Diesel engine performance improvement with suitable low cost technologies for tractor applications

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Abstract: Off-road engines for tractor applications are developed with limited space due to packaging constraints and low cost targets. Hence major challenges faced by several off-road engine manufactures are to achieve higher power density and to comply emission legislation with low cost modifications. Henceforth in this work a cost-effective research approach is investigated for conversion of naturally aspirated (NA) engine to turbocharged intercooled for off-road diesel engines performance improvement. Further, reducing the charge air temperature into the engine by using water spray cooled intercooler strategy minimised the combustion temperature, consequently power and torque increased. To reduce the exhaust emission such as oxides of nitrogen (NOx), strategies such as cooled exhaust gas recirculation (EGR) are computationally optimised. This analysis is executed for selection of the EGR cooler tube to achieve better exhaust gas cooling effectiveness. In addition to the NOx reduction strategy, substrate volume for lean NOx trap is also optimised to investigate its effectiveness in this research work.

Keywords: off-road; tractor; diesel engine; turbocharger; intercooler.

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1 Introduction and background

A diesel engine is one of the most efficient sources of power with lower CO_2 emission, which have been considered for prevention of global warming and saving of fossil fuel as well as alternatives to electric motors and hybrid engine. The advantages of diesel engines have already been proven in multiple trucks/buses/passenger cars around the world. Furthermore, off-road applications are also applied to use engines for high heat efficiency, fuel versatility, robustness and running cost. A diesel engine operated with a turbocharger increases the power output as compared to the naturally aspirated engine. For this the exhaust waste-gate turbocharger application is one of the most and useful approaches utilised in controlling the turbocharging system of an internal combustion engine. These applications are widely considered due to their simplicity, low cost, durability and easy adaptation to smaller as well as average automotive engines (Ubabwa, 1990). The waste-gate control system allows the exhaust gas to by-pass the turbine and go straight to the exhaust system. This will control boost pressure, turbine rotor speed and engine back pressure. Further, the waste-gate enables improved matching of the turbocharger parameters in a low speed engine. Whereas the conventional turbocharged low speed engine usually encounters the problem of inadequate air supply, resulting in intensive exhaust smoking and low engine efficiency (Bohn et al., 2005; Commerais et al., 2006). Therefore, engine cylinders require turbines with increased air supply at low speed. The application of a small turbine inlet area can cause a series of unusual phenomena, such as increased exhaust back pressure, which especially at higher engine speeds leads to increased fuel consumption (Basil and Kowalczyk, 1993). Because of the turbocharging process, it is possible to increase the fuel injection and achieve increased engine torque backup and low exhaust emission. Wide waste-gate valve will result in premature opening of the waste-gate valve before and during higher engine operational conditions. This usually will affect unfavourably the vehicle operational performance, durability and efficiency of the boost pressure control system. Therefore, characteristics of the compressor as well as the fuel injection system influence the engine performance. Hence varieties of diverse factors affecting the choice of the turbocharger set are to be considered for particular engine application.

The power and torque of an engine are directly proportional to the amount of air entering the combustion chamber, if mixed with the right amount of fuel. But turbocharging increases the temperature of the boost air (Mirajka and Adhikaranth Tharayi, 2012). Hence reduction in the boost air temperature increases the density of the air, which makes for denser charge entering the combustion chamber (Jyotirmoy et al., 2011). Lowering of the intake charge air temperature also eliminates the danger of pre-detonation of the fuel air charge prior to ignition timing (Heisler, 1995; Ghaffarpour and Baranescu, 1996; Vance and Mayernick, 1963). This will give an increase in power and torque if the vehicle is tuned correctly. A good intercooler package can increase the power by as much as 30% when fitted to a non-intercooled turbo vehicle. An intercooled vehicle will always outperform the same non-intercooled vehicle in the fuel consumption stakes. Intercooling will result in improved fuel consumption resulting in increased mileage and reduced fuel costs. The reason being better efficiency caused by extra power and torque for the same engine capacity and lower operating temperatures that will result in less friction. Intercooling will cool down the charge air and will result in cooler exhaust gas temperature. The most common areas affected by high exhaust gas temperatures on turbocharged vehicles are turbocharger, cylinder head and pistons. Intercooler will help keep all engine components at a stable temperature and intercooling is one of the best ways to prevent turbo failures. Moreover, intercooler also reduces the NOx emission due to lower combustion temperature. Further, black smoke during low engine speed and high load condition is also reduced due to reduction in charge air temperature (Tan and Lu, 2003).

There are two basic approaches to intercooler heat exchanger design:

- air-to-air heat exchanger.
- air-to-liquid heat exchanger.

In this research work, the naturally aspirated off road diesel engine with conventional fuel injection system is converted to turbocharged, water spray intercooled engine for improved performance. For this air-to-liquid cooling, water spray arrangements are made on the intercooler for better air cooling efficiency.

In addition, for selection of minimum NOx after-treatment technique such as EGR cooler and lean NOx trap (LNT), their effectiveness is analysed.

2 Materials and methods

2.1 Low cost enhancement strategies

Figure 1 elucidates low cost strategy options for off-road diesel engine applications. Fuel injection strategies are optimised with P-type injector of hole size 0.22 mm. Further focus is made only on conversion of naturally aspirated engine to turbocharged intercooled (TCIC) along with fuel delivery. The delivery increase is made inside the pump for enhancing the performance. The below tinted options are considered for this study.

Figure 2(a) shows NA engine setup before modification. Figure 2(b) and (c) shows TCIC engine set up after modifications. Figure 2(d) shows turbocharger selected for this research.

Table 1 shows intercooler specification. Table 2 shows engine specification and Table 3 shows turbocharger specification selected for this study.

Table 1 Intercooler specification

Intercooler design type	*Cross flow heat exchanger – water spray cooled*
Qty of air tube	9
Inner fin pitch	3.5 mm triangular
Pressure drop	3.8 kPa
Outside fin pitch	4.5 mm
Open frontal area	3.71 m^2

Table 2 Engine specification

Stroke	127 mm
Bore	91.44 mm
Compression ratio	18.5 : 1
No. of valves	2
Inlet valve open	13 deg BTDC
Atomiser setting pressure	240 kg/cm^2

Table 3 Waste- gate turbocharger specification

Oil inlet diameter	13 mm
Compressor outlet diameter	19.5 mm
Compressor inlet diameter	29.5 mm
Exhaust outlet diameter	50 mm
Turbine wheel diameter	31 mm
Compressor wheel diameter	33 mm

Figure 1 Low cost performance enhancement strategies (see online version for colours)

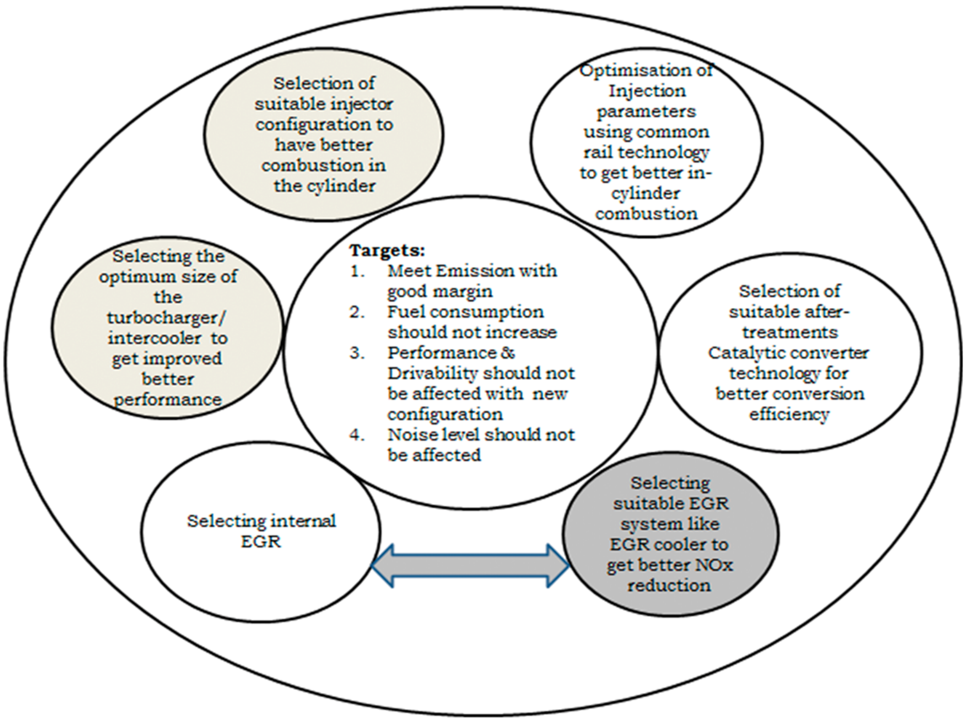
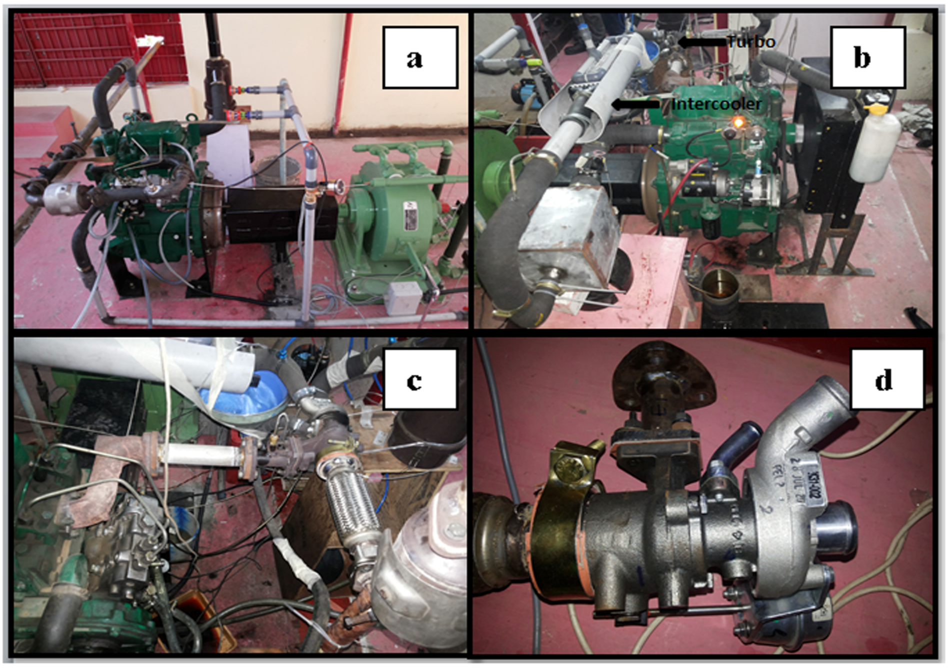


Figure 2 Experimental set up of NA and TCIC engine: (a) NA engine setup before modification; (b) and (c) TCIC engine set up after modifications and (d) turbocharger selected for this research (see online version for colours)



3 Results and discussion

3.1 Performance characteristics

Air inlet pressure (*bar*). Figure 3 elucidates air flow is increased by 42% for TCIC engine as compared to NA engine. The amount of air that can be enforced into the cylinder per cycle is increased and this improves the combustion efficiently.

Intercooler efficiency (%). Figure 4 elucidates that intercooler efficiency is between 94 to 98% due to air-to-liquid cooling arrangements. Hence increase in air density enhanced the combustion.

Torque (Nm). Figure 5 elucidates that 12% improvement in combustion pressure at 1400 rpm is due to increased fuel delivery and air flow in the TCIC engine compared to NA engine.

Engine power (kW). Figure 6 elucidates that there is power improvement from 1000 rpm to 2000 rpm, 13% maximum improvement is achieved with TCIC engine at rated speed when compared to baseline engine. This is due to increase in fuel delivery and increased air flow rate. Therefore improvement is achieved.

Brake-specific fuel consumption (kW-h). Figure 7 elucidates that there is 2% increase in fuel consumption from 1000 rpm to 1400 rpm, with TCIC engine at rated torque when compared to NA engine. This is due to increase in fuel and increased air flow rate.

Figure 3 Air inlet pressure comparison (see online version for colours)

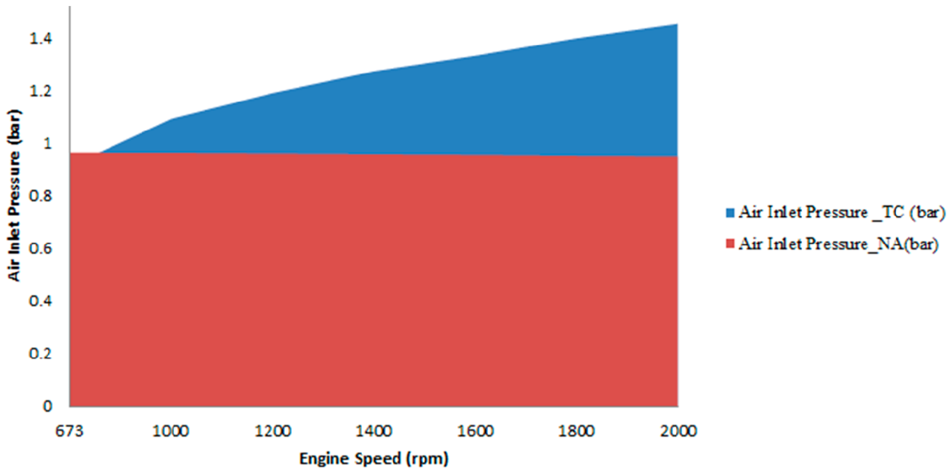
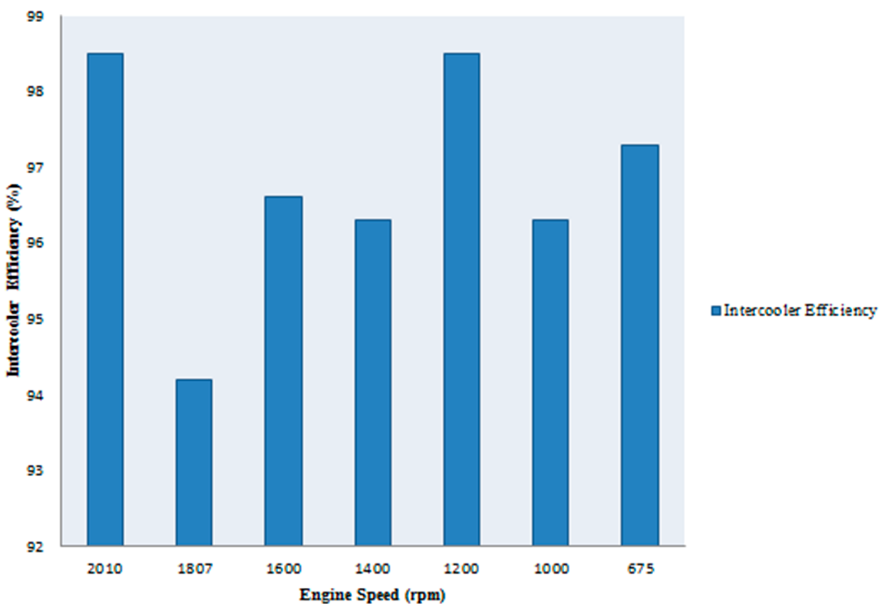


Figure 4 Intercooler efficiency (see online version for colours)



Combustion pressure (bar). Figure 8 elucidates 24% improvement in combustion pressure at 1400 and 2000 rpm, overall 94 bar pressure increased for turbocharged engine from base engine which is 71 bar. This shows that because of turbocharger and charge air cooling, the combustion performance is increased.

3.2 NOx control strategy

EGR cooler. Figure 9 elucidates that the EGR cooler technique selection for NOx reduction can be achieved by selection of optimised corrugated tube capacity based on exhaust gas temperature using thermal analysis study. For this research, the target of

<200°C exhaust outlet temperature of gas is required. Considering the above-mentioned target, corrugated tube <15 quantity is selected for this study based on thermal analysis using CFX software.

Lean NOx trap (*LNT*). Figure 10 elucidates that LNT substrate selection is based on pressure drop and maximum retention time of exhaust gas inside the substrate. For this application based on simulation, 2 litre volume substrate with 16 mbar pressure drop are selected for this study. Further, based on this catalyst, selection will be finalised.

Figure 5 Torque comparison (see online version for colours)

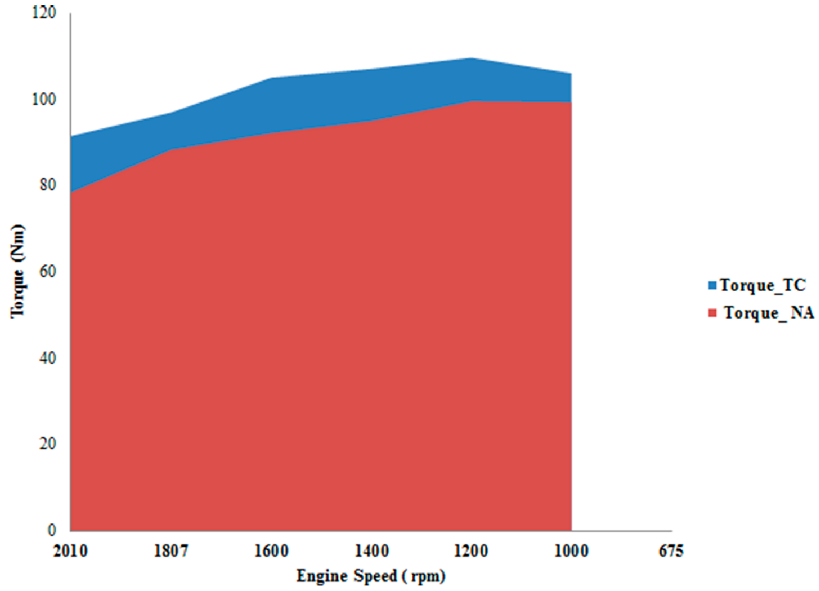


Figure 6 Power comparison (see online version for colours)

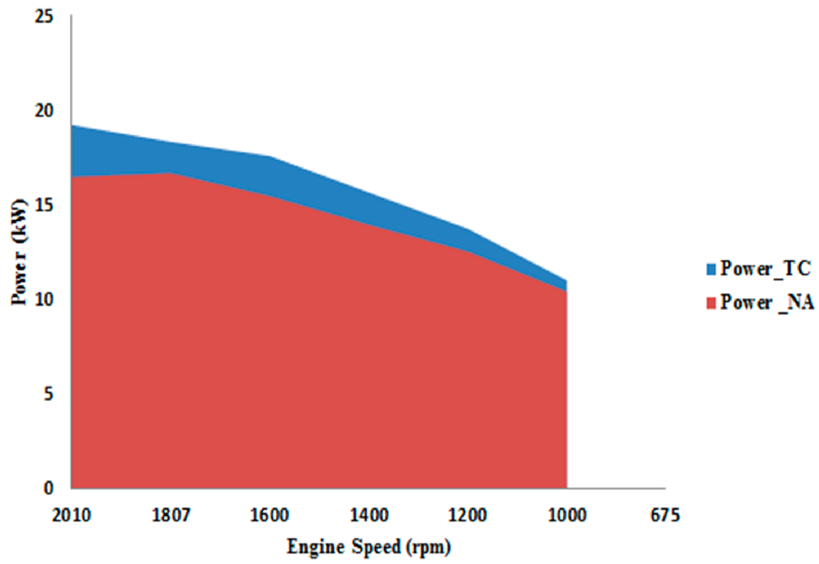


Figure 7 BSFC comparison (see online version for colours)

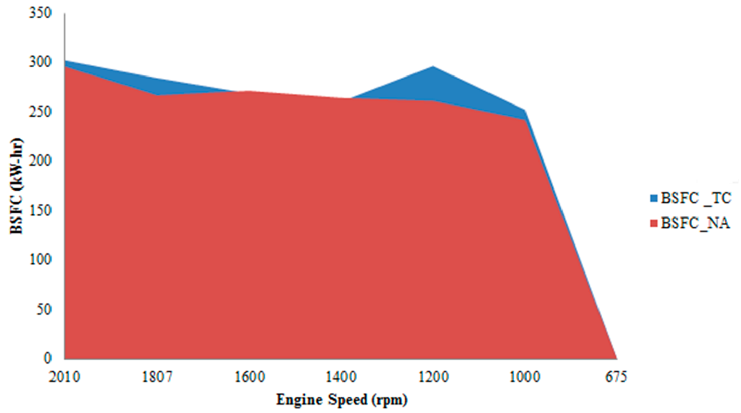


Figure 8 Exhaust temperature for TCIC (see online version for colours)

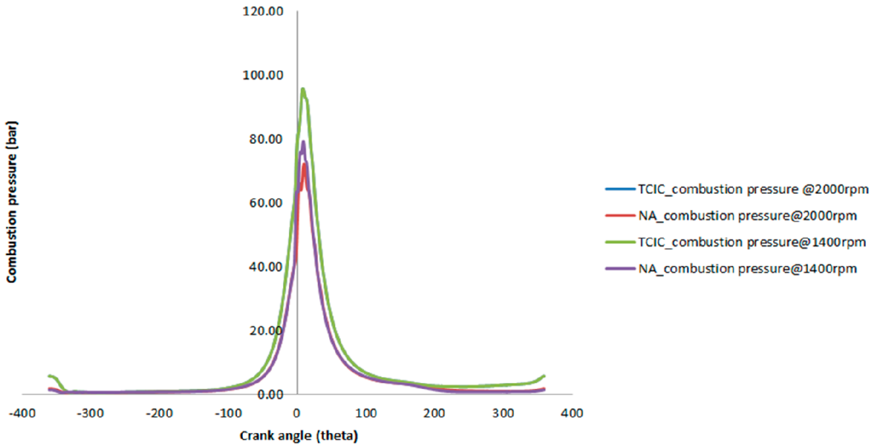


Figure 9 EGR cooler temperature profile (see online version for colours)

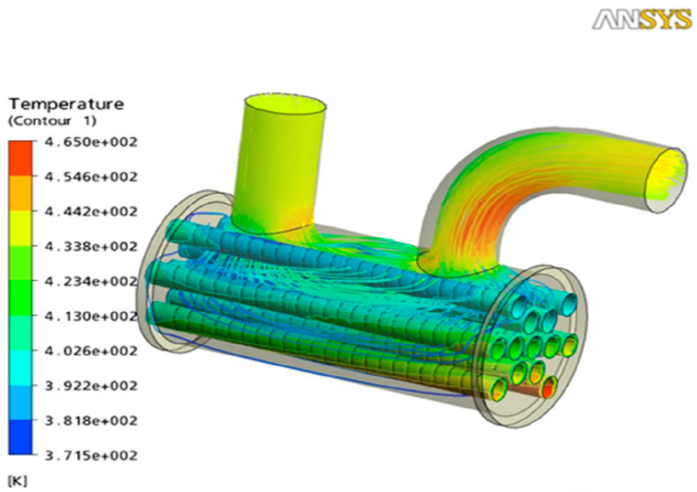
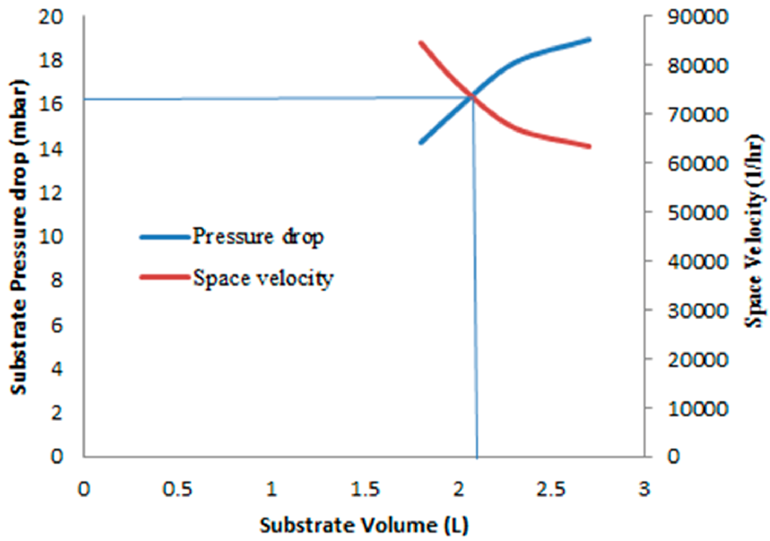


Figure 10 Substrate pressure drop, space velocity curve (see online version for colours)



4 Conclusion

For this research work, conventional fuel injection equipment is used as cost-effective solution, as against the electronic high-pressure fuel injection equipment, used in the other US tier-3 engines. These advanced injection techniques are sensitive to fuel quality and expensive to maintain further, if any inappropriate fuel is used in remote areas of developing countries, the repair cost and downtime are extortionate. Therefore, in this research the selected off-road engine with rated power of 16 kW is improved further with a mechanical fuel injection system lubricated by the engine oil.

In this study, the engine improvement from current performance and emission level to next level is made by optimum selection of hardware such as waste gate-turbocharger and with water spray cooled intercooler. Overall, engine performance after turbocharging and with intercooler installation shows increase in power by 13%. Combustion pressure has improved by 24% from base engine performance. This confirms that because of intensification in air mass, combustion is improved. Therefore, turbocharging is a key step towards meeting the future emission norms with increased specific power output, better fuel economy for small, low cost engines in off-road vehicle segments. For NOx emission reduction, two different strategies are analysed: the first strategy is related to EGR cooler technique in which the number of steel tubes are optimised to lesser than 12 based on thermal analysis. Another strategy is related to LNT technique, substrate volume of 2 litre is selected based on analysis. With these selected strategies, NOx emission performance is to be investigated. Overall, by comparing the performance improvement with low cost engine enhancement strategies, the upgraded engine is competent. This engine is more frugal than the contemporary off-road engines in cost because of usage of small waste gate turbocharger, compact intercooler and with optimised fuel consumption. Further, this study is limited with available fuel injection pump delivery. Because of more increase in fuel delivery screw adjustment smoke increased. Moreover emission levels with the optimised condition to be investigated to compare the NOx emission performance.

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