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DESIGN & DEVELOPMENT OF E-TURBO FOR SUV AND LIGHT TRUCK APPLICATIONS

Craig Balis
Chris Middlemass
S. M. Shahed
Garrett Engine Boosting Systems

ABSTRACT

The purpose of the project is to develop an electronically controlled, electrically assisted turbocharging system, e-Turbo, for application to SUV and light truck class of passenger vehicles. Earlier simulation work had shown the benefits of e-Turbo system on increasing low-end torque and improving fuel economy. This paper will present further data from the literature to show that advanced turbocharging can enable diesel engine downsizing of 10-30% with 6-17% improvement in fuel economy. This is in addition to the fuel economy benefit that a turbocharged diesel engine offers over conventional gasoline engines. E-Turbo is necessary to get acceptable driving characteristics with downsized diesel engines.

As a first step towards the development of this technology for SUV/light truck sized diesel engines (4-6 litre displacement), design concepts and hardware were evaluated for a smaller engine (2 litre displacement). It was felt that design and developments issues could be minimized, the concept proven progressively on the bench, on a small engine and then applied to a large Vee engine (one on each bank). After successful demonstration of the concept, large turbomachinery could be designed and built specifically for larger SUV sized diesel engines. This paper presents the results of development of e-Turbo for a 2 litre diesel engine.

A detailed comparison of several electric assist technologies including permanent magnet, six-phase induction and conventional induction motor/generator technology was done. A comparison of switched reluctance motor technology was also done although detailed design was not carried out.

INTRODUCTION

Diesel engines have the potential of giving a 30-50% improvement in fuel economy for passenger car, light truck and SUV applications. Turbocharged diesel engines are extensively used in Europe and have demonstrated benefits in fuel economy and derivability. About 40% of the passenger cars in Europe use turbocharged diesel engines. Contrary to expectations, diesel penetration in luxury cars is even higher – up to 70%. Variable geometry VNT Turbo technology has contributed greatly to the wide acceptance of diesel engines. SUVs and light trucks present the most likely first application of diesel engine technology in the United States.

Two open issues that need to be considered before using diesel engines are (1) their ability to meet forthcoming emissions regulations and (2) their transient response normally referred to as "turbo lag". Elsewhere in this conference, papers are presented that show that several diesel engine prototypes have demonstrated US Tier II, Bin 5 emissions capability. This paper does not deal with emissions control although turbochargers play a vital role in driving exhaust gas recirculation, in controlling particulate emissions, controlling exhaust temperature to manage the exhaust aftertreatment and catalytic processes. This paper focuses on performance and turbo lag. VNT Turbo technology has gone a long way to address this issue. The proposed technology, electrically assisted turbocharging, embodied in the "e-Turbo" not only further improves the engine/turbo response but also has the potential to improve fuel economy by enabling severe engine downsizing and electrical turbo-compounding. This paper discusses the benefits and status of electrically assisted turbocharger technology.

NOMENCLATURE

VEN- Vehicle Electrical Network
EGR - Exhaust Gas Recirculation
VNT - Variable Nozzle Turbine
SUV- Sports Utility Vehicle. Also represents the class including Minivans and Light Trucks.
EAT – Electrically Assisted Turbocharger

Benefits of Electrically Assisted Turbocharging

Electrically assisted turbocharging technology can be applied to diesel engines to realize three levels of benefits. e-Turbo system configuration in shown in Figure 1. The simplest application is to use it to eliminate turbo lag by supplying electrical power during transient accelerations. A second level of benefit can be realized by downsizing the engine. A smaller engine gives many benefits such as cost, weight reduction, packaging and friction reduction. All this contributes to fuel economy. The reduced power of the smaller engine can be restored by appropriate turbocharging.

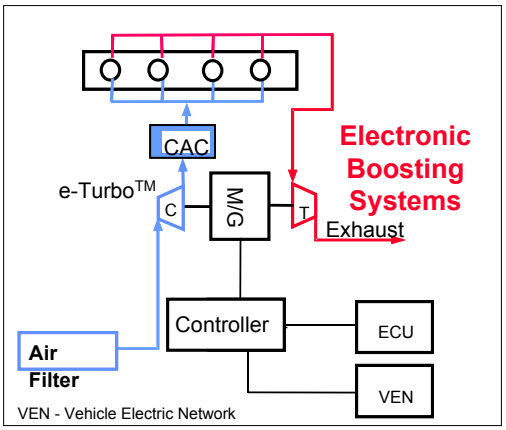


Figure 1: e-Turbo System Configuration

However conventional turbocharging may not be able to give the engine the necessary low speed torque and fast response needed to overcome the deficiencies of a downsized engine. In order to do this, electrically assisted turbocharging is required. In fact, electrically assisted turbocharging can be used to temporarily overboost the engine and get even more torque than normal. These levels of system benefits are illustrated in Figures 2 & 3.

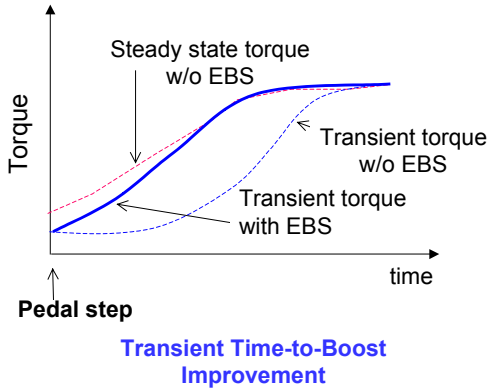


Figure 2: e-Turbo to restore Transient Torque

Figure 2 shows the use of e-Turbo to restore the torque of a downsized engine. Figure 3 illustrates the use of e-Turbo to temporarily over-boost the engine with the ability to program in the desired torque level limited only by engine structural capability. A third level of system benefit is realized by using the electrically assisted turbocharger as a part of the air management system. In such a system, EGR rates, exhaust temperature and like can be controlled to give optimum results.

As a first step, to confirm the benefits of electrically assisted turbocharging, an experiment was conducted on a downsized gasoline engine using "e-Charger" technology. An "e-Charger" is an electrically driven compressor used in series with a conventional turbocharger. It has the same response benefits as the e-Turbo, but does not have electrical turbo-compounding capabilities. In this experiment, the e-Charger was used only to establish downsizing and response benefits of electrically assisted air supply. The first assessment deals with the ability of electrically assisted turbocharging to restore the

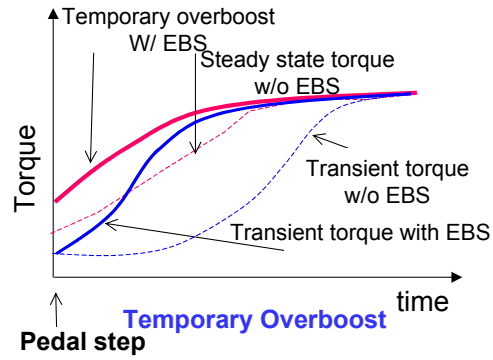


Figure 3: e-Turbo Illustrating Programmed Torque

steady state torque of a downsized engine. Figure 4 shows that even a 40% downsized engine can be calibrated to achieve the same torque as the larger, non-turbocharged engine. The second assessment deals with transient response. One very effective

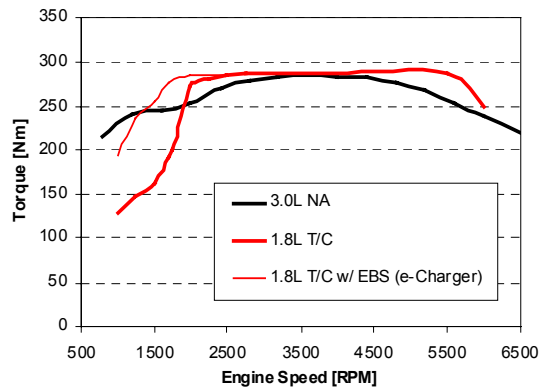


Figure 4: e-Charger Restores Steady State Torque of Downsized Engine

measure of response is - "time to boost" defined as the time it takes for the engine/turbo system to reach desired boost level (reference steady state torque at the corresponding speed) with a step increase in load at constant speed. Figure 5 shows that with electrically assisted boosting "time to boost" is reduced from 5 seconds to less than one second at all engine speeds.

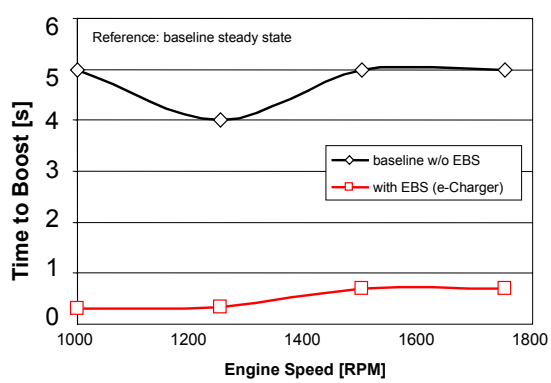


Figure 5: Turbo Response Assessment with e-Charger

Figure 6 is taken from a publication by Ricardo Consulting Engineers. It is a compilation of production vehicle fuel economy data over the European driving cycle. For selected production vehicles a back to back comparison between the original turbocharged diesel engine and a downsized diesel engine with advanced turbocharging is shown. It is seen that for the selected vehicles downsizing in the range of 10-30% is possible with fuel economy benefits ranging from 6% to 17%.

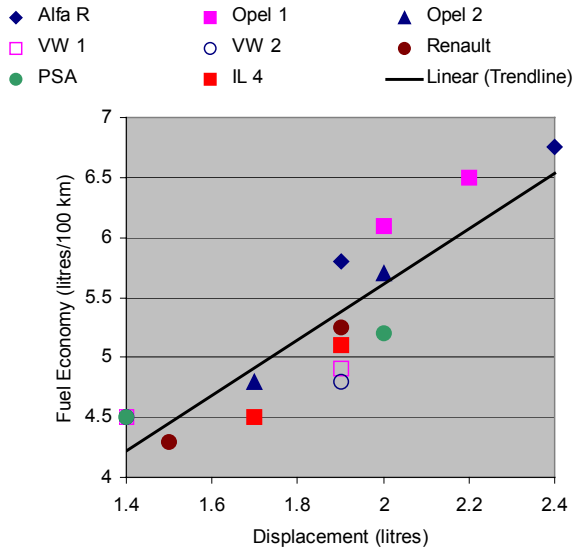


Figure 6: Effect of Downsizing on Fuel Economy-Diesel Engines – Same Vehicle for Each Engine Pair

Figure 7 is presented as a further point of interest to show that the principle of downsizing and turbocharging applied equally well to gasoline engines. In Figure 7, data from gasoline engine powered European production vehicles is shown. The turbocharged engines shown in the figure are on the average 30% smaller than the non-turbocharged engines and have a 10% better fuel economy. The data shown are compiled from European trade magazines and are for 2002-03 model year vehicles. Similar data are available over a 10 year period from 1992-93 to 2002-03 and consistently show an 8-10% improvement in fuel economy for about 30% downsized, turbocharged engines compared to larger, non-turbocharged engines of the same power.

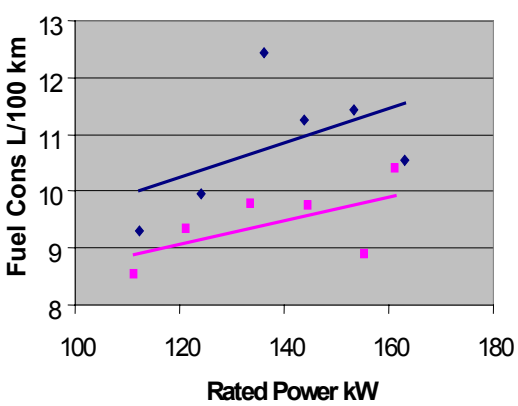


Figure 7: Effect of Downsizing on Fuel Economy-Gasoline Engines

Design Approach

Having established clear benefits of engine downsizing, it was necessary to launch the design and development process for electrically assisted turbochargers. Experience with early prototypes surfaced critical design issues and it was decided that these issues could be best addressed in the following order.

- Design and demonstrate electrically assisted turbocharger on a small ~ 2 litre diesel engine to clearly establish benefits and technology direction.
- Use two prototype electrically assisted turbochargers on a candidate ~ 4 litre SUV diesel engine to establish benefits in that vehicle size.
- Apply technologies learnt to design and demonstrate the best electrically assisted air management system for ~ 4 litre SUV engine applications.

Early prototypes also indicated the criticality of electric motor/generator design for cooling, controls and power electronics. Appropriate partnerships with suppliers were established to develop cost effective technologies.

The next step in the development process was to establish clear go/no-go criteria for e-Turbo technology. Preliminary tests and analysis showed that the following conditions were critical.

- High-speed motor/controller system to provide up to 1.4kW mechanical power at speeds up to 175kRPM total system efficiency > 70%.
- Turbocharger bearing system to carry the extra mass and length while still retaining acceptable shaft rotor-dynamic behavior up to 225kRPM.
- Turbocharger and motor cooling system to protect the motor from the extreme turbocharger thermal environment as well as from self-heating.
- Compressor aerodynamics to deliver the extra boost without suffering from surge ("stall") during the transient.

System Model

A complete system model using Matlab/Simulink software was

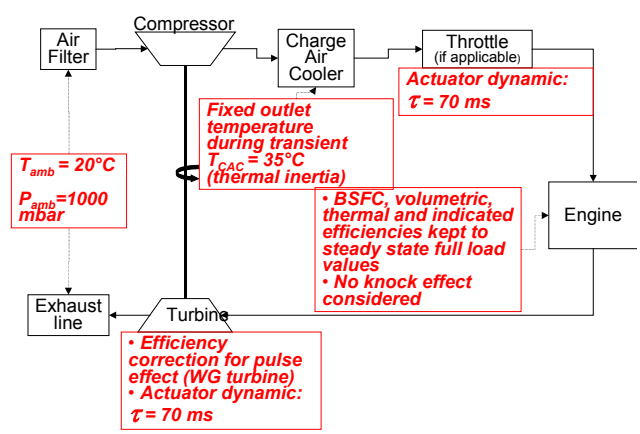


Figure 8: System Layout for Computer Simulation

developed for the air management system and its interaction with the engine/vehicle. Figure 8 shows model assumptions and system layout. Figure 9 shows a comparison of model

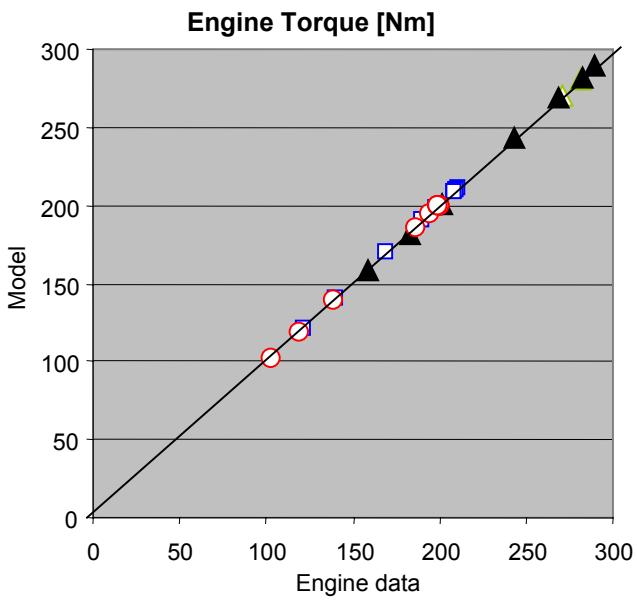


Figure 9: Comparison of Model with Engine Data for Steady State Conditions

calculations with engine measurements for wide range of steady state engine load-speed conditions. In this figure only engine torque data is compared. Similar comparisons were made for compressor pressure outlet and turbine inlet pressure calculations to establish the validity of the model but are not shown in this paper for brevity. Figure 10 shows a comparison

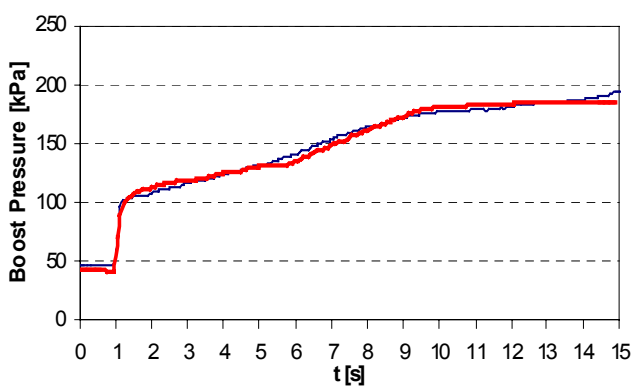


Figure 10: Comparison of Model with Engine Data for Transient Conditions with e-Turbo Off

between model and vehicle results for transient response. A 1600 kg vehicle powered by a 2 litre gasoline engine is used for this illustration. Figure 10 shows the results of accelerating the vehicle in 4th gear starting at an engine speed of 1000 rpm. The results in Figure 10, compare boost pressure vs time with the e-Turbo power turned off. It is seen that model is very successful in predicting transient behavior. Similarly Figure 11 compares boost pressure vs time with e-Turbo power turned on. Once again, model and experimental results show very good agreement. Similar comparisons of other variables such as engine, vehicle and turbo speed vs time were made to verify

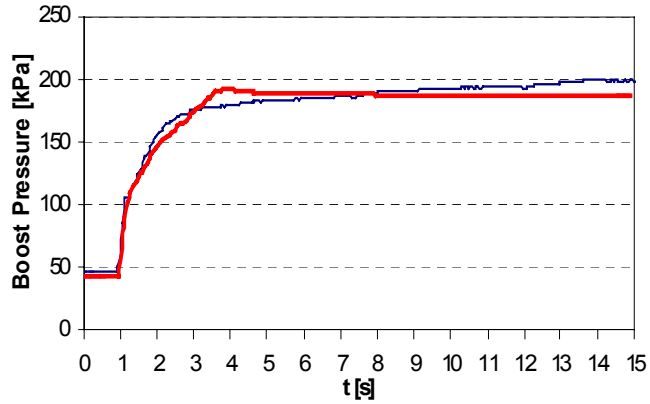
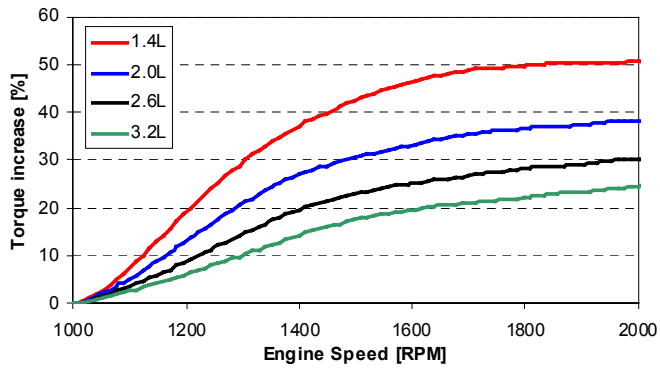


Figure 11: Comparison of Model with Engine Data for Transient Conditions with e-Turbo On

the validity of the model. These results are not presented in this paper for brevity.



- Fixed RPM ramp after load step (400 engine RPM/s)
- Electric motor mechanical power: 1250 W
- Relative value compared to transient w/o EBS
- Diesel Engine Modeling - % increase in torque in ~ 1 sec

Figure 12: Sensitivity Analysis at 1250 W e-Turbo Power

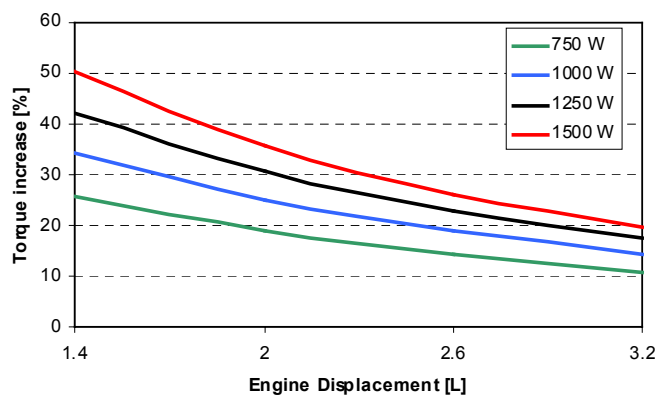


Figure 13: Sensitivity Analysis – Effect of e-Turbo Power
Same conditions as in Figure 12

The model was used to conduct a sensitivity analysis to determine the trade-off between torque increase, e-Turbo power, engine size. The results of this sensitivity analysis are shown in Figure 12 and 13 and were instrumental in developing

the criterion of 1.4 kW, 70% efficiency for the electric motor listed in the section on Design Approach.

Design Validation Results

Prototype e-Turbos were designed and built with power electronics and controls in cooperation with a supplier. Bench, engine and vehicle tests were conducted to validate the design against critical design requirements already listed and referred to above.

Performance validation results have already been presented in the shape of Figures 10 and 11. Figure 10 shows boost pressure with e-Turbo power "Off" and Figure 11 shows it with power "On". "Time to Boost" is a critical customer criterion in evaluating the performance of turbocharger/air management systems. Based on this criterion it is seen that electrically assisted turbocharging provides a substantial improvement. It is seen from Figure 10 that it takes about 6 seconds to reach 150 kPa boost pressure. Figure 11 shows that with the e-Turbo "On", it takes less than 1 second to reach 150 kPa boost pressure.

Turbochargers rotate at very high speeds. For a typical 2 litre passenger car engine turbo speeds can reach as high as 250,000 rpm. For a typical heavy duty truck engine turbo speeds as high as 70,000 rpm are common. Under such conditions the extra mass of electric machinery added to the shaft can make a critical difference in shaft stability. Shaft motion has to be minimized in order to control aerodynamic passage clearances because these have a strong impact on turbocharger efficiency. Hence design criterion relating to shaft stability was selected as a critical design parameter. Figure 14 shows that the design selected for test meets the criteria set out shaft stability.

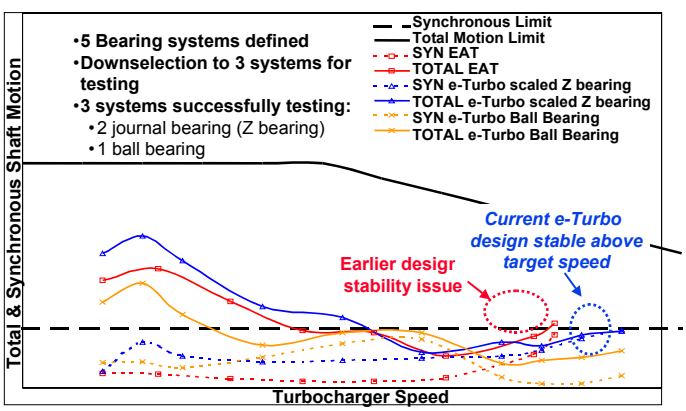


Figure 14: Shaft Motion Stability Test

Tests with early prototypes had indicated severe problems with cooling electrical machinery. In some early tests overheating of the electrical machinery and/or of the power electronics control box caused severe problems. Therefore a methodical approach to design was adopted along with design criteria listed. e-Turbo duty cycle under several conditions representing city, highway, mountain and country road driving was recorded as shown in Figure 15. The data was statistically

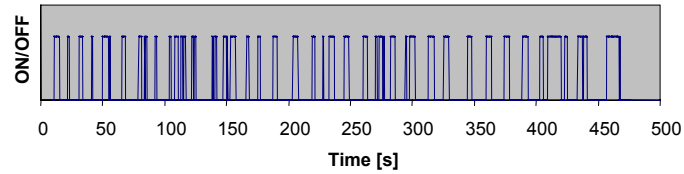


Figure 15: e-Turbo Duty Cycle Data Under Road Test

analyzed as shown in Figure 16 and summarized for the four drive conditions as shown in Figure 17. Figure 18 shows the

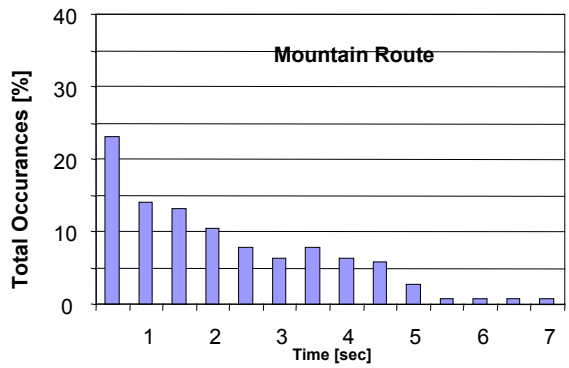


Figure 16: Statistical Analysis of Mountain Route Duty Cycle

results for typical transient thermal modeling done using the conditions of Figure 17 as input. Figure 19 shows that both

	City	Mountain	Highway	Country Road
Duty Cycle (%)	7%	19%	3%	6%
Average ON time (sec)	1.1	2.2	1.5	1.3
% ON > 2 sec	91%	58%	83%	86%

Figure 17: Statistical Duty Cycle Analysis of Four Routes

rotor and stator temperatures are within acceptable limits even under worst case driving conditions.

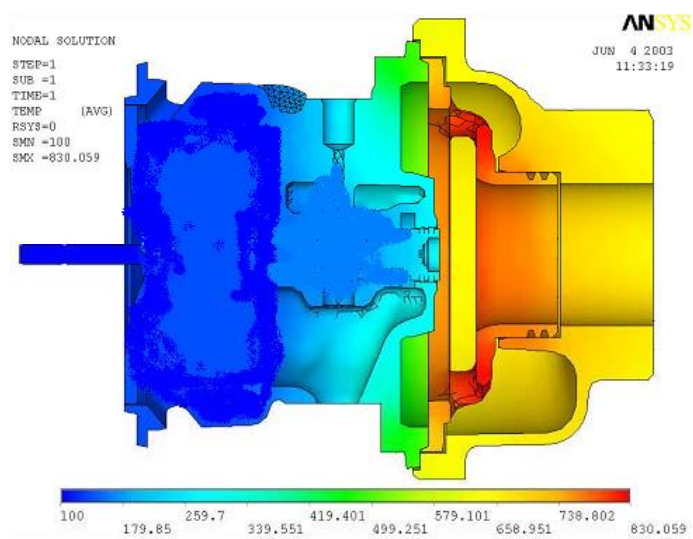


Figure 18: Thermal Model Analysis Using Duty Cycle Data

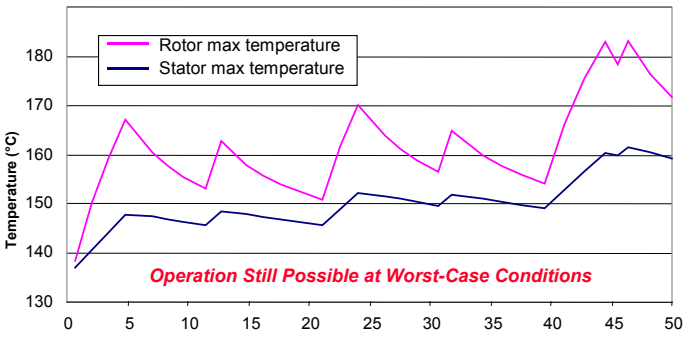


Figure 19: Thermal Modeling Results for Worst Case Conditions.

Conclusions

It has been shown that engine downsizing and turbocharging provides substantial fuel economy benefits both for diesel and gasoline engines. Benefits seem to increase with downsizing. However, with a severely downsized engine low speed torque under steady state conditions and transient response due to turbo lag can both be serious issues preventing widespread customer acceptance. Electrically assisted turbocharging can not only overcome this problem but also provide added benefits in terms of intelligent management of air supply, EGR rate and exhaust temperature for exhaust catalytic aftertreatment. Further, electric turbocompounding has the potential to give an additional 5-10% improvement in fuel economy depending on the duty cycle.

Preliminary tests with electrically assisted turbocharging were done to clearly establish the benefits. These tests also surfaced issues which were used to set clear design criteria. Results were also used to set a logical flow of technology development. (1) Design and build a prototype for a small engine. (2) Apply two such turbochargers, one on each bank of a larger SUV size engine to clearly establish benefits and surface any possible issues. And, (3) design a turbocharger specifically for a suitable SUV engine.

Designs were developed and prototypes built for a two litre diesel engine to meet design criteria set as a result of preliminary tests. Extensive design validation tests were done to show that the candidate design meets the selected criteria.

The design and technology validation program will continue along the planned path building on successful results obtained to date.

ACKNOWLEDGMENTS

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