Design & Development of e-Turbo™ for SUV and Light Truck Applications

Steve Arnold

Craig Balis

Etienne Poix

Tariq Samad

S. M. Shahed

Honeywell Turbo Technologies

Diesel Engine Emissions Reduction Conference

August, 2004

Acknowledgements

US DoE

John Fairbanks

Gurpreet Singh

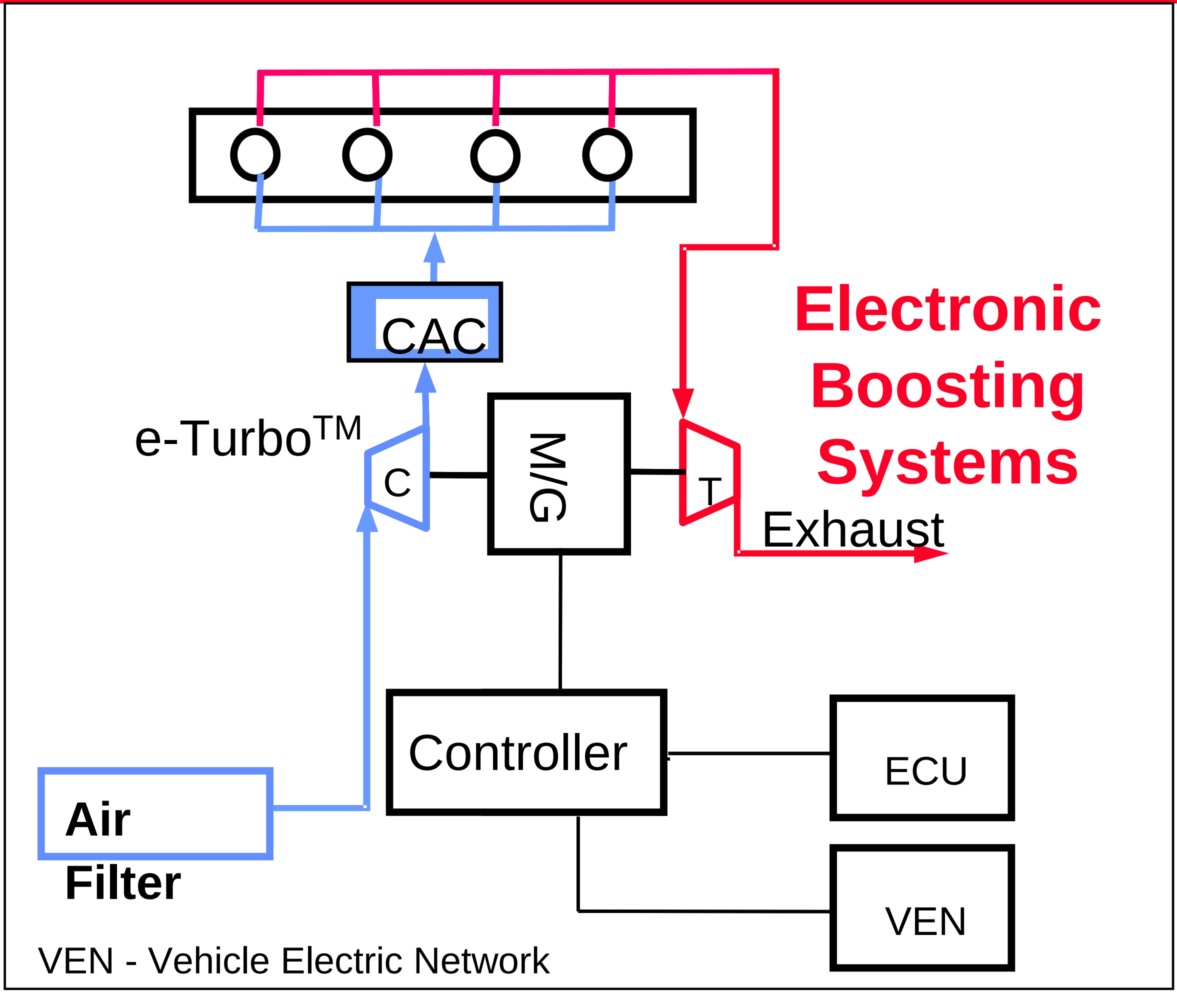
Presentation Outline

- Base Integration of Turbocharger and Electrical Machinery in Suitable Sizes
  - Background/Benefits
  - Status from 2003 DEER Conference
  - Progress - Gen 1, 2 and 3 e -Turbo
  - Define Benefits/Issues “Go/No-Go” Criteria for Larger Turbos
- Variable Geometry Compressor to Realize Full Benefits of Electrical Assist
- Innovative Low Inertia Design to Reduce Demands of Electrical Power - to be Integrated with Electrical Machinery after Proof of Concept
- Integrated Control System Development for EGR, Electrical Machinery and VNT Vane Position

Presentation Outline

- Base Integration of Turbocharger and Electrical Machinery in Suitable Sizes
  - Background/Benefits
  - Status from 2003 DEER Conference
  - Progress - Gen 1, 2 and 3 e -Turbo
  - Define Benefits/Issues “Go/No-Go” Criteria for Larger Turbos
- Variable Geometry Compressor to Realize Full Benefits of Electrical Assist
- Innovative Low Inertia Design to Reduce Demands of Electrical Power - to be Integrated with Electrical Machinery after Proof of Concept
- Integrated Control System Development for EGR, Electrical Machinery and VNT Vane Position

Background: e-Turbo™: Levels/Benefits



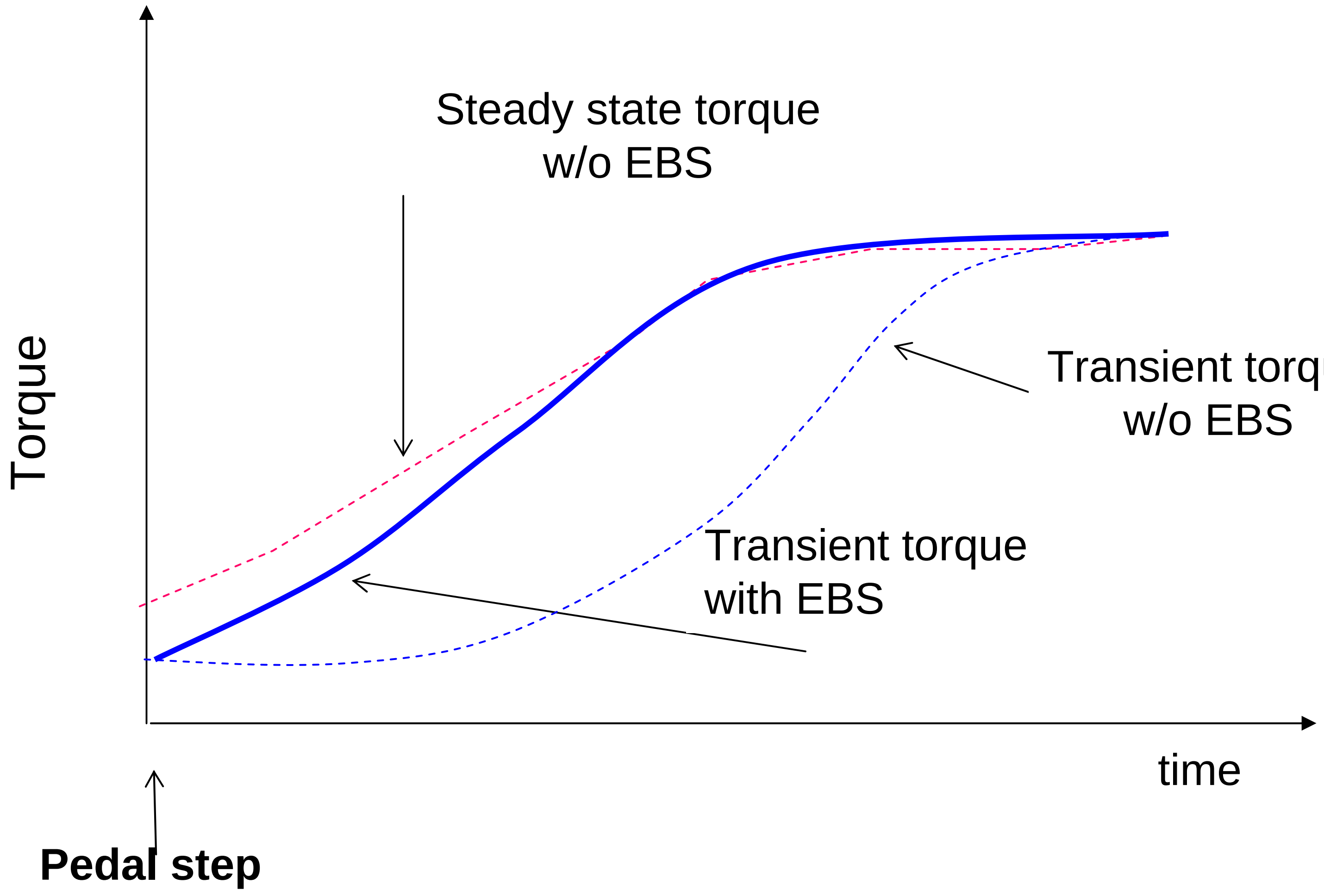
Three Levels of System Benefits

- **Performance - Eliminate Turbolag**
- **Aggressive Engine Downsizing**
- **Air Management System - Synergy with EGR, Fuel Injection, Aftertreatment, Vehicle Power Demands**

M/G - Supplier Developed 12 V DC Input 2 kW Induction Motor/Generator

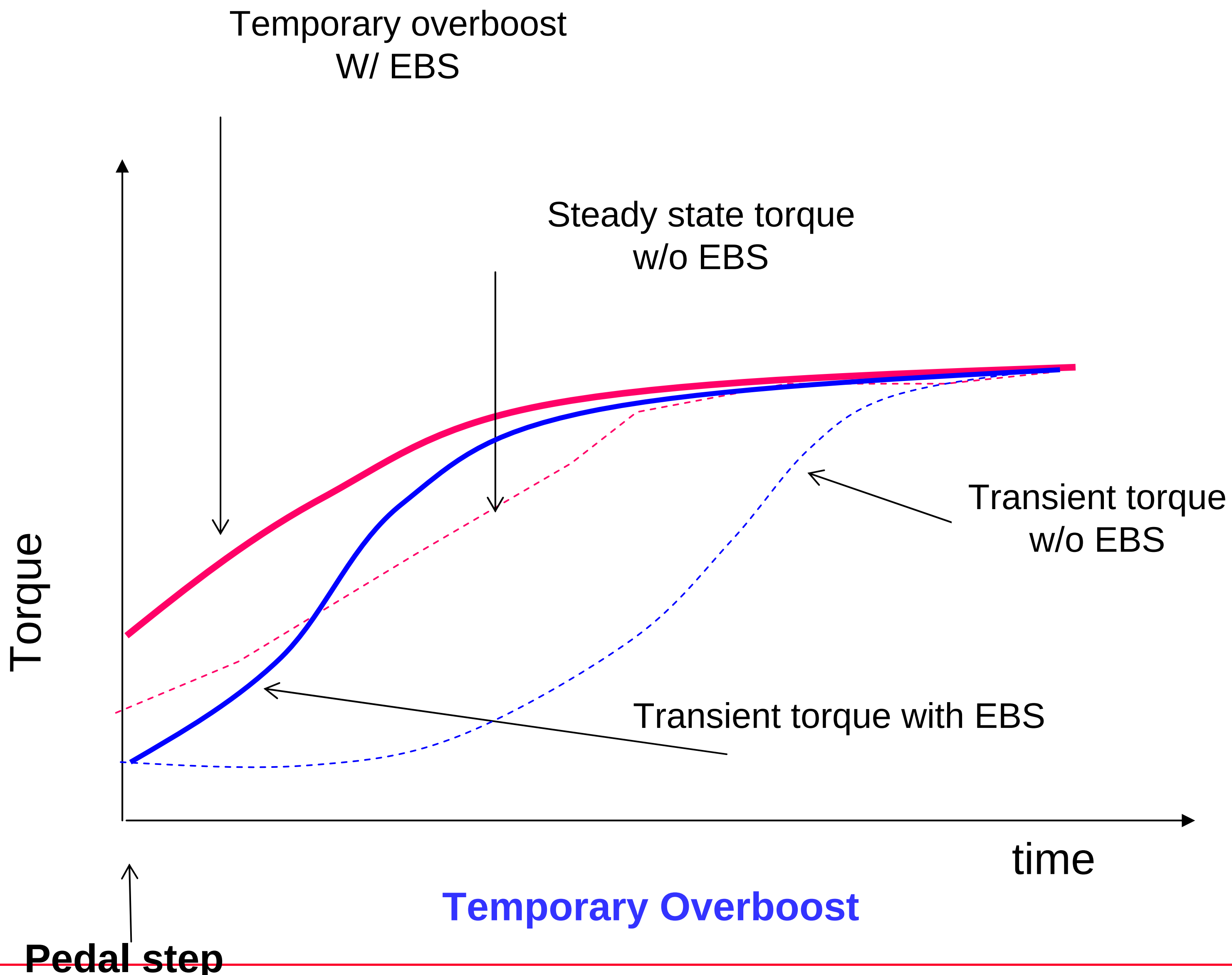
Controller - Supplier Developed

Performance Benefits Level I - Eliminate Turbo-lag



Transient Time-to-Boost Improvement

Performance Benefits – Level II Engine Rightsizing



Temporary Overboost

Status from 2003 - Critical "Go/No-Go" Criteria

- High-speed motor/controller system to provide up to 1.4kW mechanical power at speeds up to 175kRPM total system efficiency > 60%.
- Turbocharger bearing system to carry the extra mass and length while still retaining acceptable shaft rotor-dynamic behavior up to 225kRPM.
- Turbocharger and motor cooling system to protect the motor from the extreme turbocharger thermal environment as well as from self-heating.
- Compressor aerodynamics to deliver the extra boost without suffering from surge ("stall") during the transient.

Designs Successfully Establish Feasibility

Fundamental e-Turbo Technical Challenges

Design Criterion	Target	Why	Previous Design	Improved Design
Speed Limit	> 225 Krpm	Aerodynamic performance	< 190,000 rpm • Unstable bearing • Weak motor rotor	Successful
Motor Torque at low speed	0.25 Nm	Boost at low engine speed	< 0.15 Nm	Successful
High speed power	1200-1400 W	Boost performance	< 1000 W	Successful
Motor speed at target power	> 175,000 rpm	Boost up to 2000 rpm engine speed	< 150,000 rpm	Successful
Controller Efficiency	> 70%	Electrical power impact	25-50%	Close
Motor temperature	Normal duty cycle Survival at all "off" conditions	Duty cycle requirements	• Limited usage • Failure at severe "off" conditions	Successful

Technical Feasibility Demonstrated

Presentation Outline

- Base Integration of Turbocharger and Electrical Machinery in Suitable Sizes
  - Background/Benefits
  - Status from 2003 DEER Conference
  - Progress - Gen 1, 2 and 3 e -Turbo
  - Define Benefits/Issues “Go/No-Go” Criteria for Larger Turbos
- Variable Geometry Compressor to Realize Full Benefits of Electrical Assist
- Innovative Low Inertia Design to Reduce Demands of Electrical Power - to be Integrated with Electrical Machinery after Proof of Concept
- Integrated Control System Development for EGR, Electrical Machinery and VNT Vane Position

Progress with Gen 1, 2 & 3 e-Turbo

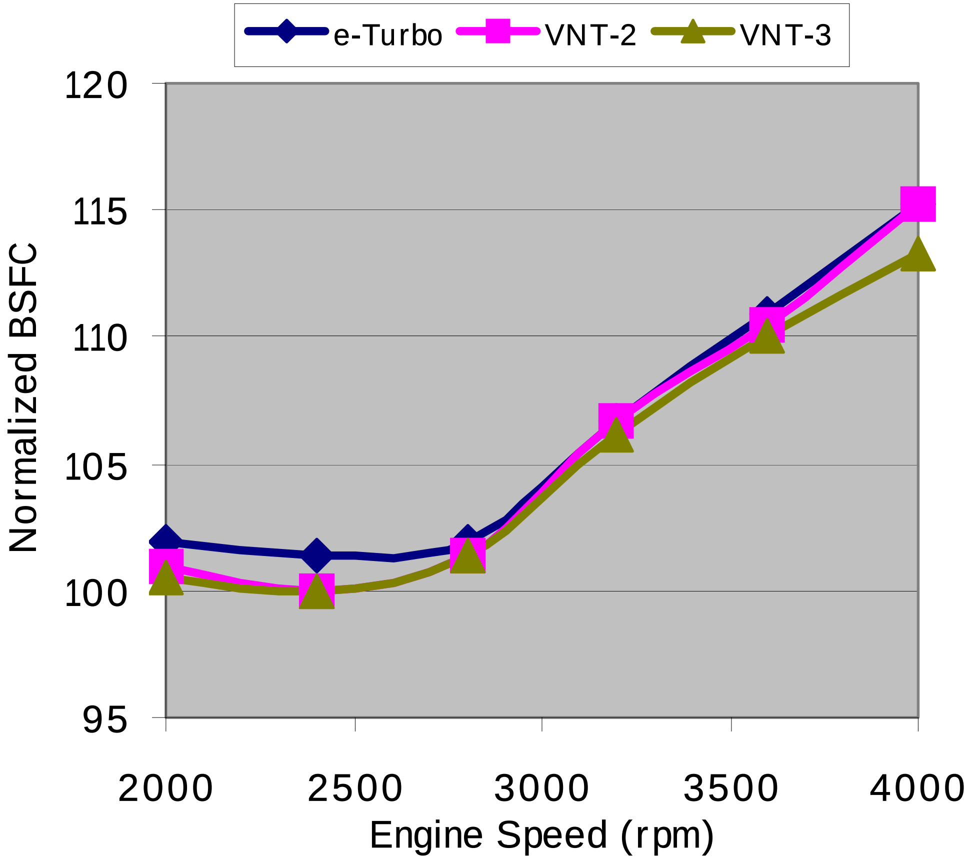
Progress with turbomachinery design and electrical machinery integration continues

Three areas of results reported

- Steady state efficiency and torque
- Transient torque
- Electrical power generation

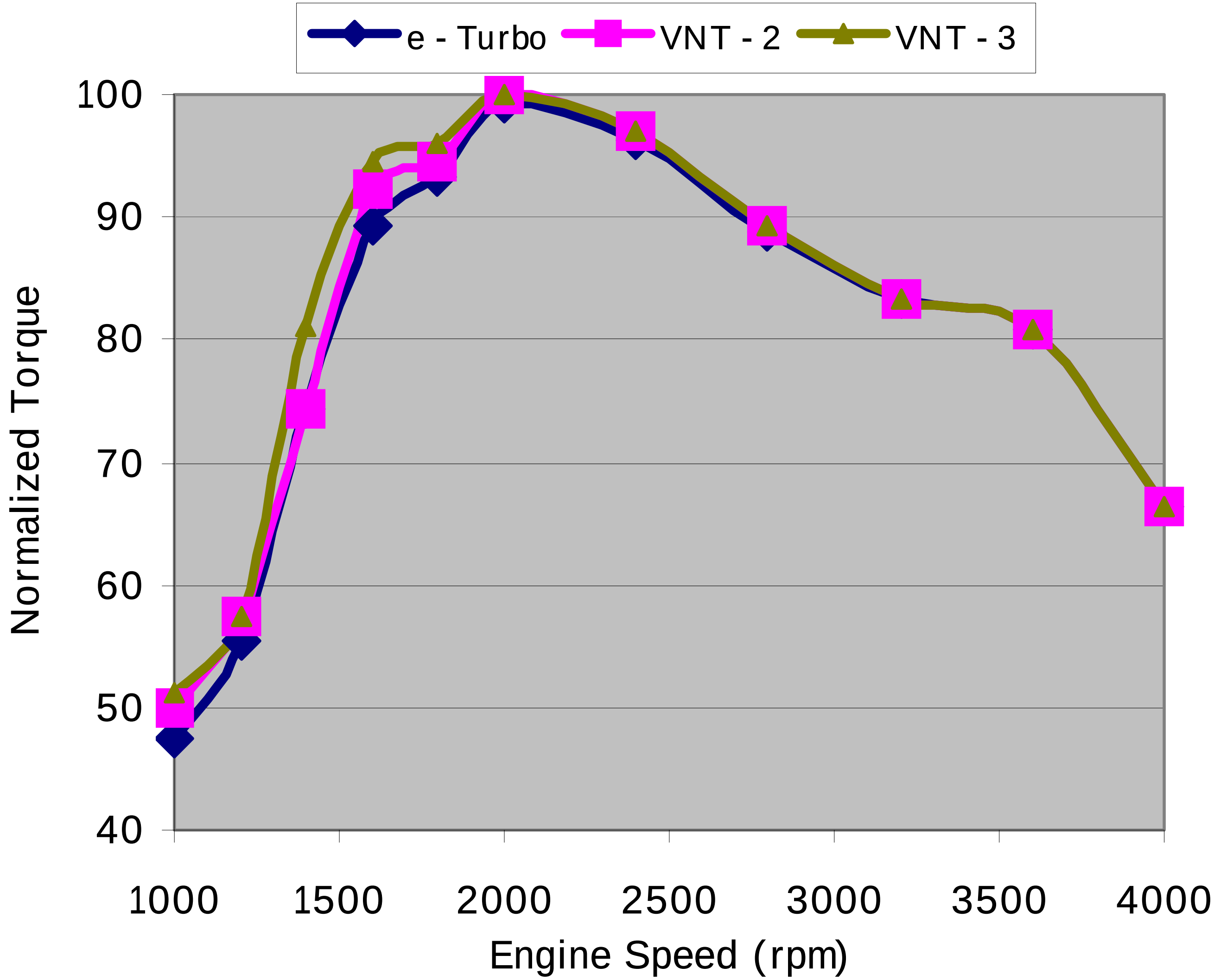
Steady-State Efficiency

- Engine efficiency w e -Turbo off: - 2% @ 2000-2800rpm
- Because engine delta P is higher
- Phenomenon more sensitive when engine speed decreases



e-Turbo™ efficiency slightly lower

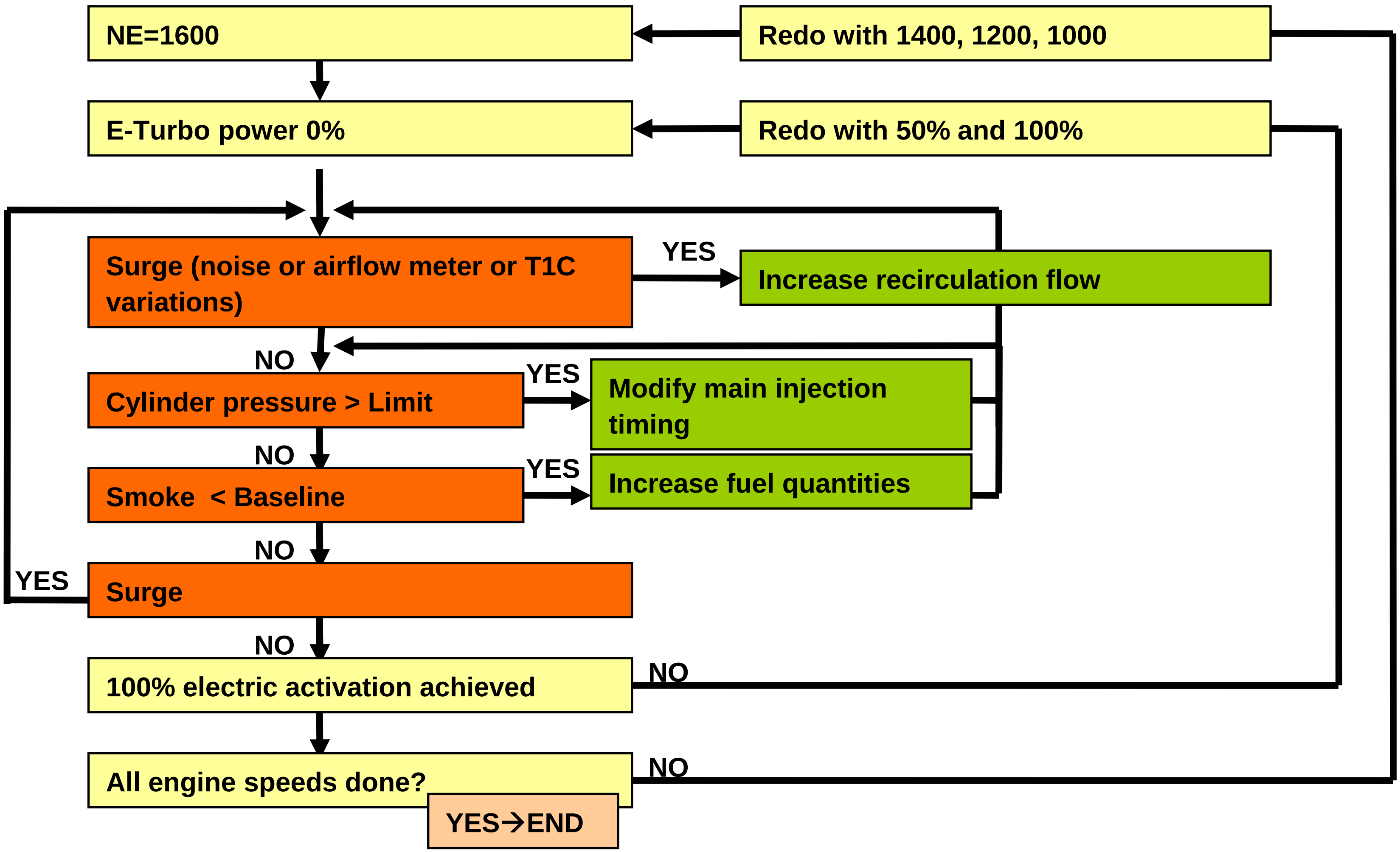
Steady-State Torque w/o Electric Activation



With recalibration, baseline torque level is recovered

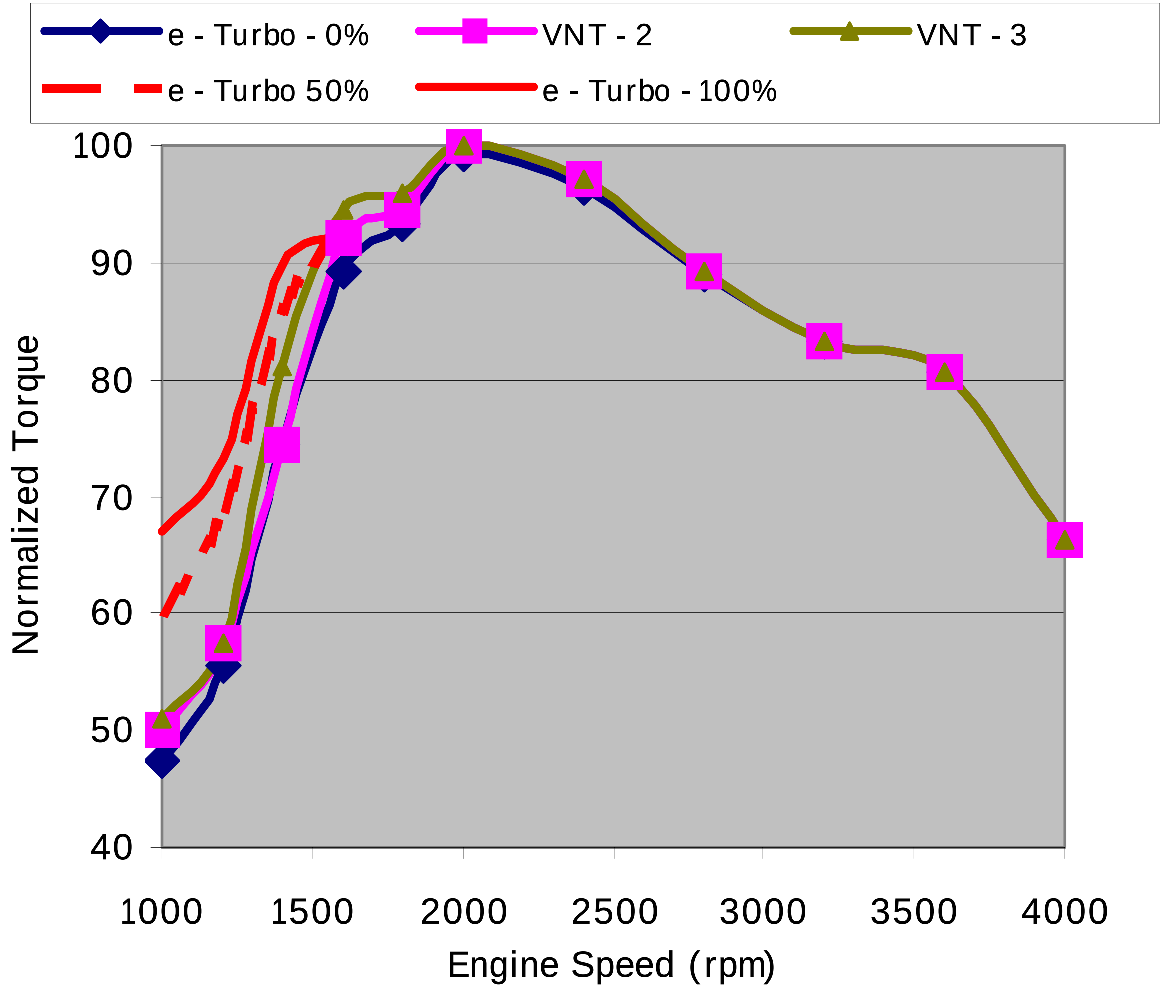
Recalibration Methodology

- e-Turbo™ activation provides more air to the engine. So, to get overtorque, this higher airflow needs a fuel recalibration:



Legend: Parameters = green boxes and Constraints = orange boxes

Steady-State Torque with Electric Activation

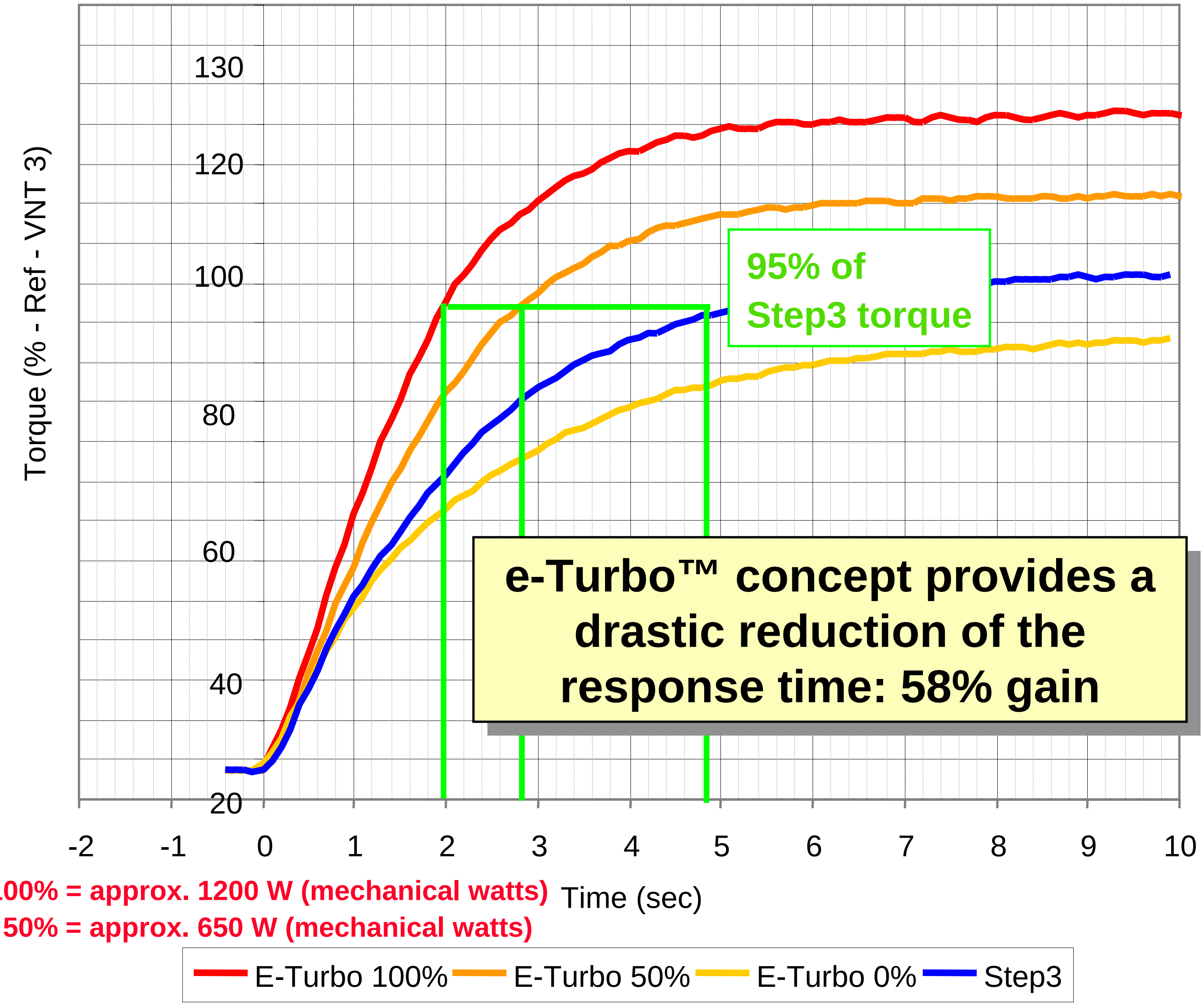


-Electric activation provides a high increase of torque:

33-27-12% more than Step 3 at 1000, 1200, and 1400rpm

43-32-21% more than e-Turbo™ off (0%)

Transient Response @1250 rpm

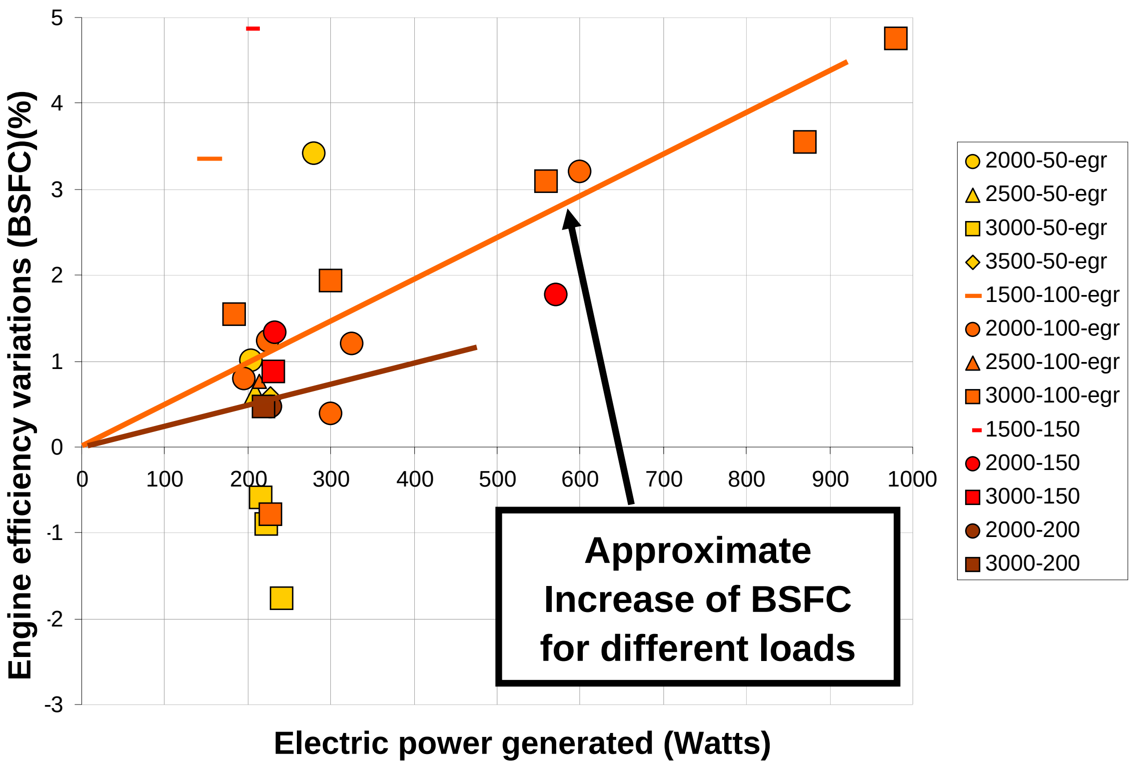


100% = approx. 1200 W (mechanical watts)
50% = approx. 650 W (mechanical watts)

	Ref: Step3	Ref: E-Turbo 0%
E-Turbo 100%	2,0s 58%	1,7s 74%
E-Turbo 50%	2,8s 42%	2,3s 65%
E-Turbo 0%		6,6s 0%
Step3	4,8s 0%	3,4s 48%

Electric Power Generation

- **Efficiency effects**
  - The BSFC increases less if exhaust enthalpy is high
  - Between 2000-3000rpm:
    - +1% for 400W @ 200Nm
    - +2% for 400W @ 100Nm
- **No major impact on NOx, HC, CO emissions**
- **Unable to quantify the BSFC variation when load and fuel flow are low**
- **Unable to generate if exhaust enthalpy is too low (example 2000-25Nm)**



- Generating electricity is possible if load isn't too low
- Cost around 1% of BSFC to generate 200W @ 2000rpm-100Nm
- It has no effect on emissions

Rough Comparison with Alternator

- **250W of electrical power output**
- **Alternator efficiency: 67-61-59% @ 1000-2000-3000rpm**
- **e-Turbo™ approximate results: from previous slide**

Operating point		*Increase of BSFC (%)*	
rpm	*load (Nm)*	*w alternator*	*w e-Turbo*
1000	25	14,3	No power
1000	50	7,1	No power
1000	100	3,6	No power
2000	25	7,8	No power
2000	50	3,9	better
2000	100	**2,0**	**better**
2000	200	**1,0**	**better**
3000	25	5,4	better
3000	50	2,7	better
3000	100	**1,3**	**same**
3000	200	**0,7**	**same**

Depending on the operating point:

-e-turbo™ unable to generate

-e-turbo™ better than an alternator

-e-turbo™ as good as an alternator

*** The variations of BSFC are lower than the noise in fuel consumption measurements**

Conclusions - Electric Assist

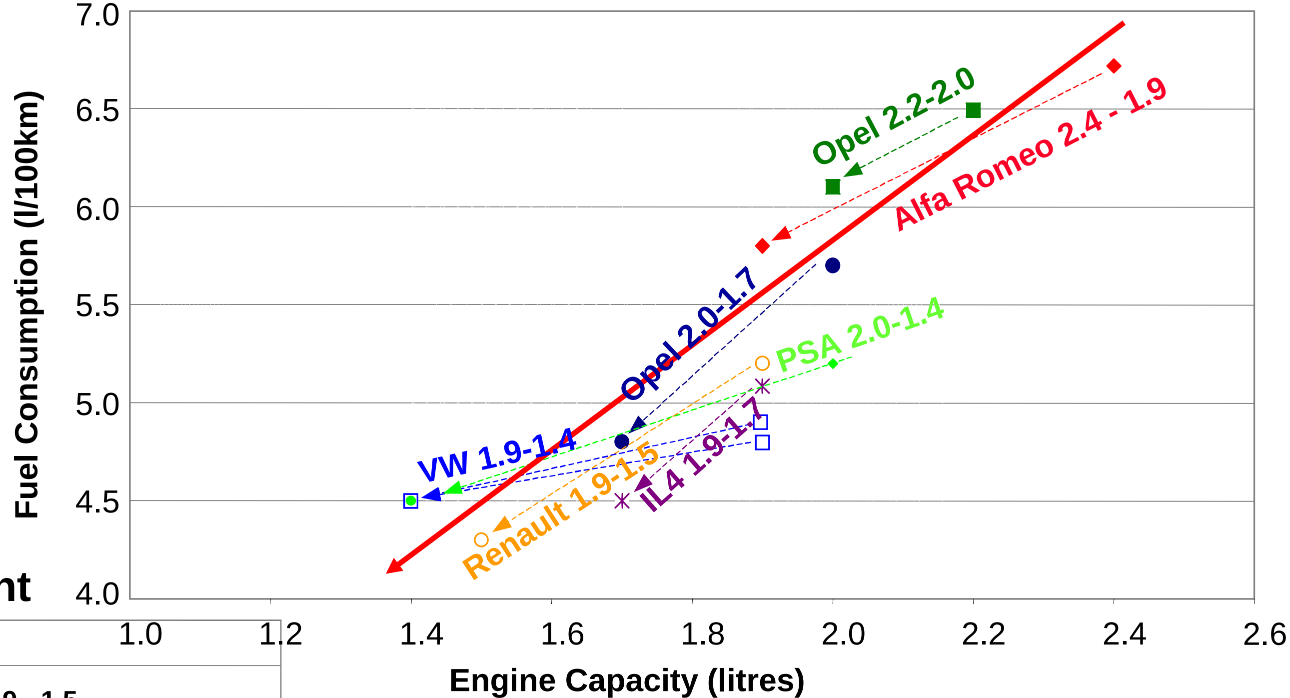
1. Steady-state torque increase
   - 43% @ 1000rpm (compared to e-Turbo™ off)
   - Could be higher if lambda value was lower

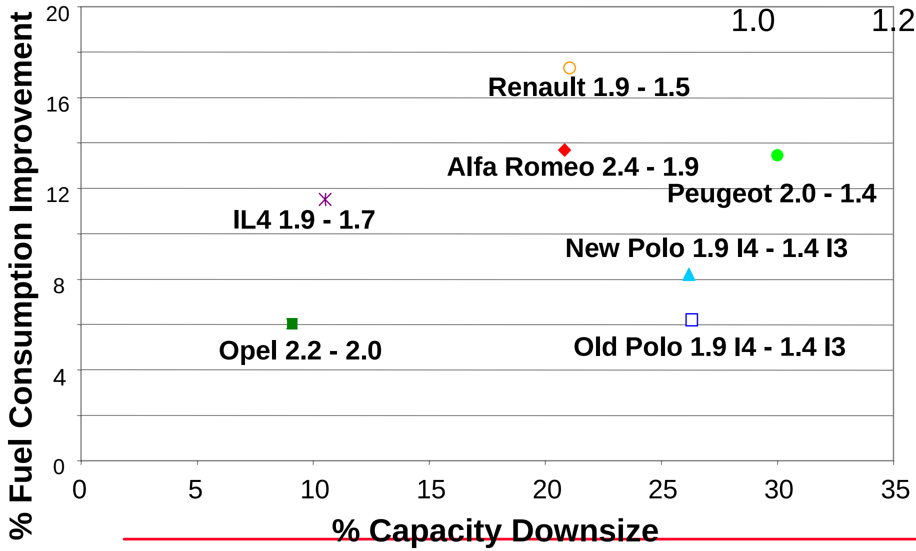
2. Better time to torque
   - Gain of around 70% between 1000-1500rpm (compared to e-Turbo™ off)
   - Could be higher if lambda value was lower

3. Electrical power generation ability
   - Seems to have a better efficiency than an alternator
   - However, generation is limited to certain conditions

Reminder: Benefits of Engine Rightsizing not Included in the Previous Discussion

European Production Models Same Vehicle





10-30% Downsizing

6-17% Fuel Economy Improvement

Credits RICARDO

Presentation Outline

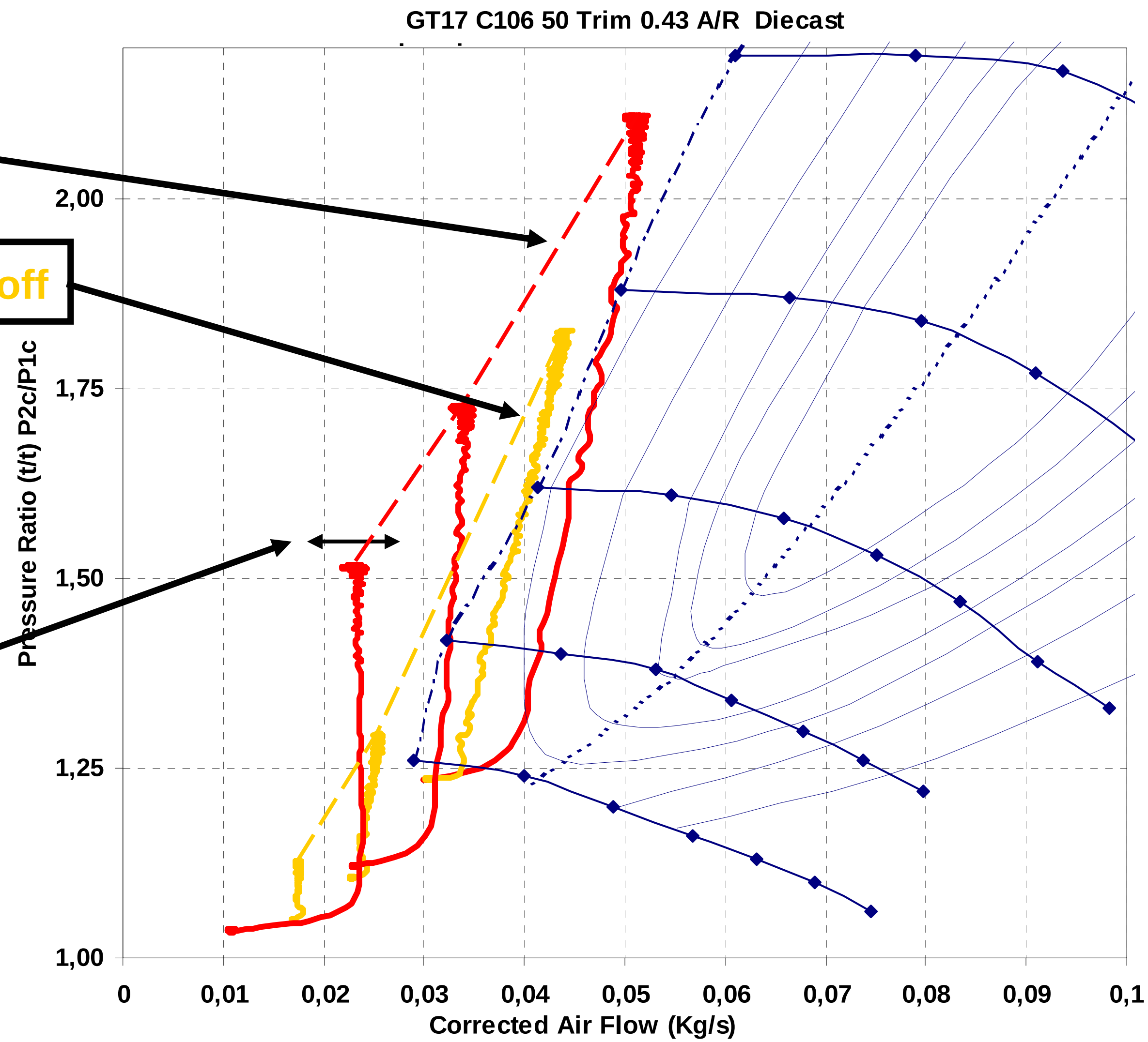
- Base Electrical Machinery Development for Integration into Turbochargers of Suitable Sizes
  - Background/Benefits
  - Status from 2003 DEER Conference
  - Progress - Gen 1, 2 and 3 e -Turbo
  - Define Benefits/Issues “Go/No-Go” Criteria for Larger Turbos
- Variable Geometry Compressor to Realize Full Benefits of Electrical Assist
- Innovative Low Inertia Design to Reduce Demands of Electrical Power - to be Integrated with Electrical Machinery after Proof of Concept
- Integrated Control System Development for EGR, Electrical Machinery and VNT Vane Position

Flow Stability at Low Speeds

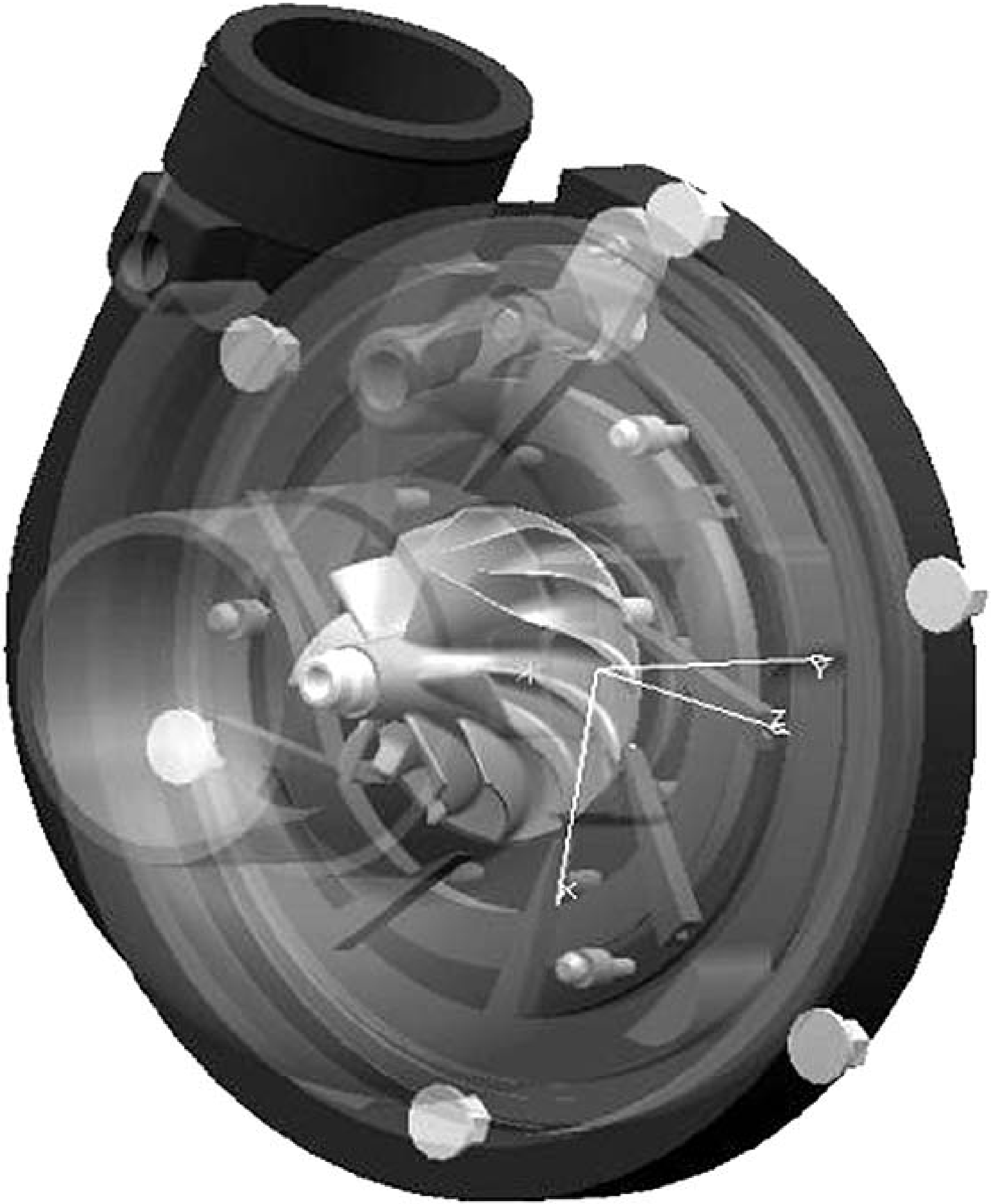
Lugline 100% or 1200W

Lugline 0% or e-Turbo™ off

Surge sometimes appears (oscillations of airflow)



Variable Geometry Compressor Concept



Presentation Outline

- Base Electrical Machinery Development for Integration into Turbochargers of Suitable Sizes
  - Background/Benefits
  - Status from 2003 DEER Conference
  - Progress - Gen 1, 2 and 3 e -Turbo
  - Define Benefits/Issues "Go/No-Go" Criteria for Larger Turbos
- Variable Geometry Compressor to Realize Full Benefits of Electrical Assist
- Innovative Low Inertia Design to Reduce Demands of Electrical Power - to be Integrated with Electrical Machinery after Proof of Concept
- Integrated Control System Development for EGR, Electrical Machinery and VNT Vane Position

Work in Progress

Presentation Outline

- Base Electrical Machinery Development for Integration into Turbochargers of Suitable Sizes
  - Background/Benefits
  - Status from 2003 DEER Conference
  - Progress - Gen 1, 2 and 3 e -Turbo
  - Define Benefits/Issues “Go/No-Go” Criteria for Larger Turbos
- Variable Geometry Compressor to Realize Full Benefits of Electrical Assist
- Innovative Low Inertia Design to Reduce Demands of Electrical Power - to be Integrated with Electrical Machinery after Proof of Concept
- Integrated Control System Development for EGR, Electrical Machinery and VNT Vane Position