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Simulation based study on improving the transient response quality of turbocharged diesel engines

ABSTRACT

Purpose: Use of fossil fuels in automotive sector is one of the primary causes of greenhouse emissions. The automotive engines need to perform at their best efficiency point to limit these emissions. Most of the quality indicators in this regard are based on near steady state global operational characteristics for engines without considering local performance. In the present study, extensive numerical simulations have been carried out covering a wide range of steady state and transient operating conditions to quantify interaction of turbocharger with engines through turbo-lag phenomena which may cause increased emissions during the load change conditions. Furthermore possible innovations have been explored to minimise turbo-lag phenomena.

Design Methodology/Approach : In this paper quality indicators have been developed to quantify the performance of turbocharged diesel engine under the transient event of rapid change in fueling rate which have been rarely investigated. The rate of fueling is changed from 40 mm3/injection to 52 mm3/injection at 1000 rpm engine speed which corresponds to normal operating condition. To improve quality of transient response, torque assistance method and reduction of inertia of compressor wheel have been used. Parametric study has been undertaken to analyze the quality indicators such as outlet pressure of the compressor and the compressor speed. The turbo-lag is quantified to obtain the close to optimal transient response of turbocharged diesel engine.

Findings: It has been shown that, with torque assist the transient response of the internal combustion engine is significantly improved. On the other hand, marginal improvement in transient response is observed by the reduction in inertia of the compressor wheel.

Research limitations/ implications: The findings indicate that turbo-lag can be minimised by providing torque assistance by active and passive means.

Practical Implications: The developed methods can be used in practice for efficient operation of vehicles.

Social Implications: The work carried out provides a way to minimise harmful emissions.

Originality/Value: The quality indicators developed provide a quantitative measure of turbo-lag phenomena and address the above mentioned problems.

Keywords: Engine simulations, Turbocharged diesel engine, turbo-lag, electric torque assistance, transient response.

Introduction: Diesel engines are extensively used in passenger cars as well as in long distance haulage sector vehicles to impart motive force. These are internal combustion (IC) engines in which fuel is burnt through compression ignition (CI) process. Differing from gasoline engine, the fuel is sprayed directly into the combustion chambers (cylinders) just when the air that has been sucked from the intake manifold into the cylinder is compressed to such an extent that it is hot enough to ignite the fuel instantaneously. The energy hence released from the burning of fuel forces the piston down and this motion is converted to forward motion of vehicles through an integrated and well-designed power train. The speed and power of the diesel engines are regulated by the amount of fuel injected [1].

Continuous improvement in internal combustion engine technology is necessary to meet the stringent performance and emission requirements. Development of modern diesel engines (Turbocharged diesel engine) is playing a vital role in enhancing the performance envelope of the diesel engines. In naturally aspirated diesel engine about 30% of the heat energy obtained through diesel combustion is wasted in the exhaust gases. Through turbocharged engines a part of this energy is recovered and used for compressing the incoming gases. Turbochargers are extensively used in diesel engines for the recovery of heat lost in the exhaust gases and boosting the power output of the engine with the same displacement volume of the engine by providing intake air with increased density and hence increased mass. Turbocharger is a device consisting of a turbine and a compressor attached to a single shaft. The exhausted gases are expanded in the turbine blades and part of the wasted energy is converted into useful work by the compressor. The compressor outlet is connected to the inlet manifold through an intercooler to increase the air density flowing into the intake manifold. In this way the volumetric efficiency of the diesel engine is enhanced by the use of turbocharger. So, turbocharging is a boosting system enabling the engine to breathe more air resulting in more power output for a given size of the engine. Turbocharging of diesel engine is the most extensively used technology for the improvement of power density, emissions and enabling downsizing of engines without compromising power. One of the major challenges in turbocharged engines is achieving good transient performance and this is still being actively pursued. As discussed by *N.J.Choi and S.M.Oh (2010),* due to the inertia of the turbocharger rotor and compressibility of the exhaust gas with engine, sudden changes in rack position do not result in instantaneous response of the turbocharger. As a result the air-fuel ratio quickly changes to undesired value, deteriorating combustion and leading to slower engine response and increased emissions. This condition is known as turbo-lag which needs to be minimized for efficient operation of turbo-charged diesel engines.

Various studies have been performed by different investigators to improve the transient response of turbocharger through the optimum design and control of turbocharger [3, 4, 5 and 6]. C.S.Lee and N.J.Choi (2002) performed detailed experimental study to improve the low speed torque and acceleration performance of the turbocharged engine system by injecting air into intake manifold during transient conditions. They found that the air injection into the intake manifold during the rapid acceleration greatly improves the combustion performance of turbocharged diesel engine. D. Cieslar (2013) investigated the transient response of turbocharged engines using boost assistance systems. He used different approaches to improve the transient response such as pre-compressor assistance, electric torque assistance, intake air assistance and exhaust air assistance. Pre-compressor assistance indicated the best performance but it required additional hardware. Electric turbo assistance and exhaust manifold air assistance offered relatively similar performances.

The studies on reducing the turbo lag and maintaining the desirable air fuel ratio are considered to be very important for making turbocharged engine complaint with current environmental regulations. For the reduction of turbo lag during transient operations, electrical hybridization of turbocharger has gained widespread attention as it has potential to be an effective method of improving the air delivery in to the engine. Generally a motor/generator is added to the turbocharger which can be integrated in various different arrangements. G Tavcar et al (2011) compared the performance of a baseline turbocharged high speed direct injection (HSDI) engine with different types of electrically assisted turbochargers as given below:

- Electrically assisted turbocharger (EAT)
- Additional electrically driven compressor (TEDC)

- Electrically split turbocharger (EST)

Analyses were carried out for different driving conditions, including tip in the gear and the new European drive cycle. They found that all electrically assisted turbocharger topologies improved the transient response of the engine and the drivability of the vehicle. These topologies could also improve the steady state torque output of the engine with retained fuelling.

Results reveal that an engine utilizing additional electrically driven compressor (TEDC) delivers the highest torque output and fastest transient response at low engine speeds. While at high engine speeds, electrically assisted turbocharger (EAT) provides high torque output in addition to transient response improvement. Electrically split turbocharger (EST) provides the same transient response as that of electrically assisted turbocharger (EAT), since both are constrained by compressor surge limit. For urban driven cycles, the utilization of electrically split turbocharger enables the reduction in fuel consumption. The study concluded that the ideal arrangement of electric turbocharger depends mainly upon the application [1]. The major disadvantage of such systems is increased inertia and their inability to meet low packaging space requirements in modern engines.

Computer simulations have gained considerable importance in predicting the performance of engine systems. They reduce the number of costly physical testings which require extensive experimental setups and incur huge running costs. The simulation results obtained by Ibaraki etal (2010) reveal 50% improvement in engine torque by a 1 kW motor assist while 100% improvement was achieved with a 2 kW motor assist. Furthermore the fuel efficiency improved by 8% with a 1 kW motor assist while 12% improvement in fuel efficiency is observed by 2 kW motor assist [6]. Similar investigation performed by D. Cieslar (2013) on time to achieve torque rise shows better performance by the 2 kW motor in comparison to 1 kW motor. However the 3 kW motor gives very little additional benefit. These studies suggest that the assistance provided by the 2 kW motor as the optimum and indicate that it is equivalent to 0.16 Nm of additional torque [4, 6]. O.Giikes and R.Mishra (2006) compared the active method of injecting air into the inlet manifold and passive method of reducing the inertial of the compressor wheel and the results show that both the methods reduce turbo lag, however active system produces superior results. Further the effect of change in inertia of compressor wheel on engine performance is investigated using different inertia values determined as a percentage change from the original compressor modeled with inertia as 6e-5 kgm^2

This paper expands upon the previous works by using a more realistic simulation through a simulation software (Lotus Engine Simulation) to further investigate the effect of reducing the inertia of turbocharged system to improve the turbo-lag as well as effect of sudden fuelling through more detailed and rigorous analyses. Furthermore novel quality indicators have been identified through which performance improvement in turbo lag can be measured.

Methodology: The engine model is developed using Lotus Engine Simulation software which can predict the complete performance of an engine system. The description of engine model is shown in Table1 which is representative of an engine used in mid-range passenger car.

Engine Type	4 Stroke Diesel
Stroke	85.0mm
Bore	88 mm
Number of Cylinders	4
Combustion System	Direct Injection
Compression Ratio	19.5:1
Connecting rod	144mm

Table 1: Engine specification

The Lotus Engine Simulation software can be used for predicting full and part load performance under steady state and transient operating conditions. As presented by R.J. Pearson et al. (2002), the engine power is given by

$$W = \frac{\bar{p}}{1200} V_{swept} N$$

Where $\bar{p}$ is the brake mean effective pressure (BMEP) in bar, V_{swept} is the engine swept volume in liters and N is the engine speed in rev/min. The primary factor for determining the power output from an engine of a given swept volume is its maximum rated speed. Hence the maximum rated speed together with the number of cylinders and swept volume is responsible for defining the engine performance envelope. The BMEP at a fixed air-fuel ratio (AFR) and given fuel specific heat value (Q_v) is related to the volumetric efficiency (η_v), thermal efficiency (η_{th}) and the combustion efficiency (η_{comb}) by equation:

$$\bar{p} \alpha \frac{Qv}{AFR} \eta_v \, \eta_{th} \, \eta_{comb}$$

Lotus engine software (LES) provides a Concept Building Tool to build a complete engine model based on these three key parameters: number of cylinders, swept volume and engine speed at maximum power. Lotus Engine Simulation uses a 'heat release' model to simulate the energy release mechanism from the mixture. In this model the mass fraction of burnt fuel is calculated using a Wiebe function. Heat transfer to the three major surfaces cylinder head, piston and liner is evaluated from the difference between the instantaneous gas temperatures and the metal surface temperature. The convective heat transfer coefficients are derived from the well-known semi-empirical relationships of Annand model [10]. Simulation of the energy release rate and the heat transfer processes enables the prediction of the in-cylinder pressure during combustion and hence a complete cycle simulation can be performed [9]. As the turbocharger is used to deliver more power out of a smaller engine, a relatively smaller engine is chosen to be modelled. A 4 cylinder, 4 stroke, compression ignition engine is modelled in this study. The engine specifications are shown in Table 1. The specifications match with the specifications of the engine used in a mid-range car as mentioned earlier.

A fully connected turbocharged engine model is shown in Figure 1. The manifolds have been modelled using plenum, pipes, valves and ports (blue at intake and orange at exhaust). The components are available in the tool kit menu and they are dragged from the menu to construct the model as per the requirement. Cylinders are selected from the tool kit tab and their specifications are provided as shown in Table 1. Bore is taken as 88.0 mm, stroke as 85.0 mm, connecting rod length as 144 mm and compression ratio as 19.5:1. Poppet valves are selected from the intake component tab and attach to the cylinder elements via connectors. Intake and exhausts valves timing are set as shown in Figure 2.

Inlet and exhaust boundaries are added to complete the basic model. Fuel element is added to the model and fuel type is selected as diesel and the fuel system is chosen as direct injection.

From the machine tool kit tab the turbocharger element is included in the model. Compressor is connected to the inlet plenum and the turbine is connected with the exhaust manifold. The block diagram for the methodology is shown in Figure 3. It highlights the steps involved in the construction of simulation model as well as the control system for the improvement of transient response of the turbocharged diesel engine.

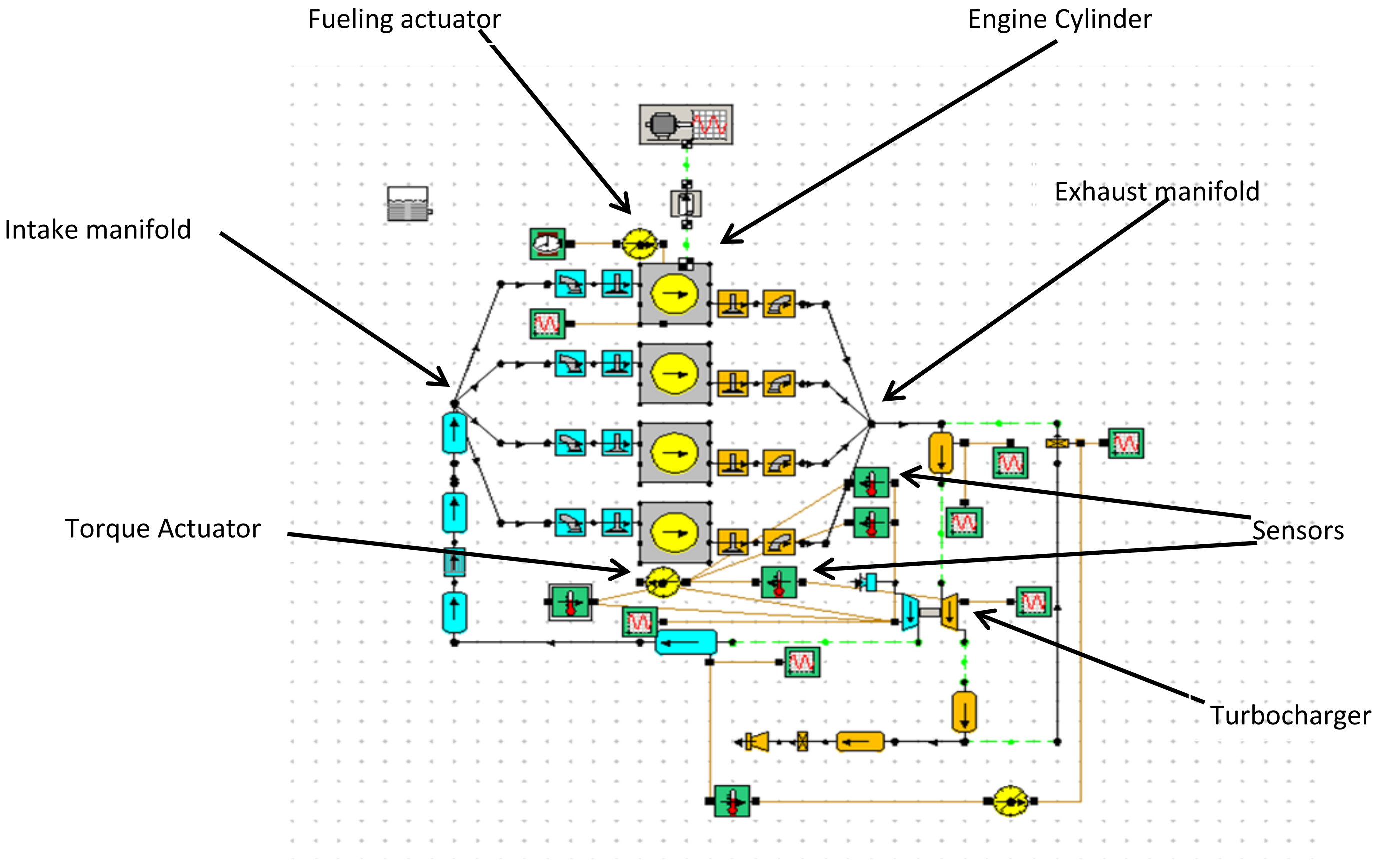


Figure 1: Turbocharged engine model

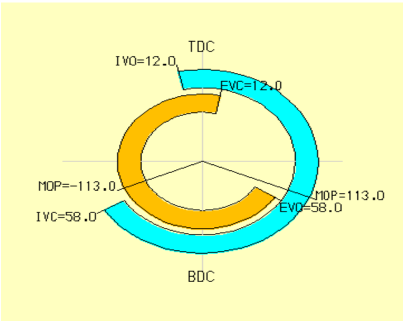


Figure 2: Valve timing diagram [9]

A control system for providing the additional power to the turbocharger is constructed using sensors and actuators. The sensors in LES monitor the compressor power and turbine power. To simulate electric turbocharger assist system, an actuator is used which adds an additional torque to the turbocharger shaft. The angular velocity of the shaft is calculated using Newton's second law for rotational Systems [11].

$$\dot{W}_{tc} = \frac{1}{J_{tc}} \left(T_{qt} + T_{qjA} - T_{qc} \right)$$

where

T_{qt} = Torque generated by turbine (Nm)
$T_{qjA} =$ Torque from Jet-Assist (Nm)
T_{qc} = Torque consumed by compressor Nm
$\dot{W}_{tc} =$ Rotational speed for turbine and compressor in rad/s
J_{tc} = Inertia of turbo system kg m^2

Simulation strategy:

The performance characteristics of the engine is affected by several parameters such as gas temperature and pressure in the cylinder, temperature and pressure characteristics of the turbocharger and the pressure variations during inlet and exhaust processes. The transient performance of the IC engine can be improved by supplying additional air into the cylinder and by controlling the fueling rate.

In the present work the transient performance of the engine has been simulated through the rapid change in fueling rate which represents a rapid increase in the load applied to the engine. Initially the model runs at 1000 rpm at part load at 12.67 bar as a steady state run, in order to initialize the transient event. During the transient, the quantity of fuel injected is increased from 40 mm^3/injection to 52 mm^3/injection and hence the boost pressure rises.

To improve the transient response of the diesel engine two strategies are considered:

1. Electric torque assist
2. Reduction in inertia of compressor

The length of the transient is taken as 6 sec. The major parameter investigated under transient conditions is compressor outlet pressure. It indicates the output response of turbocharger. This is taken as a measure of transient response of the turbocharged engine. In addition, the effect of torque assistance is also investigated on turbocharger speed. To further analyze the transient period the rate of change of important parameters have been investigated. So the quality factors under consideration are compressor exit pressure, rate of change of compressor exit pressure, compressor speed and rate of change of compressor speed.

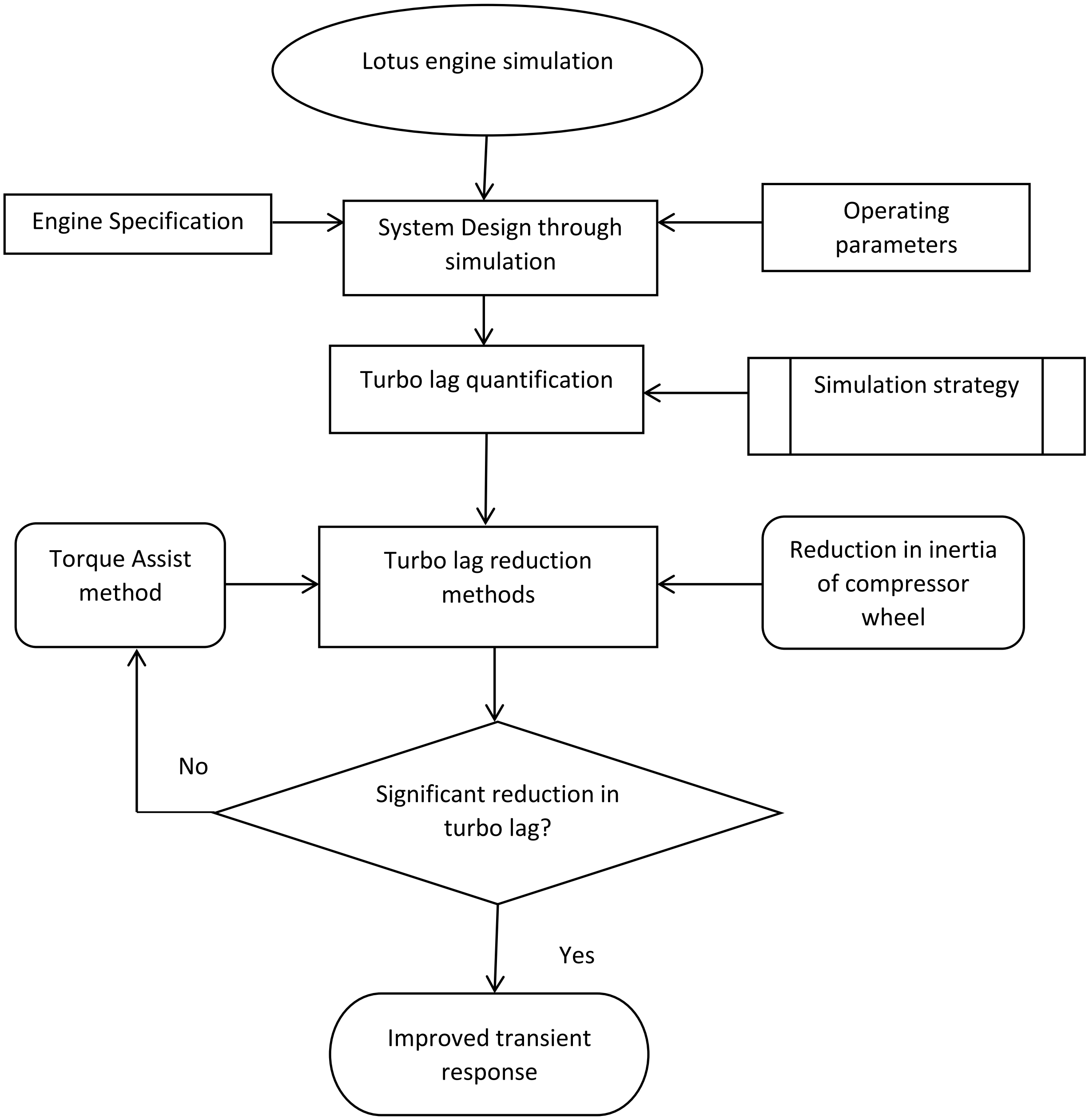
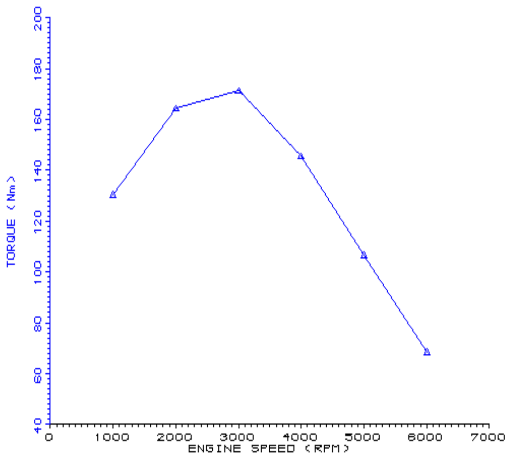


Figure 3: Block diagram for the methodology

Results: The simulation results of the proposed system are presented here. The modeling of the real system is considered by choosing the parameters from the literature. The simulations are performed for engine performance parameters as well as various turbocharging parameters.

Steady state simulations: Figure 4-7 show the engine performance characteristics with variation in different parameters shown as a function of engine speed. The plots show the variation in BSFC (Brake specific fuel consumption), brake torque, brake power and BMEP (brake mean effective pressure). Figure 4 shows that the torque rises rapidly to a maximum of around 178Nm at 3000rpm and then gradually decreases with the increase in engine speed. The brake mean effective pressure increases up to 11 bar at 3000 rpm then gradually decreases with engine speed as shown in figure 5. At lower speeds i.e. below 3000 rpm BMEP drops off due to heat losses. While at higher speeds (above 3000 rpm) BMEP decreases because it becomes difficult to ingest a full charge of air.

Figure 6 shows that the lowest value of specific fuel consumption is at around 2000 rpm. At lower engine speeds the fuel consumption increases due to increased time for heat losses from the gas to cylinder and piston wall. As the speed increases the fuel consumption also increases and the combustion efficiency decreases. The maximum power produced by the engine is about 64kW at around 4000rpm. Figure 7 shows the variation of Brake power with respect to engine speed. Initially it increases and then after 4000 rpm it starts decreasing.



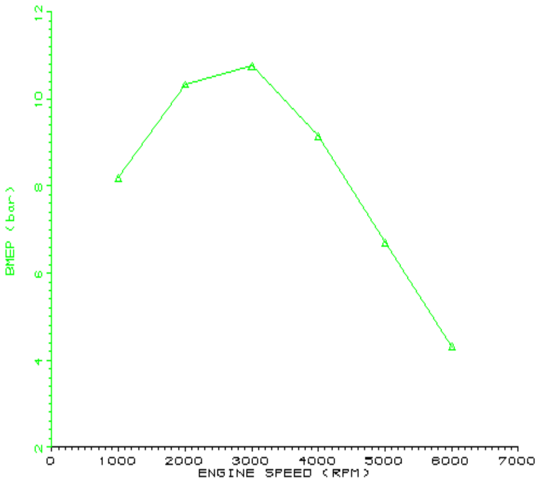
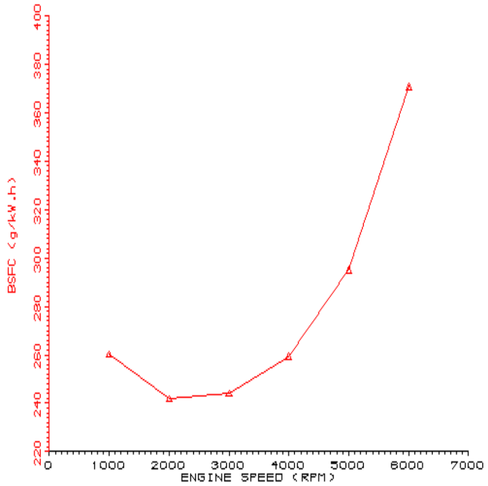


Figure 4: Brake torque

Figure 5: BMEP



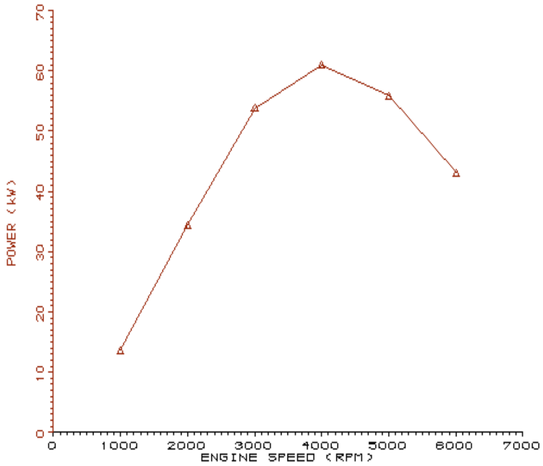


Figure 6: BSFC

Figure 7: Brake power

Transient Simulation: Different values of torque assist are taken in the range of 0-0.32 NM and investigations are performed to obtain the optimum value of torque assist for best transient response. The value of the additional torque is motivated by the studies performed by Ibaraki et al. (2006). For this purpose four different values of additional torque are taken in the selected range as 0.08NM, 0.10NM, 0.16NM and 0.32NM. The response of compressor exit pressure for the different torque assist values is as shown in Figure 8. The figure shows that initially by increasing torque assistance, the response is improved and 0.10 NM torque assist offers more benefits than 0.08NM assist but further increase in torque to a value of 0.16 NM gives almost similar but more stable response. Further increase in torque to a value of 0.32NM also gives almost same response. So the optimum value of torque assist is observed to be 0.16 NM. This is consistent with the value reported in the literature [6].

Based on the above investigations 0.16 NM torque is provided as an additional torque to the turbocharge shaft in the Lotus engine simulation environment for further evaluation. The Simulation is performed with and without electric torque assistance. The effect of torque assistance is noticeable in Figure 9. Initially the compressor outlet pressure shows an initial delay in response before reaching the steady state. As shown in figure 9 that the compressor pressure reaches the steady state condition in 4.8 seconds with no torque assistance. The compressor outlet pressure response is significantly improved with torque assistance and the compressor pressure reaches the steady state in 1.8 second. The rate of change of compressor exit pressure response is plotted in Figure 10. It shows much greater and faster rate of change for torque assist system as compared to without torque assist systems. The response time is reduced by 3 seconds with torque assist.

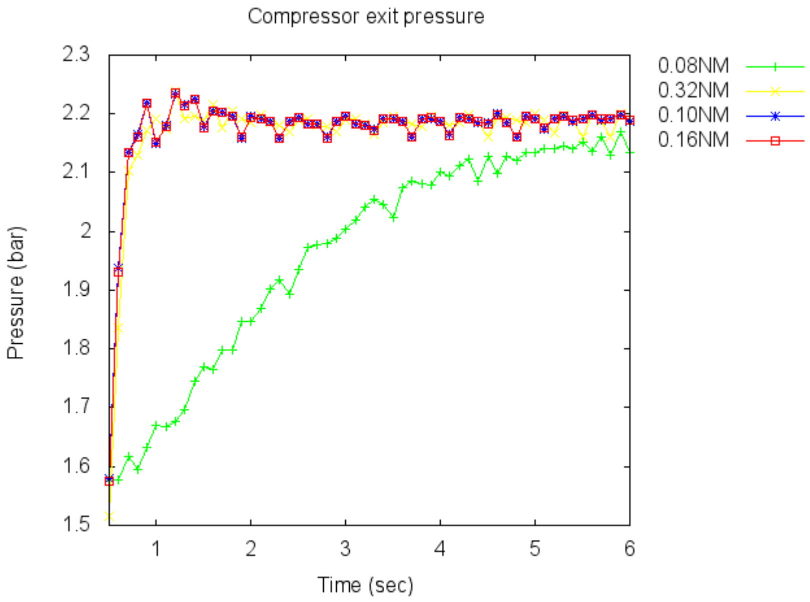


Figure 8: Compressor exit pressure response

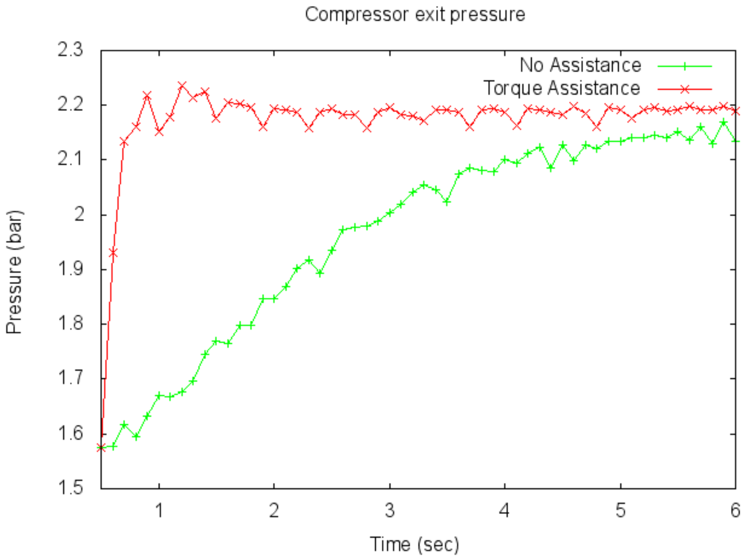


Figure 9: Compressor exit pressure response

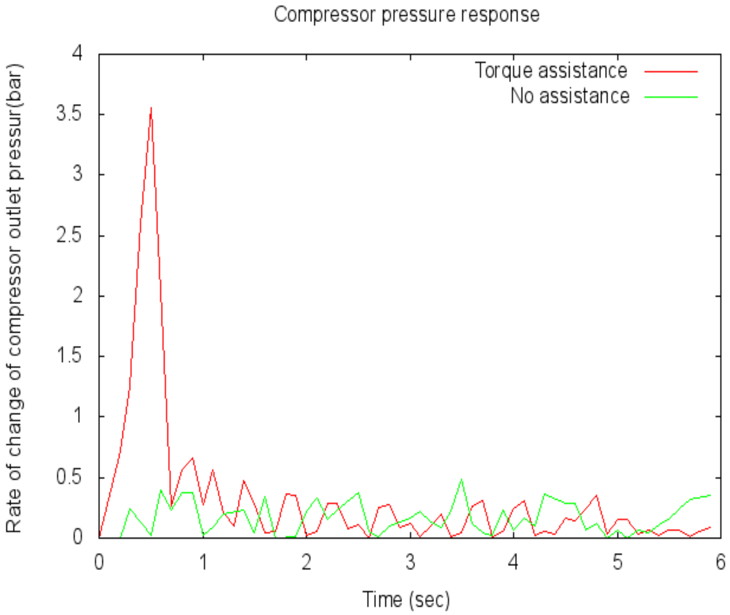


Figure 10: Rate of change of Compressor outlet pressure response

Figure 11 shows the effect of torque assistance on compressor speed response. When compared with no assist systems, it is clear that with torque assist the response time is improved by 3 seconds. This difference is more significant when rate of change of compressor speed response is plotted as illustrated in Figure 12. In case of torque assistance, greater and quicker response is observed and the difference in time to reach the equilibrium is found to be 3 seconds.

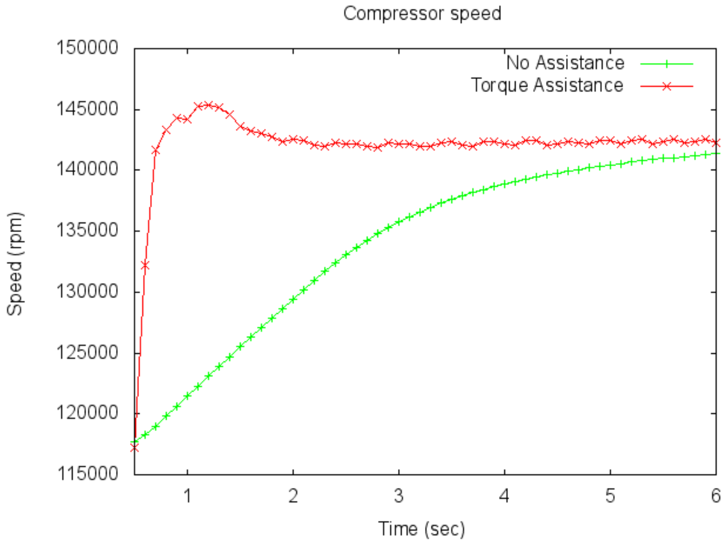


Figure 11: Compressor speed response

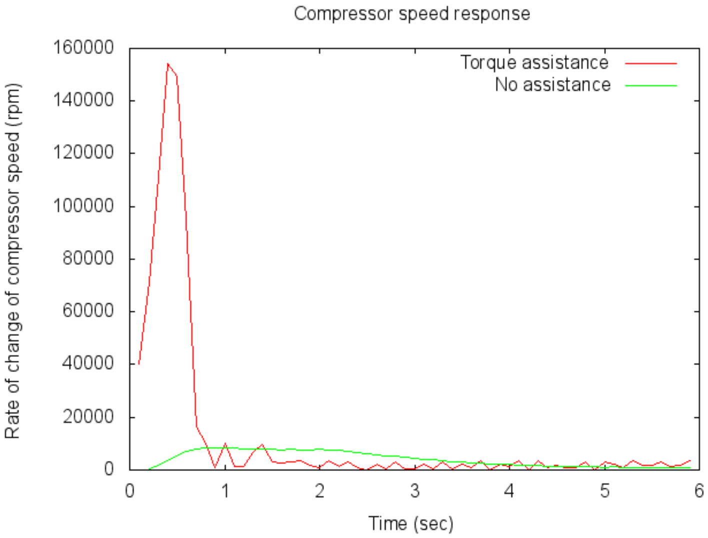


Figure 12: Rate of change of compressor speed response

Figure 13 shows the outlet pressure response of a turbocharger with different inertia values. As predicted by the previous studies [7] by reducing the inertia of the system, the delay in the response of the turbocharger is reduced. However the reduction of delay is seen to be very small.

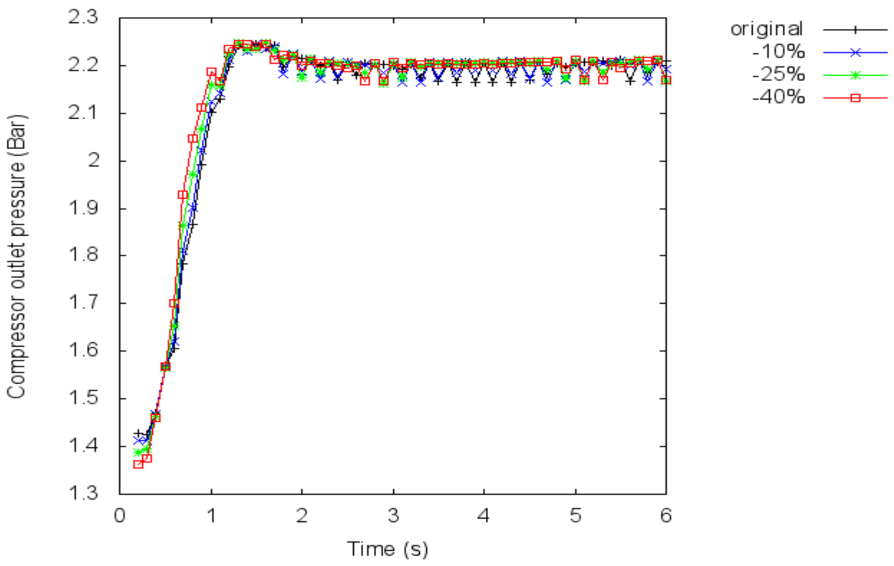


Figure 13: Compressor exit pressure with reduction in inertia values

The quantitative analysis of the two methods adopted is presented in table 2. In the first method the quality indicators are compared for the case of torque assist and of no torque assist. The analysis shows that the turbo lag is significantly reduced by the application of torque assistance. The compressor pressure reaches the steady state condition in 4.8 seconds with no torque assistance. The compressor outlet pressure response is significantly improved with torque assistance and the compressor pressure reaches the steady state in 1.8 second. The rate of change of compressor exit pressure response shows much greater and faster rate of change for torque assist system as compared to without torque assist systems. The response time is reduced by 3 seconds with torque assist. For compressor speed the response time is 5.59 seconds without torque assist while with the torque assist the response time is 1.79 seconds. So the response time is improved by 3.8 seconds. Moreover the results show the improvement in the indicated value for the case of torque assist. In the second method, compressor exit pressure is observed for the reduction in inertia of the compressor wheel. The improvement brought by this method is seen to be small.

	Torque Assist method		Reduction in inertia method	
Indicator	No Assist	Torque Assist	Inertia of compressor	Compressor exit pressure (Indicator)

	Turbo lag	Indicated value	Turbo lag	Indicated value	wheel	Turbo lag	Indicated value
Compressor outlet pressure	4.8	2.13	1.8	2.2	Original	1.20	2.13
Rate of change of Compressor outlet pressure	3.5	0.39	0.5	3.5	-10%	1.10	2.14
Compressor speed	5.59	141350	1.79	145354	-25%	1.10	2.15
Rate of change of Compressor speed	1.0	8310	0.5	154200	-40%	1.00	2.15

Table 2: Comparison of the results obtained by the active and passive methods

Conclusion:

The research presented here has been focused on determining the turbo lag from the analysis of quality indicators. Under the transient event of rapid change in fueling rate the transient performance of a turbocharged diesel engine is investigated by applying the active method of torque assistance and the passive method of reduction of inertia of compressor wheel. The turbo lag is significantly reduced using 0.16 NM torque assistance. This improves the overall performance of the engine. The reduction in the inertia of the turbocharged system also improves the transient response. However the improvement brought by the reduction in inertia is found to be very small.

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