Application of the SuperGen Electro-Mechanical Supercharger to Miller-Cycle Gasoline Turbocharged Engines

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Overview

• Program Goal & Technology Introduction

• Engine Configuration

• Modelling Technique

• Simulation Study

• Conclusion
IPTT is a joint venture company formed by Integral Powertrain Ltd. and Magna International in September 2014 to Develop and Produce the SUPERGEN Technologies.
IPTT Business

Based in Milton Keynes UK

45 Design & Development Staff

Prototype Build Facility

6 Dedicated Test Rigs

Vehicle & Subsystem Workshops

Calibration and Controls Lab

€30M invested in Product Development, Facilities and People to make SUPERGEN production ready using Magna’s proven Tier 1 Development Processes
Complex Powertrain Challenges

**CO2 Compliance – Europe & China**
- All Manufacturers must improve CO2 by @25% over 5 Years to avoid punitive fines
- Reducing Diesel Penetration In Europe
- RWDE impact on legislation
- California Particulate Phase In = Diesel Ban
- Long Term Impact Of Dieselgate
- USA CAFÉ Compliance
  - 25% reduction in fuel consumption by 2025

**Emissions Compliance**
- RWDC Europe
- Euro 6B China
- Off Cycle Compliance
- Local Government Air Quality Legislation

**Powertrain Solutions**
- Electrification
- Downspeeding
- Downsizing
- New Generation of Advanced Gasoline Engines

**Each Manufacturer will adopt their own Bespoke Solutions**
**SUPERGEN Products can Maximize the Customer Benefit of these Solutions**
Program Goals

• Next-Generation Advanced Gasoline Engines will employ:
  – Further Downsizing – Advanced Boosting
  – Enhanced Air Control – Air-led Combustion
  – Higher Compression Ratio – New Combustion Strategies
  – Advanced Valve Train Control – New modalities

• To provide “Diesel-like” Fuel Efficiency
  – <210g/kW.hr minimum BSFC
  – Much flatter BSFC to support downspeeding

• Driving Style Insensitive
  – Real-world driving fuel economy and robust emissions

• Controllable Boost-on-Demand provided by SuperGen will become essential for these engines
12V/48V pulley-driven continuously variable electro-mechanical (e-CVT) device that delivers:
- Electro-Mechanical Supercharger
- 6-14kW High Efficiency Generation
- Belt integrated Starter / Generator

...in one unit

Key Technologies
- Fully Integrated PMSM Motor, Inverter and Controller, no separate boxes
- High Power Density Inverter for 12V and 48V Applications with common platform
- ‘Near-silent’ high efficiency Power-Split roller traction transmission up to 160k RPM enabling variable-speed high power supercharging
SuperGen Functionality

Low Speed Boost
- E1 Powers E2 & Boardnet
- E2 Powers TD Carrier
- Traction Drive combined mechanical and E2 power to Compressor
- Mechanical power to TD Annulus

High Speed Boost
- E1 Powers E2 & Boardnet
- E2 Powers TD Carrier
- Traction Drive combined mechanical and E2 power to Compressor

Belt Power
- E1 power to Boardnet
- Compressor Idling

Energy Storage
- Boardnet
- Cranking / Torque-Assist
Super-Turbo Miller MHEV Demonstrator Vehicle
Jaguar F-Pace 2.0L 250hp
### Target Gasoline Miller-Cycle Engine

#### Key Specifications:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Max Power</td>
<td>300PS @5500 RPM</td>
</tr>
<tr>
<td>Max Torque</td>
<td>400Nm</td>
</tr>
<tr>
<td>Number of Cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Engine Displacement</td>
<td>1998 cm³</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>9.5 / 12.5</td>
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<tr>
<td>Injection</td>
<td>DI</td>
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<tr>
<td>Boosting System</td>
<td>FGT SuperGen + FGT (Super-Turbo)</td>
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<tr>
<td>Max. Valve Lift and Duration</td>
<td>10mm/ 232 CA Degree</td>
</tr>
<tr>
<td></td>
<td>10mm / 272 CA Degree</td>
</tr>
<tr>
<td>Fuel Used in Simulation</td>
<td>95 RON</td>
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</tbody>
</table>

#### Graph:

- Torque Nm
- Power HP

#### Diagram:

- Engine components, including intake and exhaust manifolds, injectors, boost control, and valve timing.
SuperGen Modelling in Simulink / GT

- Simulink model is created to reflect dynamic behaviour of SuperGen.
- Model runs slowly due to detailed physical SuperGen model with control system software.
Static model is created in GT-SUITE environment to run faster simulations to evaluate SuperGen performance coupled with DI T/C engine. The model doesn't capture the dynamic behaviour since it's based on e-machine efficiency maps.

Model runs much more faster than detailed physical SuperGen model with control system software.

Model has been correlated with dynamic model for 40 engine operating points.
Correlation Basis / Testing Summary

• Test Engine

• Technical Aspects – Reflected Next Generation Base Engine Goals
  – Increased Compression Ratio
  – Reduced Number Of Cylinders
  – Reduced Pumping Work
  – Reduced Friction
  – Focus on ensuring Low Speed Performance & Drivability (Downspeeding)

• Key Results
SuperGen improves fuel economy in low speed due to elimination of Overlap. Fuel economy is improved in mid speed and high speed region due to millerisation which drives lower PMEP even increased CA50.
Simulation Results - Wide Open Throttle

Miller Engine needs more boost pressure due to decreased volumetric efficiency. SuperGen is needed to supply >4kW continuous power.
Simulation Results – Partial Load 1500 RPM

1. Conventional CR and Intake Cam Duration
   - CR=10, 235degCA Intake Cam (Engine1 T/C Otto Short-Cam)
     - Standard WG Turbocharger
     - >16Bar BMEP, scavenge required to achieve BMEP.
     - Significant scavenging → in-cylinder λ<1, increased BSFC.
   - CR=10, 235degCA Intake Cam (Engine1 Otto Super-Turbo Short-Cam)
     - Standard WG Turbocharger + SuperGen, w/o scavenging
     - BSFC improvement due to eliminated scavenging and improved combustion phasing (more advanced).

2. High-CR Miller and Moderate Intake Cam Duration
   - CR=12.5, 250degCA Intake Cam (Engine2 T/C Miller Mid-Cam)
     - Standard WG Turbocharger
     - >13Bar BMEP, scavenge required to achieve BMEP.
     - Significant scavenging → sharp increase in BSFC due to in-cylinder λ<1.
   - CR=12.5, 250degCA Intake Cam (Engine2 Miller Super-Turbo Mid-Cam)
     - Standard WG Turbocharger + SuperGen, w/o scavenging
     - BSFC improvement due to eliminated scavenging and improved combustion phasing (more advanced)
     - Eliminating scavenging has some impact on combustion phasing i.e. increased EOC temperatures. Max. BMEP point is limited by CA50 limit with this 250deg duration intake camshaft.

3. High-CR Miller and Long Intake Cam Duration
   - CR=12.5, 270degCA Intake Cam (Engine 3 T/C Miller Long-Cam)
     - Standard WG Turbocharger
     - >11.5 Bar BMEP, scavenge required to achieve higher BMEP.
     - Significant scavenging → sharp increase in BSFC due to in-cylinder λ<1.
   - CR=12.5, 270degCA Intake Cam (Engine 3 Miller Super-Turbo Long-Cam)
     - Standard WG Turbocharger + SuperGen, w/o scavenging
     - BSFC improvement due to eliminated scavenging and improved combustion phasing (more advanced).
Remark: Wider and efficient compressor map can make a positive impact on BSFC results.
Simulation Study - Effect of CAC Outlet Temperature

Engine Speed: 1500 RPM
Engine BMEP: 25 Bar

Lower BSFC is achieved by using inter stage charge air cooler with same CAC outlet temperature. Increased CAC outlet temperature drives combustion phasing which leads to higher BSFC.
Simulation Study - Low Pressure EGR

EGR reduces pumping loss and heat transfer in cylinder. Up to 20% external EGR at 1500RPM and 25Bar BMEP can be achieved by SuperGen with 1.5PR / >4kW continuous power.
SuperGen improves response of the engine dramatically which is 85% improvement in terms of transient response. Maximum SuperGen compressor power reaches 7.5 kW with less than 2 kW battery power requirement at maximum compressor power.
• SuperGen improves the 2.0L DI Turbocharged Otto engine efficiency via:
  – Increased specific output with excellent drivability at all conditions
  – Increased LIVC exploitation (deep miller engine, high compression ratio)
  – Increased BMEP at LET significantly with improved BSFC (flatter BSFC map at high load)
  – Decreased pumping losses (increased $P_2 - P_3$)
  – High EGR flow rates even to higher BMEP (combustion stability is vital)
  – Continuous >4kW boosting power can achievable via SuperGen – no robustness issues due to battery, thermal or electromagnetic derating

• Boosting system, knock and heat transfer modelling is clearly critical for Super-Turbo Miller. Using GT-SUITE / Simulink coupling capability permitted deep evaluation of the total system and SuperGen accurately.

• Hardware cost is eliminated for early assessment stages of different technologies and a deeper theoretical understanding ensured.
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