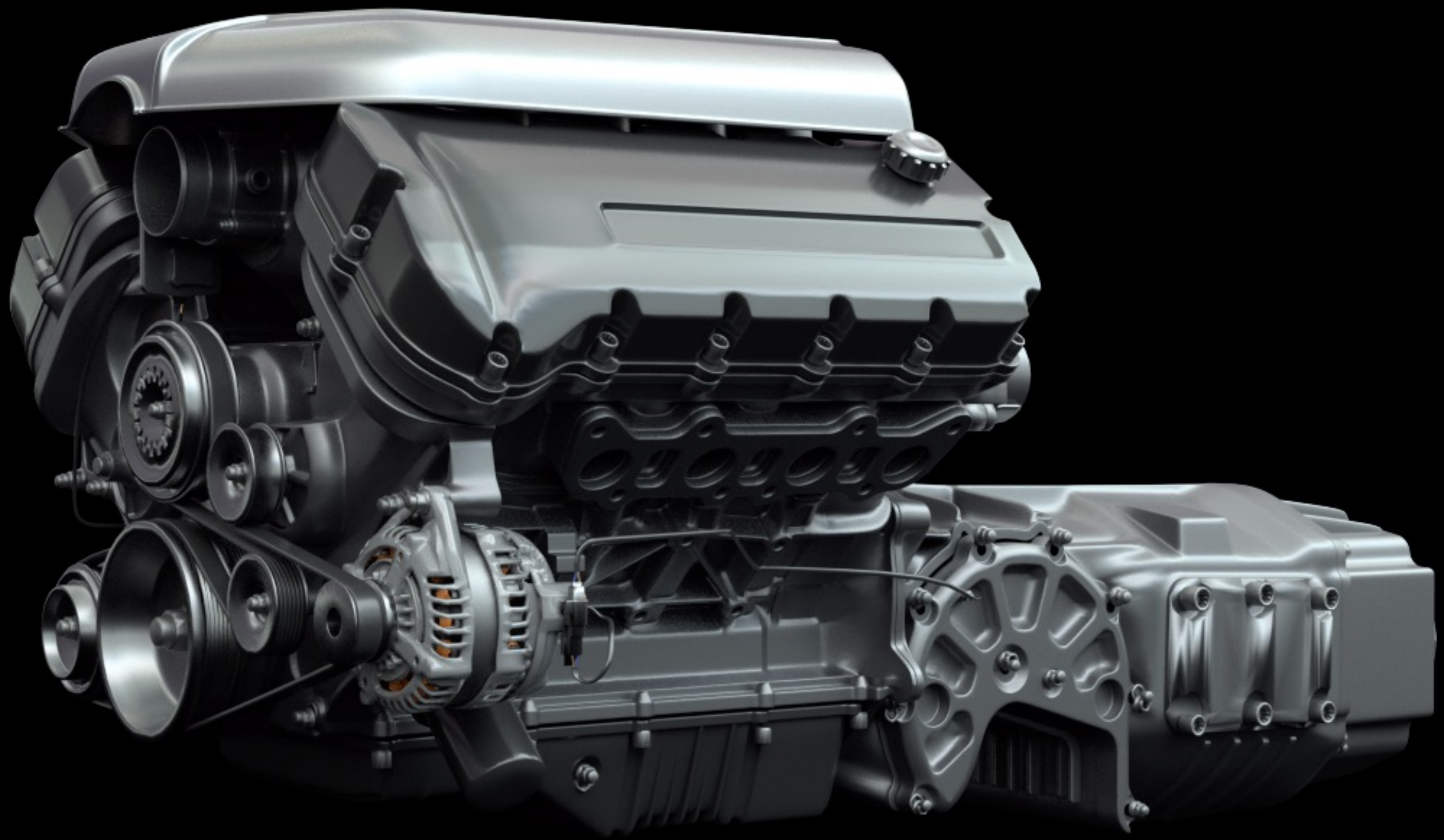
February 1, 2024

Computer Modeling of Performance Engines and Vehicles



AUTOMOTIVE CONSULTING SERVICES

automotivecs.com

Outline

- Background of ACS
- Motivation for why computer-based modeling of performance engines/vehicles is useful
- What tools are available
- How one-dimensional (1-D) models are constructed
- Examples of 1-D simulations
- Three-dimensional (3-D) modeling for flow systems
- Examples of 3-D simulations
- Outlook and Summary
- Additional Reading

Background

- This service of ACS is a specialization in engine and vehicle computer simulation.
- Typically - Engine, Valvetrain, Cooling, Lube/Oil, Vehicle Systems
- Projects are most often confidential
- For many clients, ACS becomes their “virtual” engineering department

- Diversity of project types
  - Concept propulsion systems
  - Automotive
  - Industrial/Agricultural
  - Stationary
  - Performance/Racing

Motivation

Why use computer-based simulations?

1 Cost

- Initial investment in a model is probably similar to a new dyno test run, but facility and hardware costs have enormous savings
- Still requires specialist people and equipment (computer/software)

2 Time

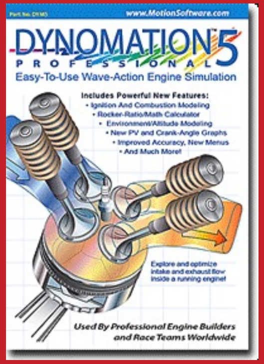
- Large test plans can be run much faster with simulations
- Set up can be just few days, depending on complexity

3 Understanding

- Much more information is available for more complete and deeper understanding
- Simulations are like a dyno test with unlimited number of data channels!

What Tools are Available? 1-D Simulation

- Basic Simulation Tools
  - Vary in basic capabilities
  - Some are “catalog” lookups correlated to basic relationships
  - Some are based on gas dynamics
  - Limited in model complexity
- Advanced Simulation Tools
  - Multi-Physics Platforms
    - Flow, Acoustics, Thermal, Mechanical, Electric, Chemistry, Controls
  - Extensive detail possible for geometry and content
  - Extensive pre and post processing
  - Distributed computing (multiple CPUs)
  - Coupling to other 3rd party software
    - 3-D CFD, engine controls, etc.



ENGINE EXPERT

WAVE 1D engine performance and NVH

Dyno Simulation Software VirtualEngineDyno.com

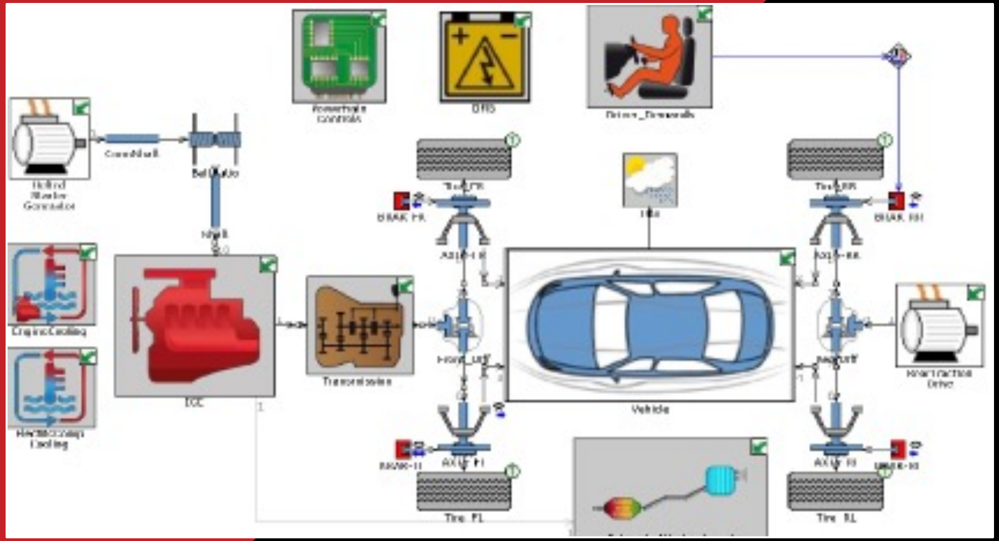
Performance Trends, Inc.

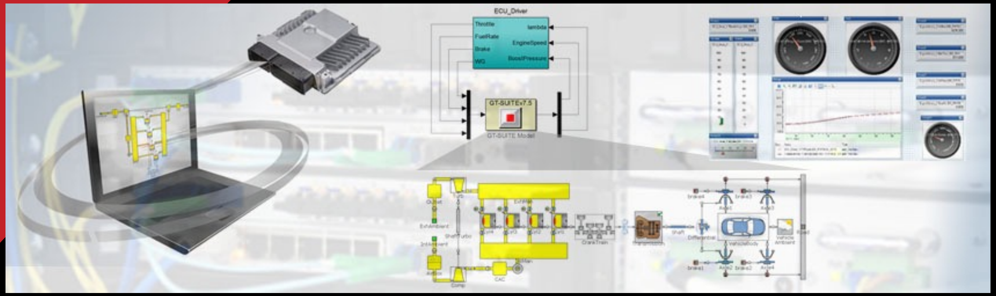
AVL BOOST™

GT Gamma Technologies

FEV VIRTUALENGINE

What Tools are Available? 1-D Simulation





- Gamma Technologies – GT Suite
  - ACS' software of choice
  - Very stable platform, continued rapid software development, and very good customer support/training/user community
  - Very good pre and post processing
  - Worldwide market leader
  - Wide array of modules
    - Pre/Post Processing
      - GT-ISE, GEM3D, GT-Spaceclaim, GT-Post
    - GT-Power, VTDesign, Cool3D, GT-Drive+, Converge-Lite
  - Couples well to 3rd party CFD and engine controls software

What Tools are Available? 3-D Simulation Tools

- 3-D Computational Fluid Dynamics (CFD) Simulation Tools
  - Multi-Physics Platforms
    - Flow, Acoustics, Thermal, Mechanical, Chemistry
  - Extensive detail possible for geometry and content
    - Moving or sliding meshes
    - Turbochargers, piston/cylinder, valves, etc.
  - Extensive pre and post processing
  - Distributed computing (multiple CPUs)
  - Coupling to other 3rd party software

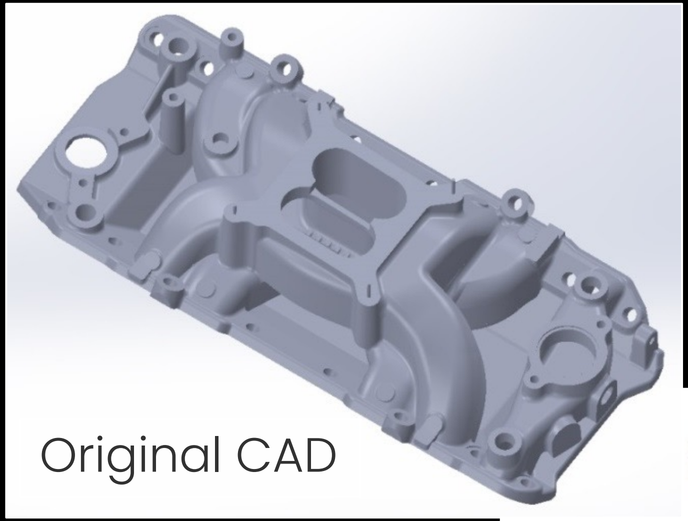
How 1-D models are Constructed

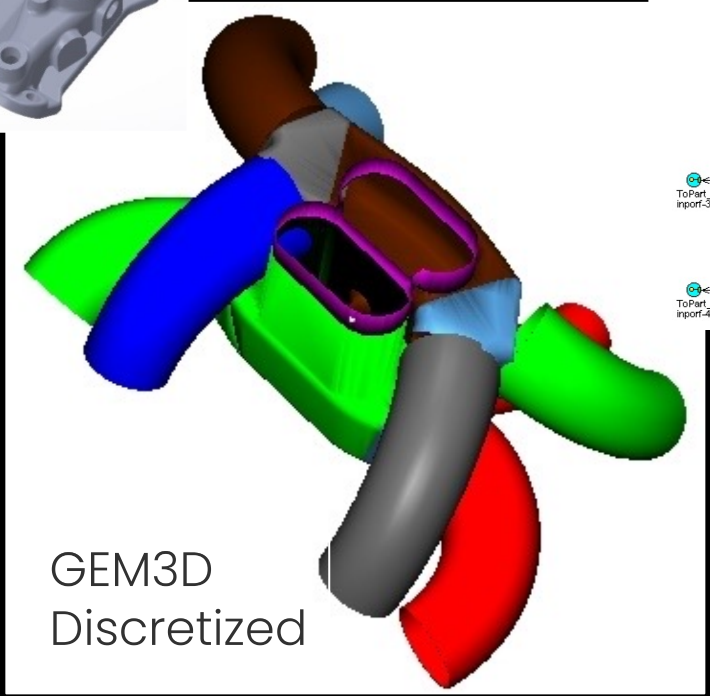
- For an engine or vehicle model…first, you need a lot of information, the more the better
  - Basic engine and/or vehicle geometry and specs
  - Engine air flow system geometry
    - 3D CAD models always preferred, but not necessary
  - Engine/vehicle operating information
    - Spark timing, fuel rate/type…
    - Transmission, clutch, final drive, tires, brakes…
    - Road/driving cycle info
  - Test data from a similar engine/vehicle for correlation
    - Power/torque, inlet restriction, exhaust backpressure, friction, crank angle-based cylinder pressure, manifold pressure…
    - Vehicle elapsed time, tractive forces, speed, acceleration…
- Almost never get all this, but we work with what is available
- With good and complete input, a well correlated baseline model could typically achieve 1-2% accuracy

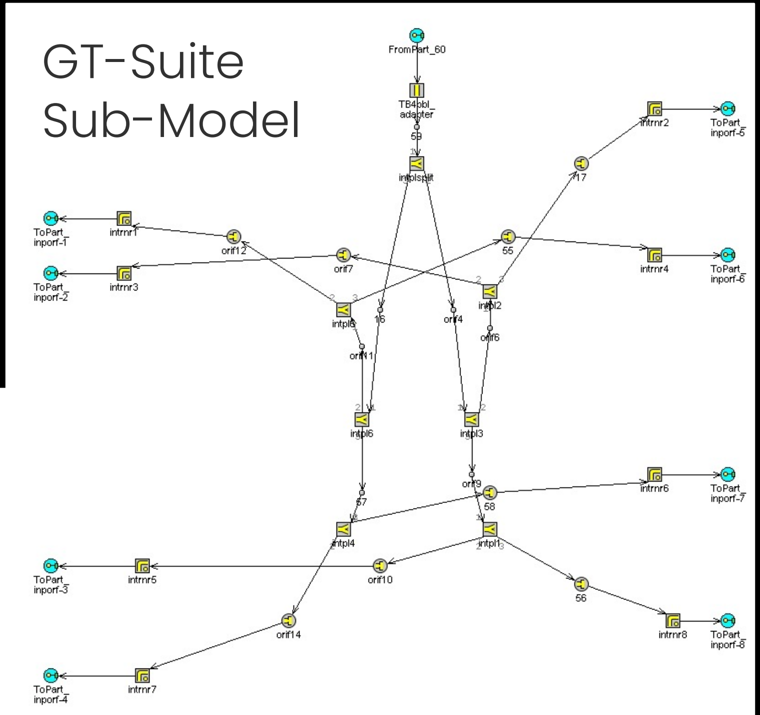
ENGINE SIMULATION INPUT LIST

ITEM	VALUE	DATA SOURCE	RESPONSIBLE
General Engine Parameters		**Engine Specifications**	
Bore, mm			
Stroke, mm			
Connecting Rod Length, mm			
Piston Pin Offset, mm			
Geometric Compression Ratio			
Cylinder Firing Order			
Cylinder Firing Separation, crank deg			
Valve Sizes		**Engine Specifications**	
Intake Outer Diameter, mm			
Number of Intake per Cylinder			
Exhaust Outer Diameter, mm			
Number of Exhaust per Cylinder			
Flow Data		**Flow bench testing at 7 kPa and a higher test pressure**	
Intake port			
Exhaust port			
Intake manifold with throttle body			
Exhaust manifolds			
Valve Lift vs Crank Angle		**Measured, or dynamic spintron, or simulated (Tabular computer file)**	
mm of net lift vs degree			
Flow System Geometry		**3D design data, hardware measurements, dyno setup**	
length and area schedule for ports			
manifold runner			
exhaust manifold			
throttle body			
induction			
air cleaner			
dyno inlet and exhaust			
Plenum Geometry		**3D design data, hardware measurements**	
Size			
Shape			
runner orientation			
Spark Timing vs Engine Speed		**Dyno test or calibration**	
deg BTDC vs rpm at Wide Open Throttle (WOT)			
Air/Fuel Ratio or Fuel Rate		**Dyno test at one or two engine speeds**	
(Engine Average and Cylinder-to-Cylinder Spread) at Wide Open Throttle (WOT)			
Fuel Characteristics		**Fuel specs**	
Octane			
Stoichiometric Ratio			
Heat Content, kJ/g			
FMEP vs Engine Speed		**Dyno cyl pressure testing at WOT firing**	
kPa vs rpm			
Inlet Restriction vs Engine Speed (MAP)		**WOT Dyno test**	
kPa vs rpm			
Exhaust Restriction vs Engine Speed		**WOT Dyno test**	
Location of measurement needed, kPa vs rpm			
Cylinder Pressure vs Crank Angle		**WOT Dyno test at one or two engine speeds for one or two cylinders**	
Table of pressure vs angle			
Intake Runner Pressure vs Crank Angle		**WOT Dyno test at one or two engine speeds for any intake manifold runner**	
Location of measurement needed, kPa vs degrees			
Plenum Pressure vs Crank Angle		**Dyno test at one or two engine speeds**	
Location of measurement needed, kPA vs degrees			

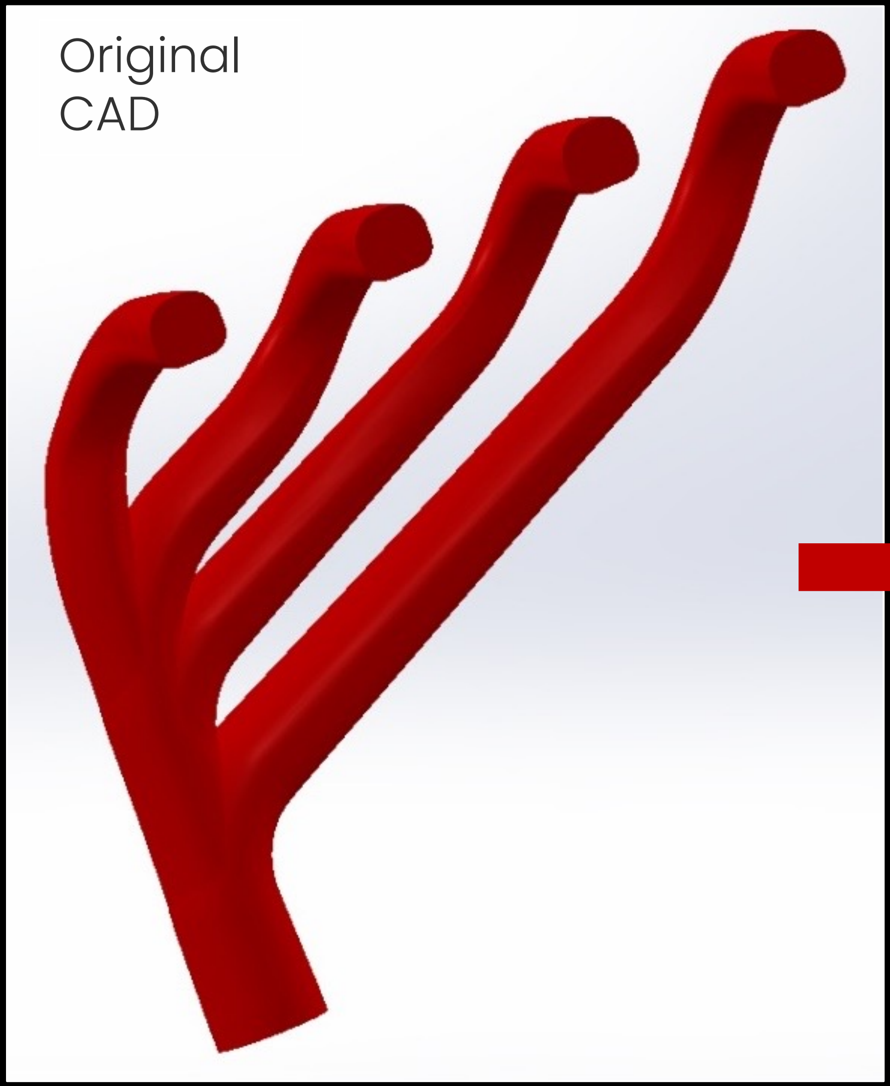
How 1-D Engine Models are Constructed – Intake Manifold

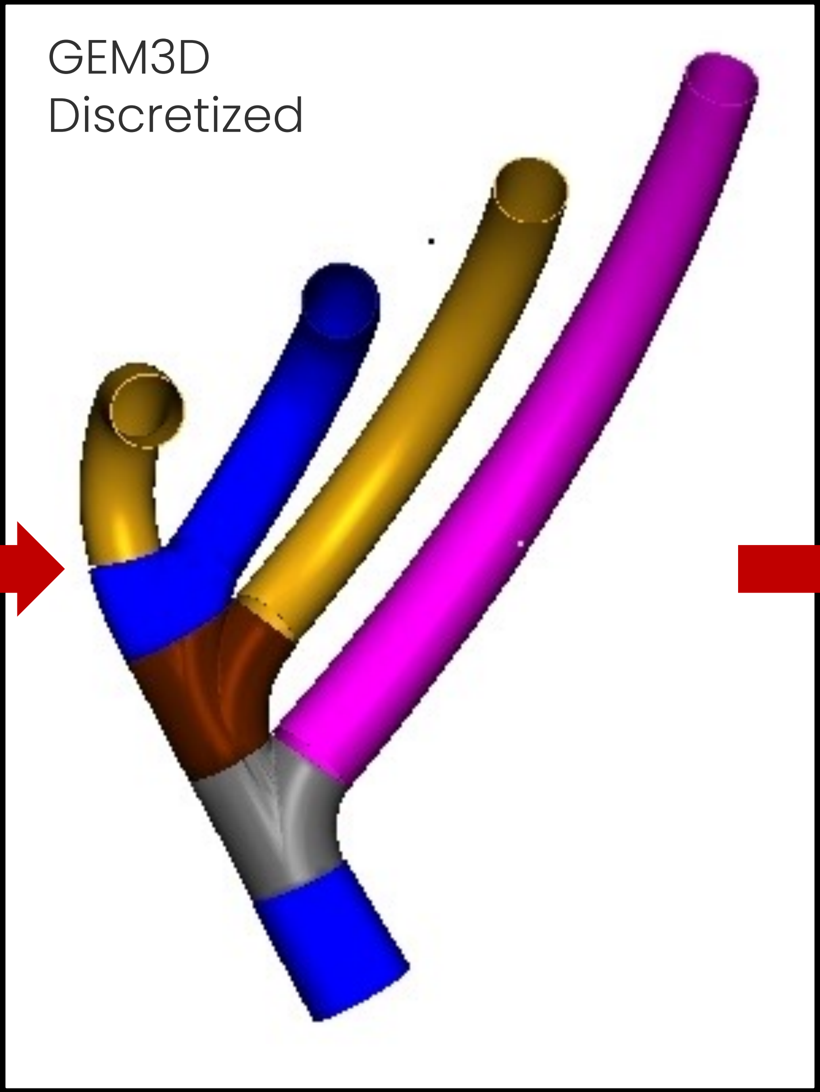


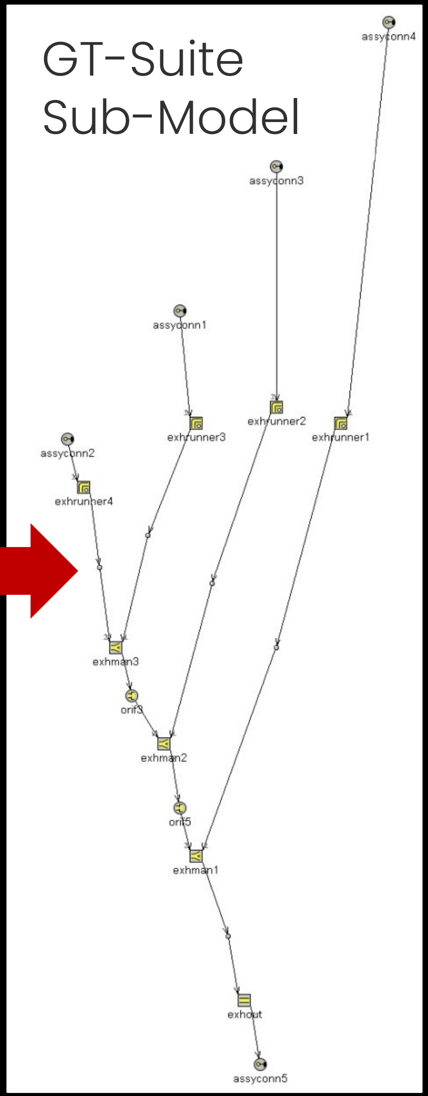




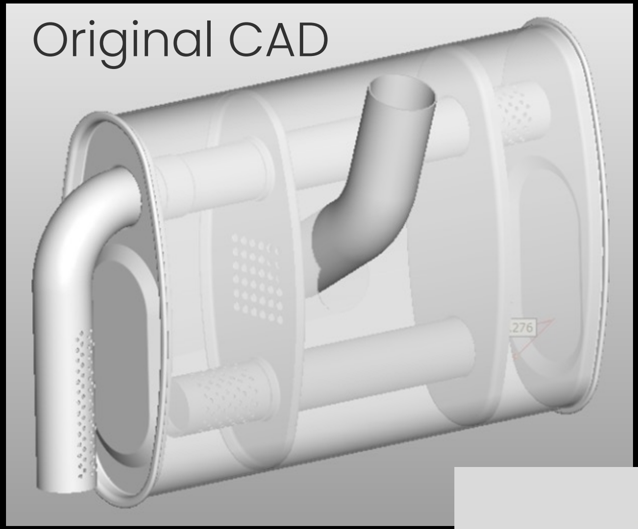
How 1-D Engine Models are Constructed – Exhaust Manifold

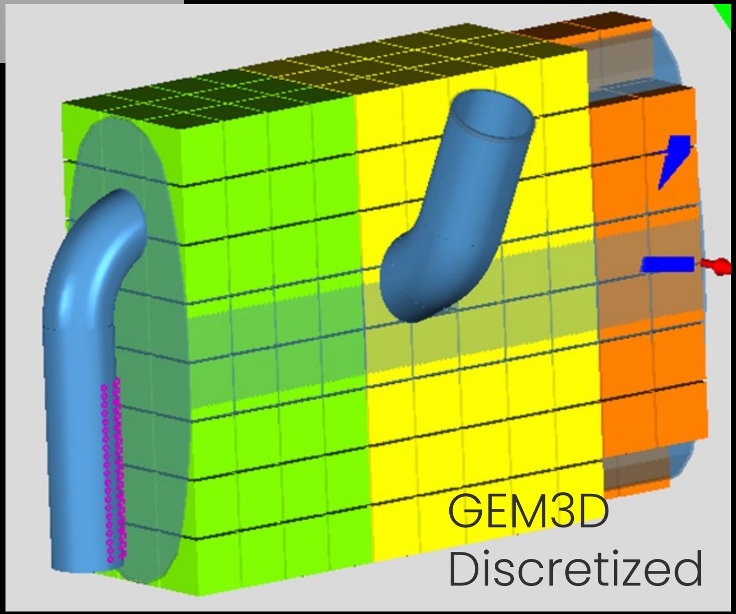


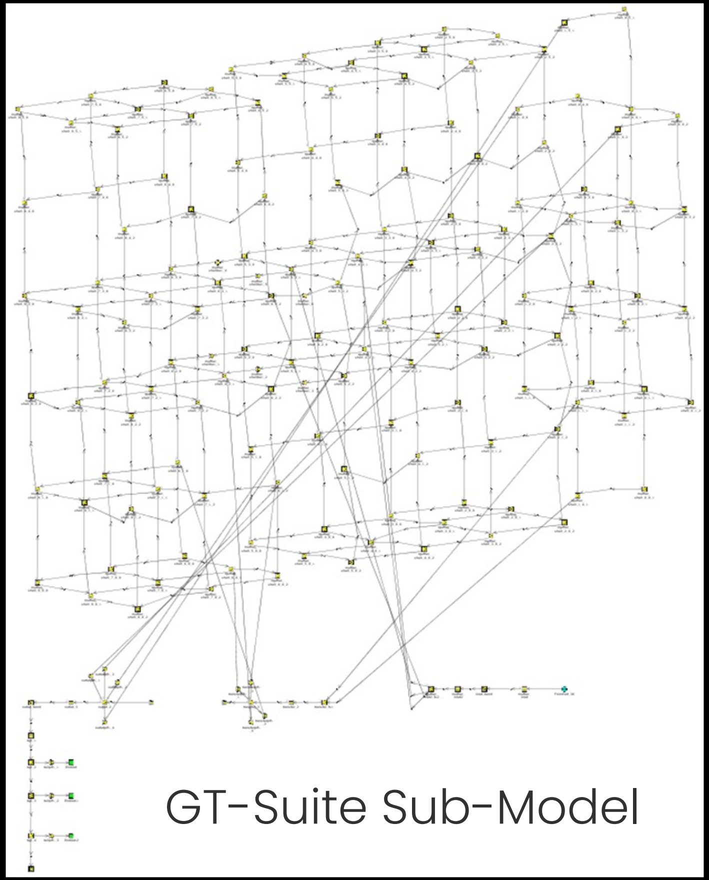




How 1-D Engine Models are Constructed – Muffler

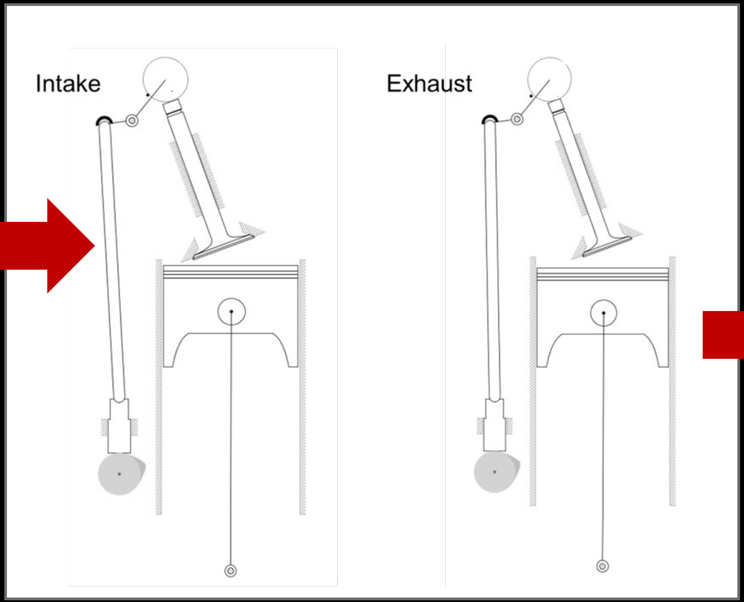




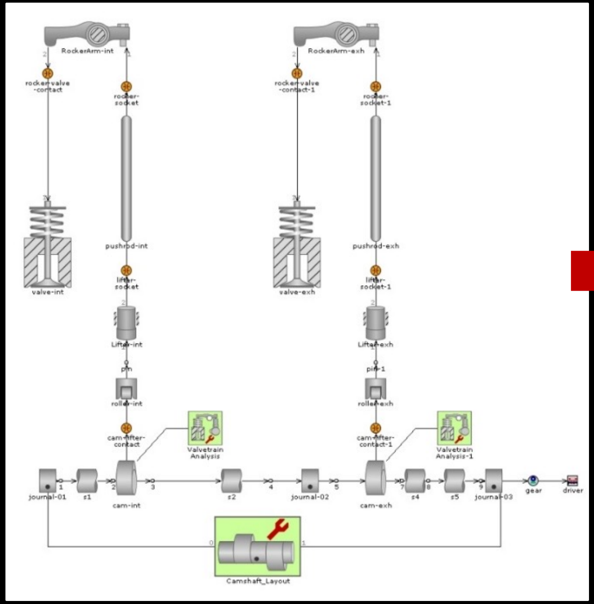


How 1-D Engine Models are Constructed – Valvetrain

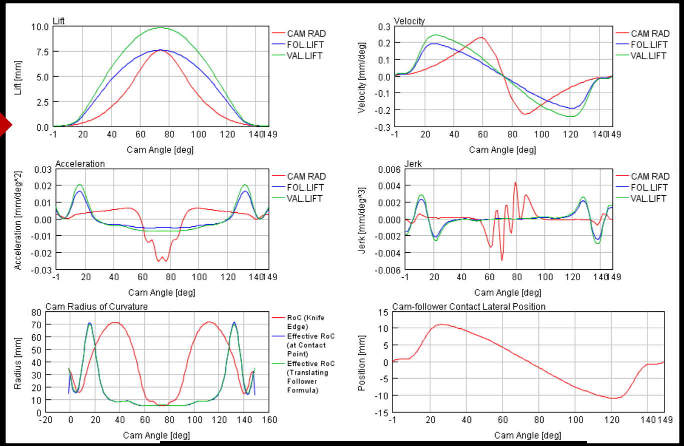
Original CAD



VTDesign Model



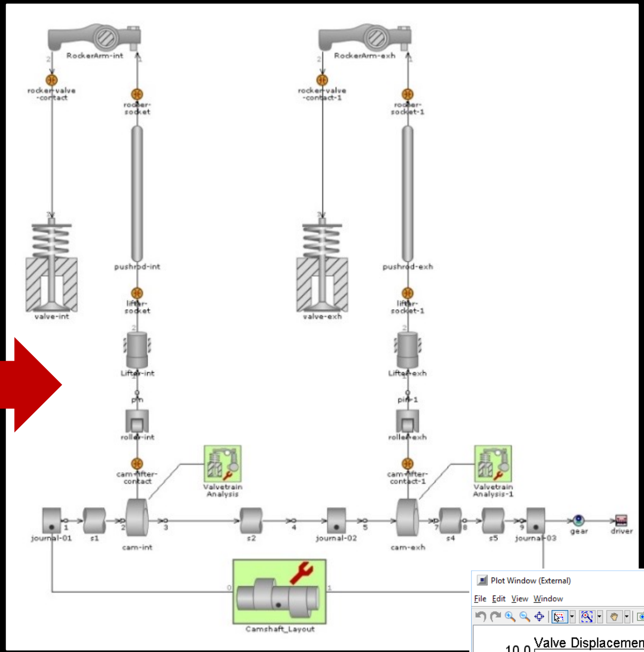
GT-Suite VT System Model

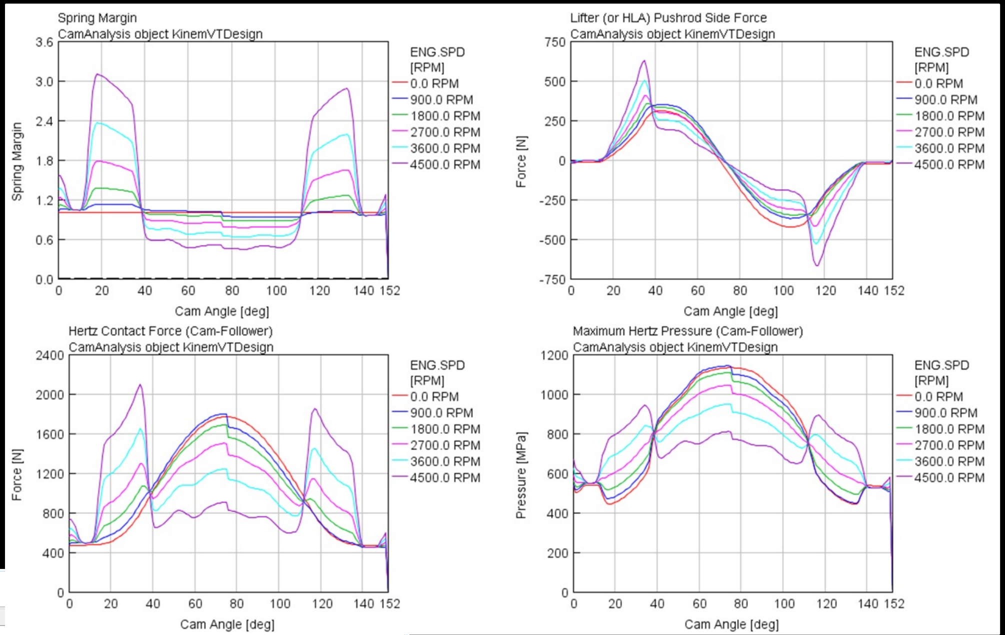


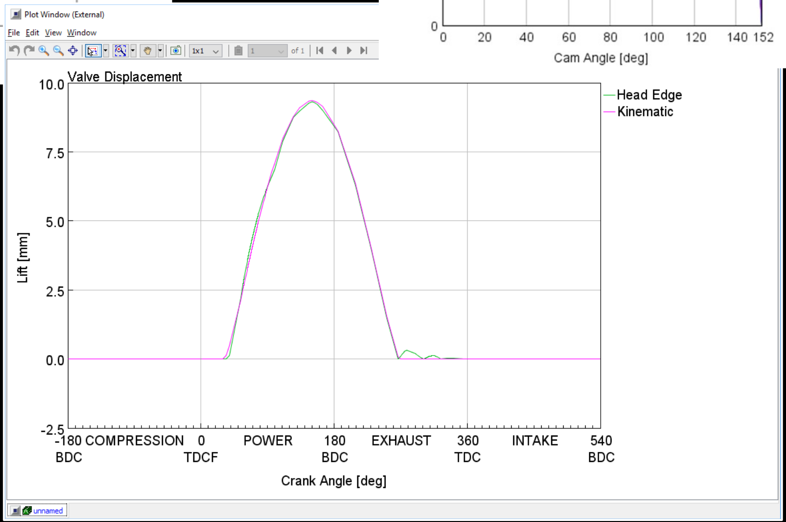
Kinematic Results

How 1-D Engine Models are Constructed – Valvetrain

GT-Suite VT
System Model

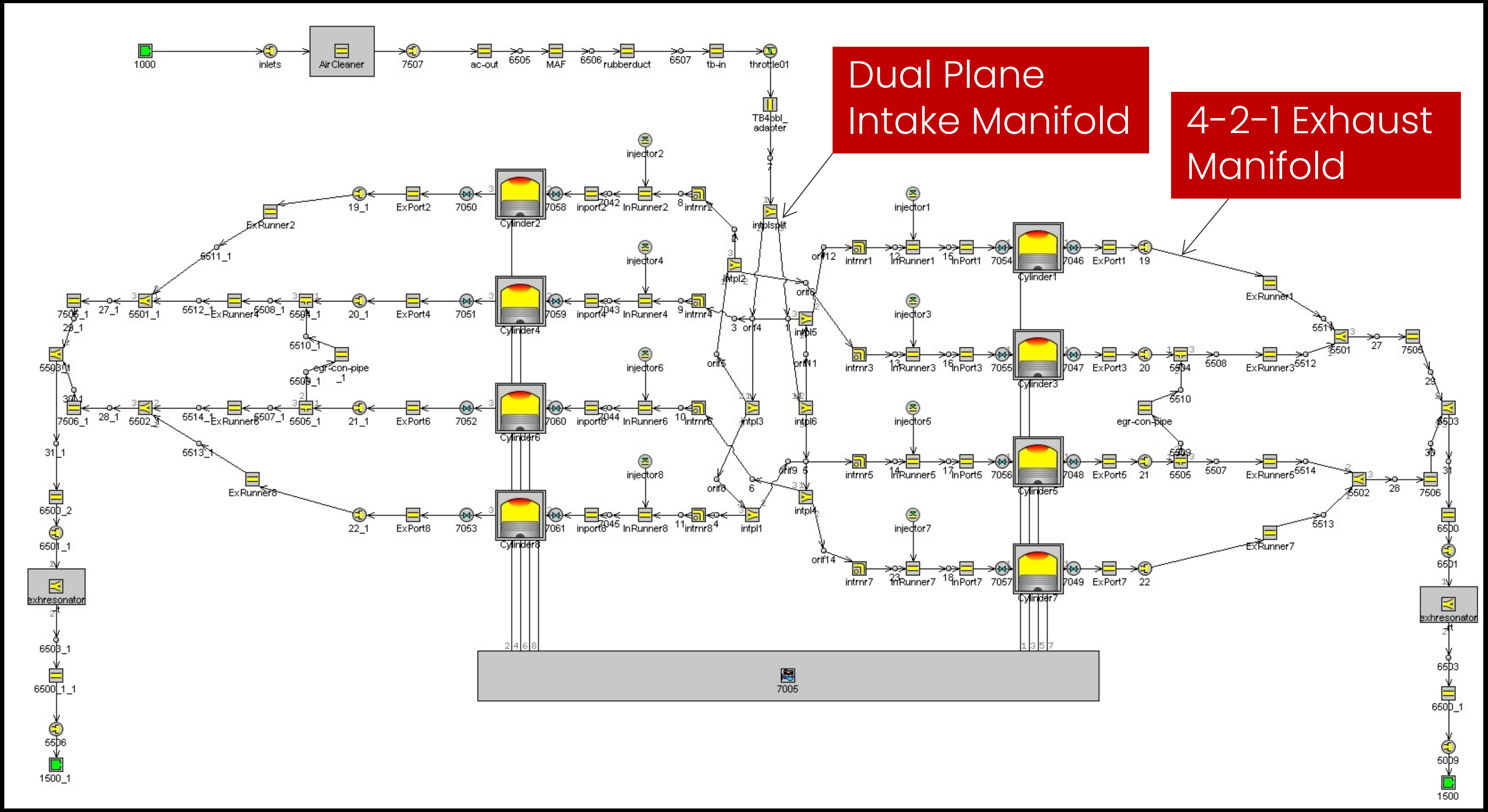




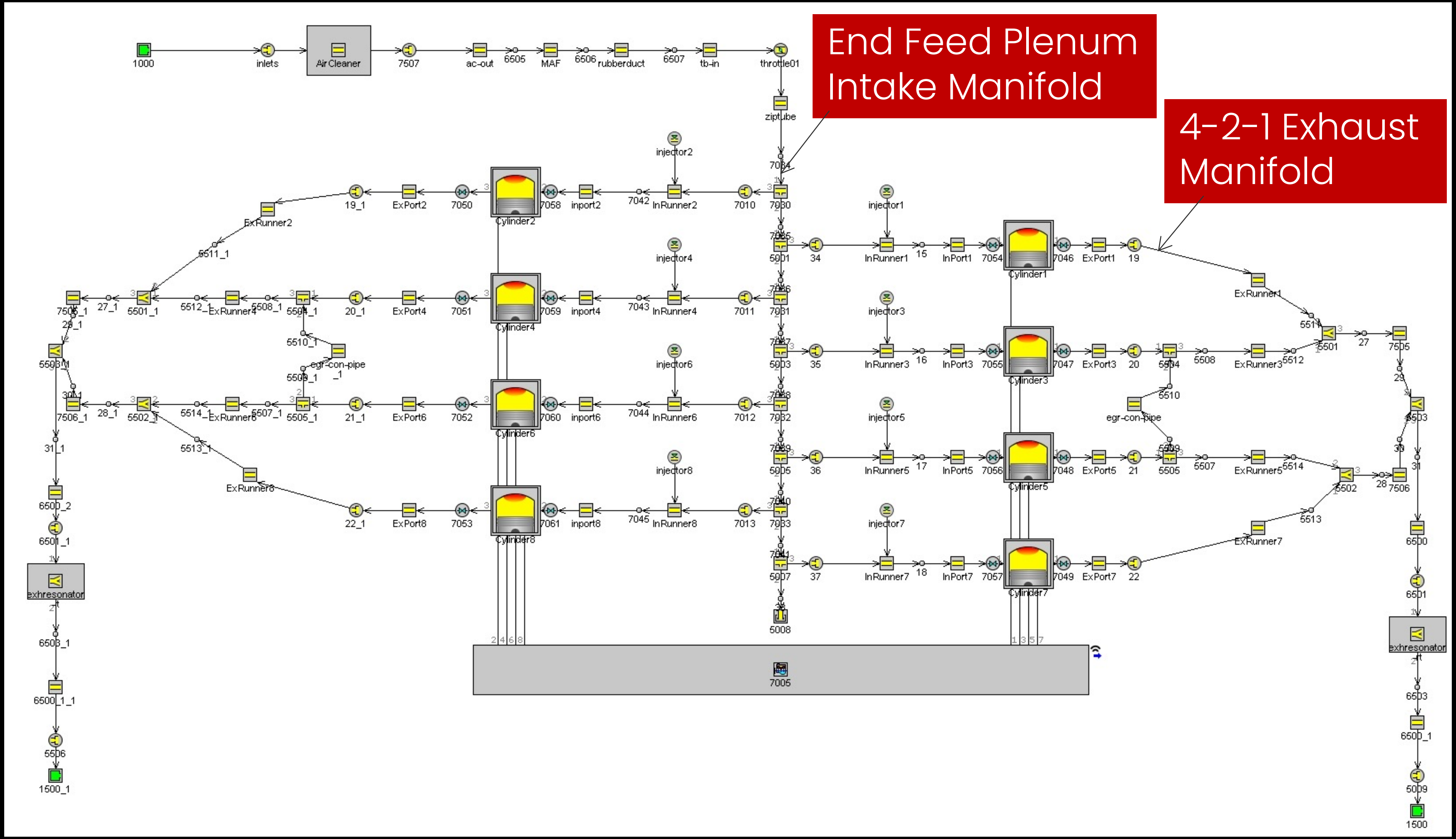


Dynamic Results

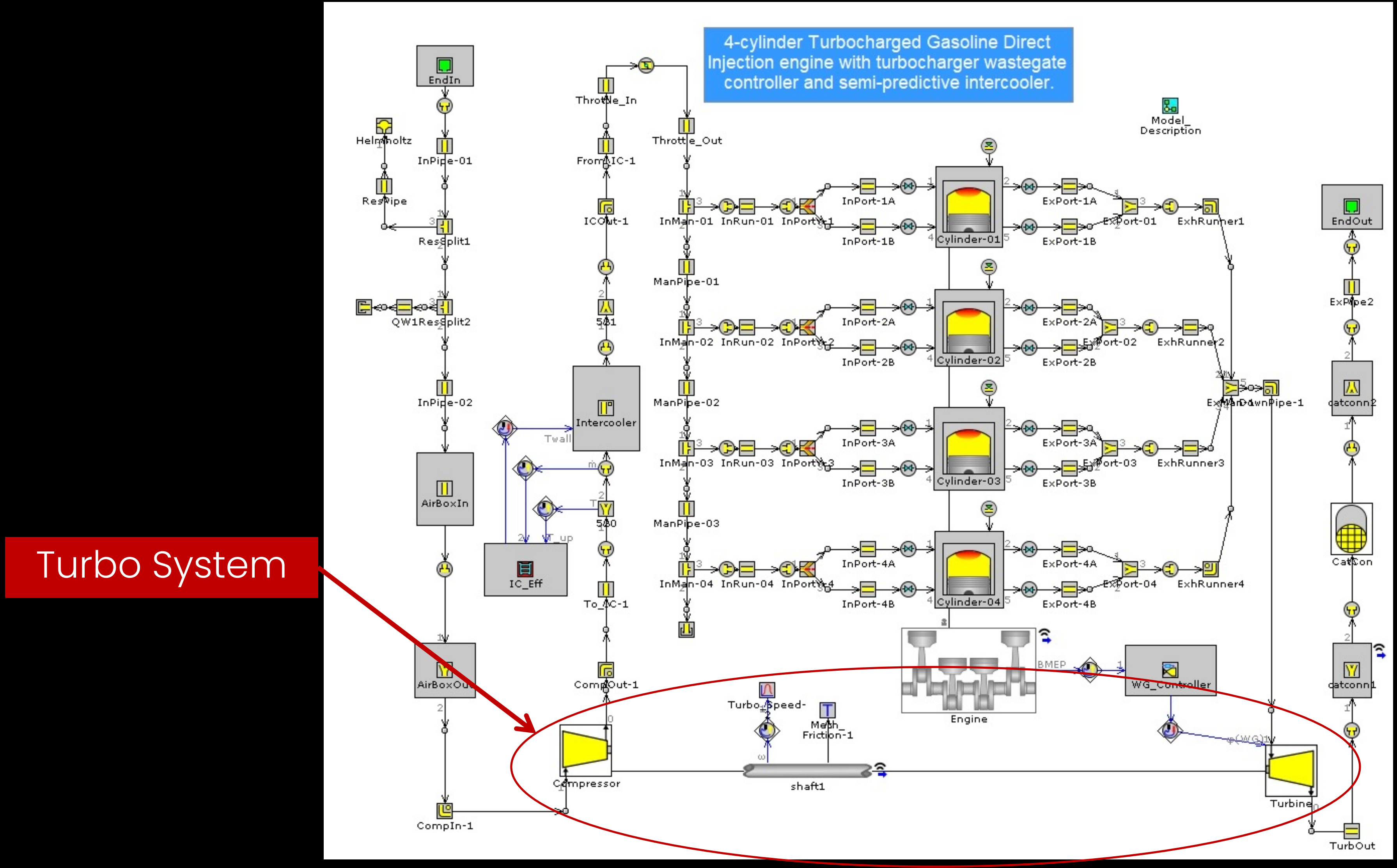
How 1-D Engine Models are Constructed – Assembled Model



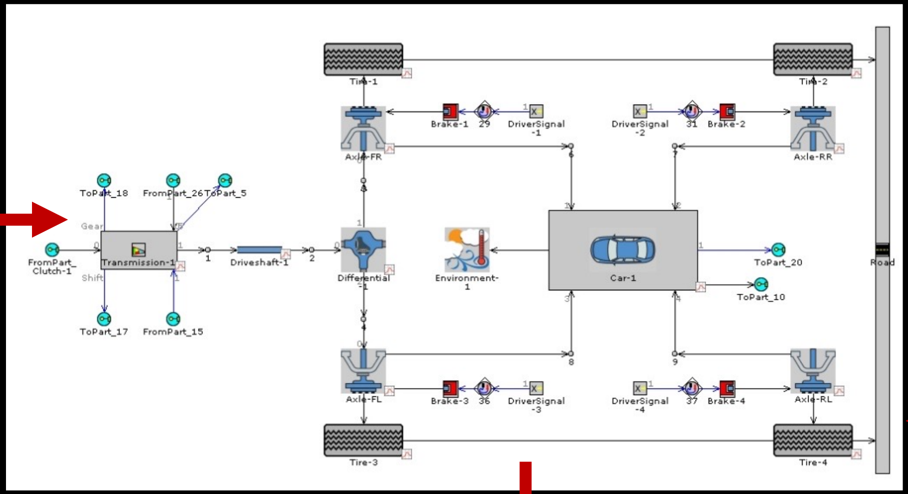
How 1-D Engine Models are Constructed – Assembled Model

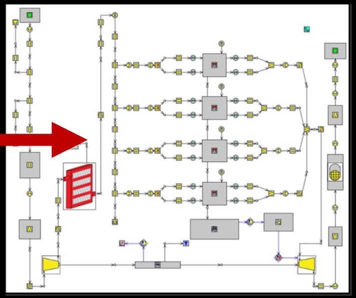


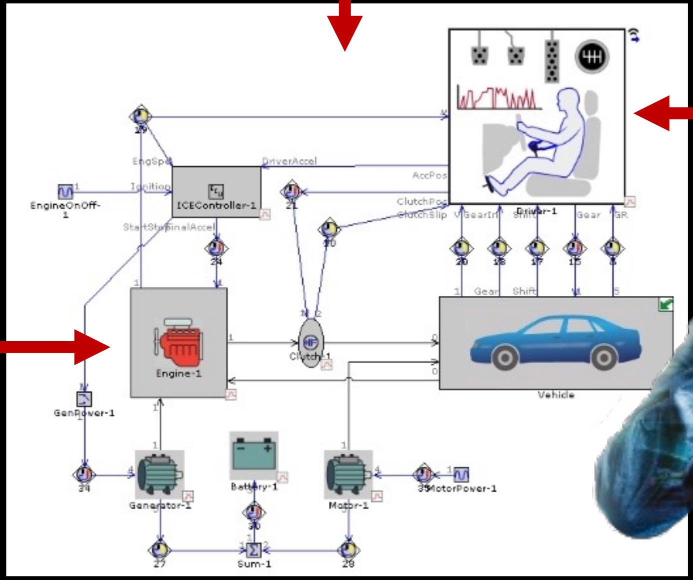
How 1-D Engine Models are Constructed – Assembled Model



How 1-D Vehicle Models are Constructed – Assembled Model



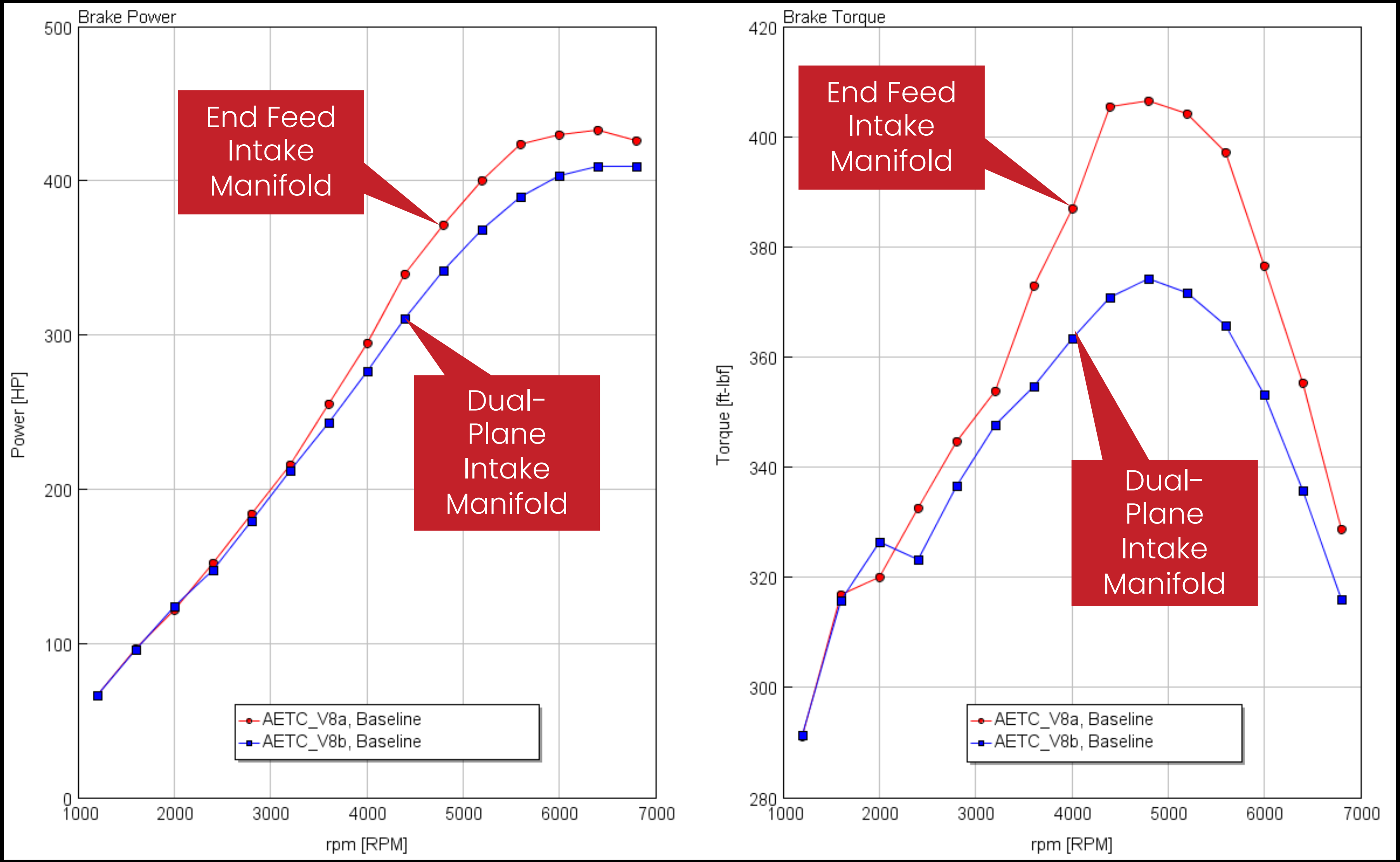




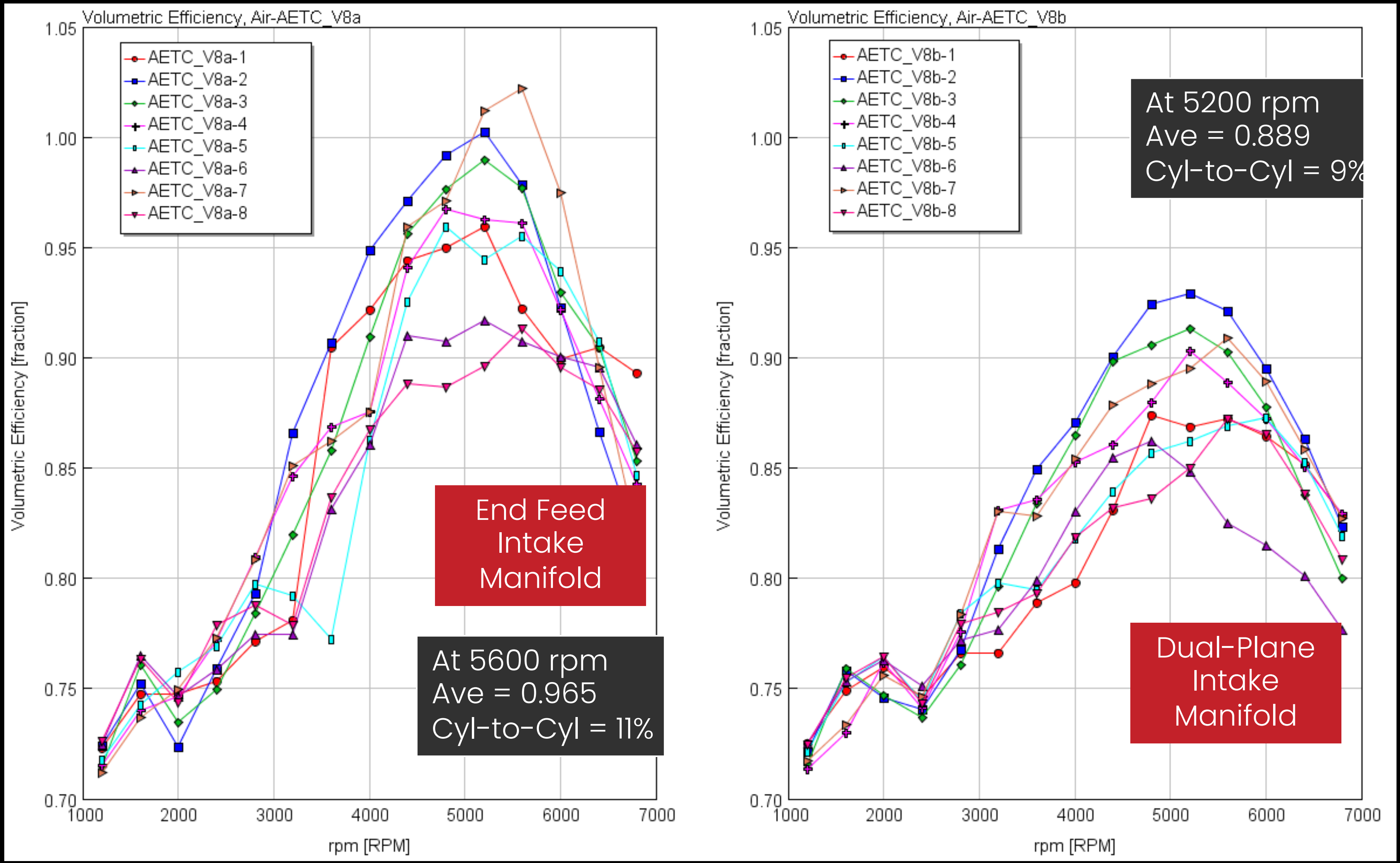
Examples of 1-D Simulations – Typical Applications

- V8 Intake Manifold
  - End feed plenum
  - Dual Plane
- Cam Timing
  - DOE sweep for intake and exhaust lobe center
- Port Flow
  - Low lift vs high lift flow?
- Firing Order
  - 1-8-7-2-6-5-4-3 vs 1-8-4-2-6-5-7-3
- Vehicle Mass
  - Evaluate the effect of mass on ¼ mile acceleration

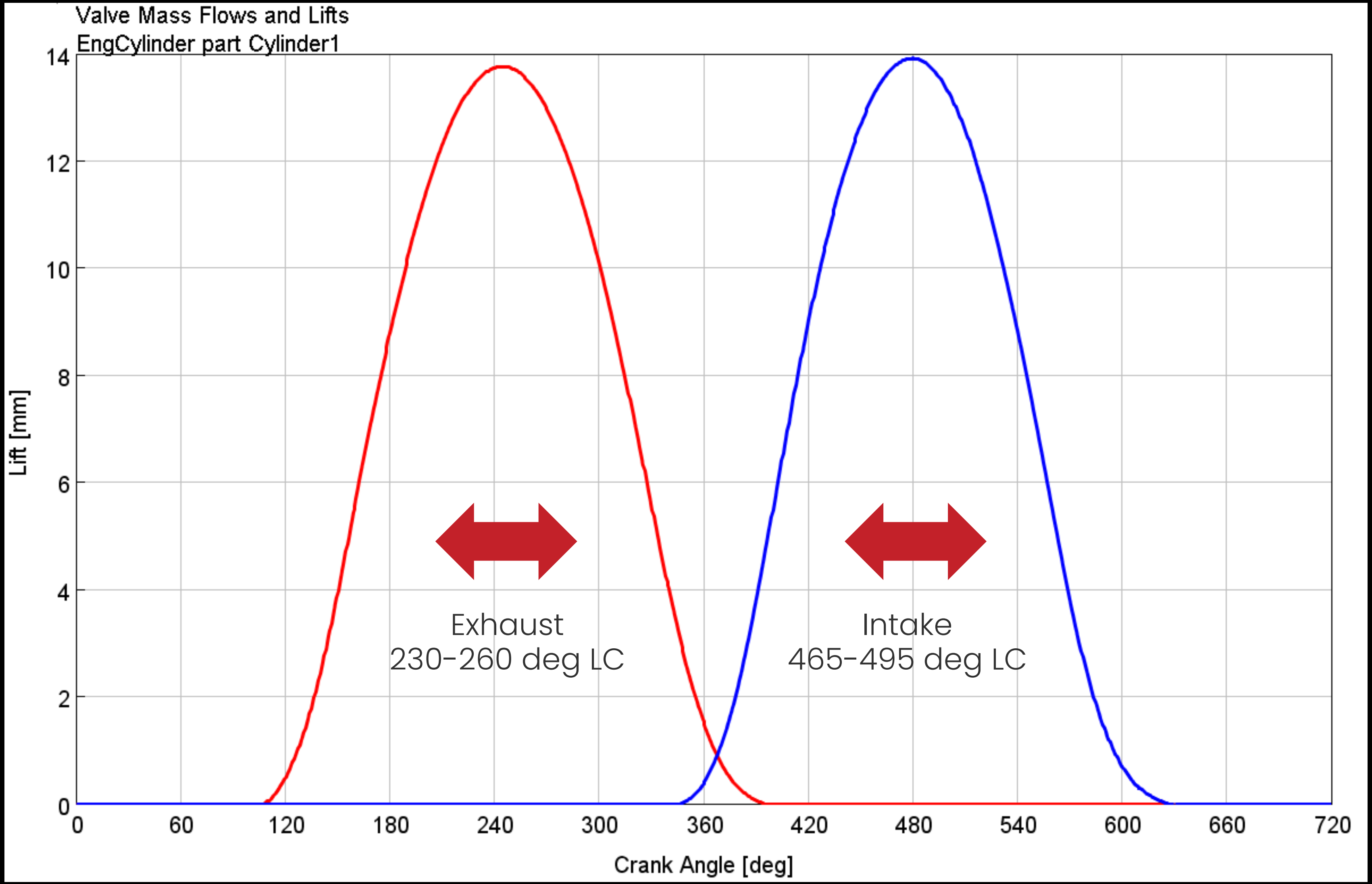
Intake Manifold – Overall Performance Differences



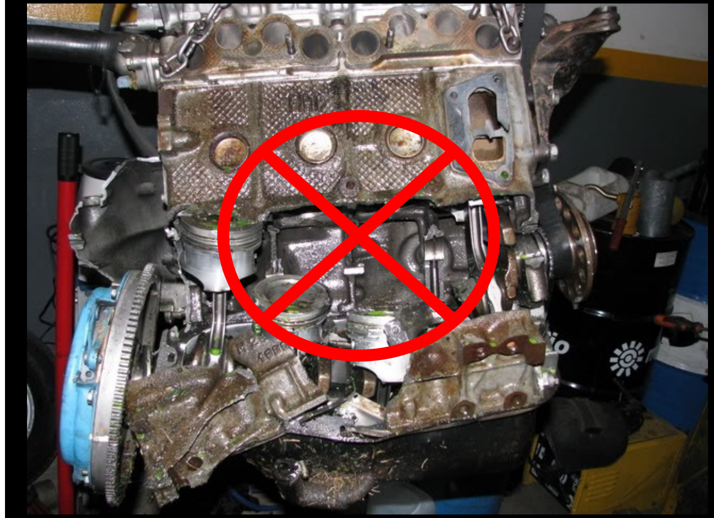
Intake Manifold – Cyl-to-Cyl Differences



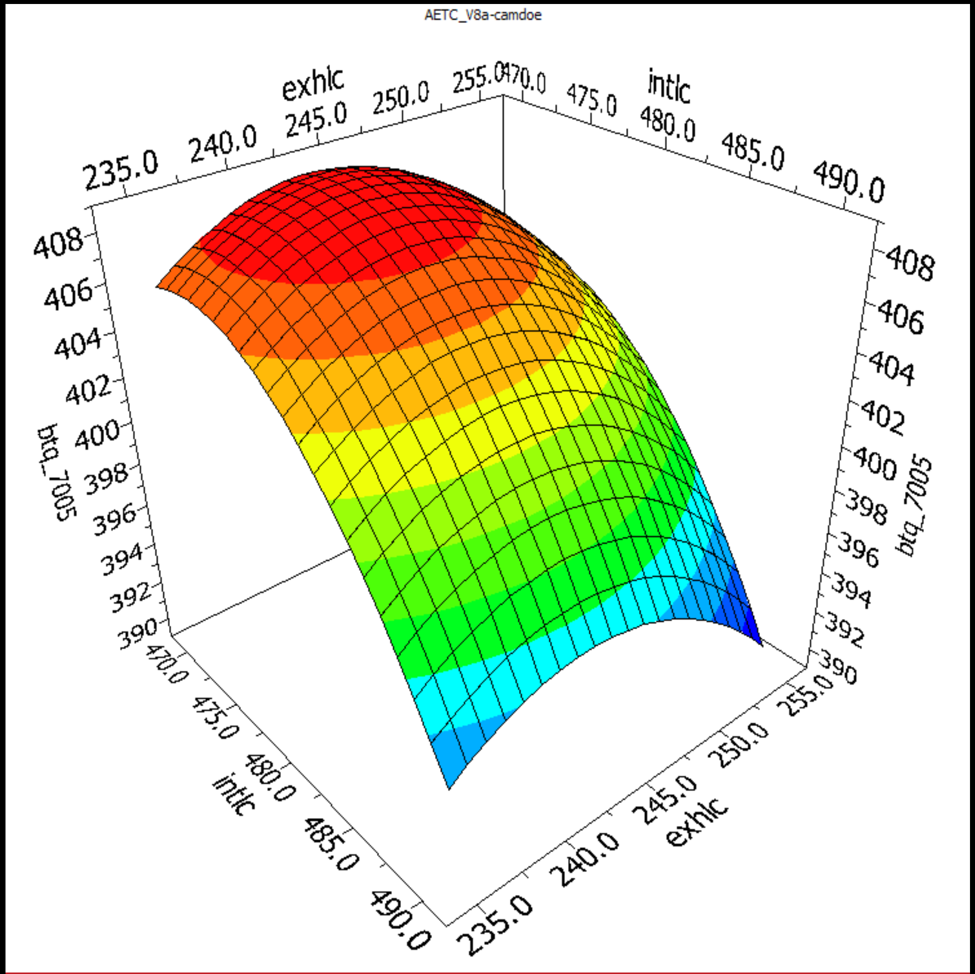
Valve Timing – DOE for Cam Timing



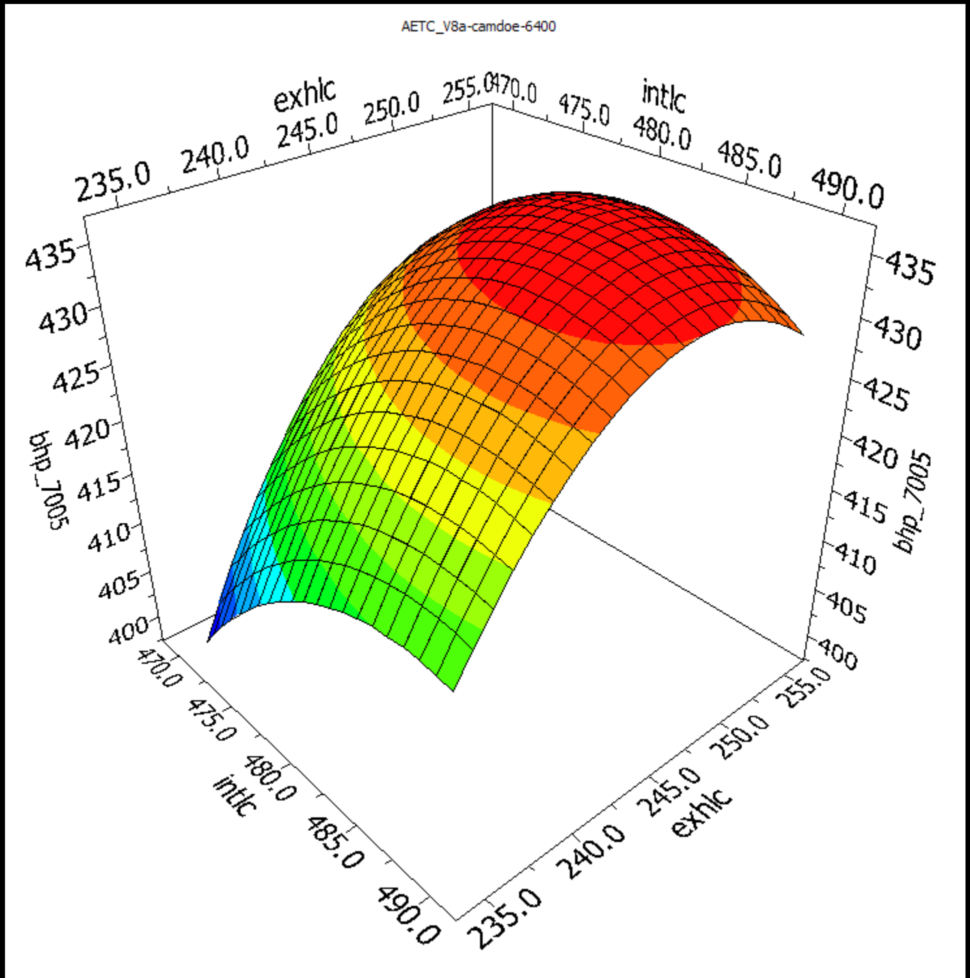
DOE set up was 150 unique combinations of LC timing



Valve Timing – DOE for Cam Timing

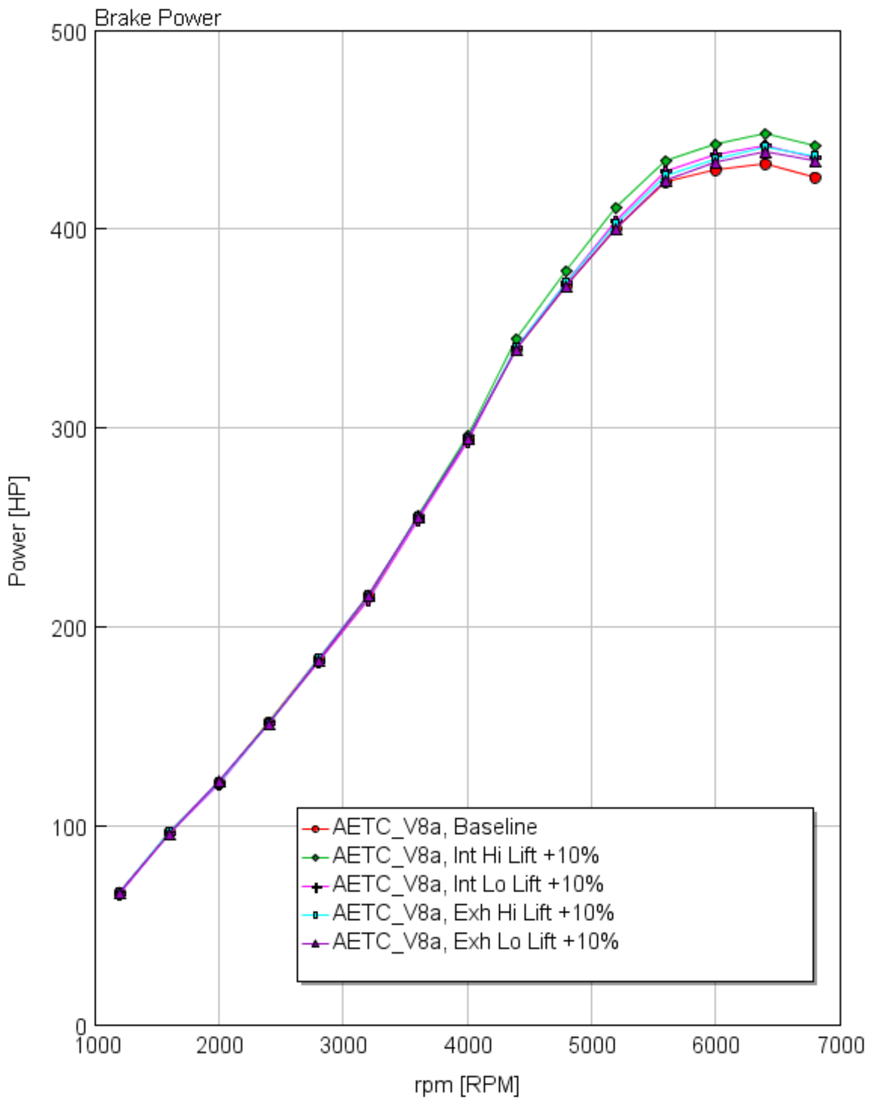


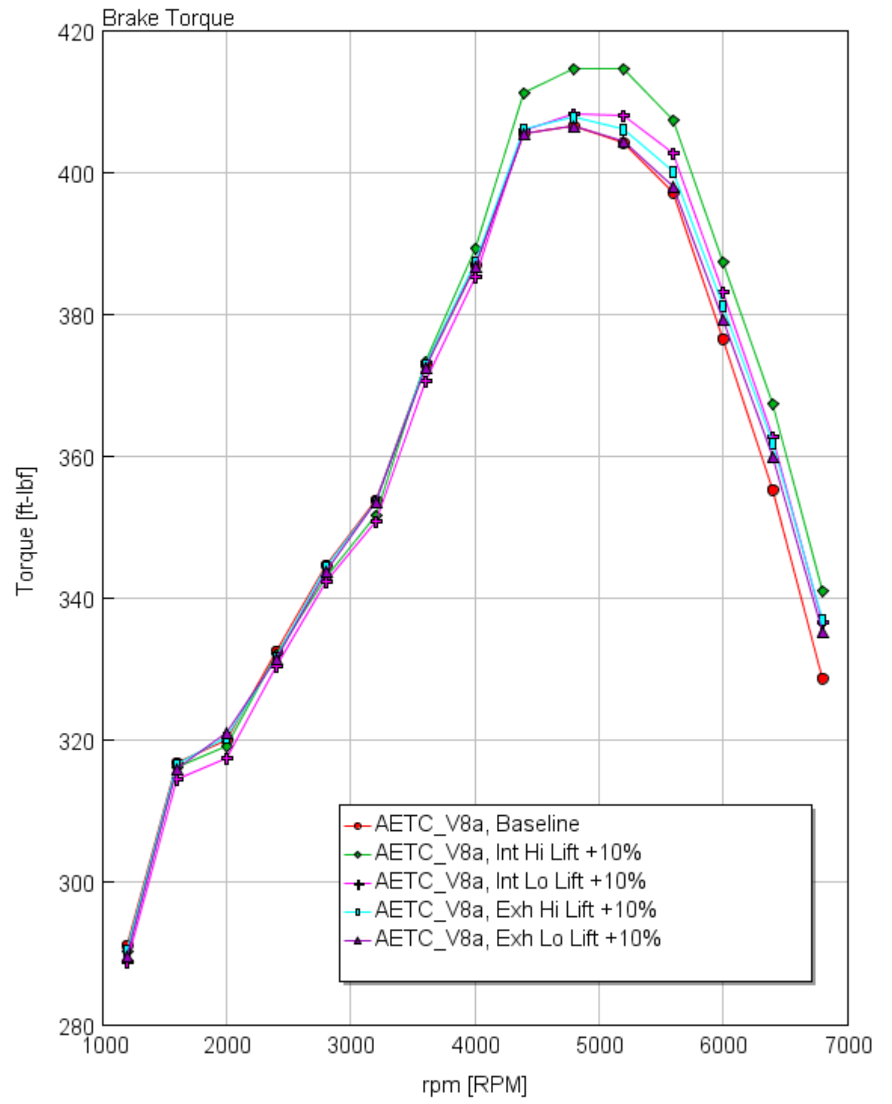
Best torque at 4800 rpm



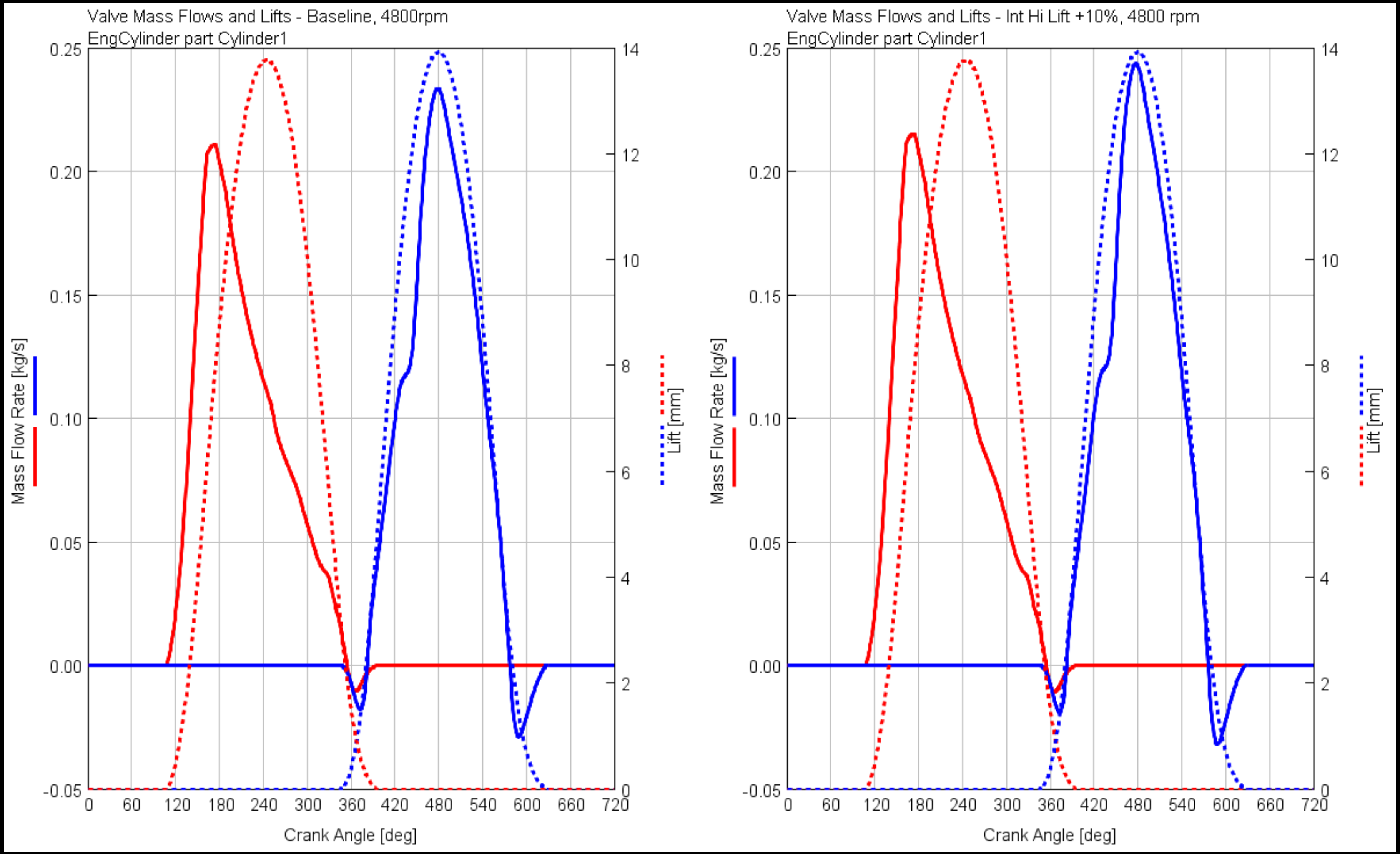
Best power at 6400 rpm

Port Flow Comparison

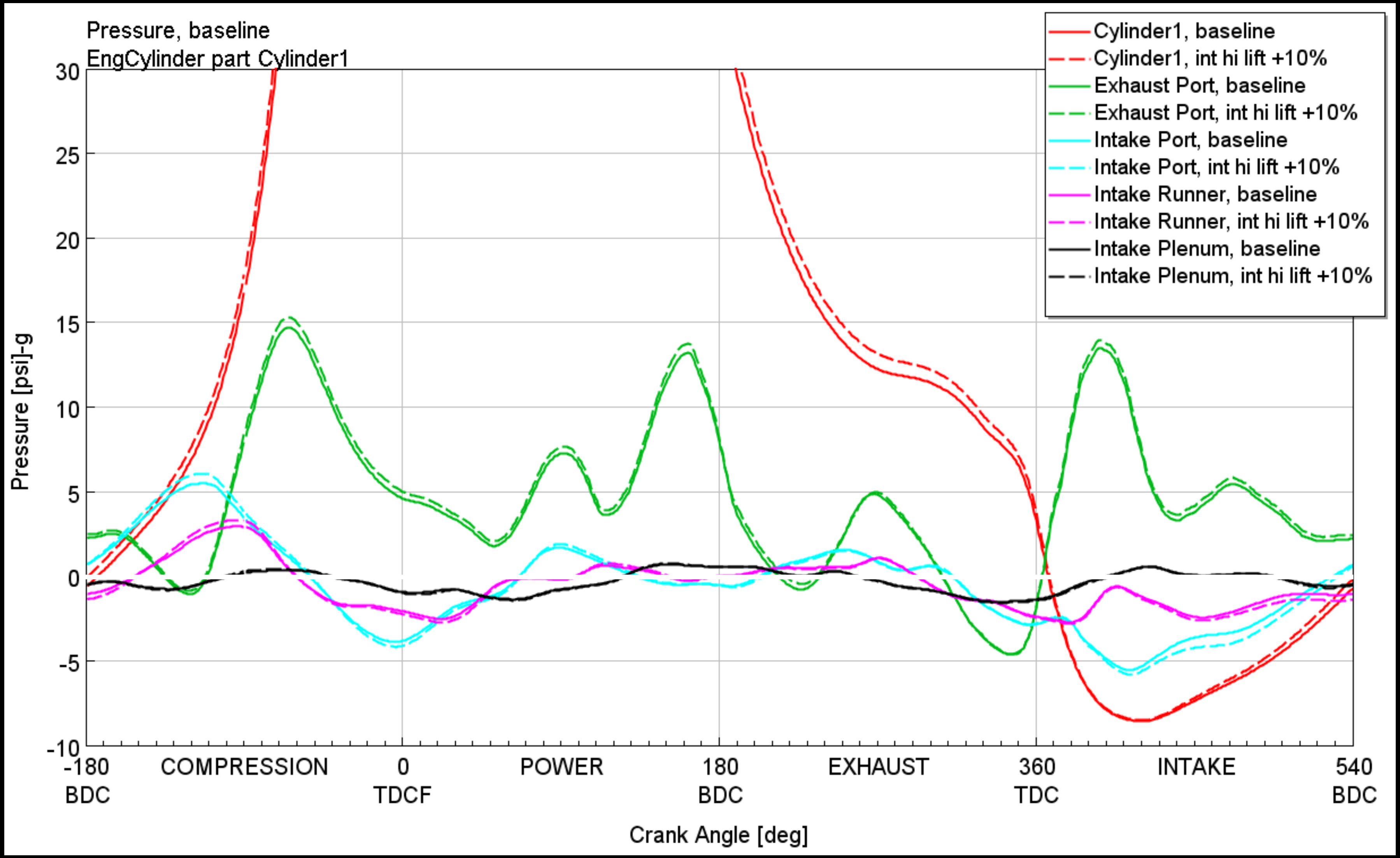




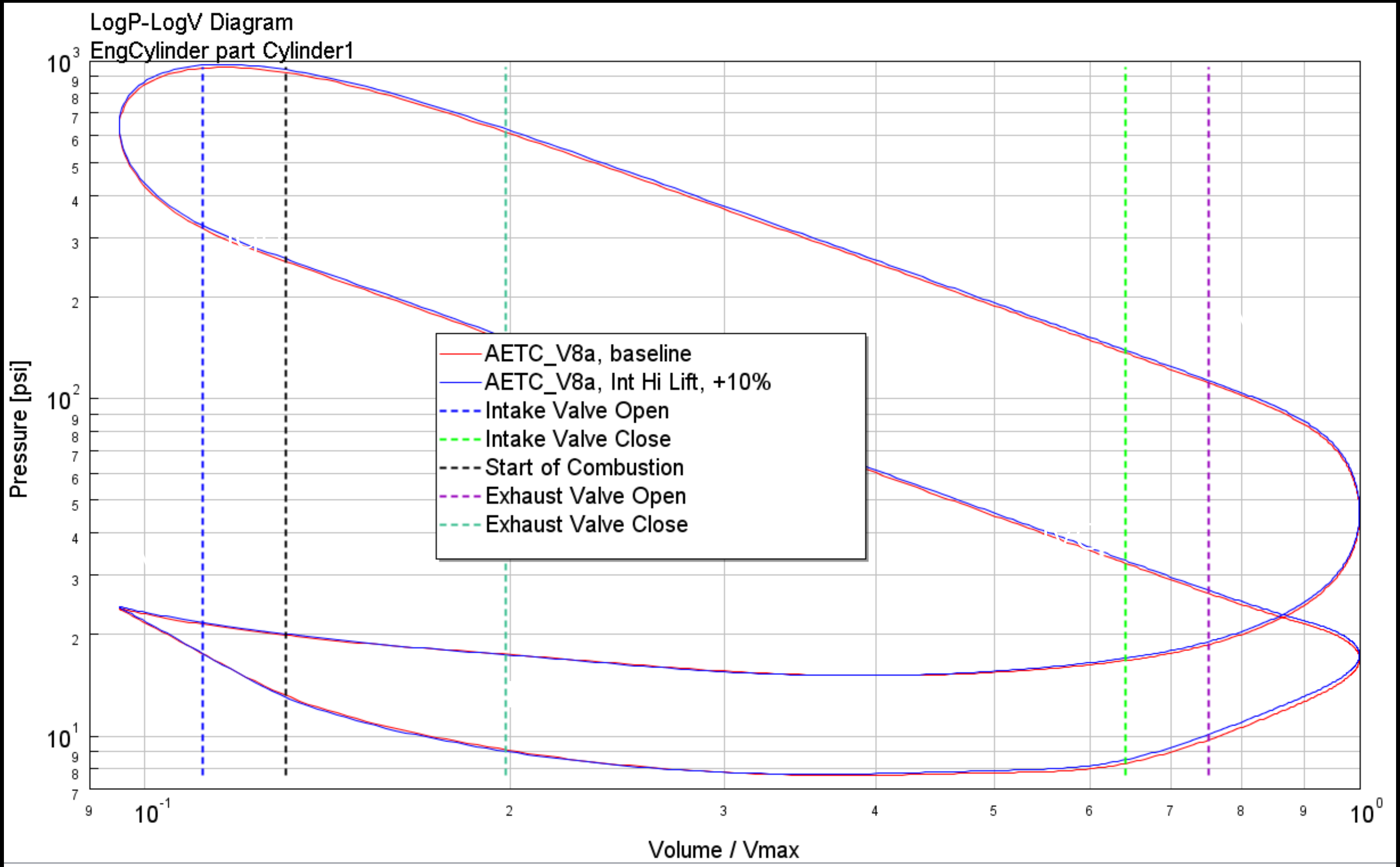
Port Flow Comparison – Flow by Crank Angle



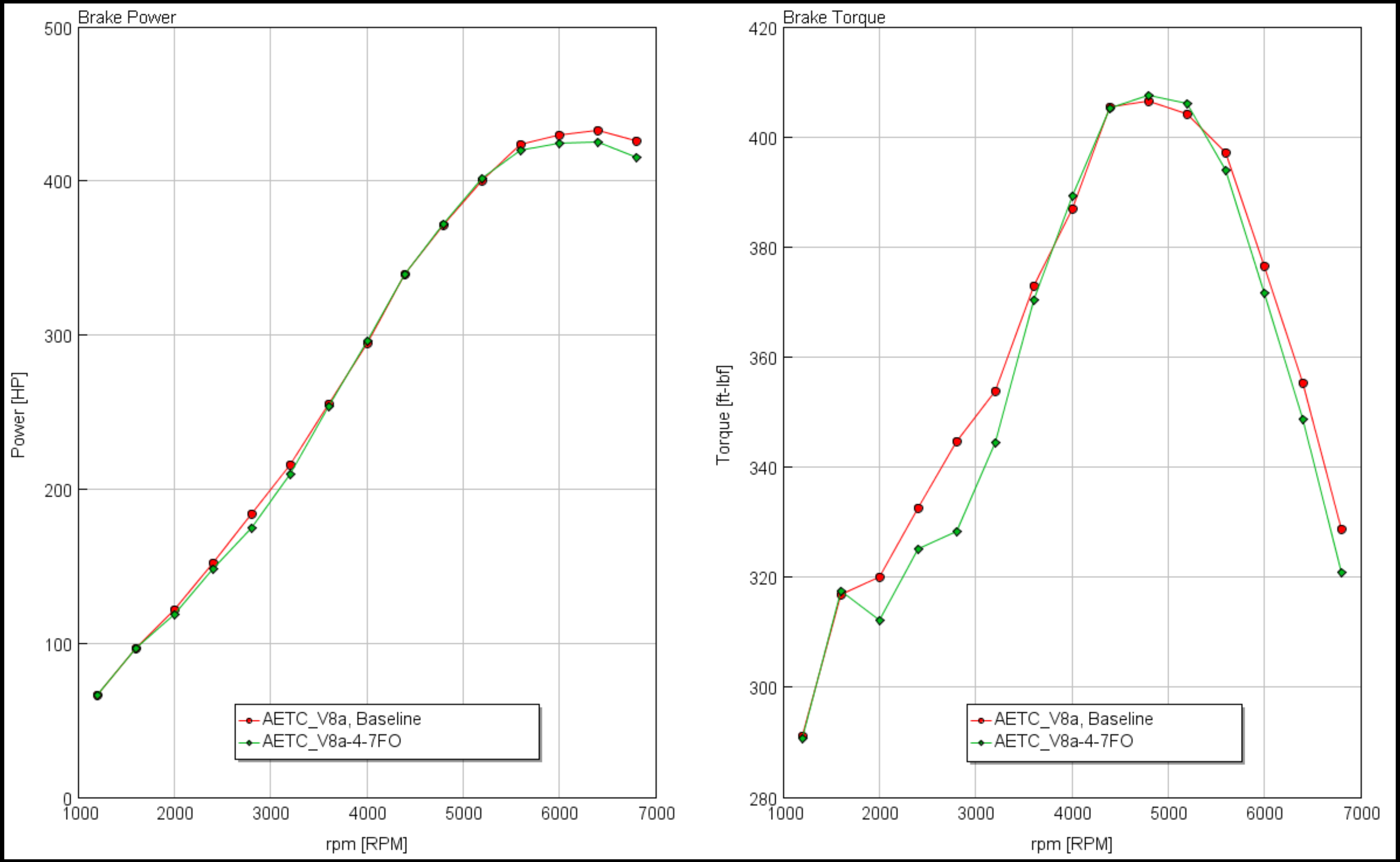
Port Flow Comparison – Flow by Crank Angle



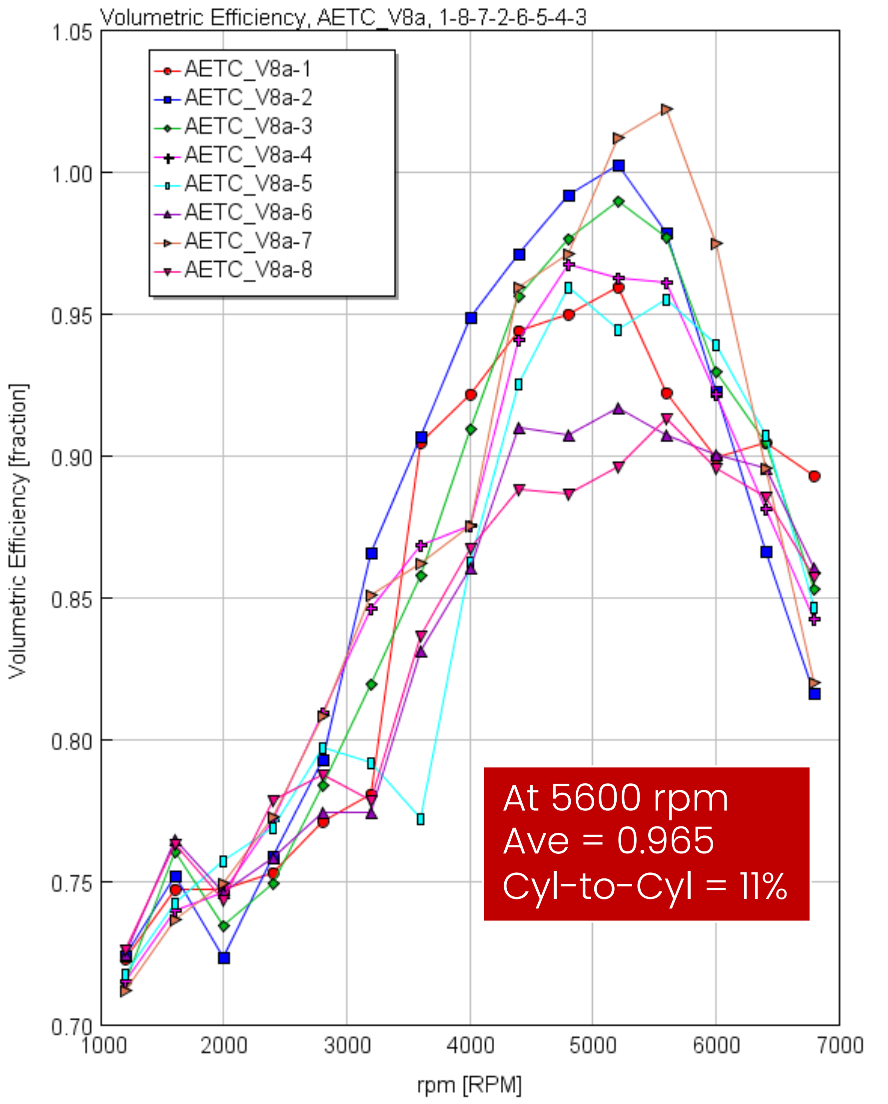
Port Flow Comparison – LogP/LogV at 4800 rpm

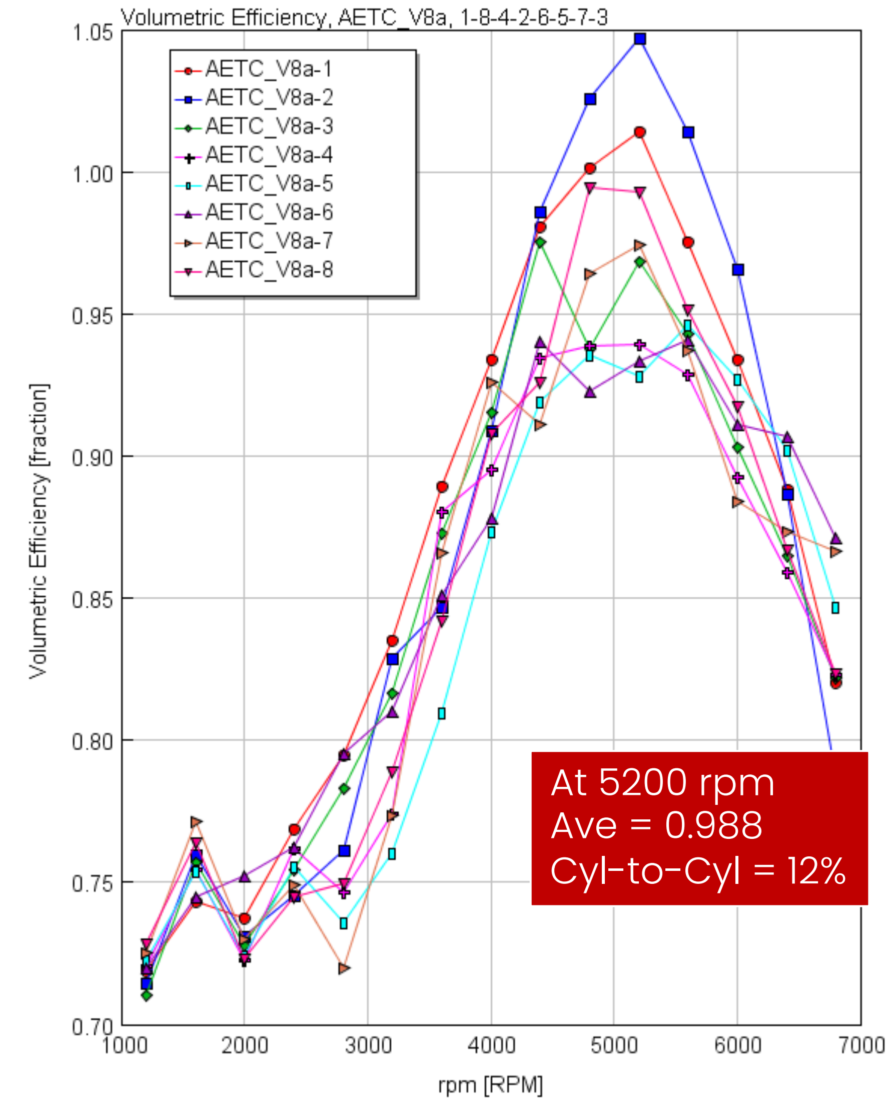


Firing Order Comparison, 4-7 Swap, Power & Torque



Firing Order Comparison, 4-7 Swap, Cyl-to-Cyl VE

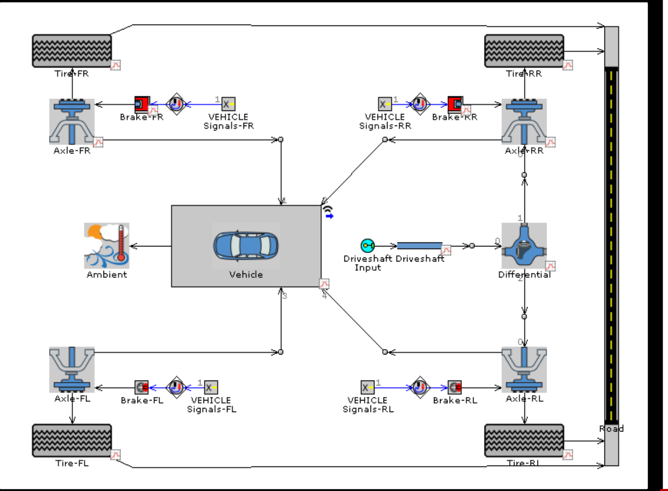


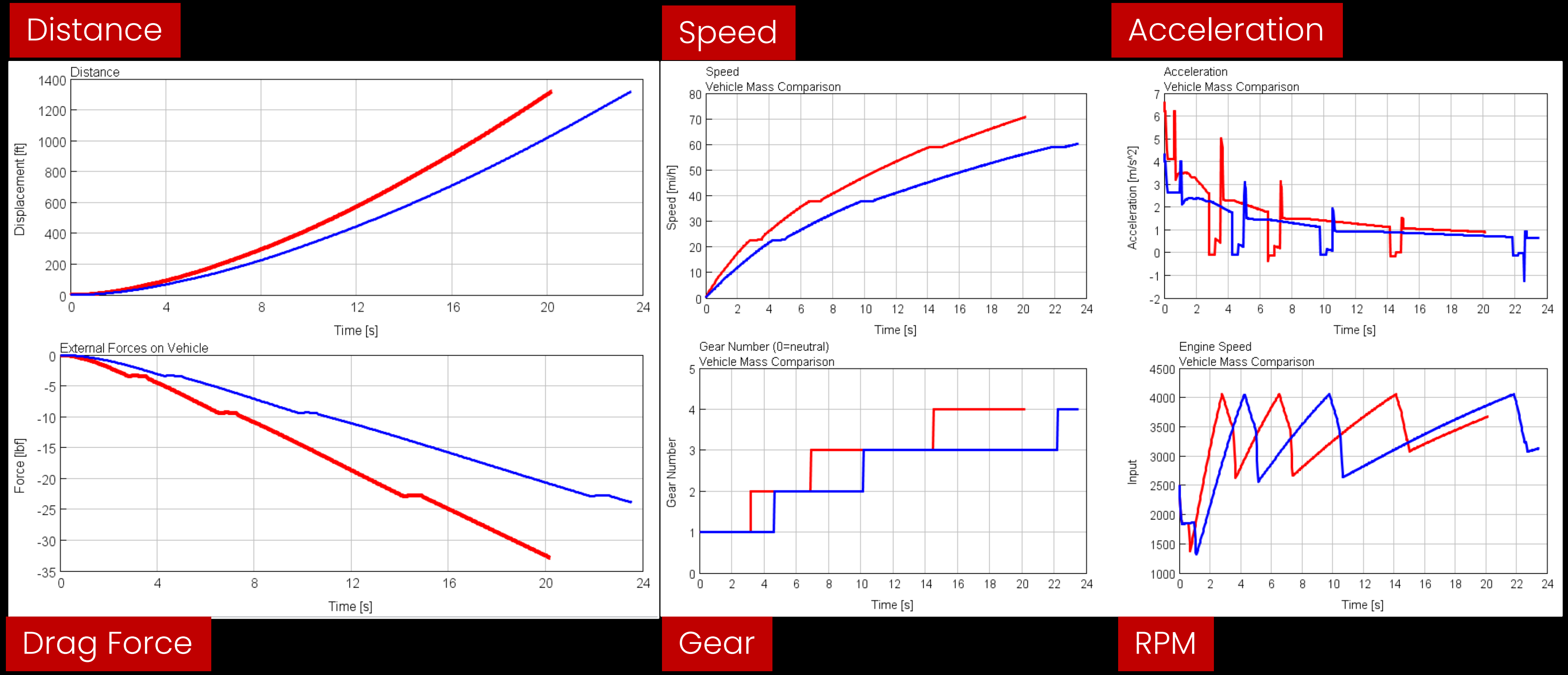


Vehicle Mass Comparison on ¼ Mile Run

Mass

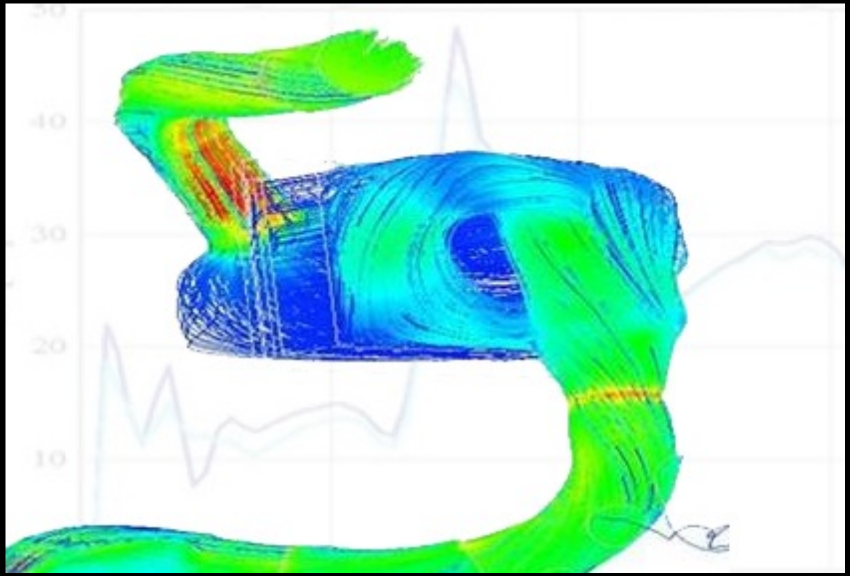
5511 lb 3306 lb

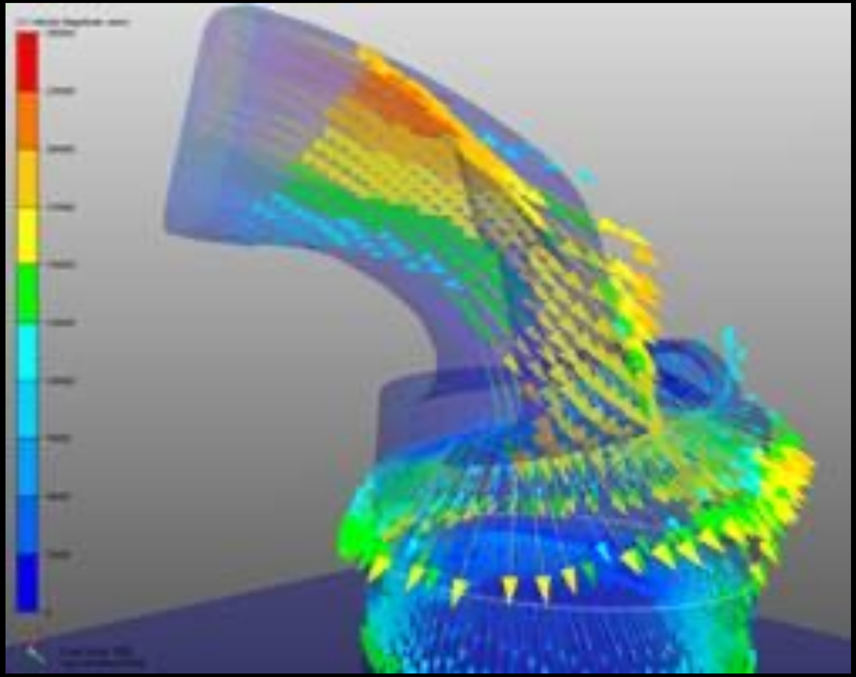




3-D Modeling for Flow Systems

- 3-D modeling for flow systems can provide even more detailed understanding of fluid flow subsystems.
  - Air cleaner induction systems
  - Intake and exhaust ports and manifolds
    - Steady or transient (pulsing) flow.
    - For transient, can be coupled to GT-Suite or use GT-Suite for boundary conditions.
  - Combustion chamber
    - Mixture motion and flame propagation
    - Moving piston and valves
  - Cooling systems
    - Cold flow distribution, or with heat transfer
- Requires more computational resources
- Rapid prototyping and flow bench testing can also be used in place of CFD, but yields little understanding

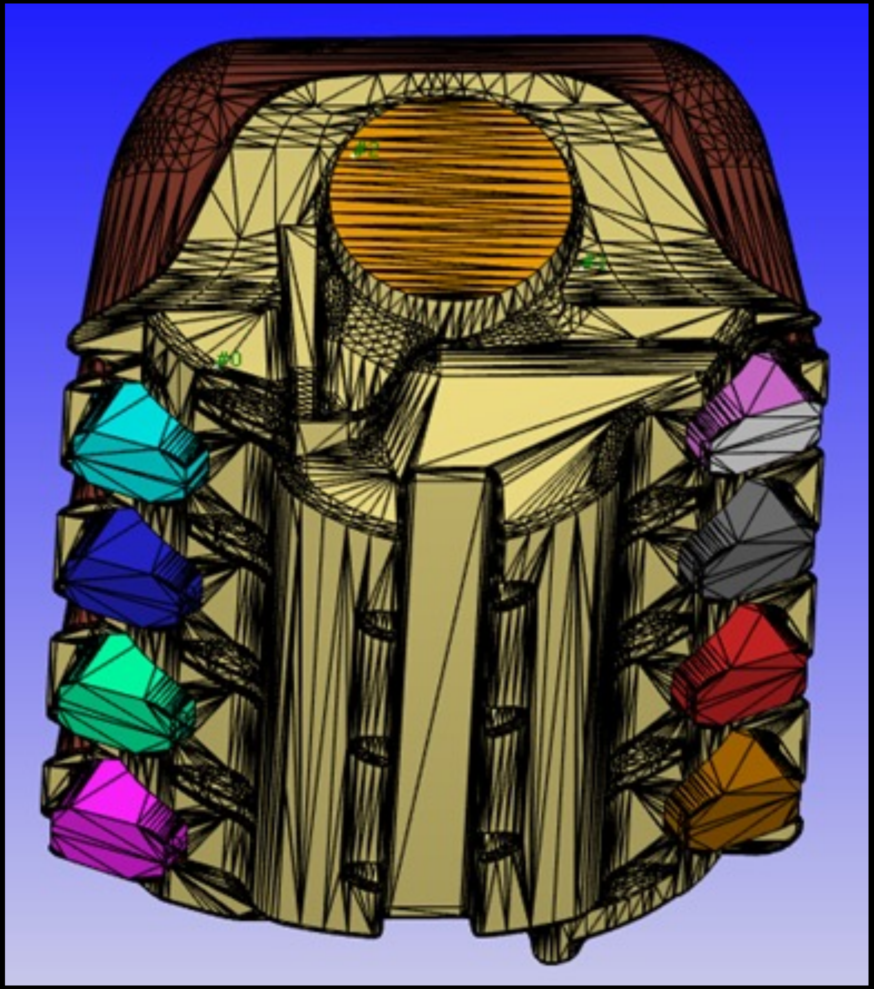


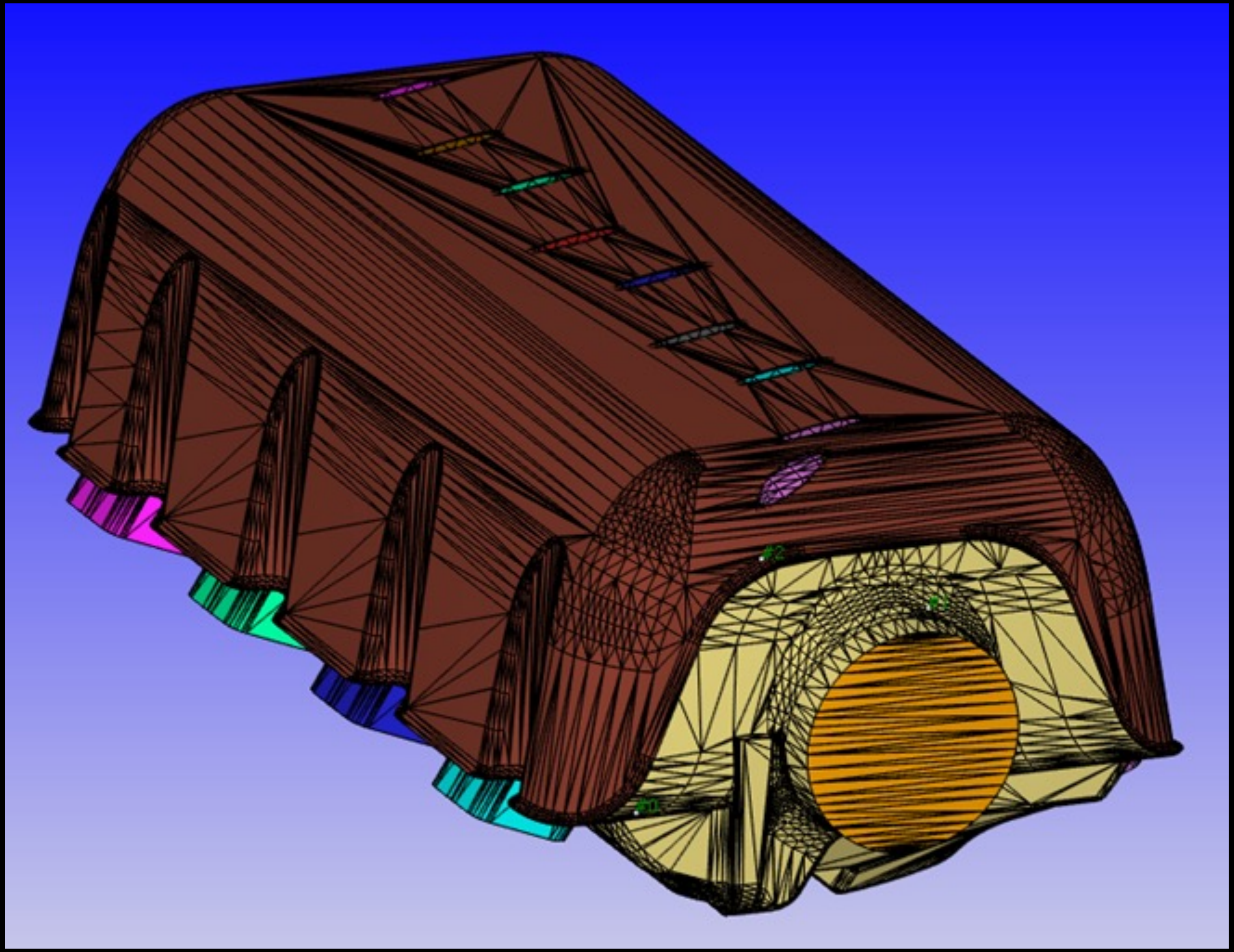


Examples of 3-D Simulations

- Steady flow intake manifold
- In-cylinder flow and combustion
- Block and head cooling system

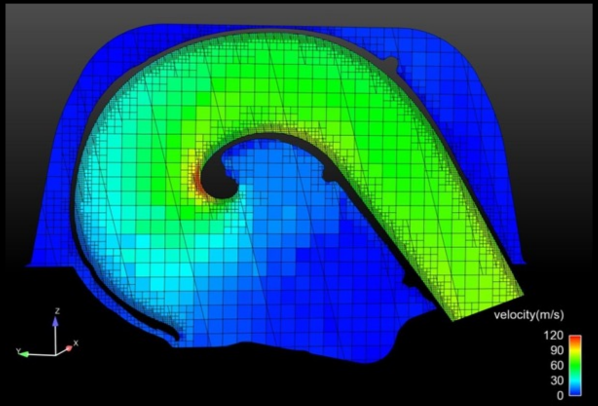
Examples of 3-D Simulations – Steady Flow Intake Manifold

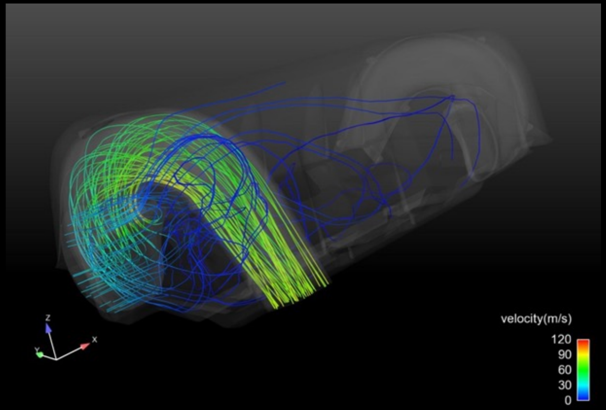


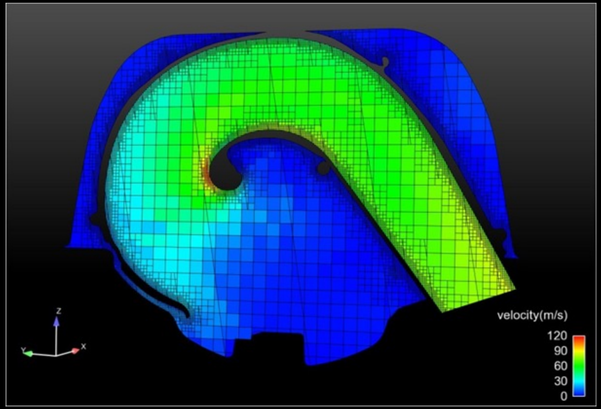


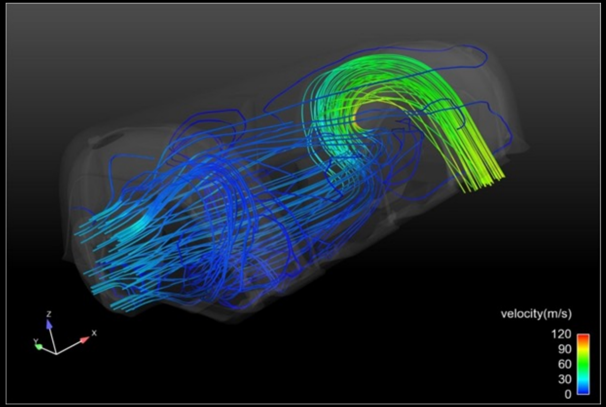
V8 Intake Manifold

Examples of 3-D Simulations – Steady Flow Intake Manifold









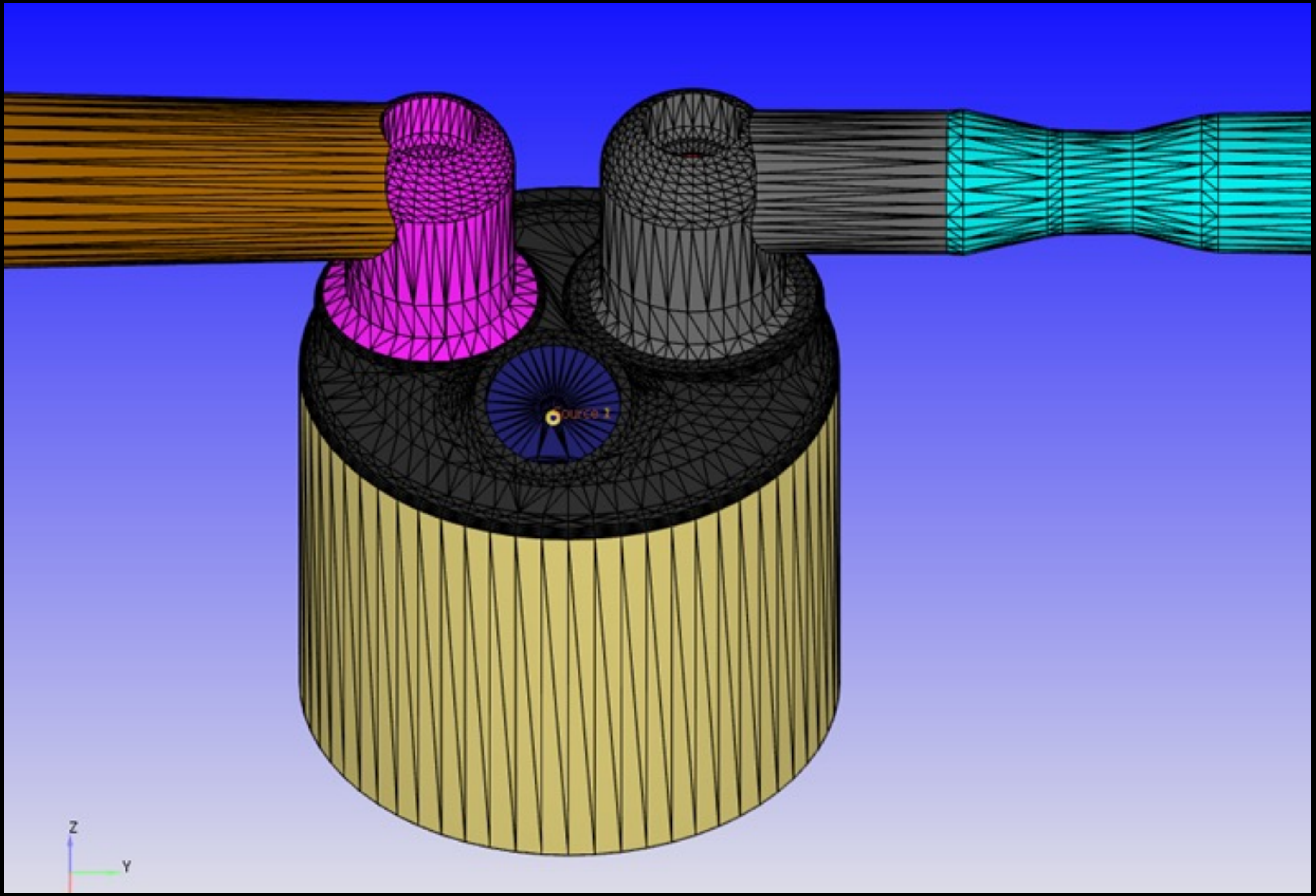
Results for runners 1 and 7 at 28 in H2O vacuum

Runner 1	Runner 7	
1.783 kg/sec	1.758 kg/sec	~ 1.4%

Mass Flow Rate

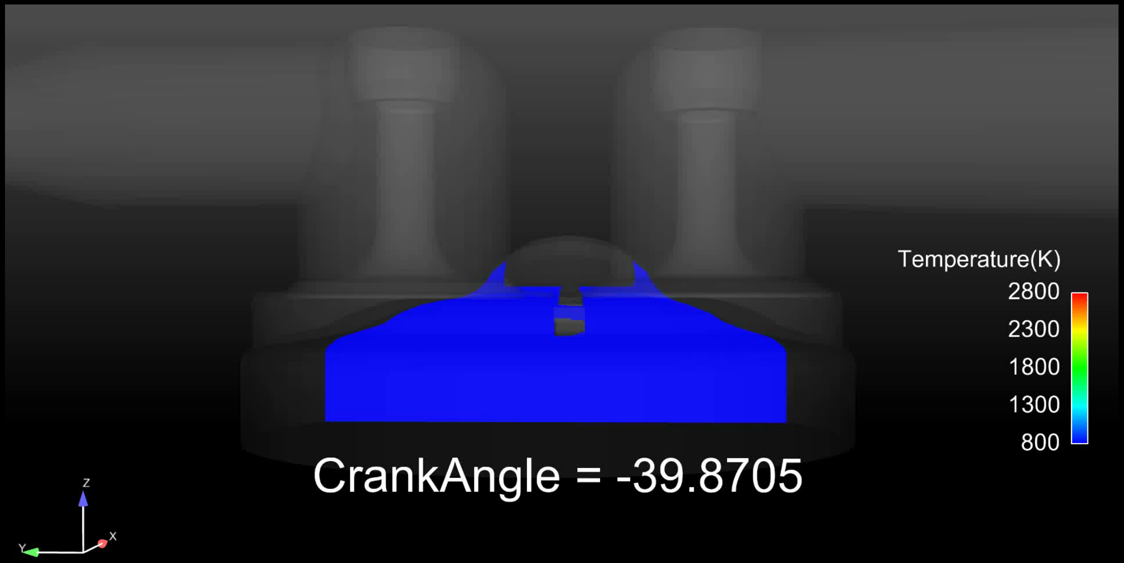
Examples of 3-D Simulations – In-Cylinder Flow and Combustion

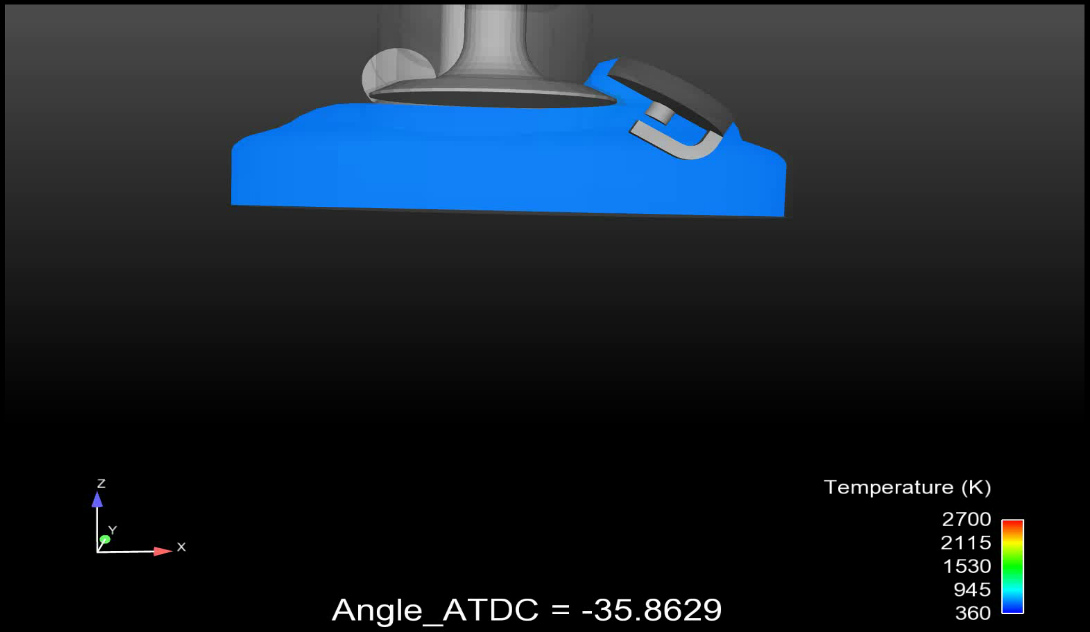
In-cylinder flow and combustion, small single cylinder engine



Examples of 3-D Simulations – In-Cylinder Flow and Combustion

Video results

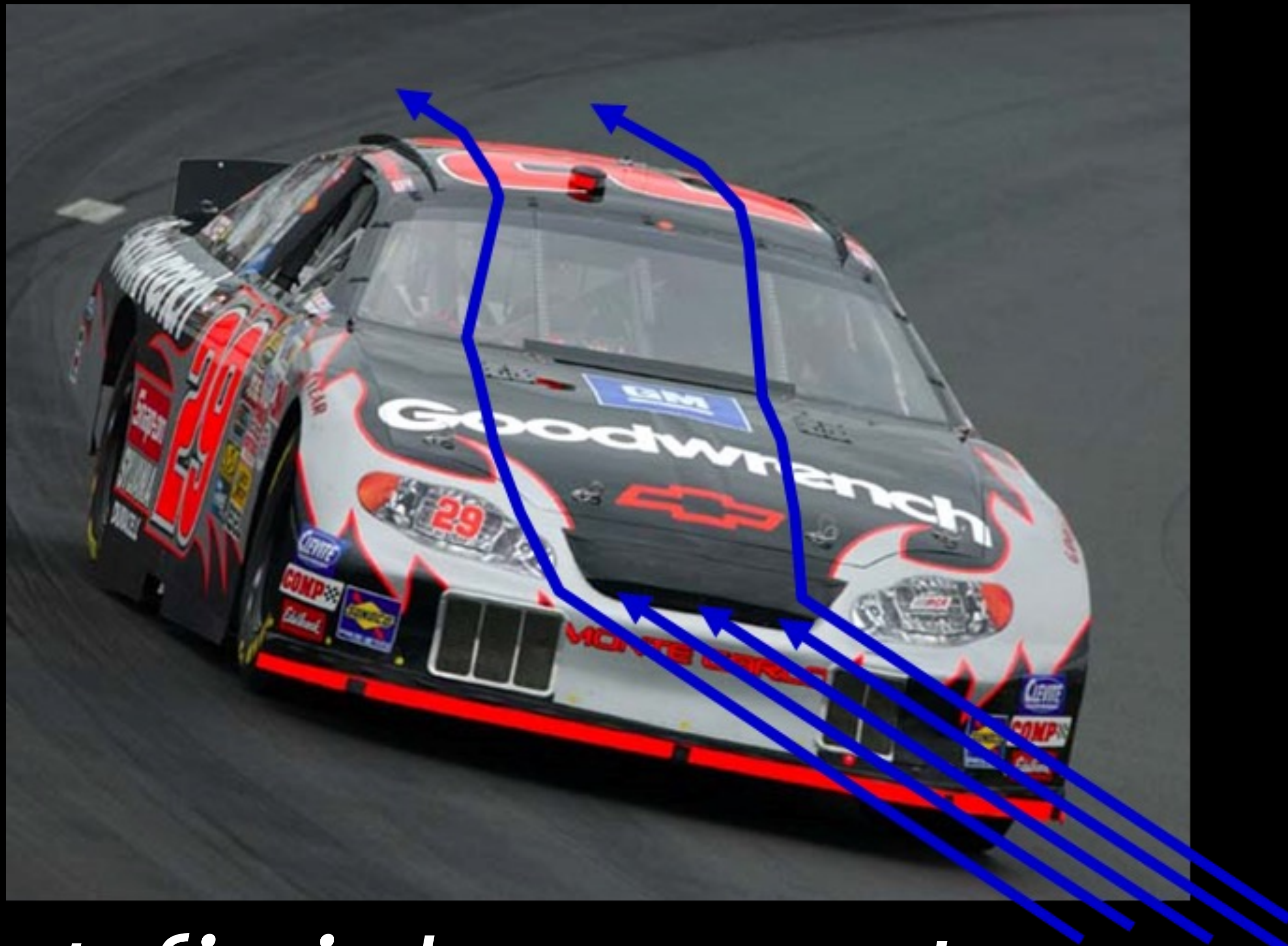




Examples of 3-D Simulations – Block and Head Cooling System

Further understand the flow patterns inside the cylinder block and head with "cold flow"

- Improve cooling efficiency
- Improve durability of components
- Improve overall aerodynamics of the vehicle

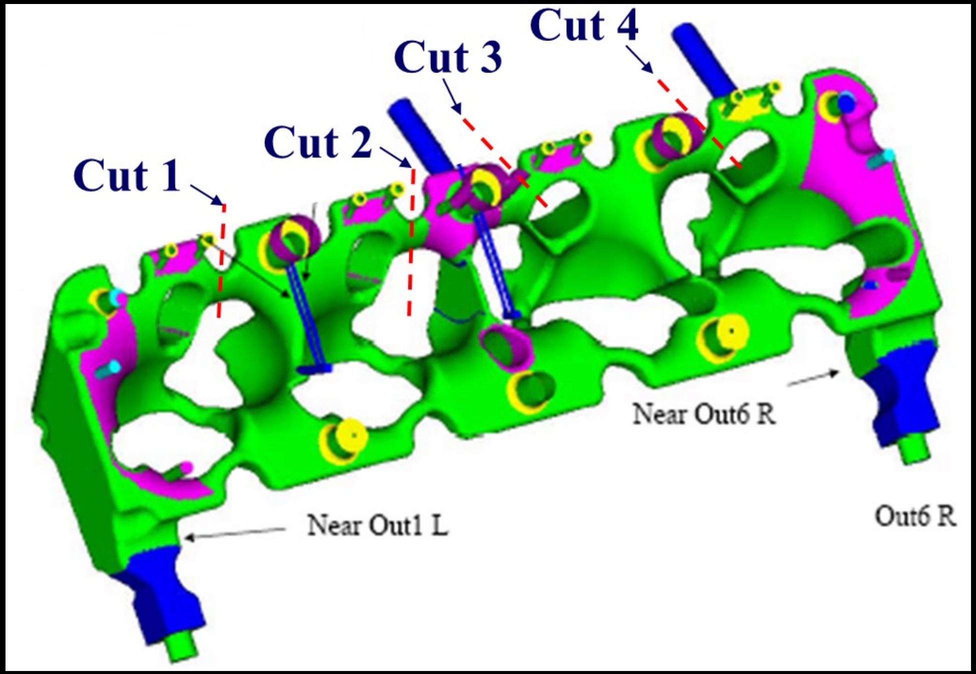


Faster cars that finish races!

Coolant Flow Optimization in a Racing Cylinder Block and Head Using CFD Analysis and Testing, SAE 2004-01-3542, D. Agnew/J. Covey/J. Ye, 2004.

Examples of 3-D Simulations – Block and Head Cooling System

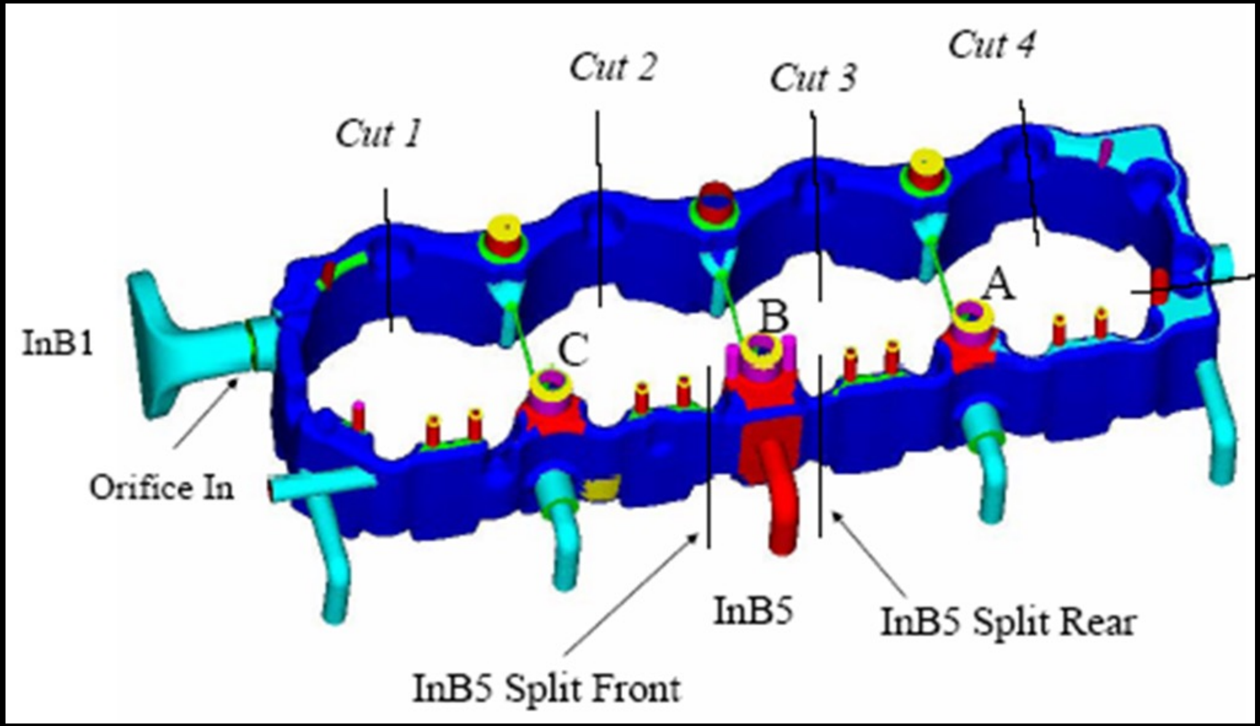
- Cylinder head section cuts 1 – 4
- Inlets through head gasket
- Cross drills
- Outlets into valley plate



CFD CYLINDER HEAD COOLANT FLOW RATE (gpm)						
GASKET DESIGN	WATER-IN LOCATION	CYL. HEAD WATER JACKET CROSS-SECTION LOCATION				
		#1 Exhaust	#3 Exhaust	#5 Exhaust	#7 Exhaust	AVERAGE
Fel-Pro 1034	Front & Side	1.03	0.53	1.96	2.41	**1.48**
Fel-Pro 1034	Side Only	1.98	1.46	0.79	1.43	**1.42**
Gasket #2	Side Only	3.51	1.02	1.15	3.73	**2.35**
Gasket #3	Side Only	2.91	1.51	1.29	2.85	**2.14**
Gasket #4	Side Only	3.44	1.75	1.66	3.42	**2.57**
Gasket #4	Front & Side	3.39	1.43	1.27	3.37	**2.37**

Examples of 3-D Simulations – Block and Head Cooling System

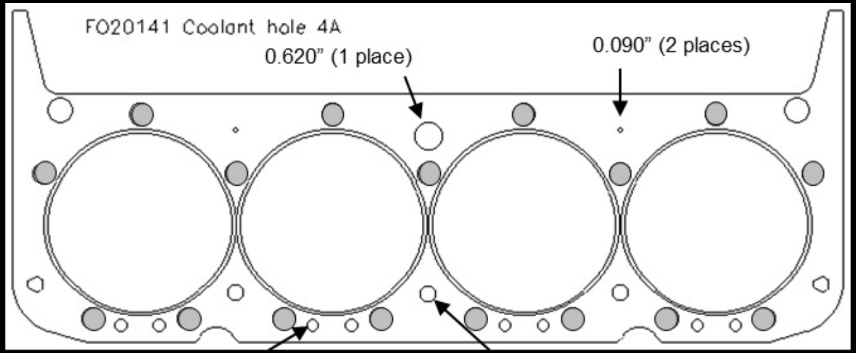
- Block section cuts 1 – 4
- Inlets water pump and block outside wall
- Cross drills
- Outlets up through head gasket

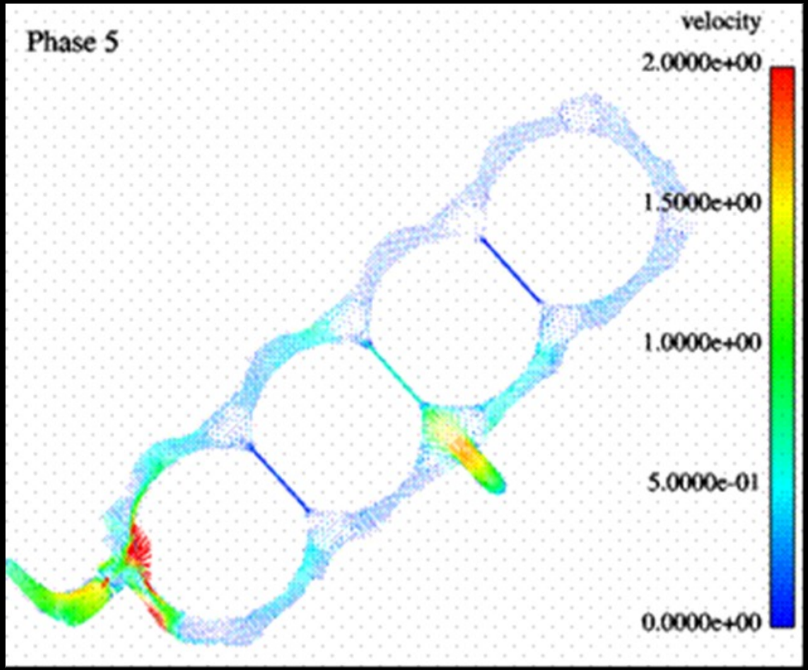


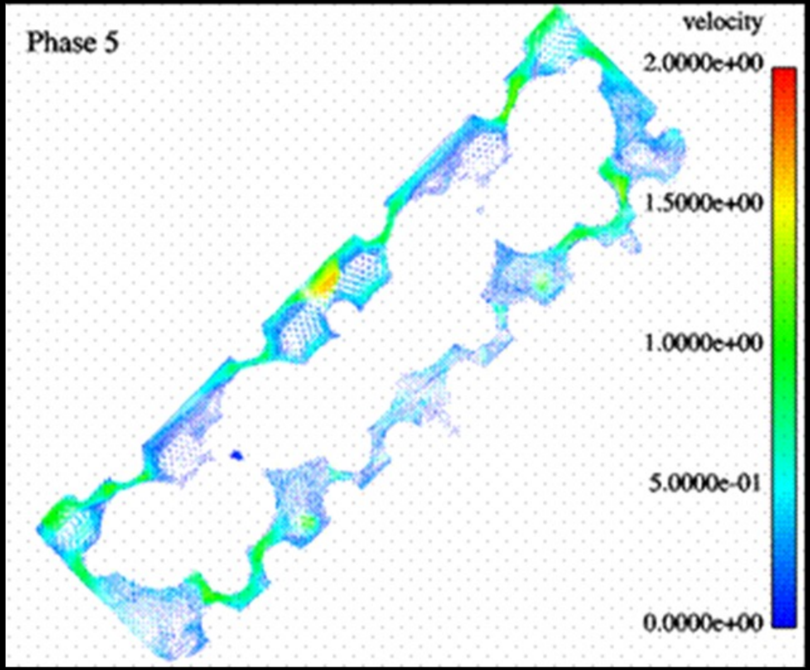
CFD IN-BOARD BLOCK COOLANT FLOW RATE (gpm)						
GASKET DESIGN	WATER-IN LOCATION	BLOCK WATER JACKET CROSS-SECTION LOCATION				
		Cylinder #1	Cylinder #3	Cylinder #5	Cylinder #7	AVERAGE
Fel-Pro 1034	Front & Side	3.17	2.64	0.54	0.03	**1.60**
Fel-Pro 1034	Side Only	1.31	0.8	1.23	1.73	**1.27**
Gasket #2	Side Only	0.11	0.05	0.02	0.04	**0.06**
Gasket #3	Side Only	5.15	5.02	5.81	5.94	**5.48**
Gasket #4	Side Only	3.6	3.51	3.93	4.03	**3.77**
Gasket #4	Front & Side	3.58	5.48	2.6	2.7	**3.59**

Examples of 3-D Simulations – Block and Head Cooling System

Qualitative Results



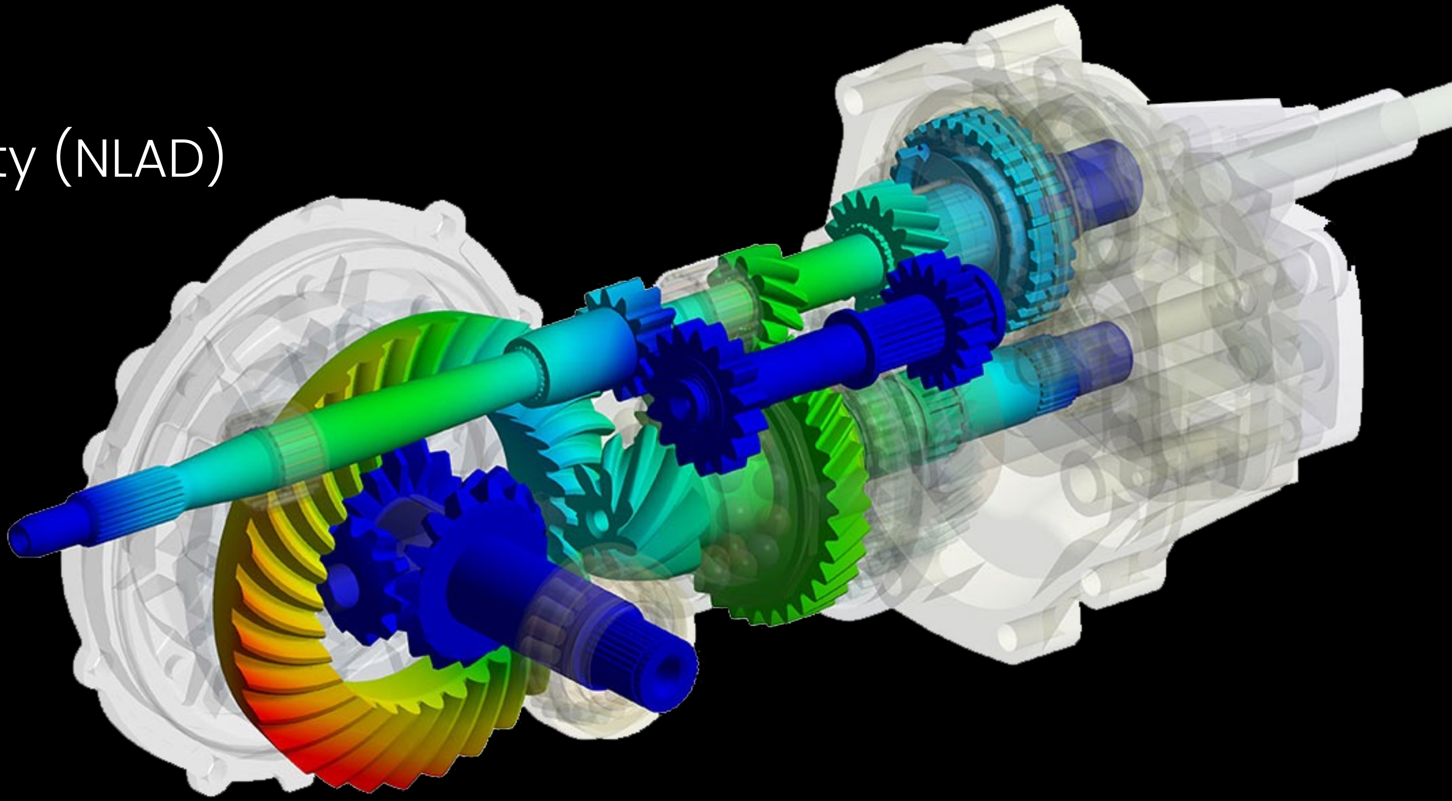




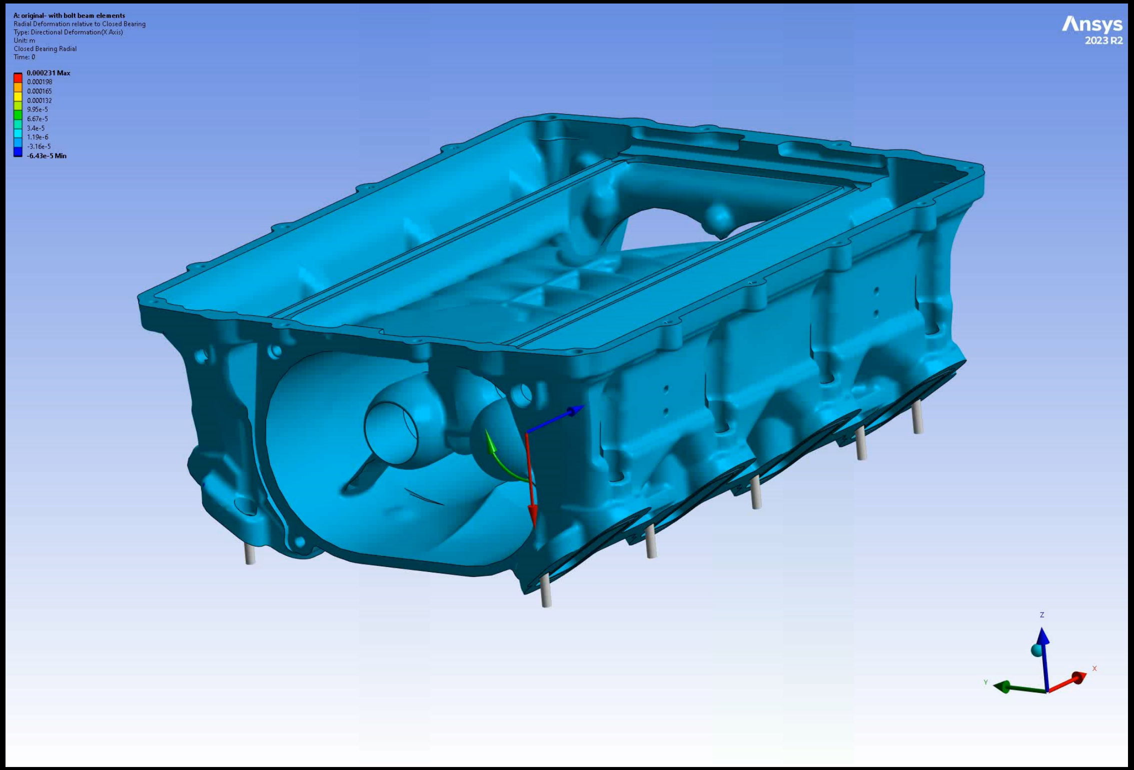
Finite Element Analysis (FEA)

- Finite Element Analysis (FEA)
  - CAD Connected
  - Advanced Materials Modeling
  - Vibration
  - Coupled Field Technology
  - Automated Meshing Adaptivity (NLAD)
  - Explicit Analysis
  - Acoustics
  - Fast Parallel Solvers
  - Linear and Nonlinear Contact
  - Crack and Fracture Modeling
  - Structural Optimization
  - Fatigue Life Analysis

Ansys

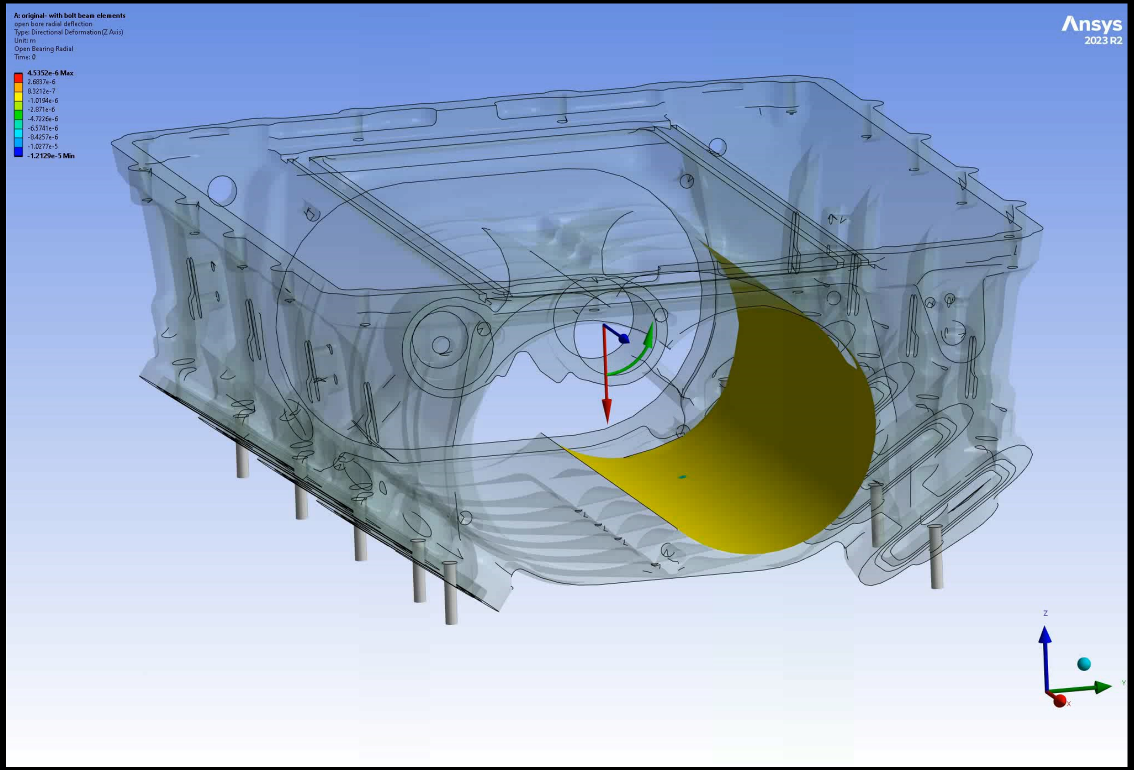


Examples of 3-D Simulations – Mechanical Stress and Deformation Analysis



Quantitative Results

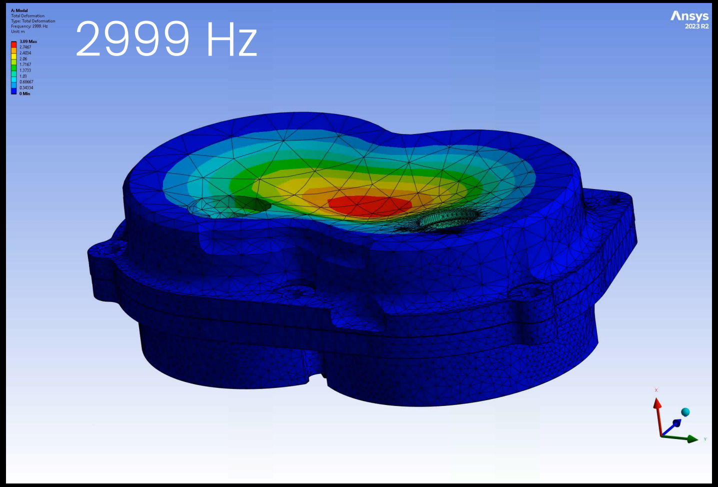
Identify areas of maximum stress and deformation

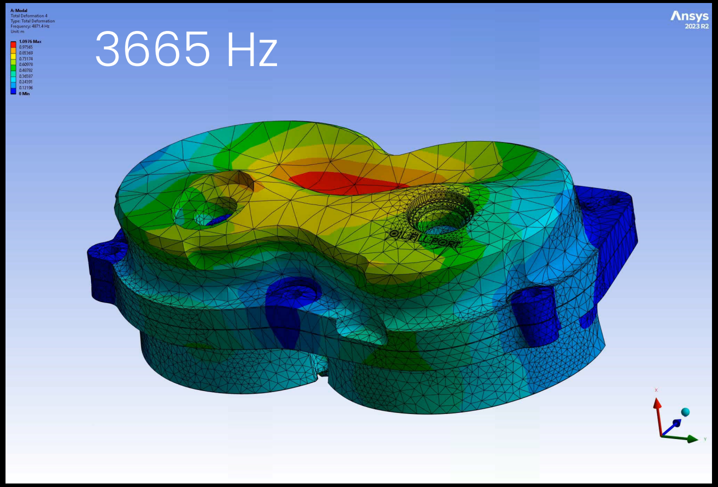


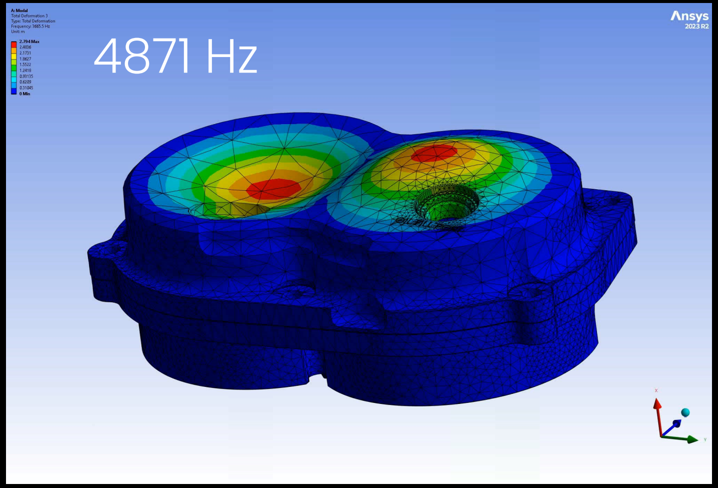
Isolate areas of concern

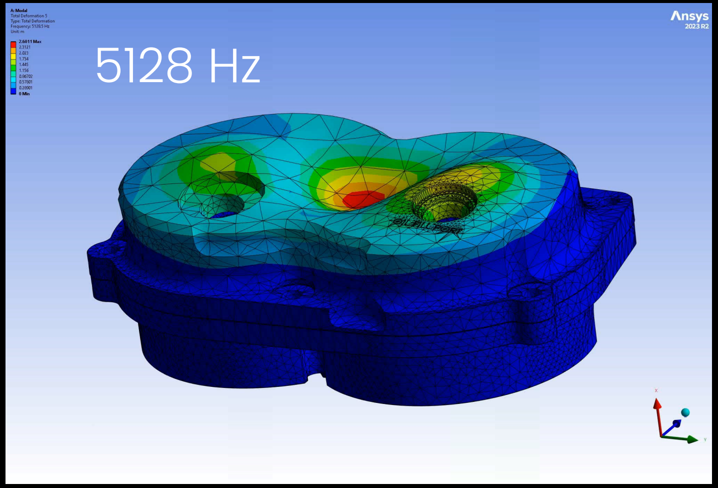
Predict of critical clearances

Examples of 3-D Simulations –Frequency Modal Analysis









- Identify frequencies and mode shapes that may align to input vibration sources (engine, wheel rotation)
- Revise design to raise natural frequencies above source
- Move Bolts to eliminate motions

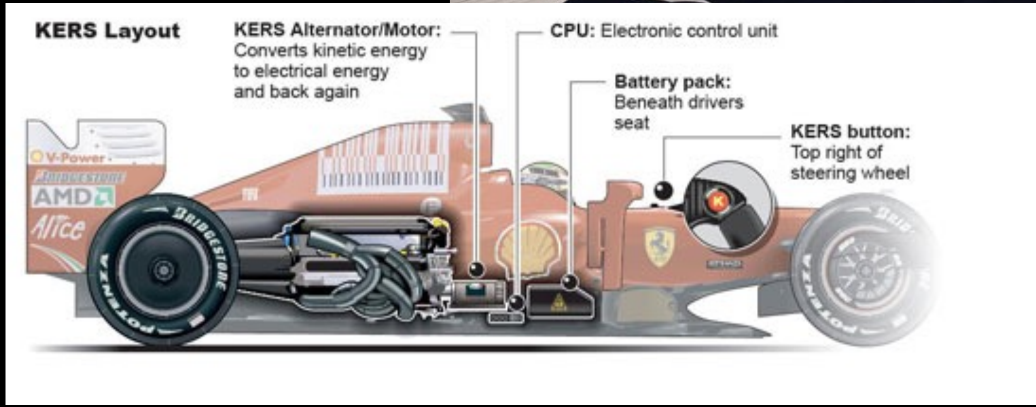
Outlook and Summary

- Continued and rapid evolution
  - Applications and simulation tools
- Battery and hybrid electric vehicles
  - OEM, racing, converters (ie. Chevrolet Volt, F1 KERS, Formula-E, Isle of Man TT Zero, Zelectric Motors)

greencarreports.com

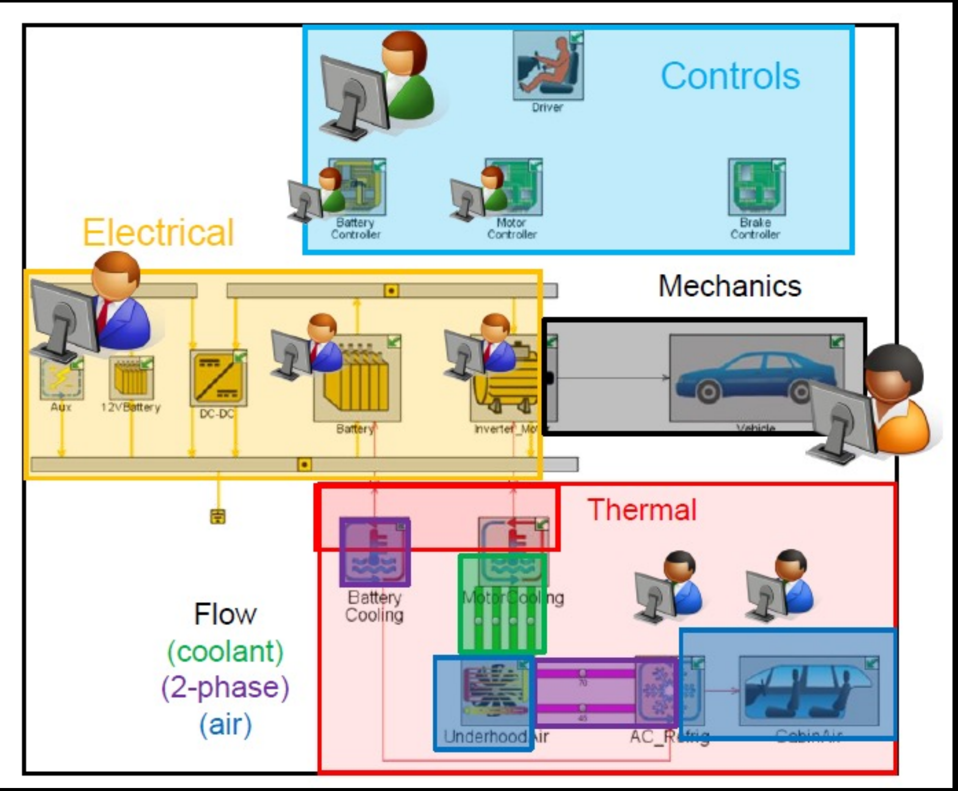
The Shop, December 2017

hybridcars.com



Outlook and Summary

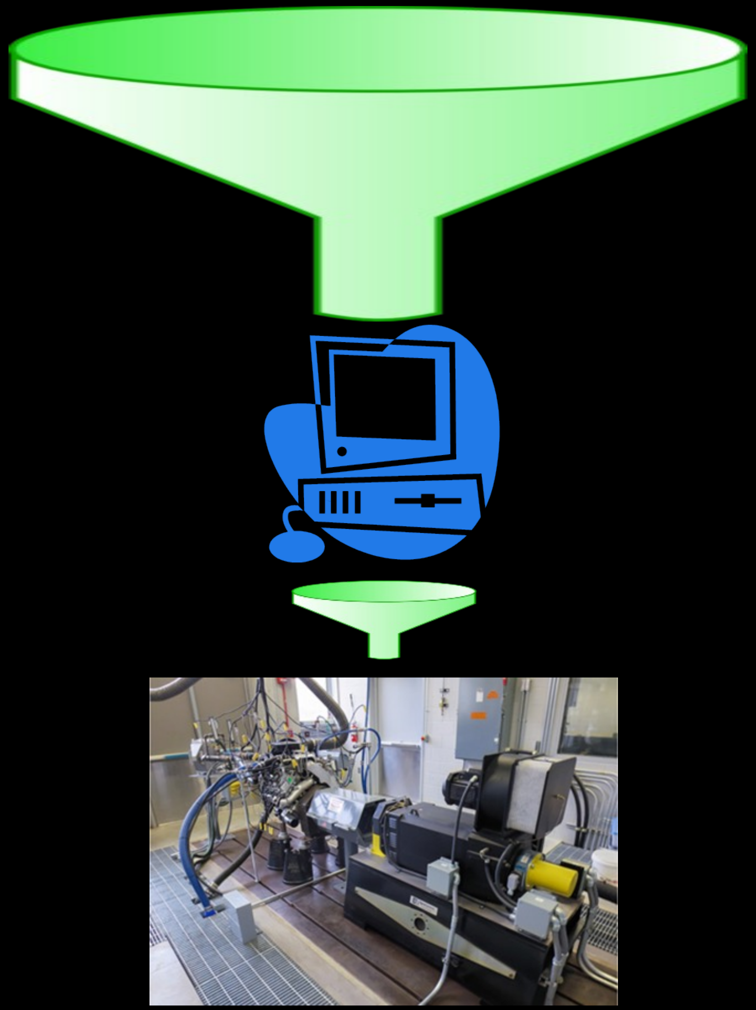
- Continued and rapid evolution
  - Applications and simulation tools
- Continued development of battery, combustion, emissions, and exhaust aftertreatment sub-models
- More “Integrated Modeling”
  - Multi-domain
  - Adaptable levels of fidelity
  - Collaborative across departments and suppliers/OEMs



“Integrated BEV & HEV Modeling in GT-Suite”,
Joe Wimmer, Peter Stopp, Gamma Technologies

Outlook and Summary

- Computer based engine simulations are not meant to replace good testing, just supplement and make that testing more efficient (time and cost), and improve understanding.
- Take those thousands of crazy ideas, boil them into just a few reasonable ones to verify with testing.
- There are lots of computer based tools and resources to pick from to help you.



Additional Reading – Recommendations From My Bookshelf

- SAE Papers
  - *What is Limiting Your Engine Air Flow: Using Normalized Steady Air Flow Bench Data*, SAE 942477, D. Agnew, 1994.
  - *Engineering an Optimum Air Flow Subsystem for Your Engine*, SAE 983049, D. Agnew/E. Romblom, 1998.
  - *Engineering a Composite Intake Manifold for the Performance Aftermarket*, SAE 2004-01-3512, D. Agnew/G. Rohrback, 2004.
  - *Coolant Flow Optimization in a Racing Cylinder Block and Head Using CFD Analysis and Testing*, SAE 2004-01-3542, D. Agnew/J. Covey/J. Ye, 2004.
- *Gas Flow in the Internal Combustion Engines*, Annand and Roe, 1974.
- *Maximum Boost, Designing, Testing, and Installing Turbocharger Systems*, C. Bell, 1997.
- *Four-Stroke Performance Tuning*, A. Bell, 2012.
- *Introduction to Engine Valvetrains*, Yushu Wang, 2007.
- *Valve Mechanisms for High Speed Engines*, Philip Smith, 1971.
- *Internal Combustion Engine, E. Obert*, 1950.
- *The Internal Combustion Engine in Theory and Practice*, C. Taylor, 1960.
- *Computer Simulation Modeling of Performance Engines*, AETC 2018, D. Agnew

Thank You