Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

Background

This cooperative program between the DOE Office of Heavy Vehicle Technology and Caterpillar, Inc. is aimed at demonstrating electric turbocompound technology on a Class 8 truck engine. This is a lab demonstration program, with no provision for on-truck testing of the system.

The goal is to demonstrate the level of fuel efficiency improvement attainable with the electric turbocompound system. Also, electric turbocompounding adds an additional level of control to the air supply which could be a component in an emissions control strategy.

Mechanical Turbocompounding

Existing turbocompound technology consists of a conventional mechanical turbocompound system. The system includes a conventional turbocharger which recovers exhaust energy in a turbine to boost the air coming into the engine in a conventional fashion.

Downstream of the turbocharger turbine, the exhaust gas goes through a second turbine. The energy recovered here is added to the engine torque through a system of shafts, gears and a fluid coupling.

The objective of this program is to demonstrate the recovery exhaust energy electrically by using high speed generator technology. Electric turbocompounding eliminates the mechanical coupling to the engine crankshaft necessary in mechanical turbocompounding. This provides more flexibility in packaging. The electric turbocompound system also provides more control flexibility in that the amount of power extracted can be varied which allows control of engine boost. Also, the generator can be operated as a motor to spin up the turbo more quickly to improve turbo response. The electric turbocompound is a natural fit in a vehicle equipped with More Electric technology.

Caterpillar is using past experience in mechanical turbocompounding to aid in developing the electric turbocompound system. The high performance turbomachinery will be married with emerging high-speed generator technology.

Program Overview

The program has started with the development of a concept of the entire system, and continues with design and procurement of components.

The components are then bench tested individually, and as a system.

The final step is an on-engine lab test to demonstrate fuel efficiency gains with turbocompounding.

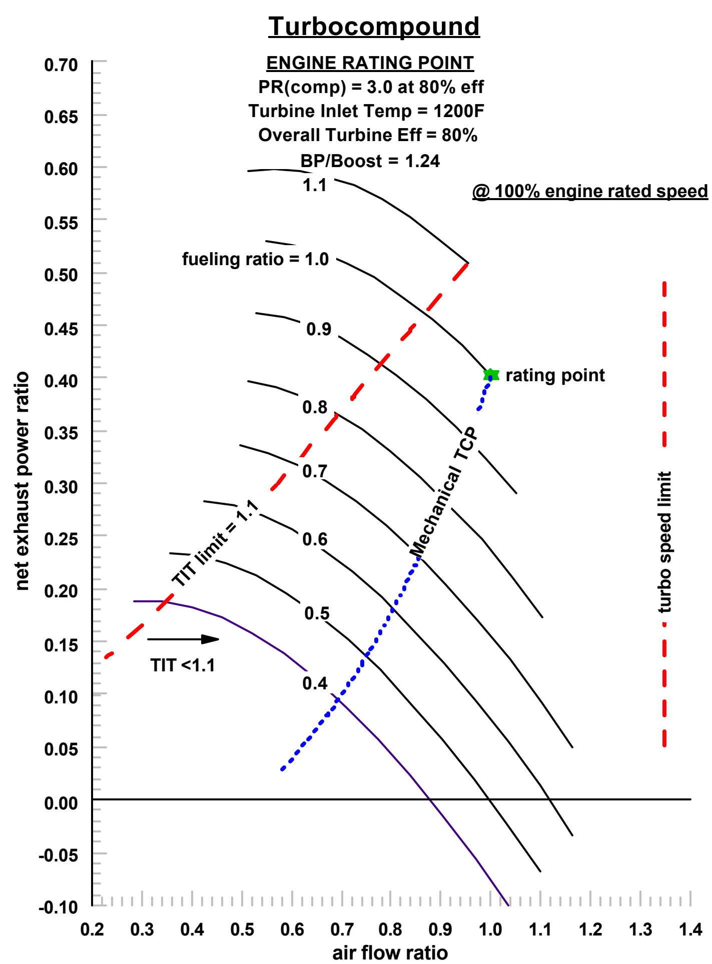
More Electric Truck

More Electric Initiative technology can be applied to an on-highway truck. Accessories that are normally driven by a belt or chain off the engine are electrically driven. Accessories can be installed where packaging and servicing are optimized. Also, accessories can be run only when needed at the required power level. A key component of the MEI truck is the crank starter/generator. This device replaces both the generator and the starter on a conventional truck engine. The crank starter/generator can also be used as a motor to convert electric power to driveline torque power.

Electric turbocompounding is a complementary technology to MEI in that the electric power generated by the electric turbocompound can be used power the MEI accessories. The electric power can also be added to the power train through the crank starter/motor/generator. Likewise, the flow of power can be reversed to power up the turbocharger if needed.

Flexible Operation

This plot illustrates the operating limits of a turbocompound. The plot applies to a single engine speed. The horizontal axis is the ratio of actual airflow to airflow at the rated condition. The vertical axis is the ratio of exhaust power available for turbocompounding to total exhaust power. The turbocompound is limited in operation on the left by the line that represents maximum turbine inlet temperature, and on the right by the line that represents maximum turbo speed. The various fueling ratio curves represent different engine power levels. A mechanical turbocompound with fixed geometry is limited to a single operating line. The addition of variable geometry to the turbocharger will increase the flexibility of the mechanical system.



The electric turbocompound can operate anywhere along a power curve between the two limits. Operating near the turbine inlet temperature limit maximizes the engine fuel efficiency.

In some circumstances, particularly at lower power levels, it may be desirable to operate nearer the turbo speed limit. This would supply excess air to the engine and improve engine response when power demand is increased. This strategy could also improve transient emissions.

Electrical System and Control Development

At this state of development, we still have a number of significant issues to resolve. Much of them deal with applying high speed generator technology to this environment.

The practicality of the system will be determined, in part, by the additional cost and size. Applying this technology to an engine environment is a concern. Suppliers of high speed generators have experience at this level of speed, but not at the power output level needed. The high frequency of the generator output is also challenging. The added flexibility of the electric turbocompound system makes controlling and optimizing the system more complicated. Requiring one turbine to drive both the compressor and generator makes this a highly loaded turbine stage.

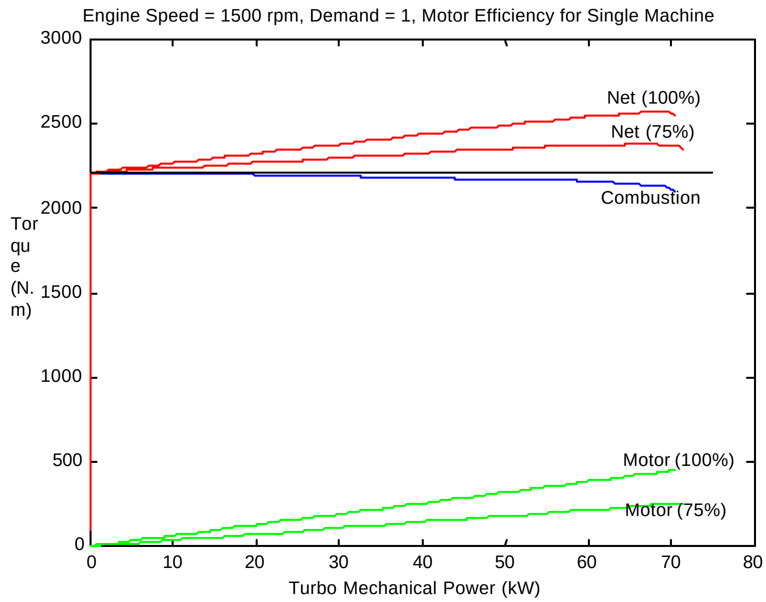
Now, let's take a look at the overall system. On the turbocharger we have a high speed generator producing electricity to a common voltage bus. The power can be applied to the motor on the engine crankshaft. Keep in mind that either of these electric machines can be operated in motoring or generating mode. Also, the turbine-generated power can be used to power attached electrical loads, i.e., MEI accessories, or applied to energy storage devices like batteries, ultra-capacitors, etc.

We also have an overall control system that interacts with the engine controller. We are controlling the amount of electrical power that is produced and consumed, subject to constraints in exhaust temperature, boost pressure, turbo speed, and the like.

To aid in performance prediction, system optimization and control development, a computer simulation model of the engine system was developed. Production engine test data were used to calibrate the model. Then maps of the electric turbocompound system were added to the model to simulate the electric turbocompounded engine. The simulation model was used to investigate control system strategies.

The engine simulation model was also used to predict the efficiency gains obtainable. The addition of turbocompounding increases exhaust backpressure on the engine. This results in a drop in engine performance. The turbocompounding adds additional power back to the engine, more than compensating for the backpressure loss. The simulation model has been used to predict efficiency gains a different engine operating points.

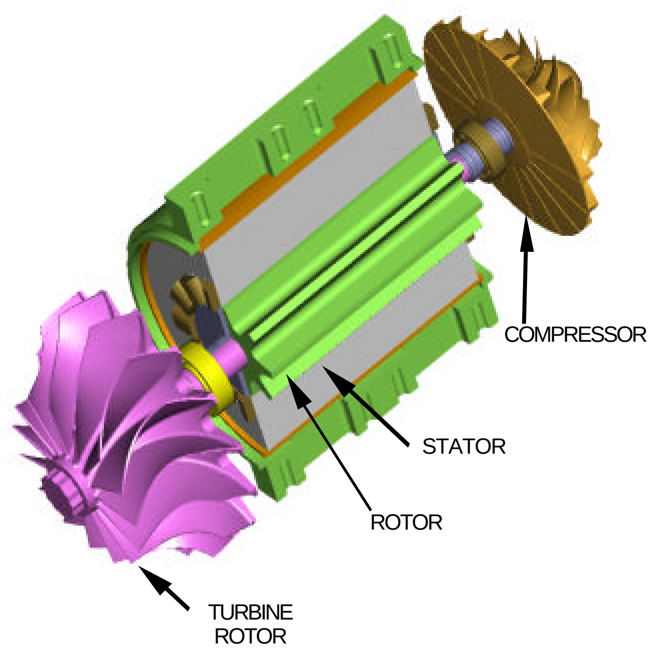
This plot illustrates the backpressure loss, and the turbocharger net gain possible at a particular engine operating point. It also shows the effect of efficiency of the motor/generators on the exhaust power recovered. Higher engine efficiency gains are possible with higher efficiency motor/generators, but gains are still possible with low efficiency components.



Air System Development

Turbocharger performance goals were similar to production requirements with the exception of efficiency. A high efficiency goal was set to get the maximum engine efficiency improvement over a wide range of operating conditions.

The turbocharger turbine will power both the compressor and the generator. A new turbine design is being developed to deliver the power level required at the needed efficiency.



The compressor used will be an existing design that Caterpillar has utilized in previous research engine developments. The compressor includes a vaned diffuser, and scrolled collector. The design will deliver the boost, map width and efficiency required for this application.

The current shaft design concept includes the generator rotor mounted between the turbine bearings. Rolling element bearings will be used to maximize efficiency and shaft dynamic stability. Preliminary shaft dynamics analysis indicates that meeting shaft dynamic requirements will be a challenge. As the turbo and generator rotor designs continue to be developed, shaft dynamics will be a major consideration.

Motor/Generator Development

Development of the high speed turbo motor/generator is underway. Candidate technologies are being evaluated before proceeding with design.

The crank starter motor/generator will utilize the design from the MEI truck program. An investigation is being made into the practicality of modifying the design so that the crank motor can absorb 100% of the power produced by the turbo generator.

Summary

Thus far in this program, the system architecture has been identified. A system model has been developed and validated which is being used to develop the control strategy. The requirements for the air handling system have been determined, and paths to development for the components have been established. The design of the high speed motor generator is underway, beginning with evaluation of available technologies. Performance predictions at important operating points have been made showing significant efficiency improvements over a non-turbocompounded engine.