Engine Technology Study for ANL

Meeting with NHTSA

Vishnu Nair, Northville, 29 September 2016

2014 Study for ANL - Background

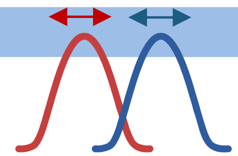
- ANL approached IAV to provide engine maps to use in Autonomie to predict vehicle fuel consumption
- IAV and ANL identified relevant engine technology combinations to investigate
- IAV used validated (production engine data) 1-D engine models in GT-POWER as a baseline and added features to assess the efficiency benefits of various technologies
- Assumptions/ correlations used in the study were based on IAVs data base of engine test data, benchmarking studies, single cylinder test data and modeling studies.
- For each concept a complete engine load/speed grid was simulated, with the following outputs delivered to the customer in standardized format
  - Engine speed, BMEP, brake torque, fuel flow rate, PMEP and FMEP (Grid 1000 rpm to max engine rpm (500 rpm steps), 1bar BMEP to full load
  - Idle fuel flow
  - Data was also provided at some negative output operation points (useful for accurate vehicle deceleration behavior predictions)

Overview of 2014 ANL Project

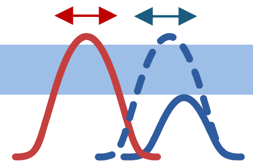
Increased efficiency

DOHC

1. VVT (baseline*)
   2.0l, 4 cylinder
   NA, PFI, DOHC,
   CR 10.2
   Dual cam VVT



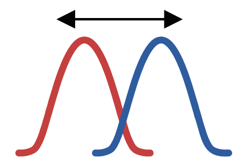
2. VVL
   Intake VVL
   Equal scaling
   (50% lift 50% duration)



3. GDI
   CR: 11
4. Cylinder deactivation
   1000 ≤ rpm ≤ 3000
   BMEP ≤ 5bar

SOHC
(no friction change)

5a. VVT (fixed overlap)



Red friction –Stage1
(0.1 bar reduction)

5b. VVT

6a. VVL

7a. GDI

8a. Cylinder deac

Red friction –Stage1
(25% reduction)

5c. VVT

6a. VVL

7a. GDI

8a. Cylinder deac

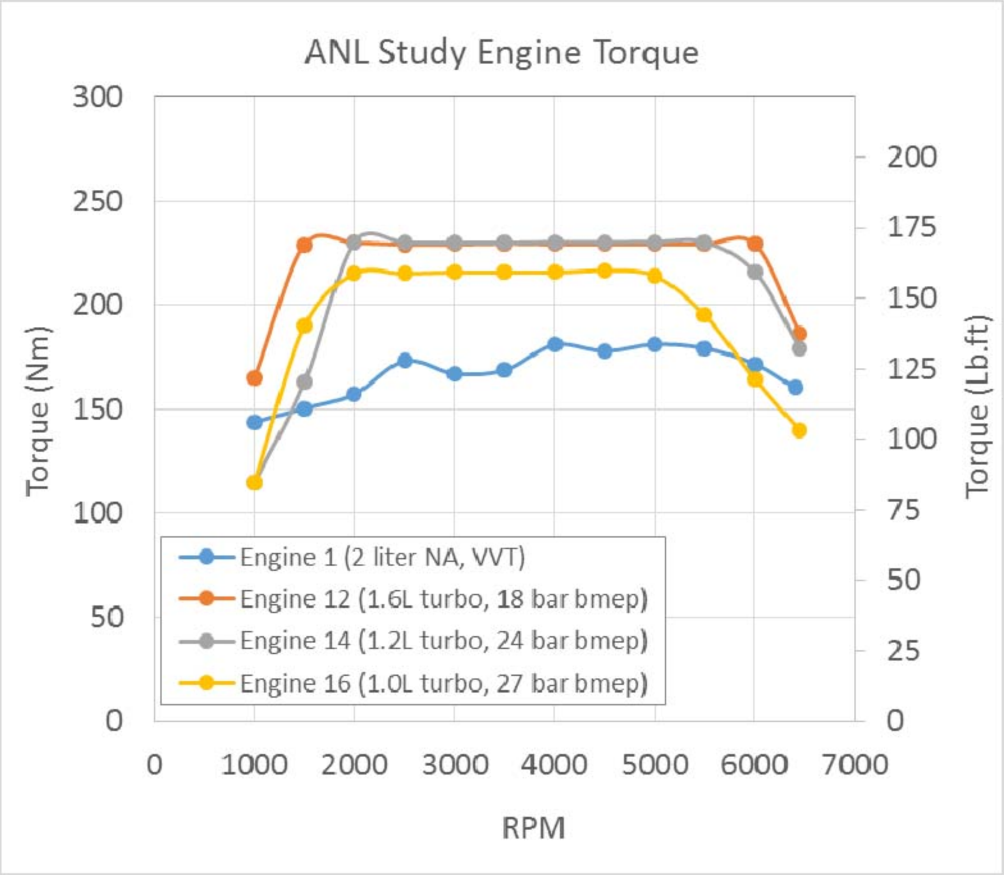
DOHC Turbo

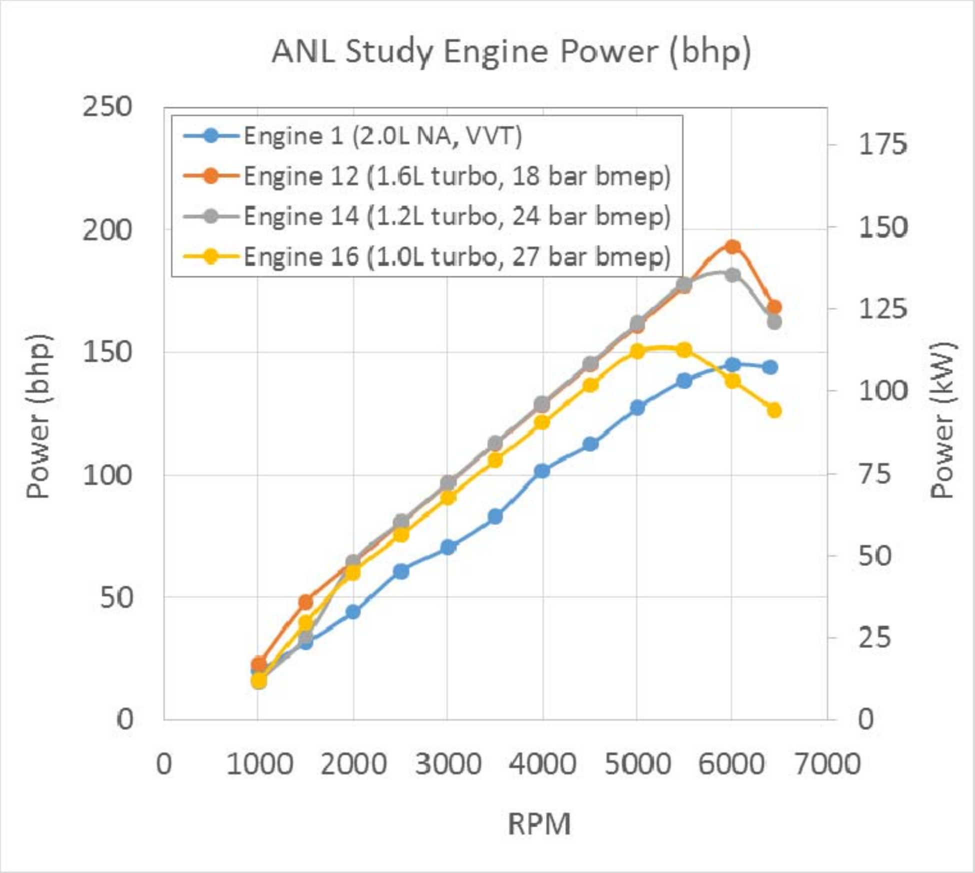
12. Downsize Level1 → 1.6l, 4cyl,18bar bmep*
    DOHC Turbo - Gasoline, Turbocharged, DI,
    Dual cam, VVT, VVL, CR 10.5
13. Downsize Level2 → 1.2l, 4cyl, 24bar bmep
14. Downsize Level2 → 1.2l, 4cyl, 24bar bmep, cooled EGR
15. Downsize Level3 → 1.0l, 4cyl, 27bar bmep, cooled EGR
16. Downsize Level3 → 1.0l, 3cyl, 27bar bmep, cooled EGR

*** Base Engine models based on detailed test data from representative production engines**

Scale Turbocharger maps and Friction

Power and Torque Range of Engines





- Typical power output of small car / crossover

Assumptions/ factors in modeling

- NA engines used 87 (R+M)/2 octane rating fuel and the TC engines used 93 octane
- All NA engines concepts were derived from the same parent model (Engines 1-8c)
- All turbocharged engines were derived from the same parent model (Eng12-16)
- Eng1(NA) and Eng12(TC) were calibrated using engine test data and all other concepts were derived from them
- Ambient conditions were fixed at T=25C / P= 990 mbar
- Stoichiometric ratio lambda=1 held throughout the majority of the operating regions
  - Enrichment was added to improve NA full load curve and to protect exhaust components at high loads based on model predicted exhaust temperatures
- Constraints on VVT camshaft phaser range honored throughout valve timing optimizations (combustion stability, hardware limitations, piston clearance)
- Predictive combustion models allowed a spark controller to target optimal phasing with allowance for a knock controller override where knocking was predicted

ANL Study Modeling Process

Baseline airflows are calibrated to match engine data (flow bench data)

Displacement normalized mechanical friction is modeled as a function of engine speed and specific load

A **combustion model** is trained to predict heat release rate in response to effects such as cylinder geometries, pressure, temperature, turbulence, residual gas fraction, etc.

A **knock correlation** based on in-cylinder conditions and fuel octane rating predicts if knock will occur and at what intensity

A **combustion stability prediction** useful for understanding EGR and EIVC tolerance is trained using covariance of IMEP data

Load Controllers

Coordination of VVT/VVL, throttle and wastegate controllers when applicable for air path control

Fuel controller targets λ=1 for low loads and enriches at high loads dependent on EGT for max power and component protection

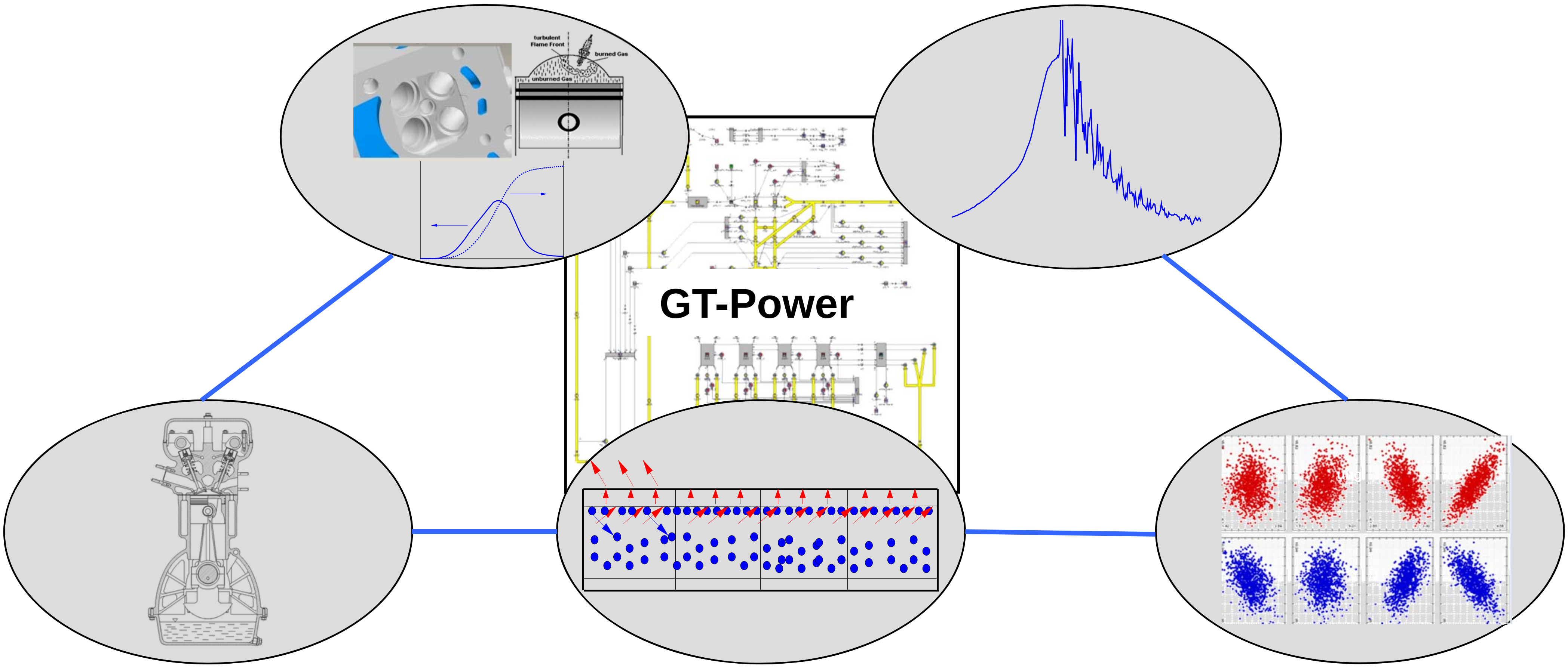
Spark Controller

Targets optimal combustion phasing within knock and combustion stability limits

GT-POWER Model development - Overview

Heat Release
Predictive combustion model

Kinetic fit Knock model
Sensitive to AFR and Diluent (EGR)



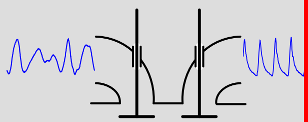
Friction model
Physics based

Heat flow / HotEnd
Physics based

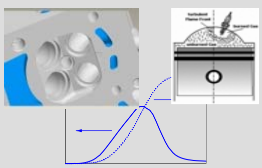
Optimization tool
IAV Engineering-ToolBox
→ coupling with GT-Power

Gas Exchange Model – Setup / Calibration

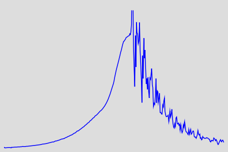
Gas Exchange



Combustion

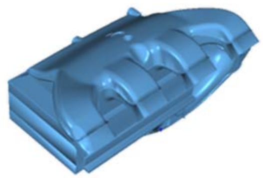


Knocking

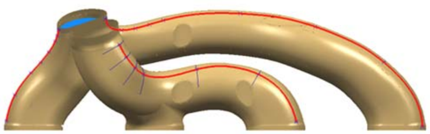


Friction

Fully automated gas exchange model adjustment



3D - CAD – geometries (ProE / Catia)



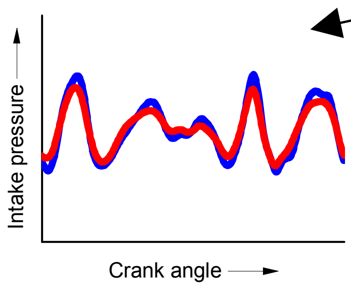
1D – Elementes / GEM 3D

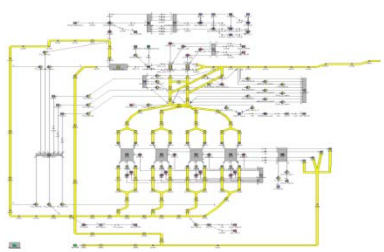
Optimization of simulated indicated data to match test data

Coupling: GT-Power & IAV Engineering Toolbox

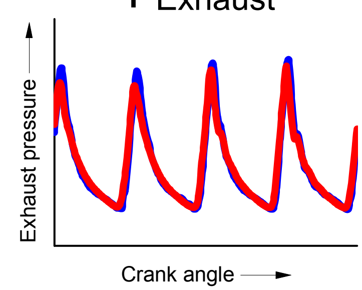
Result

p_{Intake}



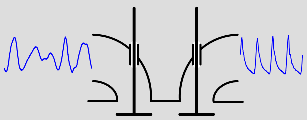


$p_{Exhaust}$

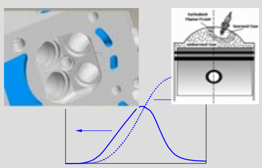


Combustion Model – Characteristics

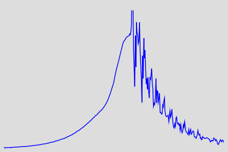
Gas Exchange



Combustion



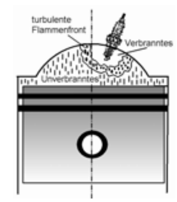
Knocking

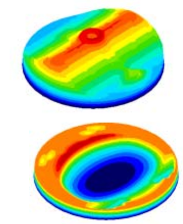


Friction

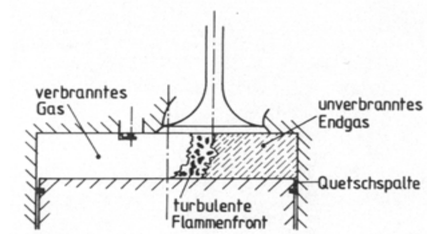
Quasidimensional combustion model / Entrainment model

→ Model to calculate the premixed combustion in gasoline engines





- Turbulence controlled combustion model
- Consideration of geometrical characteristics of the combustion chamber
- Implemented model for flame propagation



- Combustion / heat release is calculated by current thermodynamic in-cylinder conditions → physical prediction
- Captures impact of charge motion on residual gas tolerance

➔ Challenge: Development of efficient approach to get a model parameter set that fits the entire engine map

Knock Model

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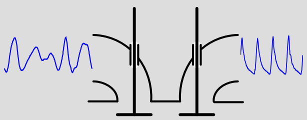
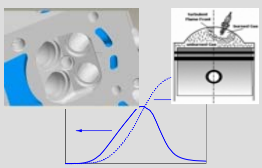
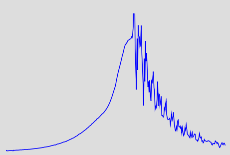
Gas Exchange



Combustion



Knocking



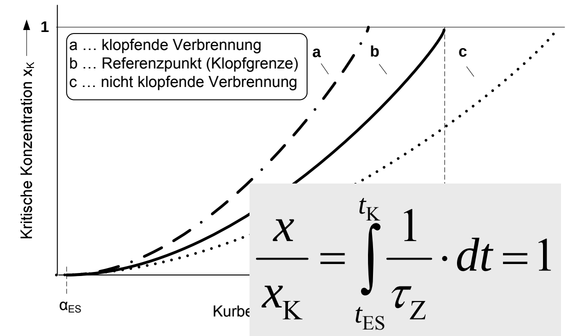
Friction

GT kinetics fit knock model – Modification of Arrhenius function

- Consideration of global influences (RGF / AFR / charge - pressure and temp.)
- Further developed with test data to predict knocking behavior due to:

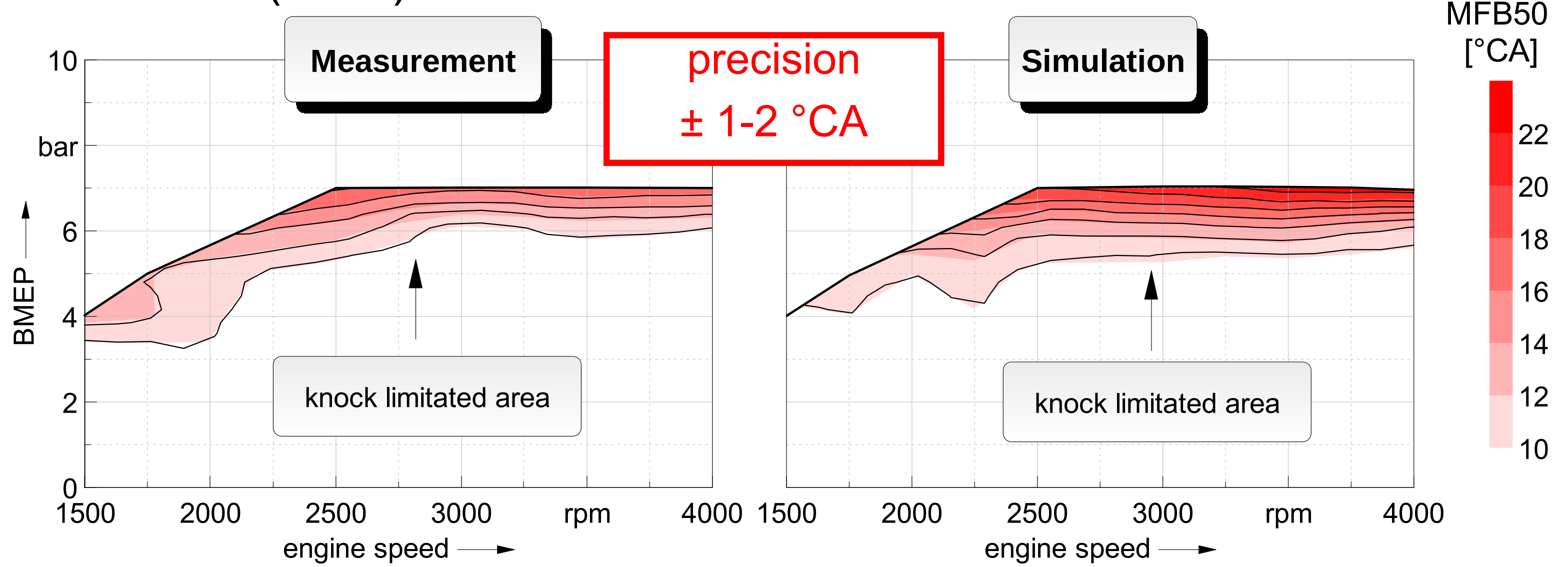
  → Lean combustion processes

  → Cooled EGR



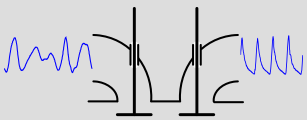
$$\frac{x}{x_K} = \int_{t_{ES}}^{t_K} \frac{1}{\tau_Z} \cdot dt = 1$$

Example: advanced calculation of knock tendency due to cylinder deactivation (DOD)

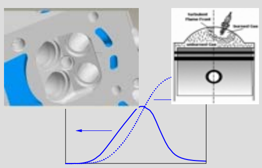


Friction Model

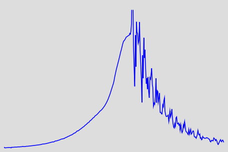
Gas Exchange



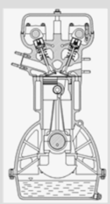
Combustion



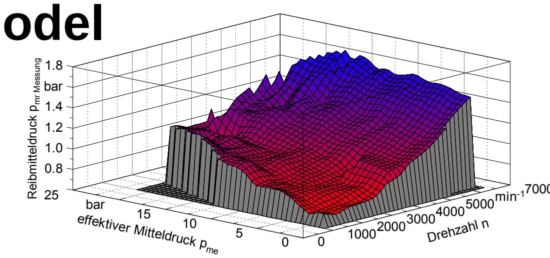
Knocking



Friction



Combination of Physics based / empirical model



Friction models within GT-Power inexact or with unavailable detail-level for:

- Studies regarding engine downsizing strategies
- Cylinder deactivation (DOD)
- Studies concerning stroke / bore influences
- Assessment of valve train strategies

geometrical influence terms

$$FMEP = FMEP\_Ref + \Delta FMEP_{\underbrace{MB/CB}_{1}/\underbrace{PG/VT/CT}_{2}/\underbrace{CP/OP}_{3}}$$

(1) Main and conrod bearing

(2) Piston group, camshaft and valve train

(3) Coolant and oil pump

Accounts for

- Change of displacement → cylinder reduction
- Stroke / bore changes

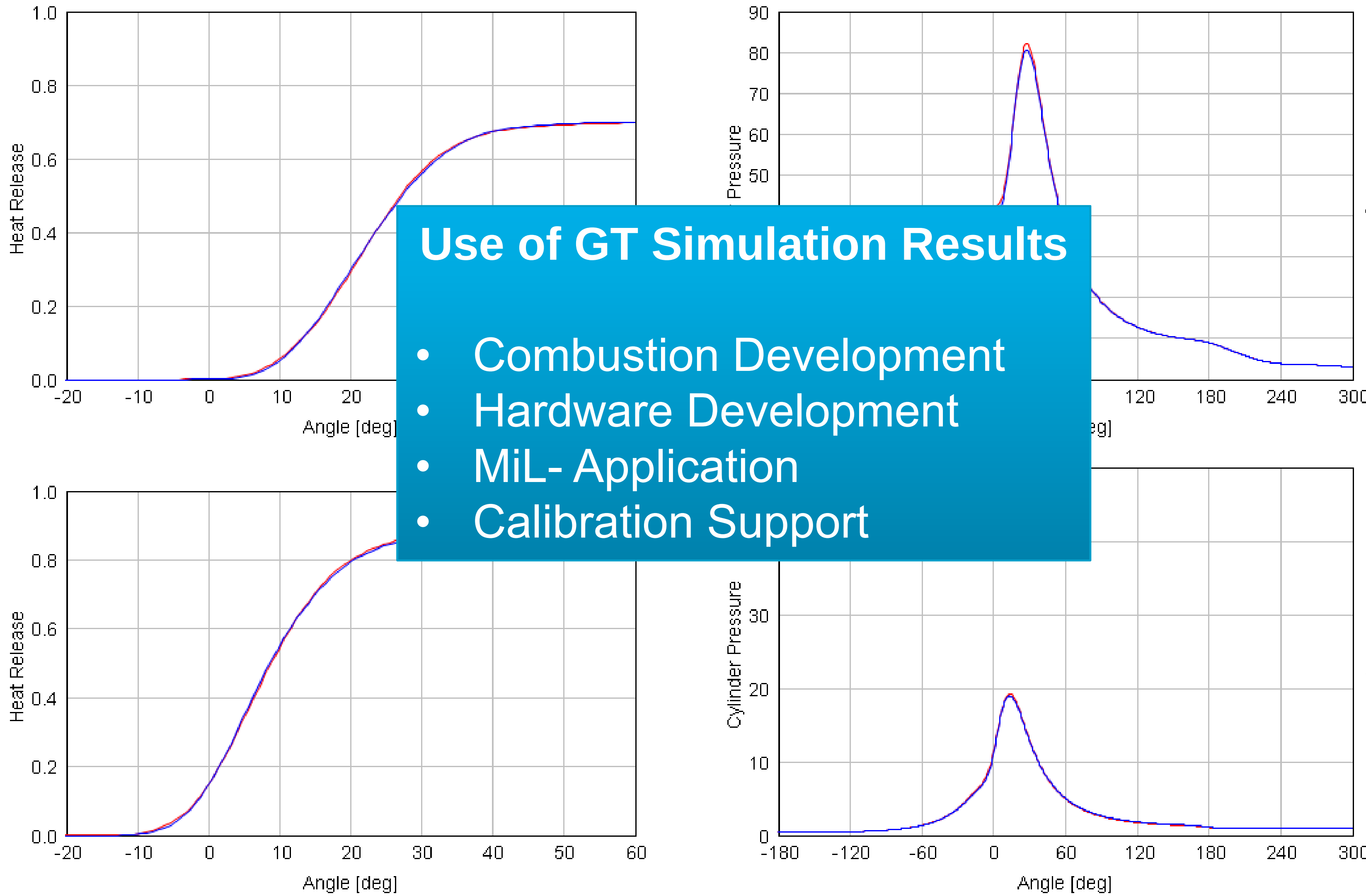
Accuracy

Heat Release

Cylinder Pressure

Measurement

Simulation



4000 rpm / Full Load

2000 rpm / Part Load

Use of GT Simulation Results

- Combustion Development
- Hardware Development
- MiL- Application
- Calibration Support

Example Model 12

1.6l, 4cyl, DOHC Turbo - Gasoline, Turbocharged (Twin scroll), Direct Injection, Intake - continuously variable valve lift. Dual cam phasing, CR 10.5

Flow

All flow sections based on detailed CAD data

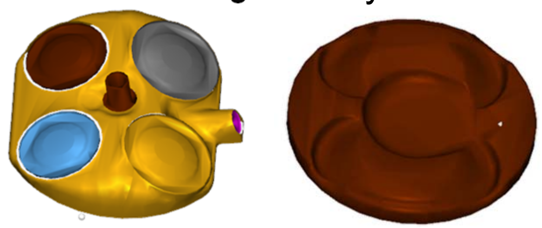
Detail calibration of friction, pressure losses and heat transfer - Air filter, Intercooler, catalyst, muffler

Valve discharge coefficients, Tumble and Swirl coefficients based on detailed measurements – Flow bench, Doppler Global Velocimetry

Production intake VVL system lift curves

Combustion

Combustion chamber (head and piston) geometry in GT-POWER for accurate flame geometry



Predictive combustion and knock models - Sensitive to Lean combustion, cooled EGR

Calibrated heat transfer models

Controllers

Load controller - coordinates variable valve lift and throttle to control load

Spark timing controller - Based on knock

Lambda controller - max power and exhaust temperature control

Extensive test and CFD data for calibration

2016 Project update

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Task 1

- Modify engine models using premium 93 octane fuel in the 2014 study to use regular 87 octane fuel and update BSFC maps (Engine 12-16 in the original study used 93 octane)

Task 2

- Simulate additional engine technology combinations that were not part of the 2014 study

Baseline - Engine 1 - (referred to as VVT in Aymeric's mail/ tables)
Gasoline, 2.0l, 4 cylinder, NA, PFI, DOHC, dual cam VVT

New engine – technology combinations

Engine 18 - 2.0l, 4 cylinder, NA, DOHC, dual cam VVT + Direct Injection (GDI)

Engine 19 - 2.0l, 4 cylinder, NA, PFI, DOHC, dual cam VVT + DEAC (fixed cylinder deac)

Engine 20 - 2.0l, 4 cylinder, NA, PFI, DOHC, dual cam VVT + VVL (on the intake) + DEAC

Engine 21 - 2.0l, 4 cylinder, NA, DOHC, dual cam VVT + Direct Injection (GDI) + DEAC

Simulation of advanced technologies

Task 3

- Suggest new engine technologies that will be likely in production by 2025 helping manufacturers meet the fuel economy targets
- IAV to provide matrix of engine size, technology combinations that are most probable/ beneficial
- Example of technologies suggested but not to be limited to
  – Variable compression ratio
  – Electric supercharger
  – Variable cylinder deactivation (similar to Tula technologies)

UNDER DISCUSSION

Thank You

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