The Application of the SuperGen Electromechanical Centrifugal Supercharger to the Ultraboost Extreme Downsizing Engine

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Overview of Presentation

Reprise the Ultraboost Project

Project Targets and Final Status
Future Potential of Downsizing

The SuperGen Variable-Speed Centrifugal Supercharger

System Overview and Sub-Systems
Modes of Operation and Principle of Power-Split Functionality

Test Results

Steady-state full-load performance
Transient performance
Part-load fuel economy

Conclusions
Reprise of the Ultraboost Project
The Ultraboost Project

• The ‘Ultraboost’ project aimed to create a highly-boosted, heavily-downsized engine to provide the torque curve and power output of the naturally-aspirated Jaguar Land Rover AJ133 5.0 litre V8 engine
  > It was funded by the UK Technology Strategy Board as part of its Low-Carbon Vehicles Programme

• Dyno-based multi-cylinder engine operation formed the core of the project, with modelling used to demonstrate ~35% reduction in CO₂
  > In a Land Rover product – 2013 MY Range Rover
  > 23% of this had to come from the engine alone
  > Operation on 95 RON pump gasoline was required

• Prior JLR studies indicated a 2.0 l engine would be required to achieve the fuel economy target

• Thus operation at very high BMEPs would be necessary
Project Target –
Power Curve for JLR AJ133 NA V8

283 kW / 380 bhp at 6500 rpm
515 Nm at 3500 rpm
32.4 bar

400 Nm at 1000 rpm
25.1 bar

415 Nm at 6500 rpm
26.1 bar

Very high requirements on combustion and charging systems
The Ultraboost charging system comprised a Honeywell GT30 turbocharger (LP) and an Eaton R410 supercharger (HP).

Charge coolers were provided both between the stages and after the supercharger.

A bypass was provided for the R410, which had to be clutched out above 3000 rpm.

The system could not deliver target steady-state torque below 1500 rpm.

To provide high system effectiveness at all times.
UB200 Full-Load Performance

Exceeding the torque target above 1500 rpm proved straightforward

Peak torque and power targets were met

The only project miss was in terms of low-speed torque <1500 rpm
Ultraboost Project Conclusions

- The Ultraboost engine in its original form met its targets in terms of maximum power and torque, and achieved most of the full-load target torque line
  > The modelling conducted for the project showed that vehicle FE and CO₂ targets could be met when friction was accounted for
- The only significant miss was steady-state torque below 1500 rpm
  > With facilitated charging, this had been easily achieved, even after taking supercharger drive torque into account
- As a consequence of the overall performance, the limit to downsizing has still not been found
  > But driveability and low-speed boosting capability needs to be addressed
  > This was the rationale for testing SuperGen on the engine
Downsizing Limits

Data from McAllister and Buckley, 2009

Moving to DF = 70% gives another 6%

If it can be achieved: will depend on driveability and low-speed torque improvement

Supercharged

Turbocharged

-Poly. (Supercharged)

Poly. (Turbocharged)
The SuperGen Variable-Speed Centrifugal Supercharger
SuperGen Overview

- SuperGen is an integrated starter-generator with hybridisation and supercharging functionality
  - Provides mild hybrid features including stop-start, recuperation and torque-assist functions
  - Instead of one large ISG motor, uses two smaller e-machines which operate together in hybrid modes and independently for boosting functions
  - Integrates a power-splitting traction drive transmission with the two electric machines to provide a fully-variable, fast-response and efficient electro-mechanical transmission system
  - Compressor speed completely decoupled from the crankshaft, >140:1 ratio at 1000rpm engine speed
  - Conventional compressor technology based on turbocharger practice, compatible with EGR and multi-stage operation
SuperGen Sub-Systems

- E1 is connected to the **input** and drives the **annulus** of the traction drive
- E2 is connected to the **planet carrier** of the traction drive
- Compressor **input** shaft is connected to the **sun wheel**
- Therefore the **speed of E2 modifies the speed of the compressor**
- **E1 and E2 can be clutched together** for stop-start, mild hybridization
- **System replaces the alternator** and is **voltage agnostic**
Modes of Operation

• **Fixed Carrier, Moving Annulus** – *i.e. 100% Mechanical*
  > E2 locked, *i.e.* planet carrier at 0 rpm

• **Moving Carrier, Fixed Annulus** – *i.e. 100% Electrical*
  > Annulus stopped, planet carrier rotates at E2 speed

• **Combined Motion**
  > Total annulus and planet carrier speeds effect on sun wheel speed is additive
SuperGen Components

SuperGen Assembly
1. FEAD pulley, 2.5-3.5:1 ratio
2. Electrical machine, E1
3. Electrical machine stator(s)
4. Epicyclic traction drive, ~10:1 ratio
5. Electrical machine, E2
6. Bearing system
7. Radial flow compressor
8. Compressor Diffuser
9. Cooling jacket (Charge-cooler circuit)
10. Integrated 14V MOSFET inverters

11. Input shaft, connected to pulley & E1
12. Annulus
13. Planet
14. Planet Bearing
15. Planet carrier, connected to E2
16. Sun-shaft, connected to compressor
17. Compressor
SuperGen Operating Functions

• Traction drive planetary transmission – roller bearing technology **without gear teeth**
  > Planetary ratio, Annulus/Sun, \( R_0 \sim -10:1 \)
  > Belt ratio \( R_1 \sim 3 \)

• System is independent of the vehicle battery (self-sustaining) - capable of continuous operation and provides vehicle alternator function
  > Steady-state boost is unaffected by a depleted battery
  > Not dependent on any particular system voltage
  > System capable of up to 15 kW boost at 12 V

• Mild hybridization
  > Smooth Stop-Start for I-4 gasoline and diesel
  > Brake energy recuperation between 4 and 10 kW depending on version
  > Torque assist, anti-stall and other functions

• **Jaguar Land Rover has funded several R&D projects to show the concept’s viability**
Power-Split Functionality

- Input power is split between the mechanical and electrical paths
  > Higher boost performance and self-sustaining for less system cost
  > Transmission is more electrical at low speeds, tending to 100% mechanical at higher speeds

- Overall isentropic efficiency (incl. compressor losses) around 50% at low speeds rising to 70% at high speeds
Test Results
Full Load, Steady State

1000 rpm torque now 358 Nm v 283 Nm for R410 (+26.5%)  

Full-load target now met from 1250 rpm  

Same valve timing  

Preliminary valve timing optimization gave 337 g/kWh at 1000 rpm and 263 g/kWh at 1500 rpm  

- AJ133 Torque  
- SG matching AJ133 Torque  
- UB200 Torque  
- UB200 BSFC
Full Load, Steady State – Matched

At 1500 and 1250 rpm, both matched to have the same full-load performance (440 Nm)

BSFCs now similar at matched torque output
The Nature of the Problem...

At 3000 rpm, the target full-load performance is 495 Nm

At 2500 rpm, the target full-load performance is 478 Nm

At 2000 rpm, the target full-load performance is 460 Nm

Turbo-only runs at constant speed
Transient Performance Tests

• Transient response is reported over 10-90% Time-To-Torque (10-90TTT)
  > Using the same valve timing and injection settings for both the UB200 Eaton build and for SuperGen
  > As per steady-state full-load data

• Note that the Eaton was not clutched out

• Further optimization of the SuperGen response could be achieved by changing the ‘flag to run’ point
  > Also, this SuperGen was sized for a 300 bhp application, unlike the Eaton

• Two sets of data are reported for SuperGen: 10 and 90% torque set by
  (1) its own absolute capability (‘SuperGen matching AJ133 torque’) and
  (2) by that of the Eaton (‘matching UB200’)
1000 rpm Torque Response

SuperGen matching AJ133 torque
SuperGen matching UB200 torque
UB200

10-90% Time-to-Torque (s)
UB200/Eaton Baseline 2.52
SuperGen matching AJ133 torque 2.11
SuperGen matching UB200 torque 0.80

68% reduction in matched 10-90% TTT
1000 rpm MAP Response

- Turbocharger dynamics
- HP stage response

MAP / [mbar]

Time / [s]

SuperGen matching UB200 torque
SuperGen matching AJ133 torque
UB200
Addressing the Problem...

**2500 rpm runs with and without SuperGen**

With SuperGen, 10-90TTT is <1.2 s

At 2500 rpm, the target full-load performance is 478 Nm

- 2500 rpm Turbo Only
- 2500 rpm Turbo plus SuperGen
## Part-Load Fuel Economy

- Four part-load minimap points were investigated
  > Corresponding to those in the main Ultraboost programme which require the supercharger to be operated
- All electrical loads are accounted for: **no net electrical input**

<table>
<thead>
<tr>
<th>Ultra-boost minimap point number</th>
<th>Engine speed (rpm)</th>
<th>Brake Torque (Nm)</th>
<th>Eaton R410 BSFC (g/kWh)</th>
<th>Super-Gen BSFC (g/kWh)</th>
<th>Change: Super-Gen v Eaton R410 (%)</th>
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<tbody>
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<td>4</td>
<td>1500</td>
<td>200</td>
<td>251.5</td>
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<td>1500</td>
<td>300</td>
<td>261.7</td>
<td>250.5</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

**SuperGen derives a benefit from no requirement to bypass it and its centrifugal compressor efficiency**

**Vehicle modelling is underway and will be reported in a later publication**
Conclusions
Conclusions

- The SuperGen electromechanical centrifugal supercharger was tested on the Ultraboost extreme downsizing demonstrator engine as the high-pressure stage
  - *The low-pressure turbocharger and chargecooler system were unchanged*
- Results for full-load performance, transient response and part-load fuel consumption all showed improvements over the Roots-type supercharger that the engine had been developed with
  - *Torque at 1000 rpm was increased by 75 Nm (+26.5%)*
  - *Transient response at low speed now approaches naturally-aspirated levels*
  - *Part-load fuel consumption was improved by up to 4.3%*
- SuperGen can also provide stop-start mild hybrid and mild-hybrid capabilities, even at 12 volts
- The ability to improve low-speed torque and transient response may enable downsizing to be taken beyond 60%, with further significant fuel economy potential
THANK YOU FOR LISTENING