Methods for Low Engine Speed Torque Improvement of Natural Gas Engine for Commercial Vehicles: Experimental Observations with Turbocharger and Supercharger

P. J. Suple\textsuperscript{1}, C. R. Sonawane\textsuperscript{1}, S. S. Thipse\textsuperscript{2}, J. P. Mohite, N. B. Chougule\textsuperscript{3}

\textsuperscript{1}Symbiosis Institute of Technology, Mechanical Engineering Dept., Pune, India
\textsuperscript{2}Automotive Research Association of India, Pune, India
\textsuperscript{3}Tata Motors, Pune, India

crsonawane@gmail.com

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: Low speed torque improvement, natural gas engine, turbocharging, supercharging

1. 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].
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 infrastructure for re-filling, natural gas shall continue to be a popular choice for different vehicles. This shall prove to be an 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].

2. Engine modifications for low speed torque improvement

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.

| Parameters          | Specifications                  |
|---------------------|---------------------------------|
| Bore x Stroke       | 97mm x 128 mm                   |
| No. 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](https://example.com/figure1.png)  
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. Figure 2 represents engine test bed layout where interconnections action between different engine testing devices are shown in simple block diagram.

**Figure 2** Layout of engine test bed

### 3. 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.

| Sr. No | Parameters | Effect |
|--------|------------|--------|
| 1.     | Use of Turbocharger [14-22] | a. Provides considerable enhancement in torque and power, can extract waste exhaust energy, enhancing overall efficiency  
       |            | b. Lower the inertia of wheels, higher the output  
       |            | c. Combining supercharger and turbocharger delivers good response  
       |            | d. Two-stage turbocharger provides more boost delivering more engine power  
       |            | e. Use of VGT delivers enhanced transient response and avoids turbo lag  
       |            | f. Use of sequential turbocharger delivers better response and faster acceleration  
       |            | g. Using electrical turbocharger deliver about 20% more boost pressure |
| 2.     | Modifications to base engine [27-28, 30-32, 36-44, 47-48] | a. Reducing engine size for similar outputs helps enhance efficiency  
       |            | b. Leads to better mean effective pressures |
| 3.     | Use of Variable Valve Timing [34, 45-46] | a. Speed dependent higher engine output by about 15-20%  
       |            | b. 10% better volumetric efficiency |
4. Use of Variable valve timing and higher compression pressure [50]
   a. High volumetric eff. with lesser valve overlap, irrespective of compression ratio
   b. Valve timing affects specific fuel consumption as well as compression ratio
   c. Better efficiency with higher compression ratio and valve overlaps

5. Electronic Wastegate controls [49]
   a. Better power output and low speed engine output
   b. Precise control over mass flow rates
   c. Higher in-cylinder pressures than pneumatic wastegate

6. Swirl or Tumble air motion [33]
   a. More swirl, more pressure drop, lesser volumetric efficiency
   b. Better mass burn fraction with better swirl, better flame radius
   c. Swirl delivers better flame growth rate than tumble

7. Direct Fuel Injection [23-26, 29]
   a. Higher engine efficiency by about 4-5%.
   b. Enhanced volumetric efficiency

8. HCNG with high compression ratio [51, 52]
   a. Better torque specific fuel consumption, partial limitations
   b. Better heat release, high cylinder pressures

9. Cylinder pressure [35]
   a. Diesel engines have higher cylinder pressure than CNG engine
   b. Use of high compression ratio and better volumetric efficiency are main reasons

4. 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 3. 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.
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.

Comparison of different engine parameters indicated that simulation is acceptable and the model is appropriately validated and faithful representation of actual engine. In figure 4, the combustion pressure trace of actual engine and simulated model show a close resemblance. 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.

| Parameters       | Test Data | Sim. data | % Diff |
|------------------|-----------|-----------|--------|
| 2500 RPM @ Max Power | 357.11    | 356.76    | 0.10   |
| Torque           | 93.44     | 93.401    | 0.04   |
| Power            | 355.65    | 348.29    | 2.07   |
Table 1: Performance Parameters at 1500 RPM @ Max Torque

| Parameter          | Meas  | Sim  | Error |
|--------------------|-------|------|-------|
| Fuel flow (kG/hr)  | 22.09 | 21.53| 0.56  |
| BMEP               | 7.91  | 7.89 | 0.25  |
| Brake thermal eff. | 30.5  | 30.65| -0.15 |

Figure 5 indicates heat release rate for engine speed of 2500 RPM, corresponding to maximum power. It can be observed that the values follow each other closely. The measured values are captured on a high speed data acquisition system and most of the noise in signal is filtered out. 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 6 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.
5. Turbocharging

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.

However, like any other machine, the exhaust gas turbine is able to convert only a part of exhaust energy into mechanical work. The quantum of conversion depends on differential pressure across the turbine and turbine efficiency. As differential pressure increases across turbine, as the turbine efficiency increases, as the transmission efficiency increases the engine efficiency also increases. Selection of proper turbocharger and effective design of exhaust system can help to realize higher engine performance. Adequate studies have been carried out on exhaust design and turbocharging, while various factors affecting the transient response of engine have also been examined. These studies included in this paper focuses on enhancing the output of engine at low speeds, for a typical city mass transport vehicle application.

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. 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.

Based on the simulations and other experimental verifications carried out for optimizing output of engine at low engine speeds, the six cylinder engine under consideration shows different options and extent to which each of these affect low speed torque. The summarized results show the potential for improving low speed engine torque with different options.

One dimensional modelling of engine under consideration allows to study most points of discontinuity under the model with suitable variation to fluid flow coefficient and engine parameters. Fairly faithful representation of simulated model with actual engine is essential for optimization of various parameters on virtual model. This will ensure its co-relation with actual engine. To evaluate the extent of variations in output based on simulated inputs, a sensitivity study is also conducted.

The numerical effect of turbocharging and its various factors on engine low speed torque is obtained from one dimensional virtual engine model. To have a realistic representation of engine under consideration, appropriate simulation software is used. The output of one dimensional model is then compared with engine performance data as available from test beds that includes combustion pressure traces and other critical parameters.

The engine under consideration here is a six cylinder inline engine operating on stoichiometric air fuel ratio. In turbocharged configuration, three cylinders form one bank and rest three the other bank.
The engine will be modelled accordingly, to include intercooler as well. Pipe connections, other junctions, restrictions, sequential injectors etc. are logically placed onto the model.

As the sole purpose of modelling the engine in virtual environment it to observe the effect of turbochargers and its allied systems, the pressure measurements are of prime importance. Correspondingly, the engine testing includes pressure measurements in exhaust pipes, as well. Similarly, the combustion pressure sensor is also included on the actual engine test bed testing and serves as an indication of closeness of virtual model to actual engine testing. Different temperature measurements are also included in engine measurements from test bed engine performance capturing activities.

The engine performance in virtual conditions is captured in the one dimensional model, as described. The transfer of heat from fuel to cylinder walls is based on Woschni formula. The combustion is simulated by referencing the heat release with respect to crank angles, described in terms of rotational degrees of crank shaft. The heat release patterns are captured with respect to crank angle domain. Other aspects of combustion as required for study are recorded using appropriate data acquisition systems.

The figure 7 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.

Figure 8 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.
In the figure 9 it is seen that lower the turbocharger speed at which the desired pressure ratio can be met, better are chances of delivering higher engine torque. Thus, the speed at which pressure ratio can be achieved, in relation to intake conditions plays an important role in turbocharger selection. This parameter also affects the temperature of exhaust gases exiting the turbine.

Figure 10 refers to average power used to drive the turbocharger. This power is extracted from exhaust gases, and represents useful work done that would have been otherwise wasted. Principally this is a turbine characteristic of the turbocharger assembly. For enhancing output at low engine speeds, higher shaft power is a preferred. This assures better work extraction from the exhaust gases to spin the turbine, thus moving it into higher pressure ratio operation zone of the air compressor.

Figure 11 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. This it is important the selection of turbine should by such that efficiency should be as high as possible in the desired engine operating region to have higher engine output.

Figure 12 Turbine pressure ratio

Figure 12 refers to pressure ratio of turbine and it can be observed that as the pressure ratio of the turbine increases the engine torque also increases. However, it is important to note that efficiency of turbocharger also plays an important role. Lower pressure ratio with higher efficiency can compensate for lower output pressure, but maintains desired boost and thus the engine output.

Figure 13 Turbine inlet pressure

Figure 13 refers to average pressure difference between turbine inlet and outlet pressures. Under ideal conditions, the inlet pressures are similar in each case, the variation observed in graphs is due to variation in output pressure that represents effective use of turbine. It is observed that higher the pressure difference, better is the turbine able to deliver higher boost, leading to higher engine output. However, other factors too are to be taken into consideration such as average efficiency and turbine speeds are also to be taken into consideration.
From the figure 14 it is seen that higher exhaust temperatures exists only at high engine speed and load regions. In zones of lower engine speeds, the area of our interest, the exhaust temperatures for different turbochargers are comparable.

The figure 15 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.

As the pressure of the air at compressor outlet increases, so does its temperature. This reduces the effective mass flow rate of air as density reduces due to elevated temperatures. In most of the engine fitted with a kind of compressor arrangement to provide air at higher pressures, an intercooler is
commonly found device that can add to efficiency of the system without much loss. Thus, lower the
temperature of air at outlet of compressor, better will be the mass flow rate. Refer figure 16.

![Compressor Efficiency](image1)

**Figure 17** Compressor efficiency

The figure 17 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 performance of an actual turbo machine is always inferior to that of a frictionless and loss free ideal machine. Generally losses occur in compressors principally due to mechanical friction at bearings, windage losses, friction between blade and moving fluid etc.

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. 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 18.

![Measured Vs Simulated Engine Output](image2)

**Figure 18** Measured vs simulated engine output for turbocharger sample 1

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 data and simulation output comparison

| Parameters      | Test Data | Sim. data | % Diff |
|-----------------|-----------|-----------|--------|
| 1500 RPM @ Max Power |           |           |        |
| Torque          | 651.11    | 655.34    | -0.65  |
| Power           | 102.22    | 102.89    | -0.65  |
| BMEP            | 14.41     | 14.51     | -0.69  |

Since these match closely, the simulated model adequately represents the turbocharger sample 1 and hence the simulations of other turbocharger and subsequently the supercharger can be taken as applicable.

6. Supercharging

Supercharging 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.

As the compressor draws power from engine mechanically, the mass flow output of compressor does not diminish with respect to reduced load or air flow. As spark ignited engines are throttled with help of throttle valve, obviously air flow to engine reduces at part loads, when the throttle valve is partially closed. To overcome this situation where the compressor mass air flow does not reduce whereas engine fair flow demand reduces, a typical re-circulating valve is introduced that re-circulates or by-passes air from high side of the compressor to the low side, while maintaining the desired air flow to engine. This also helps to limit the maximum boost pressure at each speed and load as the valve’s position changes as per driver demand. On the positive note, this behaviour of compressor can assist to have higher engine output at low engine speeds.

Virtual model of supercharger used in our study can be seen in figure 19. 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.

![Simulated supercharged engine](image)

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.

Figure 20 Turbocharged & Supercharged engine torque

Figure 20 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 21 Turbocharged & Supercharged engine pressure ratio

The figure 21 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 22, magnitude of supercharger power consumption can be observed.
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. In case of turbochargers, this power is usually extracted from exhaust gases, thus enhancing specific fuel consumption. Superchargers thus suffer from poor fuel efficiency. Refer figure 23.

The figure 24 represents efficiency of supercharger modelled to the base engine under consideration. In the area of interest i.e. the low engine speed region, it can be observed that the efficiency of supercharger as a compressor drops away rapidly. The compressor runs close to surge limit while operating in this zone. This is also a reason for poor efficiency of supercharger in desired zone of engine running.
7. Conclusion

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. Essential aspect of this study is to enhance output at low engine speeds. Investigation shows effect turbocharger has on overall impact on natural gas engine performance. It is further seen that there is a scope of improvement for in near future. Important conclusion that can be drawn are as follows:

- It is observed that the characteristics of turbocharger assembly considerably raises the availability of air for combustion, based on pressure ratio and mass flow rate. This presents opportunity for combusting more fuel and leads to higher engine outputs. In many cases, the turbocharger selection is done taking into consideration the maximum engine power and the maximum engine torque. It so happens that the availability of air and other critical turbocharger performance parameters specific to low engine speeds are neglected.

- 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. Diesel engines are quality governed and large lambda fluctuations are normal in its usual operations. 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. Thus there is a big difference in minimum and maximum air flow of a natural gas engine. The high exhaust temperatures associated with typical natural gas engines are beyond safe working temperature limits of most common turbine and turbine housing materials used for diesel engine. At times it is required to have coolant circulated through bearing housing of main shaft to keep bearings from overheating, thus making it a complicated design to manufacture.

- Apart from availability, the matching of turbochargers for natural gas engines is critical. Usually the boost pressures associated with natural gas engines are lower than diesel counterpart. Beyond this, the matching of turbochargers to provide desired boost with help of wastegate is a concern. The wastegate for natural gas engines are softer than diesel applications. The spring is soft and questions of consistency of performance are always raised. Spring hysteresis makes matter more difficult. Since the turbochargers for natural gas engines run hotter, the pneumatic hose leading from compressor to wastegate is to be specially designed to withstand high temperatures. For these reasons as well, use of electronic wastegate is a problem with natural gas engines.

- 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. This means that drive ratio has to be larger than normally used for cars, thus raising additional design problems. It is also to be noted that the use of supercharger shall significantly lower the fuel efficiency as all the power is drawn from crankshaft.
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.

The actual application of means of boosting the engine to enhance torque output at low engine speeds involves careful evaluation of many parameters. However, these means provide significant enhancement as compared to naturally aspirated version of base engine. These, however are expensive and demand a lot of piping, controls, etc. that should be fitted in tight spaces, under the engine hood. The elevated maximum pressures of cylinders, mostly requiring careful re-consideration of materials strength and design as well. High exhaust temperatures associated with high power engines is yet another concern. However, considering the flexibility of different application that can be driven by a high torque engine such as air conditioner, pneumatic suspensions etc. use of these means to boost output at low engine speeds is worth considering.

References

[1] B S Reddy “Transportation, Energy and Environment: A Case Study of Bangalore”, Economic and Political Weekly: Vol. 30(3), 161-170, Jan. 1995.
[2] R S Parker and C E Pettijohn “The Use of Alternative Fuels in the Private Trucking Industry: Is There a Viable Target Market?” Journal of Marketing Theory and Practice: Vol. 5(4), 88-93, Fall 1997.
[3] Frost & Sullivan, “HD Transit Bus Market—Global Analysis”, presentation in market engineering, NF63-18, Mar. 2016.
[4] Frost & Sullivan, “Heavy Duty Truck Engine Platform Strategies”, presentation in market engineering, NECE-18, Mar. 2016.
[5] A T Khan, V Kakde, V G Ramkrishnan “Strategic Analysis of the Light and Small Commercial”, presentation in market engineering, Frost & Sullivan, P61F-18. Dec. 2012.
[6] Frost & Sullivan, “Global Powertrain Outlook 2015”, presentation in market engineering, NF22-18, Mar. 2015.
[7] J Jacob, Y Abhimanyu, A H Kumar and S Singh “Strategic Analysis of Compressed Natural Gas (CNG) Passenger Cars Market in Europe”, presentation in market engineering, MA30-18, Sep. 2014, Frost & Sullivan
[8] M I Khan, T Yasmeen, A Shakoor, B N Khan et. al., “Exploring the Potential of Compressed Natural Gas as a Viable Fuel Option to Sustainable Transport: A Bibliography (2001-2015)”, Journal of Natural Gas Science and Engineering, Vol. 31(2016), doi:10.1016/j.jngse.2016.03.025
[9] S Sudhakar, B Lakshminarssinh, S Kar and S Singh “Strategic Analysis of the Medium- to Heavy-duty Natural Gas Commercial Vehicle Market in Europe”, presentation in market engineering, M8D2-18, Feb. 2013, Frost & Sullivan
[10] Frost & Sullivan, “Natural Gas Engines & Bio-Methane as Transportation Fuel”, presentation in Energy & Power Systems, TechVision, D960 Oct. 2015.
[11] C Kailasam, V Shankar, F Leveque and L Whalen “Strategic Analysis of the Global City Truck Market”, presentation in strategic insight, ND32-18, Oct. 2014, Frost & Sullivan
[12] S Kumar and V Kakde “Impact of Regulatory Trends on Commercial Vehicles Industry in India”, presentation in market engineering, P4ED-18, Jun. 2012, Frost & Sullivan
[13] N Kulkarni, M Sharma, V Kakde and V G Ramkrishnan “Indian Vehicle Technologies Evolution Road Map”, presentation in market engineering, P62C-18, Jan. 2013, Frost & Sullivan
[14] E Pipitone, F Cagnes and A Beccari “Performance Prevision of a Turbocharged Natural Gas Fuelled S.I. Engine”, SAE Technical Paper 2008-36-0058, series E, doi:10.4271/2008-36-0058
[15] E G Giakoumis “Review of Some Methods for Improving Transient Response in Automotive Diesel Engines through Various Turbocharging Configurations”, Front. Mech. Eng. 2:4, May. 2016, doi:10.3389/fmech.2016.00004
[16] K T Garrett, K Newton and W Stedds “Turbocharging and supercharging” Chapter 16, The Motor Vehicle, Sep. 2007, ISBN 9780080537016
[17] U Kesgin, “Effect of turbocharging system on the performance of a natural gas engine”, Energy Conversion and Management 46 (2005) 11–32, doi:10.1016/j.enconman.2004.02.006
[18] S Marelli, G Marmarotto and M Capobianco “Evaluation of heat transfer effects in small turbochargers by theoretical model and its experimental validation”, Energy 112 (2016), 264-272, doi:10.1016/j.energy.2016.06.067
[19] A Ghareghhani, M Koochak, M Mirmalim and T Yusaf “Experimental investigation of thermal balance of a turbocharged SI engine operating on natural gas”, Applied Thermal Engineering, 60 (2013) 200-207, doi:10.1016/j.applthermaleng.2013.06.029
[20] E Codan and C Christen “Further development of two-stage turbocharging systems for large engines”, 11th International Conference on Turbochargers and Turbocharging, 2014, Pages 189–203, Woodhead Publishing, doi:10.1533/978081000342.189
[21] L Eriksson, L Nielsen, J Brugard, J Bergstrom et. al., “Modelling Of A Turbo Charged SI Engine”, IFAC Proceedings Volumes, (34) 1, Mar. 2001, doi:10.1016/S1474-6670(17)34425-7
[22] S Thipse, A Dsouza, S Sonawane, S Rairikar et al., "Development of Multi Cylinder Turbocharged Natural Gas Engine for Heavy Duty Application," SAE Int. J. Engines 10(1):2017, doi:10.4271/2017-26-0065.
[23] A Boretti and S Jiang “Development of a two stroke direct injection jet ignition compressed natural gas engine”, Journal of Power Technologies, 94 (3) (2014) 145–152.
[24] M A Kalam and H H Masjuki “An experimental investigation of high performance natural gas engine with direct injection”, Energy 36 (2011) 3563-3571, doi:10.1016/j.energy.2011.03.066
[25] D Sankesh, J Edsell, S Mazlan, and P Lappas “Comparative study between early and late injection in a natural-gas fuelled spark-ignited direct-injection engine”, Energy Procedia 110 (2017) 275 – 280, doi:10.1016/j.egypro.2017.03.139
[26] J Song, M Choi and S Park “Comparisons of the Volumetric Efficiency and Combustion Characteristics between CNG-DI and CNG-PFI engines”, Applied Thermal Engineering (2017), doi:10.1016/j.applthermaleng.2017.04.110
[27] M Costa, F Catapano, P Sementa, U Sorge et. al., “Mixture preparation and combustion in a GDI engine under stoichiometric or lean charge: an experimental and numerical study on an optically accessible engine”, Applied Energy 180 (2016) 86–103, doi:10.1016/j.apenergy.2016.07.089
[28] T Wang, X Zhang, J Zhang and X Hou “Numerical analysis of the influence of the fuel injection timing and ignition position in a direct-injection natural gas engine”, Energy Conversion and Management (2017), doi:10.1016/j.enconman.2017.03.004
[29] J Sevik, M Pamminger, T Wallner, R Scarcelli et al., "Performance, Efficiency and Emissions Assessment of Natural Gas Direct Injection compared to Gasoline and Natural Gas Port-Fuel Injection in an Automotive Engine," SAE Int. J. Engines 9(2):1130-1142, 2016, doi:10.4271/2016-01-0806.
[30] P Zoldak and J Naber "Spark Ignited Direct Injection Natural Gas Combustion in a Heavy Duty Single Cylinder Test Engine - AFR and EGR Dilution Effects," SAE Technical Paper 2015-01-2808, 2015, doi:10.4271/2015-01-2808.
[31] P Zoldak and J Naber "Spark Ignited Direct Injection Natural Gas Combustion in a Heavy Duty Single Cylinder Test Engine - Start of Injection and Spark Timing Effects," SAE Technical Paper 2015-01-2813, 2015, doi:10.4271/2015-01-2813.
[32] P Zoldak and J Naber "Spark Ignited Direct Injection Natural Gas Combustion in a Heavy Duty Single Cylinder Test Engine - Nozzle Included Angle Effects," SAE Technical Paper 2017-01-0781, 2017, doi:10.4271/2017-01-0781.
[33] Y T Anbese, A A Rashid and Z A Karim “Flame Development Study at Variable Swirl Level Flows in a Stratified CNG DI Combustion Engine using image Processing Technique”, Journal of Applied Sciences, 11(10): 1698-1706, 2011 ISSN 1812-5654, doi:10.3923/jas.2011.1698.1706
[34] J Wheeler, J Stein and G Hunter "Effects of Charge Motion, Compression Ratio, and Dilution on a Medium Duty Natural Gas Single Cylinder Research Engine," SAE Int. J. Engines 7(4):1650-1664, 2014, doi:10.4271/2014-01-2363
[35] Semin, A Ismail and T Nugroho “Experimental and Computational of Engine Cylinder Pressure Investigation on Port injection Dedicated CNG Engine Development”, Journal of Applied Sciences 10(2):107-115

[36] R Tilagone and S Venturi “Development of natural gas demonstrator based on an urban vehicle with a down-sized turbocharged engine”, Journal of Oil and Gas Science and Technology, 59 (6) 581-591, Nov. 2004, doi:10.2516/ogst:2004042.

[37] A Kaleli, M Ceviz and K Erenturk “Controlling spark timing for consecutive cycles to reduce the cyclic variations of SI engines”, Applied Thermal Engineering 87 (2015) 624-632, doi:10.1016/j.applthermaleng.2015.05.042

[38] I Semin, A Ismail and A Bakar “Investigation of Torque Performance Effect of development of Sequential Injection CNG Engine”, Journal of Applied Sciences 9(13): 2416-2423, 2009.

[39] D R Johnson, R Heltzel, A C Nix, N Clark, et.al., “Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development”, Applied Energy 206 (2017) 739–750, doi:10.1016/j.apenergy.2017.08.234

[40] Q Tang, J Fu, J Liu, F Zhou, et al. “Performance improvement of liquefied natural gas (LNG) engine through intake air supply”, Applied Thermal Engineering 103 (2016) 1351–1361, doi:10.1016/j.applthermaleng.2016.05.031

[41] B Yan, H Wang, Z Zheng, Y Qin, et.al., “The effect of combustion chamber geometry on in-cylinder flow and combustion process in a stoichiometric operation natural gas engine with EGR”, Applied Thermal Engineering (2017), doi:10.1016/j.applthermaleng.2017.09.067

[42] B Yadollahi and M Boroomand “The effect of combustion chamber geometry on injection and mixture preparation in a CNG direct injection SI engine”, Fuel 107 (2013) 52–62, doi:10.1016/j.fuel.2013.01.004

[43] C Wu, K Deng und Z Wang “The effect of combustion chamber shape on cylinder flow and lean combustion process in a large bore spark-ignition CNG engine”, Journal of the Energy Institute xxx (2015) 1-8, doi:10.1016/j.joei.2015.01.023

[44] Q Zhang, M Li, G Li, S Shao and P Li “Transient emission characteristics of a heavy-duty natural gas engine at stoichiometric operation with EGR and TWC”, Energy (2017), doi:10.1016/j.energy.2017.05.039

[45] A A Sabaruddin, S Wiriaididja, A S MohdRafie, F I Romli et. al., “Engine Optimization By Using Variable Valve Timing System At Low Engine Revolution”, Journal of Engineering and Applied Sciences, 10 (20), Nov. 2015, ISSN 1819-6608

[46] A-F M Mahrous, A Potrzebowski, M L Wyszynski, H M Xu et.al., “A modeling study into the effects of variable valve timing on the gas exchange process and performance of a 4-valve DI homogeneous charge compression ignition (HCCI) engine”, Energy Conversion and Management 50 (2009) 393–398, doi:10.1016/j.enconman.2008.09.018

[47] D Ramasamy, Z A Zainal, K Kadirgama, H W Briggs, “Effect of dissimilar valve lift on a bi-fuel CNG engine operation”, Energy 112 (2016) 509-519, doi:10.1016/j.energy.2016.06.116

[48] M Baratta, D Misul, J Xu, A Fuerhapter et al., “Development of a High Performance Natural Gas Engine with Direct Gas Injection and Variable Valve Actuation,” SAE Int. J. Engines 10(5):2017, doi:10.4271/2017-24-0152

[49] L Romani, G Vichi, A Bianchini, I. Ferrari et. al., “Optimization of the Performance of a Formula SAE Engine by means of a Wastegate Valve Electronically Actuated”, presented at 71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16, Sep. 2016, Energy Procedia 101 (2016) 654 – 661.

[50] S H Khudhur, A M Saleh and M T Chaichan “The Effect of Variable Valve Timing on SI Engine Performance and Emissions”, International Journal of Scientific & Engineering Research, 6(8), Aug. 2015, ISSN 2229-5518

[51] J Zhao, F Ma, X Xiong, J Deng et. al., “Effects of compression ratio on the combustion and emission of a hydrogen enriched natural gas engine under different excess air ratio”, Energy 59 (2013) 658-665, doi:10.1016/j.energy.2013.07.033

[52] H B Mathur and L M Das “Performance Characteristics Of A Hydrogen Fuelled S.I. Using Timed Manifold Injection”, Int. J. Hydrogen Energy, Vol. 16, No. 2, pp. 115-127, 1991.