# ANL Project Final Deliverables Meeting

## GT Power Study – BSFC Maps of Multiple Engine Concepts

IAV Northville, 2/27/2014

Phillip Bonkoski, Heiko Schilling

# ANL Project Final Deliverables Meeting
# Agenda

**Agenda proposed by ANL**

1. Wrap up presentation from IAV
   - Data delivered
   - Final summary of assumptions
   - Process overview
   - Conclusions
2. Review maps and efficiency values post processed by ANL
3. Additional project related questions/ discussions
4. Joint presentation to the USDRIVE – ACEC tech team
5. Any additional open items/ final wrap-up

# ANL Project Final Deliverables Meeting
# Original Overview Diagram

automotive engineering iav

Increased efficiency

**DOHC**
**(Reference engine 2.0l 4V I4 PFI)**
1. Dual cam VVT
2. VVL
3. GDI
4. Cylinder deactivation

**SOHC**

5. VVT (fixed overlap)
6. VVL
7. GDI
8. Cylinder deactivation

**OHV**

9. GDI
10. Cylinder deactivation
11. VVT

**DOHC Turbo**

12. Turbo – Downsized Level1 → 1.6l - BMEP = 18bar
13. Turbo – Downsized Level2 → 1.2l - BMEP = 24bar
14. Turbo – Downsized Level2 → 1.2l - BMEP = 24bar + cooled EGR
15. Turbo – Downsized Level3 → 1.0l - BMEP = 27bar + cooled EGR

16. Turbo – Downsized Level3 → 1.0l - BMEP = 27bar + cooled EGR (3 cylinder as option)

**Diesel**

17. Diesel (small Diesel engine → BSFC map of an engine with comparable size to #16)

# ANL Project Final Deliverables Meeting
# Final Overview Diagram

automotive engineering iav

Increased efficiency

**DOHC**

1. VVT (baseline*)
2. VVL
3. GDI
4. Cylinder deact

**SOHC**

(no friction change)
5a. VVT (fixed overlap)

(Red friction –Stage1)
5b. VVT
6a. VVL
7a. GDI
8a. Cyl deact

(Red friction –Stage2)
5c. VVT
6b. VVL
7b. GDI
8b. Cyl deact

**DOHC Turbo****

12. Downsize Level1 → 1.6l, 4cyl,18bar bmep
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

**Diesel**

17. Diesel engine → 2.2l, 4cyl

*baseline - Gasoline, 2.0l, 4 cyl, NA, PFI, DOHC, dual cam VVT (Each additional engine 2,3,4 adds a technology on top of the previously added technologies)
**DOHC Turbo - Gasoline, Turbocharged, DI, dual cam VVT, VVL

# ANL Project Final Deliverables Meeting
# Summary of Data Delivered

- Engine speed, BMEP, brake torque, fuel flow rate, PMEP and FMEP data provided in a standardized format for all simulated engines 1-16*
- These channels were provided from 1000RPM to the max engine speed and from 0bar BMEP to full load to provide a full operation map
- Fuel flow rates at zero output torque for engines 1-16 are provided separately from 650RPM (defined idle) to 6000 RPM
- Negative torque data provided (EngSpd, BMEP, Brake_torque, Fuel_flow, PMEP, Throttle)
  - Minimum fueled torque curve from baseline engine concept
  - Unfueled motoring curves from baseline concept (Throttle% 0, 0.4, 2.6, 6.3, 11.5, 18.2, 100)
  - Unfueled motoring curve from cylinder deactivation concept at WOT
- Measurement data from diesel engine (Eng17) with EngSpd, BMEP, Brake_torque, Brake_power, bsfc channels provided

*Data delivered in 4 packages (some with overlapping content): 1.Engine1.xlsx 2.NA_MapsDelivered.xlsx 3.FinalMapsDelivered.xlsx 4. Final_maps_FMEP

# ANL Project Final Deliverables Meeting
# Assumptions / Constants

**Gasoline engine simulations**

- All maps use gasoline with LHV = 41.3 MJ/kg but the naturally aspirated (NA) concepts were calibrated with 87 (R+M)/2 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 gasoline concepts were derived from the same parent model (Eng12-16)
- Ambient conditions were fixed at T=25C / P= 990 mbar
- Stoichiometric ratio lambda=1 held throughout the majority of the operating regions
- Slight enrichment was added to improve NA full load curve and extra fuel is added to protect exhaust components at some high loads based on model predicted exhaust temperatures
- VVT camshaft phaser ranges of motion honored throughout valve timing optimizations
- Predictive combustion models allowed a spark controller to target optimal phasing with allowance for a knock controller override where knocking was predicted

# ANL Project Final Deliverables Meeting
# Process Overview

- All simulation results were completed using software within GT-Suite developed by Gamma Technologies
- Parent models Eng1(NA) and Eng12(TC) were calibrated using engine test data and all other concepts were derived from them (the following process is repeated for each parent model)

## Modeling process/details

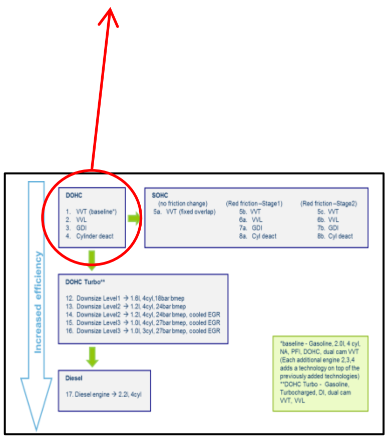
- Relevant engine geometries/parameters are measured and modeled with friction/flow losses, heat transfer, etc. and calibrated to match measurements
- Displacement normalized mechanical friction is modeled as a function of engine speed and specific load
- A combustion model is trained to predict fuel heat release rate in response to physical effects such as cylinder geometries, pressure, temperature, turbulence, residual gas concentration, 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 threshold prediction is trained using covariance of IMEP data and is used for understanding EGR tolerance especially at low loads
- Load controllers are developed for fuel/air path actuators and targeting controllers drive optimal and knock limited combustion phasing just as in a physical engine
- Careful modeling practice is used to provide confidence that calibrations will scale and predict reasonable /reliable predictions as parameters are changed throughout the various technology concept studies

# ANL Project Final Deliverables Meeting
# Process Overview

automotive engineering iav

**DOHC**

1. VVT (baseline)
2. VVL
3. GDI
4. Cylinder deactivation

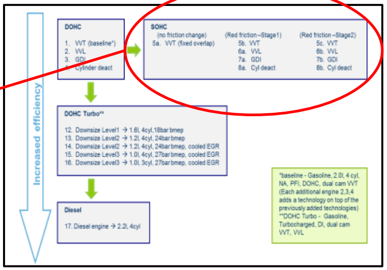



- Eng1 - gasoline, 2.0l, 4 cyl, NA, PFI, DOHC, dual cam VVT
  - Calibrations fully optimized for best bsfc and maximum torque (comb. phasing, valve timing, lambda, etc)
- Eng2* - VVL system was added to the intake valves on Eng1
  - Valve lift and timing optimized
  - Benefit (1) Reduced pumping work at low loads (2) More torque at low speeds from reduced intake duration
- Eng3* - Eng2 (PFI) converted to direct injection
  - Comp ratio raised from 10.2 to 11.0 and injection timing optimized
  - Benefit - DI provides greater knock tolerance, allowing higher comp ratio and increased efficiency over entire map
- Eng4* - Cylinder deactivation added to engine Eng3
  - Engine fires only 2 cylinders at low loads and at speeds below 3000 RPM by deactivating valves on 2 cylinders
  - Benefit - Effective load doubled on 2 cylinders providing less pumping work and higher efficiency

*All inputs/parameters are held constant unless specifically mentioned

# ANL Project Final Deliverables Meeting Process Overview

| SOHC | | |
|---|---|---|
| (no friction change) | (Red friction –Stage1) | (Red friction –Stage2) |
| 5a. VVT (fixed overlap) | 5b. VVT | 5c. VVT |
| | 6a. VVL | 6b. VVL |
| | 7a. GDI | 7b. GDI |
| | 8a. Cyl deact | 8b. Cyl deact |



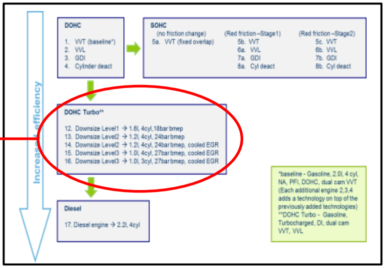

- Eng5a* - Eng1 converted to SOHC (gasoline, 2.0l, 4 cyl, NA, PFI, single cam VVT)
  - Valve timing optimized for fixed overlap camshaft with standard friction model from DOHC concepts
  - Benefit - Potential friction reduction (not added in Eng5a) at the expense of maximum power
- Eng5b/ Eng6a/ Eng7a/ Eng8a* - Reduced friction from Eng5a/ Eng2/ Eng3/ Eng4 respectively
  - Engine FMEP reduced by 0.1 bar over entire operation range to understand friction benefit from SOHC
  - Benefit (1) Reduced friction improves efficiency at all load points (2) Raises full load line
- Eng5c/ Eng6b/ Eng7b/ Eng8b* - Reduced friction from Eng5a/ Eng2/ Eng3/ Eng4 respectively
  - Engine FMEP reduced by 25% over entire operation range to understand potential of ‘extreme’ friction reduction (this is a “what if” study which doesn’t necessary represent what is currently possible)
  - Benefit (1) 25% friction reduction shows large improvements in efficiency especially at higher speeds where friction is very high (2) Raises full load line

*All inputs/parameters are held constant unless specifically mentioned

# ANL Project Final Deliverables Meeting
# Process Overview

**DOHC Turbo****

12. Downsize Level1 → 1.6l, 4cyl,18bar bmep
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




- Eng12 - gasoline, 1.6l, 4 cyl, turbocharged, DI, DOHC, dual cam VVT, intake VVL
  - Calibrations fully optimized for best bsfc (comb. phasing, valve timing, lambda, etc)
- Eng13* - Eng12 downsized to 1.2l
  - Turbocharger maps scaled to improve torque at low engine speeds
- Eng14* - High pressure cooled EGR added to Eng13
  - Cooled EGR target set points optimized
- Eng15* - Eng14 downsized to 1.0l
  - Cooled EGR target set points re-optimized and turbocharger maps re-scaled
- Eng16* - Eng15 converted to 3cyl, 1.0l concept
  - Intake and exhaust piping scaled to account for larger mass flows through each cylinder and cooled EGR target set points re-optimized

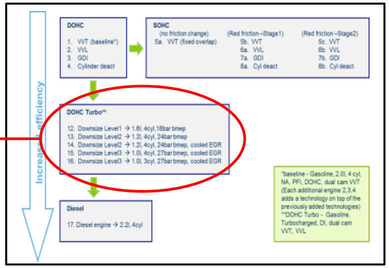
Benefits summarized on the following page

*All inputs/parameters are held constant unless specifically mentioned

# ANL Project Final Deliverables Meeting
# Process Overview

**DOHC Turbo****

12. Downsize Level1 → 1.6l, 4cyl,18bar bmep
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



## Overview of benefits

- Downsizing - Allows for operation at a higher engine load point (increased efficiency) at a given vehicle torque demand
- Cooled EGR - (1) Cooled burned gas lowers in-cylinder temperatures causing a reduced knock tendency and thus improved combustion phasing (2) Reduced in-cylinder temperatures lead to reduced exhaust temperatures and therefore a reduced need for enrichment to protect exhaust components

## Other modeling notes

- Bore/stoke ratio was held constant in Eng12-16 with compression ratio of 10.5

# ANL Project Final Deliverables Meeting Conclusions

automotive engineering iav

## Important assumptions/conclusions

- Predictive friction equation (FMEP) calibrated from test data used in Engines 1-8b to allow for a smooth and systematic friction study but may under predict FMEP at high loads with late combustion phasing
- Map based FMEP lookup compiled from test data used for Engines 12-16
- Due to different methods we cannot draw direct conclusions on NA vs downsized engine friction
- Compression ratio / combustion system/ bore stroke sizing optimization would further improve fidelity of downsizing and CEGR findings
- Maximum torque line on boosted engines is adjustable based on boost pressure (Eng12 especially could have higher torque potential)
- NA engines should be considered as comparable to boosted engines even considering lower max torque because boosted engines suffer from slower torque response

## Potential future study suggestions

- Transient performance analysis could improve understanding of performance tradeoffs of various concepts
  - Turbocharger / torque response comparisons for NA vs downsized vs extreme downsized engines
- Continued simulation of new engine concepts
  - Variable compression ratio, SI lean, HCCI, eboosting systems, cylinder deactivation via crankshaft decoupling, ect.

# Thank You

IAV Automotive Engineering Inc.
15620 Technology Drive
Northville, MI 48168

Phone:  +1 734 233-3300
info@iav-usa.com