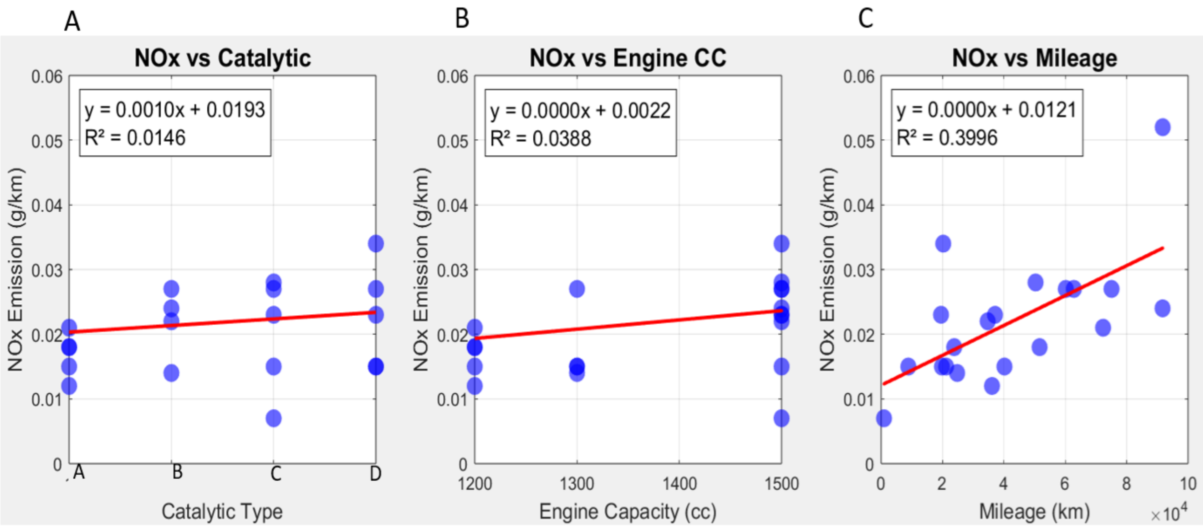



**Figure 7.** Illustration of NOx emissions: (A) on catalytic type; (B) on engine capacity; and (C) vehicle mileage.

## THC Emissions as a Function of Catalytic Converter Type, Engine Capacity, and Vehicle Mileage

Figures 8A, 8B, and 8C analyze total hydrocarbon (THC) emissions related to catalytic converter type, engine capacity, and vehicle mileage. Figure 8A depicts the relationship between THC emissions and the type of catalytic converter. The regression line y = −0.0079x + 0.0688 indicates a strong negative correlation, with an $R^2$ value of 0.4899. This relatively high $R^2$ value indicates that the type of catalytic converter significantly influences total hydrocarbon (THC) emissions, with emissions decreasing as the catalytic converter type number increases. This trend suggests that more advanced catalytic converter types effectively reduce THC emissions, underscoring the importance of utilizing high-performance converters to meet emission standards.

Figure 8B shows the relationship between THC emissions and engine capacity. The equation y = −0.0000x + 0.1059 reflects a weak negative correlation with an $R^2$ value of 0.1822. Although there is a slight trend of decreasing THC emissions with larger engine capacities, the relationship is not particularly strong. The low $R^2$ value indicates that engine capacity is not a major determinant of THC emission levels, and other factors may play a more significant role in influencing THC emissions. Figure 8C examines the correlation between THC emissions and vehicle mileage. The regression line y = 0.0000x + 0.0399 shows a moderate positive correlation, with an $R^2$ value of 0.2043. This suggests that THC emissions tend to increase with higher vehicle mileage, although the correlation is not as strong as that observed in Figure 8A. The increase in THC emissions with mileage may be due to the gradual degradation of the vehicle's emission control system, resulting in reduced catalytic efficiency over time.

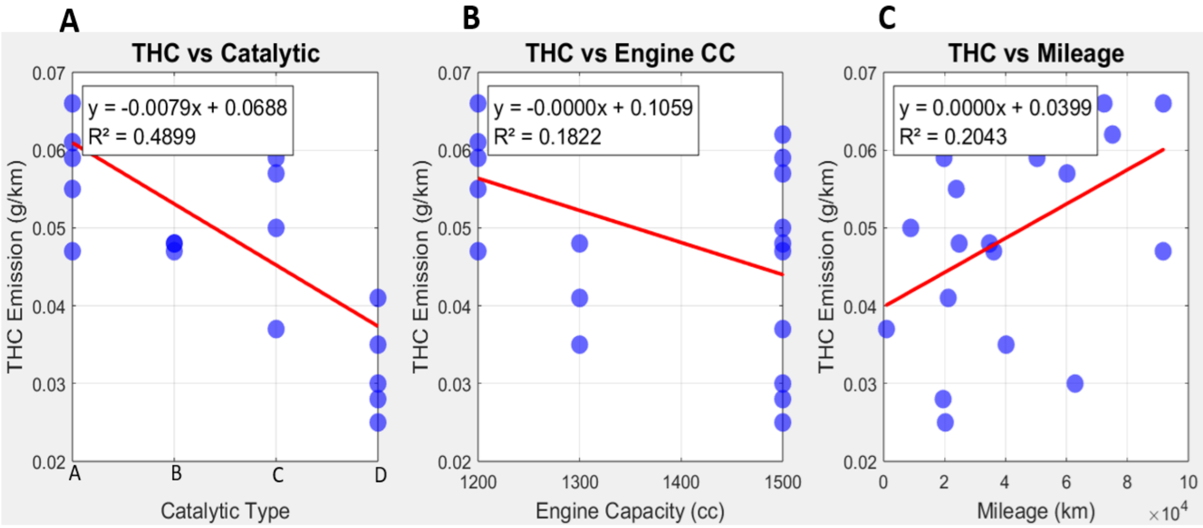



**Figure 8.** Illustration of THC emissions: (A) on catalytic type; (B) on engine capacity; and (C) vehicle mileage.

## Catalytic Performance Degradation on CO, THC, and $NO_x$ Emissions

This analysis aims to understand how different types of catalysts (A, B, C, and D) affect emissions of CO, THC, and NOx as the mileage of a vehicle increases. For CO and THC emissions, a first-order reaction kinetics model is applied. This model is commonly used to describe processes where the rate of change is proportional to the current value, such as the degradation of catalyst efficiency leading to increased emissions. By fitting the CO and THC emission data to an exponential model, we can assess how effectively each catalyst maintains low emission levels as mileage increases. The fitted model helps quantify the rate at which catalyst performance decays. The First-Order Reaction Model equation 1 is written as:

$$y(t) = y0\, e^{-kt} \tag{1}$$

where *y(t)*: the emission level at time *t* (e.g., mileage), $y_0$: The initial emission, *k*: The rate constant, which dictates how quickly the emission level decays, and *t* the time of mileage in this context. This equation describes an exponential decay. In the case of catalytic degradation, y(t) could represent the emission of a pollutant, and the constant k represents how fast the catalytic converter loses its efficiency in reducing emissions.

Figures 9A, 9B, 9C, and 9D illustrate the relationship between mileage and CO emissions for catalytic converters A, B, C, and D, respectively. Each plot shows experimental data points and a first-order exponential fit to highlight trends in CO emissions as vehicle mileage increases. In Figure 9A, the relationship between mileage and CO emissions for Catalyst A is depicted. The exponential fit equation $y = 0.2714e^{0.0000x}$ indicates a slight positive trend, suggesting that CO emissions increase marginally as mileage accumulates. However, the increase is relatively small, indicating that Catalyst A maintains reasonable performance over time, but there is a gradual degradation in emission control efficiency as mileage increases. Figure 9B presents the data for Catalyst B, with the equation $y = 0.3495e^{0.0000x}$. The trend line indicates a more pronounced increase in CO emissions with mileage than Catalyst A. This suggests that Catalyst B experiences a more significant decline in performance as the vehicle's mileage increases, resulting in higher CO emissions over time. In Figure 9C, the trend for Catalyst C is shown with an equation $y = 0.4334e^{-0.0000x}$, indicating a negative relationship. This suggests that CO emissions decrease as mileage increases, which is counterintuitive and may point to inconsistencies in the data or the possibility of other external factors influencing emission levels. The trend implies that Catalyst C may have a unique characteristic or effect that leads to reduced emissions over time, though further investigation is needed to validate this behavior. Figure 9D shows the data for Catalyst D, with the equation $y = 0.4139e^{-0.0000x}$. Like Catalyst C, the trend line indicates a decrease in CO emissions with increased mileage. This negative relationship suggests that Catalyst D maintains or even improves its emission control effectiveness over time, although this trend may also be due to data variability or external factors affecting the results.

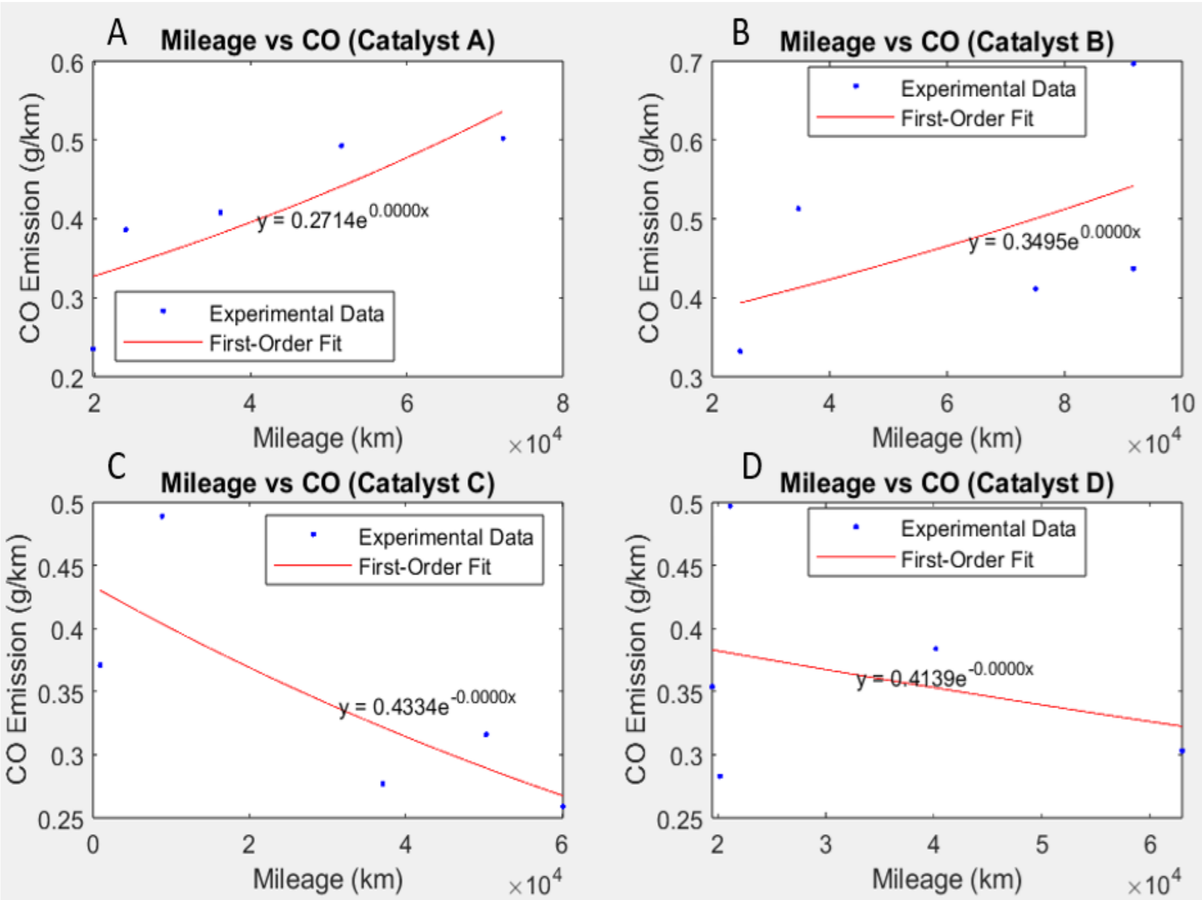



**Figure 9.** Illustration of catalytic performance degradation on CO emission: (A) Catalyst type A; (B) Catalyst type B; (C) Catalyst type C; and (D) Catalyst type D.

Figures 10A, 10B, 10C, and 10D illustrate the relationship between mileage and THC emissions for different types of catalytic converters: A, B, C, and D, respectively. Each plot shows experimental data points and a first-order exponential fit to highlight trends in THC emissions as vehicle mileage increases. Exclude Catalyst C. Overall, the image of THC emission compared to CO was nearly the same, excluding Catalyst type C, which, as shown in Figure 10C, increased. The differences in THC compared to CO emissions are the Constanta, where in Figure 10A, the relationship between mileage and THC emissions for Catalyst A, the exponential fit equation $y = 0.0498e^{0.0000x}$ = indicates a slight positive trend. Figure 10B presents the data for Catalyst B, with the equation $y = 0.04495e^{0.0000x}$. The trend line indicates almost the same in THC emissions with mileage compared to Catalyst A. In Figure 10C, the trend for Catalyst C is shown with an equation $y = 0.0439e^{0.0000x}$, indicating a positive relationship. This suggests that THC emissions increase as mileage increases; the trend implies that Catalyst C may have a unique characteristic or effect that leads to reduced CO emissions over time, but not for THC.

Further investigation was needed to validate this behavior. Figure 10D shows the data for Catalyst D, with the equation $y = 0.0426e^{-0.0000x}$. Similar to Catalyst B, but slightly decreased, the trend line indicates a decrease in THC emissions with increased mileage. This negative relationship suggests that Catalyst D maintains or even improves its emission control effectiveness over time, although this trend may also be due to data variability or external factors affecting the results.

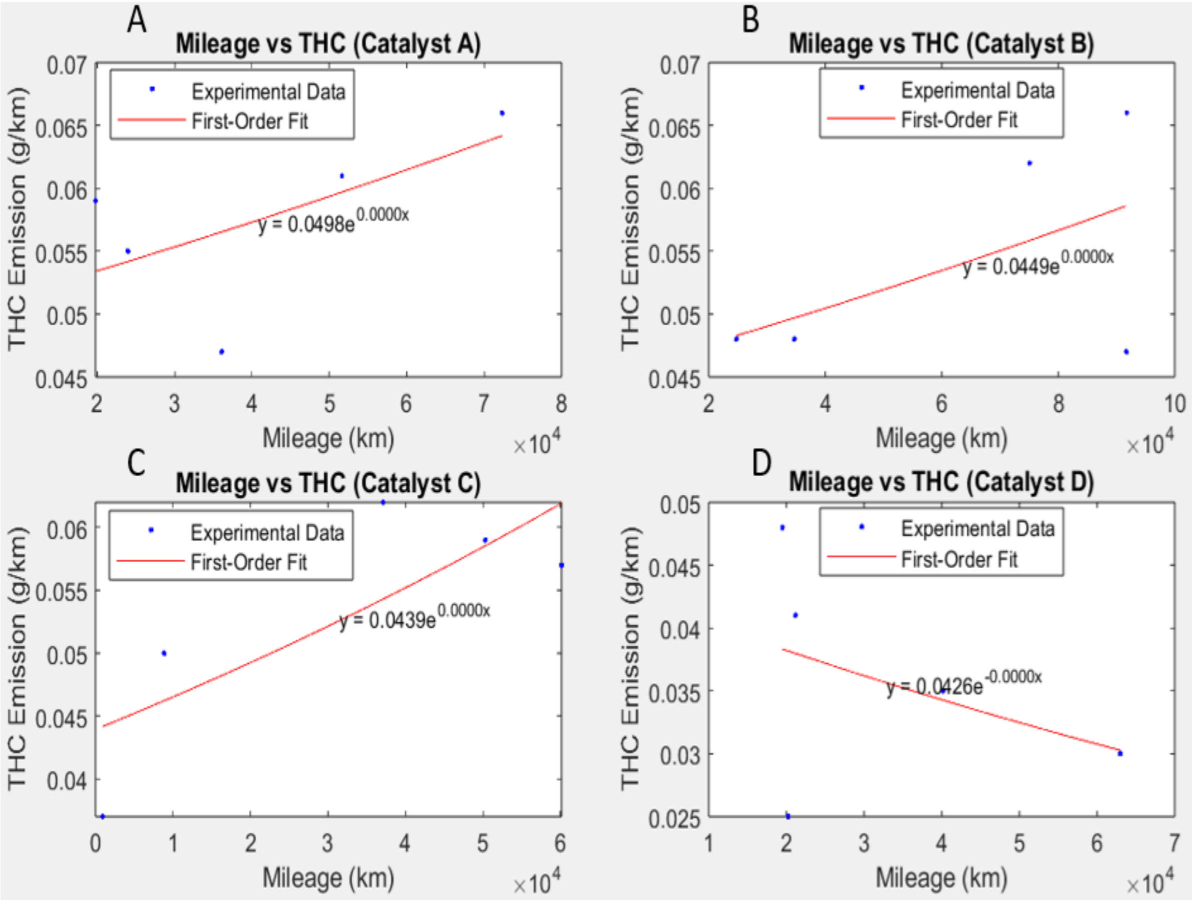



**Figure 10.** Illustration of catalytic performance degradation on THC emission: (A) Catalyst type A; (B) Catalyst type B; (C) Catalyst type C; and (D) Catalyst type D.

In the case of NOx emissions, the Arrhenius-type model is utilized. The Arrhenius equation is often used to describe the temperature dependence of reaction rates, but in this context, it is adapted to model the change in NOx emissions over mileage. This approach provides insights into the degradation behavior of catalysts, specifically their efficiency in reducing NOx emissions as they are subjected to prolonged use. The fitted Arrhenius model allows us to understand how the efficiency of each catalyst decreases, which in turn impacts NOx emissions. Arrhenius Equation 2 (Wang *et al*., 2016).

$$k = Ae^{-Ea/RT} \tag{2}$$

where $k$: The rate constant of the reaction, $A$: The pre-exponential factor (a constant), $Ea$: The activation energy required for the reaction, $R$: The universal gas constant, and $T$: Temperature (in Kelvin).

The Arrhenius-type model helps describe how external factors, such as increased mileage, might accelerate the production of certain emissions, especially NOx, which is often sensitive to temperature or engine load changes. The simplified exponent model used in the MATLAB script is equation 3:

$$y = ae^{bx} \tag{3}$$

where *y*: The emission level (e.g., NOx), *a:* A scaling factor, *b:* Represents the impact of mileage (proxy for time), and *x*: mileage (proxy for a stressor like temperature or aging).

Figures 11A, 11B, 11C, and 11D depict the relationship between mileage and NOx emissions for different catalytic converters: A, B, C, and D. Each graph displays experimental data points and an Arrhenius fit to analyze how NOx emissions change as vehicle mileage increases. In Figure 11A, the Arrhenius fit equation $y = 0.0130e^{0.0000x}$ indicates a clear positive trend, showing that NOx emissions increase as vehicle mileage accumulates. The data points and the fitted curve suggest that Catalyst A experiences a noticeable decline in its efficiency in controlling NOx emissions over time, pointing to potential wear and aging effects on the catalyst's performance.

Figure 11B illustrates the relationship for Catalyst B, with the Arrhenius equation $y = 0.0118e^{0.0000x}$. The trend is similar to Catalyst A, showing an increase in NOx emissions with higher mileage. The curve indicates a steady rise, suggesting that Catalyst B also undergoes a reduction in NOx emission control efficiency as the vehicle is used for longer periods. In Figure 11C, the data for Catalyst C is represented with the equation $y = 0.0119e^{0.0000x}$. The positive trend confirms that NOx emissions increase with mileage, albeit slightly less steeply compared to Catalysts A and B. This implies that Catalyst C has a moderate decline in NOx control efficiency, but the effect remains significant as the vehicle accumulates mileage. Mileage vs NOx Emission for Catalyst D was shown in Figure 11D. The performance of Catalyst D, with the Arrhenius fit $y = 0.0133e^{0.0000x}$, the graph reveals a clear positive correlation, indicating that NOx emissions rise as vehicle mileage increases. The trend for Catalyst D is comparable to that of Catalyst A, reflecting a similar decline in performance over time.

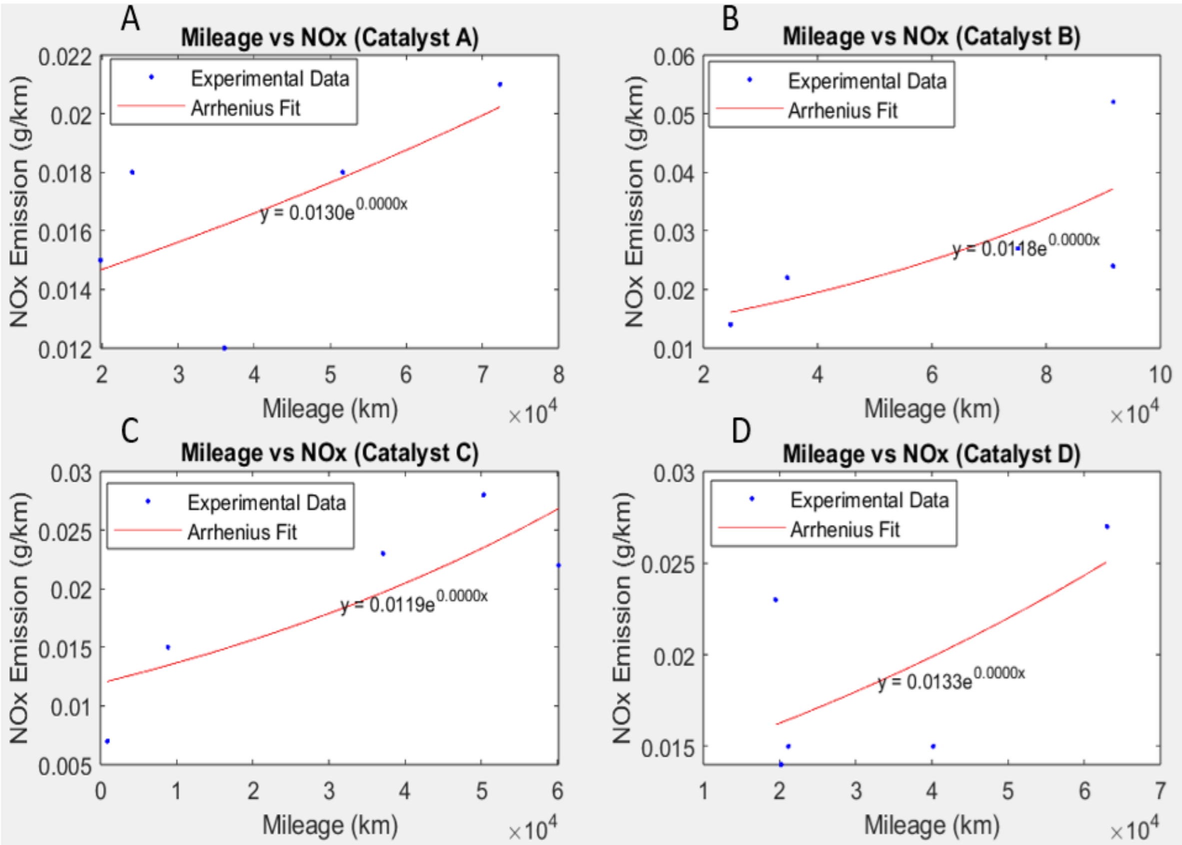



**Figure 11.** Illustration of catalytic performance degradation on NOx emission: (A) Catalyst type A; (B) Catalyst type B; (C) Catalyst type C; and (D) Catalyst type D.

## CONCLUSION

This study shows that the performance of the catalytic converter was degraded by operational lifetime. The NOx degradation factor (DF) was the highest, at 5.78, at a mileage near 100 km. This study also showed that catalytic converter type D has the best performance for CO and THC emissions, with stable degradation across its lifespan. On the other hand, the catalytic converter type B degraded significantly, at 9.0. NOx emissions indicate that all types of catalytic converter performance were decreasing at almost the same rate of deterioration. Future research may provide a deeper analysis of the catalytic material, which impacts the reduction of CO and THC, and is more significant for NOx. Selecting vehicle samples that have received the same maintenance treatment throughout the vehicle's life may enable the collection of a homogeneous sample and reduce unnecessary factors that influence the degradation performance of catalytic converters.

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