Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

Department of Energy Contract
DE-SC05-00OR-99OR22734

Ulrich Hopmann
Caterpillar Inc.

2004 DEER Conference
August 30-Sept 2, 2004
San Diego, California
Agenda

• Program Objectives and Electric
  Turbocompound (ETC)
  System Background

• Update on Component Developments
  – Turbo-shaft generator and crankshaft motor
  – Air handling system
  – Control system
  – Component testing

• Cost/Value Study

• Next Steps and Summary
Diesel Electric Turbocompounding (ETC)

• **Primary Objectives:**
  – Demonstrate technical feasibility
  – Improve fuel economy

• **Program Goals and Milestones:**
  – Conceive and design optimum ETC system
  – Develop and bench test turbomachinery
  – Develop control system and strategy
  – Rig test ETC hardware
  – Lab engine test of ETC system
FEATURERES

- No mechanical coupling between turbo and crankshaft
- Flexibility in turbo operation
- Provides turbo-assist capabilities
- Predicted 5 to 10% reduction in fuel consumption

Working Principle

Inputs

Overall System Controller

1
2
3
4

Engine Control

Powertrain

Motor Generator

Engine

Power Electronics

Common Voltage Bus

Cooler

Exhaust Gases

Compressor

Generator Motor

Turbine

Electric Loads

Energy Storage

Available Turbine Power kW

Engine Power kW

Turbine Compressor Power kW

Surplus

FEATURES

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- Next Steps and Summary
Final Design

- Water Cooling
- Rotor/Stator
- Bearing Housing
- Turbine
- Compressor
### Final Design

<table>
<thead>
<tr>
<th>Turbo Shaft M/G</th>
<th>Turbocharger Structure</th>
<th>Aero Components</th>
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</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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<td><img src="image4.png" alt="Image" /></td>
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<td><img src="image6.png" alt="Image" /></td>
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- **Voltage:** 340 V
- **Power:** 40 kW / 60 kW
- **Rotor Length:** 70 mm
Turbo Shaft – Generator/Motor

Rotor

Stator

Windings

Dyno Testing
Crank Shaft - Motor/Generator

Flywheel Housing with Crank Shaft M/G

340 Vdc Crank Shaft M/G

Electronics
# Compressor and Turbine

## Compressor Scroll and Compressor Wheel with Diffuser

<table>
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<th>Design Point</th>
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<tr>
<td>- Pressure Ratio (t-s) 3.1</td>
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<tr>
<td>- Efficiency (t-s) 82%, max. 85%</td>
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</table>

## Turbine Scroll and Turbine Rotor with Nozzle

<table>
<thead>
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<th>Design Point</th>
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<tr>
<td>- Pressure Ratio (t-s) 3.7</td>
</tr>
<tr>
<td>- Efficiency (t-s) 84%, max. 85%</td>
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</tbody>
</table>
Turbo Shaft & Bearing Housing

Turbo Shaft w/ Ball Bearings

Rotor Assembly with Balancing Fixture
### Assembled ETC Turbocharger

<table>
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<tr>
<th>Turbine Housing</th>
<th>Housing for Motor/Generator</th>
<th>Compressor Volute</th>
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<tbody>
<tr>
<td>Proximity Probes</td>
<td>Speed Pick-Up</td>
<td>Electrical Power Take Off</td>
</tr>
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</table>
ETC Control System

- System Simulation in Simulink
- Controller Implemented in dSpace
- Virtual Instrumentation Capabilities

Map Boost / Speed / Load

Boost at Optimum Fuel Consumption

Set Point for Transient Behavior

Boost Pressure Feedback
Exhaust Manifold Temperature Feedback
Turbocharger Speed Feedback

ETC Controller - Power Electronics - Electric Machine - Engine

Compound Power at Turbo Shaft - kW
Fuel Consumption - %
Relative Boost - %

Caterpillar Engine Research
Diesel & Emissions Technology
Component Testing

- Turboshaft and crankshaft motor/generator (M/G) have been tested on separate test rigs
- Measured peak efficiency of crankshaft M/G at target level
- ETC turbocharger is being tested on gas stand
  - Rotor dynamics check
  - Compressor map
  - Turbine map
- Engine test planned for October 2004
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- Next Steps and Summary
Cost/Value Study

Value of ETC Technology

- 3 to 5% bsfc reduction
- No need for waste gate
- Enhanced braking power through
  - Higher boost
  - Regenerative braking with crank m/g
- Turbo assist capabilities
- Control A/F ratio (gas engines)
- Improved cold startability
- Altitude capability

Program is based on MY 2000 engine
System – Cost/Value: Example On-Highway Truck

- ETC system cost
  - System cost: $ 2000 to $ 3400
  - Powerelectronics account for half the cost

- Customer Benefit
  - Payback period between 13 (best case) and 38 months
Next Steps for ETC Development

- Complete test of ETC turbocharger in gas-stand lab-setting
- Complete engine testing with ETC system
- Assess ETC on low emission engine
  - Packaging
  - Aerodynamics
  - Cost effective design
  - Reliability/durability demonstration
Summary

- Turbocharger and ETC system have been designed and analyzed
- Performance predictions indicate 3 to 5% fuel economy improvement for cycle, 10% at key operating point
- Opportunity for reduced emissions and improved drivability
- E-Machine hardware testing completed
- Cost/value analysis shows high customer value