EGR System Analysis of a Turbocharged Diesel Engine

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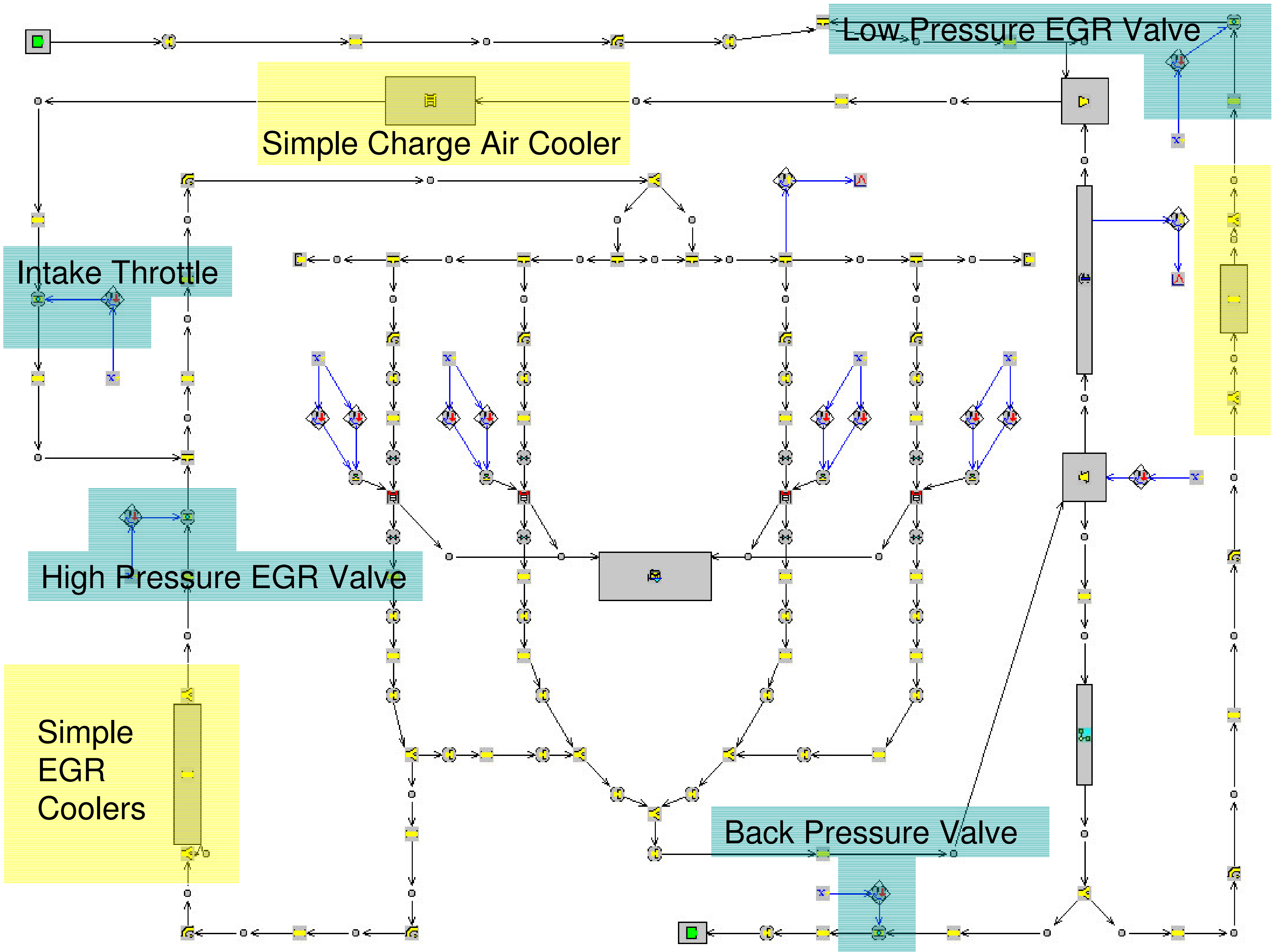
Agenda

- Engine and controller description
- Additional physics added to the existing charge air cooler
- Charge air cooler slave air flow sensitivity
- Additional physics added to egr coolers
- EGR distribution study
- Low pressure egr cooler sizing
- Summary

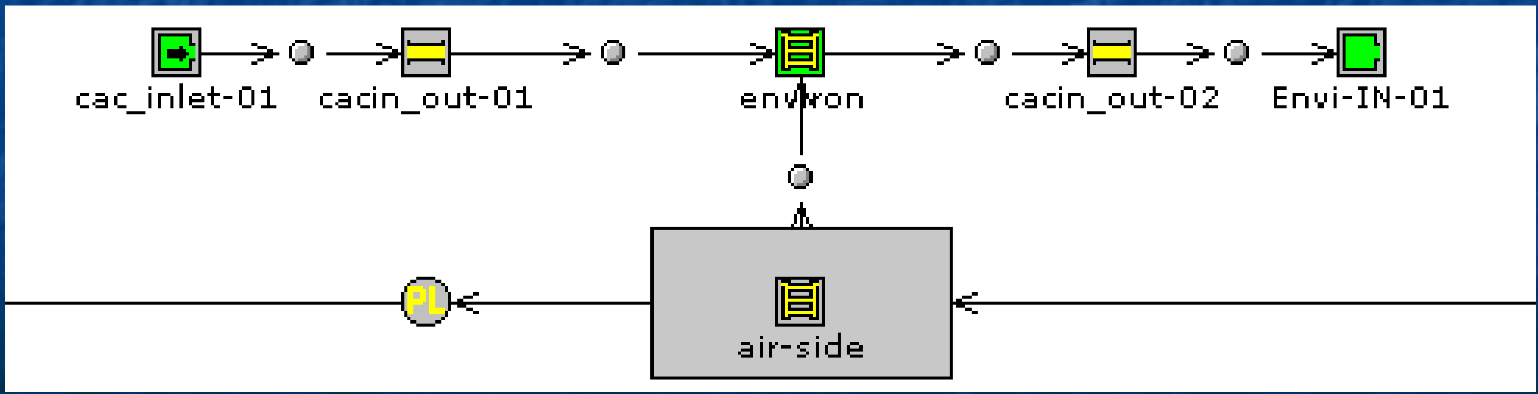
Engine Description

- 1.9 L Turbocharged diesel engine, 4 cyl
- Equipped with both low pressure and high pressure egr circuits
- Controls in place to control the following
  - Low pressure egr rate
  - High Pressure egr rate
  - Boost pressure
  - Engine Load
  - EGR cooler size (latter simulations)


Low Pressure EGR Valve
Simple Charge Air Cooler
Intake Throttle
High Pressure EGR Valve
Simple
EGR
Coolers
Back Pressure Valve

Charge Air Cooler

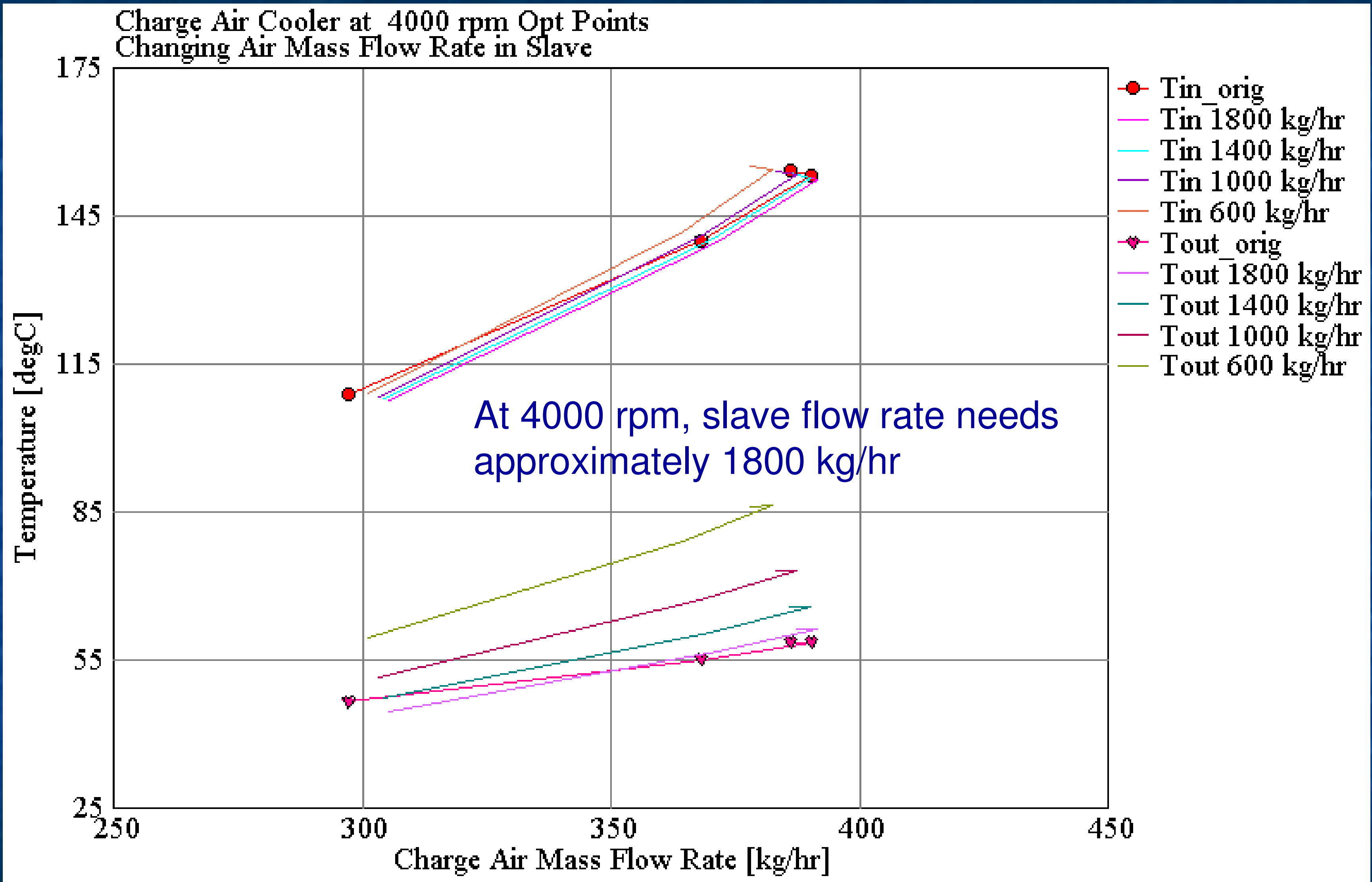
- Performance data was available for the charge air cooler – cross flow air to air
- Data was entered in the HxNuMap and Nu correlations were calculated by GT-POWER
- Fitting was successful with about 3% mean relative error
- Old 'black box' cooler was replaced with more detailed model



Charge Cooler Sensitivity

- The first sweeps were to investigate the sensitivity of results to the slave side mass flow rate.
- Original models were set to sweep rack position at fixed load and fixed egr. The new cac components were placed in the same model and then run.
- Next slides show comparisons of inlet and outlet temperatures of cac.

Sweep of Slave Flow Rate



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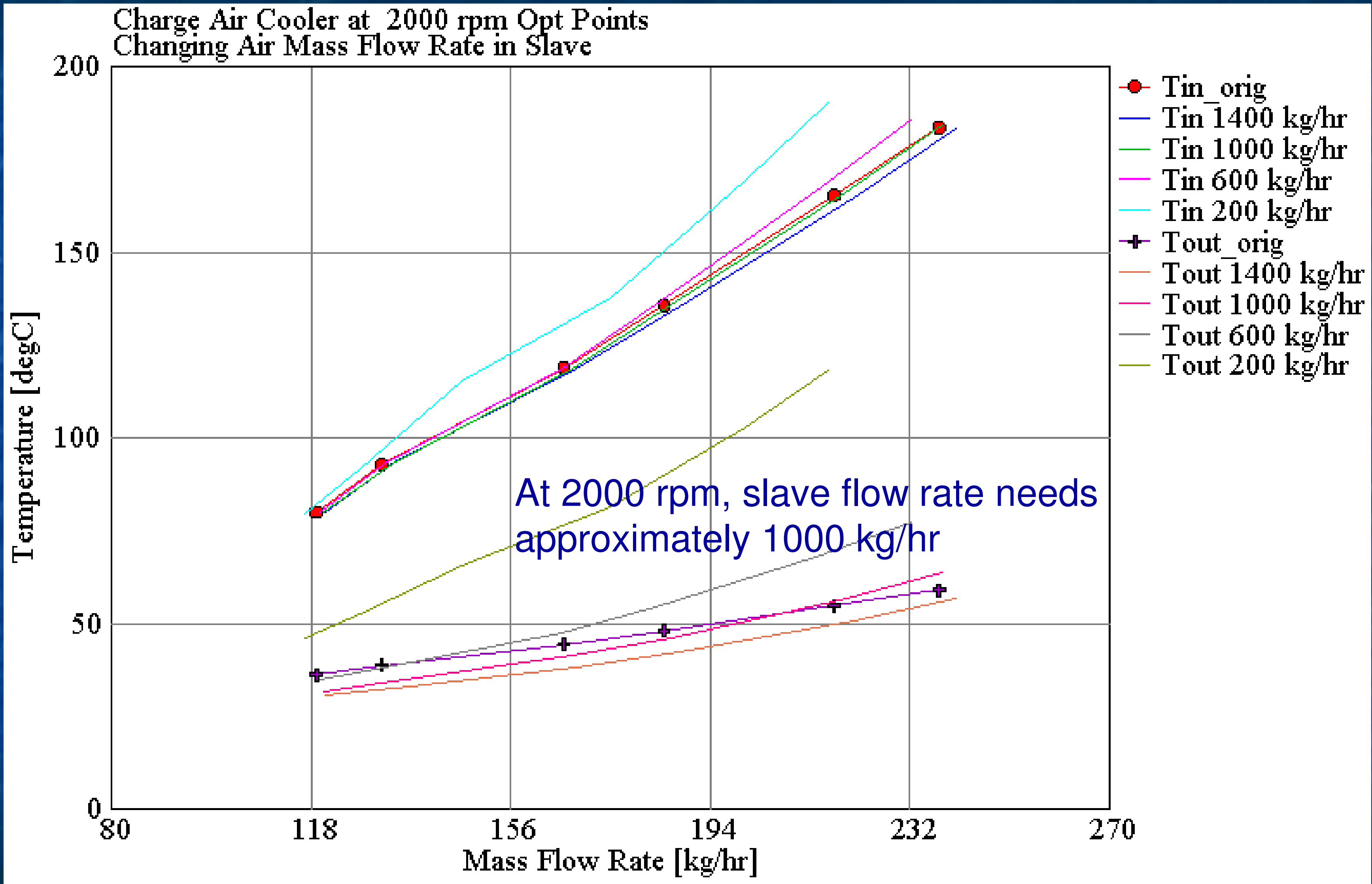
Sweep of Slave Flow Rate (2)



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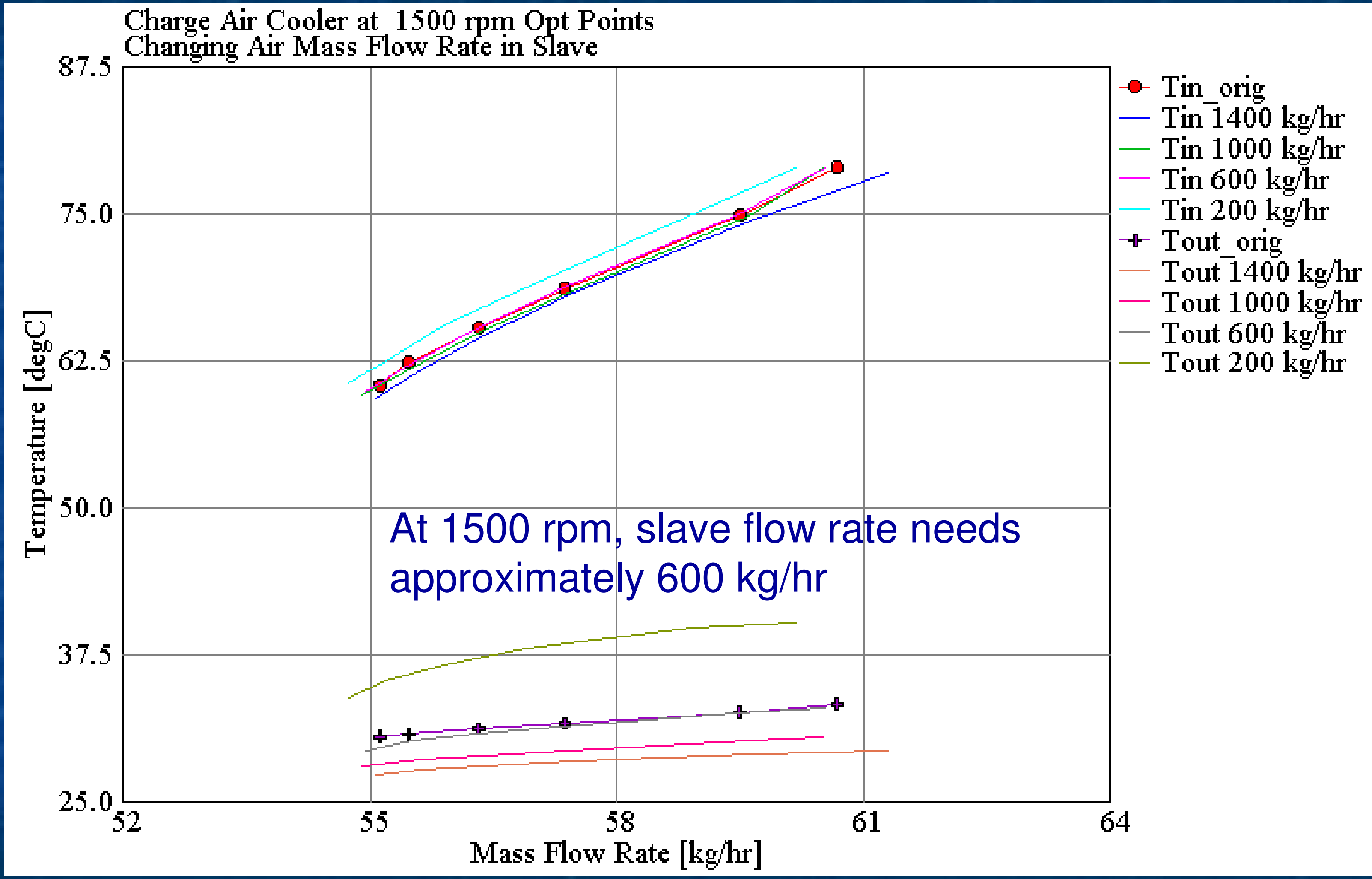
Sweep of Slave Flow Rate (3)



Observations

- Estimation of the slave side mass flow rate is important to overall results.
- Comparing results to the original charge air cooler performance gives a guideline for values to use when running future egr studies.

EGR Coolers

- Original coolers are single pass, shell and tube design (air to coolant)
  - 40 round tubes
  - 5.5 mm diameter
  - 300 mm length
- No performance data available
- Initially, the slave side mass flow rate and temperature rise and master side temperature drop were estimated
- GT-POWER then used this data to determine Nu correlations.
- This method did not produce a good result
  - errors in estimation and fitting
  - h*A not realistic

Nu Correlation

- A new approach was then taken. For the internal Nu correlation the Dittus-Boelter (DB) equation was used.
- The DB equation is for fully developed, turbulent flow in a smooth circular tube.
- Same equation form as fit in HXMap.

$$Nu_D = 0.023 \, \mathrm{Re}_D{}^{0.8} \, \mathrm{Pr}^{0.3}$$

- The equation was modified slightly for the Nu correlation for the outer surface of the tubes.
- In SAE 2004-01-0122, Nu correlations were done on similar design cooler which further validated the use of DB equation.

Multiple Circuits

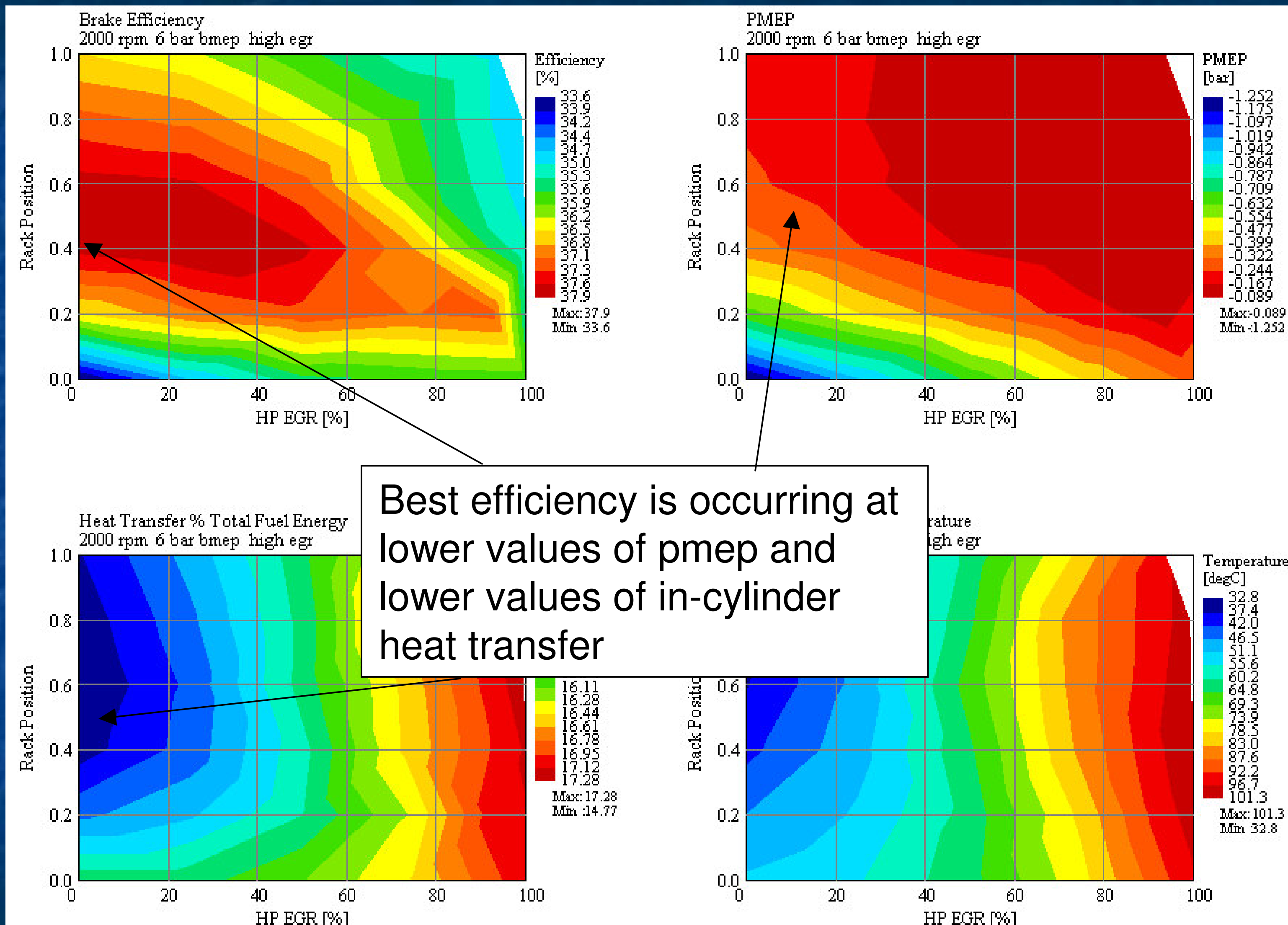
- Adding the slave side components of the cooler to the model resulted in liquid and air circuits in the same model.
- v6.2 was needed to run these circuits.
- Different convergence criteria and solution method (explicit/implicit) can be chosen for each circuit.

EGR Distribution Study

- At a given speed, load, and total egr rate, how does the high pressure and low pressure egr distribution affect performance?
- For this presentation we will show 2 cases
  - 2000 rpm, 6 bar bmep, medium egr (>30%)
  - 4000 rpm, 12 bar bmep, lower egr (>10%)

- In following figures x-axis is in % HP egr
  - In each plot, total egr is fixed
  - 0% HP egr means all egr is coming from low pressure circuit
  - 100% HP egr means all egr is coming from high pressure circuit

2000 rpm, 6 bar bmep, high egr



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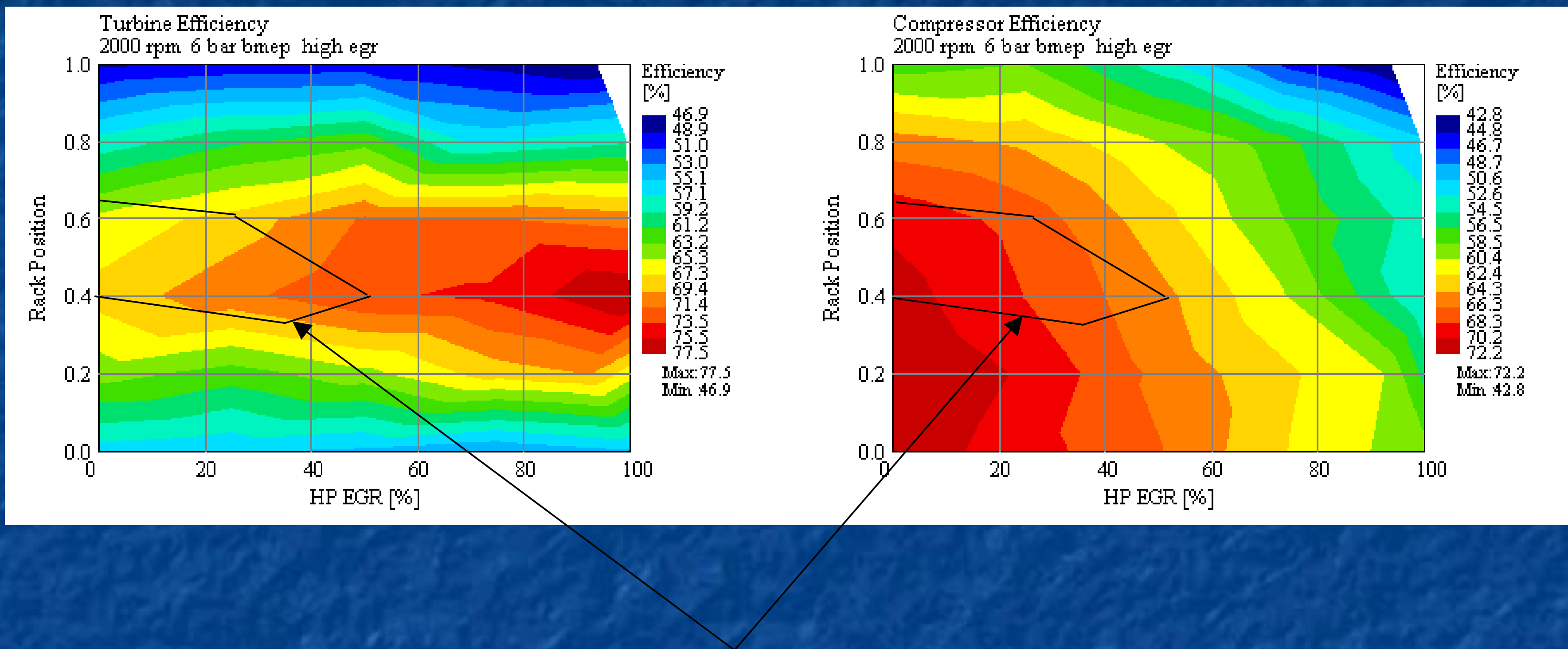
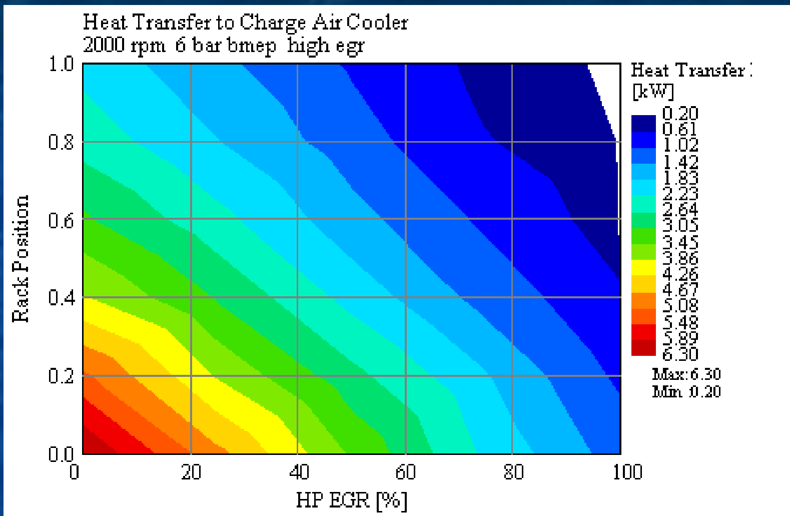
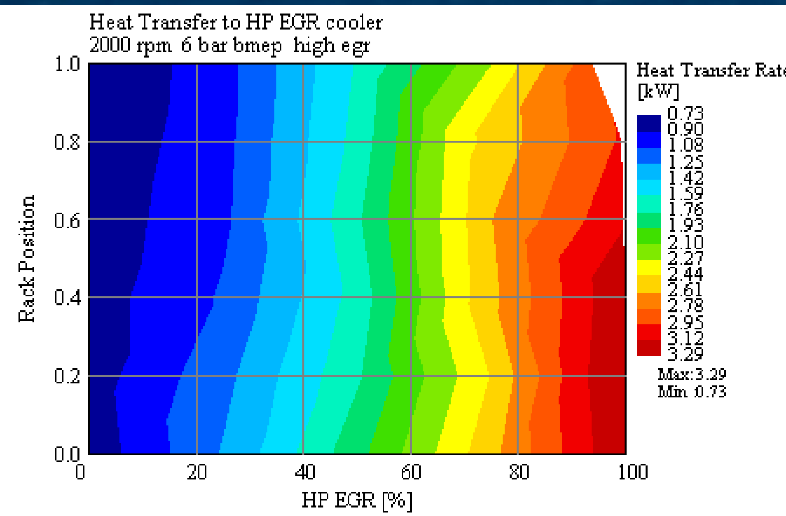
2000 rpm, 6 bar bmep, high egr

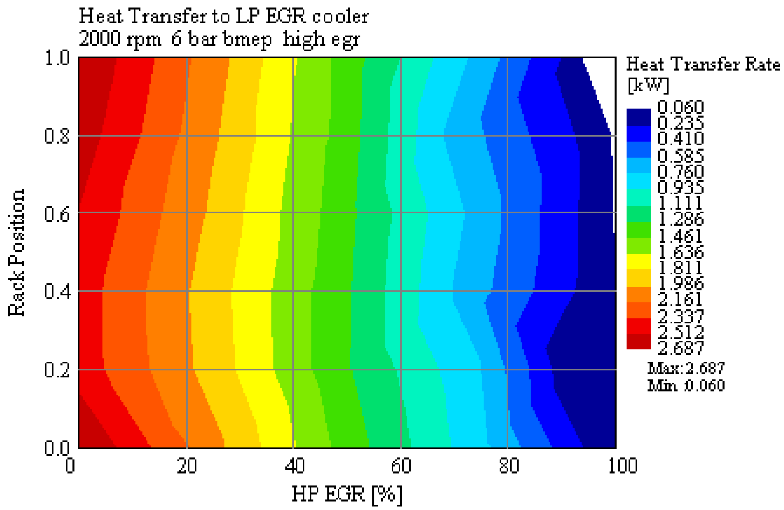


Peak brake efficiency (outline) following closely to peak turbine and compressor efficiencies.

2000 rpm, 6 bar bmep, high egr

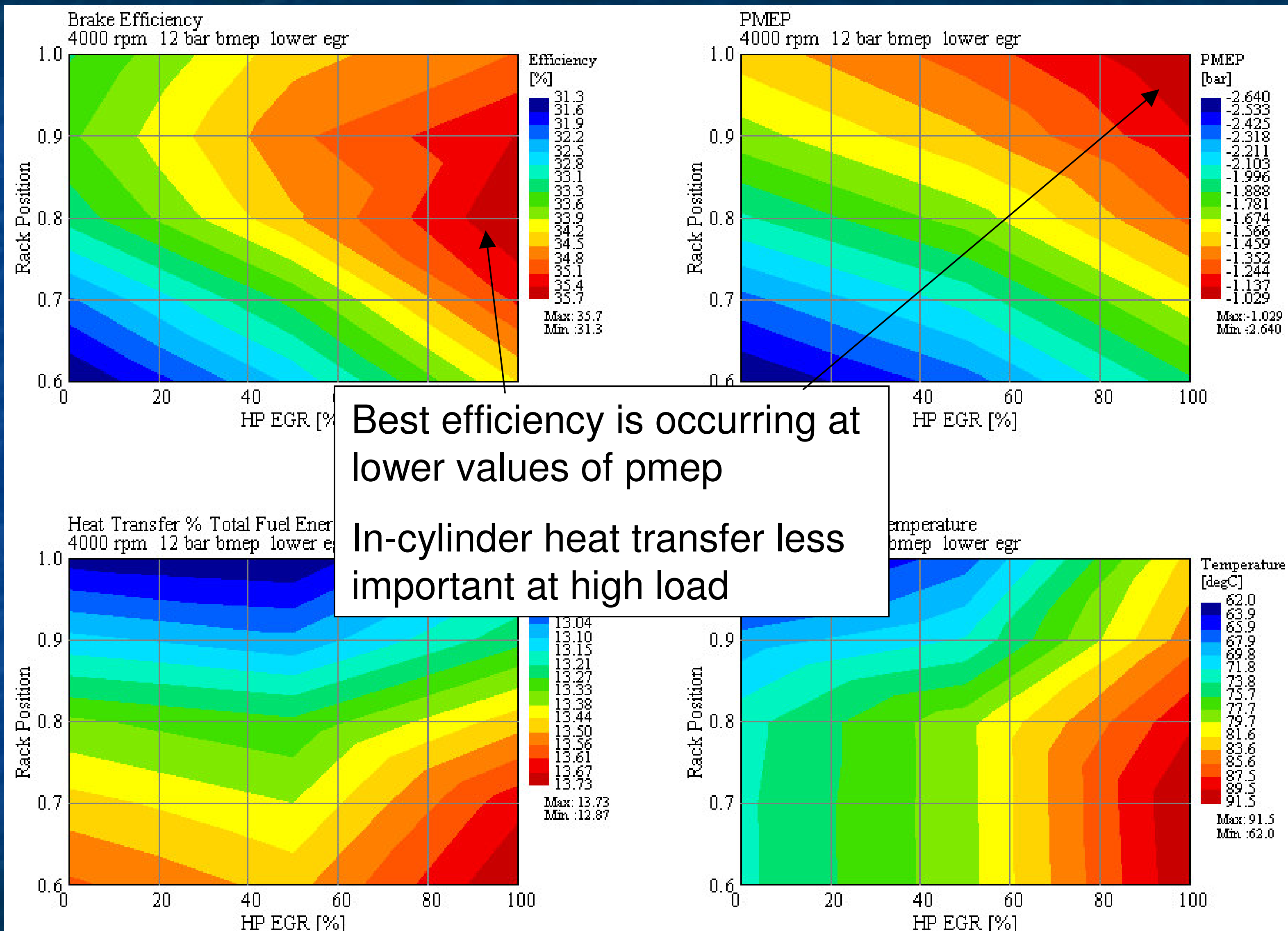






Brake efficiency results on previous slide not entire story, since they do not include parasitic losses of coolant pumps, increased frontal areas, etc.

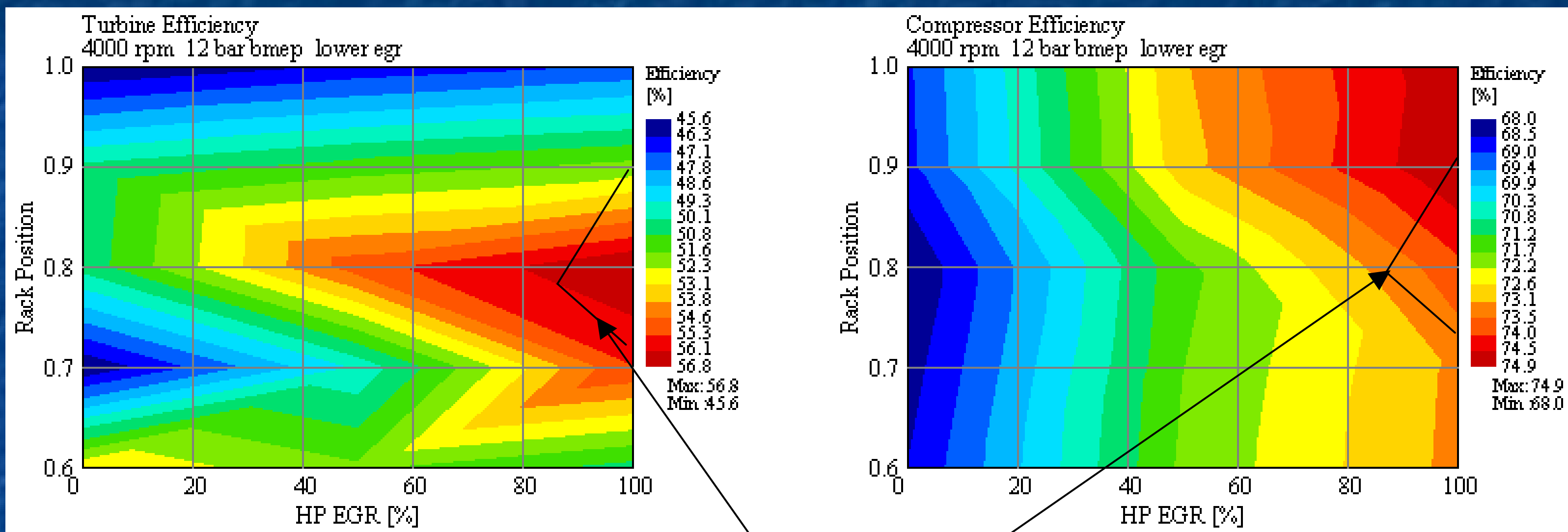
4000 rpm, 12 bar bmep, medium egr



Best efficiency is occurring at lower values of pmep

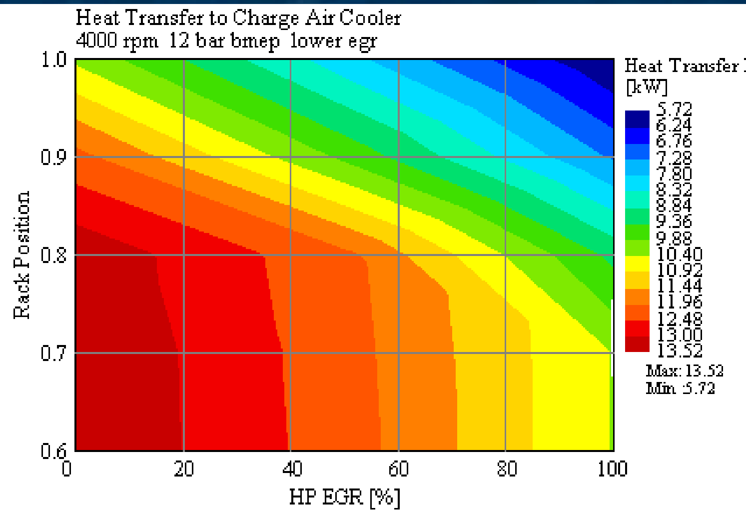
In-cylinder heat transfer less important at high load

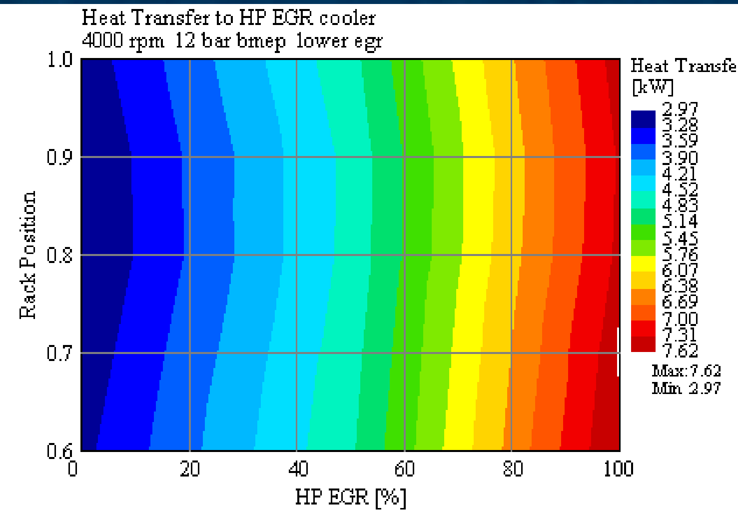
4000 rpm, 12 bar bmep, medium egr

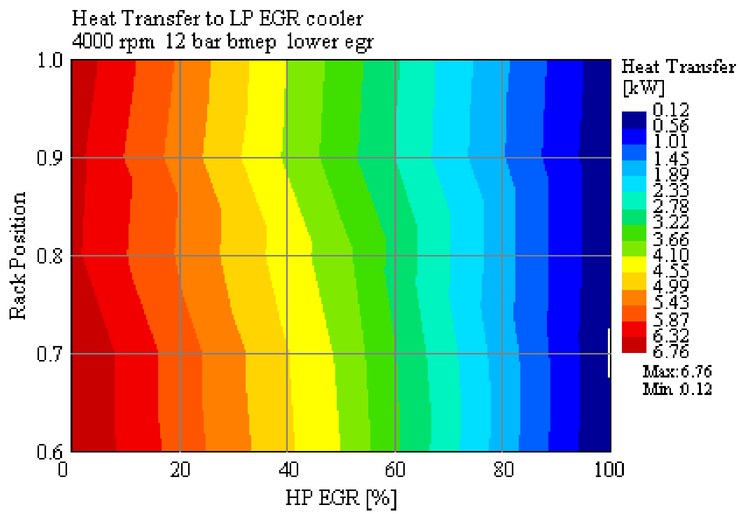


Peak brake efficiency (outline) following closely to peak turbine and compressor efficiencies.

4000 rpm, 12 bar bmep, 20% egr







Again, brake efficiency numbers are not influenced by cooling loads.

EGR Cooler Core Sizing (low pressure egr)

- The next task was to determine what cooler core size was necessary to stay within temperature limits of 100 ºC compressor inlet and 200 ºC compressor outlet for the range of speeds and loads.
- Boost and egr sweeps for several of the primary operating points were run.

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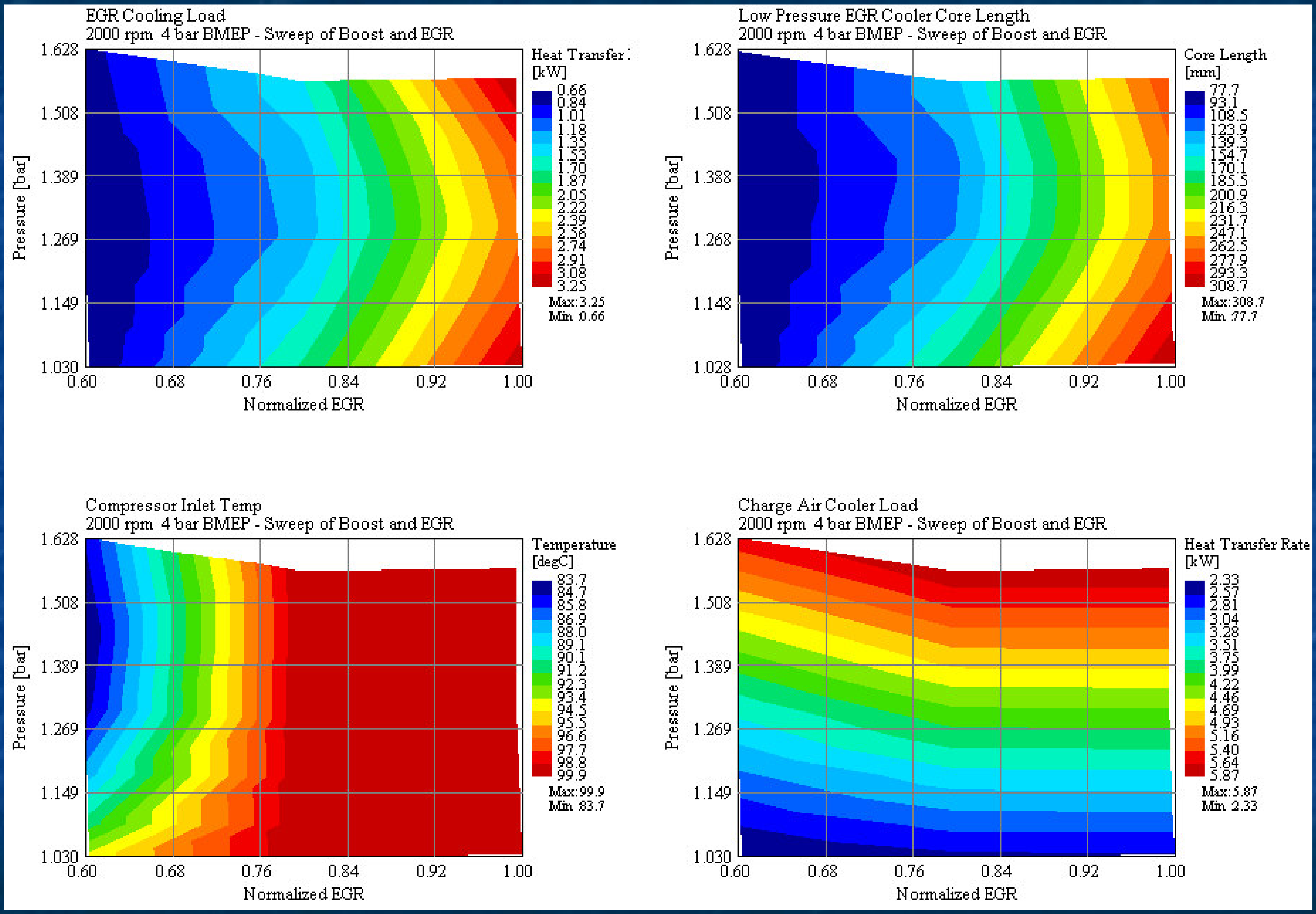
Detailed Sweeps

- Determine cooling load and core sizes to stay within temperature limits.
- Control in model was set so that cooler core length would not increase until compressor inlet temperature approached 100 ^{o}C.
- A minimum cooler core length was chosen in order to maintain validity of the DB equation.

Detailed Sweeps (2)

- GT-POWER optimizer was set up to search egr cooler core lengths from 75 mm to 400 mm.
- This presentation will cover 2 of these sweeps.
  - 2000 rpm, 4 bar BMEP
  - 2500 rpm, 12 bar BMEP

2000 rpm 4 bar BMEP



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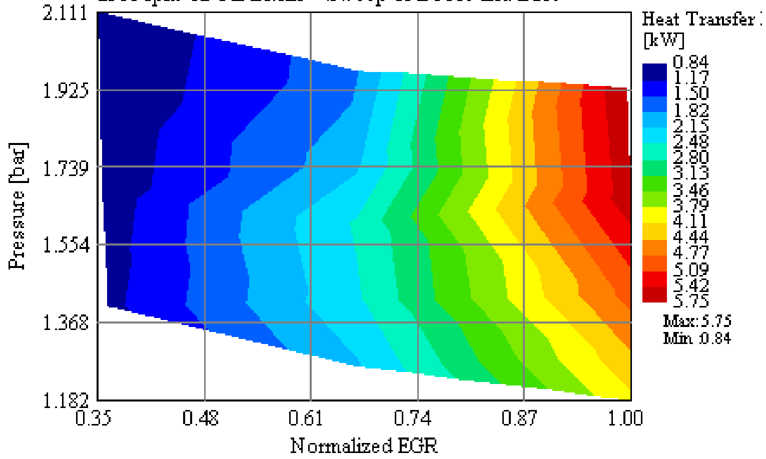
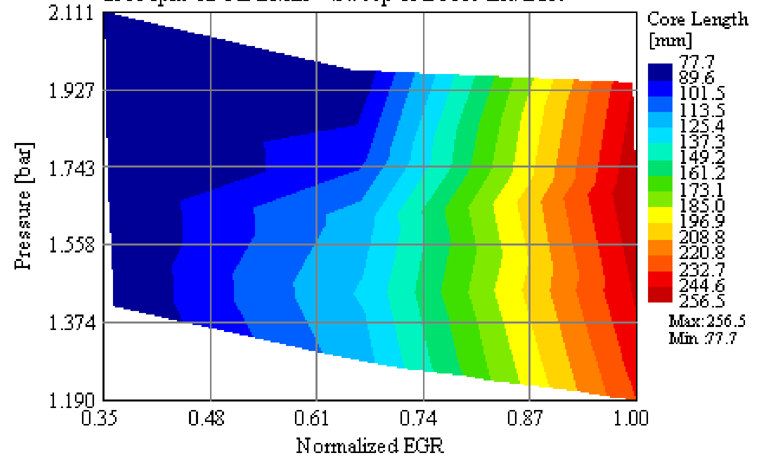
2500 rpm 12 bar BMEP

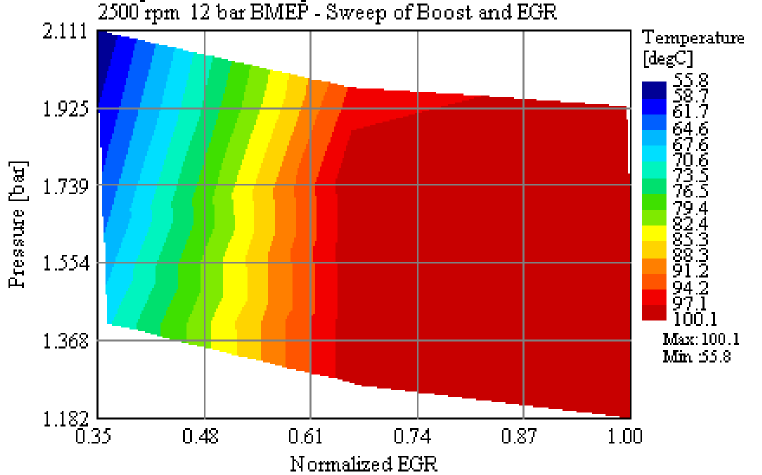
EGR Cooling Load
2500 rpm 12 bar BMEP - Sweep of Boost and EGR



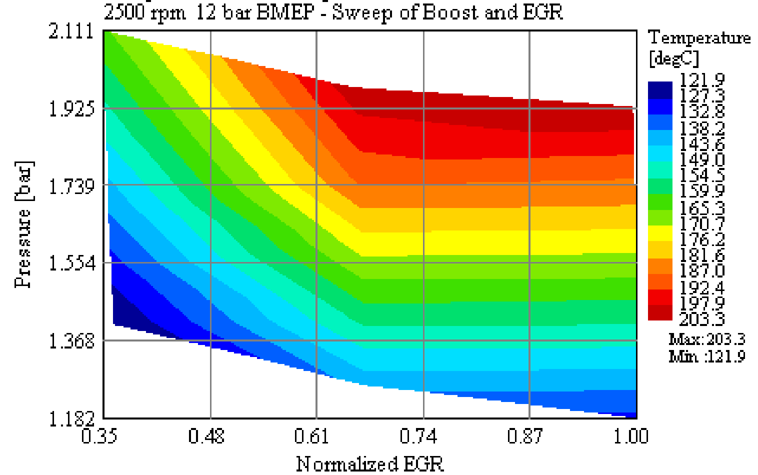
Low Pressure EGR Cooler Core Length
2500 rpm 12 bar BMEP - Sweep of Boost and EGR



Compressor Inlet Temp
2500 rpm 12 bar BMEP - Sweep of Boost and EGR



Compressor Outlet Temp
2500 rpm 12 bar BMEP - Sweep of Boost and EGR



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Summary

- More complex models of charge air cooler and egr coolers added to existing GT-POWER model.
- These models are necessary to evaluate egr distribution and cooler core sizing.
- Charge air cooler slave flow rate and egr cooler slave flow rate (not shown here) are important to results.

Summary (2)

- Best efficiency occurs at different egr distributions depending on operating condition
  - Low load – low speed conditions favor more low pressure egr
  - Higher load – higher engine speed favor more high pressure egr
- Once the user is comfortable with the Nu correlations, optimizers may be set up to size cooler cores.
  - Sizing may be set so not to exceed temperature limits on compressor or intake manifold
  - The limit may also be set so that the egr gas is not cooled too much
- Model Limitation
  - No brake dependency on cooling loads
  - No combustion variations for a given speed, load, and egr rate