Exhaust Gas Analysis of SI Engine and Performance Of Catalytic Converter

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ABSTRACT

Exhaust system, the least concerned section by the people has the most effective role on the environment as it is that portion of an automobile through which exhaust gases get out from the combustion chamber to pollute the air by their contaminated contents. The exhaust system components like catalytic converter, muffler and resonator make it possible to let out the least possible contaminated gas from the engine exhaust manifold. The performance of the emission control system particularly by the catalytic converter and the noise control are the main concern of this paper. To make a comparison of the exhaust gas emission providing with catalytic converter or not, an exhaust gas analyzer was used to collect experimental data. All the experimental data and graphical representation concludes that the carbon content in the exhaust gas from the car, Toyota E-90 has been reduced to a great extent with the help of catalytic converter & the noise has been reduced as well for the proper attachment of muffler in exhaust system.

***Keywords* -** Exhaust system, Catalytic converter, Substrate, Catalyst, Muffler, Noise control.

I. Introduction

A catalytic converter (colloquially, "cat" or "catcon") is a vehicle emissions control device which converts toxic by-products of combustion in the exhaust of an internal combustion engine to less toxic substances by way of catalyzed chemical reactions [1]. This paper presents the performance of a specific catalytic converter analyzing the emitted exhaust gases (NO, NO_2, CO, CO_2, O_2, SO_2) of a SI engine at different engine speed and torque. From different graphical representations it is very clear that the catalytic converter reduces CO_2, NO_2, & SO_2 emission in a large extend. In addition, it minimizes the CO& NO emission at a specific engine speed. Lately this paper presents the performance of the muffler showing the engine noise level with & without the muffler.

II. Construction

The catalytic converter consists of following several components:

2.1 The Core or Substrate

The core is often a ceramic honeycomb in modern catalytic converters, but stainless steel foil honeycombs are used, too. The honey-comb surface increases the amount of surface area available to support the catalyst, and therefore is often called a "catalyst support".

TABLE 1
SPECIFICATION OF ENGINE

Features	Description
Type	Gasoline 1.3L, Straight, 4 cylinder, 2E
Bore	73.0 mm
Stroke	77.4 mm
Displacement	1295cc
Ignition timing (with vacuum advancer off)	10 degree before TDC
Ignition timing (as per Haynes Datebooks	5 degree before TDC @ 800rpm

2.2 The Washcoat

A washcoat is used to make converters more efficient, often as a mixture of silica and alumina. The washcoat, when added to the core, forms a rough, irregular surface, which has a far greater surface area than the flat core surfaces do, which then gives the converter core a larger surface area, and therefore more places for active precious metal sites. The catalyst is added to the washcoat (in suspension) before being applied to the core(in suspension) before being applied to the core[2].

(a) (b)

Fig 1: (a) Cutaway of a metal-core converter; (b) Ceramic -core converter [3].

2.3 The Catalyst

The catalyst itself is most often a precious metal. Platinum is the most active catalyst and is widely used. It is not suitable for all applications, however, because of unwanted additional reactions and/or cost. Palladium and rhodium are two other precious metals used. Platinum and rhodium are used as a reduction catalyst, while platinum and palladium are used as an oxidization catalyst.

III. Types Of Catalytic Converter

The two types of catalytic converter as told earlier is discussed below:

3.1 Two-Way Catalytic Converter

A two-way catalytic converter has two simultaneous tasks [2]:

Oxidation of carbon monoxide to carbon dioxide:

$2CO + O_2 \rightarrow 2CO_2$

Oxidation of unburnt hydrocarbons (unburnt and partially-burnt fuel) to carbon dioxide and water:

$C_xH_{2x+2} + 2xO_2 \rightarrow xCO_2 + 2xH_2O$ (a combustion reaction)

This type of catalytic converter is widely used on diesel engines to reduce hydrocarbon and carbon monoxide emissions.

3.2 Three-Way Catalytic Converter

Since 1981, three-way catalytic converters have been used in vehicle emission control systems in North America and many other countries on roadgoing vehicles. A three-way catalytic converter has three simultaneous tasks:

Reduction of nitrogen oxides to nitrogen and oxygen:

$2NO_x \rightarrow xO_2 + N_2$

Oxidation of carbon monoxide to carbon dioxide:

$2CO + O_2 \rightarrow 2CO_2$

Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water:

$C_xH_{(2x+2)+} 2xO_2 \rightarrow xCO_2 + 2xH_2O$

These three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point. This is between 14.6 and 14.8 parts air to 1 part fuel, by weight, for gasoline. The ratio for LPG, natural gas and ethanol fuels is slightly different, requiring modified fuel system settings when using those fuels. Generally, engines fitted with 3-way catalytic converters are equipped with a computerized closed-loop feedback fuel injection system employing one or more oxygen sensors, though early in the deployment of 3-way converters, carburetors equipped for feedback mixture control were used. While a 3-way catalyst can be used in an open-loop system, NOx reduction efficiency is low. Within a narrow fuel/air ratio band surrounding stoichiometry, conversion of all three pollutants is nearly complete. However, outside of that band, conversion efficiency falls off very rapidly. When there is more oxygen than required, then the system is said to be running lean, and the system is in oxidizing condition. In that case, the converter's two oxidizing reactions (oxidation of CO and hydrocarbons) are favored, at the expense of the reducing reaction. When there is excessive fuel, then the engine is running rich. The reduction of NOx is favored, at the expense of CO and HC oxidation.Unwanted reactions can occur in the three-way catalyst, such as the formation of odiferous hydrogen sulfide and ammonia. Formation of each can be limited by modifications to the washcoat and precious metals used. It is very difficult to eliminate all these byproducts entirely. For example, when control of hydrogen sulfide emissions is desired, nickel or manganese is added to the washcoat. Both substances act to block the adsorption of sulfur by the washcoat. Hydrogen sulfide is formed when the washcoat has adsorbed sulfur during a low temperature part of the operating cycle, which is then released during the high temperature part of the cycle and the sulfur combines with HC.

IV. Model for the Three-Way Catalytic Converter

The mathematical model of a catalytic converter contains two elements. The first is the kinetic reaction model and the second is the transport equations for the mass, momentum and energy. We used a kinetic model based on the mechanistic steps. The transport model was based on the modeling of a single channel of the converter.

4.1 The Kinetic Model

We consider a reaction scheme represented by a set of four global reactions:

$2CO + O_2 \rightarrow 2CO_2$

$2CO + 2NO \rightarrow N_2 + 2CO_2$

$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$

$C_2H_2 + 2.5O_2 \rightarrow 2CO_2 + H_2O$

4.2 The Transport Equation Model

The transport equation model is based on the modeling of the single channel of a catalytic converter. It describes the equations for mass, momentum and energy. As this model has not been our concern in this study it has not been discussed in detail.

V. Mechanism through the Catalytic Converter

Catalytic converter is a device which is incorporated into the exhaust system of an automobile that reduces the amount of pollutants in the automobile's exhaust gases.

A catalytic converter consists of an insulated chamber containing a porous bed, or substrate, coated with catalytic material through which hot exhaust gas must pass before being discharged into the air. The catalyst is one of a variety of metal oxides, usually platinum or palladium, which are heated by exhaust gas to about 500º C (900º F, 737 K). At this temperature unburned hydrocarbons and carbon monoxide are further oxidized, while oxides of nitrogen are chemically reduced in a second chamber with a different catalyst. Problems with catalysts involve their intolerance for leaded fuels (lead-free gasoline must be used otherwise the beads in the catalytic converter will become coated with lead and cease to function properly) and the need to prevent overheating. However because of the conversion of carbon monoxide to carbon dioxide it therefore causes an increase in greenhouse gases and in the process of removing toxic gases to less non-toxic gases it causes an increase in the greenhouse effect

$HC + O_2 \rightarrow CO_2 + H_2O$

This reaction is oxidization of the hydrocarbon.

$2CO + O_2 \rightarrow 2CO_2$

This reaction is oxidization of Carbon monoxide.

$2NO \rightarrow N2 + O2$

This reaction is reduction of Nitrogen oxide.

By using both a reducing and oxidizing catalytic converter, we can lower the activation energy for the HC, CO and NO so that they more quickly react to form less noxious products. The reactions that occur in the catalytic converter are due to a catalyst. The catalyst is in a separate phase to the reactants is said to be heterogeneous, or contact catalyst. Contact catalysts are materials with the capability of adsorbing molecules of gases or liquids onto their surfaces.

TABLE 2
STANDARD VALUE OF DIFFERENT EXHAUST COMPONENT [4]

Exhaust Component (%)	Driving Mode			
	Idling	Cruising	Accelerating	Decelerating
(CO)	5.2	0.8	5.2	4.2
(HC)	0.075	0.03	0.04	0.4
(NO)	0.003	0.15	0.3	0.006

VI. Conversion by Catalytic Converter Substrates

A substrate is a substance on which some other substance is absorbed or in which it is absorbed. (Catalytic conversion requires a precisely balanced air-to-fuel ratio, hence the need for oxygen sensors.) In dual-bed converter systems the exhaust gases are first reduced in order to eliminate the oxides of nitrogen; then they are oxidized with added air in order to eliminate carbon monoxide and unburned hydrocarbons [2]. In more advanced three-way converters individual catalysts accomplish reduction of each species simultaneously. Catalysts are either platinum-group metals or base metals such as chromium, nickel, and copper. Platinum-group metals or noble metals are any of several metallic chemical elements that have outstanding resistance to oxidation, even at high temperatures; the grouping is not strictly defined but usually is considered to include rhenium, ruthenium, rhodium, palladium, silver, osmium, iridium, platinum, and gold. In base-metal catalysts the active surfaces are actually ceramic oxides of the metals. Because platinum metals are extremely expensive, they are deposited on ceramic catalyst supports as salts and then reduced to finely divided metal particles.For efficiency of conversion, extremely large surface areas are required. These are accomplished by ingenious micro-structural engineering of the ceramic support structure. Two types of structure are made pellets and honeycomb monoliths. The pellets are porous beads approximately 3 millimetres (1/8 inch) in diameter. With a single pellet having up to 10 square millimetres of internal pore surface area, one litre of pellets can have up to 500,000 square metres of support surface [2]. The pellet material is often alumina (aluminium oxide, Al2O3). High internal porosity is achieved by carefully burning off the organic additives and by incomplete sintering. Honeycomb monoliths have 1,000 to 2,000 longitudinal pores approximately one millimetre in size separated by thin walls [5]. The material is commonly cordierite, a magnesium aluminosilicate (Mg2Al4Si5O18) known for its low thermal expansion. The extruded cordierite structure is coated with a wash of alumina, which in turn supports the platinum catalyst particles. The surface area of the monolith is typically in the range of one square meter; however, this figure must be multiplied many times because of the porosity of the alumina on the surface.

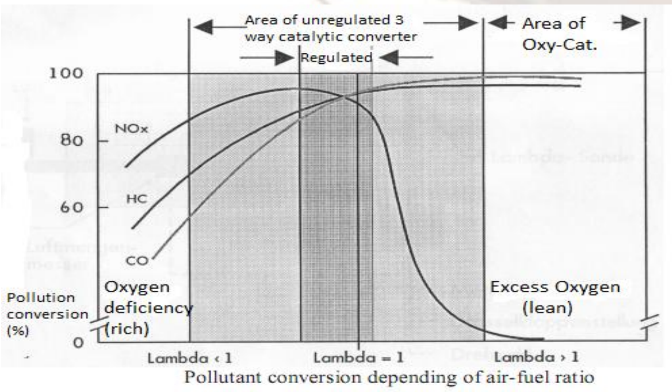
Monolith supports are much more expensive than pellet supports, but they cause a smaller pressure drop in the exhaust system. Both types of catalyst support, because of their inherent friability, are susceptible to vibrational degradation. Containment of the supports is also difficult. A good seal must be achieved and maintained without imposing external stresses on the friable structure.

Fig 2: Catalytic converter to be welded in exhaust system of the car, Toyota E-90 in MIST welding shop.

VII. Summarized Chemical Reactions

Surface studies of the adsorption of CO and O2 on single crystals and model catalysts have led to the development of a possible mechanism for the oxidation of CO. Dissociatively adsorbed O atoms undergo a surface reaction with adsorbed CO, to form CO2.Under slightly fuel-rich conditions, where there is insufficient oxygen present for complete oxidation, CO can be removed by the water-gas shift reaction, using water produced in the combustion process in the engine. This is promoted by ceria.Hydrocarbons can be removed by oxidation or by reaction with water (a process known as steam reforming).

Both CO and hydrocarbons can be removed by reaction with NO under stoichiometric or fuel-rich conditions. The NO-CO redox reaction is believed to proceed eitherby dissociation of NO(ad) followed by N atom combination, or by pairing of NO (ad) to give a dinitrosyl species, followed by dissociation. Whatever the detailed mechanism, Rh is particularly active for this reaction, and as such is currently an essential ingredient of the three-way catalyst.Cerium oxide plays a number of important roles in the three-way catalyst: it is a structural promoter, stabilizing both the noble metals and the support against particle growth and sintering; it is an oxygen-storage component, storing oxygen under fuel-lean conditions, and releasing it under fuel-rich conditions; it is a promoter for the water-gas shift



and steam reforming reactions and it can enhance the low-temperature activity of the catalyst after certain types of pretreatment.

Fig 3: Pollutant conversion depending of air-fuel ratio [2]

VIII. Performance Analysis

8.1 Increment in the amount of preferable oxygen

Figure 4 shows the effect of catalytic converter on the amount of oxygen emitted from the engine. It shows that the highest amount of oxygen (19.2%) is emitted from the engine when the speed is between 10-30 km/hr while the exhaust system is attached with catalytic converter. Again from this figure the amount of oxygen emitted from the engine is equipped with catalytic converter. has been reduced significantly with the absence of catalytic converter while the best possible amount of oxygen is 18.1% which occurred around 10km/hr of engine speed. The amount of oxygen emitted from engine stabilizes while the engine speed increases with the absence of catalytic converter but the amount is still lower than the condition while the exhaust system.

8.2 Significant reduction in the amount of CO2

From figure 5, CO2 emitted from the engine is always less than 7ppm while the minimum amount of CO2 emission from engine without catalytic converter is greater than 7ppm. This implies a significant improvement in reduction of CO2 presented in the exhaust gas. In both the cases the amount of CO2 increases constantly with increase in speed. Highest speed causes to emit the highest amount of CO2 from the engine exhaust.

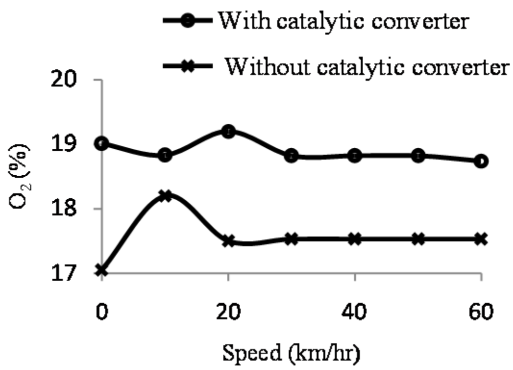


Fig 4: Percentage of O_2vs Speed (km/hr)

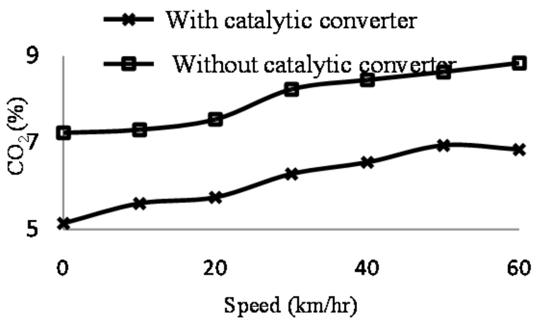


Fig 5: Percentage of CO_2vs Speed (km/hr)

8.3 CO Increases Linearly With the Engine Speed

The figure 6 shows the linear characteristic of CO emission with the change of engine speed. In both the cases the amount of CO increases with the engine speed. But with the use of catalytic converter it is possible to lower the amount except the peak point of emission which occurs around the speed of 30km/hr.

8.4 Less But Still Significant Improvement in NO Emission

Though the emission of NO is a little bit less without catalytic converter at the start of the engine, the amount of NO increases with the speed and at a certain speed the emission level goes much higher in comparison with the condition when the exhaust system is attached with catalytic converter as shown in figure 7.

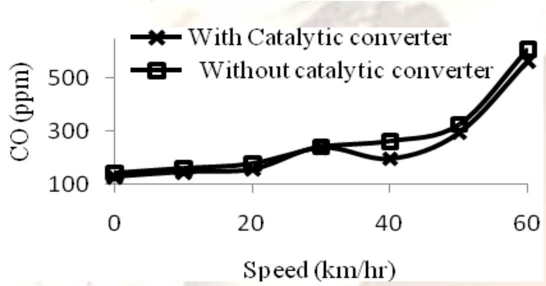


Fig 6: CO (ppm) vs Speed (km/hr)

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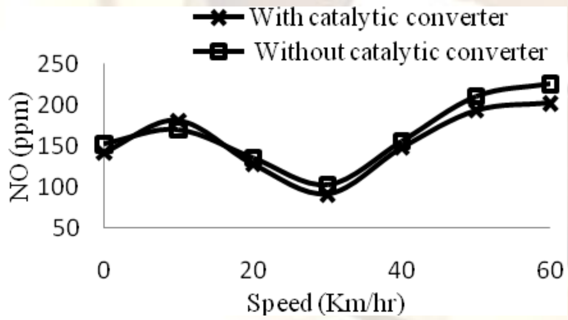

Fig 7: NO in ppm vs speed (km/hr)

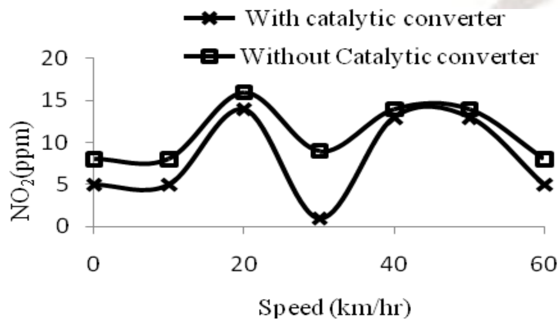

Fig 8: NO_2 in ppm vs Speed (km/hr)

8.5 Reduction in NO_2 Emission with a Point Tends To Zero

From figure 8 it is very clear that the amount of NO2 reduces drastically with the attachment of catalytic converter when the speed is between 20-40km/hr. This point shows the actual effect of catalytic converter on the amount of NO2 from the exhaust emission.

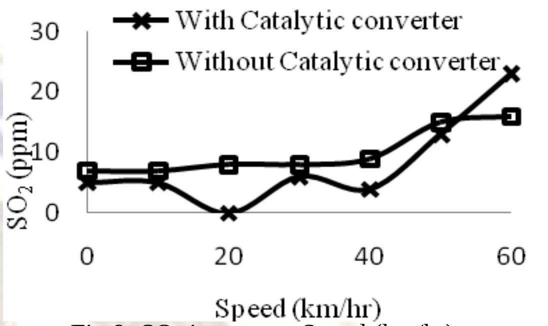

Fig 9: SO_2 in ppm vs Speed (km/hr)

8.6 Improvement in SO_2 Emission with an Exception

One of the most harmful elements is SO2 the amount of which is very less with catalytic converter in the exhaust system. Fig 9 represents that although the amount increases with the engine speed and surprisingly it goes even higher than the condition of without having catalytic converter.

IX. Emission Contents at Different Engine Torque

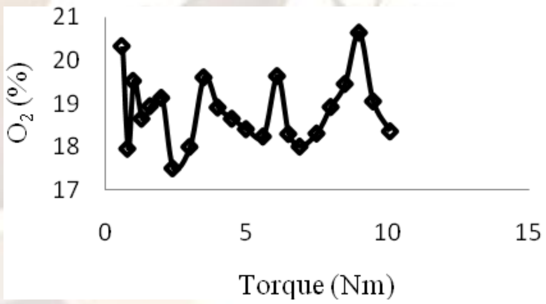

Fig 10: Torque (Nm) v/s O_2

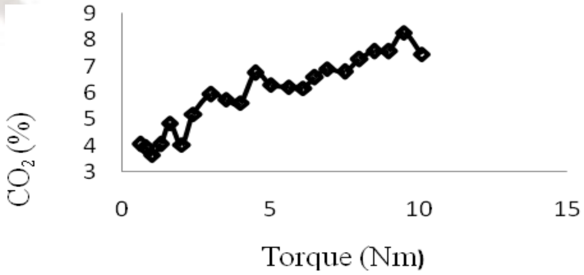

Fig 11: Torque (Nm) v/s CO_2 (%)

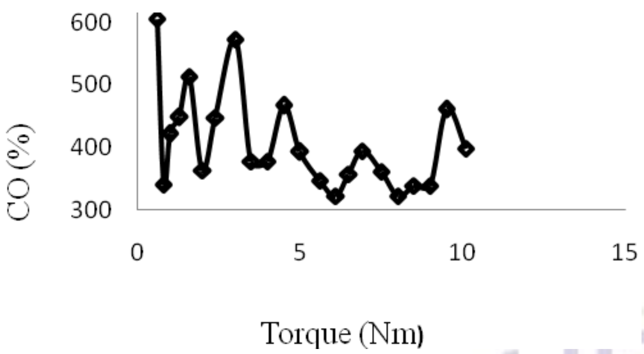

Fig 12: Torque (Nm) v/s CO (%)

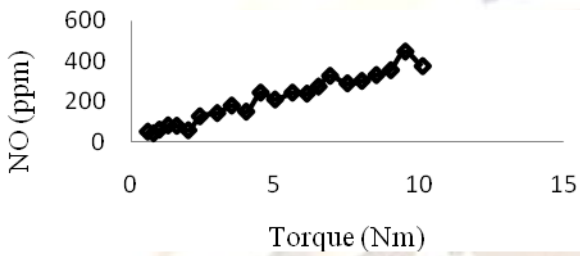

Fig 13: Torque (Nm) v/s NO (ppm)

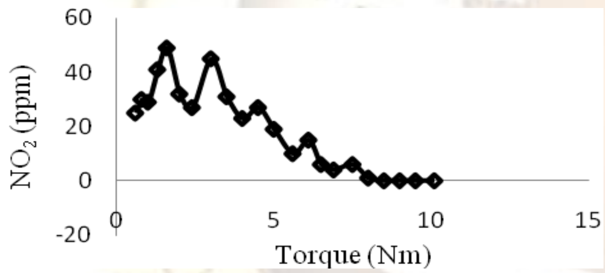

Fig 14: Torque (Nm) v/s NO_2 (ppm)

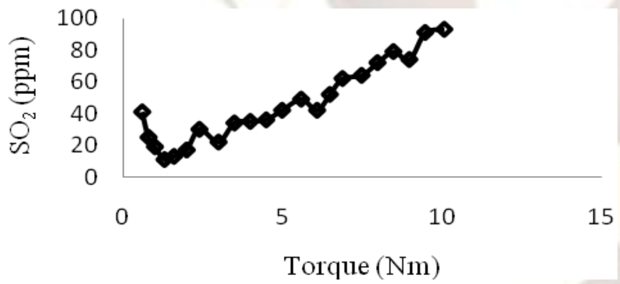

Fig 15: Torque (Nm) v/s SO_2 (ppm)

X. Exhaust Noise Controlling

The following can be used for controlling engine noise: Reactive Mufflers, Absorptive Silencers, eactive/Absorptive Mufflers, Tail Pipe Design, and Tuned Resonators Tail pipe resonances

$$F_n = \frac{nC}{2L}$$

Where, Fn is resonance frequency of pipe, n = 1, 2, 3….; C is speed of sound;L is length of pipe (ft)and resonance occurs L=n/2.

This example goes through the various steps required to design a tail pipe for a 4-cycle engine. The frequencies to avoid are 15 Hz, 30 Hz, 45 Hz, 60 Hz, 75 Hz, 90 Hz, 105 Hz, etc.The most important frequency is the 90 Hz EFR. The wavelength at 90 Hz is 20 feet, so we want to avoid a tail pipe length of 10 feet, 20 feet, 30 feet, etc. The best length is exactly 5 feet because this will cancel the 90 Hz tone at the outlet.In our car we use a special type of muffler which is integrated with a resonator.

Fig16: Muffler with built in resonator [6].

A chamber called a resonator is connected to the first chamber by a hole. The resonator contains a specific volume of air and has a specific length that is calculated to produce a wave that cancels out a certain frequency of sound unit. When a wave hits the hole, part of it continues into the chamber and part of it is reflected. The wave travels through the chamber, hits the back wall of the muffler and bounces back out of the hole. The length of this chamber is calculated so that this wave leaves the resonator chamber just after the next wave reflects off the outside of the chamber. Ideally, the high-pressure part of the wave that came from the chamber will line up with the low-pressure part of the wave that was reflected off the outside of the chamber wall, and the two waves will cancel each other out.

In reality, the sound coming from the engine is a mixture of many different frequencies of sound, and since many of those frequencies depend on the engine speed, the sound is almost never at exactly the right frequency for this to happen. The resonator is designed to work best in the frequency range where the engine makes the most noise; but even if the frequency is not exactly what the resonator was tuned for, it will still produce some destructive interference [7].Resonator with muffler is as effective as a single resonator. Located inside the muffler is a set of tubes. These tubes are designed to create reflected waves that interfere with each other or cancel each other out [8]. Resonator also reduces vibration of the car.

TABLE 3
ANALYZER CONDITION

Condition	Description
Frequency (HZ)	64.6
Resolution (F: Hz,T:ms)	F = 5.38 ; T = 185.8
Level Range	Automatic
Sampling Rate (kHz)	44.1
Frequency weighting	Flat
Time resolution	1x
FFT size	8192
Channels	1ch
Frequency axis	Log
Frequency range	Automatic

Figure-17 shows that unlike engine block noise, exhaust noise increases significantly with engine load. Graph shows noise level vs. speed for a 4-cylinder engine. Speed vs engine exhaust noise shows that maximum exhaust noise is 93 dB. The overall noise level from most unsilenced engine exhaust systems varies from about 60 dB to 93 dB, when measured 1 meter from the pipe outlet. The exhaust noise spectrum will always contain strong tones associated with the rate of cylinder firings

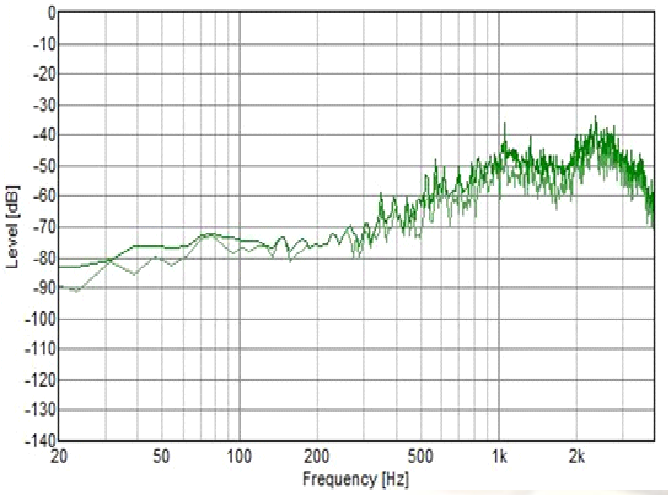

Fig 17: Frequency (Hz) vs sound level (dB) at unsilenced Condition

In 4-cycle engines each cylinder fires once every other revolution of the drive shaft. The engine firing rate is generally the strongest tone in the exhaust spectrum. From figure 18 it is very clear that, engine block noise, exhaust noise decreases. Speed vs engine exhaust noise graph shows that noise decreases with speed. Using resonator with muffler noise level decreases to 80 dB where unsilenced noise was 93 dB. By using resonator we were capable of reducing noise of 13 dB.

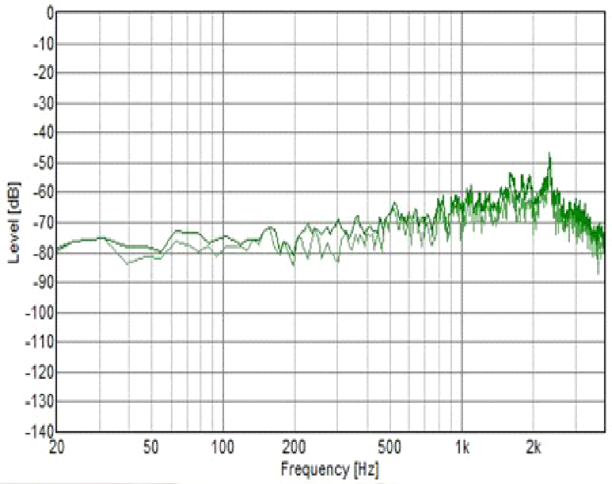

Fig 18: Frequency (Hz) vs sound level (dB) at silenced condition

XI. Environmental Impact

Catalytic converters have proven to be reliable and effective in reducing noxious tailpipe emissions. However, they may have some adverse environmental impacts in use:

The requirement for a rich burn engine to run at the stoichiometric point means it uses more fuel than a "lean burn" engine running at a mixture of 20:1 or less. This increases the amount of fossil fuel consumed and the carbon dioxide emissions of the vehicle. However, NOx control on lean burn engines is problematic and difficult.

Although catalytic converters are effective at removing hydrocarbons and other harmful emissions, most of exhaust gas leaving the engine through a catalytic converter is carbon dioxide (CO2), one of the greenhouse gases causes of global warming. Additionally, the U.S. Environmental Protection Agency (EPA) has stated catalytic converters are a significant and growing cause of global warming, due to their release of nitrous oxide (N2O), a greenhouse gas over 300 times more potent than carbon dioxide.

Catalytic converter production requires palladium and/or platinum; part of the world supply of these precious metals is produced near the Russian city of Norilsk, where the industry (among others) has caused Norilsk of most polluted places.

XII. Discussions

All the experiments were accomplished in a condition which was not influenced by temperature, pressure, relative humidity, moisture or any other external factors of the environmental situation.At both the conditions the engine was made to run at an idle speed for about 15 minutes to make sure that the engine gets into a stable condition which is favorable for taking the measurements.The graphical representation shows us the reduction of hydrocarbon content with the attachment of catalytic converter.The harmful contents like CO2, CO, NO2, NO have been reduced in quantity to a great extent with the presence of catalytic converter.

XIII. Conclusion

The presence of catalytic converter is must in an exhaust system as it reduces the pollutant content to a great extent except for sulphur di oxide the amount of which increases with the increase in speed even with the presence of catalytic converter. Although more study can be done with the latest designed catalytic converter along with other emission control devices. The graphical representation actually indicates the reduction of hydrocarbon and other harmful contents with the attachment of catalytic converter.

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