Reduction and mitigation strategy of carbon dioxide emissions from internal combustion engine: An engine development initiative for sustainable environment

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Reduction and Mitigation strategy of Carbon Dioxide Emissions from Internal Combustion Engine: An Engine Development Initiative for Sustainable Environment

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Research Highlights

- Methanol-Gasoline blending to test and compare CO_2 emissions
- Engine testing for emissions and performance
- Mitigation of CO_2 emissions through a four muffler design replacement
- Sustainability study of replacing the fuel and exhaust muffler in CO_2 reduction.

Abstract:

This study reports various methods to reduce and mitigate the CO_2 emissions from internal combustion engines. In order to achieve this, the gasoline fuel is replaced with Gasoline-Methanol blend of 5%, 10% and 15% of methanol by volume. Then the emissions and performance tests are carried out to catch CO_2 emissions from a spark ignition engine operating in different combinations of torque (2Nm, 3Nm and 5 Nm) and speed (500 rpm, 1000 rpm and

1500 rpm). In order to further mitigate the CO_2 emission, four different design mufflers are manufactured and replaced for testing to see the effect on CO_2 emissions.

Keywords: CO_2; mitigation; methanol blend; muffler; chamber; turbo type; gasoline

1. Introduction

Carbon dioxide (CO_2) emissions are one of the major constituents of greenhouse gases. Automobiles are a major source of CO_2. Rapid increase in the use of automobiles, powered by fossil fuels, emit CO_2, CO, NO_x and HC on a large scale to the environment. Urban areas are more prone to environmental degradation compared to rural ones due to increased vehicle density. This creates an imbalance of atmospheric constituents, leading to a health hazard to people. Mega cities like Delhi, Shanghai, Tokyo etc. have already passed through the phase of the dangerous effects of CO_2 emissions. Society is so dependent on vehicles that it is difficult to consider an alternative way of moving around. Alternative power systems that produce less CO_2 emissions, such as electric vehicles and hybrid technologies for vehicles are being developed, but their current cost and the supportive infrastructure is prohibitive for most cities. Indeed, even well-developed economies are introducing these at a slow and steady pace to enable technology to be established (ref). In the UK, the overall carbon target to largely decarbonized road transport sector by 2050. To achieve this from 2040 onwards every single car or van to be sold to be ultra-low emission vehicles (Office of low carbon vehicle UK, 2013). For many more years the internal combustion engine will remain an inherent part of vehicles in most regions in the world. The current requirement is to reduce the emission levels without significantly modifying the engine infrastructure. Many attempts are being made in to reduce emission from engines operated on fossil fuel. One of the promising methods is to replace traditional fuel (gasoline/ diesel) with fuels which have been blended with lighter components. The objective of this work is to adopt the fuel variation in the engine through replacements of Gasoline with B_5, B_{10} and B_{15}. Also to implement muffler design modification for monitoring the trend of CO2 in an SI engine.

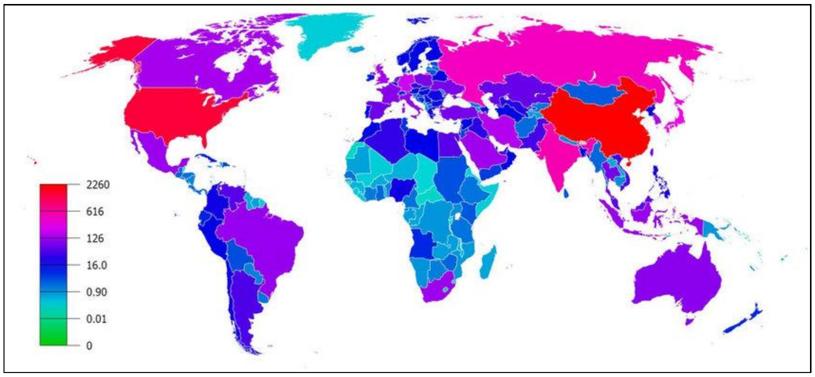

Fig.1 World Carbon dioxide emission levels (this figure to be updated)

2. Background Motivation

Carbon dioxide (CO_2) from automotive vehicles is a major source of emissions. It is a contributor to climate change. Increases in atmospheric temperatures and rising sea levels are the indicators of a heavy presence of CO_2 in the atmosphere (Ekwurzel et al., 2017). (Terrenoire et al., 2007) carried out anthropogenic CO_2 emission recording for 343 cities. Here data from individual cities are subject to quality control to separate from those of other greenhouse gases. Through this analysis, some set of ancillary data from other sources (socio-economic and traffic indices) or calculated (climate indices, urban area expansion) and combined with emission data. (Aye et al., 2017) studied the effect of economic growth (EG) on CO_2 emission using a dynamic panel threshold framework. The results show the EG has a negligible effect on CO_2 emissions. There is evidence of a significant causal relationship between CO_2 emission, economic growth, energy consumption and financial development. The findings emphasize the need for transformation of low carbon technologies aimed at reducing emissions and sustainable economic growth. This may include energy efficiency and switching away from non-renewable energy to renewable energy. (Abeydeer et al., 2019) identified sulphur dioxide, nitrogen dioxide and carbon dioxide as prime causes of global climate change. Out of them, CO_2 is recognized as a good agent for exploring the strategy for carbon reduction and mitigation. It can be seen that evaluating greenhouse gas emissions and estimating the carbon footprint is a preferred method for most research in this area. Moreover, climate change and environmental effects of carbon emissions were also significant points of concern in carbon emission research. The key findings of this study will be beneficial for the policymakers, academics, and institutions to determine the future research directions as well as to identify with whom they can consult to assist in developing carbon emission control policies and future carbon reduction targets. (Valihesari et al., 2019) tested a blend of gasoline, oxygenate additive; Methanol and metal nanoparticles: Fe_2O_3 and TiO_2 in a 4-stroke engine to investigate the effects of the new blend on the engine parameters, such as power and torque and also the amount of target pollutant gases emitted which are CO_2, CO, NO_x and HC. The research being undertaken, around the world is now mainly focusing on reducing the engine emissions, while using fossil fuels. (Verhelst et al., 2019) carried out a review on the use of methanol as a pure fuel or blend component for ICEs. They summarized various method of methanol production and also the health and safety issues associated with the use of methanol as fuel for ICEs. Many properties of methanol (for example high heat of vaporization) are superior to that of gasoline. These help make blended fuels a suitable improved alternative to traditional automotive fuel compositions. It is necessary to address changes in hardware, materials and heat recovery to improve the engine efficiency when using methanol. Furthermore, the behaviour of methanol fuel such as, mixture formation, normal/abnormal combustion, high latent heat, fast burning velocity, high knock resistance etc.

are reviewed for the modelling aspect. Blended fuels show promising performance as compared to traditional gasoline or diesel fuel. (Shrivastava et al., 2019) through transesterification of a bio-diesel from karanja and roselle oil, tested for emissions and performance. They achieved lower thermal efficiency with reduction of exhaust gas temperature by 1.48% and 1,38%. But brake specific fuel consumption increased by 4.13% compared to traditional diesel fuel. The use of blend shows 15.3% less NOx and 1.92% more CO_2 compared to diesel. Through this analysis, an ANN model was developed to predict the output parameter through multi variable response. (Mourad et al., 2019) studied the blending of Gasoline-ethanol and Gasoline-butanol (25,5%,10%,15%) on the emissions and power of an engine. They observed a 13.7% reduction in CO_2, 25.2% reduction in hydrocarbon, 8.22% reduction in fuel consumption. However they also reported an 11.1% reduction in engine power.

Due to the uncontrolled use of vehicles operating on fossil fuels, regulations are defined to curb emission level at a regional or country wide level. (Olabi et al., 2020) carried out a review of the regulations and techniques to eliminate toxic emissions from diesel engine cars. (Rao et al., 2018) carried out a review on Performance of the IC Engine Using Alternative Fuels. An attempt is made to design and develop IC engine parts that are most suitable for alternate fuels, that can last longer without affecting the performance of the engine.

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(Mishra et al., 2020; Gupta et al., 2019) aimed to fully evaluate the effects of petrol-methanol blends on the emission and performance of engines and the corresponding noise levels. Petrol blended with 5%, 10% and 15% of methanol was used in three separate tests, which are conducted at constant torque and variable speed conditions. The exhaust emission analysis was done using a six gases emissions analyzer. The emission levels were measured, while the engine was mounted in a special purpose engine test bed fitted with an eddy current dynamometer capable of controlling the speed and torque of the engine. The noise level of the silencer was also measured to understand the effects of methanol percentage on engine knock. The analysis predicts the blend of 5%, 10% and 15% methanol with petrol exhibited less emissions and knocking behaviour compared to pure petrol. In some cases, the NO_x emissions of richer fuel blends was higher than that of leaner ones. However, other emission constituents were significantly reduced when using the methanol blend in place of pure petrol.

Based on this broad literature review, it is understood that most of the research concentrated on use of blending, while few of them reported modelling and simulation. Very few reported the cumulative effect of fuel blends and engine modification on emissions, especially CO_2 and its reduction and mitigation strategy.

2. Materials and Methods

Different techniques are considered to achieve a reduction and mitigation of CO_2 in an ICE. One such technique is to replace pure gasoline with a gasoline-methanol blend. It is not possible to operate the engine with pure methanol as the fuel is hugely toxic and burns with an invisible flame. Furthermore, pure methanol is very corrosive to the engine components (). To manage these negative effects, the methanol percentage is maintained at low levels of 5%, 10% and 15% respectively.

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2.1 Gasoline-Methanol blend preparation and characterization

The composition of blend in this study is made to (95% by vol. of Gasoline and 5% by vol. of Methanol) B_5, (90% by vol. of Gasoline and 10% by vol. of Methanol) B_{10} and (85% by vol. of Gasoline and 5% by vol. of Methanol) B_{15}. The blending is done manually, and is effective due to the high diffusivity of methanol.

The density of the blend of two liquids can be numerically computed as per equation (1)

$$\rho_{blend} = \frac{\rho_g v_g + \rho_m v_m}{v_g + v_m} \quad (1)$$

Again, kinematic viscosity for the blend can be estimated numerically using three different methods; Gambill method (Gambill et al., 1959), Refuta equation and chevron formula as given in Eq. (2), Eq(3) and Eq(5) respectively.

$$\kappa_{blend} = x_g \kappa_g^{\frac{1}{3}} + x_g \kappa_g^{\frac{1}{3}} \quad (2)$$

As per (Maples et al., 2000), Refuta-mass fraction basis yields $VBN_i = 14.534 \times \ln\left(\ln\left(\kappa_i + 0.8\right)\right) + 10.975$ (3)

$$VBN_{blend} = \sum_{i=0}^{n=0} x_i VBN_i \quad (4)$$

$$\kappa_{blend} = \exp\left(\exp\left(\frac{VBN_{blend} - 10.975}{14,534}\right)\right) - 0.8 \quad (5)$$

Chevron formula (volumetric basis)

$$VBN_i = \frac{\ln\left(\kappa_i\right)}{\ln\left(1000 \times \kappa_i\right)} \quad (6)$$

$$VBN_{blend} = \sum_{i=0}^{n=0} v_i VBN_i \quad (7)$$

The octane number of a blend is calculated on basis of the formula given in Eq. (8)

$$OCT_{blend} = OCT_{gasoline} \times \left(v_{gasoline}\right) + OCT_{methanol} \times \left(v_{methanol}\right) \quad (8)$$

Once the blend is ready, the fuel characteristics of the blend are studied with particular focus on how those desired properties are similar to the pure gasoline which is being replaced. Table 1 shows the comparative value of B_5, B_{10} and B_{15} with gasoline and methanol.

Table 1 Comparative values of blend with respect to gasoline and methanol

Fuel properties	*Testing standard*	*Gasoline*	*B5*	*B10*	*B15*	*Methanol*
Density (kg/L)	ASTM 4052	0.745	0.742	0.736	0.732	0.784
Kinematic viscosity (C Stoke)	ASTM D445	0.88	0.86	0.84	0.81	0.65
Acid value (mg KOH/g)	ASTM D664	0.32	0.30	0.295	0.29	12.5
Flash point (^{o}K)	ASTM D93	246	244	242	241	285
Calorific value (kJ/kg)	ASTM D240	47300	47230	47129	46965	22700
Auto-ignition temperature (^{o}C)	ASTM E659	580	573	564	540	420
Octane number	ASTM D2700 (MON)	92	96	98	99	130
	ASTM D2699 (RON)	100	100	101	101	102

2.2 Material for muffler manufacturing

In this study, one of the CO_2 mitigation techniques is considered to be muffler design modification. The mufflers are manufactured out of GI pipes and sheets (*E=200GPa, v=0.29*). The fabrication process includes, metal sheet forming, welding, hole drilling and assembly. All the activities are performed in the Central Workshop of KIIT University Bhubaneswar. Fig. 2 shows the four different mufflers prepared for this analysis.

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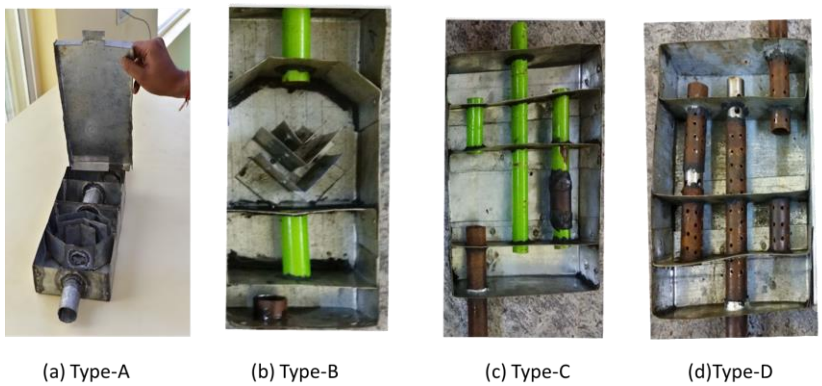

Fig.2 Muffler manufacturing, (a) Type A: Chamber non-perforated, (b) Type B: Chamber perforated, (c) Type C: Turbo non-perforated and (d) Type D: turbo perforated

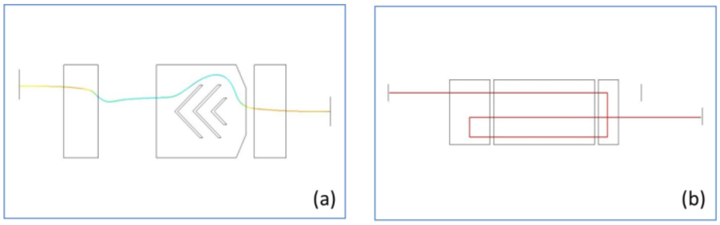

Fig.3 Exhaust gas path (Mishra et al., 2020) in: (a) Chamber type muffler, (b) Turbo type muffler

2.3 Details of Engine-Test bed-Emission Analyzer

The engine used for this particular testing of emissions and performance is a four stroke, single cylinder, double valve, 105.6 cc engine (Mishra et al., 2020). It has bore to stroke dimension of 49.0 x 56.0 mm and a compression ratio of 9:1. It can deliver power maximum up to 6 kW with 7500 rpm. It has the provision of wet sump lubrication, fin cooling and used wet type multi-plate clutch. It is fitted with a four-speed constant mesh type gear transmission system. Figure 4(d) shows the engine of this specification mounted in the test bed for testing.

Fig.4 Emission measurement, (a) Emission data acquisition, (b) performance data acquisition, (c) emission sensing at exhaust and (d) Engine test bed

The table 2 shows the specification of the dynamometer for this study. The dynamometer used here is eddy current type with maximum engine torque of 90 Nm and 7000 rpm. APPSYS WED 38S type magnetic water strainer is used here along with a water flow switch, reaction type torque sensor, torque calibration arm and magnetic pick up sensor. The control panel is equipped with PC hardware, PCI data card and a data acquisition system to view and control the torque (Nm), speed (rpm), mechanical power (kW/HP), pressure (N/m^2) and temperature (^0C). Data acquired can be stored in an excel sheet along with various graphical outputs. The dynamometer can be controlled either in automatic mode or manual mode.

Table 2 Specification of water-cooled Eddy current dynamometer with 38 kW power rating (Mishra et al., 2020)

Attributes	*Details*
Model	APPSYS WED 38S

Rated absorption Power (KW)	38 kW (50 hp).
Maximum torque (Nm)	90 Nm
Maximum Torque at Speed Range	1400 to 4031 rpm
Maximum Speed (R / Min)	7000 rpm (for Speed more than 7000 rpm high speed bearings are used.)
Torque measurement precision (F. S.)	± 0.5 FS%, 0.1 Nm resolution
Speed measurement precision (F. S.)	± 0.5 FS %, 1 rpm resolution
The direction of rotation	Both Direction, Clock wise & Anti-Clock wise
Max. Water Flow (Ltrs / hr) with Pressure	1400 Ltrs/hr at 1 – 2 bar pressure
Drainage maximum temperature (° C)	65
Moment of inertia (kgm²)	0.018

2.4 Emission measurement using HORIBA MEXA-584L Emission Analyzer

The emission analyzer used in this study is the HORIBA MEXA-584L, which can simultaneously sense CO, HC and CO_2 using non-dispersive infrared (NDIR) technique. The air-to-fuel-ratio or excess air ratio (A) is also measured with this analyzer. The analyzer is a mobile system, it can even be used outdoors and has a single screen. Also, O_2, NO_x, engine speed and oil temperature can be measured in this instrument. Table 3 provides the detail specifications of the emission analyzer.

Table 3 Specification of Horiba Mexa 584-L emission gas analyzer (Mishra et al., 2020)

Attributes	*Details*
Measured gas components (standard)	• CO, CO_2, LAMBDA (Unburnt HC), O_2 and NO_x
Measuring principle	• CO, HC, CO_2: Non-dispersive infrared (NDIR) • Air-to-fuel ratio (AFR), Lambda: Carbon balance method or Brettschneider method with O_2 measurement. AFR and lambda are calculated by carbon balance in standard configuration.
Conformed standard	• OIML Class 0-CE-FCC.
Ambient humidity	• Under 90% relative humidity.

The fig. 4(a) shows this emission analyzer in action, measuring exhaust gases from the engine. It should be ensured that the source of power is stable. Before switching on the analyzer, it is ensured that the sensing pipe end is made leak proof using a rubber cap. After a warmup period of 300s, it automatically starts the leak detection test. If it fails the leak detection test, the leak proofing should be inspected and the procedure is repeated. If it passes the leak detection test, the measuring of HC following the removal of the cap can be undertaken. Once the HC hang up test was done, the analyzer is ready to measure the emissions from the engine. There is one communication software in MEXA-584L, which can interface the machine with the computer with sampling rate and sampling time. The data can be recorded once every 3s for 120s and stored in an excel sheet.

2.5 CO_2 Emission formation mechanism

There are basically three types of emission formed in a running engine; exhaust emissions, crank case emissions and evaporative emissions. In this analysis, we shall consider the exhaust emissions. As per earlier studies (Gupta et al., 2019), 100 % CO/CO_2 emissions are from the exhaust of combustion gases. The emissions formation mechanism of CO_2 is a two-step process (NPTEL IITK, 2012). The first step is conversion of HC to CO, where several oxidation reactions are involved in the formation of intermediate compounds like small HC molecules, aldehyde, ketones etc. as given in equation (1)

$$RH \rightarrow R + O_2 \rightarrow RCHO \rightarrow RCO \rightarrow CO \qquad (1)$$

With availability of sufficient oxygen in air conversion of CO to CO_2 is ensured. The chemical reaction is given in equation (2). The formation of CO_2 is the reassurance that complete combustion has occurred and sufficient oxygen and time were available to eliminate unburned

HC from the exhaust gases. However, the quantity of CO_2 is a directly related to the performance of the engine. The trend in modern engines is to reduce fuel consumption and thus reduce the CO_2 emissions by reducing fuel consumption, improving combustion processes and reducing the overall engine mass and friction through improved engine refinement.

$$2CO + 2OH \rightarrow 2CO_2 + H_2 \quad (2)$$

2.6 CO_2 Emission Measurement

In this study, we have implemented a single cylinder spark ignition engine, the details of which is given in fig 4(d) earlier. The engine is operated at different combinations of torque and speed to acquire the CO_2 emissions by using the HORIBA MEXA emissions analyzer. The testing is done by using the different gasoline blends, B_5, B_{10} and B_{15} to obtain three different sets of results for the fuels. A universal engine test bed fitted with an eddy current dynamometer is engaged to mount the engine. Through this arrangement, this engine is mounted on a universal test bed that is equipped with an eddy current dynamo meter with control panel arrangement for load, torque and speed monitoring through digital/PC mode. Before recording performance parameters, the dynamometer is subjected to a ‘load calibration test’ to ensure that the sensed digital data and the computerized data are correct. A 10 kg weight is used to perform this calibration. As the load arm is 50 cm, the torque monitor should show 49 Nm torque reading on both left and right side of the arms as shown in fig. 5. It is done to ensure that the digital as well as computerized data acquisition systems are accurate. Continuous water circulation into the eddy current dynamo meter is ensured by an external pump arrangement to extract the frictional heat out of the dynamometer due to engine braking. Such monitoring is done by observing the green color of the indicator light provided in the data acquisition monitor for dynamometer water supply.

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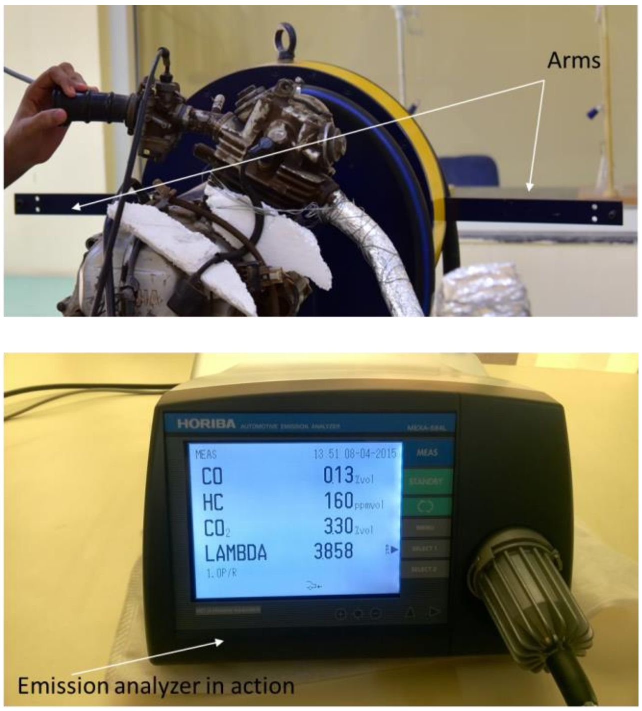

Fig.5 Dynamometer arm and emission analyzer in measuring mode

3. Results and Discussions

3.1 Emission Analysis Results and Discussion

Fig. 6(a-d) show CO_2 response to engine torque (2Nm, 3 Nm, 5 Nm) at 500 rpm. In all cases (Gasoline, B_5, B_{10} and B_{15}) chambered type muffler (Type-A and Type-B) shows less CO_2 emission compared to turbo type muffler (Type-C and Type-D). Chambered type non-perforated muffler (Type-A) has the lowest (2.76 by % vol) amount of CO_2 emissions from pure gasoline fuel at 2 Nm. The turbo perforated (Type-D) muffler has the highest CO_2 emissions (9.52 by % vol). Perforation led to a 42% increase in CO_2 for all chambered type mufflers at 2 Nm and 5

Nm, while using gasoline at 500 rpm. The effect of perforation in the chambered type muffler shows less difference in CO_2 emission at 500 rpm. For the turbo type muffler, running on pure gasoline fuel the difference is less, but for blended fuels (B_5, B_{10} and B_{15}) larger differences of CO_2 emissions are observed, and more so in the case of the perforated turbo type (Type-D). The chambered type mufflers have almost half the level of CO_2 emissions as compared to turbo mufflers.

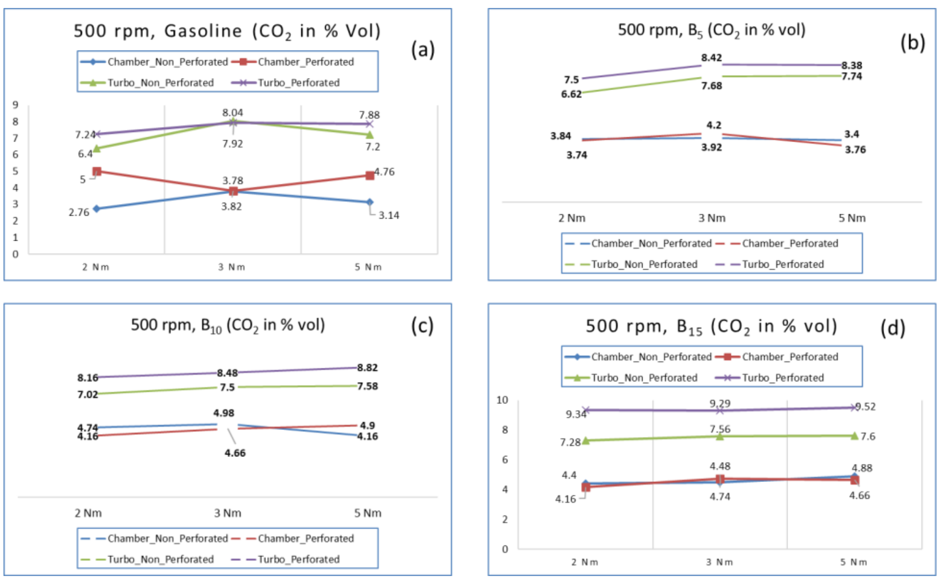

Fig.6 CO_2 response to engine torque, (a) Gasoline at 500 rpm, (b) B_5 at 500 rpm, (c) B_{10} at 500 rpm and (d) B_{15} at 500 rpm

Figs. 7(a-d) show the CO_2 response to engine torque (2 Nm, 3 Nm and 5 Nm) at 1000 rpm. As the speed increases from 500 rpm to 1500 rpm, the CO_2 emissions increase in all cases. Lowest value of CO_2 emissions is 4.12 by % vol. at 2 Nm for the chambered type non-perforated muffler (Type-A). Similarly, at 1000 rpm the turbo perforated muffler (Type-D) shows maximum CO_2 emissions of 9.64 by % vol at 3 Nm. The effect of perforation has again less effect in case of the chamber type muffler at 3 Nm, which is 0.18,0.08, 0.66 and 0.22 for gasoline blends B_5, B_{10} and B_{15}, respectively. Perforations lead to a maximum 59.3% increase in CO_2 emission in case of using the chamber type muffler with B_{10} at 2 Nm. Furthermore, the turbo type muffler gives a maximum 29.9% increase in CO_2 emission B_{15} at 2 Nm.

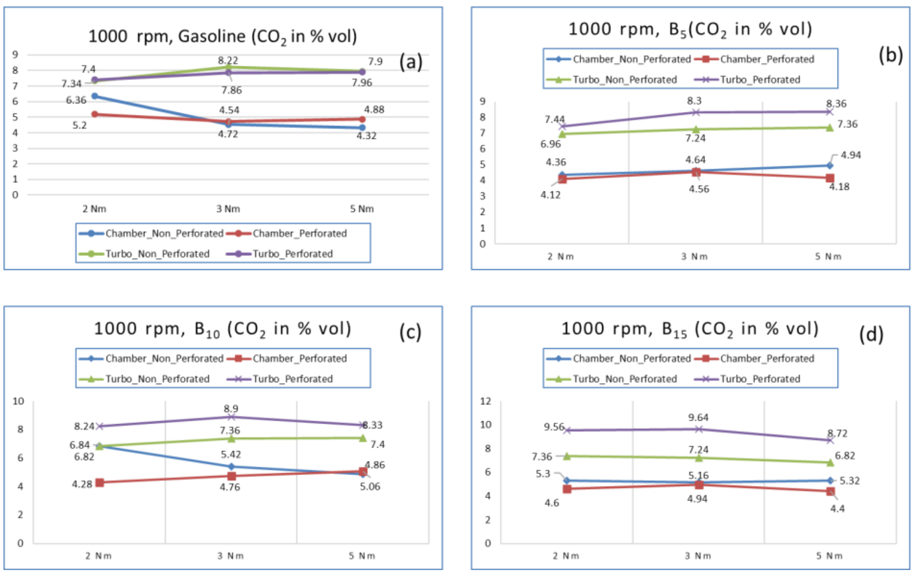

Fig.7 CO_2 response to engine torque, (a) Gasoline at 1000 rpm, (b) B_5 at 1000 rpm, (c) B_{10} at 1000 rpm and (d) B_{15} at 1000 rpm

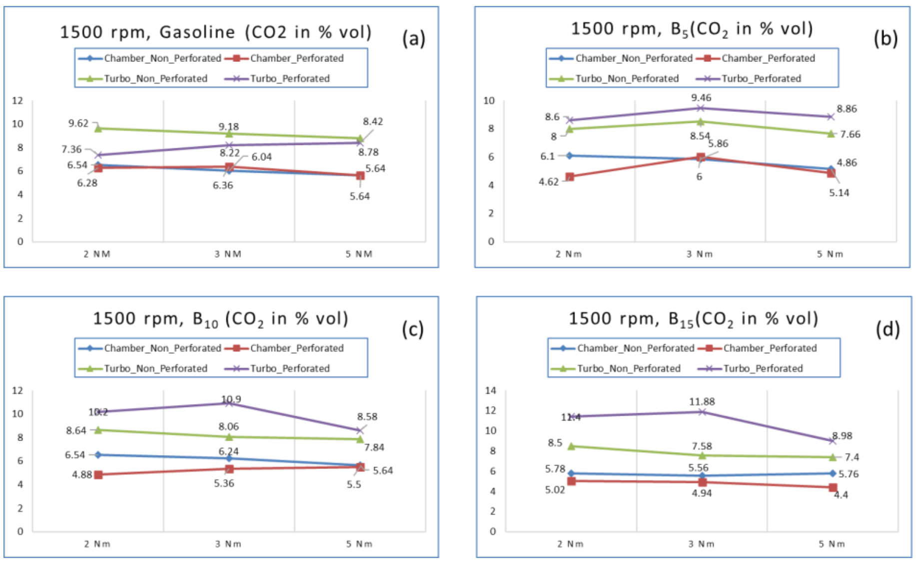

Fig.8 CO_2 response to engine torque, (a) Gasoline at 1500 rpm, (b) B_5 at 1500 rpm, (c) B_{10} at 1500 rpm and (d) B_{15} at 1500 rpm

Fig. 8 (a-d) show CO_2 response to engine torque at 1500 rpm for Gasoline, B_5, B_{10} and B_{15} respectively. The lowest CO_2 emissions at this speed are observed to be 4.28 by % vol. for the type-A muffler at 2 Nm. The highest CO_2 formation (11.88 by % vol) occurs at 3 Nm for the type-D muffler. For the turbo type muffler, the effect of perforation enhances the CO_2 emissions by 56.7 % at 3 Nm for B_{15}, while for the chamber type muffler, the effect of perforation enhances CO_2 emissions by 34.01% for B_{10} at 2 Nm. At 3 Nm, for the Chamber type, muffler perforation has negligible effect on CO_2 emissions (0.32, 0.14, 0.88 and 0.62) by % vol. for all fuels (Gasoline, B_5, B_{10} and B_{15}). The effect of perforations in the turbo type muffler has the highest impact on CO_2 emission with (0.96, 0.92, 2.84 and 4.3) by % vol. for (Gasoline, B_5, B_{10} and B_{15})

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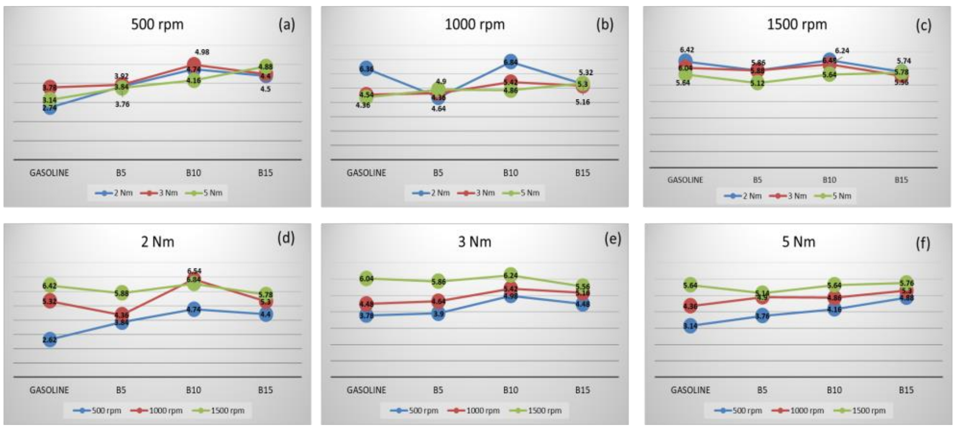

Fig.9 CO_2 response to fuel type at: (a) at 500 rpm, (b) 100 rpm, (c) 1500 rpm, (d) 2 Nm, (e) 3 Nm and (f) 5 Nm

Figs. 9(a-f) show the CO_2 response to fuel change (Gasoline, B_5, B_{10} and B_{15}). When gasoline is replaced with B_5, the emission levels are found to increase (0.14,0.36, 0.24, -1.06, 0.16 and 0.54) by % vol. at (500 rpm, 1000 rpm, 1500 rpm, 2 Nm, 3 Nm and 5 Nm). Similarly, when gasoline is replaced by blend B_{10}, the emission levels are also found to increase (1.2,0.88, 0.6, 1.52, 0.94 and 0.5) by % vol. at (500 rpm, 1000 rpm, 1500 rpm, 2 Nm, 3 Nm and 5 Nm). Furthermore, when gasoline is replaced by blend B_{15}, the emission levels are found to increase (-0.1, -0.1, -0.46, -1.36, -0.26 and 0.44) by % vol. at (500 rpm, 1000 rpm, 1500 rpm, 2 Nm, 3 Nm and 5 Nm).

3.2 Muffler CFD Simulation results and discussions

In order to understand the muffler exhaust performance, we have decided to carry out computational fluid dynamics simulation in Ansys fluid, Prior to such analysis, the solid model of all four mufflers are prepared, conforming to the geometries of fabricated ones. (Mishra et al. 2018) explained the step-by-step build-up procedure for solid modelling using CATIA. Later, such models are imported to ANSYS fluid, which are compatible to it. The very first step in

ANSYS is to create mesh model of the mufflers. Details of the mesh such as number of elements, number of nodes, element size, element type etc. are automatically selected by ANSYS work bench. Here the element type auto-selected are tetrahedral with 18o curvature normal angle. The first step of CFD is pre-processing, which includes defining inlet and outlet surface of the control volume of muffler. Table 4 shows the parameter required under inlet boundary conditions, that includes densities, enthalpies and viscosities for gasoline, B_5, B_{10} and B_{15}. The table 5 shows the velocity variation at inlet for all muffler design at gasoline, B_5, B_{10} and B_{15} use. Table 6 and 7 show the other input parameter and the mass fraction at inlet respectively as drawn from the emission measurement. The mesh model along with input parameters are loaded in the solver for output data generation.

Table 4 Parameters under inlet boundary conditions.

Models/Parameters	*Inlet Boundary*			
	Pure	B5	B10	B15
Density (kg/m^3)	1.021	1.0271	1.0170	1.024
Enthalpy (j/kg)	163675	156911	160984	159136
Viscosity (kg/m-s)	0.0000172	0.0000172	0.0000172	0.0000172

Table 5 Velocity (m/s) variation at the inlet.

Models/Blends	*Pure*	*B5*	*B10*	*B15*
Type-A&B	0.1051	0.1084	0.1144	0.119
Type-C&D	0.1050	0.1085	0.1144	0.119

Table 6 Other input parameters

Parameter	*Pure*	*B5*	*B10*	*B15*
Temperature(^0C)	363	357	360	359

Mass Flow Rate (Kg/sec)	0.00052	0.00055	0.00057	0.0006
HT Coefficient (W/m^2K)	35	42	46	52

Table 7 Mass fraction at inlet (As input parameter).

Cases/Gases	*CO*	*NOx*	*HC*	*CO2*	*O2*
Pure Gasoline	0.027544	0.00011	0.000064	0.06241	0.17668
B_5	0.0331	0.0001924	0.000082	0.062602	0.17531
B_{10}	0.027301	0.00014208	0.0000610	0.06057	0.17975
B_{15}	0.026771	0.00021227	0.0000556	0.077116	0.16402

The solver used in this analysis is a pressure-based solver, where heat transfer is address through energy model and assumed that flow of heat occurs from hot exhaust gas to the walls of the muffler. The mixture of exhaust gases considered at muffler inlet are NO_x, CO, CO_2 and HC. Mass fraction of each constituent exhaust gas was calculated in terms of SI unit. Further enclosed walls are considered stationery with non-slip specific boundary with zero diffusion ability. As the exhaust gas moves faster, geometrical obstruction opposes the flow and creates back pressure. The mesh convergence and grid independent tests were carried out to ensure correction grid formation and that of mesh size. The figures (10-13) shows muffler performance parameters for all four models. Fig. 10 shows velocity streamline from inlet to outlet, maximum velocity of 0.28 m/s occurs at type-B muffler, while lowest 0.1643 m/s observed in case of type-D muffler.

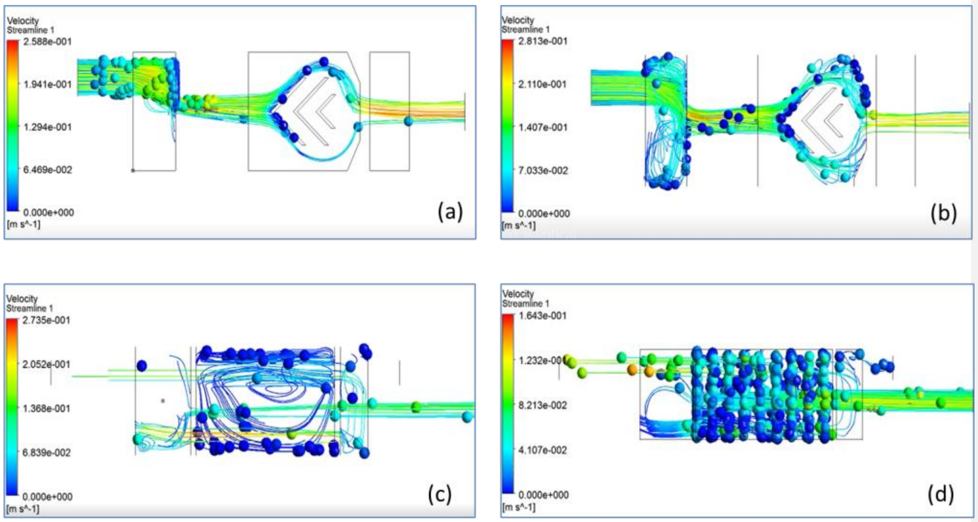

Fig.10 Velocity stream line from CFD simulation of: (a) Type-A muffler, (b) Type-B muffler, (c) Type-C muffler and (d) Type-D muffler

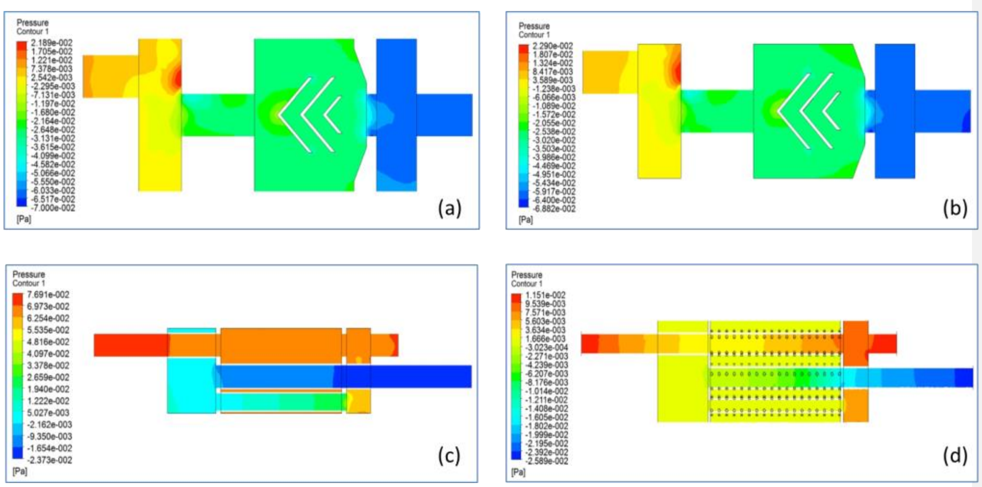

Fig.11 Back pressure from CFD simulation of: (a) Type-A muffler, (b) Type-B muffler, (c) Type-C muffler and (d) Type-D muffler

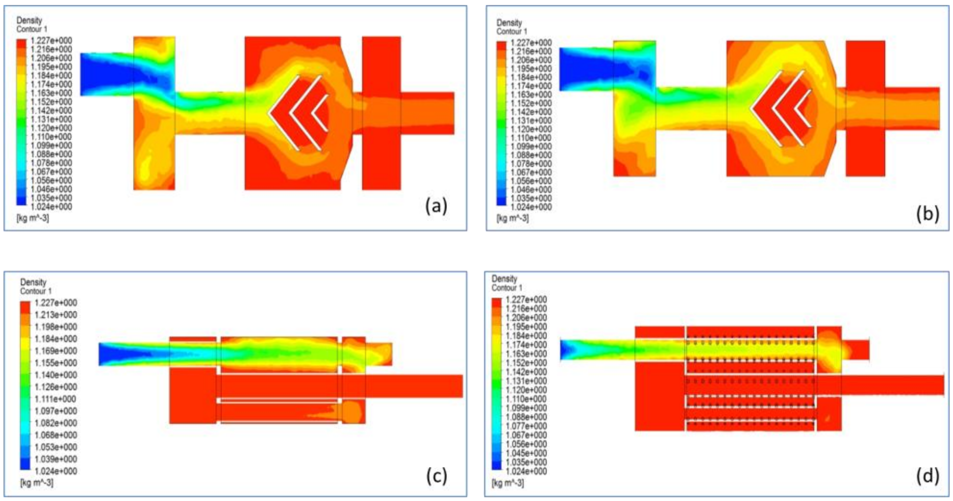

Fig.12 Emission gas density from CFD simulation of: (a) Type-A muffler, (b) Type-B muffler, (c) Type-C muffler and (d) Type-D muffler

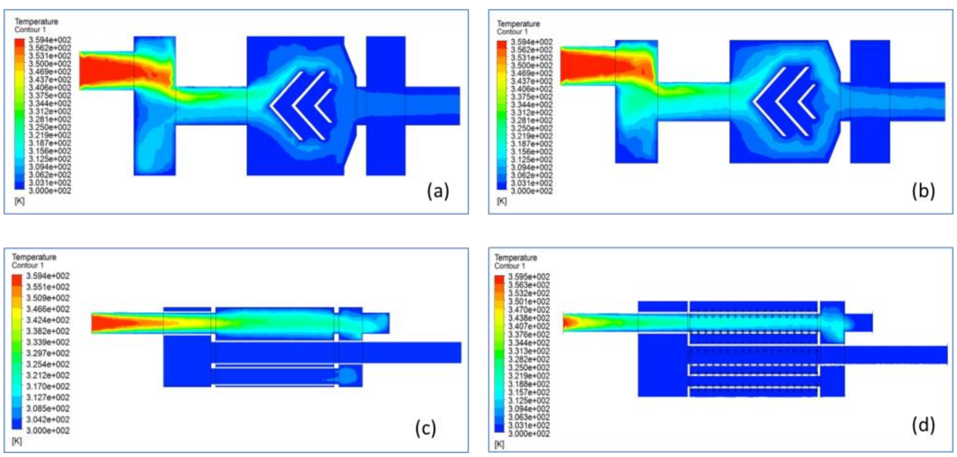

Fig.13 Emission gas temperature from CFD simulation of: (a) Type-A muffler, (b) Type-B muffler, (c) Type-C muffler and (d) Type-D muffler

Fig. 11 shows the back-pressure mapping of the four different mufflers, result obtained from CFD simulation. The highest back pressure of 0.0769 Pa observed for turbo non-perforated muffler, while the lowest of 0.0151 Pa found in case of turbo-perforated one. The fig 12 shows the density distribution in the muffler control volume. Not much variation in the density is observed. Fig. 13 shows the temperature distribution of the four different models. The distribution of temperature is more in the turbo mufflers compared to chambered type mufflers. In table 8 the key exhaust performance parameters are summarized.

Table 8 Summary of key exhaust performance parameters.

Muffler detail and blend detail	Maximum value of velocity in (m/s)	Maximum value of density in (kg/m^3)	Maximum value of back pressure in (Pa)x10^{-2}	Maximum value of exhaust temperature in (^0K)
Type-A&B muffler using pure gasoline	0.24	1.22	6.2	362
Type-C&D muffler using pure gasoline	0.146	1.25	1.4	362
Type-A&B muffler using B5	0.25	1.22	6.7	357
Type-C&D muffler using B5	0.152	1.27	1.49	357
Type-A&B muffler using B10	0.25	1.22	7.3	360
Type-C&D muffler using B10	0.158	1.26	1.5	360
Type-A&B muffler using B15	0.27	1.22	7.7	359
Type-C&D muffler using B15	0.164	1.30	1.65	359

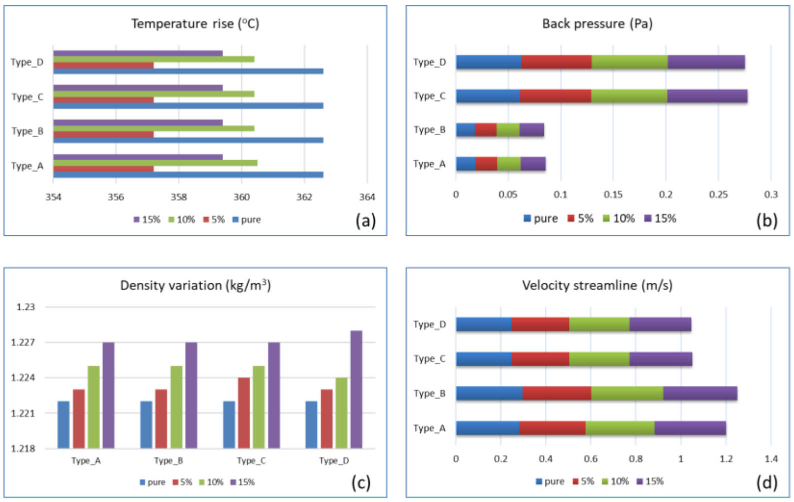

Fig.14 Bar chart of muffler performance, (a) Temperature rise, (b) back pressure variations, (c) density variation and (d) velocity stream line

Fig**.** 14(a-d) show the performance of the mufflers, which include surface temperature, back pressure, density and stream line velocity respectively. Surface temperature (fig.14-a) is almost independent to the muffler design. This is highest in case of pure gasoline fuel and lowest in the case of blend B_{10}. The back pressure (fig. 14-b) is the higher in case of the chambered type (Type-A and Type-B) mufflers as compared to the turbo types (Type-C and Type-D). Fig. 9-c shows the density variation of exhaust gas, which increases with % increase of methanol in the blend. As we proceed to the higher order of the blend, the combustion improves and yields more dense emission constituents. As shown in fig. 14-d, the velocity streamline is higher, in case of the chamber type design, as the path is simple, while in case of the turbo design the path is circulatory and more complex.

Commented [RI8]: Don't we need to ask why?

5. Sustainability analysis

The sustainability of the design modification and fuel change is worth discussing here. As mentioned earlier, the maximum blending possible is up to 15%. Higher order of methanol content is not encouraged in this analysis, and the reason is the toxicity of methanol content and also the flameless combustion. Secondly, methanol is easily available and it can be produced in the Petro-chemical facilities with minimal additional investment. There is absolutely no change in engine infrastructure required for such small fuel changes. The direct advantage is that the CO_2 formation is reduced as compared to pure gasoline. This direct benefit is available for no changes in engine structure or materials and minimal costs in fuel preparation as no separate blending facility is needed. Therefore, the improved impact on the environment from the reduction of engine emissions of CO_2 outweighs the potential cost of blending and providing this fuel directly to the pump for vehicle users. Furthermore, it can potentially reduce the demand on pure gasoline by 15% volume. Which could result in financial benefits for the oil companies. It has the potential of creating a new 'Methanol Economy' which can create opportunities for economic prosperity.

6. Conclusion

This study has investigated how it is possible to improve the CO_2 emissions from a gasoline engine by using blended gasoline-methanol fuels without negatively impacting the engine performance, or having a hugely detrimental effect on the engine structure.

Commented [RI9]: We need to qualify this last statement as there has been no investigation into the materials or components of the engine.

In addition to the gasoline-methanol blends, the design of the muffler have also been investigated for their effect on CO_2 emissions. The key findings are summarized as:

- Chambered type non-perforated muffler (Type-A) is best among all designs for reduced CO_2 emissions.
- Turbo perforated (Type-D) muffler has most CO_2 emissions compared to all designs.

- For chambered type muffler, effect of perforation is negligible at 3 Nm for all range of engine speed (500, 1000,1500) rpm.
- Effect of perforation is maximum at 3 Nm for turbo type muffler.
- At constant speed, the CO_2 emissions are higher for lower torque and at constant torque, CO_2 emissions are is lower for lower speed.

Such minor modifications has immediate implication to the automotive sectors and fuel manufacturers. Introduction of methanol could reduce burden on petroleum reserves with the benefit of reduced CO_2 emissions. The limitation of the current analysis is that the methanol is restricted to 15% in the blend. This is to eliminate the toxic effect and rapid degradation of engine components.

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