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Analysis of HC and CO Pollutants in Relation to the Physical Properties of Noble Metal Catalysts under Varying Engine Conditions

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Abstract

This study explores the environmental implications of automobile emissions in relation to the sourcing and performance of platinum group metals used in catalytic converters. Platinum group metals such as platinum, palladium and rhodium are critical components in emission control technologies, but are sourced through energy-intensive mining processes that themselves have significant environmental footprints. The combustion of fossil fuels in vehicles contributes heavily to air pollution, releasing hydrocarbons and carbon monoxide, especially under varying engine loads and speeds. Catalytic converters, coated with noble metal catalysts, mitigate these pollutants. However, their performance is influenced by the structural properties and degradation of the catalyst over time. Using a fresh catalytic converter embedded with noble metal catalysts, emissions were analysed on a research engine test bench. Results showed that usage alters catalyst surface area, pore structure, and noble metal content, affecting conversion efficiency. Emissions of HC and CO were notably higher at low engine loads and speed conditions common in urban environments, highlighting both the role and limitations of noble metal catalysts in emission control. This study links the environmental costs of mining noble group metals with their downstream benefits in reducing vehicular emissions, offering a broader perspective on the lifecycle impact of clean air technologies.

Major Findings: *Hydrocarbon and carbon monoxide emissions are higher at low engine load and speed due to incomplete combustion, subsequently decreasing as load and speed increase. Driving conditions in cities are characterised by lower speeds, which contribute to higher pollution levels. Analysis of a fresh catalytic converter showed notable alterations in pore structure and surface area during operation, such as relating to engine conditions, catalyst degeneration and emission levels.*

Keywords: *Catalytic Converter, Exhaust pollutant Analyser, Monolith, Single Cylinder VCR Engine*

1.0 Introduction

Transportation-related emissions are a major source of air pollution, driven by the increasing number of vehicles and fossil fuel consumption. This poses significant risks to environmental and public health. In response, many countries plan to phase out the sale of new gasoline and diesel vehicles between 2030 and 2035. There are currently hundreds of identified and distinguishable air pollution chemicals. People who are exposed to carbon monoxide at levels higher than 1000 [mg/km] may experience a decrease in their mental acuity. CO is a known poisonous substance that has a stronger affinity for blood haemoglobin than oxygen. Though stringent

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regulations are made in BS-6 pollution norms, such as CO 1000 (mg/km), THC 100 (mg/km), NMHC 68 (mg/km) and Nox 60 (mg/km)[1]. Among the most commonly observed contaminants are those that arise from burning solid, liquid, and gaseous fuels, such as carbon dioxide, sulphur dioxide, nitrogen oxides, including nitrogen dioxide and nitrogen oxides, dust, and secondary pollutants like carbon dioxide, ozone, and others[2]. The number of vehicles is expected to increase quickly in the upcoming years, along with the alternative source of power[3]. When hydrocarbons partially burn, carbon monoxide is produced. It always occurs when there is insufficient oxygen present during combustion, making it directly reliant on the engine's fuel-air ratio[4]. There is a steady growth in the vehicle population. The market for the catalytic converter directly proposed the growth and demand of the vehicle[5]. Air pollution is directly linked to negative health outcomes like allergies, cardiovascular disease, and respiratory disorders on a daily basis[6]. The transportation sector is responsible for about 29% of the nation's overall emissions, with road transportation being the primary source. This sector alone contributes to more than 90% of carbon dioxide (CO_2) emissions[7]. Standards for air quality are established to protect the general population from possible health risks[8]. In addition, photochemical reactions generate pollutants such as ozone and nitrogen dioxide (NO_2), both of which are harmful to the environment and also contribute to the greenhouse effect[9]. Under BS-6 regulations, exhaust systems are designed and implemented differently for petrol and diesel vehicles[10]. These standards include protecting the high-risk category of safety for groups in the general public such as the elderly, pregnant women, young infants, and people suffering from anaemia, cardiovascular and human respiratory-linked diseases from automotive exhaust pollution[11,12]. Road traffic emissions are known to contribute significantly to the overall concentrations of HC and CO in metropolitan areas, and exposure to vehicle emissions has been shown to have negative health effects[13]. Air pollution in urban areas is largely caused by vehicle emissions, fugitive road dust, vehicle-induced air turbulence, and re-entrained wayside dust give possible health consequences[14]. Concerns are increasing regarding the enhancement of ambient air quality in metropolitan regions[15]. There is growing concern about an improvement in ambient air quality in metropolitan areas[16,17]. Guidelines for air quality have recently been strengthened by the World Health Organisation (WHO)[18]. Due to the possible health consequences, there is growing worry about the decline in ambient air quality in urban areas[19,20].

The conversion of three pollutant emissions, including carbon monoxide (CO) into CO_2, nitrogen oxides (NOx) into nitrogen, and unburned hydrocarbons (HC) into CO_2 and water in engine exhaust gases[21]. It is a well-known function of automotive catalysts in catalytic converters that contain the precious metals palladium (Pd), platinum (Pt), and rhodium (Rh)[22,23]. The amount of ozone in the atmosphere is decreased by air pollution, and when ozone is depleted, ultraviolet radiation can reach Earth and cause skin cancer, cataracts, snow blindness, weakened immunity to infectious diseases, malaria, and herpes[24]. Additionally, pollutants are produced by photochemical processes, specifically ozone and NO_2, which are harmful to the environment and start the greenhouse effect as well[25]. Exhaust systems of BS-6 regulations are installed differently in petrol and diesel vehicles, as shown in Figure 1. Petrol vehicles use a simple catalytic converter, which regulates oxidation of HC and CO, whereas diesel vehicles have DPF, SCR (selective catalytic reduction) and DOC (diesel oxidation catalyst) separately for HC-CO, NOx and particulate matters[26]. Exhaust pollution also varies as the speed and gross vehicle weight of the vehicle increase and decrease, as the engine has different breathing capacity during the function[27,28].

The reactions that occur in catalytic converters are given in Equations 1, 2 and 3[16].

- The oxidisation catalytic converter

$$2CO + O_2 \rightarrow 2CO_2 \quad (1)$$

$$HC + O_2 \rightarrow CO_2 + H_2O \quad (2)$$

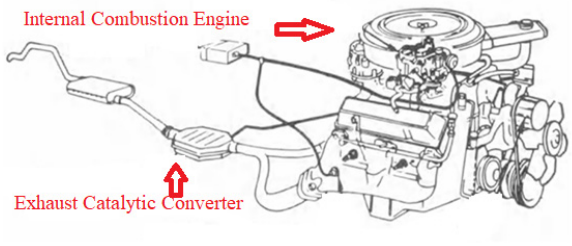


Figure 1. Positioning of the catalytic converter in automotive.

(Oxidation of CO to CO_2 and HC to carbon dioxide and water)

- The reduction catalytic converter

$$2NOx \rightarrow xO_2 + N_2 \quad (3)$$

(Reduction of NOx to N_2 and O_2)

As shown in Figure 2, A catalytic converter is composed of a monolith (ceramic or metallic substrate), coating catalysts, swell matting, thermal insulation, and housing. The monolith contains numerous small, parallel channels. A washcoat: typically made of alumina, titanium dioxide, or silicon dioxide and is applied to increase surface area. Catalysts such as platinum, palladium, and rhodium are then dispersed on this surface.

2.0 Materials and Methodology

2.1 Catalytic Converter

The study experimentally evaluates a noble metal-based catalytic converter to analyse exhaust emission parameters. The converter, sourced from an unused 600cc petrol engine (26 kW, four-cylinder, manual gearbox), was tested using a single-cylinder, 4-stroke variable compression ratio petrol engine with an open ECU research test setup. Parameters such as pollutant levels, engine performance under varying loads, and throttle positions were assessed. The results will be used for comparison with a laboratory-developed non-noble metal catalyst.

Figure 3 refers to the dismantling process of readily available fresh exhaust catalytic converters, which consist of a ceramic monolith (coated with noble catalyst), casing and thermal insulator with 400 cpsi (cells per square inch) porosity and monolithic structure. The catalyst preparation for the above-shown monolith has been characterised and examined for XRD and SEM for the catalyst coating property and composition.

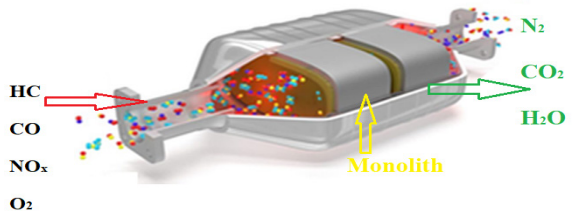


Figure 2. Catalytic converter structure.

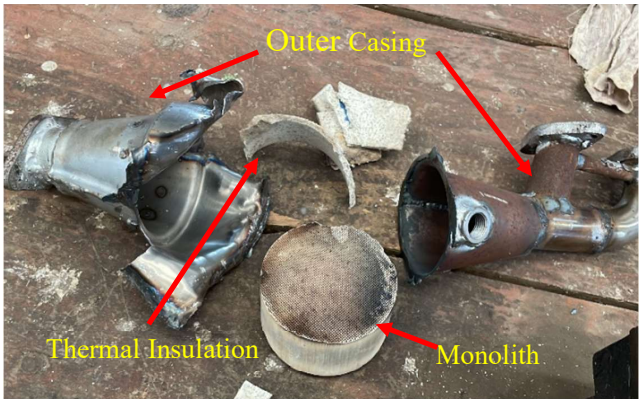


Figure 3. Exploded view of a fresh catalytic converter of a 600cc petrol engine.

2.2 Examination of the Catalyst's Structural Parameters

High-resolution and sensitivity images of the catalytic process were obtained using a JEOL JSM-6010 LA-Japan Scanning Electron Microscopy (SEM) analyser. The crystalline structure of catalytic converters was investigated using a Bruker, Germany, D2-phaser (XRD) instrument.

2.3 Experimental Setup

The catalytic converter was also tested for its performance in the exhaust reaction over the single cylinder petrol engine multifuel variable compression ratio test setup, for the various testing parameters such as throttle position, load, speed, and the engine's exhaust pollutants.

Figure 4 and 5, shows the internal combustion engine laboratory test setup for the multi-fuel engines (petrol and diesel fuels). Table 1 represents computerised engine specifications, over which the number of experiments has been conducted to identify research details of available noble metal catalysts for emission. Exhaust gas analysis has been identified on the AVL (444N) smoke unit. It operates on the principle of the Hartridge smoke meter and measures the smoke opacity. It also measures exhaust emissions such as CO, CO_2, NO_x, HC and O_2.

3.0 Results and Discussion

3.1 Characterisation of Catalyst

3.1.1 SEM Analysis

Structure characterisation of the dismantled converter's catalyst, examined under the SEM, as per Figures 6 and 7.

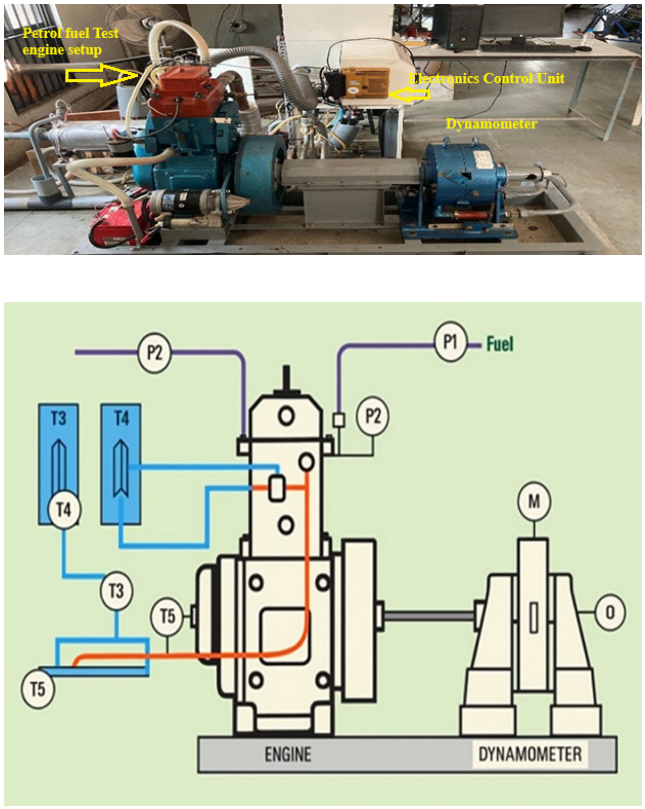


Figure 4. An experimental multi-fuel single-cylinder engine test setup with ECU.

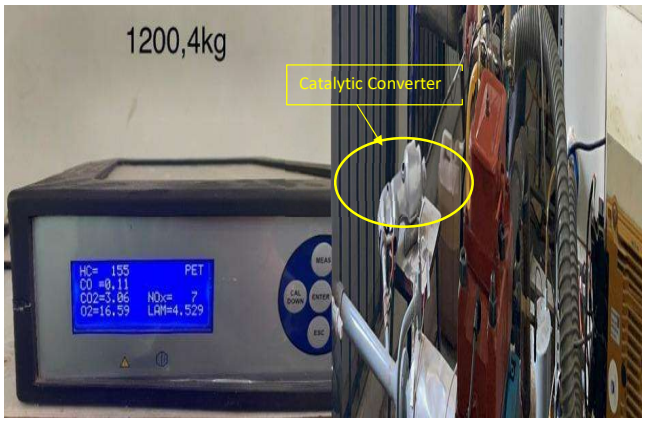


Figure 5. Installation of a catalytic converter in the exhaust stream and an AVL make exhaust analyser.

When the surface images are examined, it is clear that a significant amount of pollutants accumulates on the surface; this accumulation causes a significant decrease in the pore structure. One of the most significant variables influencing catalytic activity is pore structure. Narrowing of the pore structure makes it harder to reach active catalytic sites.

Table 1. Detailed specification of the engine test setup

Product	**Research Engine test setup single cylinder, 4 stroke, Multifuel, variable Compression ratio.**
Petrol Engine	Make Kirloskar, water cooled, stroke 110 mm, bore 87.5 mm, 661CC, 4.5 KW@1500 rpm, Speed range 1200-1800 rpm, CR: 6-10.
Dynamometer	Eddy current, water-cooled with a loading unit.

Pore structure significantly influences catalytic activity. This study found that reduced pore size limits the surface area for pollutant oxidation and narrows the catalyst structure, decreasing converter efficiency. Pore clogging increases exhaust back pressure, harming engine performance and causing thermal deactivation at high temperatures. Micro-channels coated with catalysts of different particle sizes (~20 µm and 10 µm) were analysed microscopically to examine their molecular and granule characteristics (JEOL JSM-6010 LA, Japan). An SEM pattern was used to identify the spectroscopic and surface characterisation of the catalyst area and its hollow fibre composite. Hollow fibre samples of 15mm size were taken to identify the effect of the catalyst deposition for CO oxidation. The average crystallite dimension was estimated by the Scherrer equation[11].

$$D = \frac{K\lambda}{\beta cos\theta} \quad \frac{0.9\times0.15406}{\beta cos\theta}$$

where, D is the average thickness in a vertical direction of the crystal face, K is the Scherrer constant, λ is the wavelength of the x-ray, β is the full width at half maximum, θ is the Bragg diffraction angle[11].

3.1.2 XRD Analysis

To confirm the catalyst structure, a non-destructive analysis was done. An X-ray Diffraction Pattern (XRD) analysis is referred to provide the catalysts containing material regarding the structure, catalyst phase, crystal orientation, lattice parameter and crystallite size as shown in Figure 8, and various patterns are examined in the microscopic examination to reveal the necessary parameters.

This method operates on the principle that every crystal phase produces a distinct X-ray diffraction pattern based on its specific atomic structure. The scanning range of 2θ



Figure 6. Noble metal catalyst prepared for characterisation under the SEM equipment.

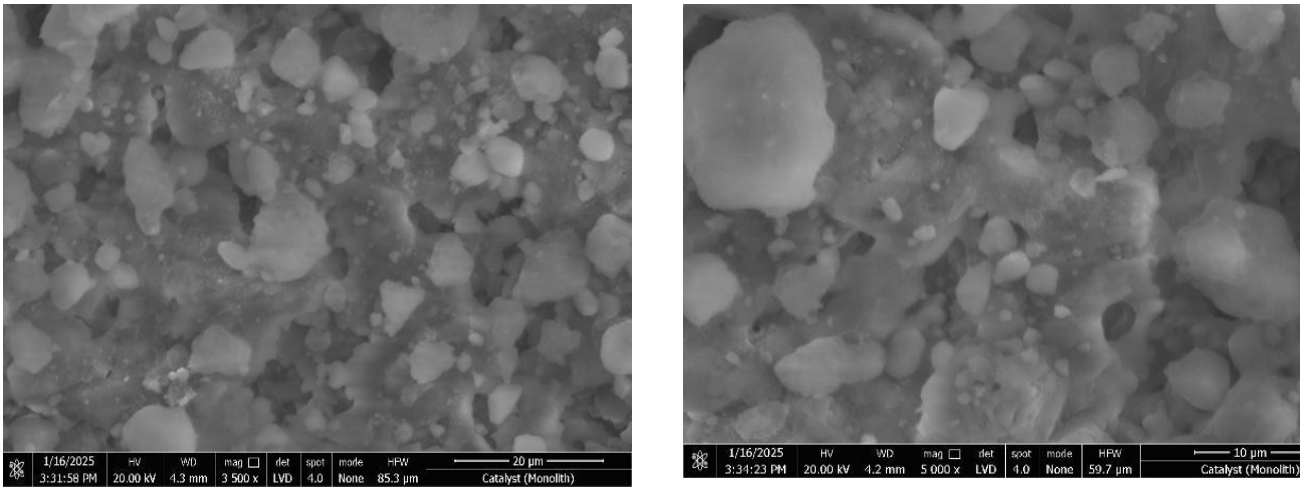


Figure 7. SEM images of catalyst 20.00 and 10.00 KX inside the substrate.

is 20–165° with a scan rate of 10° min^{-1}. Scanning electron microscopy was used to observe the microstructure of the catalyst. It is evident from Figure 8 that peaks corresponding to cordierite noble group precious metal catalysts were identified in the sample. It was found that the intensity vs angles 2θ = 18.67°, 22.28°, 28.31°, 30.11°, 32.95°, 48.35° and 67.24°. The observed peaks align with the standard characteristic peaks of noble group metals, which exhibit a cubic crystal structure.

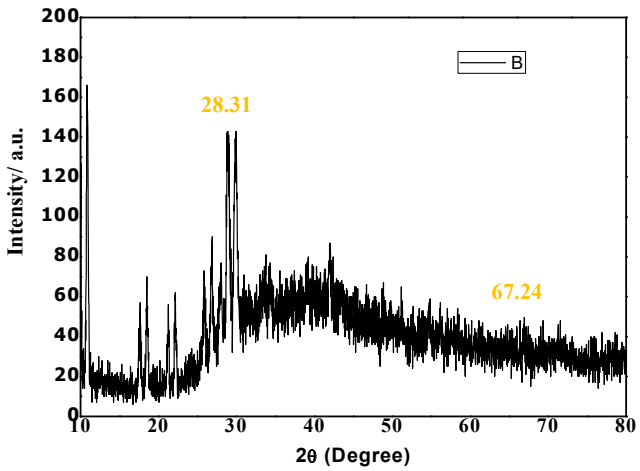


Figure 8. X-ray diffraction pattern of a noble catalyst.

3.2 Engine Test Results

3.2.1 Engine Description

With the help of laboratory equipment as shown in Figure 5, 4-S- single cylinder, variable fuel/air compression

ratio research engine setup, the major pollutants from petrol vehicles, HC and CO, have been observed through the engine operation and analysed for their intensity at various speeds and loading conditions. The setup engine connected to the eddy current dynamometer. It is provided with necessary instruments for combustion pressure, crankangle, airflow, fuel flow, temperatures and load measurements. These signals are interfaced to a computer through a high-speed data acquisition system. Rotameters are provided for cooling water and calorimeter water flow measurement. In petrol mode engine works with a programmable open ECU, Throttle Position Sensor (TPS), fuel pump, ignition coil, fuel spray nozzle and trigger sensor.

CO is produced due to the non-availability of oxygen during the combustion process in the engine. CO pollutants are colourless and have toxicity, and it is also generated at lower temperatures. The emission rate of carbon monoxide changes with different working conditions of the engine, such as temperature, load and rpm, as illustrated in Figures 9 and 10. When the load increases, CO decreases significantly. Rich fuel-air mixture does not have enough oxygen to react with, hence, CO emissions increase. At all load conditions, Emissions were found to decrease remarkably.

3.2.3 *Hydrocarbon Emission (HC)*

Higher level of HC in pollutants in the environment causes serious environmental problems. Hydrocarbon emission from the internal combustion engine produces

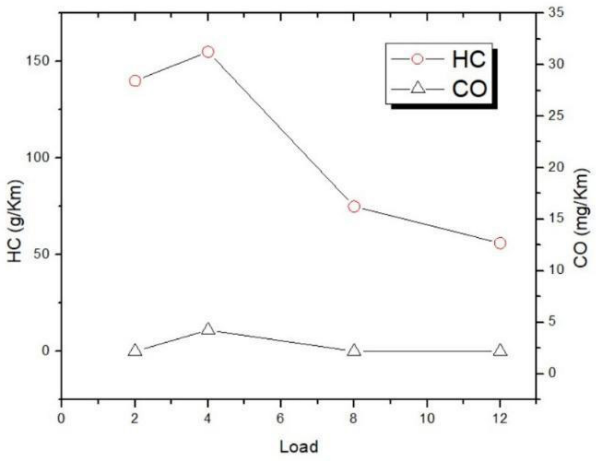


Figure 9. HC and CO at 1200 rpm.

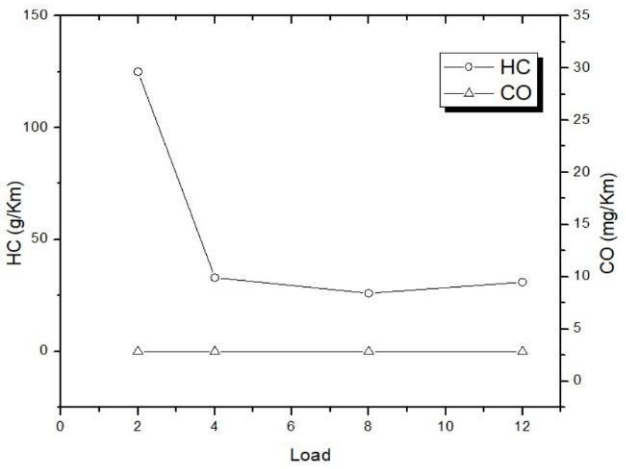


Figure 10. HC and CO at 1600 rpm.

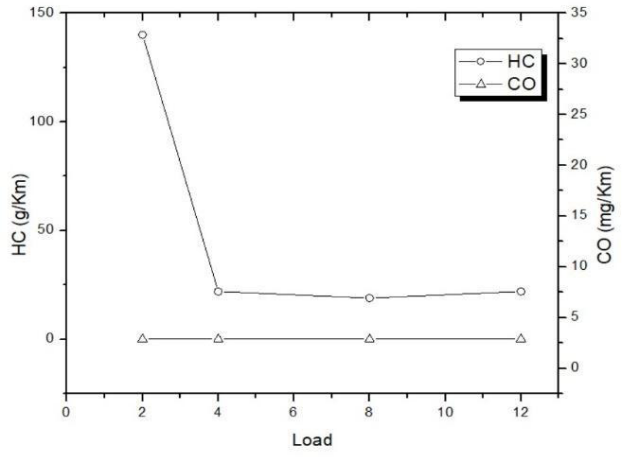


Figure 11. HC and CO at 1800 rpm.

the greenhouse effect as an increased rate of HC leads to the depletion of the ozone layer, which in turn leads to global warming. Experimental observations indicate that the intensity of HC emissions rises with initially lower loads, but it then decreases as the load increases at 1200 rpm shown in Figure 9. The values derived from emissions under the different load conditions have indicated substantially greater levels compared to the CO emission readings.

4.0 Conclusion

This study is an attempt to assess the physical properties of noble metal catalysts of catalytic converters and analyse the HC and CO pollutants under the varying

engine conditions to compare the results with numerous automotive studies. For that work of study a fresh catalytic converter have been taken for a detailed study and assessment to identify environmental pollution from petrol vehicles of HC and CO, based on the physical characteristics of catalytic converter monolith catalyst and engine operating variables such as load, speed and throttling position, as indicated in Table 2-4. Simultaneously, surface area analyses using SEM and XRD were conducted on samples obtained from fresh catalytic converters to identify the adhering capacity and pores of the structure. The finding shows the significant changes in hydrocarbon and carbon monoxide pollutants from the catalytic converter after the combustion. As shown in Figure 10 and Figure 11, The observation shows that the level of HC and CO pollutants is higher when the load and speed are lower because less heat and energy are available to burn the fuel completely at the initial condition, and subsequently decreases when the load and speed are increased. This study directly relates the automotive operating condition on the road to the speed. The vehicles driven in an urban area as well as in heavy traffic conditions have been operated at lesser speed, approximately around 20-40 kmph (1000-3000 rpm approx.) along with gross vehicle weight (here the weight analysed as a load onto the engine) which can increase the amount of pollutants from the engine while driven in city areas as the operating condition is lower and increases harmful effects on environment. Furthermore, it has a direct effect on the internal structure of catalytic activity according to the catalyst coating layer.

Table 2. Pollutants with different operating loads at 1200 rpm

Speed [rpm]	Load [kg]	HC [g/km]	CO [mg/km]
1200	2	140	0.07
	4	155	0.11
	8	75	0.04
	12	56	0.03

Table 3. Pollutants with different operating loads at 1600 rpm

Speed [rpm]	Load [kg]	HC [g/km]	CO [mg/km]
1600	2	125	0.07
	4	33	0.04
	8	26	0.03
	12	31	0.02

Table 4. Pollutants with different operating loads at 1800 rpm

Speed [rpm]	Load [kg]	HC [g/km]	CO [mg/km]
1800	2	140	0.07
	4	22	0.04
	8	19	0.03
	12	22	0.02

Carbon monoxide emission (CO)

5.0 Acknowledgments

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