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

Dr J.W.G. Turner, D. Marshall, Dr R. Patel,
A. Popplewell and S. Richardson
*Powertrain Research and Technology*
*Jaguar Land Rover, UK*

L. Barker and J. Martin
*Integral Powertrain Limited, UK*

A.J.G. Lewis, Dr S. Akehurst, Prof. C.J. Brace
and Dr C.D. Copeland
*Powertrain and Vehicle Research Centre*
*University of Bath, UK*

# 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*

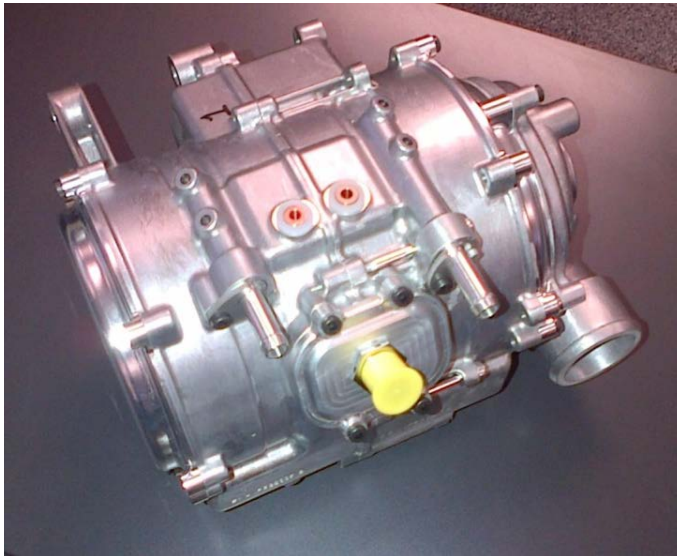
## *Test Results*

### *Steady-state full-load performance*

### *Transient performance*

### *Part-load fuel economy*

## *Conclusions*

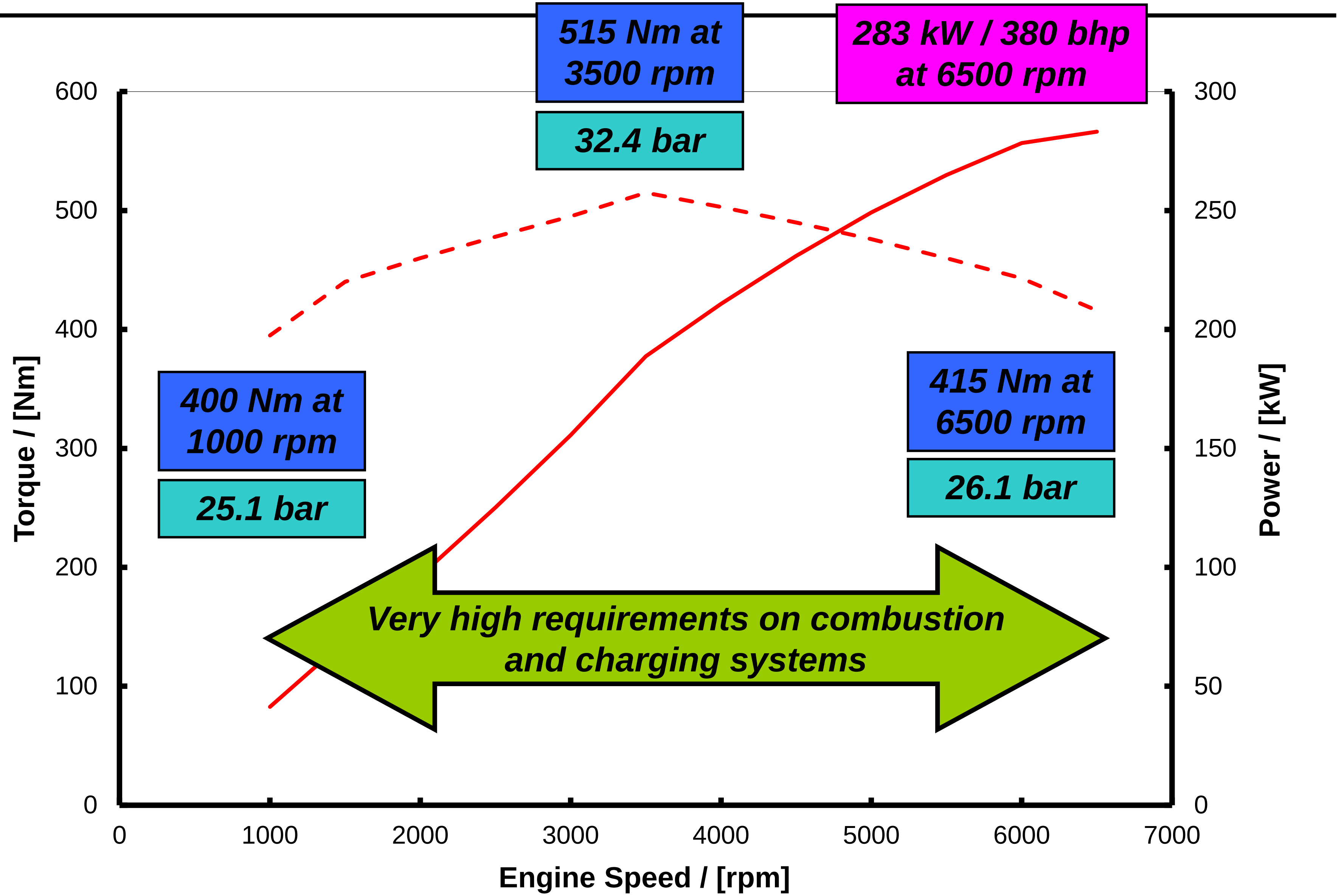


# Reprise of the Ultraboost Project

# The Ultraboost Project

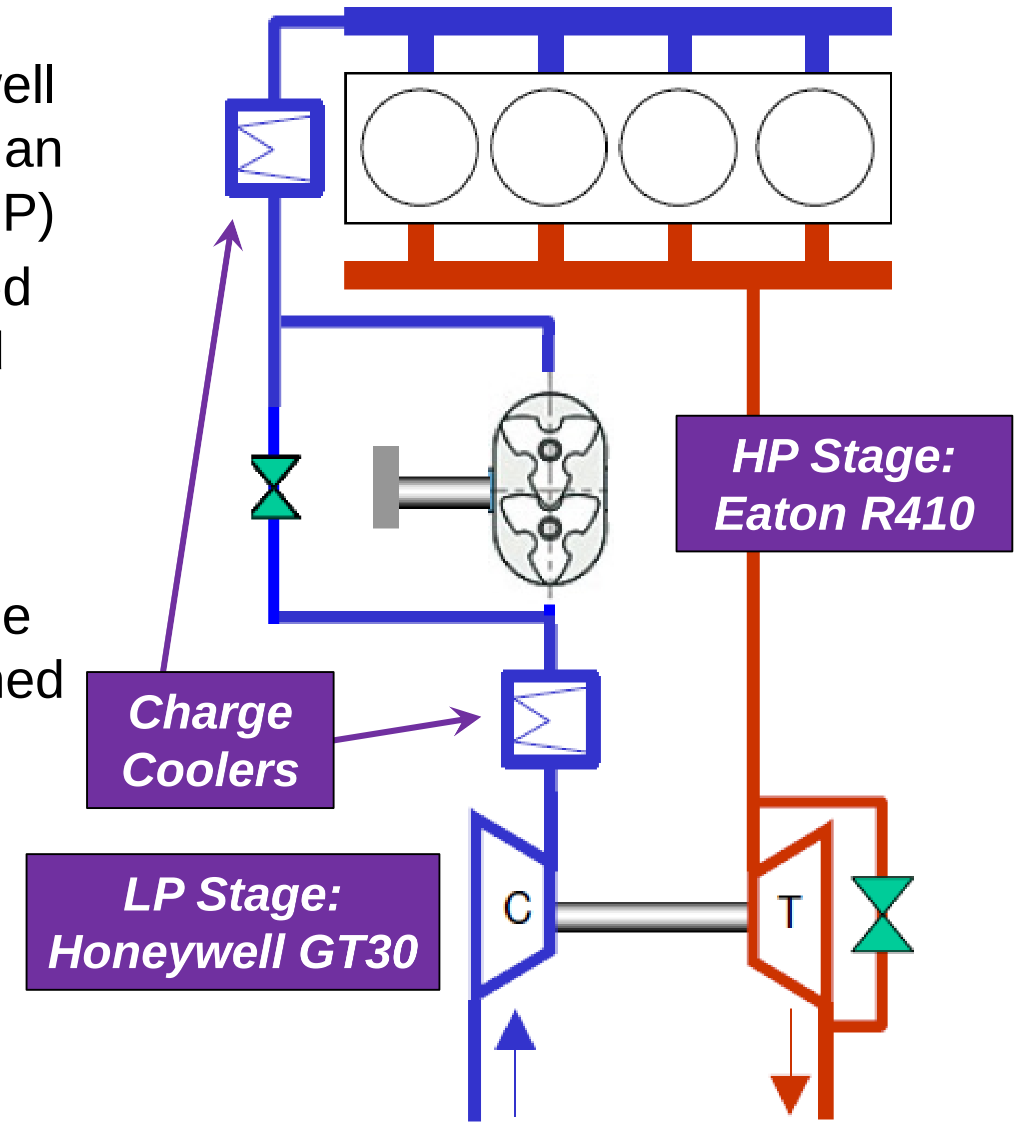
- The ‘Ultraboost’ project aimed to create a highly-boosted, heavily-downsized engine to provide the torque curve and power output of the naturally-aspirated Jaguar Land Rover AJ133 5.0 litre V8 engine
  - > *It was funded by the UK Technology Strategy Board as part of its Low-Carbon Vehicles Programme*
- Dyno-based multi-cylinder engine operation formed the core of the project, with modelling used to demonstrate ~35% reduction in $CO_2$
  - > *In a Land Rover product – 2013 MY Range Rover*
  - > *<u>23% of this had to come from the engine alone</u>*
  - > *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

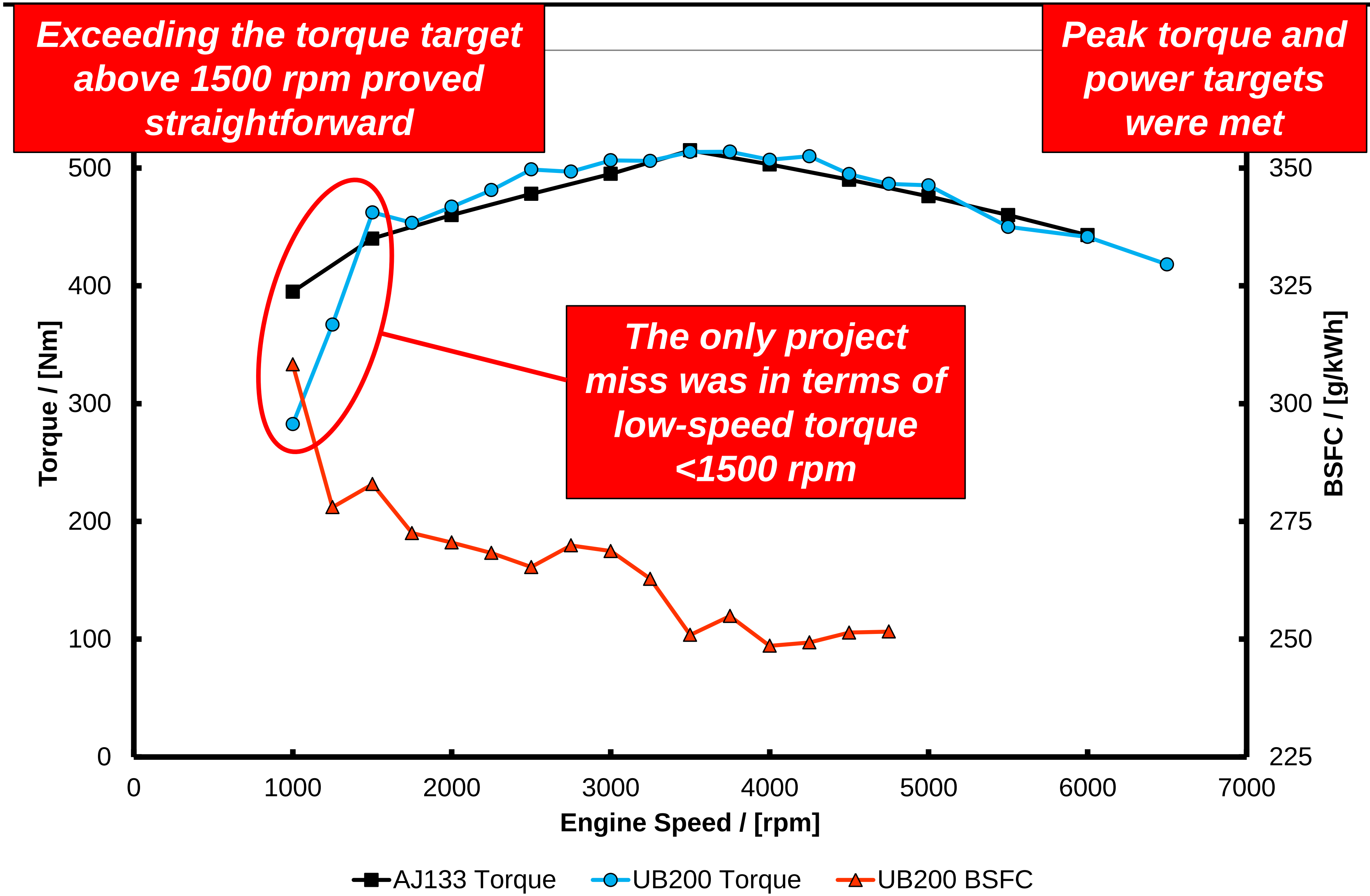


# Ultraboost Charging System

- 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
  - > *To provide high system effectiveness at all times*
- A bypass was provided for the R410, which had to be clutched out above 3000 rpm
- The system <u>could not deliver target steady-state torque below 1500 rpm</u>



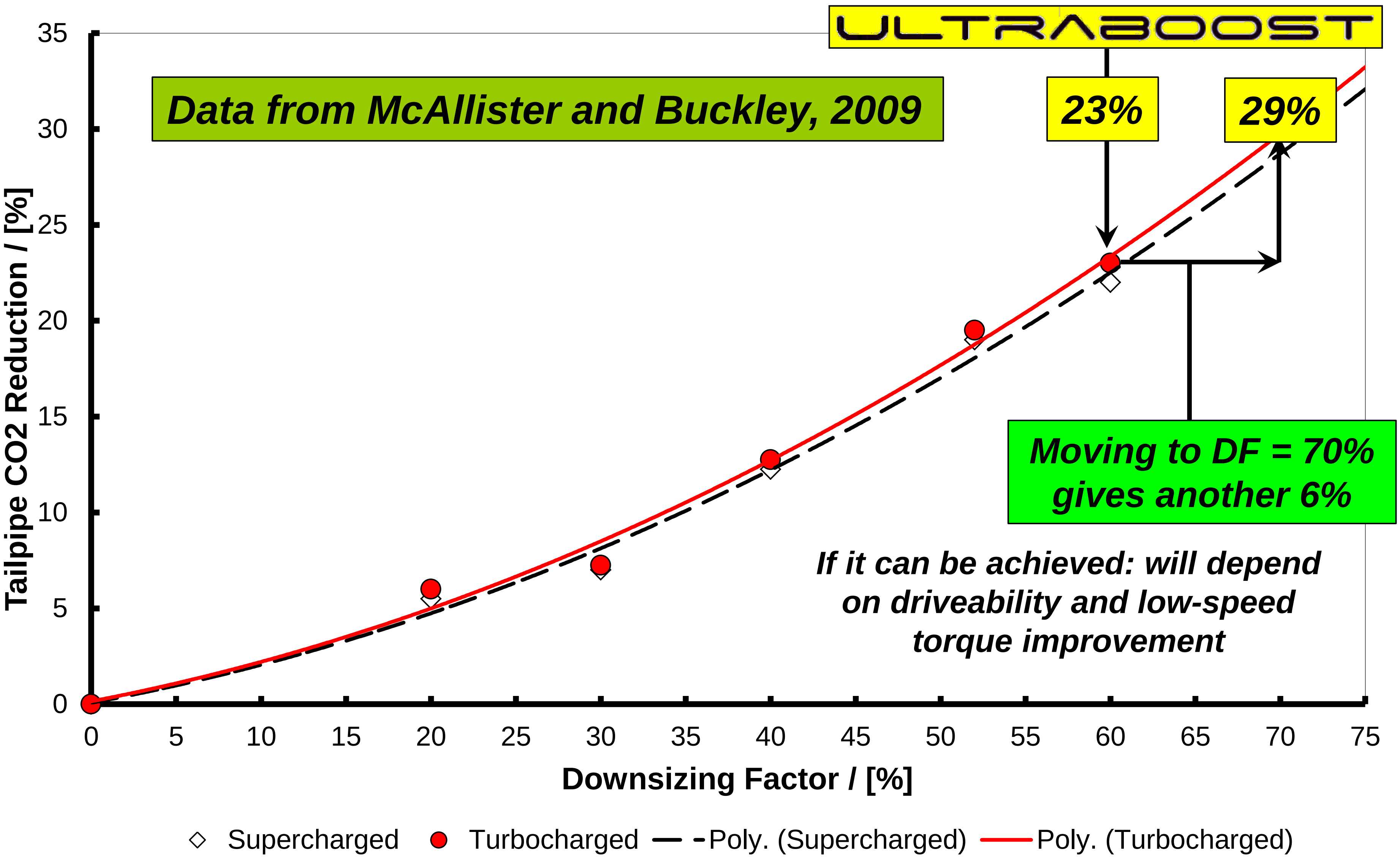
# UB200 Full-Load Performance



# 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 $CO_2$ 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, <u>even after taking supercharger drive torque into account</u>*
- 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



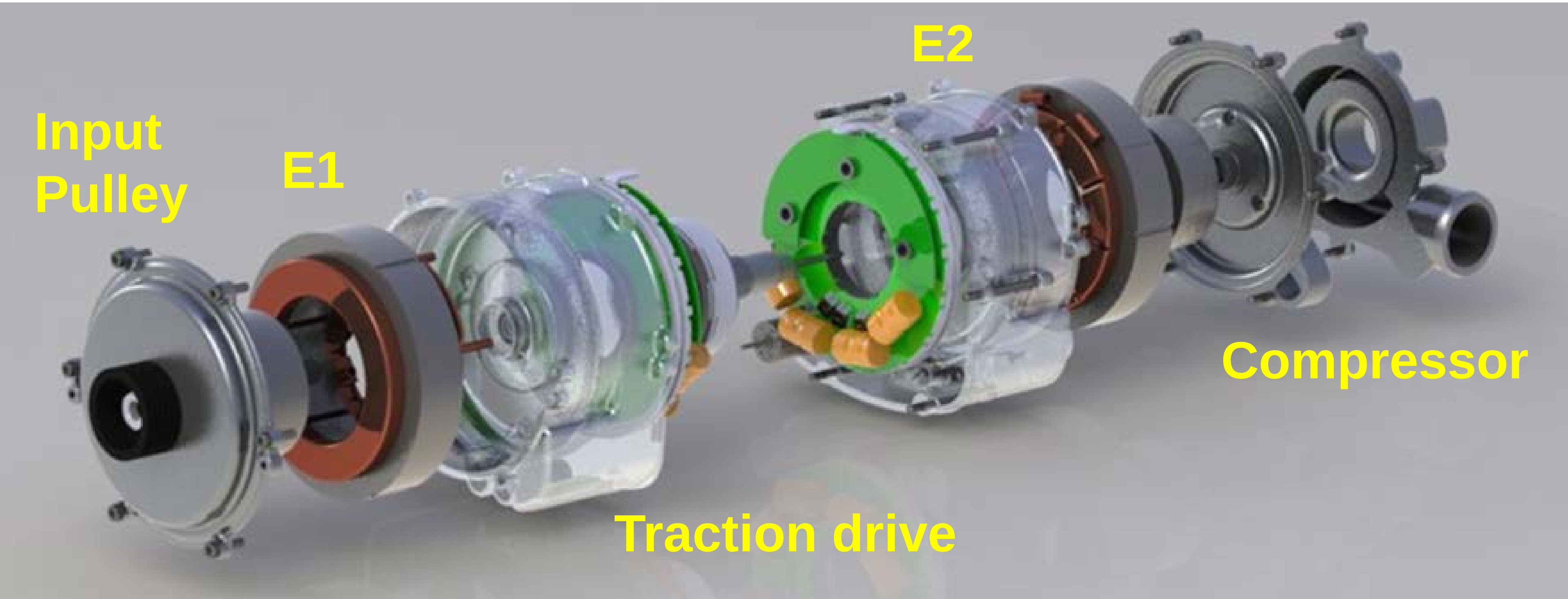
# The SuperGen Variable-Speed Centrifugal Supercharger

# 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

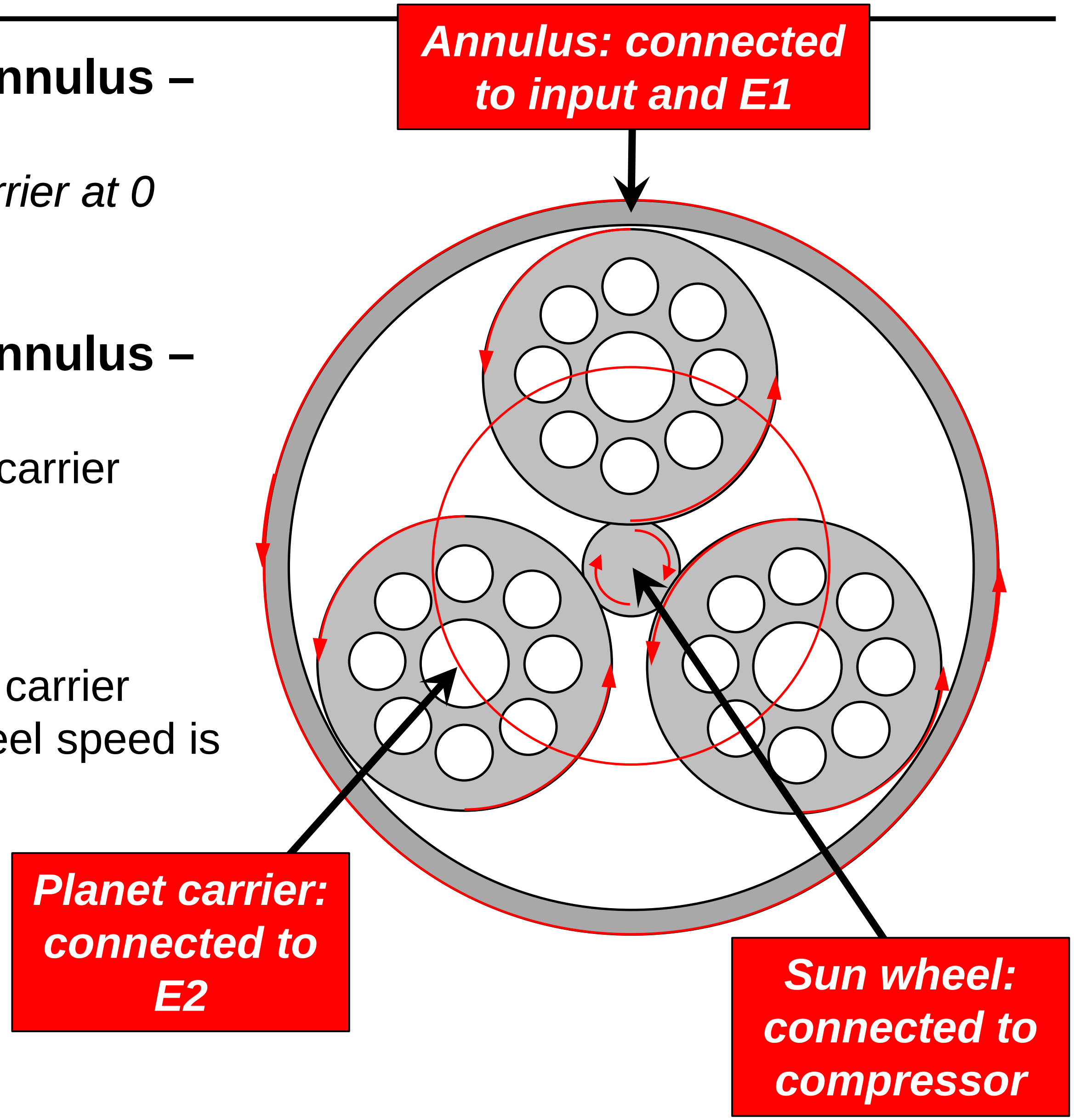


# Modes of Operation

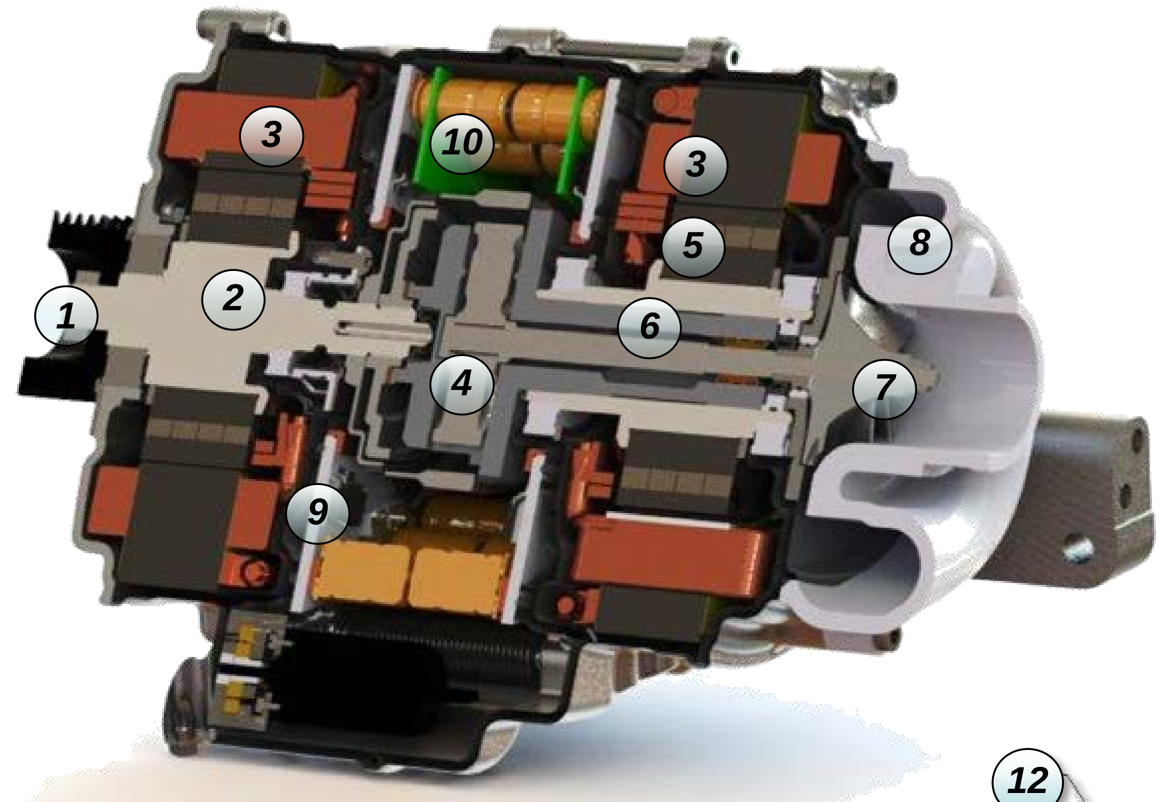
- **Fixed Carrier, Moving Annulus –**
  ***i.e.100% Mechanical***
  > *E2 locked, i.e.. planet carrier at 0 rpm*

- **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 **<u>additive</u>**

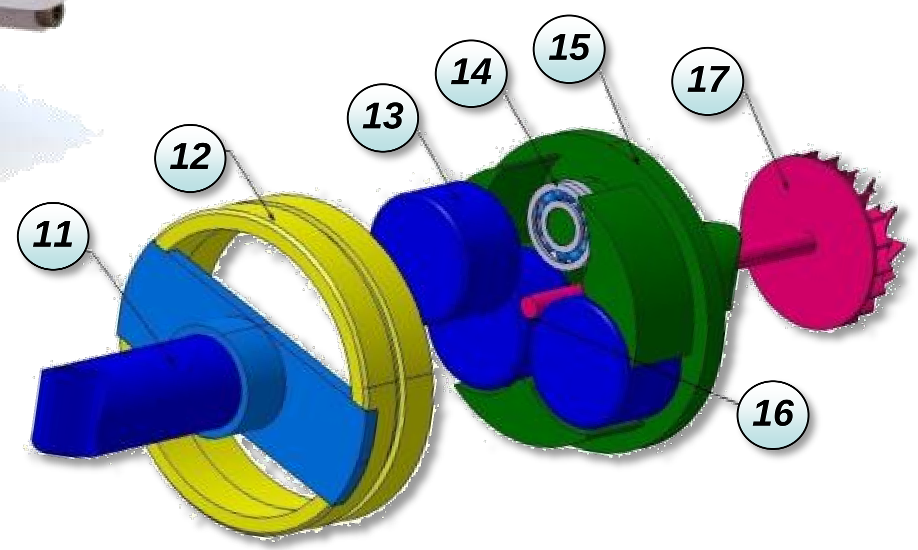


# SuperGen Components




## 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

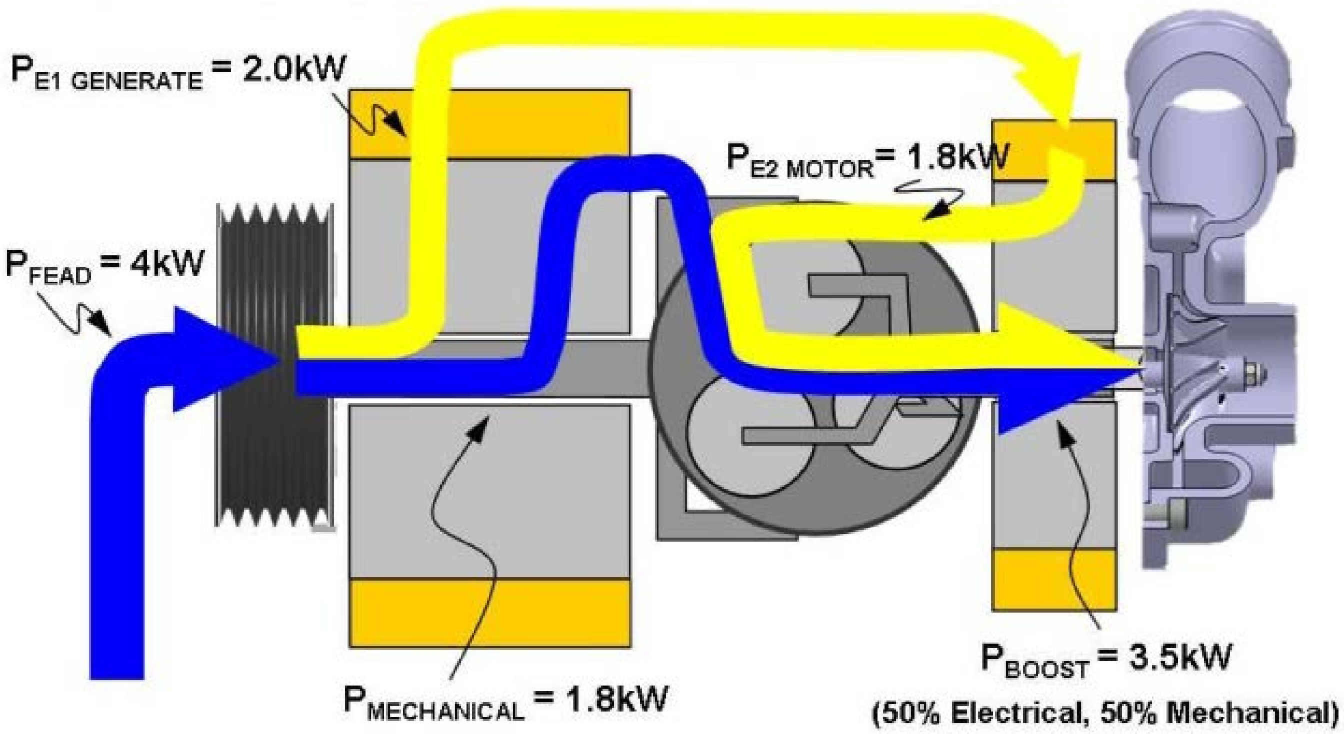
# SuperGen Operating Functions

- Traction drive planetary transmission – roller bearing technology <u>without gear teeth</u>
  - *Planetary ratio, Annulus/Sun, R0 ~ -10:1*
  - *Belt ratio R1 ~ 3*
- System is independent of the vehicle battery (self-sustaining) - capable of continuous operation and provides vehicle alternator function
  - *<u>Steady-state boost is unaffected by a depleted battery</u>*
  - *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***

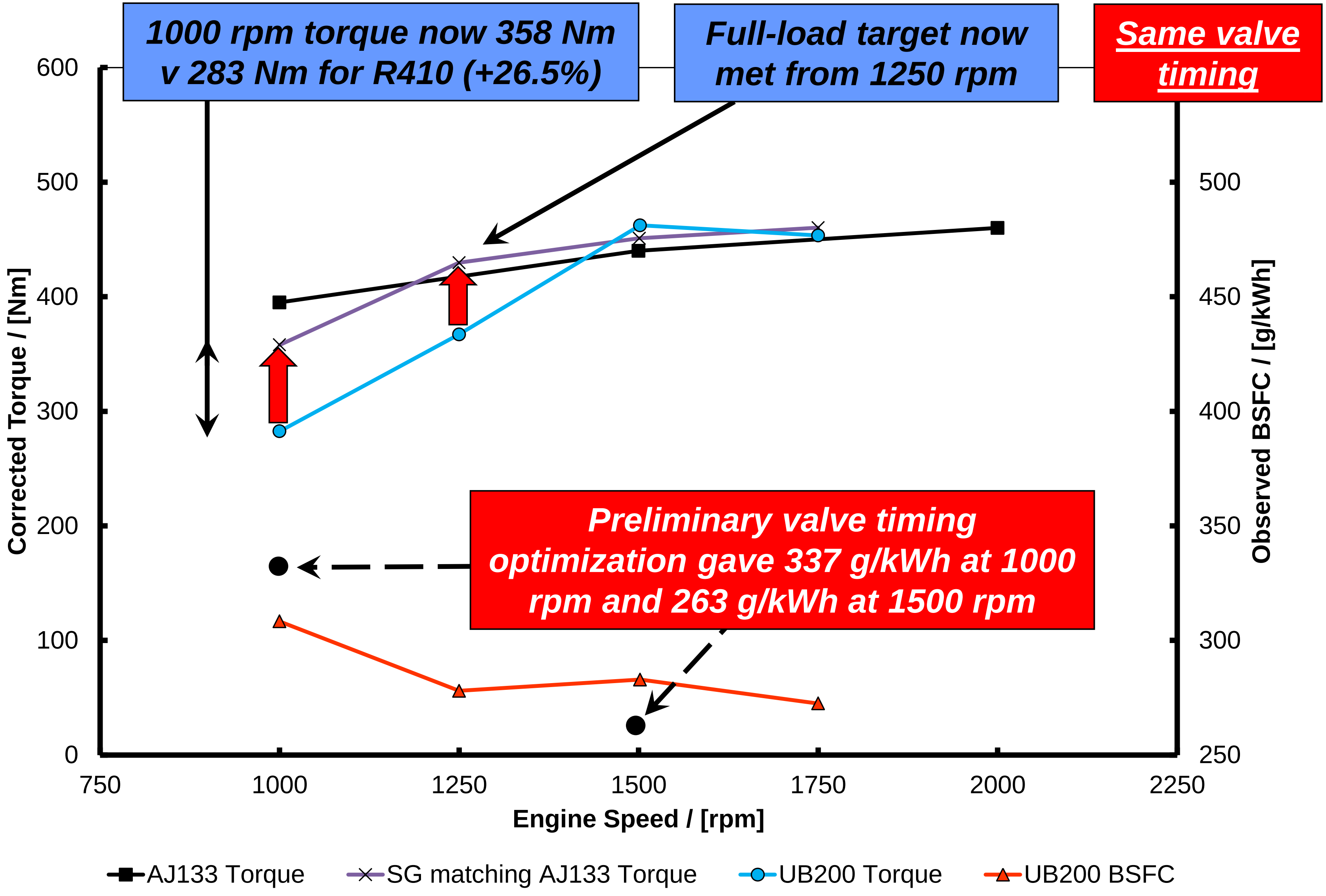
# Power-Split Functionality

- 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

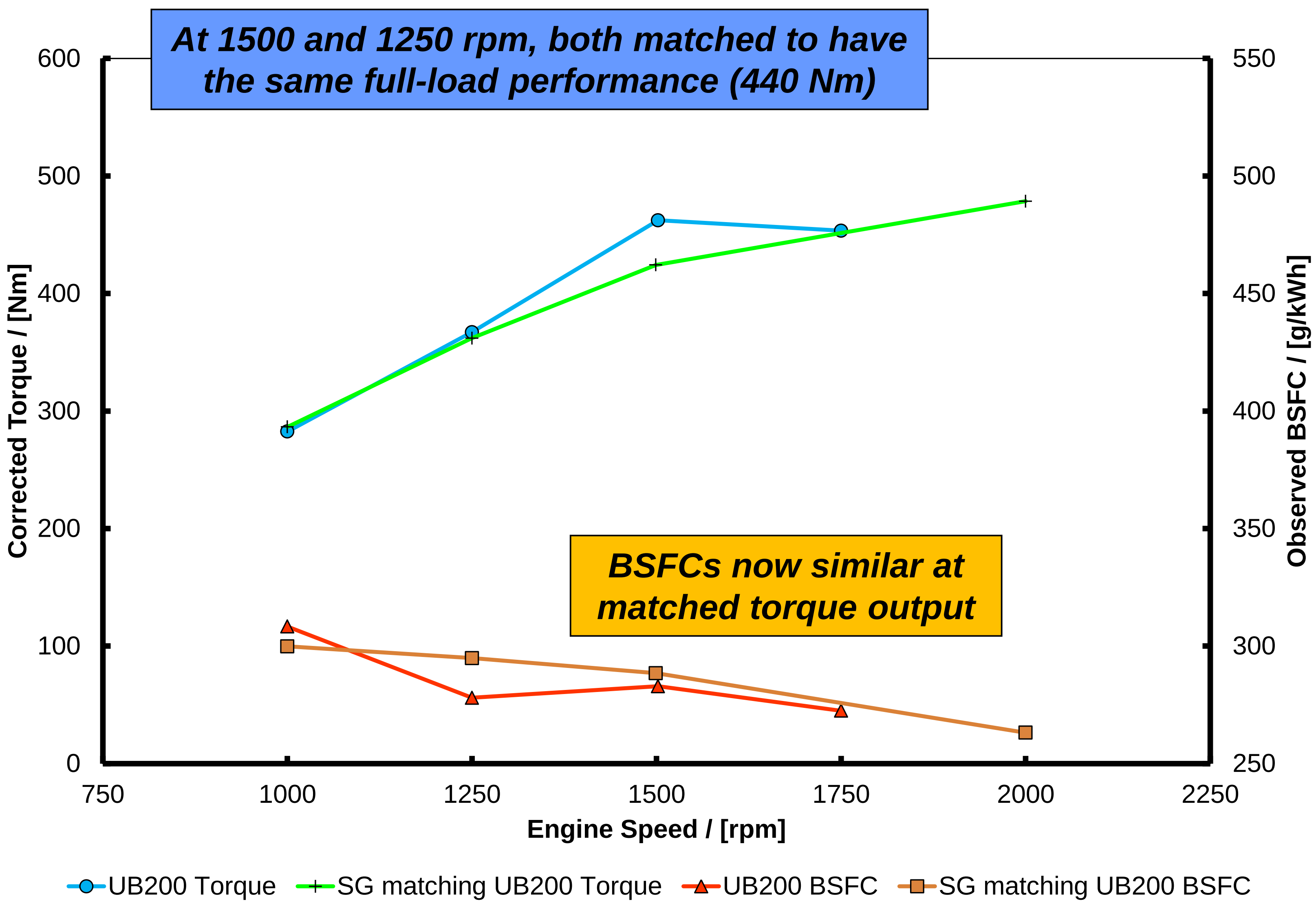


# Test Results

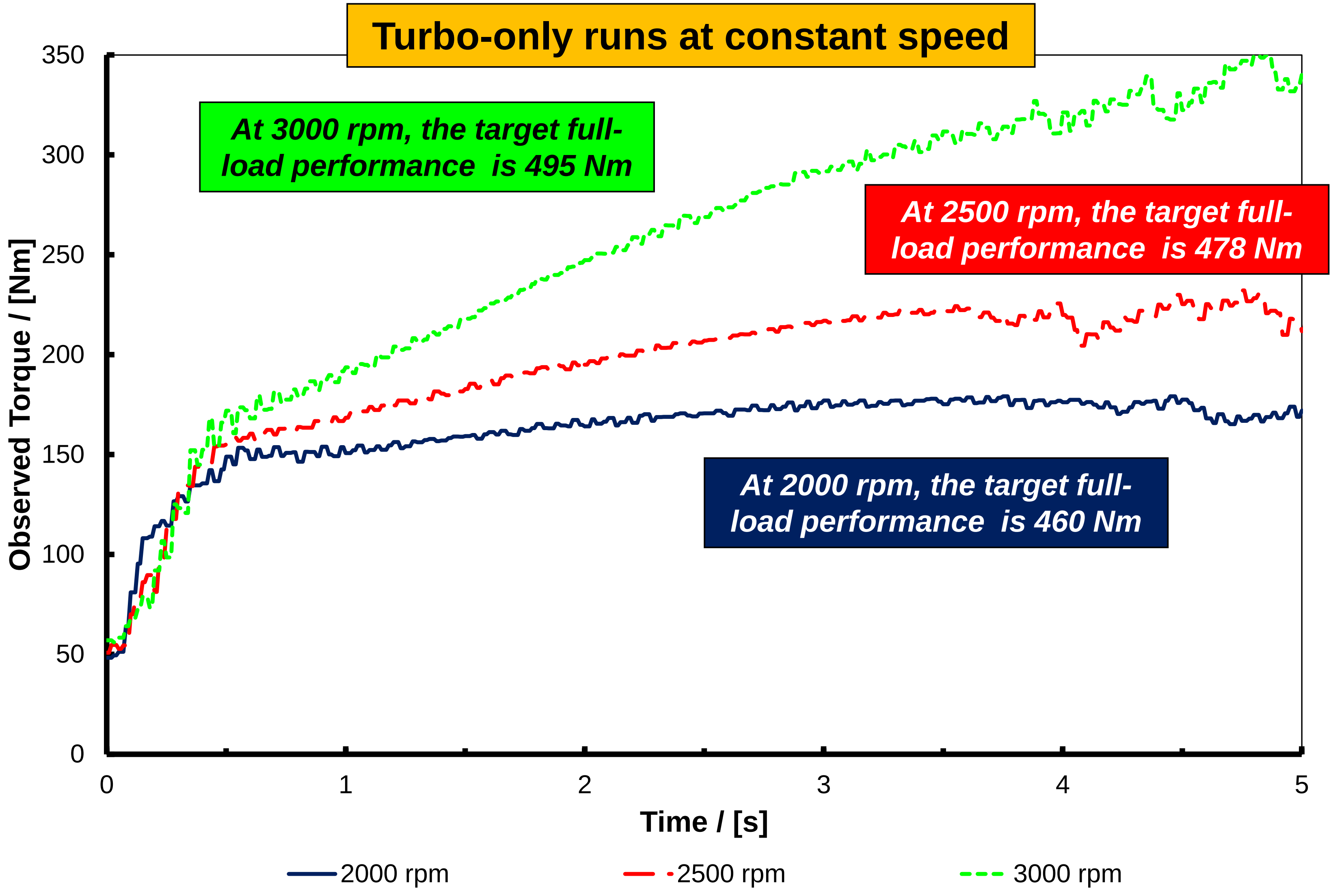
# Full Load, Steady State



# Full Load, Steady State – Matched



# The Nature of the Problem…

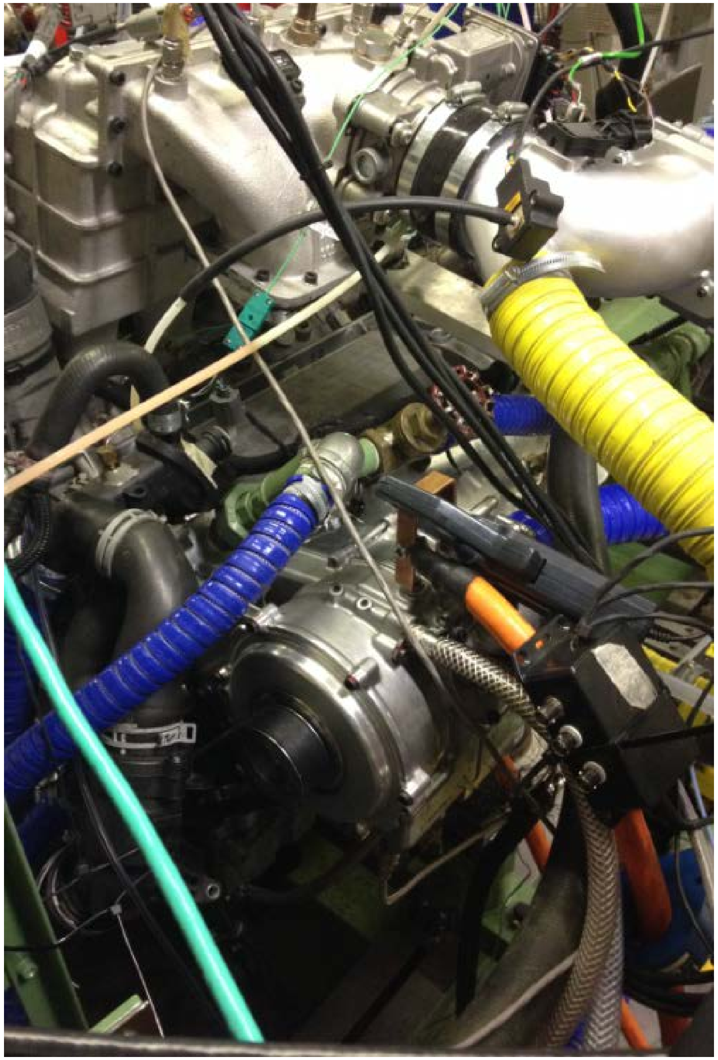


# Transient Performance Tests

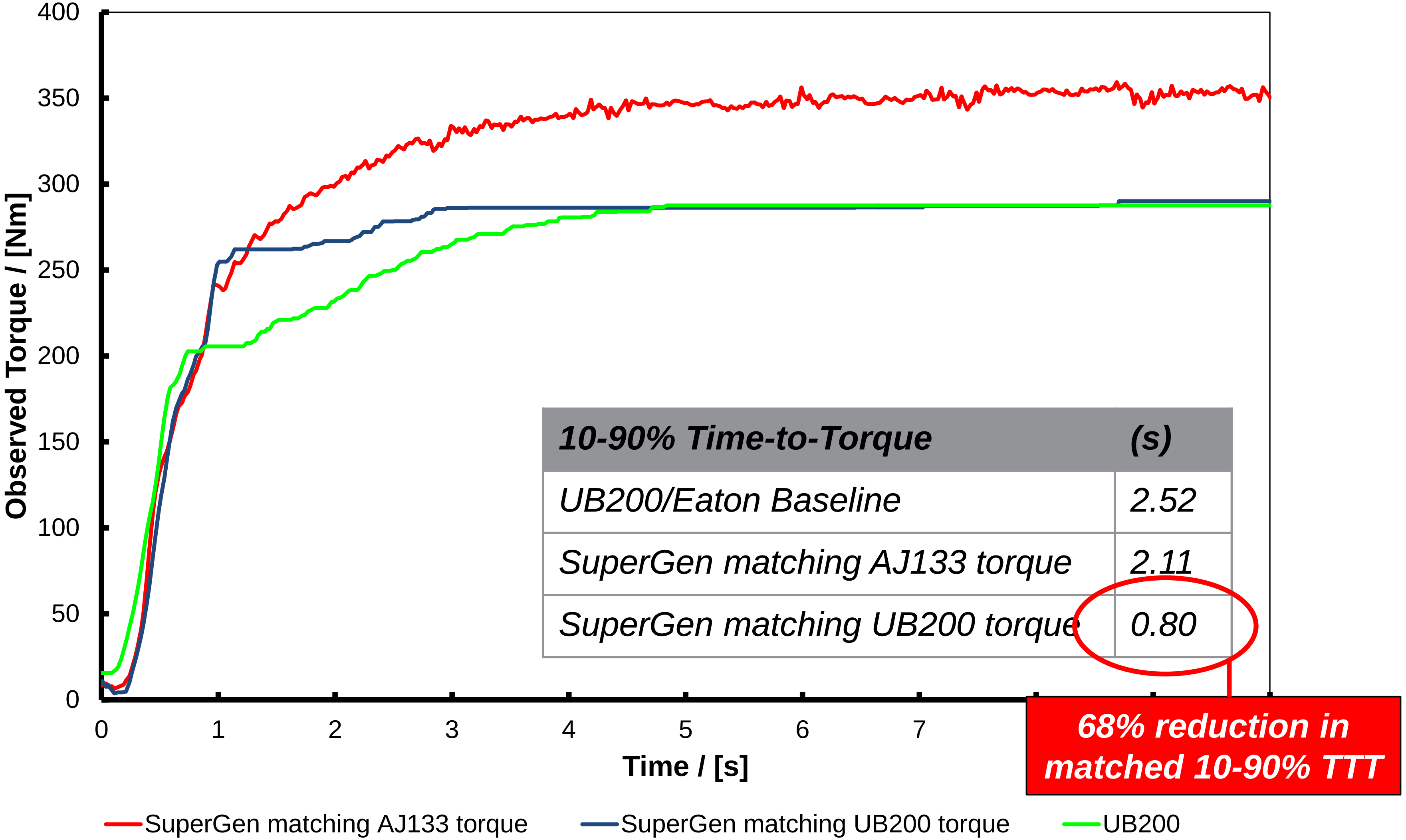
- Transient response is reported over 10-90% Time-To-Torque (10-90TTT)
  - > *Using the same valve timing and injection settings for both the UB200 Eaton build and for SuperGen*
  - > *As per steady-state full-load data*
- Note that the Eaton was <u>not</u> clutched out
- Further optimization of the 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’)*

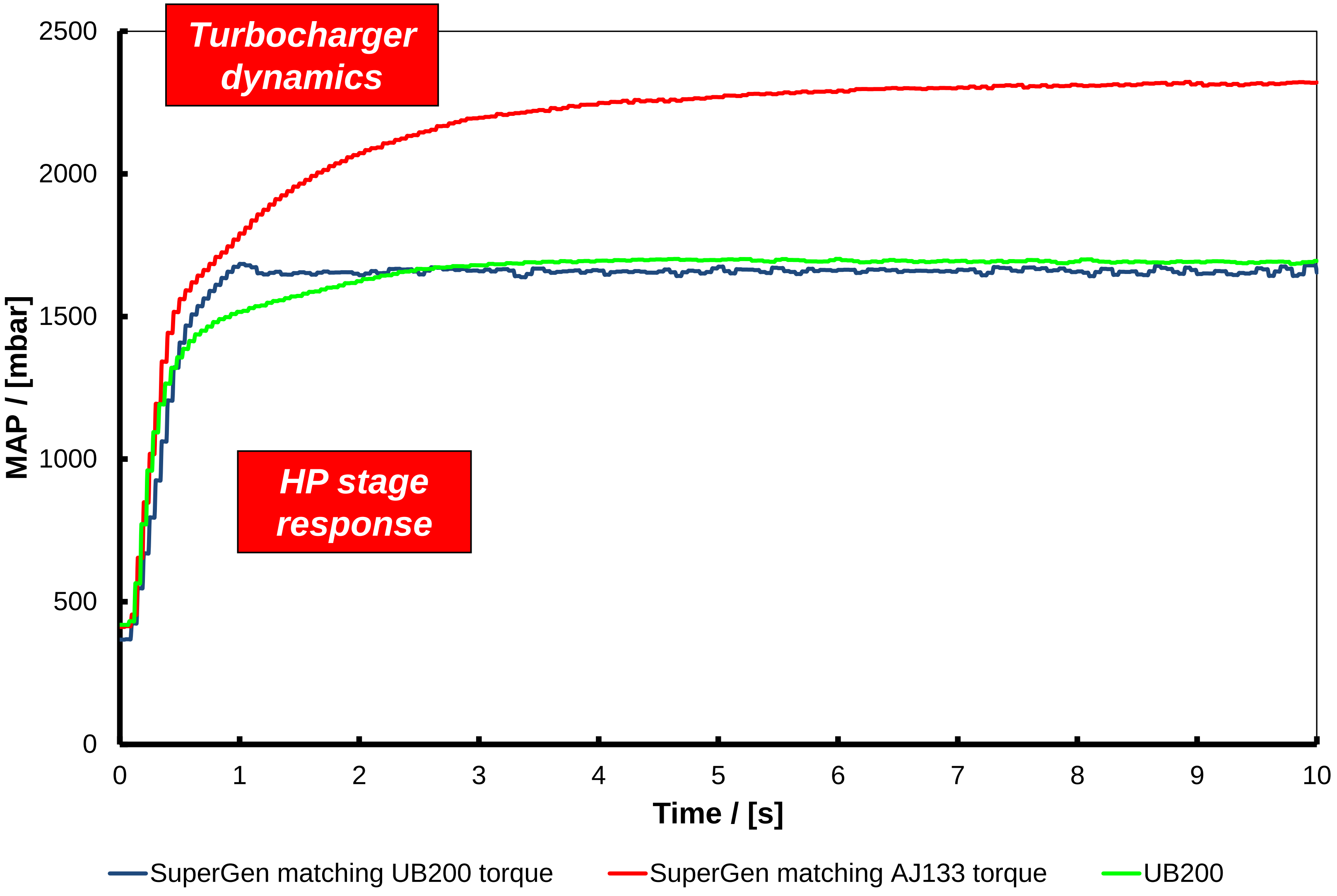


# 1000 rpm Torque Response

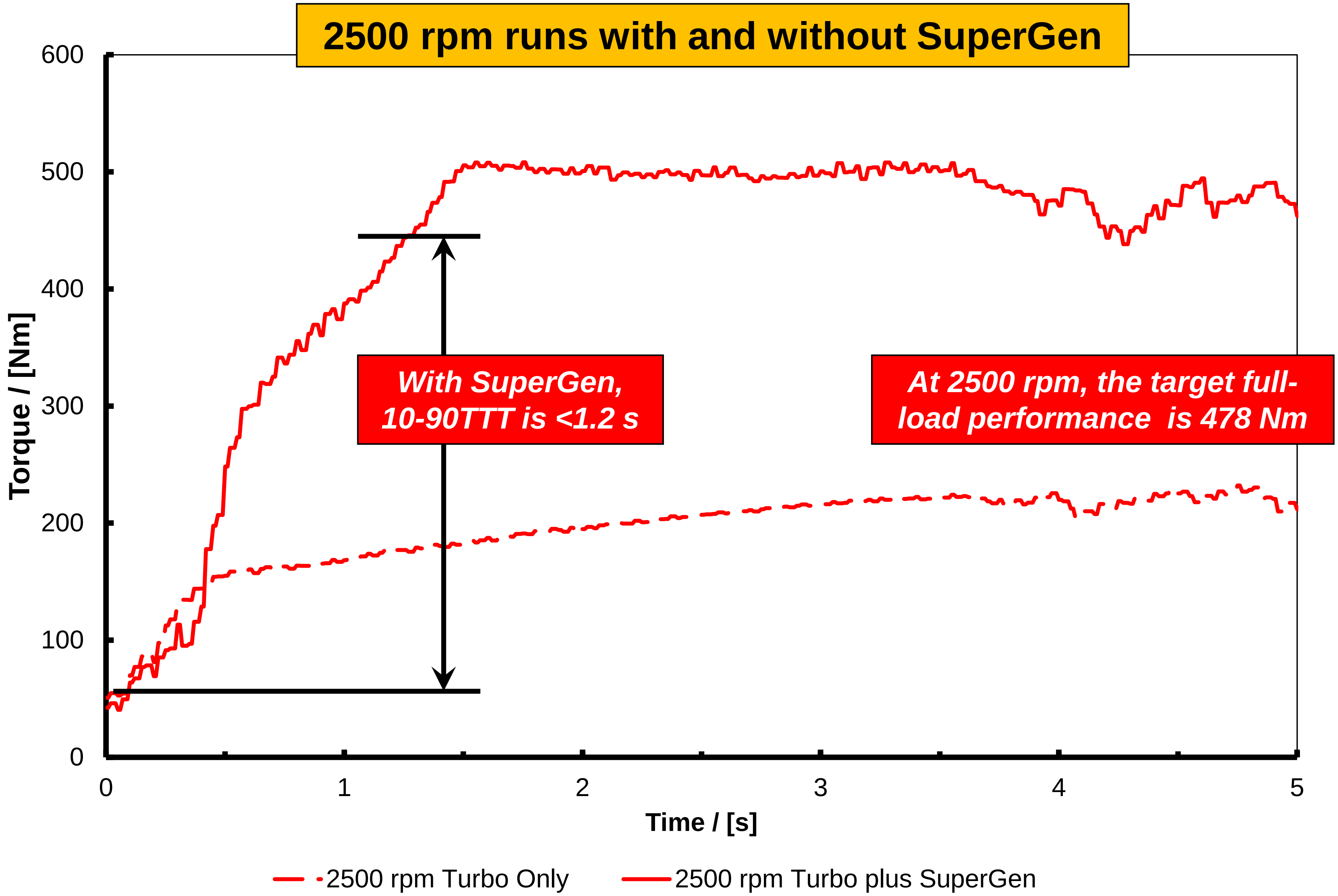



| ***10-90% Time-to-Torque*** | ***(s)*** |
|---|---|
| *UB200/Eaton Baseline* | *2.52* |
| *SuperGen matching AJ133 torque* | *2.11* |
| *SuperGen matching UB200 torque* | *0.80* |

# 1000 rpm MAP Response



# Addressing the Problem…



# 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

| Ultra-boost minimap point number (-) | Engine speed (rpm) | Brake Torque (Nm) | Eaton R410 BSFC (g/kWh) | Super-Gen BSFC (g/kWh) | Change: Super-Gen v Eaton R410 (%) |
|---|---|---|---|---|---|
| 4 | 1500 | 200 | 251.5 | 248.2 | -1.3 |
| 6 | 2000 | 200 | 254 | 244.8 | -3.6 |
| 11 | 1350 | 240 | 258.5 | 255 | -1.4 |
| 12 | 1500 | 300 | 261.7 | 250.5 | -4.3 |

***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