NOVEL APPROACHES TO EVALUATION, MODELLING AND EMULATION OF ADVANCED BOOSTING SYSTEMS

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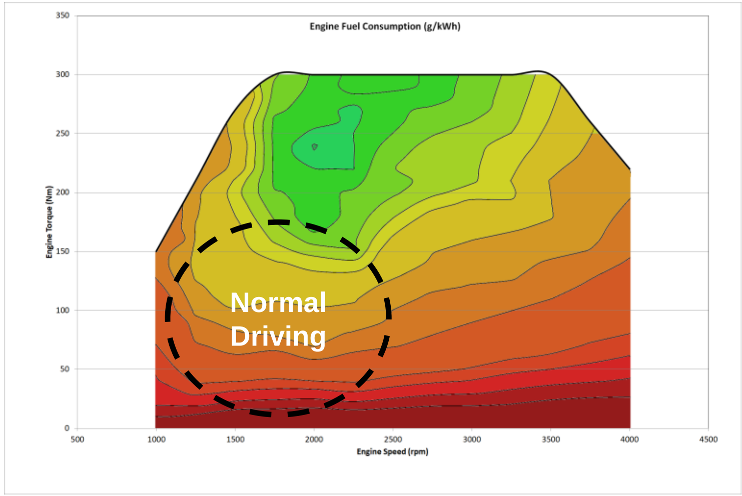
Introduction – Why boost an engine?

Engines are efficient at high load



Drive for reduced Fuel Consumption

Shift high efficiency region towards lower torques

Smaller engines do this by reducing overall friction & throttling losses at part load,
Boosting system required to recover torque curve of smaller engine

Replace big engines…

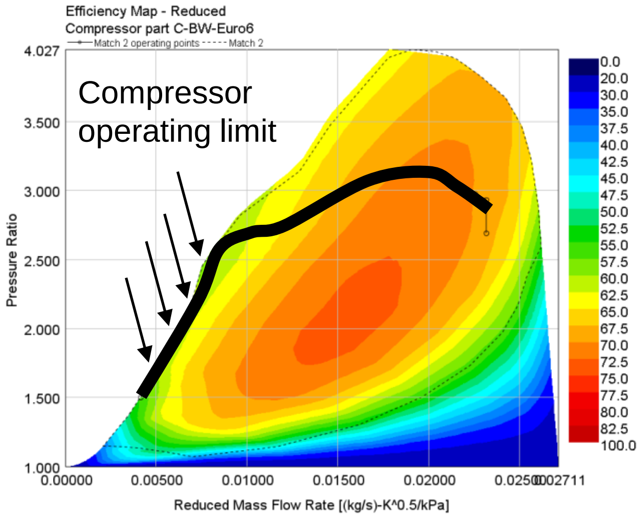
With Smaller Engines????

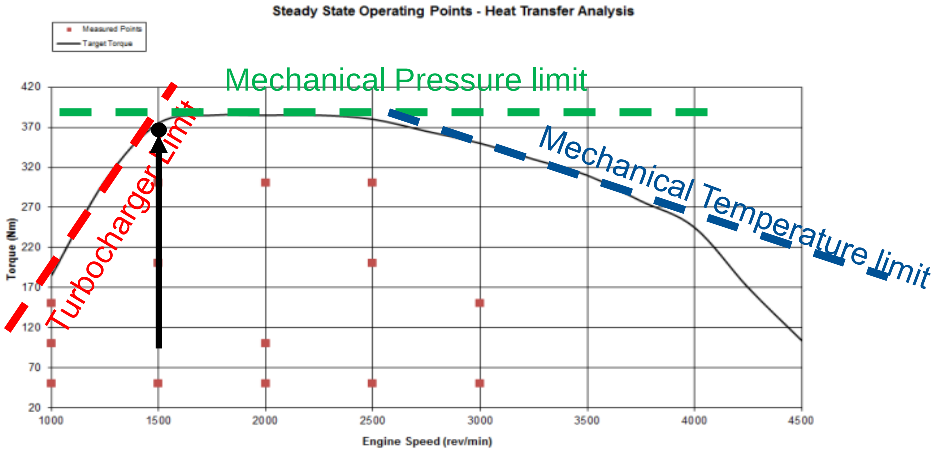
109,000 bhp Wärtsilä-Sulzer RTA96-C

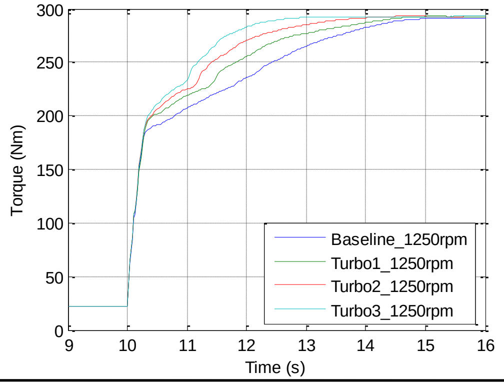
Length 26.59 metres (87 ft)
Height 13.5 metres (44 ft)
Dry weight over 2,300 tons
Bore 960 mm, Stroke 2,500 mm Displacement 1810 litres per cylinder
Engine speed 22–120 RPM
Best specific fuel consumption 160 g/(kW·h)

140PS (~103kW) Ford Fox 3 cylinder 1L
210Nm torque, BSFC~ 240g/kWh

Boosting Challenges







Requirements of a future Airpath

- Emissions
- Fuel economy
- Transient response
- Electrification
- Thermal management
- All in real world operating conditions

Contents

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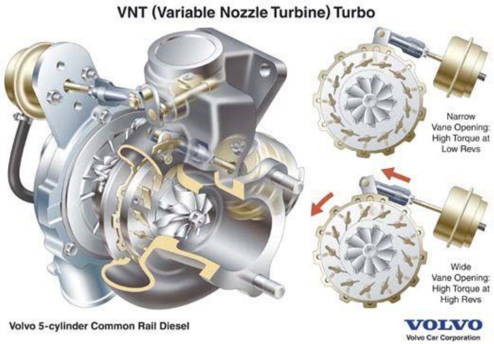
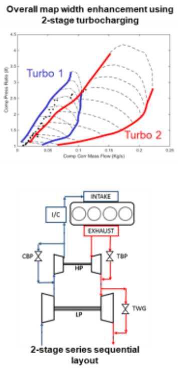
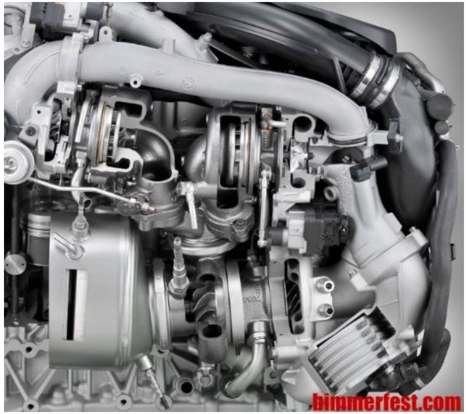
Boosting Technologies

VG Turbine (multiple turbines) /VG compressors (Multiple Compressors)



Multi-stage turbocharging





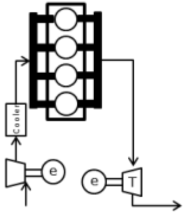
Turbo super and mechanical compounding

Torotrak V-Charge System

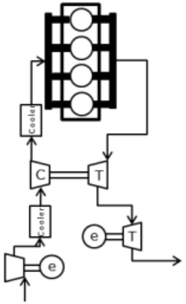
Van Dyne Super Turbo

Boosting Electrification

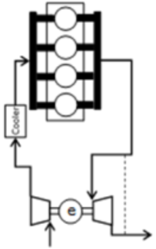
E-Turbo application



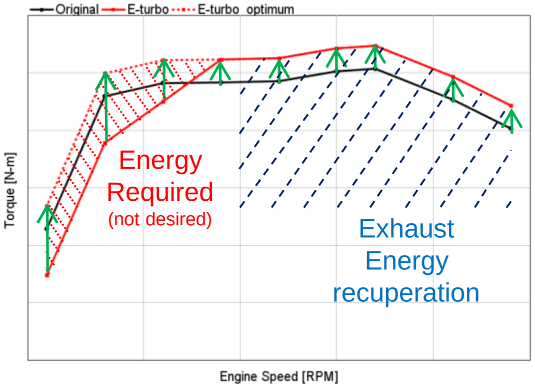
Electric turbine with an electrically or mechanically driven compressor

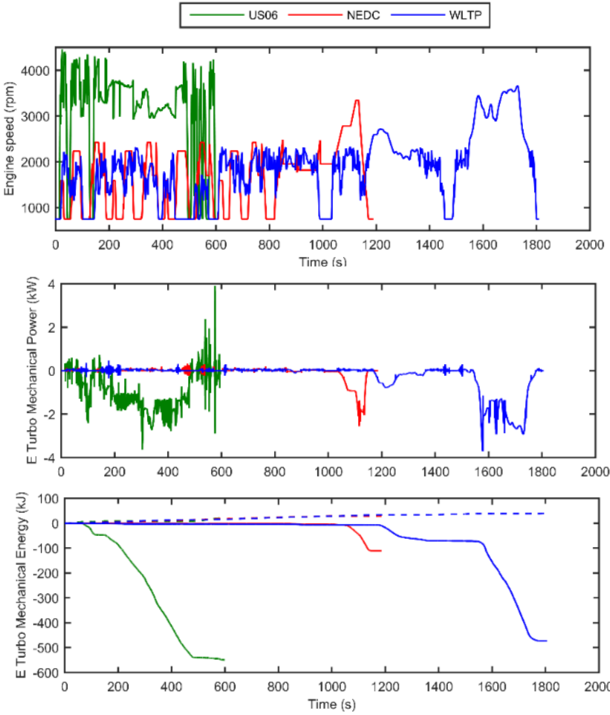


Two-stage system



Electric turbocharger





Dimitriou, P, Burke, R, Zhang, Q, Copeland, C & Stoffels, H 2017, 'Electric Turbocharging for Energy Regeneration and Increased Efficiency at Real Driving Conditions' Applied Sciences, vol 7, no. 4, 350. DOI: 10.3390/app7040350

Boosting Electrification

System Opportunities

Offers a low weight option for deployment of electrical energy

Offers the possibility to recuperate exhaust heat

Can improve transient response

Can lead to fuel economy benefits by relaxing transient requirements of other engine features

System Challenges

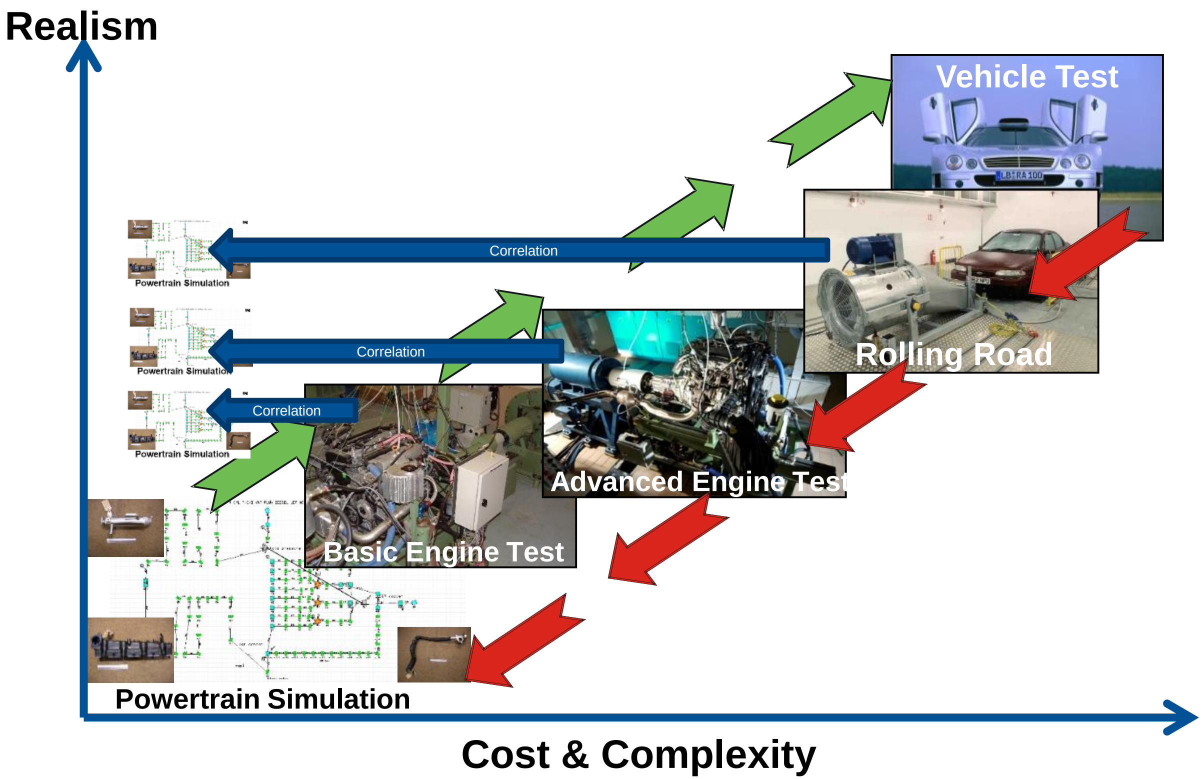
Energy flow need to be managed carefully with other systems

Benefits are only apparent with review of full system design (not simply a retrofit)

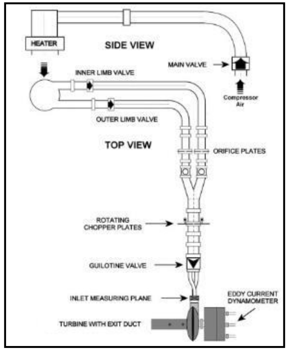
System needs to be designed and controlled in an optimal way

Contents

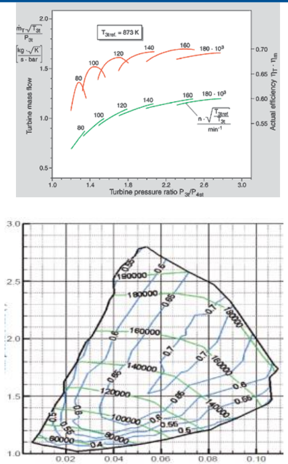
Powertrain Development



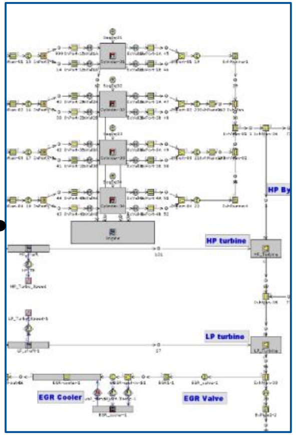
Modelling Disconnect



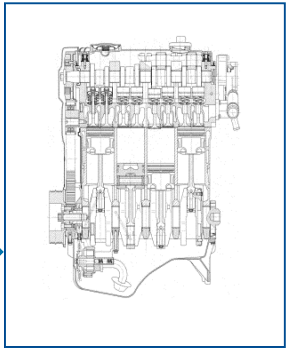
TURBO GAS STAND



TURBO MAPS



GT POWER SIMULATION



REAL ENGINE PERFORMANCE

Disconnect due to:
- Pulsating flows
- Heat transfer
- Inlet/outlet pipe geometry
- Working fluid

LIMITED DATA RANGE (TURBINE) → WIDE PULSE OPERATION

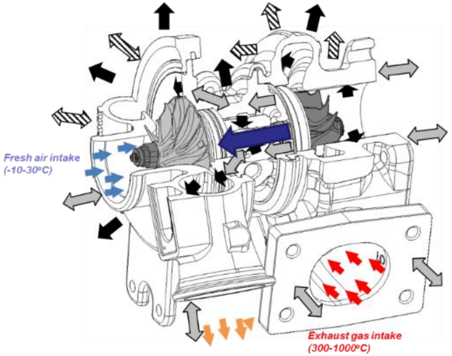
LIMITED DATA RANGE (COMPRESSOR) → DRIVE CYCLE ASSESSMENT

STEADY FLOW → QUASI-STEADY → UNSTEADY FLOW

COLD FLOW/ADIABATIC EFFICIENCY → HOT FLOW/ NON-ADIABATIC

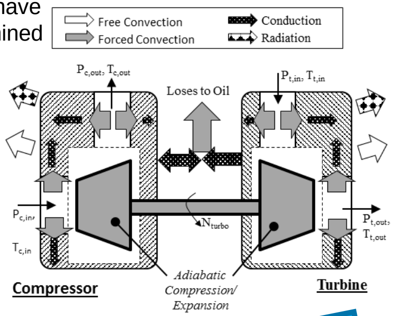
Turbocharger Heat Transfer

Complex Heat transfer in turbochargers affects accuracy of 1D models in predicting exhaust gas temperatures and multi stage system performance



Create Simple HT models

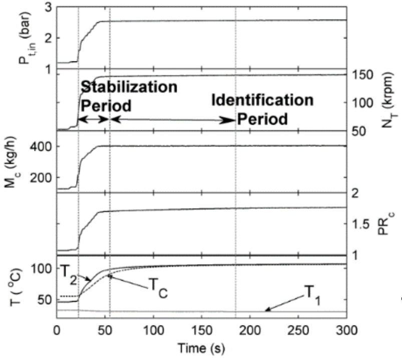
Lumped Capacitance Models have many parameters to be determined



Option 1:
Destructive testing Campaign
EXPENSIVE

Option 2:
Parameter prediction by 3D Simulation
UNCERTAIN

Option 3: Simultaneous transient characterisation of efficiency and heat transfer

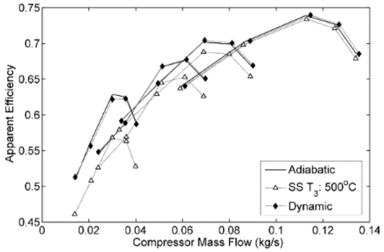


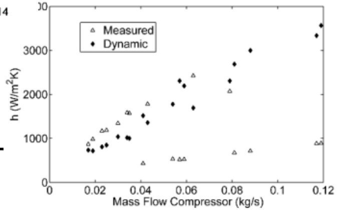
Status:

- Concept demonstrated for Compressor in idealised situation

Turbocentre focus:

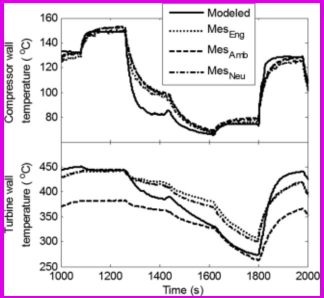
- Confirmation for compressor in non-idealised situation
- Application to turbine

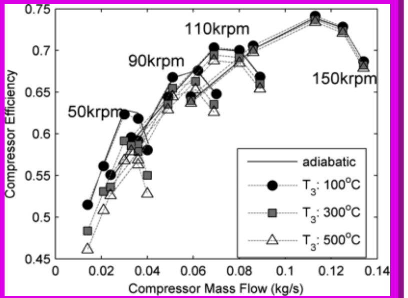


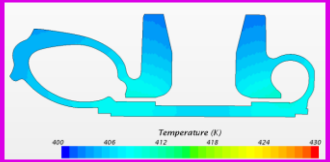


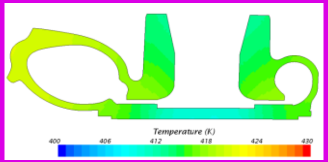
Turbocharger Heat Transfer

Understand the problem by experiments and 3D simulation

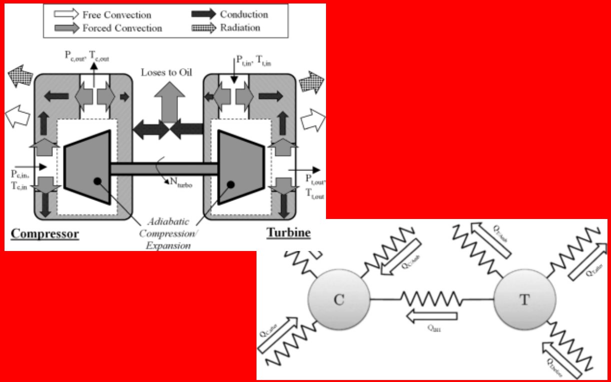




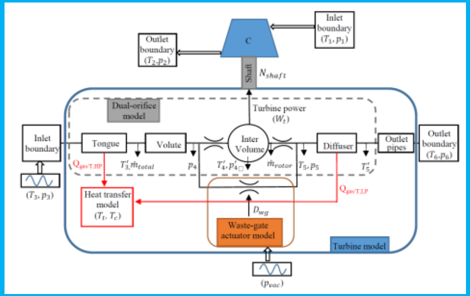




Create simplified model structure



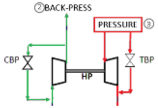
Integrate with other models



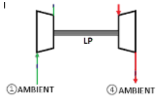
2-stage System Mapping

Conventional Approach

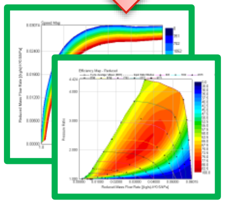
1. Map HP Stage on Gas Stand

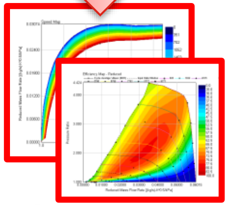


2. Map LP Stage on Gas Stand

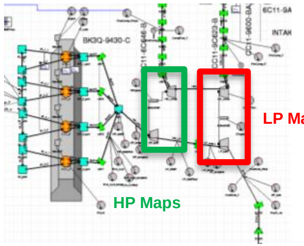


3. Produce 2 sets of maps





4. Maps combined into system in 1D environment



LP Maps

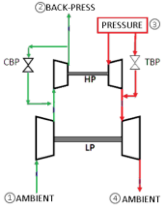
HP Maps

No knowledge of inter-stage phenomenon and resulting losses

Proposed Approach

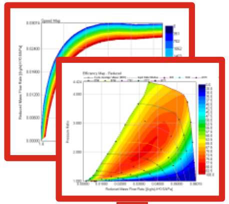
$$N_{eq} = \frac{N_{LP}^2}{N_{HP}}$$

1. Define a monotonically increasing speed metric for full system

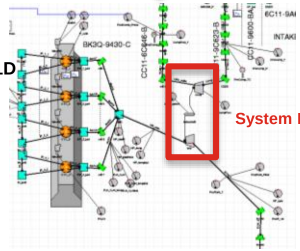


2. Map The 2-stage system as a whole on gas stand

3. Produce a single set of system maps



4. Use system maps in 1D environment



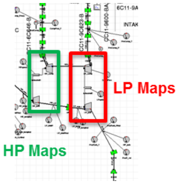
System Maps

Inter-stage phenomenon and resulting losses are inherently captured in the system map

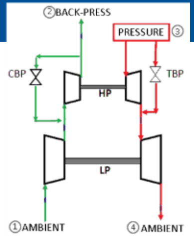
Avola, C., Copeland, C., Burke, R. and Brace, C., 2017. Effect of inter-stage phenomena on the performance prediction of two-stage turbocharging systems. Energy, DOI: https://doi.org/10.1016/j.energy.2017.06.067

2-stage system mapping

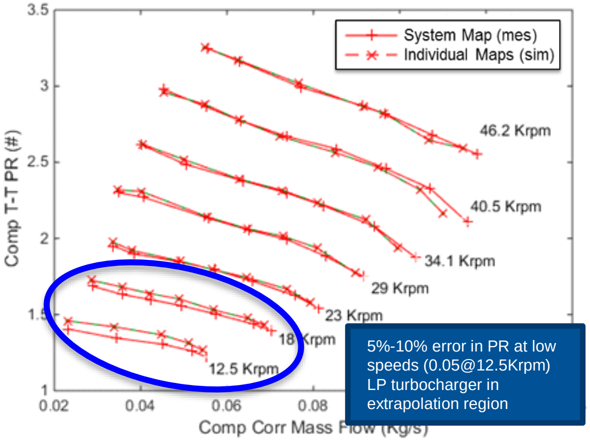
Compressor Maps



Ricardo Wave simulation of combination of individual maps *Vs.* ***Measured Full system performance***



Mass Flow

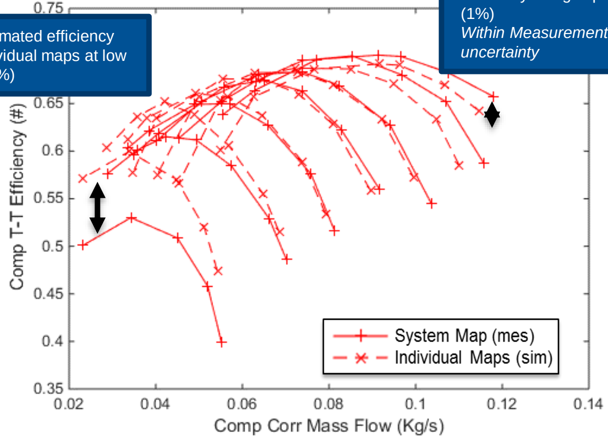


5%-10% error in PR at low speeds (0.05@12.5Krpm) LP turbocharger in extrapolation region

Efficiency

Over-estimated efficiency from individual maps at low speed (8%)

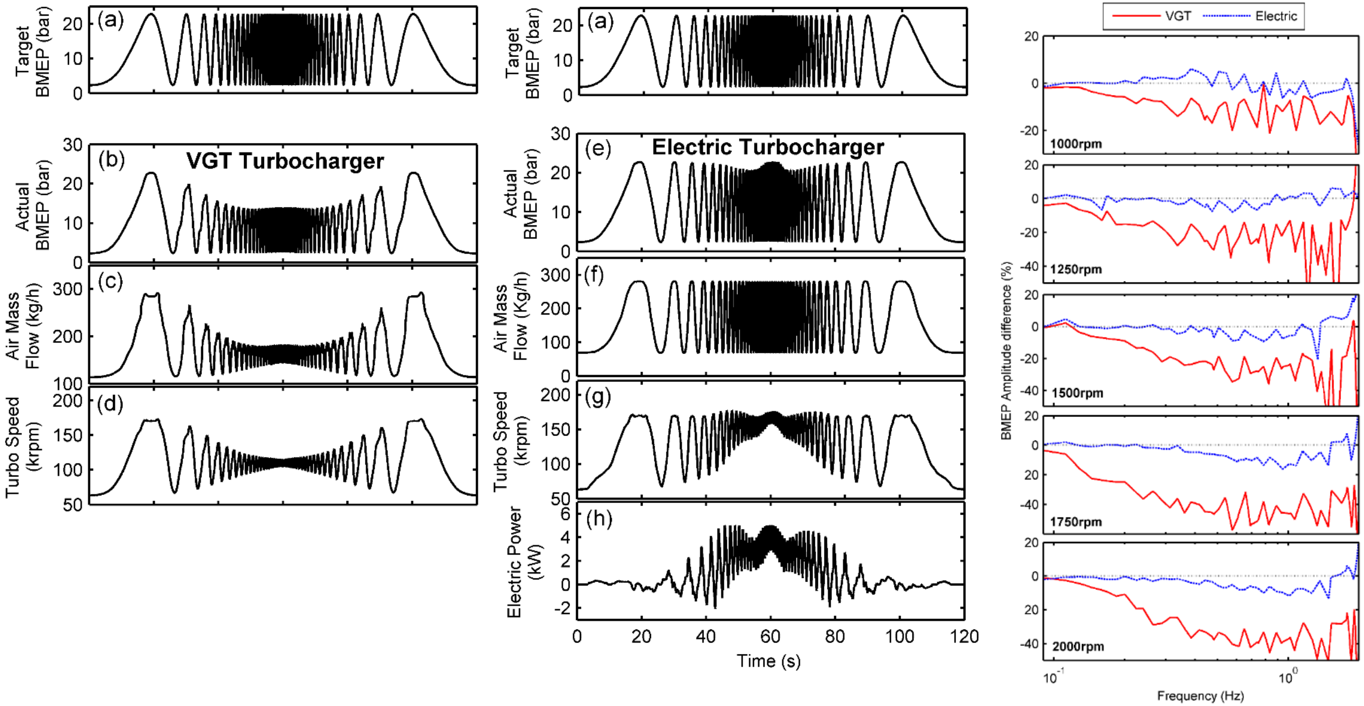
Small underestimate of efficiency at high speeds (1%)
Within Measurement uncertainty



**All speeds are equivalent speeds*

Simulation over-estimates pressure ratio at low speed ➔ Extrapolation on the LP map
Efficiency is also over-estimated at low speed and under-estimated at high speeds

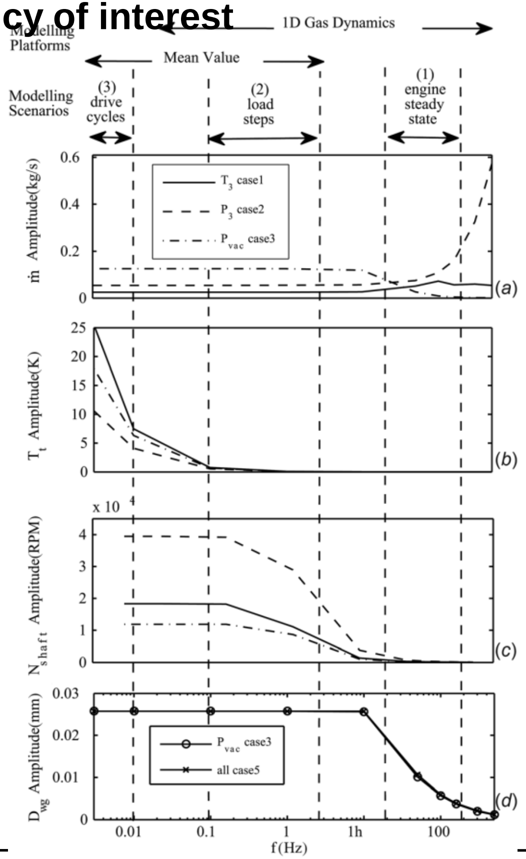
Electric boosting - Transient evaluation



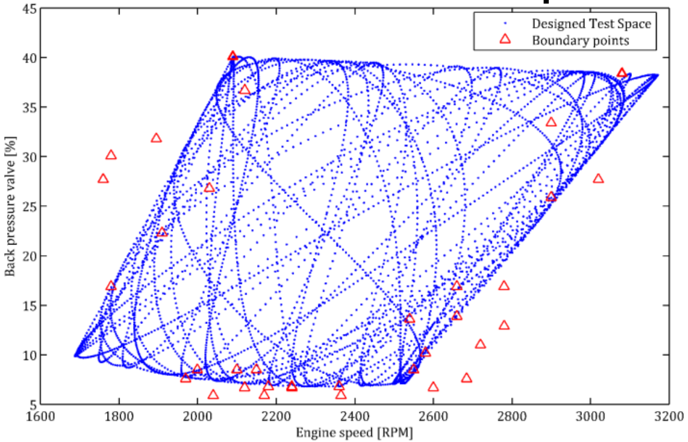
Burke, RD 2016, 'A numerical study of the benefits of electrically assisted boosting systems' Journal of Engineering for Gas Turbines and Power: Transactions of the ASME, vol 138, no. 9, 092808. DOI: 10.1115/1.4032764

Dynamic Turbocharger Maps

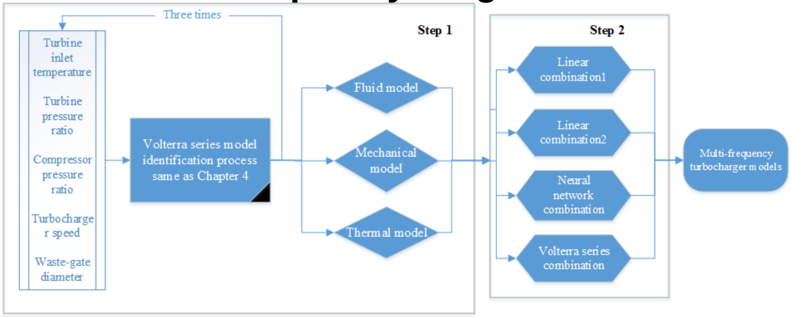
Identify frequency of interest



Transient characterisation experiment



Dynamic Regression model at appropriate frequency range



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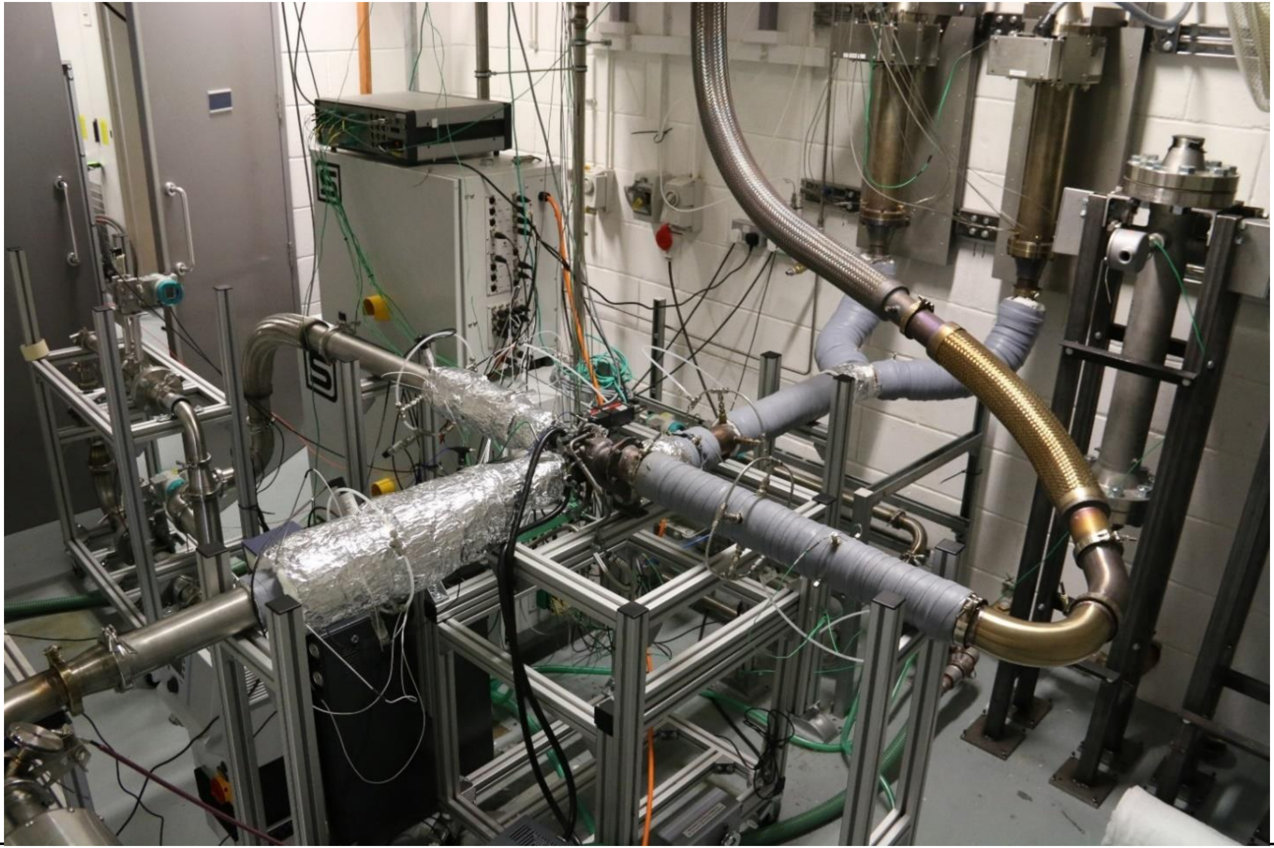
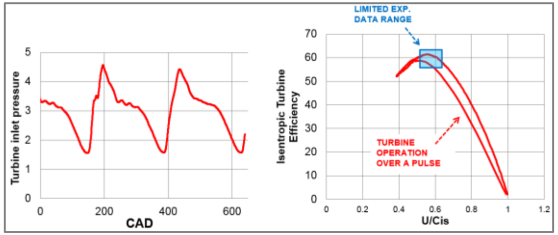
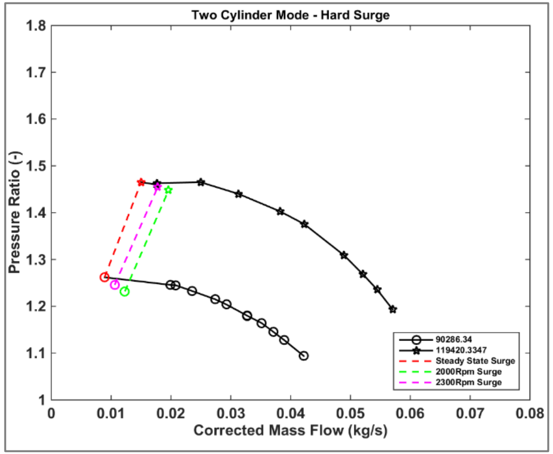
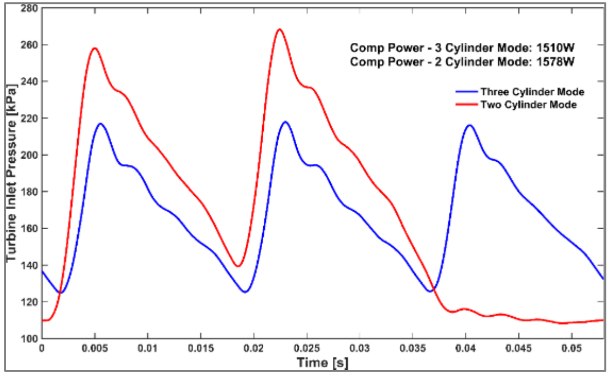
Steady flow Gas Stand

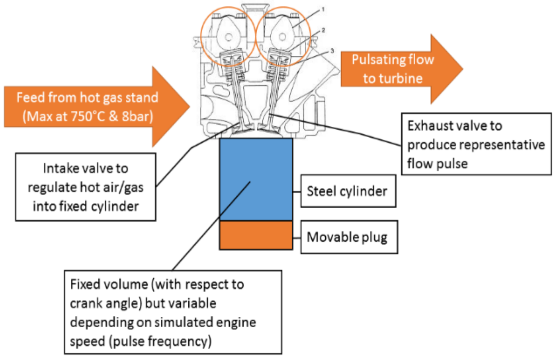


Effect of Pulsations



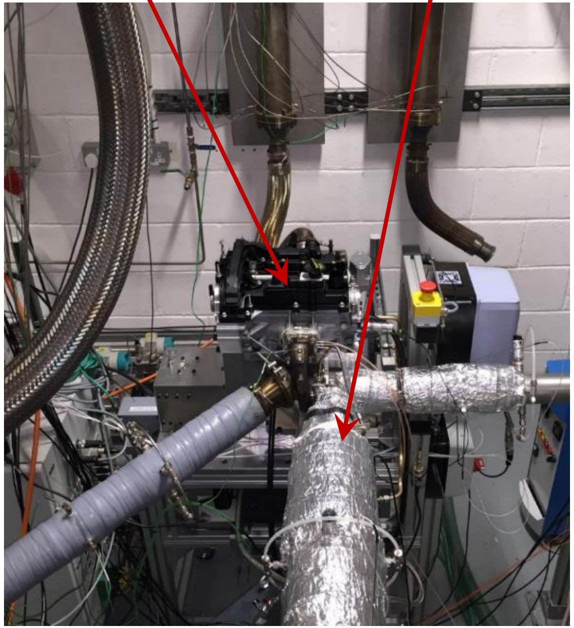






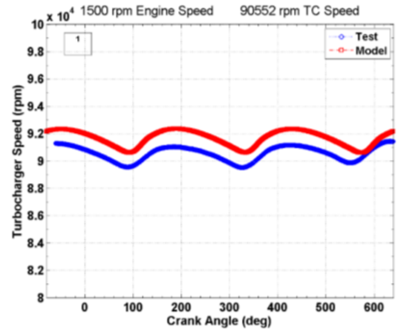
Pulsation flow at the turbine inlet

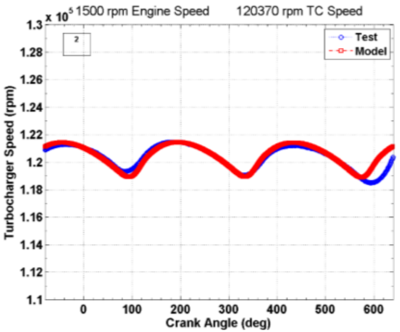
Back pressure valve at compressor outlet



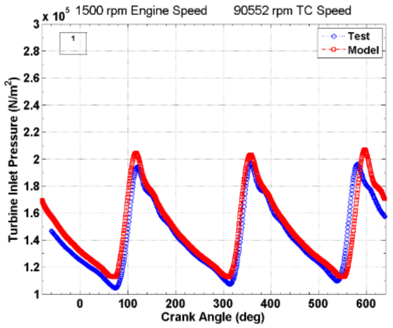
Pulsation Generator Performance

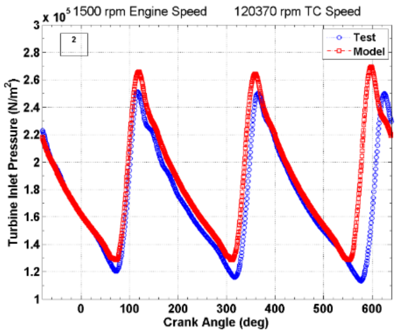
Turbocharger Speed



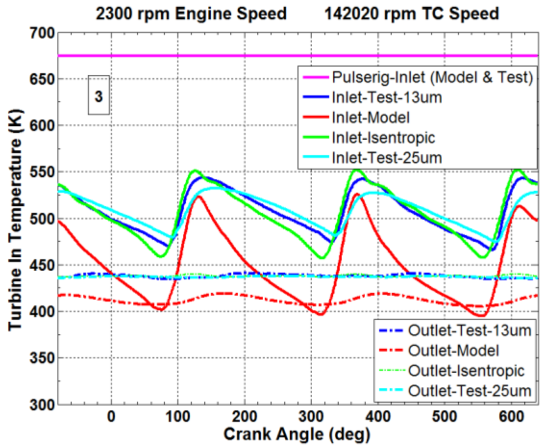


Turbine Inlet Pressure



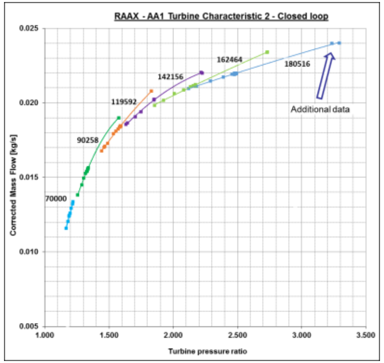


Fast Temperature Measurement

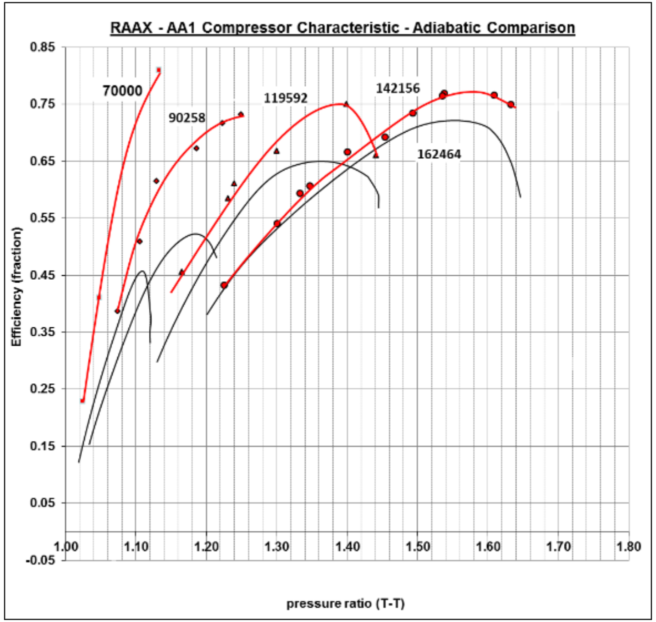


Advanced Mapping techniques

Closed loop compressor



Adiabatic Mapping



X-i-L testing methods – Engine/Airpath

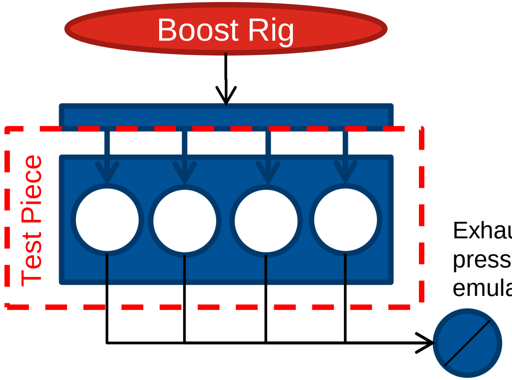
Turbomachinery without engine

Gas Stand, Engine Gas Stand

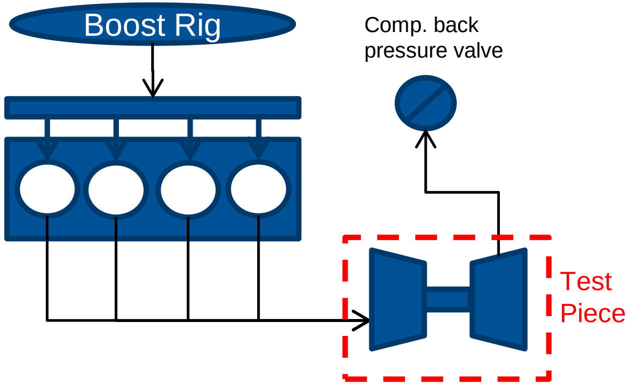
Engine without boosting hardware

Boost emulation rig

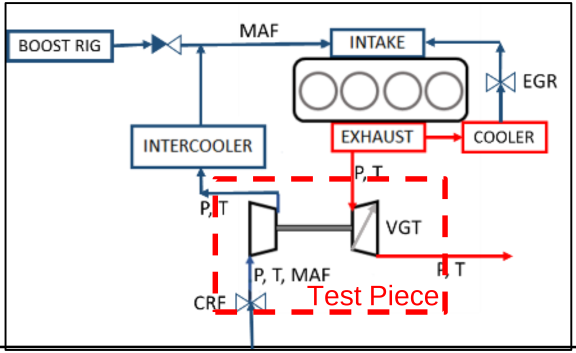
Boosting system emulation



Engine Based Gas Stand A

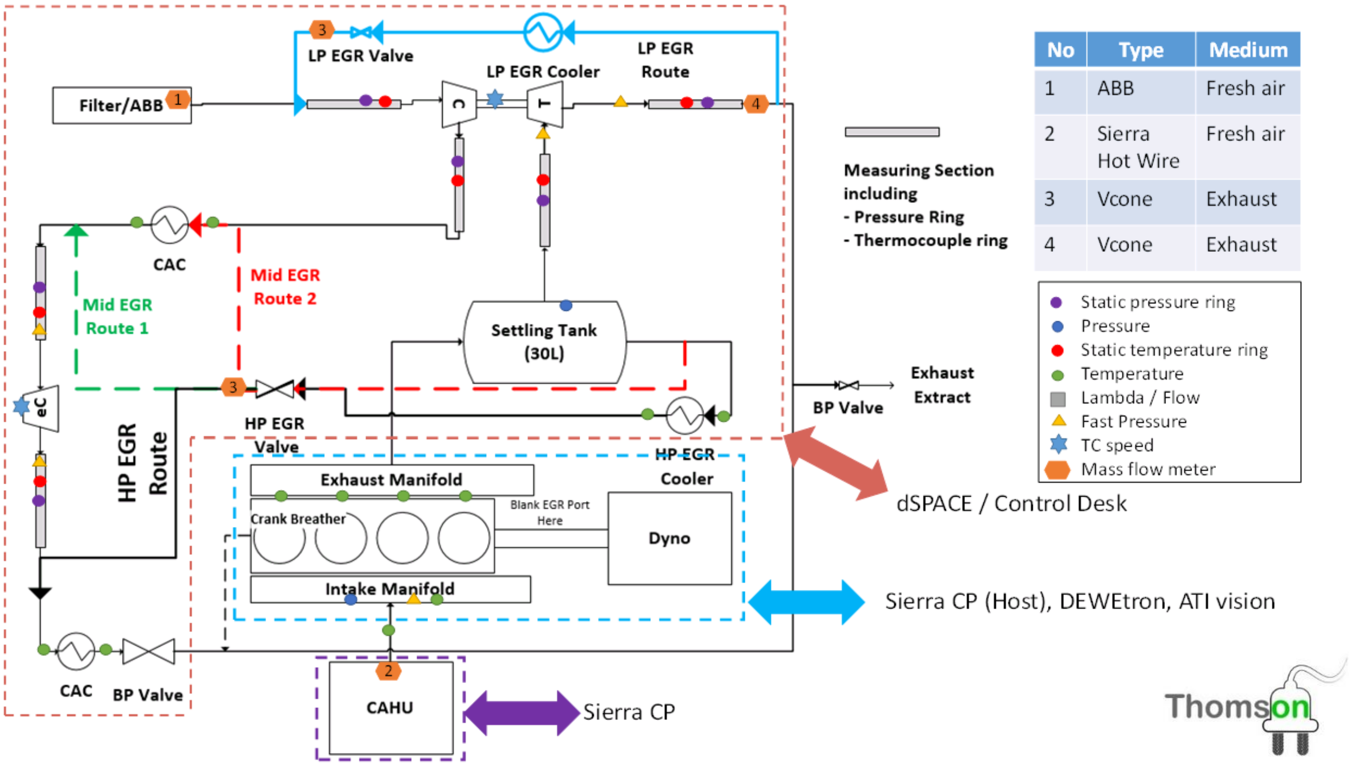


Engine Based Gas Stand B



X-i-L testing methods – Airpath

System based Test rig replicating air path layout



No	Type	Medium
1	ABB	Fresh air
2	Sierra Hot Wire	Fresh air
3	Vcone	Exhaust
4	Vcone	Exhaust

X-i-L testing methods – Airpath

- Built around a 2.2L PUMA Diesel Engine and a Boost rig
- Component level test– Turbocharger turbine & compressor & E-Booster
- Rig successfully commissioned and a range of test data collected

Settling Tank

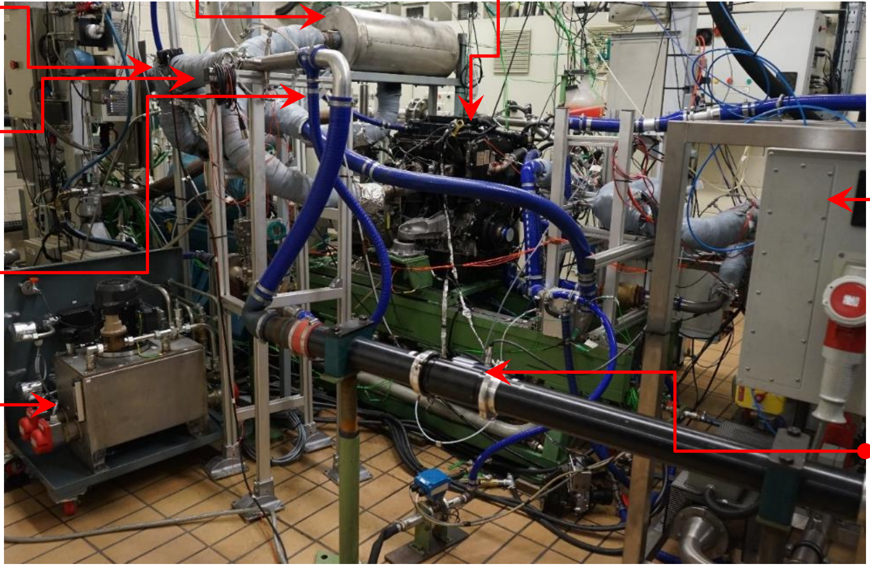
2.2L Diesel engine

VGT Turbo

Measuring Sections

LP EGR to Compressor Inlet

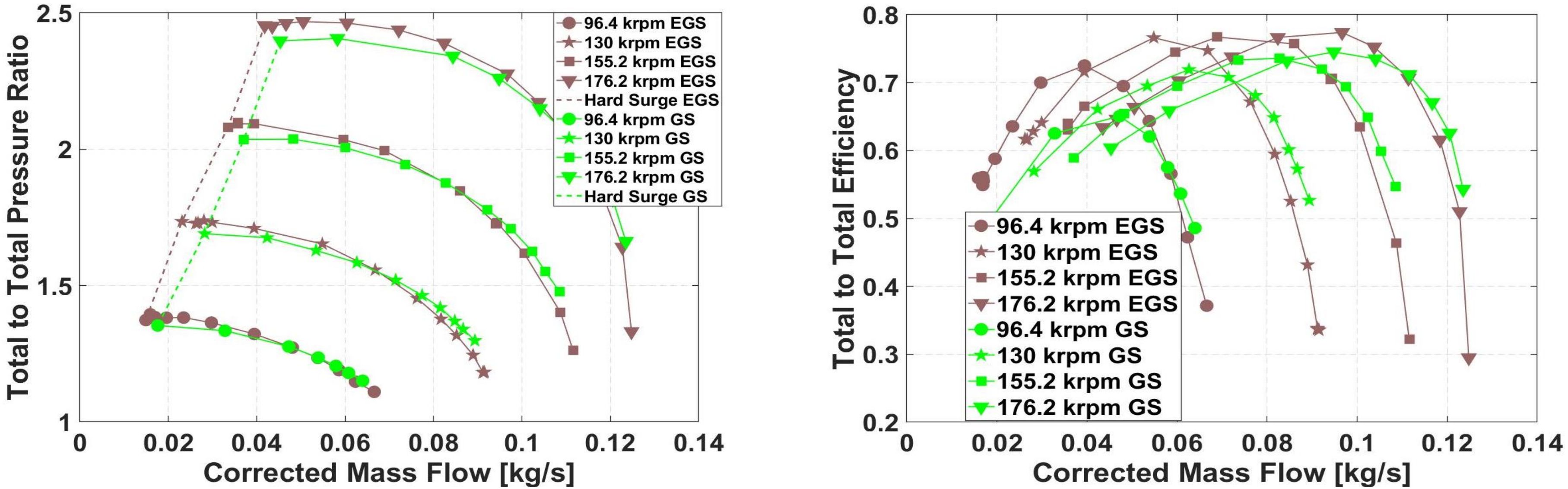
Oil conditioning Unit



Boost rig (8bar Max)

ABB flow meter (0-720kg/h)

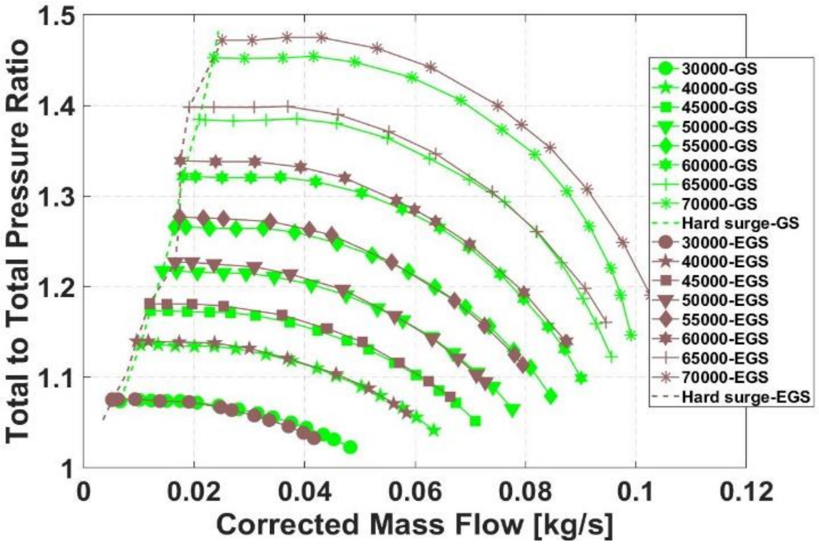
Experimental Result

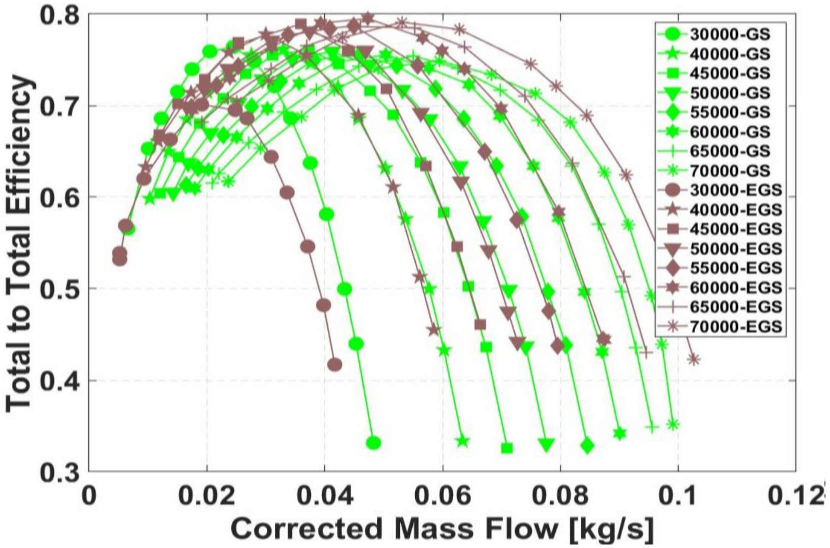


Component level example 1: Turbocharger compressor map

- Steady flow compressor map from the EGS and conventional GS
- Marginally higher PR and lower heat transfer increase compressor efficiency in EGS

Experimental Result



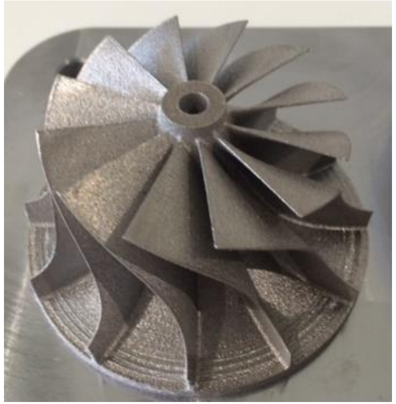


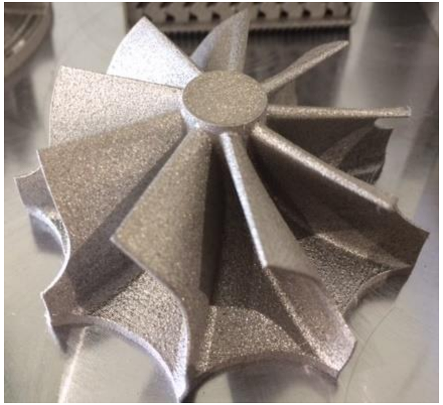
Component level example 3: eBooster map

- EGS Vs Manufacturer map – good agreement in MFR Vs PR.
- Marginally higher PR in EGS due to difference in pipe work resulted in marginally higher PR and hence higher compressor efficiency in EGS

Contents

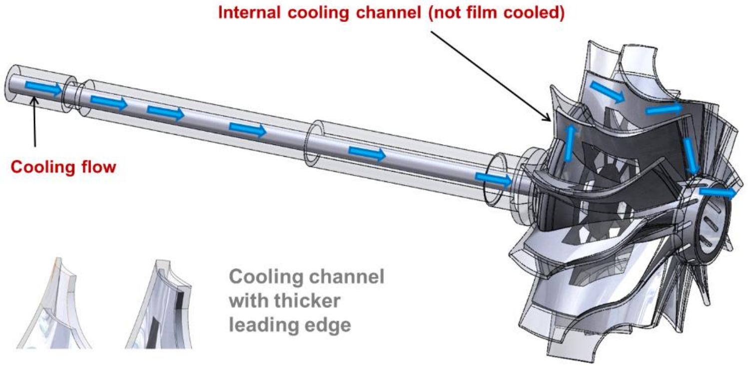
CHARM: Cooled, High temp Auto Radial Machinery

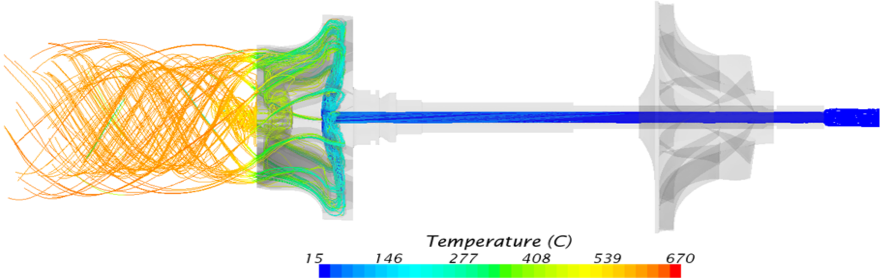


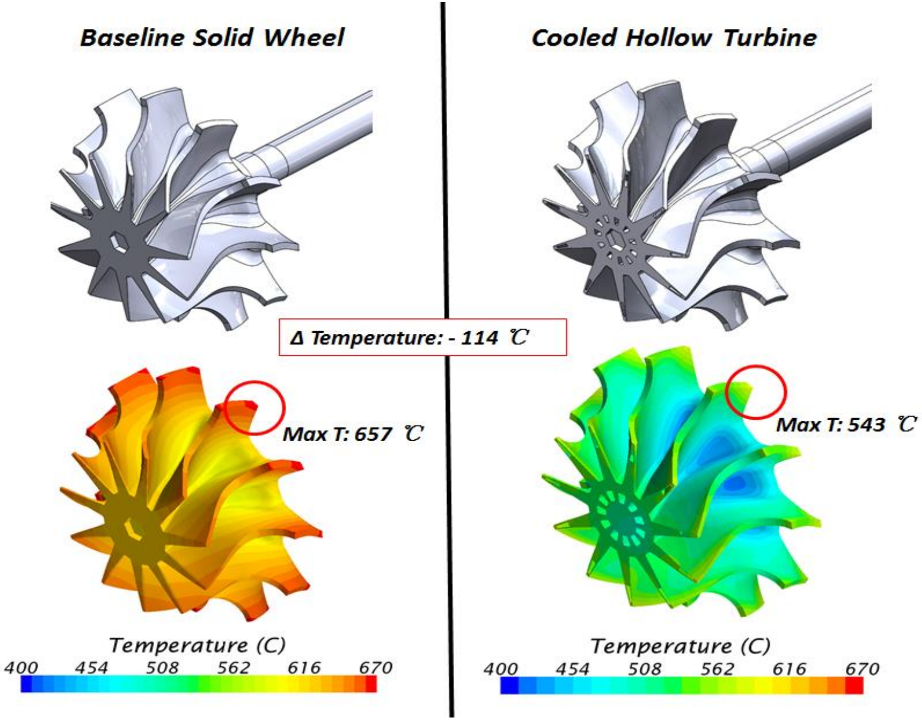


Project Objectives: Deliver AM, air-cooled nickel superalloy radial turbine for automotive applications, capable of operating at high exhaust temperatures.

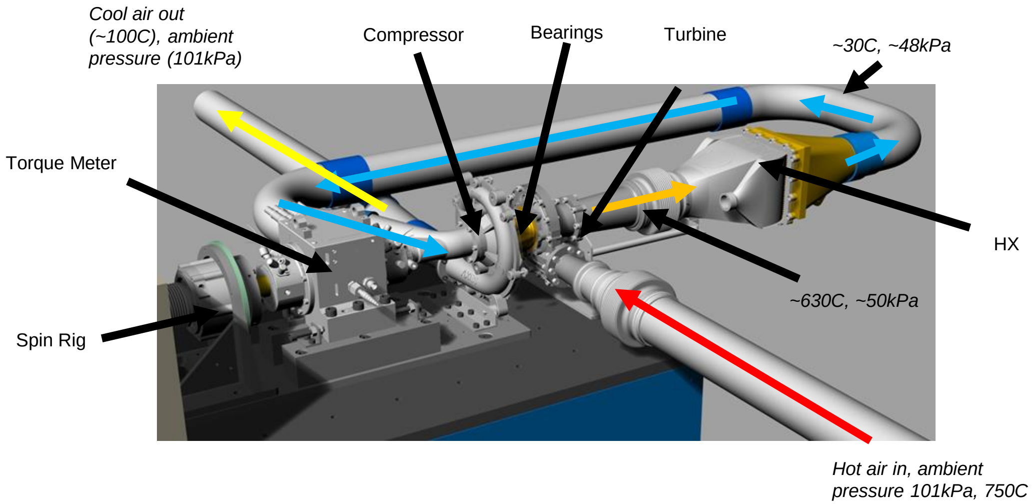
SLM Internally Cooled Turbine Wheel

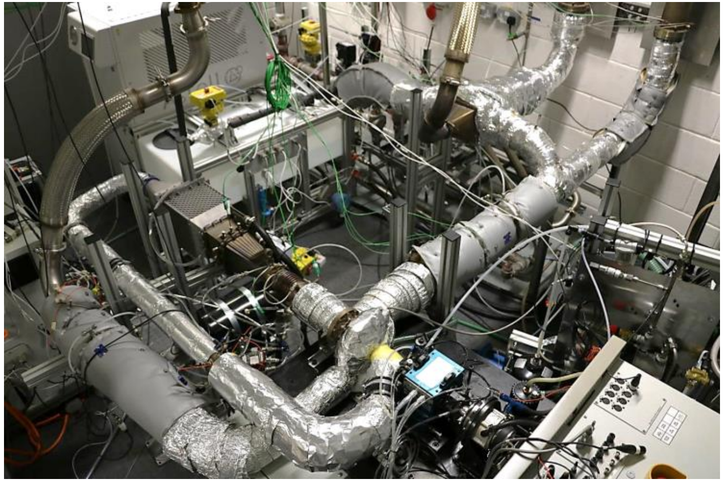






Direct Exhaust-energy Heat-recovery





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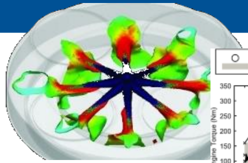
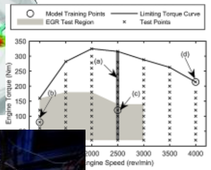
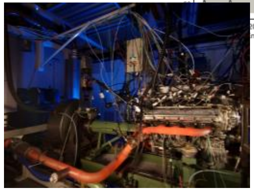
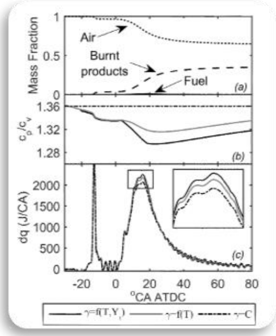
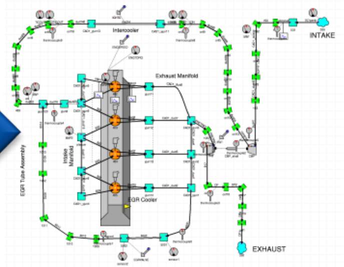
Future Vision: Model Creation







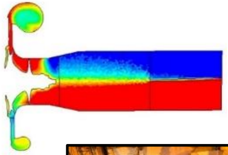


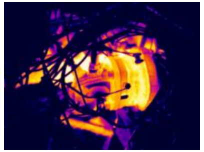


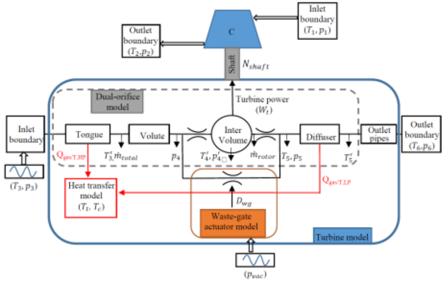
High Order models and HiL testing

Parameterized low order models

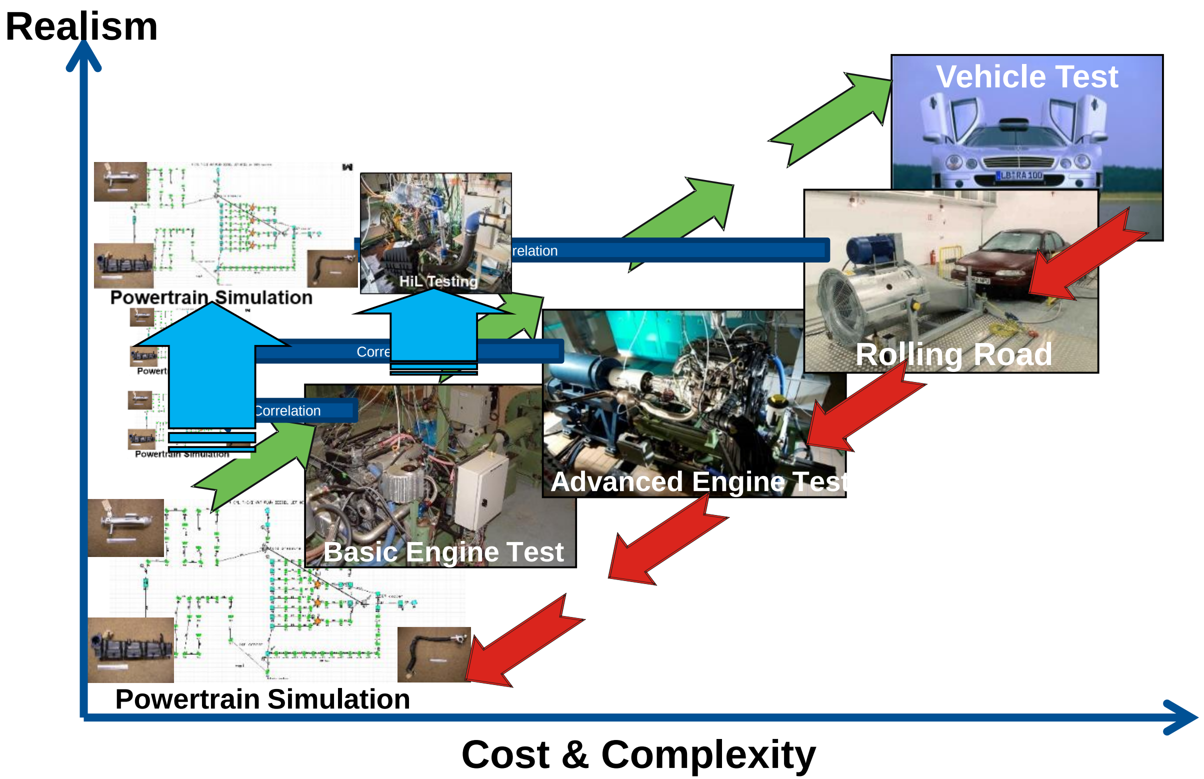
HW/Control optimization in system simulation







Powertrain Development



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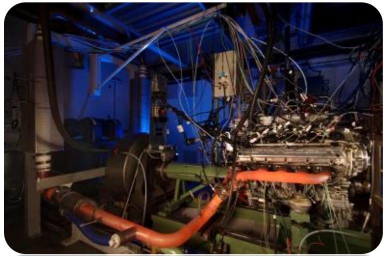
Thank you, Any questions?



Thank you

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Thanks to my colleagues Dr Richard Burke, Dr Colin Copeland and many others

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