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Strategies for Low Engine Speed Torque Enhancement of Natural Gas Engine: Observations with Turbocharger and Supercharger

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Abstract

Diesel engines have been powering a range of commercial vehicles for a many years. Considering air pollution, there is a thrust on use of natural gas (NG). Thereafter, natural gas engines for commercial vehicles have been subject of development, particularly to meet drivability demands and emissions requirements. Bus used for intra-city mass transportation of passengers is probably the most common form of natural gas commercial vehicle. Considering typical city applications, such vehicles is characterized by low speeds, frequent gear changes, start-stops, traffic conditions etc. For better drivability, they need higher traction at low engine speeds. This study captures few means of torque enhancement and motive is to integrate a selective ones as not much research is available mentioning enhancements specifically at low engine speeds.

Turbocharging of natural gas engine is complicated due to high exhaust temperatures. As most turbocharger manufacturers cater to requirements of diesel engine, turbochargers for natural gas are simply not available. Many compromises are thus to be made. Under this study, four different turbochargers and one supercharger shall be simulated for experimenting and optimizing to enhance torque at low engine speeds. A virtual model of reference, naturally aspirated engine is built in appropriate software and its output is verified against test bed performance, to establish model faithfulness. Next, simulation runs with different turbochargers and superchargers are carried out. Various parameters are recorded and compared. Findings are recorded and it is noted that there is room for enhancement based on different hardware capabilities.

Keywords**;** *Natural gas engine, turbocharging, supercharging*

I. INTRODUCTION

One usually finds different kinds of vehicles in cities that serve different purposes. A closer look at energy expenditure reveals that these vehicles are consume more energy as compared to mass transport public vehicles [1].Considering conservation and environmental policies, there has been a motivation to use alternate fuels as compared to conventional ones [2]. Vehicles powered by natural gas shall be popular as an attempt to reduce emissions [3]. As the market demand surges, OEM's shall be increasingly depending on platform technology, a minor changes shall suffice market requirements [4]. As predicted, share of light and small commercial vehicles shall continue for upcoming years [5]. The design of such vehicles shall include advanced powertrain and transmission options, with more focus on alternate fuels [6]. Use of natural gas an alternate fuel shall help to curb rising pollution levels and its performance shall improve the outlook of observers towards green mobility [7]. From viewpoint of economics, design feasibility, combustion control and optimization etc. natural gas is a preferred choice [8]. In spite of limited

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infrastructure for re-fulling, natural gas shall continue to be a popular choice for different vehicles. This shall prove to be important step towards emission control and environment conservation. Newer methods such as dual fuel engines, more efficient storage systems etc. shall find its way in mass transport vehicles [9]. Bio-Methane, obtained by decomposing of organic materials can be substituted as a transport fuel. Before this could be done, a primary treatment consisting of increasing methane content and storage pressure is to be completed for practical usage [10].

The sale of commercial vehicles in India increased by about 22% in 2010-2011 and compounded growth rate of about 9.3%. These include different vehicle configurations. As operating cost remains key selection factor, vehicle manufacturers shall be keenly offering natural gas powered vehicles, and it is estimated that these shall constitute about 22% of total vehicles. Compulsion to use natural gas for urban mass transport and rising environmental concerns, sale of natural gas powered vehicles is set to increase [11]. Implementing new safety standards such as Universal Bus Specifications, dictates eight different aspects of vehicle design that must be catered considering passenger safety and comfort. [12]. Evolution of different technologies on vehicles now highlights manufacturer's commitment to develop prime movers on alternate fuels, most of their popular vehicles shall be available with natural gas options [13]

II. ENGINE MODIFICATIONS FOR LOW SPEED TORQUE ENHANCEMENTS

Engine chosen for purpose of study consists of six cylinders natural gas, is naturally aspirated and powers a bus for city applications. Critical specifications can be seen in table 1.

Table 1 Specifications of base engine

Bore x Stroke	97 x 128
Number of cylinder	6 Cylinder, Inline
Firing order	1st-5th-3rd-6th-2nd-4th
Rated speed	2500RPM
Swept volume	5.7L
Aspiration	Natural
Compression ratio	12.5:1 +/-1

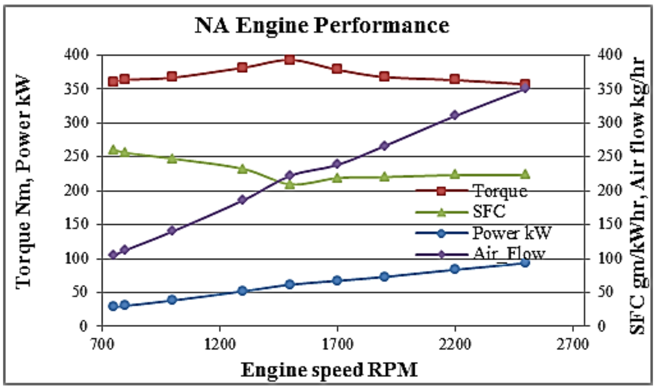

Figure 1 Graphical representation of base engine performance

Increasing torque output at low engine speeds needs changes to basic hardware. Since the engine under consideration is derived from a diesel engine, there are practical design constrains. Engine output at different speeds can be seen in the above figure 1. Other important engine operating parameters are also recorded simultaneously.

III. DIFFERENT MEANS OF ENHANCING ENGINE OUTPUT

There are many means of increasing torque output of an engine. They can be categorized in manner in which they affect engine operation. Table 2 lists these approaches. It gives an insight of different findings about particular approach has on engine performance.

Table 2 Various approaches to enhance engine output

Sr. No	Parameter	Effect
1	Turbocharging	Provides significant increase in torque and power, helps to recover wasted exhaust energy
2	Changes to	Downsizing helps gain

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	engine	efficiency
3	Variable Valve Timing	Enhanced power output by about 15-20%
4	VVT & increased compression ratio	Enhanced volumetric efficiency with reduced valve overlap, with different compression ratio.
5	Electronic Wastegate	Enhances power output
6	Swirl / Tumble motion	High swirl leads to pressure drop and lowers volumetric efficiency
7	Direct / Jet Injection	Enhanced engine efficiency by about 4-5%.
8	Increasing CR in HCNG engine	Enhanced torque and fuel efficiency, with some limitations.
9	In-cylinder pressure	Higher cylinder pressure in diesel engine than in CNG engine

IV. SIMULATION AND ENGINE TESTING

In order to evaluate effect of various approaches on engine low speed torque, it is planned to first simulate a model of engine and then validate it against engine testing data available.

As a part of virtual testing, one dimensional model of engine under consideration is built in software GT ISE. Once the model converged, it was capable to predict engine performance based on changes in valve overlaps, different valve timings, different compression ratios etc. Schematic virtual representation of engine under consideration can be seen here, in figure 2. Actual components of engine and their arrangements are numerically represented. Geometric attributes and limiting conditions are applied as inputs to the model. Simulation runs are then conducted at wide open throttle to observe various parameters at different engine speeds.

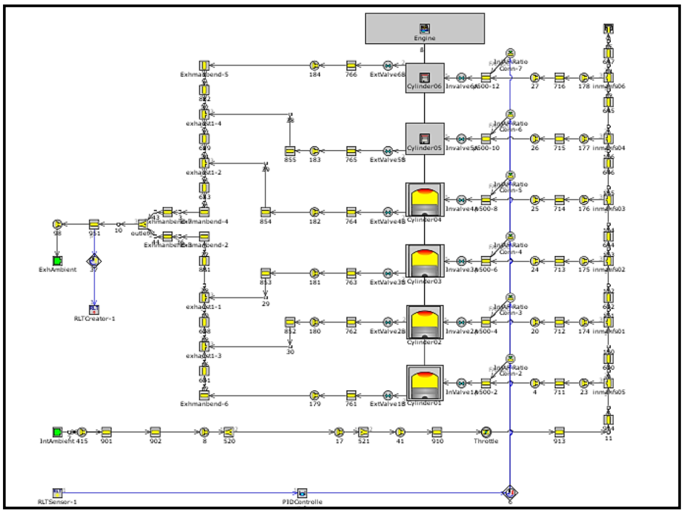

Figure 2 Base natural gas engine as modeled in software

Closeness of simulated and measured values is desired to assure resemblance of simulated model to actual engine. Thus, 1D simulation of the engine under consideration was carried out using the various dimensions and parameters from base engine specifications. The output of virtual model was then compared with data available from engine testing.

Similarly, table 3 highlights measured as well as simulated values for critical engine performance parameters for engine speeds corresponding to maximum power and maximum torque. It can thus be said that as these values match closely and model is a true representation of engine under consideration, based on which other virtual trials can be carried out.

Table 3 Test data and simulation output comparison

Parameter	**Test Data**	**Sim. Data**	**% diff.**
2500 RPM @ Max Power			
Torque	357.11	356.76	0.10
Power	93.44	93.401	0.04
Air flow (kG/hr)	355.65	348.29	2.07
Fuel flow (kG/hr)	22.09	21.53	2.54
BMEP	7.91	7.89	0.25

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Brake thermal eff.	30.5	30.65	-0.49
1500 RPM @ Max Torque			
Torque	392.96	389.26	0.94
Power	61.69	61.11	0.94
Air flow	221.9	216.03	2.65
Fuel flow	13.38	13.13	1.87
BMEP	8.71	8.43	3.21
Brake thermal eff.	33.9	33.05	2.51

This validated model will now serve as base onto which different technologies such as different compression ratios, valve timings etc. shall be iterated to verify the extent by which engine output is affected and to optimize it for better low speed torque. Actual prototype assembly and respective testing shall then be carried out. It may require further optimization, which shall be determined after extensive analysis of simulated data.

Figure 3 shows comparison between simulated and measured engine torque and power. One can see that the closeness of different parameters assures model is well adapted to represent the engine configuration and any outputs based on other iterations can be taken as valid for comparing gain or loss of output.

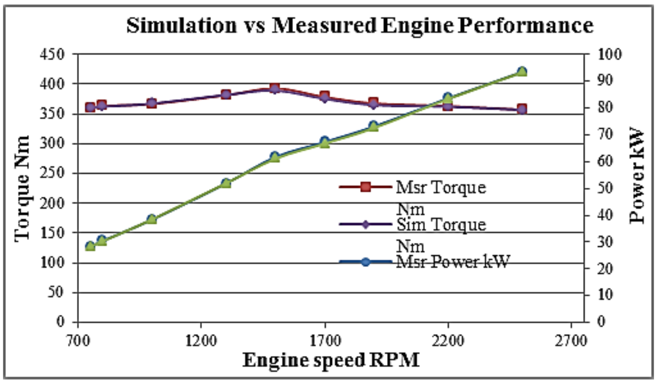

Figure 3 Simulated and measured engine torque and power

Turbocharging: - For effectively utilizing energy of exhaust gases that would have otherwise been wasted a turbocharger is one of the convenient device. However, to do so the exhaust gases have to be moved from cylinders to the turbine, where the energy of exhaust gases is converted into mechanical work, required to drive the compressor.

In the scope of work mentioned herewith in this paper, a six cylinder engine is considered for experimentation purposes. The subject engine is naturally aspirated as of now and shall be turbocharged with objective on enhancing torque at low engine speeds.

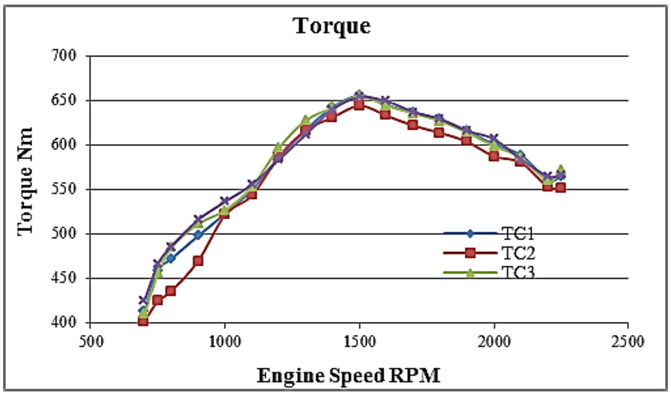

Figure 4 Torque with different turbochargers

For this, four different turbocharger configurations and one supercharger are available. Focus shall be on speeds lesser than maximum torque speeds. One dimensional simulations, optimizations and experimental verification are engaged to carry out required optimization. The figure 4 shows torque output for different turbochargers assembled virtually on base engine. Variation in torque at low engine speeds, below maximum torque of 1500 RPM is to be observed. The difference in engine torque is due to different turbochargers that exhibit different characteristics. Objective is to identify these and provide a directions so that one can chose turbocharger appropriately that shall provide enhanced low speed torque.

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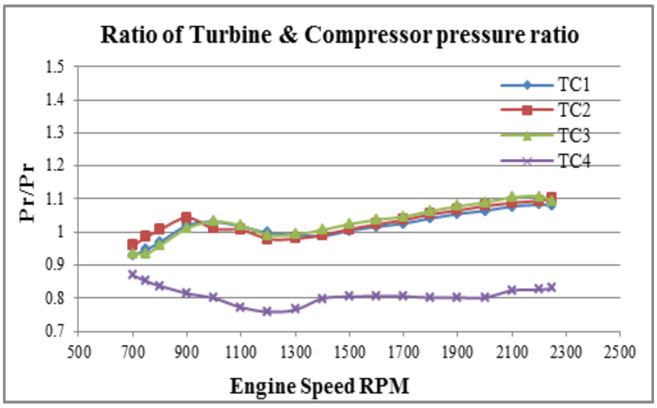

Figure 5 Ratio of pressure ratios

Figure 5 shows ratio of turbine pressure ration to the compressor pressure ratio, a dimension less parameter that helps in understanding of engine torque at low speeds. Based on the observations, it can be seen that lower this dimensionless number of ratio of turbine pressure ratio to the compressor pressure ratio, the engine output is better. Thus for better low speed torque, it is important that the compressor pressure ratio be as high as possible.

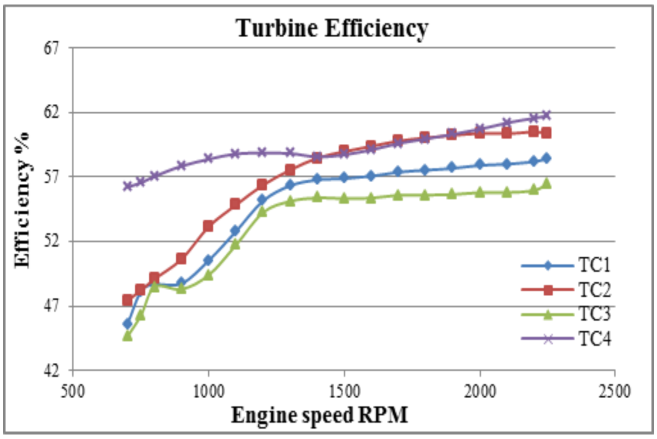

Figure 6 Turbine efficiency

Figure 6 here refers to efficiency of turbine and it is needless to say that higher the efficiency of turbine, higher will be the pressure ratio, leading to higher pressures on the compressor side. As more energy is converted into useful work, the turbine with higher efficiency shall provide higher boost and higher engine torque.

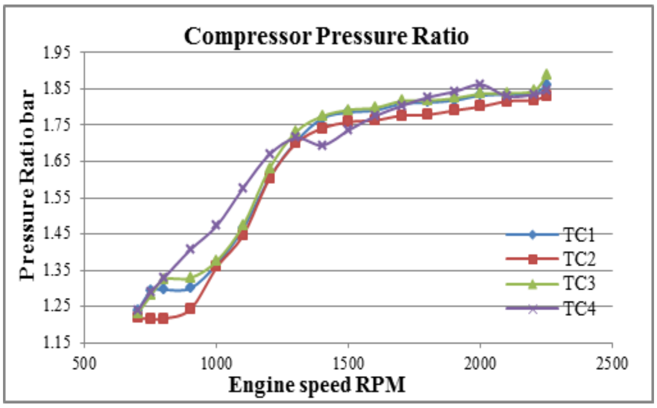

Figure 7 Compressor pressure ratio

The figure 7 above represents pressure ratio of the compressor and it can be seen that higher the pressure ratio, higher is the boost pressure and thus, higher the engine output torque in respective zone. It is to be noted that the inlet conditions to compressor are more or less the same and the pressure ratio is governed by the output pressures of the compressor.

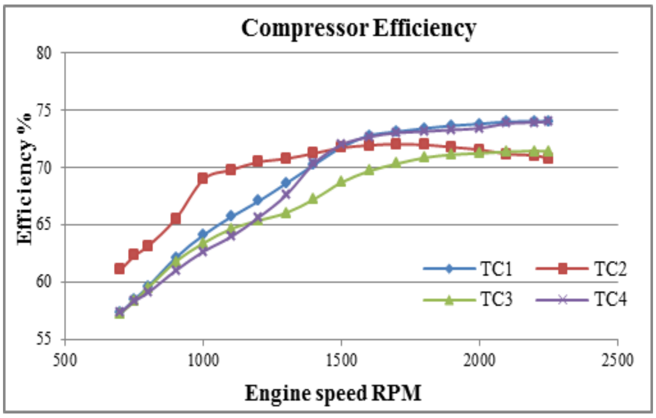

Figure 8 Compressor efficiency

The figure 8 above represents average efficiency against ideal condition. Theoretically speaking it is a ratio of ideal (Isentropic) power of the compressor to the actual power that it can possess. Thus, lower this value higher the engine torque

The actual engine performance on turbocharged version was run with turbocharger 1 and data was recorded on a modern and efficient engine test bed facility, equipped with high speed data recording devices.

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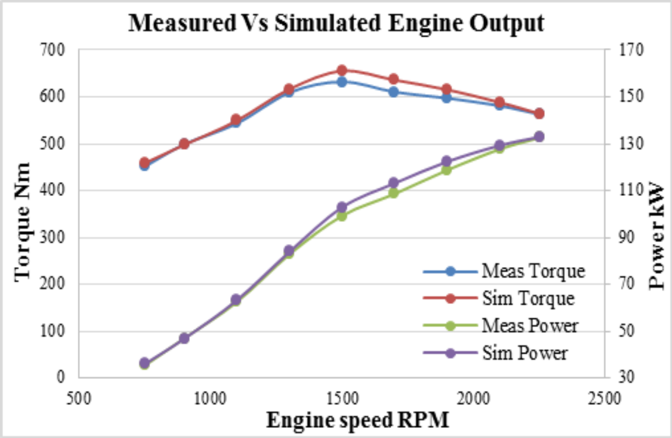

Figure 9 Measured vs simulated engine output for turbocharger sample 1

In addition to pressures and temperatures at different locations, the captured data also included typical engine performance describing data such as power, torque, turbocharger critical data, evaluation of lubrication & cooling systems etc. The recorded performance was compared with simulation results. Refer figure 9. From the table 4, it can be seen that there is good representation between simulated data and engine test bed performance parameters, acknowledging accuracy of virtual engine model and measured variables. Thus as per the virtual model pressures and other simulated engine output, based on crank angle domain prove the true representation of model and same can be used for evaluating different means that affect the low speed torque.

Table 4 Test vsSimulated data

Parameter	Test Data	Sim. Data	% diff.
1500 RPM @ Max Torque			
Torque	651.11	655.34	-0.65
Power	102.22	102.89	-0.65
BMEP	14.41	14.51	-0.69

Supercharging: - It refers to use of a compressor that is mechanically powered by crankshaft using an appropriate means such as gear or belt drive etc. This compressor draws air from atmosphere through an air filter and delivers it to intake manifold via an intercooler. As the compressor is mechanically coupled, the boosted charge is available almost instantly without any lag, but at the same time, as the energy is drawn from the crankshaft, it takes away a significant part of useful engine output, ultimately affecting fuel consumption.

Virtual model of supercharger used in our study can be seen in figure 10. Essential characteristics are captured in required detail to enable setup to be as close as possible to realistic scenario. A typical representation is made for re-circulating valve to bypass the compressed air at part load running of engine. Similarly throttle body is introduced as a primary control of air entering into the engine.

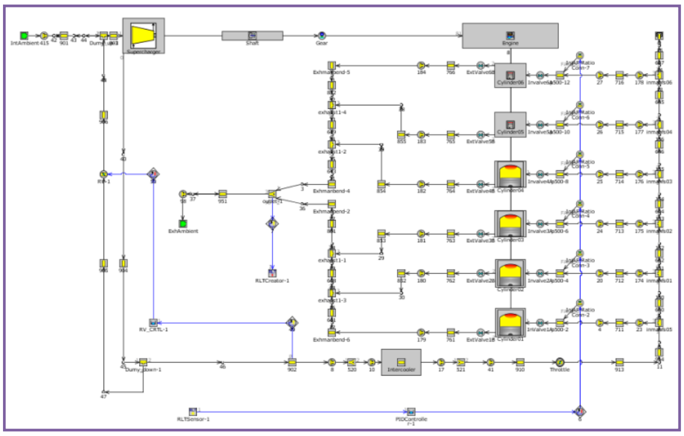

Figure 10 Simulated supercharged engine

The critical parameters from simulation of supercharged engine are compared against those from simulation of turbocharged versions. To have a realistic representation the simulated supercharged model is programmed to deliver same output as turbocharged version of engine so that the comparison can be more realistic.

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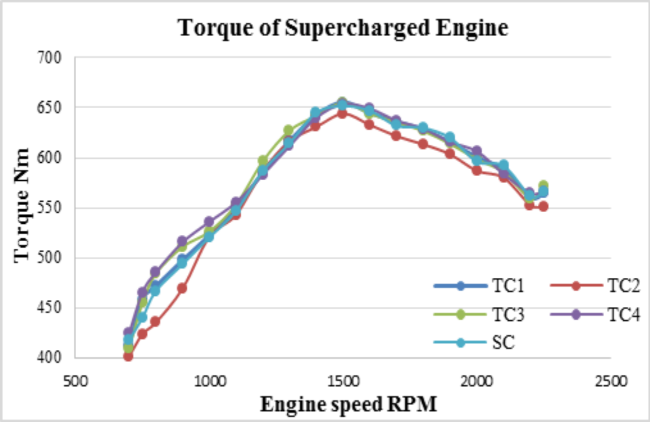

Figure 11 Turbocharged & Supercharged engine torque

Figure 11 represents torque output from 5 different configurations that are simulated one after the other on same base naturally aspirated engine, under consideration. Throttle valve position is varied to produce the desired torque. The intent is to compare other parameters such as specific fuel consumption etc. that are to be compared to decide better of two options when it comes to enhance low speed torque of engine.

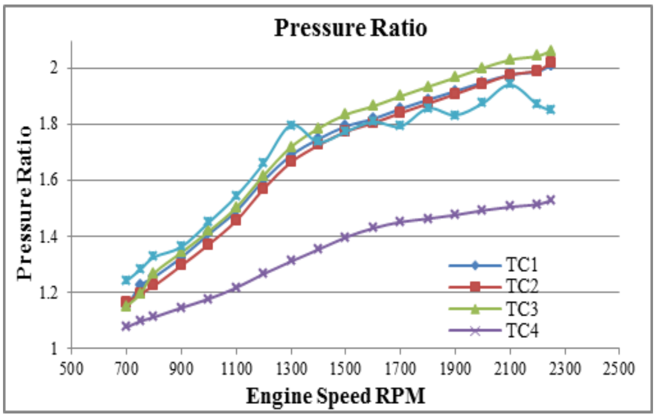

Figure 12 Turbocharged & Supercharged engine pr. ratio

The figure 12 above represents pressure ratio for compressor for supercharger. It is to be noted that boost pressure requirements to deliver same torque in turbocharger as well as supercharger remains more or less the same, across the engine speed. However, to deliver these levels of boost while maintaining the similar air flow rate, the supercharger draws considerable power from engine. In the figure 13, magnitude of supercharger power consumption can be observed.

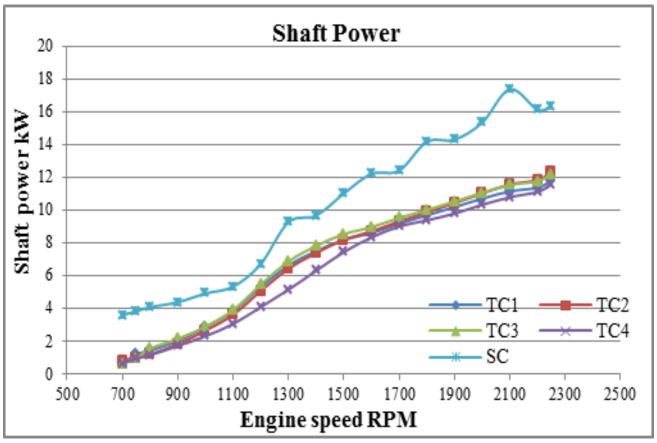

Figure 13 Turbocharger & Supercharger shaft power

The power consumed to run the supercharger is drawn from crankshaft and is a part of usable power that could have been made available to propel the vehicle. Refer figure 14.

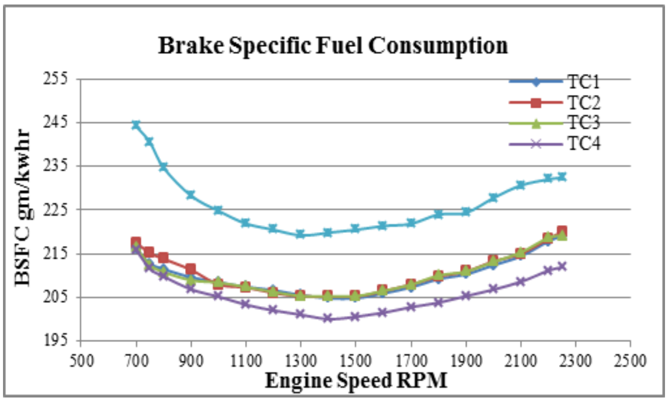

Figure 14 Turbocharged & Supercharged engine sfc

V. CONCLUSIONS

It is seen that both superchargers as well as turbochargers are capable of delivering the desired torque and provide low engine speed boost. However, it is to be noted that the supercharger does so at expense of useful work being derived from crankshaft, which ultimately lowers the overall fuel efficiency.

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If adequate boost is made available at low speed zone, the turbocharger may prove to be smaller for higher engine outputs and can unnecessarily raise the inlet turbine pressures, causing difficulties to engine to expel the exhaust gases. This leads to waste of useful work. The benefits of turbocharger are thus not evident in such cases. Thus an ideal balance is to be maintained so that one achieves best combination of low engine speed torque as well as desired maximum engine power. A turbocharger aimed to enhance output at low engine speeds needs to bypass a lot of exhaust gases at high engine speeds, else the boost is high and engine tends to knock

Turbocharging presents its own set of challenges. Firstly, most of the turbochargers for commercial vehicles are made considering diesel engine as end applications. These usually operate at lower exhaust temperatures and high boost pressures. Natural gas engines in the other hand need precise control of air as well as fuel. The stoichiometric air fuel ratio is to be maintained at all times, as the engine is quantity governed, a throttle valve controls the amount of charger entering the engine as per load demand.

Apart from availability, the matching of turbochargers for natural gas engines is critical. Usually the boost pressures associated with natural gas engines are low than diesel counterpart.

On the other hand, using supercharger to enhance low speed torque seems to be a relatively simple option considering the fact the high exhaust temperature material requirement is no longer significant. However, just like turbochargers, superchargers are not designed specifically for commercial vehicles. Thus, the drive arrangement of superchargers has to be carefully evaluated as most of the superchargers are designed for engine that runs at relatively higher speeds than commercial vehicles

Secondly, a lot of compressed air is to be re-circulated at part loads. This wastes a lot of useful work done as most of the compressed air re-introduced into low pressure side. Considering tighter emission norms, a close loop control is to be introduced in addition to electronic throttle for the engine, making the engine management more complicated.

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