Advanced boost system development for diesel HCCI/LTC applications

2012 DOE Peer Review

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Project ID: ace037

Timeline

- Project start: Oct. 1, 2007
- Project end: Sept. 30, 2012
  (No-cost extension)
- Percent complete: 80%

Budget

- Total project funding
  - DOE: $1,495K
  - Contractor: $1,495K
- FY08 (received): $75.4K
- FY09 (actual): $235K
- FY10 (actual): $331.5K
- FY11 (actual): $301K
- FY12 (estimated): $552K

Barriers

Barriers addressed

- Improve low end efficiency while maintaining high end flow capacity of the turbocharger
- Improve engine fuel economy on customer driving cycles while accommodating high EGR that is required for future emission regulations
- *Program targets*: 2-3% fuel economy improvement on customer driving cycles and 15-20 % extension of operation range

Partners

- Ford Motor Co. (project lead)
- ConceptsNREC
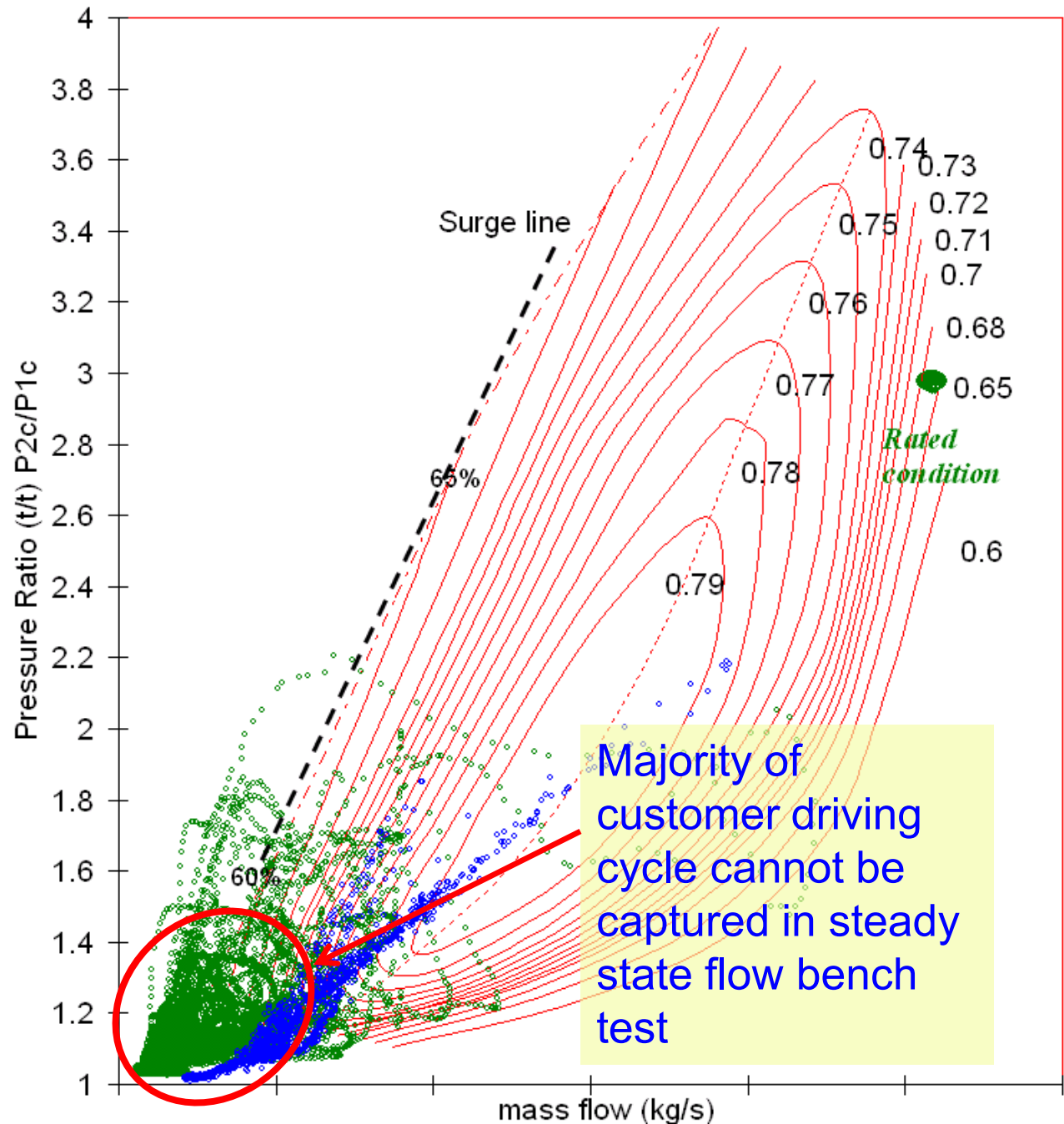- Wayne State University
- Three turbocharger suppliers

Emission regulation:
Heavy EGR needed for LTC pushes the operation points into less efficient or even surge area

Market competitiveness:
Centrifugal compressor needs to have wide range for high horse power and better efficiency at low end for better fuel economy on customer driving cycles

Objectives:
2-3% fuel economy improvement on customer driving cycles and 15-20% extension of turbo operation range
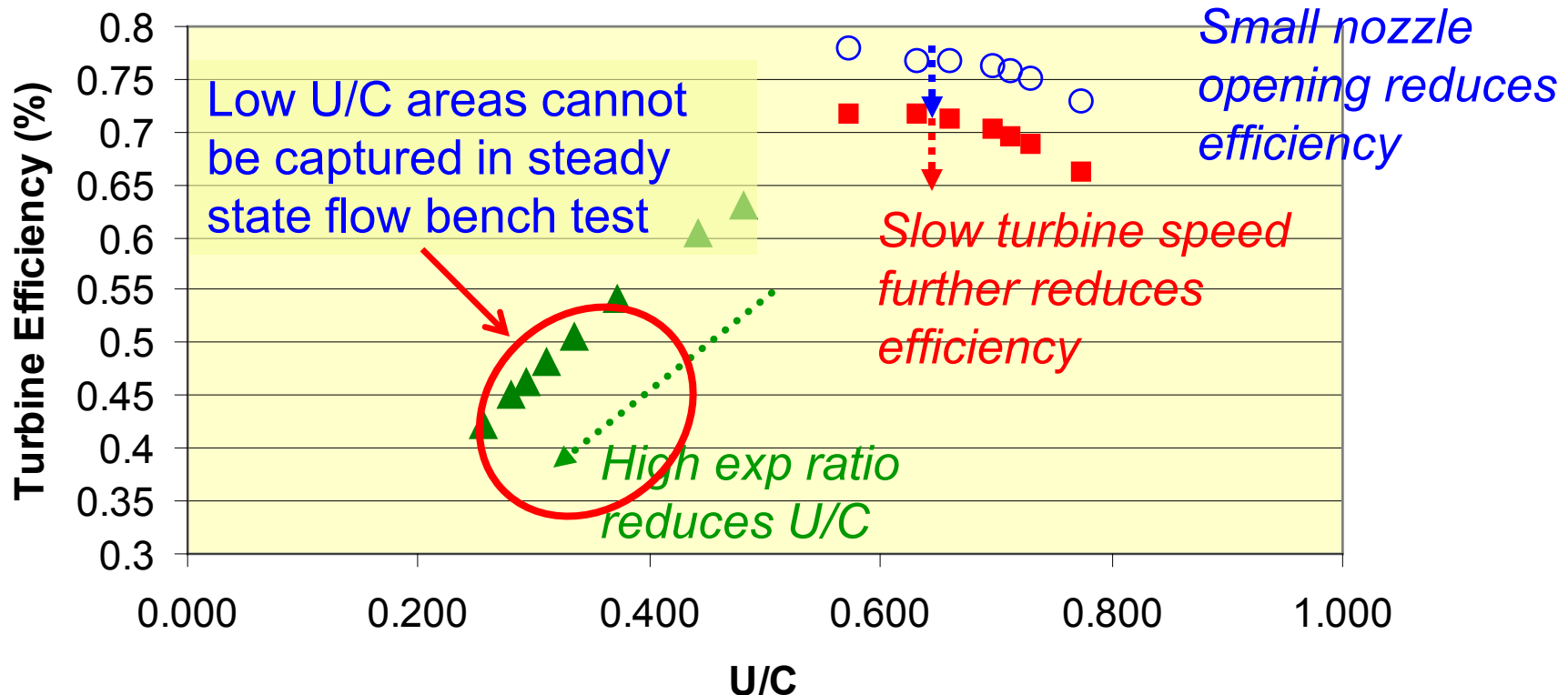

Majority of customer driving cycle cannot be captured in steady state flow bench test

Turbine Efficiency vs. U/C

$$\frac{U}{C} = \frac{U}{\sqrt{2C_p T_0\left[1-(\pi_T)^{-0.285}\right]}}$$

Small nozzle opening reduces efficiency

Low U/C areas cannot be captured in steady state flow bench test

Slow turbine speed further reduces efficiency

High exp ratio reduces U/C

○ 60% open, high speed   ■ 40% open, high speed   ▲ 40% open, low speed

Conventional radial flow VGT has low efficiency at small nozzle open positions and low U/C. Heavy EGR, bigger turbo pushes part load turbine operation points into less efficient areas, i.e. more stringent emission requirement may penalize the fuel economy
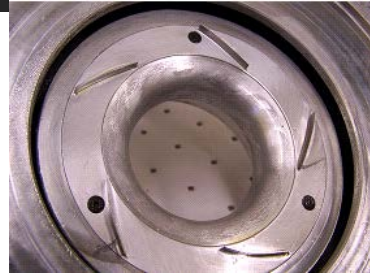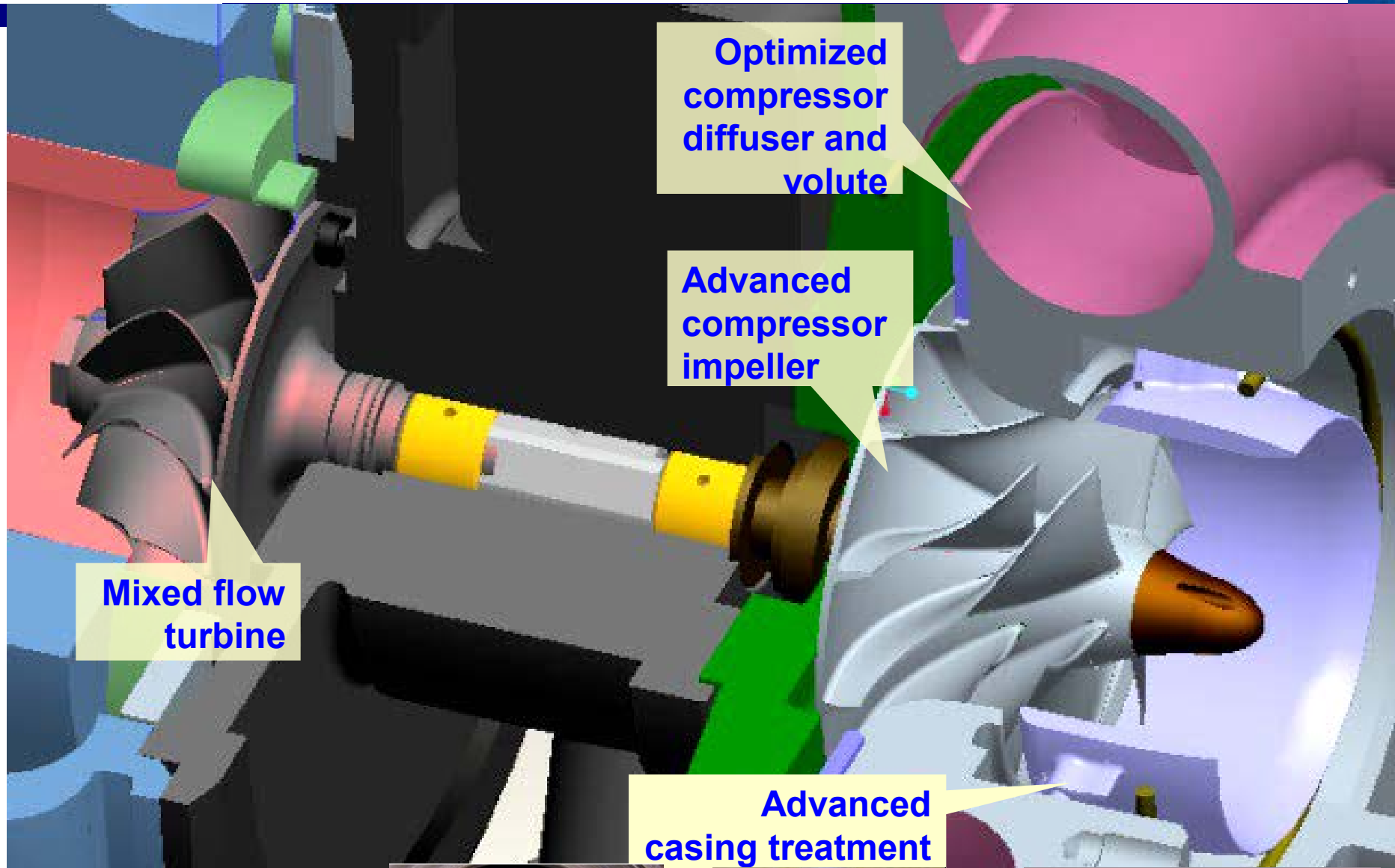
Relevance/objectives

Turbine Speed Ratio (U/C) Distribution over EPA City Cycle

Heavy EGR shifts the operation points to low U/C

Legend: No EGR (1998MY) — With EGR, 2010MY
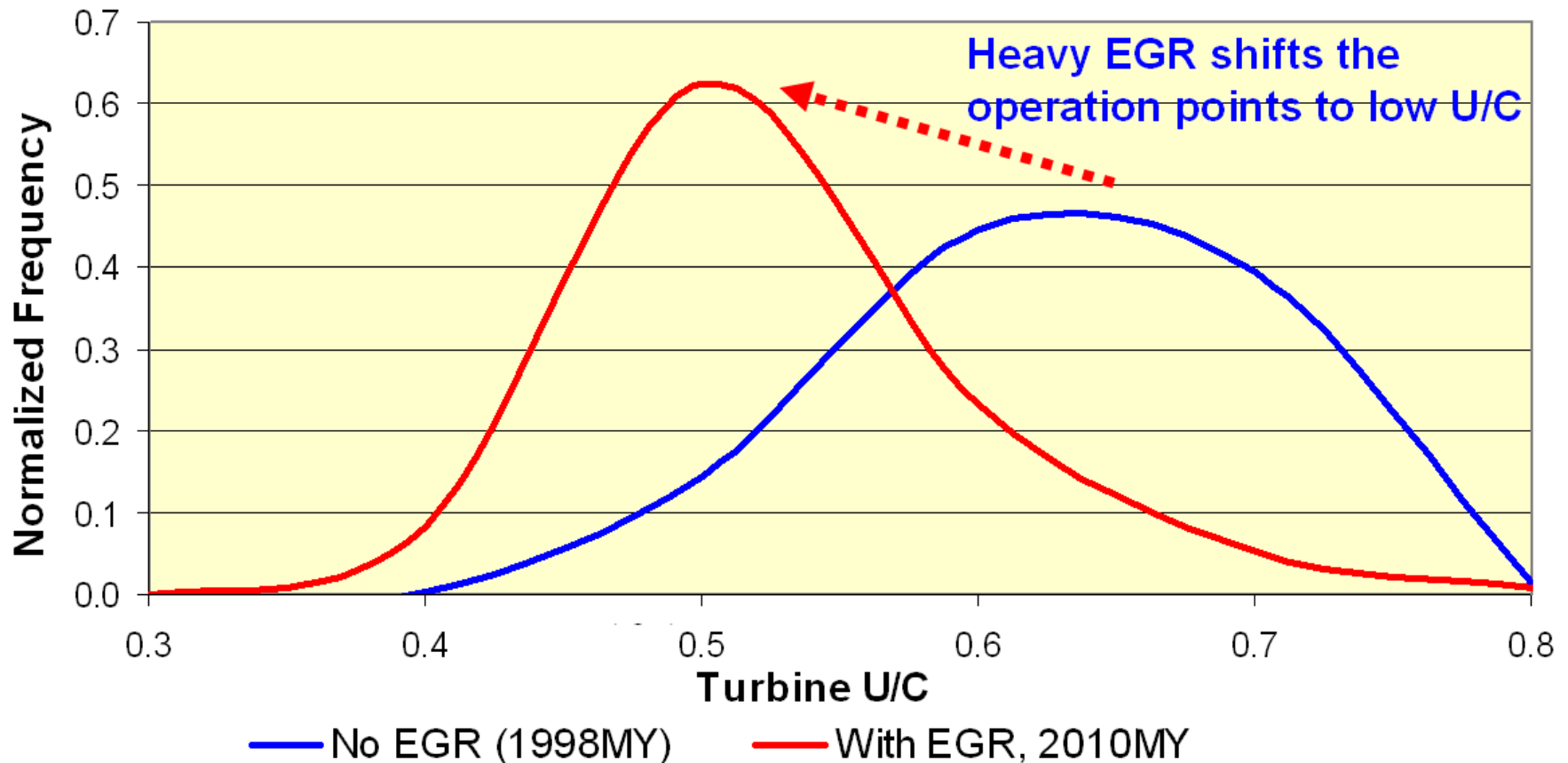
As more EGR is used for NOx reduction, turbine spends more time in low U/C area. Therefore future diesel application requires that turbine should have high efficiency in low U/C areas. Improvement of turbine efficiency at low U/C is critical for engine fuel economy
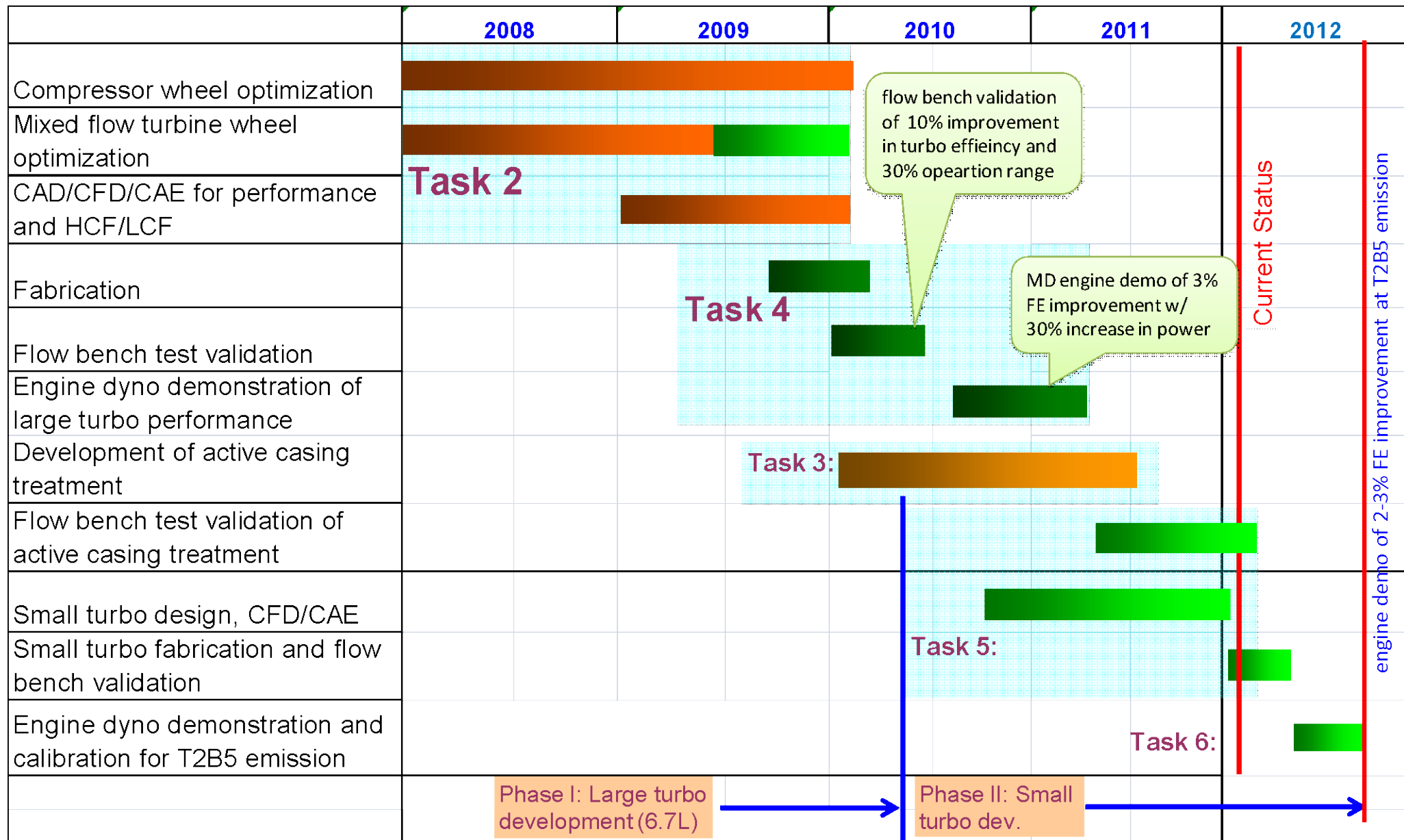
Objectives

Optimized compressor diffuser and volute

Advanced compressor impeller

Mixed flow turbine

Advanced casing treatment

Objectives

1. *About 20-40% of engine power is used to drive turbocharger for diesel applications. Therefore this study aims at 10-15% turbocharger efficiency improvement, which will translate into 2-3% fuel savings on customer driving cycle, for both medium duty and light duty diesels that are capable of meeting US Tier2 Bin5 emission regulations*

2. *Development of advanced compressor technology that is capable of driving high level of EGR required for diesel LTC/HCCI combustion while increasing choke flow capacity*

3. *Development of advanced mixed turbine technology that has superior efficiency at low U/C and low wheel speed while increasing efficiency when operating near choke conditions*

4. *Demonstrate superior turbocharger performance on flow bench*

5. *Demonstrate engine fuel economy improvement and T2B5 emission compliance on engine dynamometer with a LD diesel*
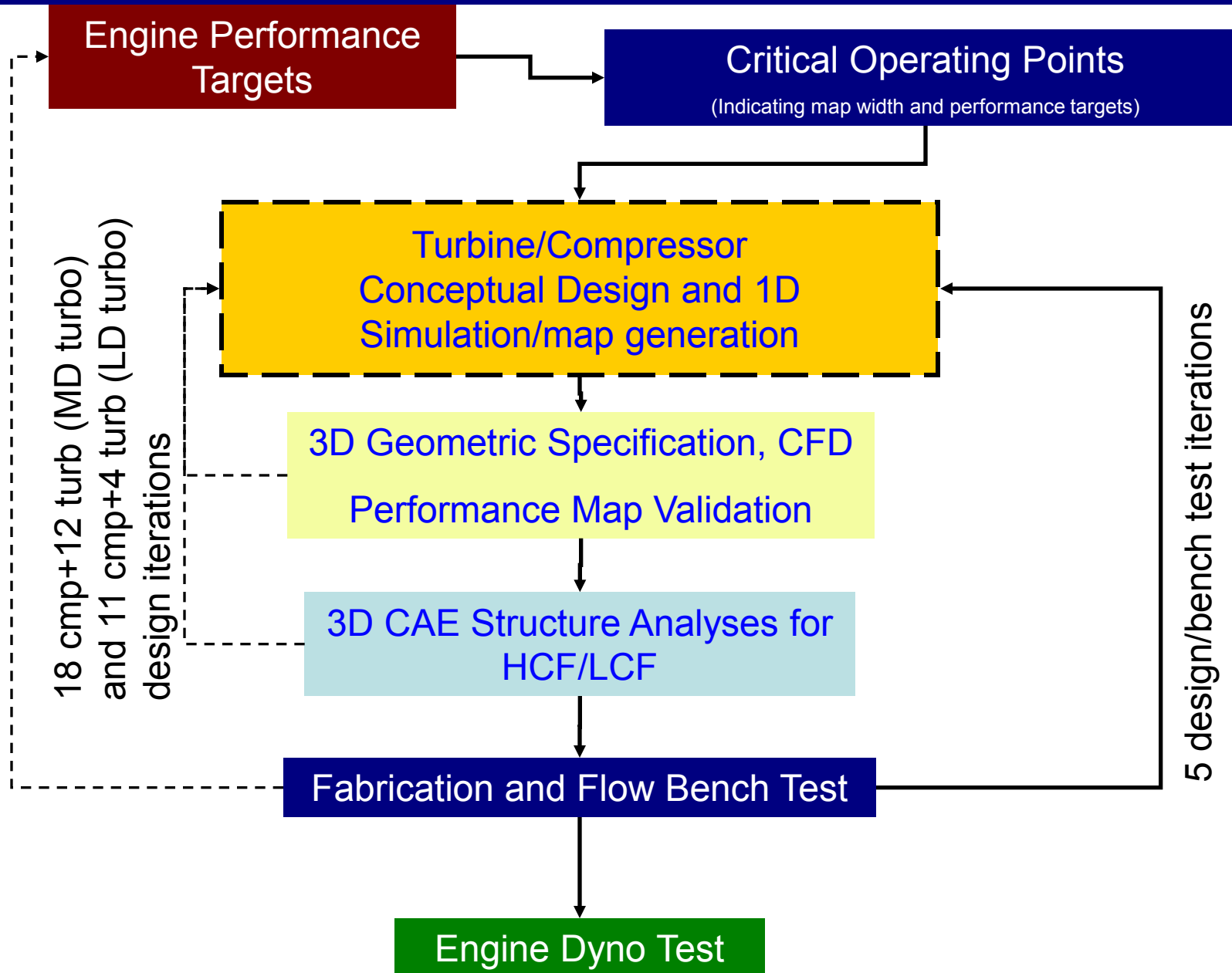
Milestone

	2008	2009	2010	2011	2012
Compressor wheel optimization					
Mixed flow turbine wheel optimization					
CAD/CFD/CAE for performance and HCF/LCF					
Fabrication					
Flow bench test validation					
Engine dyno demonstration of large turbo performance					
Development of active casing treatment					
Flow bench test validation of active casing treatment					
Small turbo design, CFD/CAE					
Small turbo fabrication and flow bench validation					
Engine dyno demonstration and calibration for T2B5 emission					

Task 2

Task 4

Task 3:

Task 5:

Task 6:

flow bench validation of 10% improvement in turbo effieincy and 30% opeartion range

MD engine demo of 3% FE improvement w/ 30% increase in power

Current Status

engine demo of 2-3% FE improvement at T2B5 emission

Phase I: Large turbo development (6.7L)

Phase II: Small turbo dev.

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Approach/*Strategies*

Engine Performance Targets → Critical Operating Points (Indicating map width and performance targets) → Turbine/Compressor Conceptual Design and 1D Simulation/map generation → 3D Geometric Specification, CFD Performance Map Validation → 3D CAE Structure Analyses for HCF/LCF → Fabrication and Flow Bench Test → Engine Dyno Test

18 cmp+12 turb (MD turbo) and 11 cmp+4 turb (LD turbo) design iterations

5 design/bench test iterations

Approach: integrations of numerical analyses + test validations

Approaches

1. *Large (MD) turbo development*

- *Compressor impeller with arbitrary surface to extend operation range to enable more powerful engine while shifting high efficiency zone to low mass flow area to enable better fuel economy on customer driving cycles*

- *Compressor with <u>active casing treatment</u> to extend surge margin/operation range.*

- *Mixed flow turbine to improve efficiency and shift peak efficiencies to low speed ratio (U/C. i.e. small vane position and low turbo speed) to adapt to high EGR applications and better utilize pulsation energy from the exhaust gas*

- *Hot flow bench (supported by turbo suppliers) test validation*

- *Engine dynamometer test at Ford for BSFC demonstration*

2. *Small (LD) turbo development*

- *More than a scaling down from the MD/large turbo since small turbo has 30% more operation range*

- *More technical innovations are needed (e.g. adv. VGT technology, relatively large compressor impeller with ruled surface, etc.) and will be investigated*

- A new concept to "de-couple" the trade-off between low end efficiency and flow capacity in compressor design (via active casing treatment) is refined and successfully validated on flow bench and engine dynamometer tests.

- The design, numerical analyses and fabrication of active casing treatment control and actuation device is completed

- Compared to the MD donor turbo, the advanced MD compressor with active casing treatment has demonstrated the extension of choking flow capacity by 30% w/o compromising efficiency

- The MD/large turbo has been tested on engine dyno, which demonstrated 3%+ BSFC improvement at light loads over the base donor turbo on a Ford 2010MY diesel engine. Compared with the donor turbo, the advanced MD turbo delivered 30% more power with 35 deg C lower turbine inlet temperature

- The design and analytical validation of LD/small turbo for LD diesel application is completed. Fabrication of the prototypes will be completed in the next few weeks

Efficiency on customer driving cycle will impact FE, emission and transient response

Base vs. Advanced Compressor

Choke capacity extended 30%

Efficiency (t-t)

Mass Flow (kg/s)

Base — Advanced Compressor
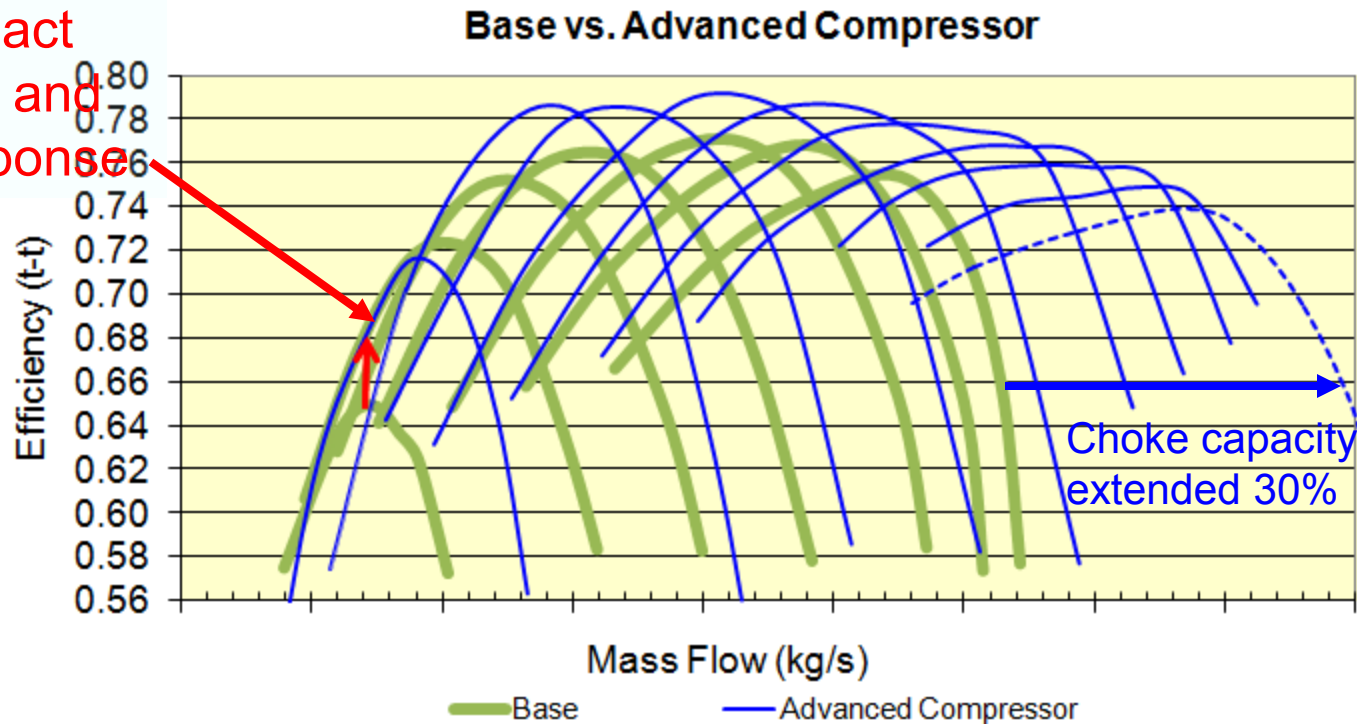
Advanced compressor (MD) with adv. casing treatment demonstrated better efficiency and wider operation range than the base donor compressor that enables BSFC and performance improvement
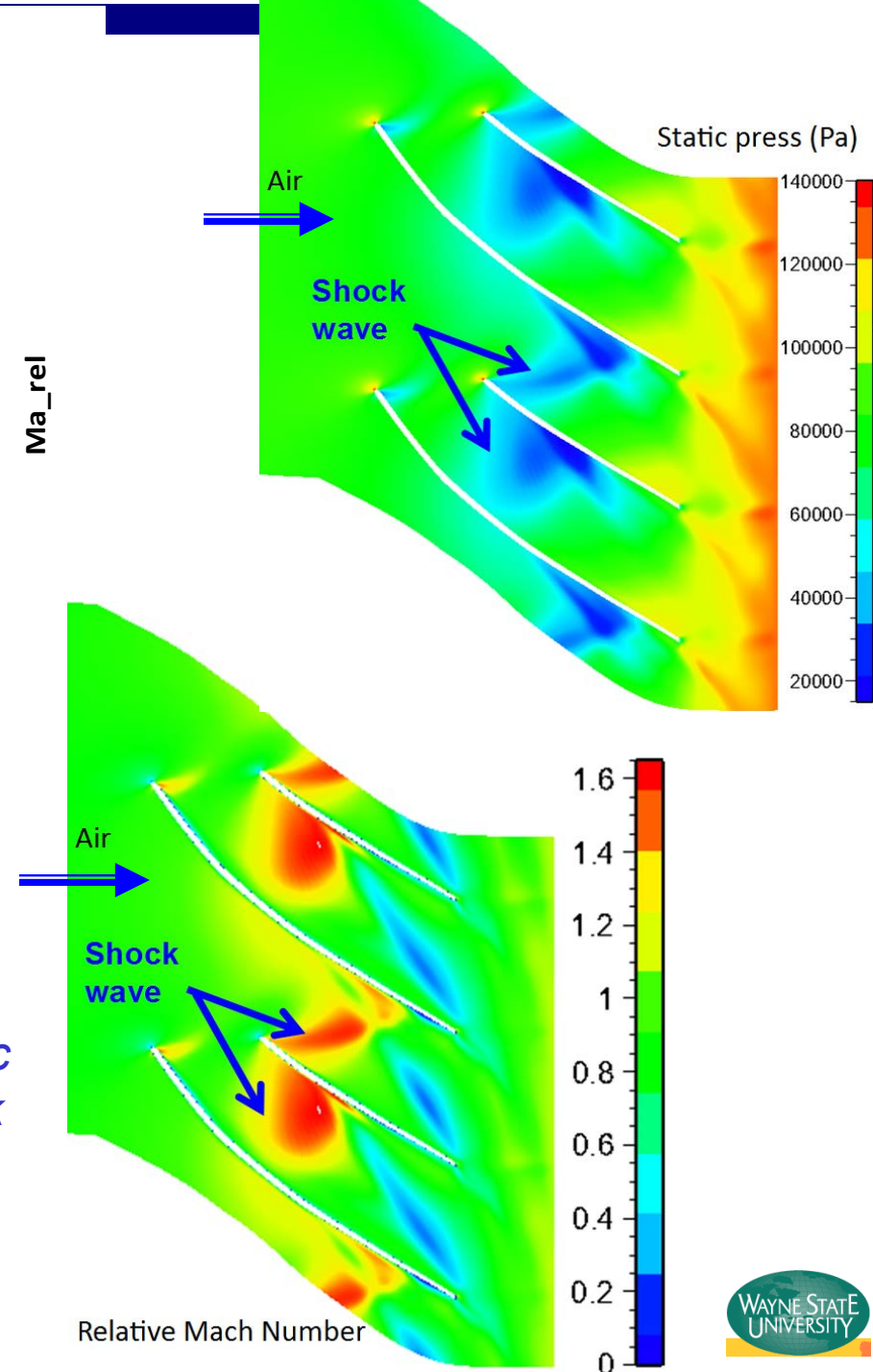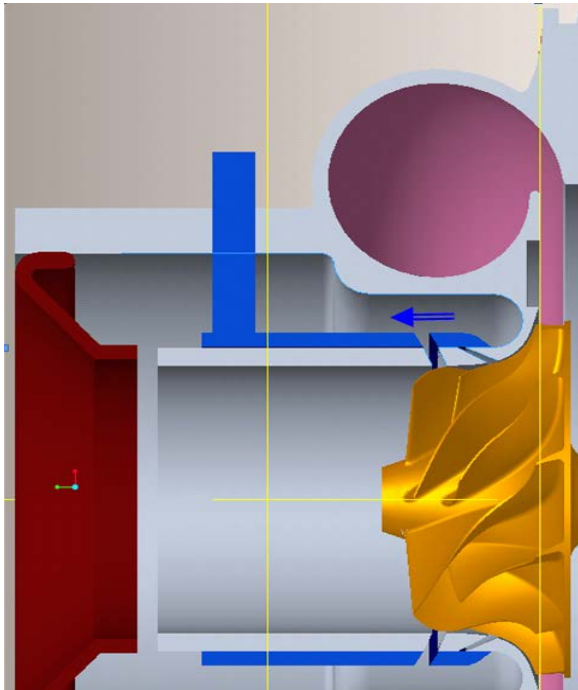
CONCEPTS NREC

WAYNE STATE UNIVERSITY
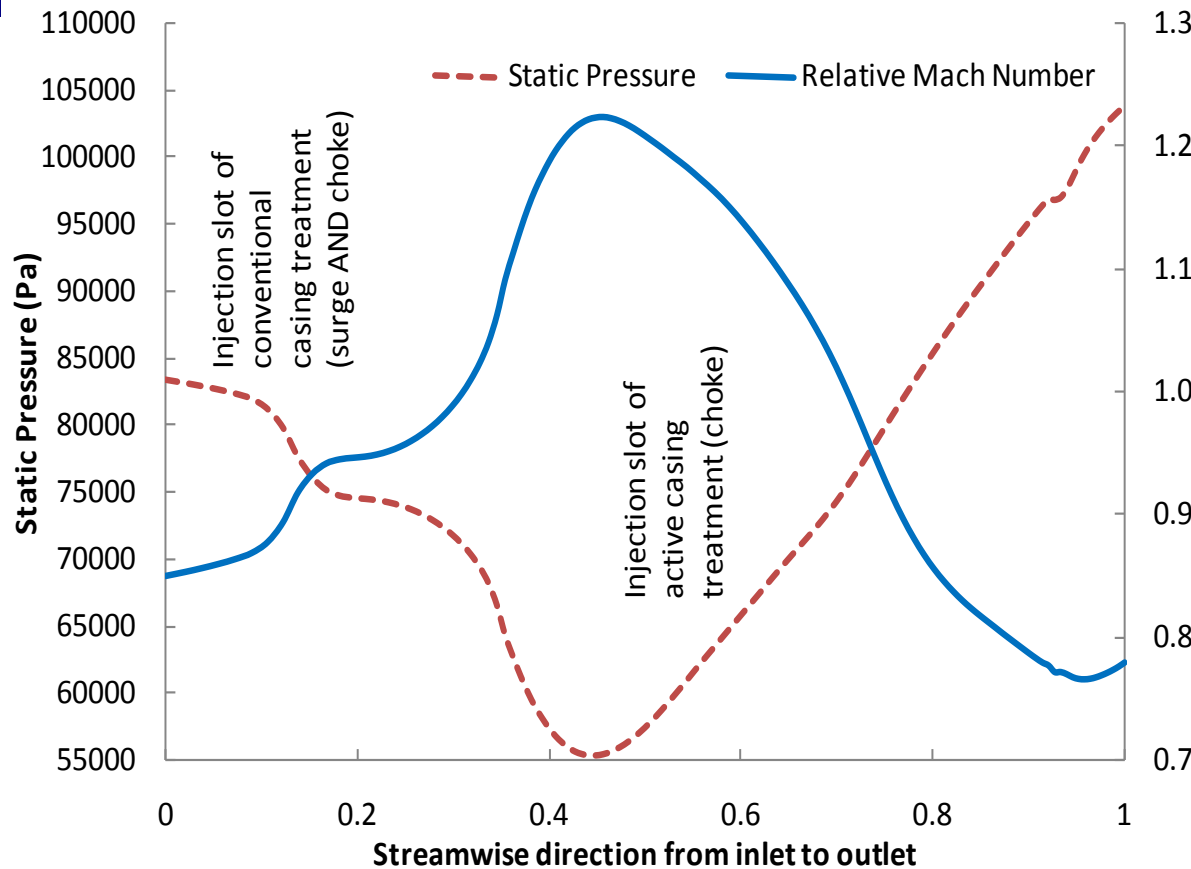
Active casing treatment: a new concept in compressor design:

Advanced impeller design may have the aerodynamic throat located near splitter blades which create shock wave at near choke conditions. This shock wave induced aerodynamic blockage could be utilized…

The surge slot "1" can be optimized to improve low end efficiency and surge margin

Surge control

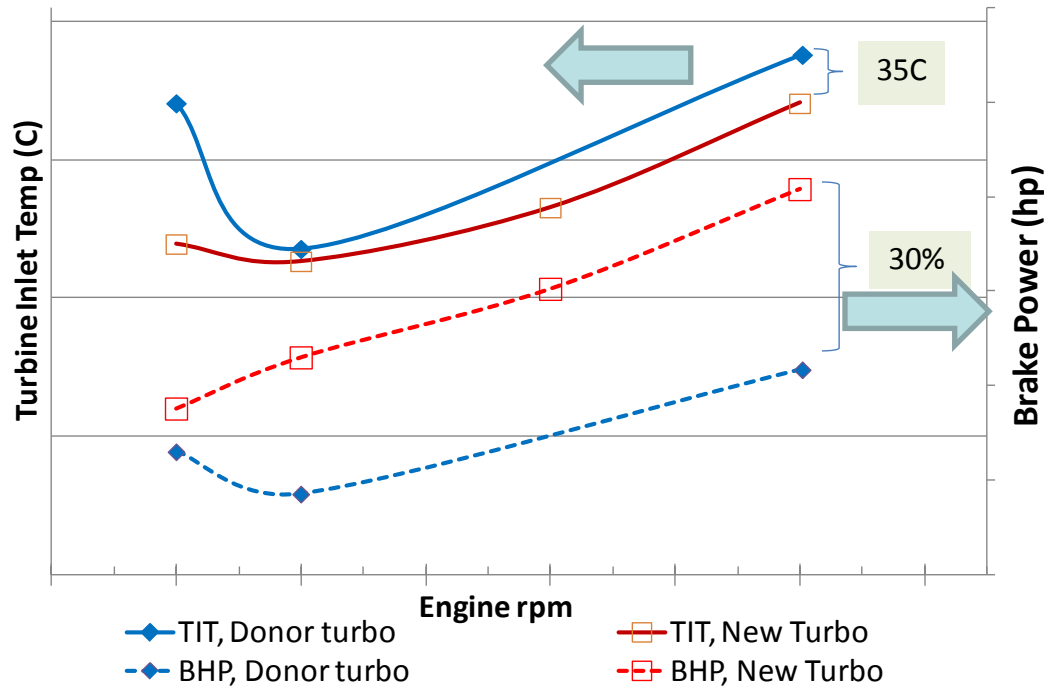**The choke slot "3"** can be designed to maximize choke flow capacity

Choke control

The dual, switchable slots, or **Active casing treatment,** can be used to address the surge and low end performance and choke flow capacity separately
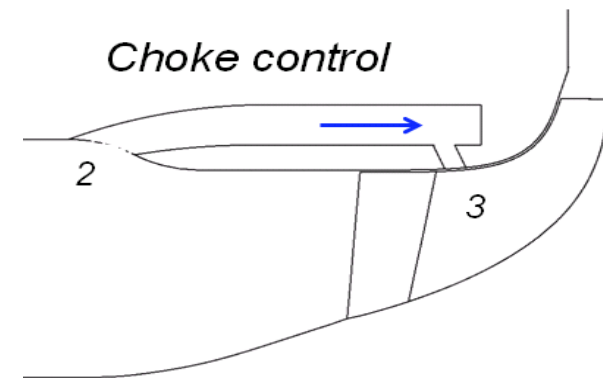
The choke slot utilizes the pressure drop after the shock wave to induce extra air at near choke conditions to extend choke flow capacity

Full load comparison (turbine temp and power)

Turbine Inlet Temp (C)

Brake Power (hp)

35C

30%

Engine rpm

— TIT, Donor turbo   — TIT, New Turbo
-- BHP, Donor turbo   -- BHP, New Turbo

The engine dynamometer test demonstrated that the advanced MD turbo delivers 30% more rated power at 35ºC lower turbine inlet temperature.

The advanced MD turbo on a steady state engine dynamometer test also demonstrated ~3% BSFC improvement over MD base turbo at part load; the advanced MD turbo showed more advantageous when operating at lower feed gas NO_x (or higher EGR) conditions, i.e. it was optimized for LTC/HCCI applications.
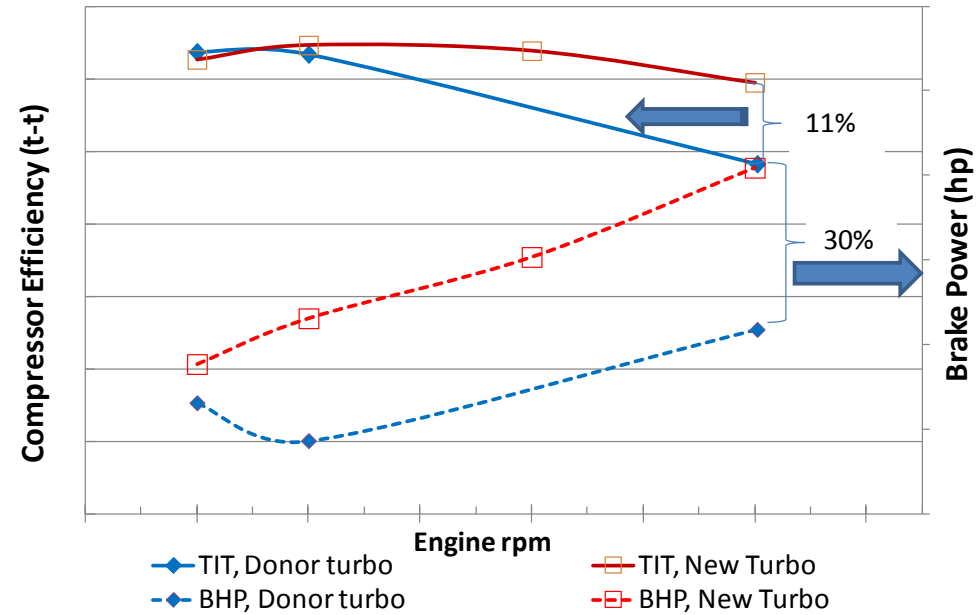
3bar@1250rpm

BSNOx (g/kW-h)

3%

5%

■ New Turbo
◆ Donor turbo

BSFC(kg/kW_hr)

3bar@1250rpm

FGNOx (g/kW) vs TurbInP-CmpOutP (kPa)
- ■ New turbo
- ◆ Donor turbo
- 13.3kPa
- 10.7kPa
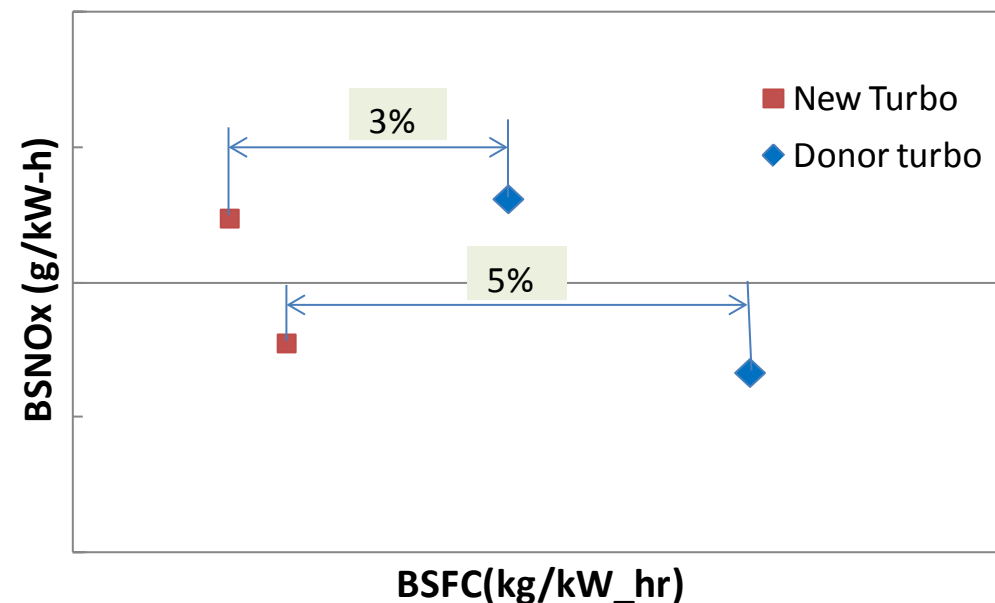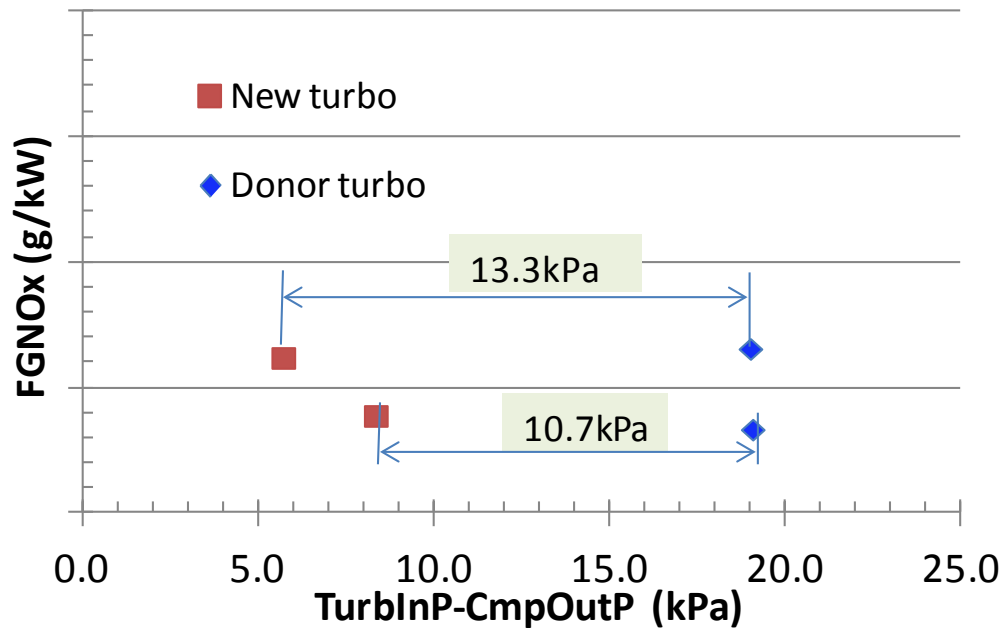
Full load comparison (Compressor efficiency& power)

Compressor Efficiency (t-t) / Brake Power (hp) vs Engine rpm
- 11%
- 30%
- ◆— TIT, Donor turbo
- ◆-- BHP, Donor turbo
- □— TIT, New Turbo
- □-- BHP, New Turbo

3bar@1250rpm

Smoke vs Compressor Efficiency
- ■ New turbo
- ◆ Donor turbo
- 27 pts
- 17 pts
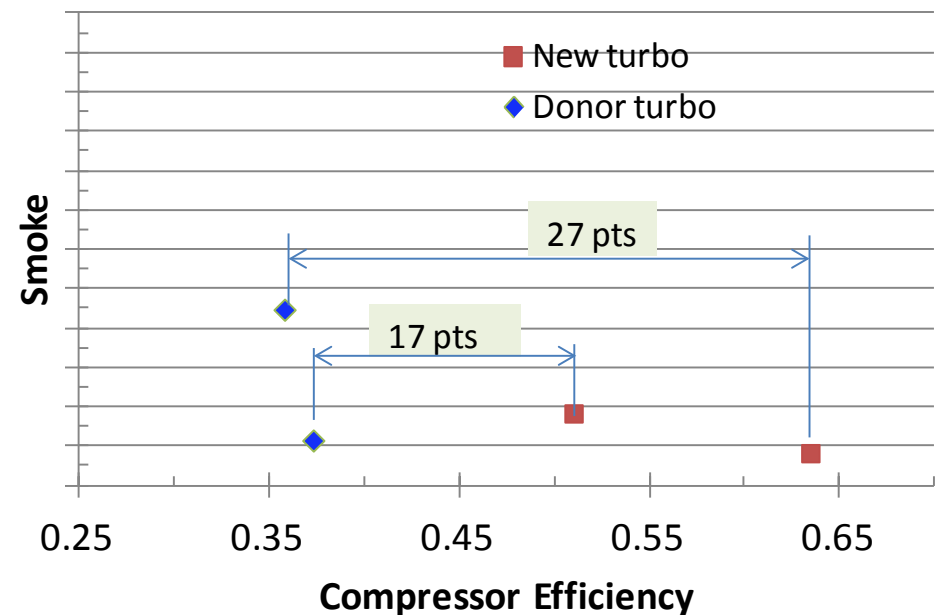
- The engine performance improvement at full load and part load is attributed to turbo efficiency and compressor flow capacity improvement (thus pumping loss reduction)
- At part load conditions, the exhaust pulsation flow, interactions between compressor and turbine makes turbo perform in the area that could not be captured in and projected from steady state flow bench test, i.e. benefit of mixed flow turbine could not be fully demonstrated on steady state flow bench
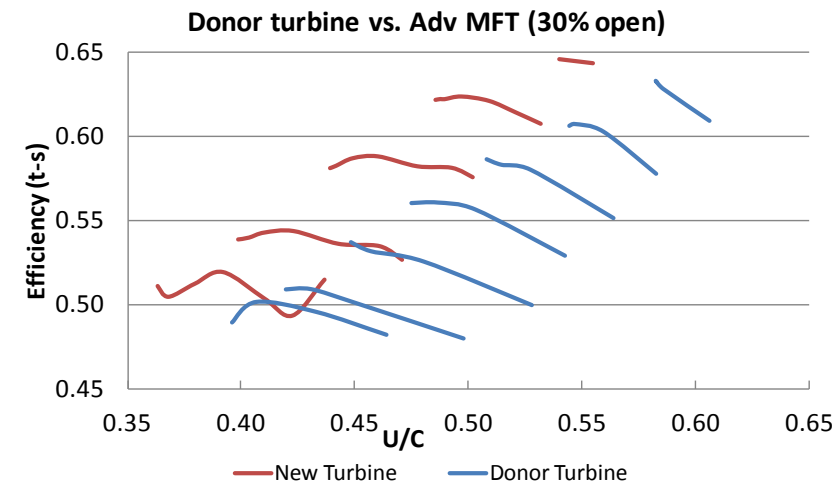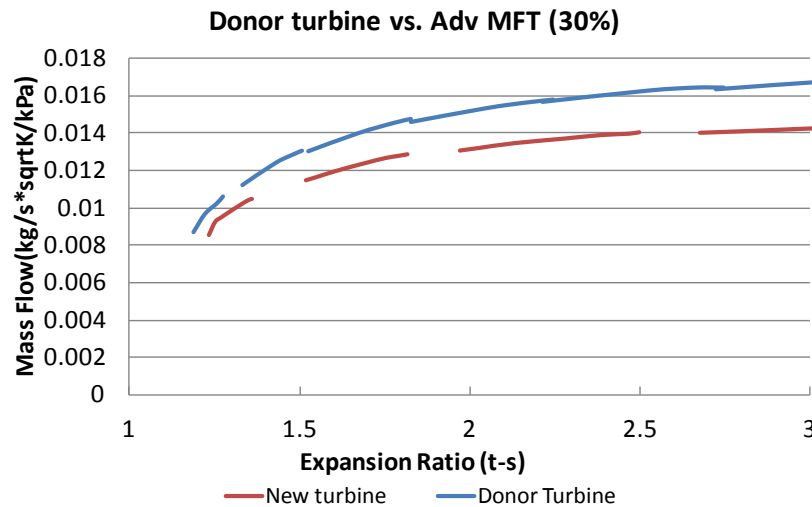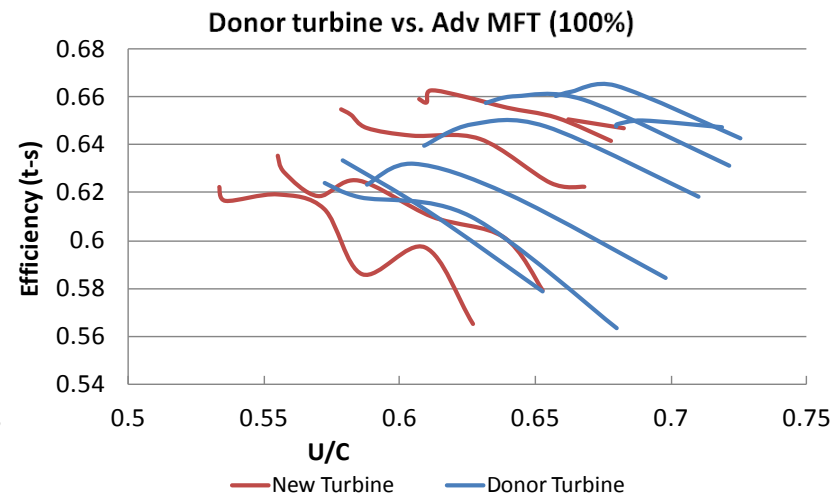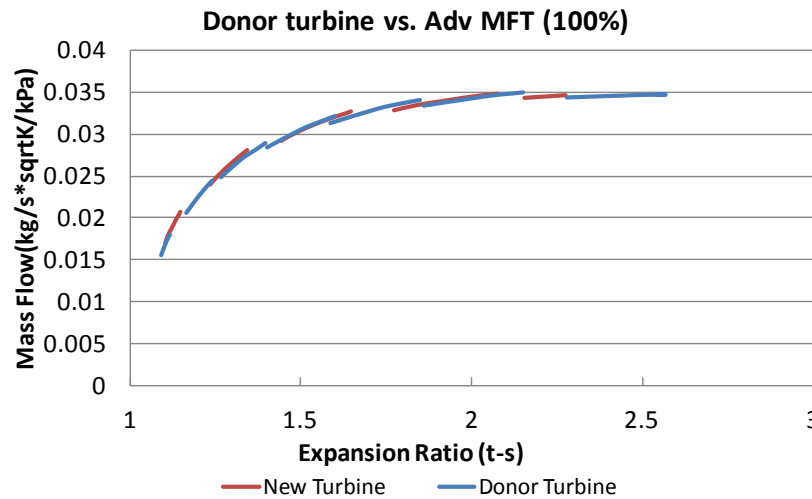
CONCEPTS NREC

Mixed flow turbine is the key!

Same VGT nozzle

Same flow capacity

Same bearing

Different efficiency!

Donor turbine vs. Adv MFT (100%)

Donor turbine vs. Adv MFT (100%)

Donor turbine vs. Adv MFT (30%)

Donor turbine vs. Adv MFT (30% open)

Compared with the base donor turbine, the advanced mixed flow turbine (MD) demonstrated better efficiency at low U/C area on flow bench test even though they had identical VGT nozzle, flow capacity and bearing, which is consistent with engine test data.
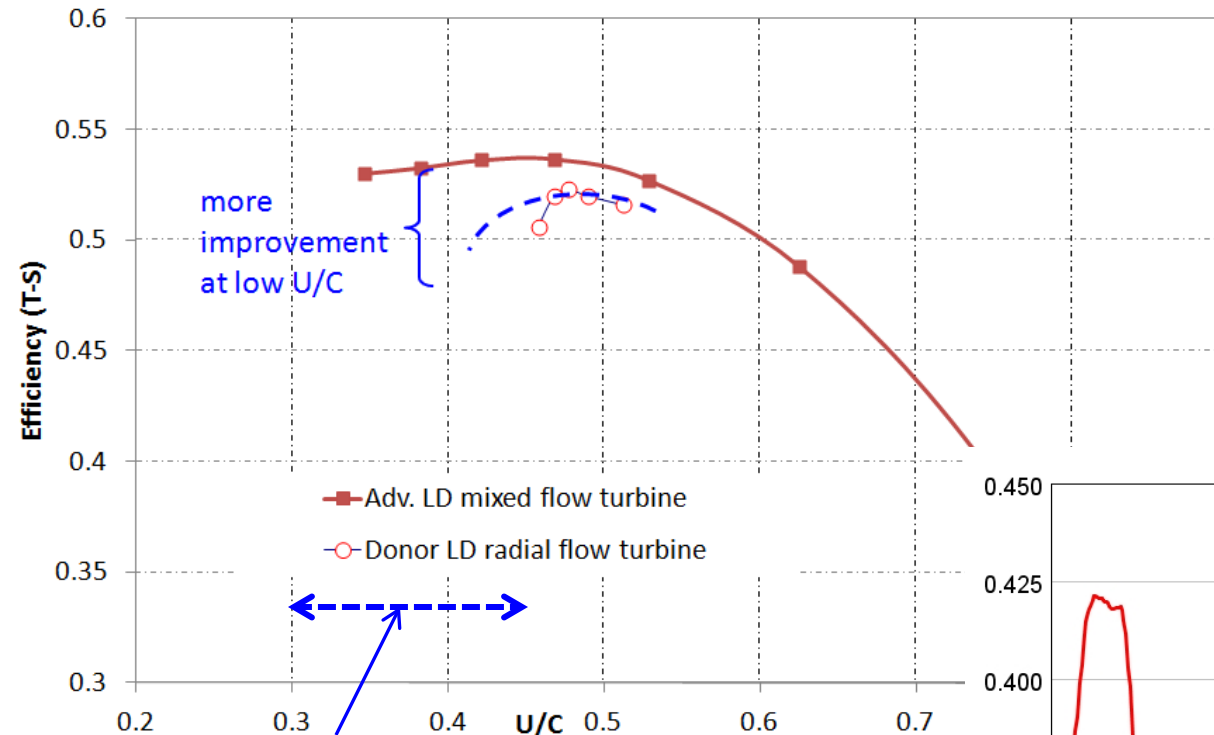
Turbine efficiency prediction at fully close position
Adv. LD mixed flow vs. donor (radial) turbine

- Adv. LD mixed flow turbine
- Donor LD radial flow turbine
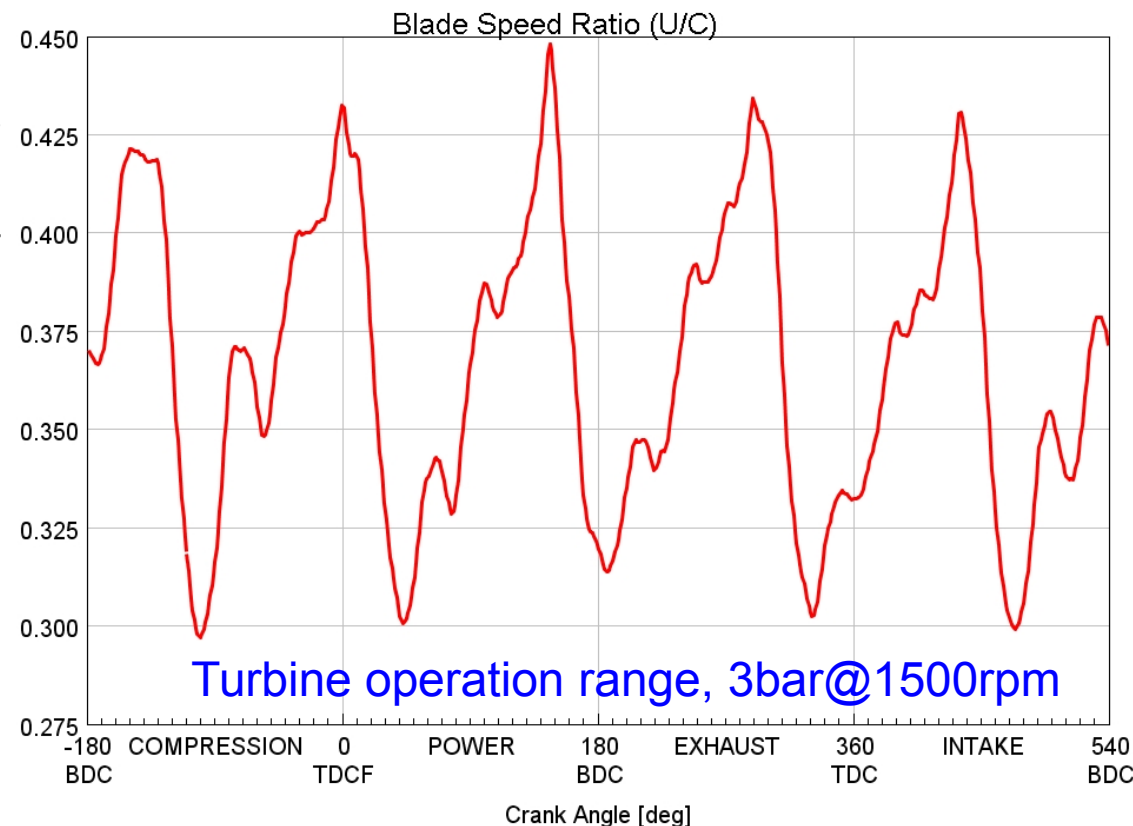
more improvement at low U/C

Turbine operation range, 3bar@1500rpm
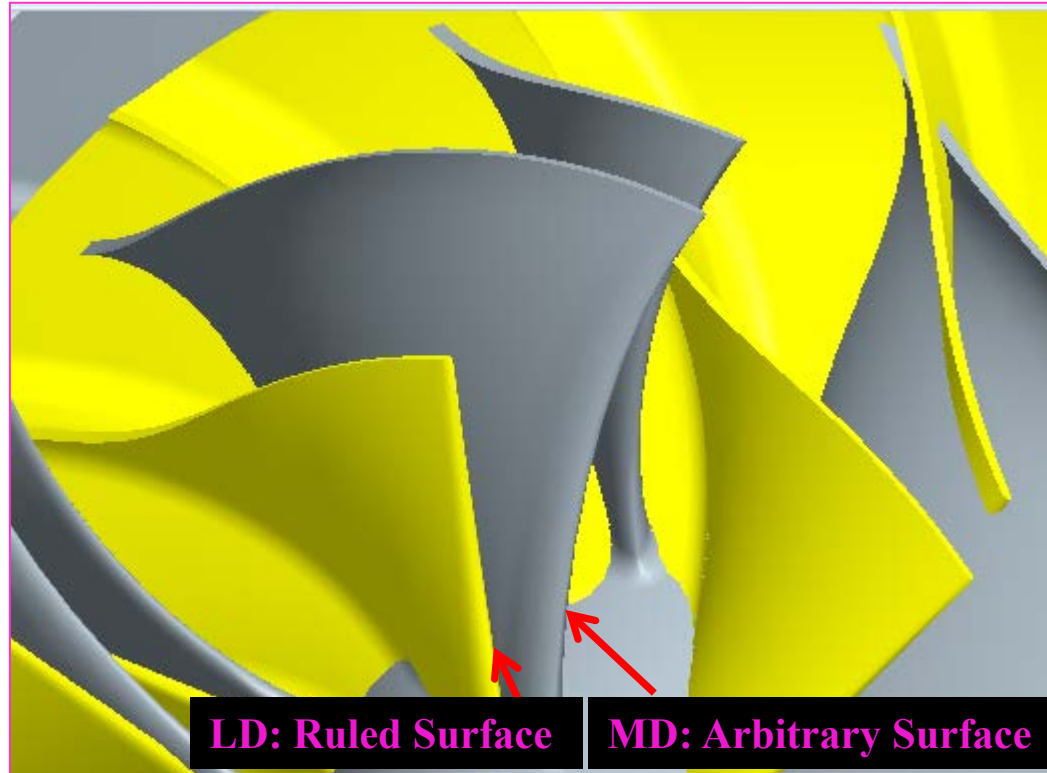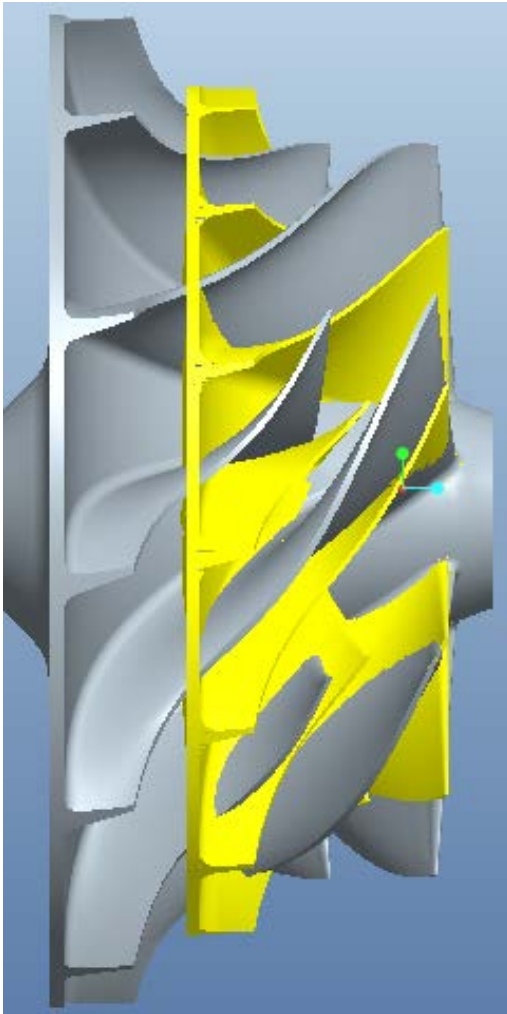
MD mixed flow turbine

LD mixed flow turbine
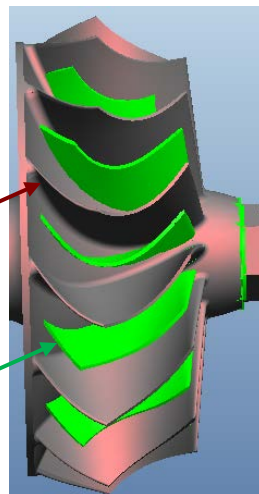
Performance prediction of LD mixed flow turbine, which outperforms radial flow turbine but unfortunately cannot be demonstrated by typical steady state flow bench test due to limited U/C range in the test

Blade Speed Ratio (U/C)

Turbine operation range, 3bar@1500rpm

Crank Angle [deg]

CONCEPTS NREC

LD: Ruled Surface   **MD: Arbitrary Surface**

MD impeller: **arbitrary** surface impeller, compact, high milling cost

LD impeller: **ruled** surface impeller, high inertia (relative to its flow capacity), but low milling cost
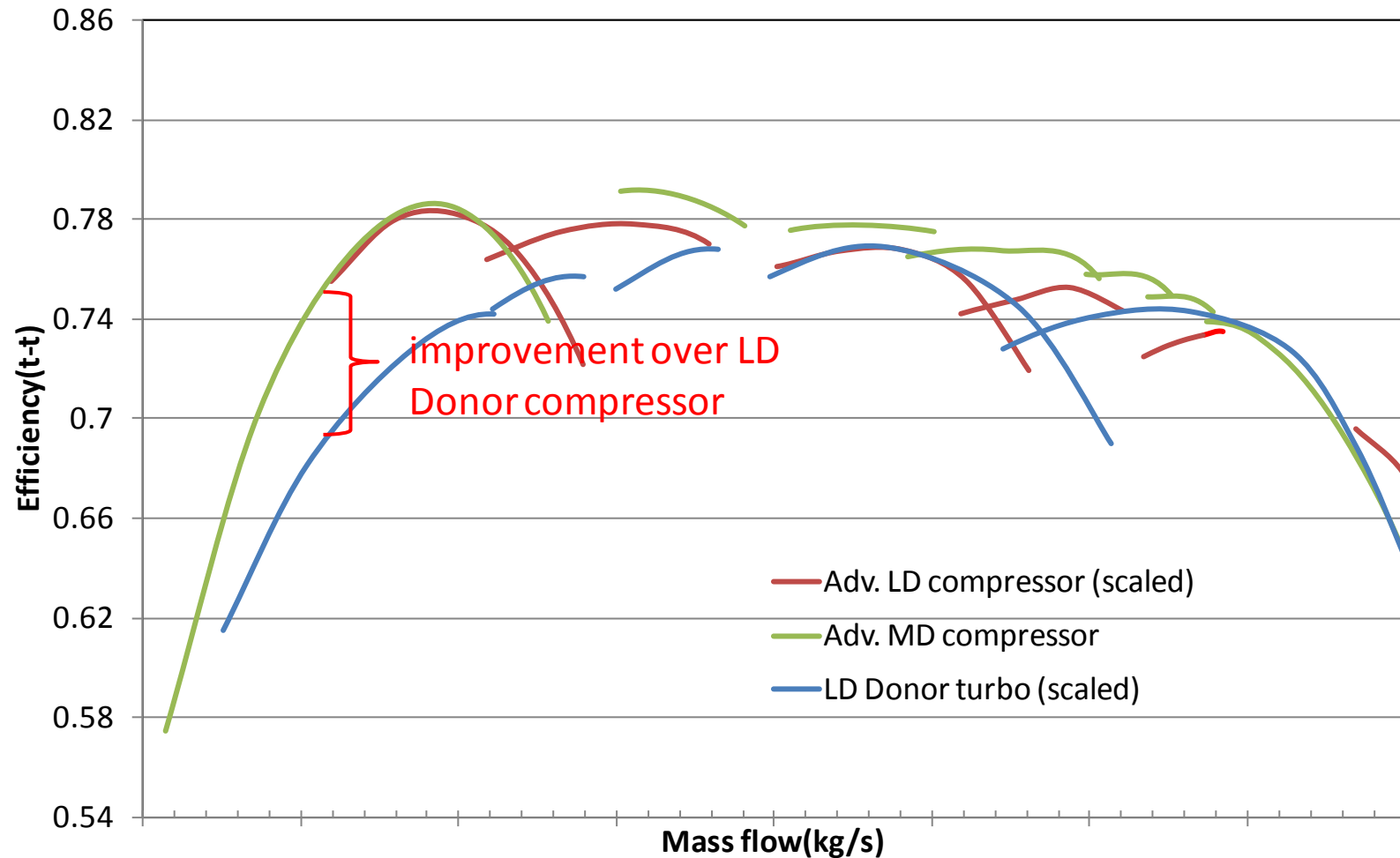
Compressor design strategy evolves from MD compressor to LD compressor

Efficiency Comparison of the scaled LD (Advanced and donor) compressor with advanced MD compressor

When scaled up, the LD advanced compressor with ruled surface performs the same as adv. MD compressor (w/ arbitrary surface) but substantially better than LD donor compressor.

Collaboration with other institutions

- Partners
    - Ford (resp: lead, system integration/simulation, control, dyno test)
    - ConceptsNREC (resp: design, analysis, development, fabrication)
    - Wayne State University (resp: CAE and CFD)
    - Three turbocharger suppliers (resp: provide donor turbo, bench test, fabrication support, design review/evaluation)

- Technology Transfer
    - Work with existing turbocharger suppliers to incorporate the findings from this research into their new turbo development
    - Under discussion with other parties for potential technology transfer (two patents filed and one published)

- Fabrication and flow bench test validation of LD/small turbo performance;

  - Since the LD turbo has 30% wider operation range thus the development of LD turbo is more than a "scaling" down;

  - Compressor of LD has ruled surface to cut milling time/cost

- Control and actuation system for active casing treatment system demonstration

- Engine dyno test demonstration:

  - Steady state and transient performance and emission calibration out of a production engine that was at Tier II Bin 8 emission level to demonstrate Tier II Bin 5 tail pipe emission (more challenging than original project scope since original donor engine was assumed for T2B5 emission, i.e. potentially combustion, emission aftertreatment and calibration upgrade may be needed)

  - Engine dyno test demonstration for fuel economy improvement at T2B5 emission level with LD donor turbo and new advanced turbo.

- The active casing treatment is a major technical breakthrough that, together with mixed flow turbine, has enabled the successful demonstration of advanced MD turbocharger during flow bench and engine dynamometer test validations (Ford is working with a major turbo supplier for migration of this active casing treatment technology to other applications).

- Back to back comparison between advanced MD turbocharger with mixed flow turbine and compressor with active casing treatment and base donor turbocharger has demonstrated consistent results:

  - Flow bench data showed 30% extension of flow capacity on compressor;

  - Compressor efficiency is improved over wide range

  - Turbine efficiency is improved 6-10% at low speed ratio (U/C) area for various vane open positions that helped to deliver more power at lower turbine inlet temperature.

  - Engine dyno test showed 3%+ BSFC reduction at light load and full load

  - Real improvement of turbocharger efficiency at light loads with pulsation flow can only be validated on engine dyno since flow bench test has limited operation range

- LD/small turbo development:

  - Advanced LD compressor impeller with ruled surface will be investigated. Analytical data showed that it will achieve similar steady state performance as MD compressor with arbitrary surface

  - Parts fabricated and engine dynamometer test validation will finish late September.

Technical Back-up Slides

$$mass\_flow : \frac{m_M}{m} = \frac{p_{1M}}{P_1} * \sqrt{\frac{T_1}{T_{1M}}} * \frac{1}{K_l^2}$$

$$so, K_l^2 = \frac{m}{m_M} * \frac{p_{1M}}{P_1} * \sqrt{\frac{T_1}{T_{1M}}}$$

$$diameter\_scaling\_factor : K_l = \frac{D_t}{D_{tM}}$$

$$speed : \frac{n_M}{n} = K_l * \sqrt{\frac{T_{1M}}{T_1}}$$

$$pressure\_ratio : \pi_M = \pi$$

$$efficiency : \eta_{ad,M} = \eta_{ad}$$