INTEGRATED TURBOGENERATION, ELECTRIFICATION AND SUPERCHARGING (ITES)
Integrated Turbogeneration, Electrification and Supercharging (ITES)

Agenda

- ITES System
  - Motivation
  - Technology Description
  - MD Application
  - HD Application

- Summary
Integrated Turbogeneration, Electrification and Supercharging (ITES)

Agenda

- ITES System
  - Motivation
  - Technology Description
  - MD Application
  - HD Application
- Summary
Increase engine efficiency, but at what cost? Affordability is the key…

Source: FEV

Integrated Turbogeneration, Electrification and Supercharging (ITES)

© by FEV – all rights reserved. Confidential – no passing on to third parties
FEV’s Integrated Turbogeneration, Electrification and Supercharging System (ITES) integrates technologies while minimizing cost and maximizing efficiency.

**Ideal Technology Package Components**

- Electric Motor
- Secondary Compressor
- Electric Motor Generator
- 48V Battery
- Power Electronics
- WHR Turbine (Turbocompound/ORC)
- Turbo Generator
- Fluid Coupling
- Geartrain

**FEV-ITES Approach**

- Electric Motor Generator
- 48V Battery
- Power Electronics
- WHR Turbine (Turbocompound/ORC)
- Geartrain
- Planetary Gear with Dog Clutch and Band Brake

Source: FEV, www.enginecompare.co.uk, Borg Warner, A123, Cummins, John Deere

Integrated Turbogeneration, Electrification and Supercharging (ITES)
Integrated Turbogeneration, Electrification and Supercharging (ITES) Agenda

- ITES System
  - Motivation
  - Technology Description
  - MD Application
  - HD Application
- Summary
The basic concept of ITES system is to integrate a secondary compressor, turbocompound or ORC turbine, motor-generator unit over a planetary gear set.

Source: FEV, Cummins, John Deere, Borg Warner
Integrated Turbogeneration, Electrification and Supercharging (ITES)
ITES system operated in 4 different modes in specific regions of the engine map to maximize engine efficiency gains with each technology.

Mode A
- Mechanical Turbocompounding
- ORC Turbine

Mode B
- Electric Turbocompounding
- ORC Turbine
- Mild Hybrid (Mode B)

Mode C
- Powersplit Turbocompounding
- ORC Turbine
- Supercharging
- Mild Hybrid

Mode D
- Integrated Turbogeneration
- Electrification and Supercharging (ITES)

Source: FEV, Cummins, John Deere, Borg Warner
How can we integrate the technologies that have a significant potential in increasing engine efficiency while addressing their integration challenges?

- Reduced friction and increased mechanical efficiency
- Ebooster power consumption
- Electric auxiliary, BSG, regen boost
- Power transfer limit of belt system
- Waste exhaust energy recuperation using turbocompound turbine
- Low turbine power output and parasitic losses at low loads with mechanical integration
- 48V P0 Mild Hybridization on MD and HD ~4.6%
- Waste heat recovery ~2-4%
- Potential ~10% Fuel Consumption Reduction

Source: FEV, www.enginecompare.co.uk, Borg Warner, Continental, CPT

Integrated Turbogeneration, Electrification and Supercharging (ITES)
ITES technology description video

Source: https://www.youtube.com/watch?v=exfKr94PgDI
Integrated Turbogeneration, Electrification and Supercharging (ITES)
Integrated Turbogeneration, Electrification and Supercharging (ITES)

Agenda

- ITES System
  - Motivation
  - Technology Description
  - MD Application
  - HD Application
- Summary
ITES system applied on medium heavy duty engine installed in a class 6-7 vocational application

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Engine</th>
<th>Downsized Engine with ITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement [L]</td>
<td>7.7</td>
<td>5.1</td>
</tr>
<tr>
<td>No of Cylinder [-]</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Bore [mm]</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Stroke [mm]</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>Compression Ratio [-]</td>
<td>17.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Peak Power [kW]</td>
<td>228@2200rpm</td>
<td>228@2200rpm</td>
</tr>
<tr>
<td>Power Density [kW/L]</td>
<td>29.6</td>
<td>44.7</td>
</tr>
<tr>
<td>Peak Torque [Nm]</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Air System [-]</td>
<td>Turbocharged with HP EGR</td>
<td>Turbocharged with HP EGR and ITES unit (15kW M/G, 20kW Turbine, 5kW Compressor)</td>
</tr>
<tr>
<td>Water Pump [-]</td>
<td>Driven by Engine</td>
<td>Electrically Driven</td>
</tr>
<tr>
<td>Start-stop, Regen, Torque Assist [-]</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dimensions [mm]</td>
<td>1272x862x987</td>
<td>1045x864x984</td>
</tr>
<tr>
<td>Engine Weight [kg]</td>
<td>650</td>
<td>575</td>
</tr>
<tr>
<td>System Cost (DMC) [$]</td>
<td>13,000</td>
<td>12,500-13,000</td>
</tr>
</tbody>
</table>

Source: FEV, Daimler

Integrated Turbogeneration, Electrification and Supercharging (ITES)
Baseline 7.7L fast running engine model developed in GT-POWER and validated against experimental data

### Component/Process Model

<table>
<thead>
<tr>
<th>Component/Process</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor and Turbine</td>
<td>Manufacturer Provided Performance Maps</td>
</tr>
<tr>
<td>EGR Cooler/Charge Air Cooler</td>
<td>Semi-predictive Effectiveness Model</td>
</tr>
<tr>
<td>In-cylinder Heat Transfer</td>
<td>Woschni GT</td>
</tr>
<tr>
<td>Friction</td>
<td>Chen Flynn</td>
</tr>
<tr>
<td>Cylinder Filling/Air path/Exhaust path</td>
<td>Navier-Stokes</td>
</tr>
<tr>
<td>Combustion/Fuel Injection</td>
<td>DI Pulse (GT Manual)</td>
</tr>
<tr>
<td>NOx Emission</td>
<td>Zeldovich</td>
</tr>
<tr>
<td>Aftertreatment</td>
<td>Quasi-Steady Solver (GT Manual)</td>
</tr>
<tr>
<td>EGR, Lambda, Fueling Control</td>
<td>Model Based / PID</td>
</tr>
</tbody>
</table>

Source: FEV (SAE 2018-01-0887, ASME_ICEF2018-9703)

Integrated Turbogeneration, Electrification and Supercharging (ITES)
GT model for 5.1L downsized engine with ITES system developed from 7.7L baseline model

Source: FEV (SAE 2018-01-0887)

Integrated Turbogeneration, Electrification and Supercharging (ITES)
The ITES system enabled an average of 8% reduction in engine fuel consumption on the downsized engine in comparison to the baseline engine.
Baseline 6 cylinder engine downsized to 4 cylinder engine and integrated independently with E-booster, Mechanical Turbocompounding and BSG for comparison with ITES

Source: FEV (SAE 2018-01-0887)

Integrated Turbogeneration, Electrification and Supercharging (ITES)
In comparison to independent integration approach, ITES provides higher efficiency improvement along with the advantage of lower cost and package size.

Source: FEV (SAE 2018-01-0887), Borg Warner, CPT, www.enginecompare.co.uk

Integrated Turbogeneration, Electrification and Supercharging (ITES)
ITES system analyzed on engine test cycles for on-highway and off-highway MD application

OFF-HIGHWAY

Source: FEV
Up to 13% reduction in cycle averaged engine fuel consumption on engine test cycle for MD application

### On Highway

<table>
<thead>
<tr>
<th>Cycle Averaged BSFC [g/kWh]</th>
<th>Baseline</th>
<th>Down sized with ITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSFC Reduction as compared to Baseline [%]</td>
<td>13</td>
<td>12</td>
</tr>
</tbody>
</table>

### Off Highway

<table>
<thead>
<tr>
<th>Cycle Averaged BSFC [g/kWh]</th>
<th>Baseline</th>
<th>Down sized with ITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSFC Reduction as compared to Baseline [%]</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

Source: FEV, Daimler, John Deere

Integrated Turbogeneration, Electrification and Supercharging (ITES)
ITES system can enable 11% increase in vehicle fuel economy of class 6-7 vocational truck on ARB transient cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Mass [lb]</td>
<td>12151</td>
</tr>
<tr>
<td>Passenger Cargo Mass [lb]</td>
<td>20000</td>
</tr>
<tr>
<td>Final Drive Ratio [-]</td>
<td>4.8</td>
</tr>
<tr>
<td>Tire Rating [-]</td>
<td>11R22.5</td>
</tr>
<tr>
<td>Axle Configuration [-]</td>
<td>4x2</td>
</tr>
<tr>
<td>Transmission Type [-]</td>
<td>Allison 2100 6-speed</td>
</tr>
<tr>
<td>Tire Rolling Resistance [kg/t]</td>
<td>6.2</td>
</tr>
<tr>
<td>Aerodynamic Drag Coefficient [-]</td>
<td>0.65</td>
</tr>
<tr>
<td>Vehicle Frontal Area [m²]</td>
<td>4.2</td>
</tr>
<tr>
<td>Tire Rolling Radius [m]</td>
<td>0.512</td>
</tr>
</tbody>
</table>

$4,500 Fuel Cost Savings / 100,000 miles

Source: FEV (ASME_ICEF2018-9703), Daimler

Integrated Turbogeneration, Electrification and Supercharging (ITES)
Integrated Turbogeneration, Electrification and Supercharging (ITES)

Agenda

- ITES System
  - Motivation
  - Technology Description
  - MD Application
  - HD Application

- Summary
ITES system implemented on a HD engine with ORC turbine expander for class 8 tractor application

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Engine</th>
<th>Powerdense Engine with ITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement [L]</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>No of Cylinder [-]</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Bore [mm]</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Stroke [mm]</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>Compression Ratio [-]</td>
<td>17.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Peak Power [kW]</td>
<td>322@1700rpm</td>
<td>403@1700rpm</td>
</tr>
<tr>
<td>Power Density [kW/L]</td>
<td>30.1</td>
<td>37.7</td>
</tr>
<tr>
<td>Peak Torque [Nm]</td>
<td>2000@1100rpm</td>
<td>2500@1100rpm</td>
</tr>
<tr>
<td>Air System [-]</td>
<td>Single Stage VGT with HP EGR</td>
<td>Single Stage VGT with HP EGR and ITES unit (15kW M/G, 5kW Compressor)</td>
</tr>
<tr>
<td>ORC System</td>
<td>No</td>
<td>Yes (Ethanol Based with 20kW Turbine Expander)</td>
</tr>
</tbody>
</table>

Source: FEV, Cummins, International

Integrated Turbogeneration, Electrification and Supercharging (ITES)
Baseline 10.7L engine GT model validated against experimental data

Source: FEV, Cummins, International
Integrated Turbogeneration, Electrification and Supercharging (ITES)
Ethanol Based ORC system modeled in GT and model predictions compared with published literature

Source: FEV, (SAE 2019-01-0229)

Integrated Turbogeneration, Electrification and Supercharging (ITES)

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>Positive Displacement</td>
<td>Displacement: 5cm³, Isentropic Efficiency: 70%</td>
</tr>
<tr>
<td>Expander</td>
<td>Two-Stage Turbine Expander</td>
<td>Max Pressure Ratio: 25, Max Isentropic Efficiency: 77%, Max. Operating Speed: 70,000 rpm</td>
</tr>
<tr>
<td>EGR Evaporator</td>
<td>Shell-Tube Counter-flow</td>
<td>Effectiveness at Peak Power: 0.79</td>
</tr>
<tr>
<td>Exhaust Evaporator</td>
<td>Shell-Tube Counter-flow</td>
<td>Effectiveness at Peak Power: 0.77</td>
</tr>
<tr>
<td>Condenser</td>
<td>Plate and Frame Counter-flow</td>
<td>Fluid: Ethanol, Effectiveness at Peak Power: 0.96, Coolant Temperature: 40°C</td>
</tr>
</tbody>
</table>
ITES system enabled powerdense engine with ORC system to achieve an average of 5% reduction in BSFC on the engine map in comparison to baseline engine.
Up to 1% increase in engine efficiency observed with the ITES system in comparison to independent integration of ORC system, E-booster and mild hybridization.

Source: FEV, Cummins
Integrated Turbogeneration, Electrification and Supercharging (ITES)
Integrated Turbogeneration, Electrification and Supercharging (ITES)

Agenda

- ITES System
  - Motivation
  - Technology Description
  - MD Application
  - HD Application

- Summary
Integrated Turbogeneration, Electrification and Supercharging (ITES)

Summary

- ITES system provides a lower cost, smaller package and higher efficiency approach to integration of turbogeneration, low voltage electrification and supercharging

- MD Application
  - 8% average BSFC reduction in steady-state engine operation
  - Up to 5% improvement over independent integration of technologies in steady state operation
  - 12% and 13% BSFC reduction on WHTC and FTP cycle respectively
  - 8% and 10% BSFC reduction on off-highway tillage and front loader application cycles
  - 11% increase in fuel economy for a class 6-7 vocational truck on ARB transient cycle

- HD Application
  - 5% average BSFC reduction in steady state engine operation
  - Up to 1% improvement over independent integration of technologies in steady state operation

Source: FEV

Integrated Turbogeneration, Electrification and Supercharging (ITES)
Thank you,
Questions?

Satyum Joshi
Senior Engineer
Commercial Engines
joshi_s@fev.com
FEV North America, Inc.

Source: FEV
Integrated Turbogeneration, Electrification and Supercharging (ITES)