Using Multi-Physics Simulation to Optimize Your Camshafts

Dan Agnew and Steven Ruiz, Automotive Consulting Services December 12, 2024

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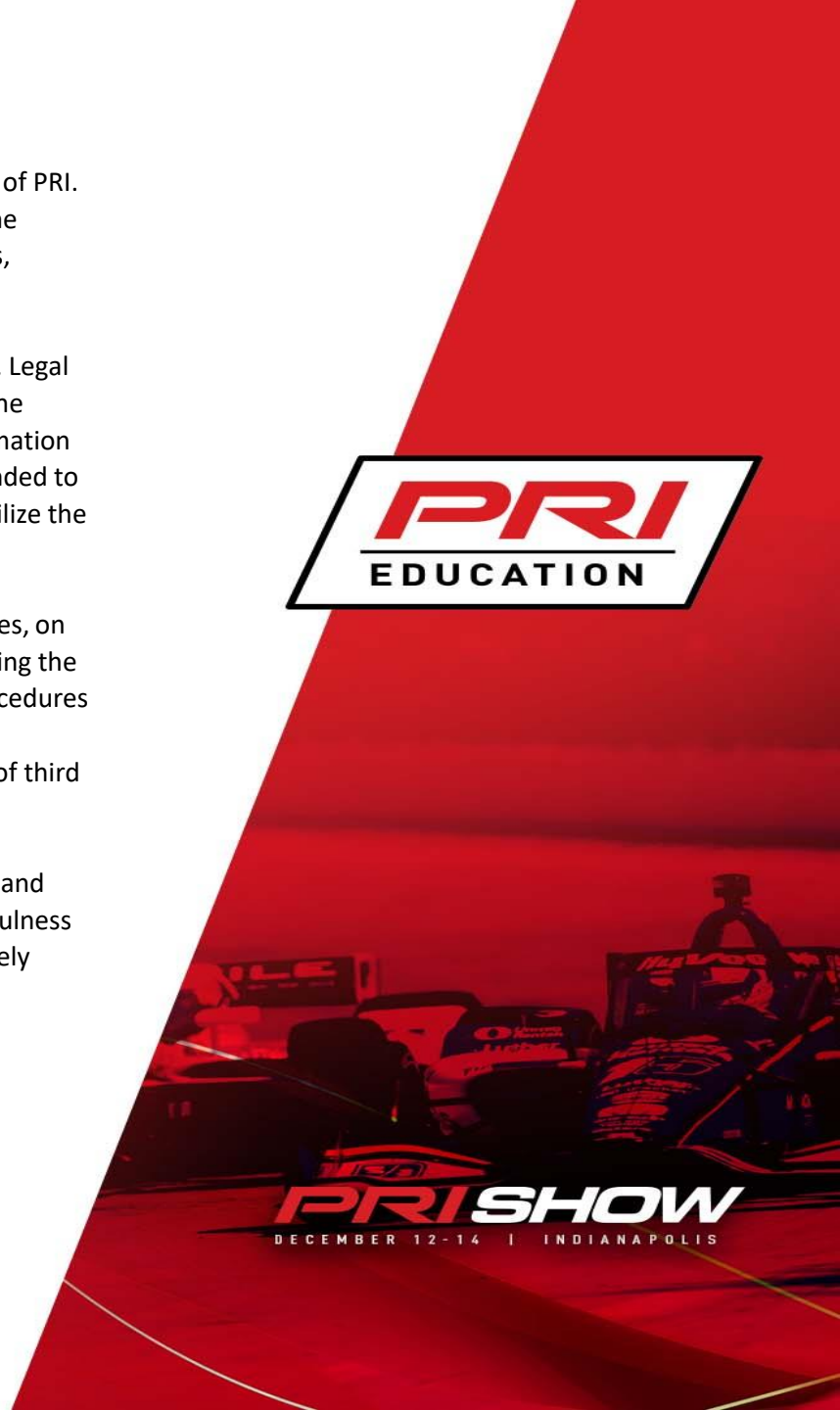


Outline

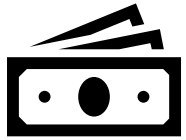
- Background of Automotive Consulting Services (ACS).
- Motivation for why computer-based simulation modeling of performance engines/vehicle is useful.
- What one-dimensional (1-D) tools are available?
- How (1-D) models are constructed.
- Using the model for cam optimization.
- Using the results in calibration.
- Summary.

Background of ACS

- Specialists in product development, calibration, computer aided engineering (CAE), emissions compliance, operations, and business strategy in the aftermarket and OEM space.
- For CAE, typically engine, valvetrain, cooling, lub/oil, structural, and vehicle systems.
- Projects are most often confidential.
- For many clients, ACS becomes their “virtual engineering department”.
- Diversity of project types include…
  - ✓ Concept propulsion systems.
  - ✓ Automotive.
  - ✓ Industrial/Agricultural.
  - ✓ Performance/Racing.

Motivation

Why use computer-based simulations?



1 Cost

Initial investment in a model is typically similar to a new dyno test, but for facility and hardware costs there are 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 a few days, depending on complexity.

3 Understanding

Much more information is available for more complete and deeper understanding.

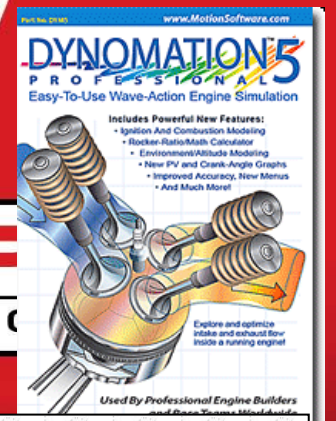
Simulations are like a dyno test with unlimited number of data channels!

Available 1D Multi-Physics Tools

- **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, Emissions, Thermal, etc.

ENGINE EXPERT

DYNO SIMULATION SOFTWARE VIRTUALENGINEDYNO.COM



Performance Trends, Inc.

FEV VIRTUALENGINE

REALIS

GT Gamma Technologies

AVL BOOST™

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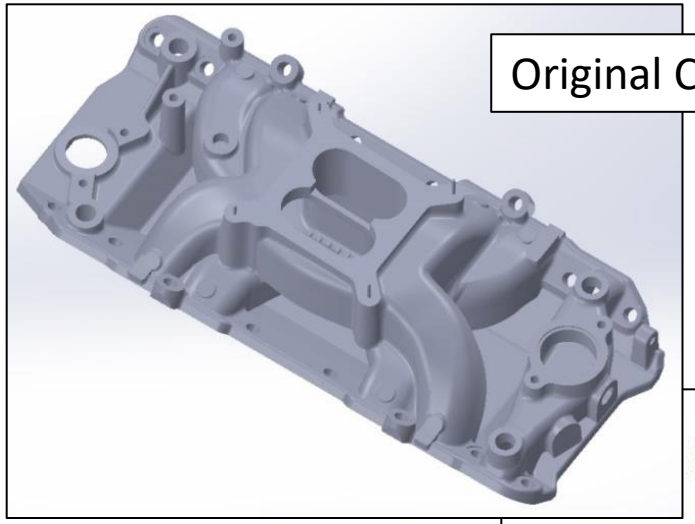
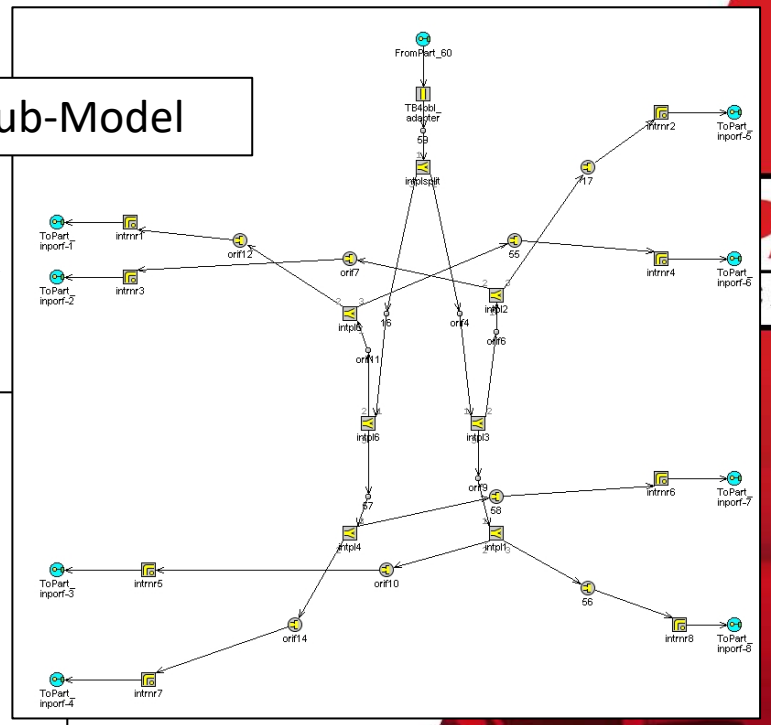
How a 1-D Model is Constructed

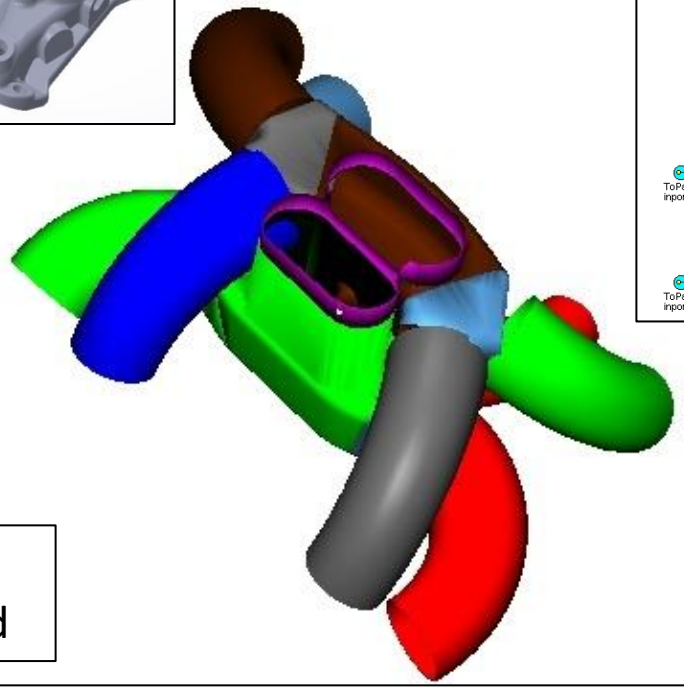
Intake Manifold



Original CAD



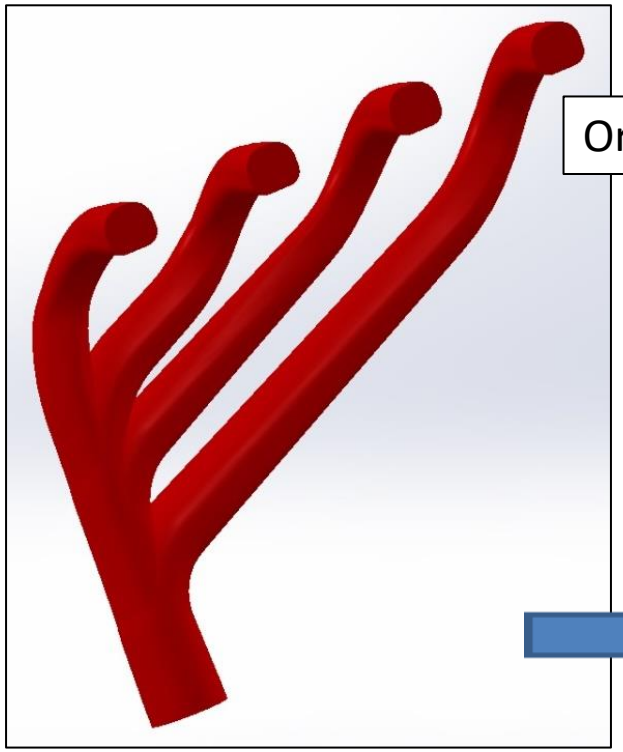
GT-Suite Sub-Model



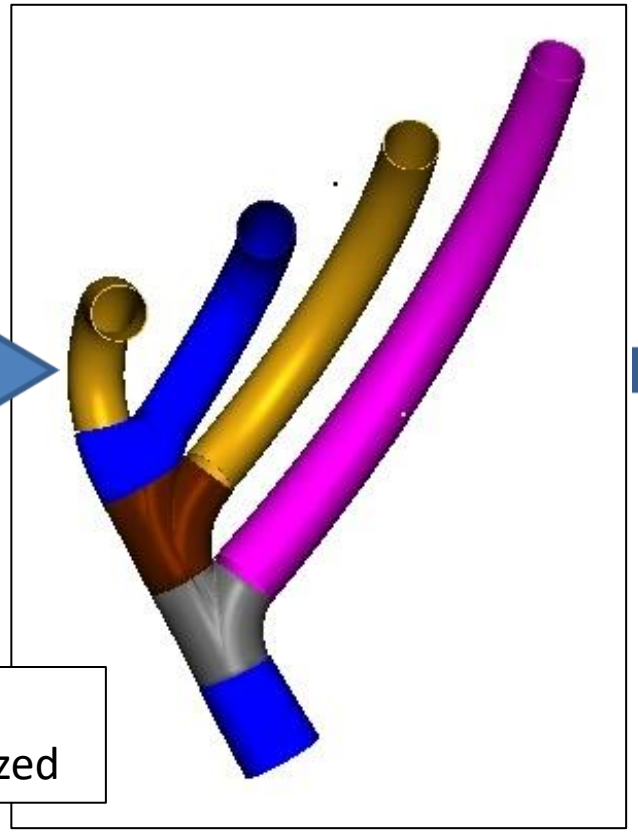
GEM3D Discretized

How a 1-D Model is Constructed

Exhaust Manifold

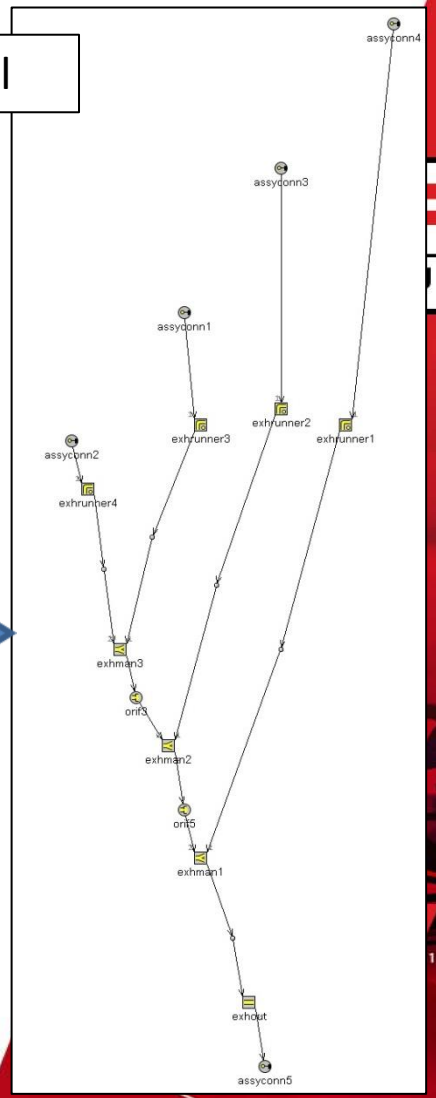


Original CAD



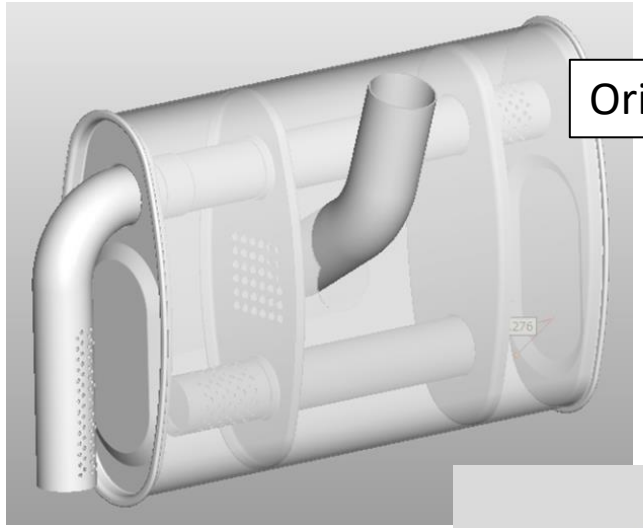
GEM3D
Discretized

GT-Suite Sub-Model

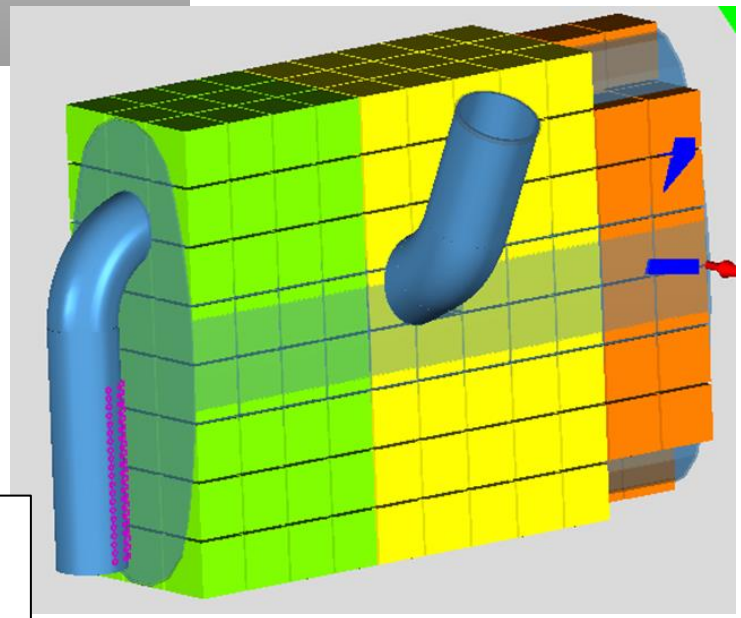


How a 1-D Model is Constructed

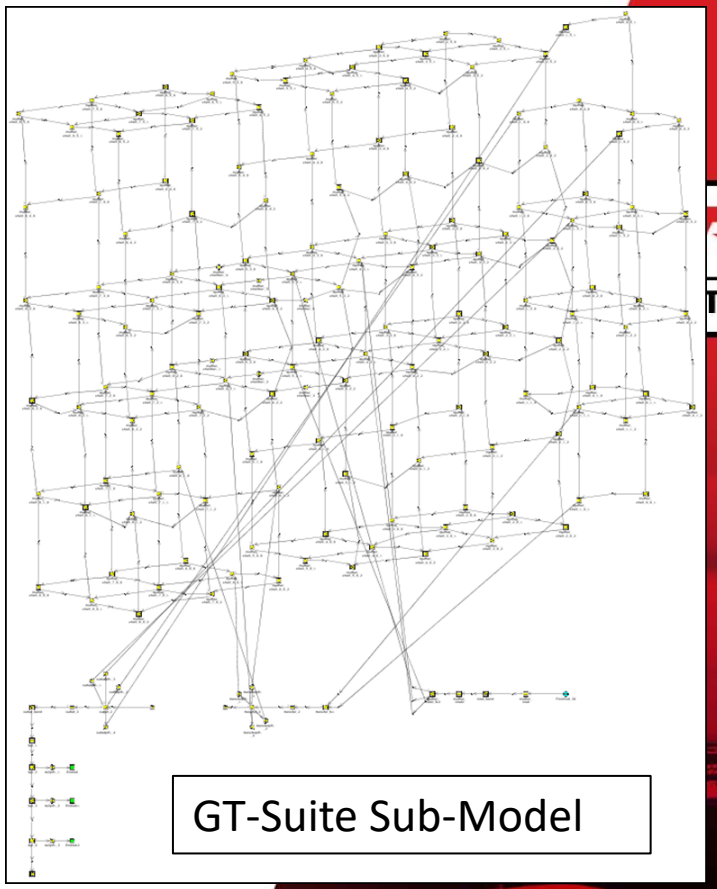
Muffler



Original CAD



GEM3D
Discretized



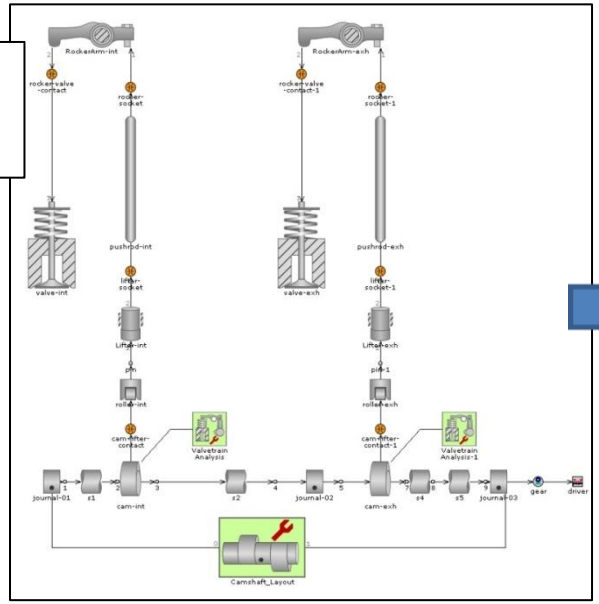
GT-Suite Sub-Model

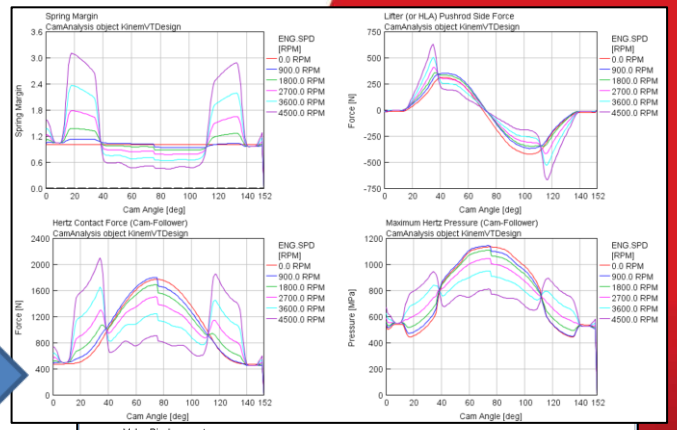
How a 1-D Model is Constructed

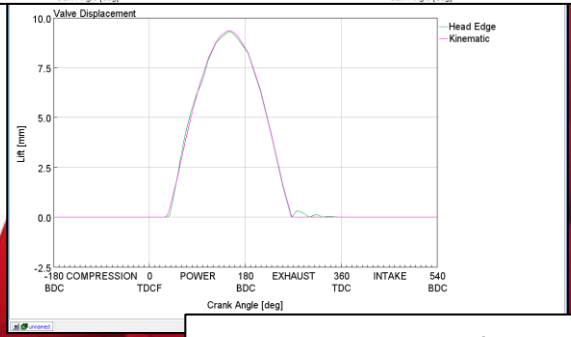
Valvetrain

Original CAD

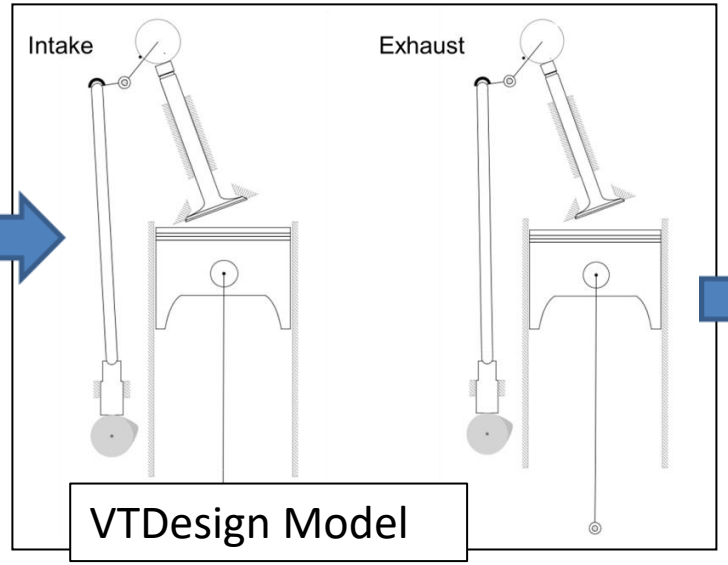
GT-Suite VT
System Model



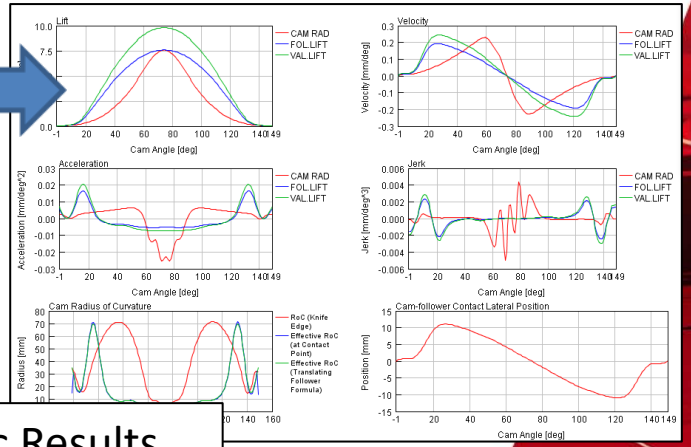




Dynamic Results



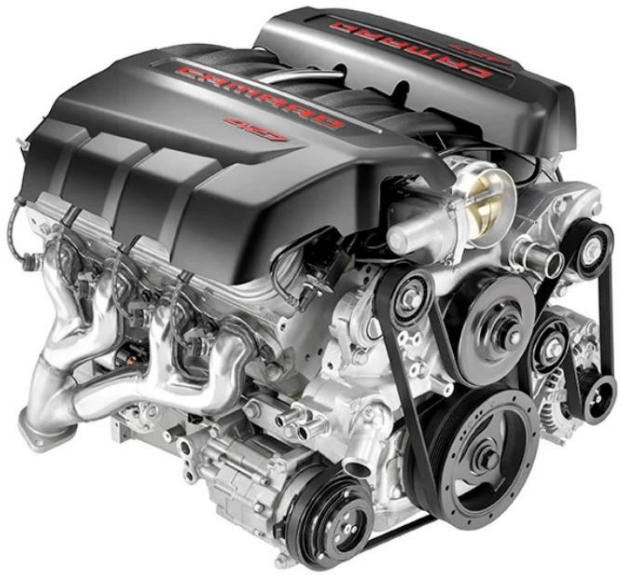
VTDesign Model

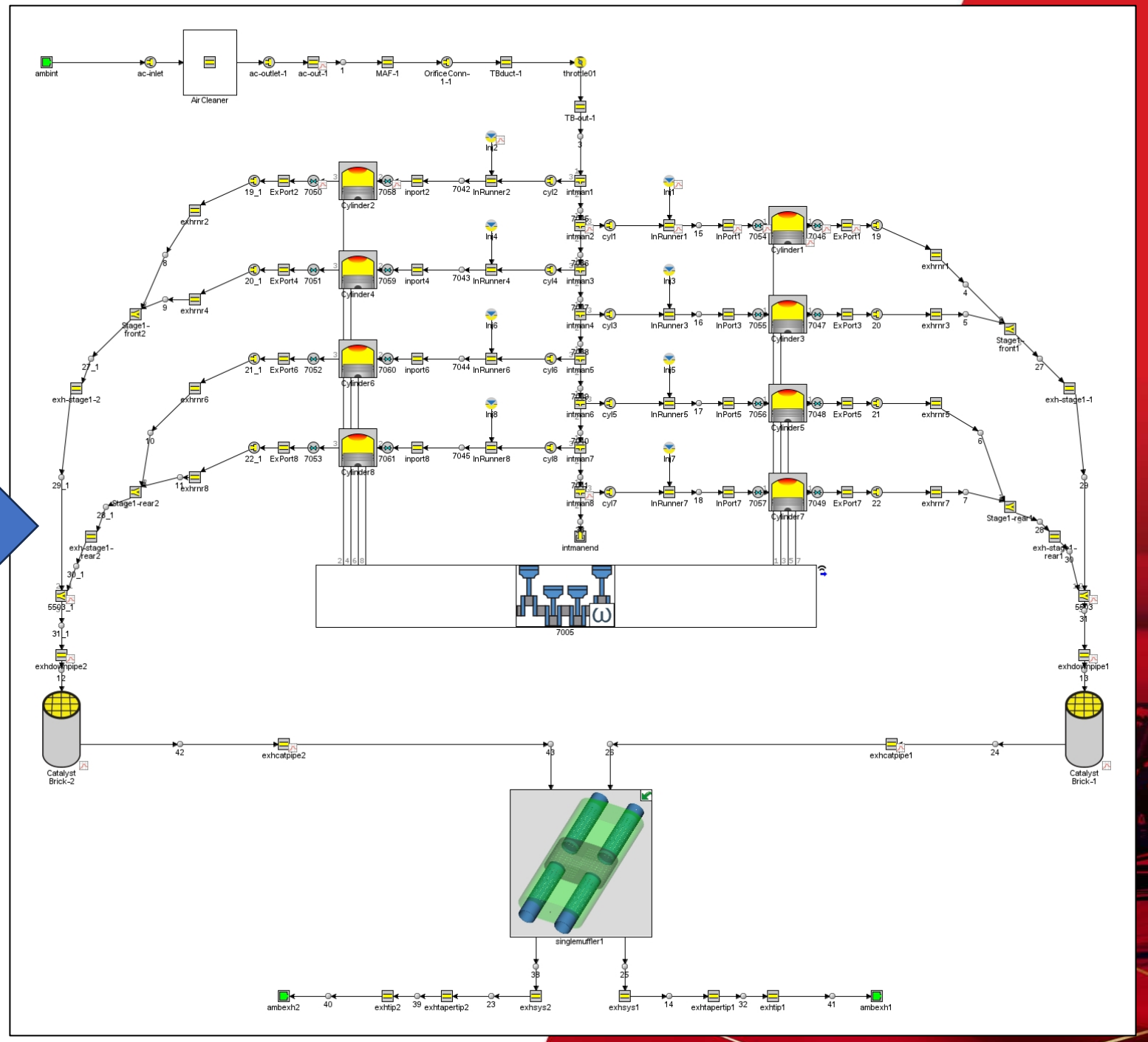


Kinematic Results

How a 1-D Model is Constructed

- Example of LSx Based Engine Model
- Aftermarket Based Dual Exhaust Vehicle System
- Cams From Goldbold Engineering





Using the Model for Cam Optimization

The Process for this Design of Experiments (DOE)

Parameters to be Optimized for Both Intake and Exhaust:
- Lobe Centers (LC)
- Peak Lift
- Duration

Determine Reasonable Limits

Optional ?

Detailed Valvetrain Profile Design for Lift, Velocity, Acceleration, Jerk, and Dynamics…

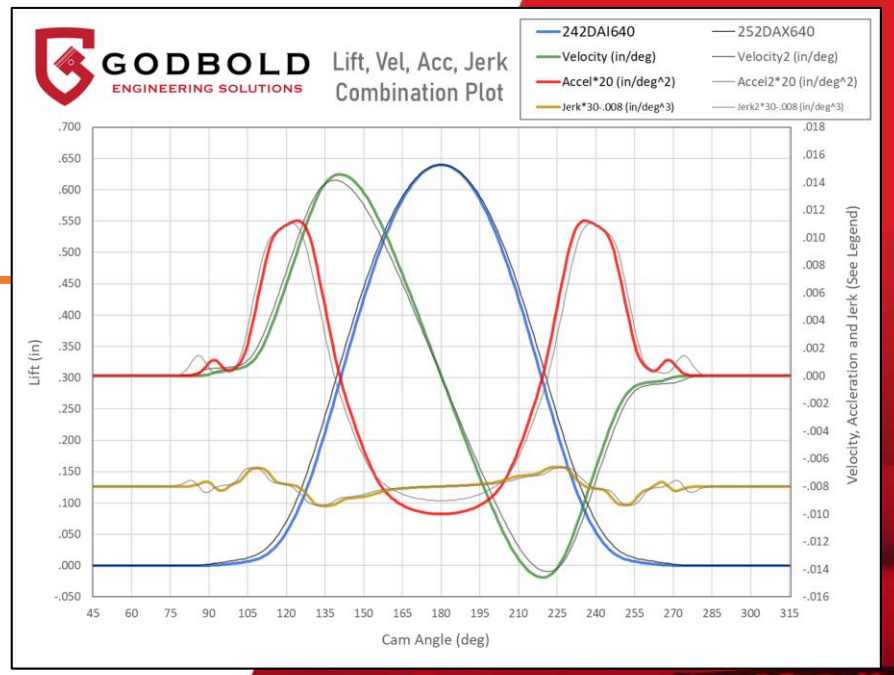
GT-Suite DOE with Timing and Scalar Multipliers for Lift and Duration

Review and Narrow DOE Results to Select Few Options, or Array of Timing vs RPM/Load

Confirm Results with Detailed Valvetrain Profile Design for Dynamic Lift, Velocity, Acceleration, Jerk…

Optimized Profile and Timing(s)

Send VVT Timing Tables to Calibration



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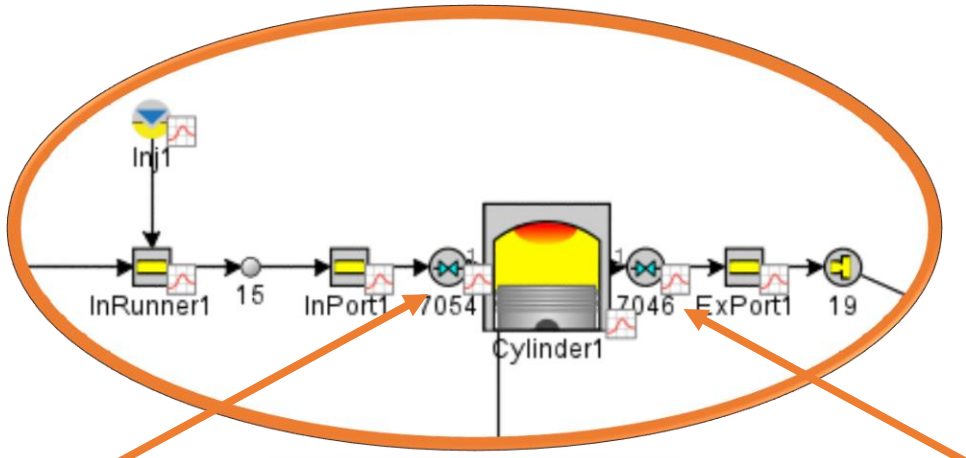
Using the Model for Cam Optimization

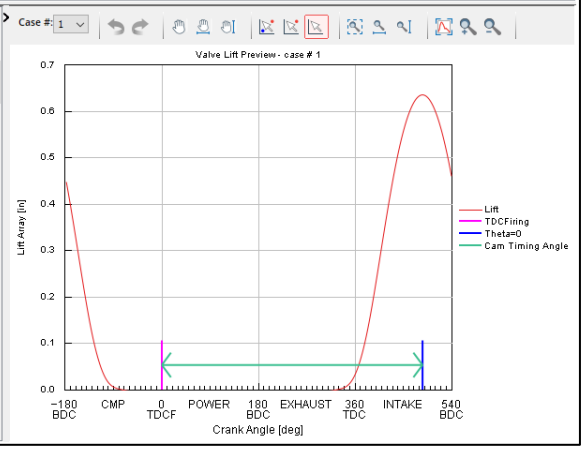
Valvetrain Object Inputs to Engine Model



Timing | Lift | Flow Coefficients | Output

Attribute	Unit	Object Value
Valve Lash	See Case S...	[ILASH]
Variable Profile Dependency Object		ign
Dwell at Maximum Lift	Cam Angle	ign
Angle Multiplier		[intDurmult]
Anchor for Angle Multiplier		Theta=0
Lift Multiplier		[intLmult]

Attri...	Angle Array	Lift Array
	Crank Angl...	in
1	-194	0
2	-192	0.0000005
3	-190	0.0000032
4	-188	0.0000106
5	-186	0.0000262
6	-184	0.0000563
7	-182	0.0001104
8	-180	0.0002001
9	-178	0.000337
10	-176	0.0005302
11	-174	0.0007832
12	-172	0.0010922
13	-170	0.0014474
14	-168	0.0018375
15	-166	0.0022518
16	-164	0.0026836
17	-162	0.0031317
18	-160	0.0035994
19	-158	0.0040928
20	-156	0.0046199
21	-154	0.0051909
22	-152	0.0058204



Timing | Lift | Flow Coefficients | Output

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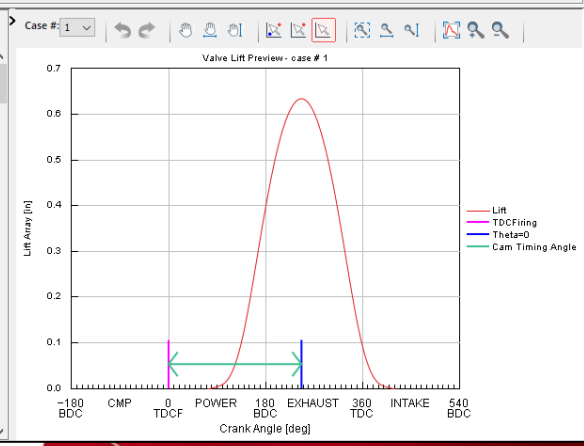
Valve Lash	See Case S...	[ELASH]
Variable Profile Dependency Object		ign
Dwell at Maximum Lift	Cam Angle	ign
Angle Multiplier		[exhDurmult]
Anchor for Angle Multiplier		Theta=0
Lift Multiplier		[exhLmult]

Attri...	Angle Array	Lift Array
	Crank Angl...	in
1	-206	0
2	-204	0.0000006
3	-202	0.0000039
4	-200	0.0000128
5	-198	0.0000318
6	-196	0.000069
7	-194	0.0001367
8	-192	0.0002501
9	-190	0.0004241
10	-188	0.0006709
11	-186	0.000995
12	-184	0.001391
13	-182	0.0018464
14	-180	0.0023456
15	-178	0.0028736
16	-176	0.0034187
17	-174	0.003975
18	-172	0.0045407
19	-170	0.0051163
20	-168	0.0057034
21	-166	0.0063042
22	-164	0.0069215



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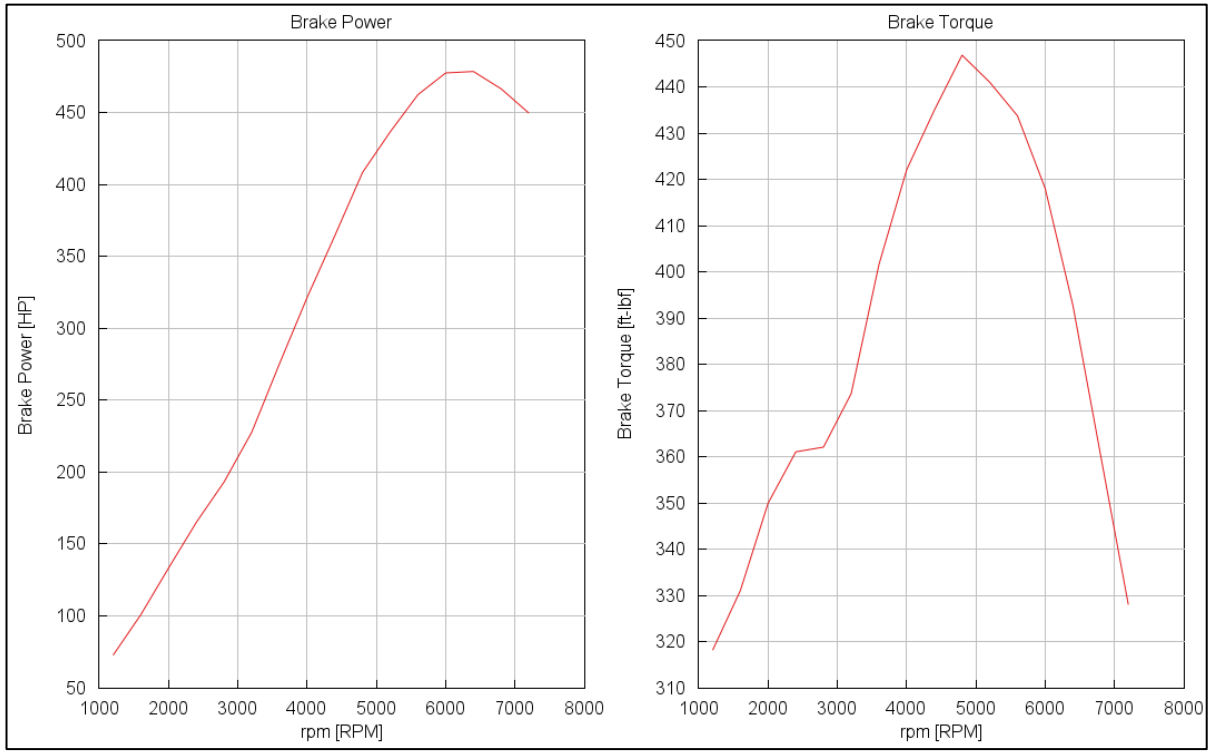
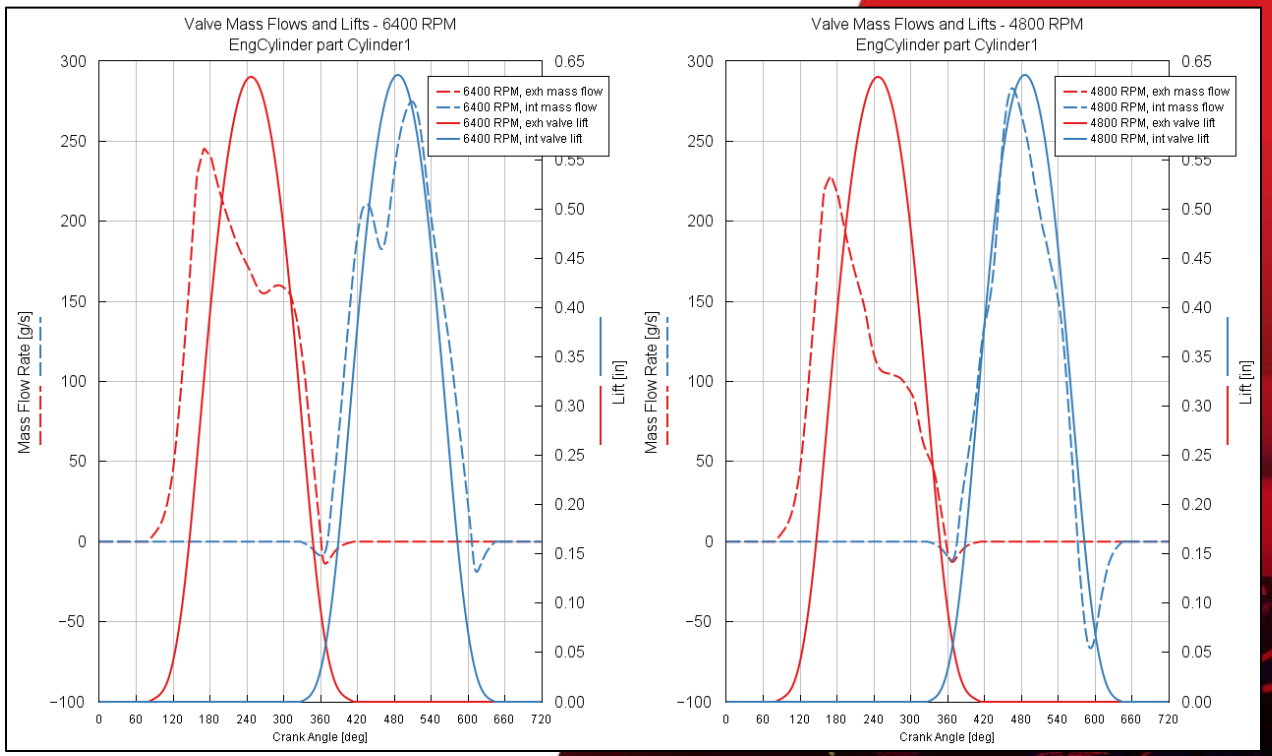
Using the Model for Cam Optimization

The Starting Point…

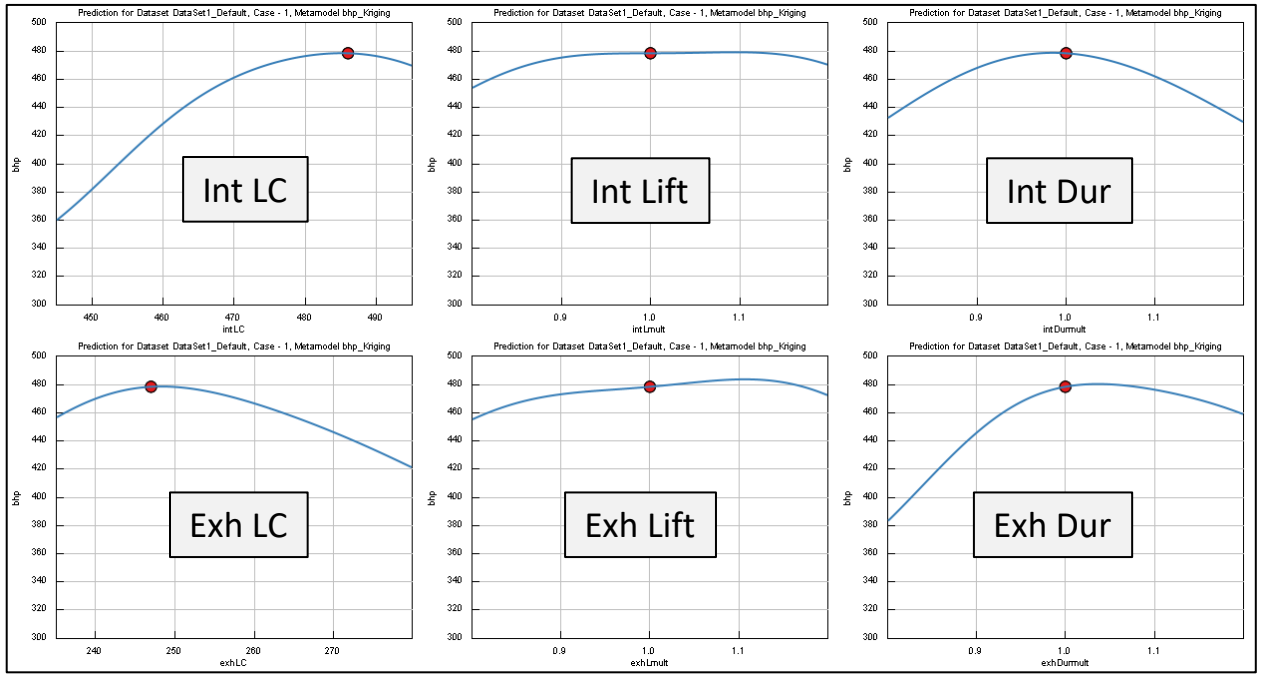




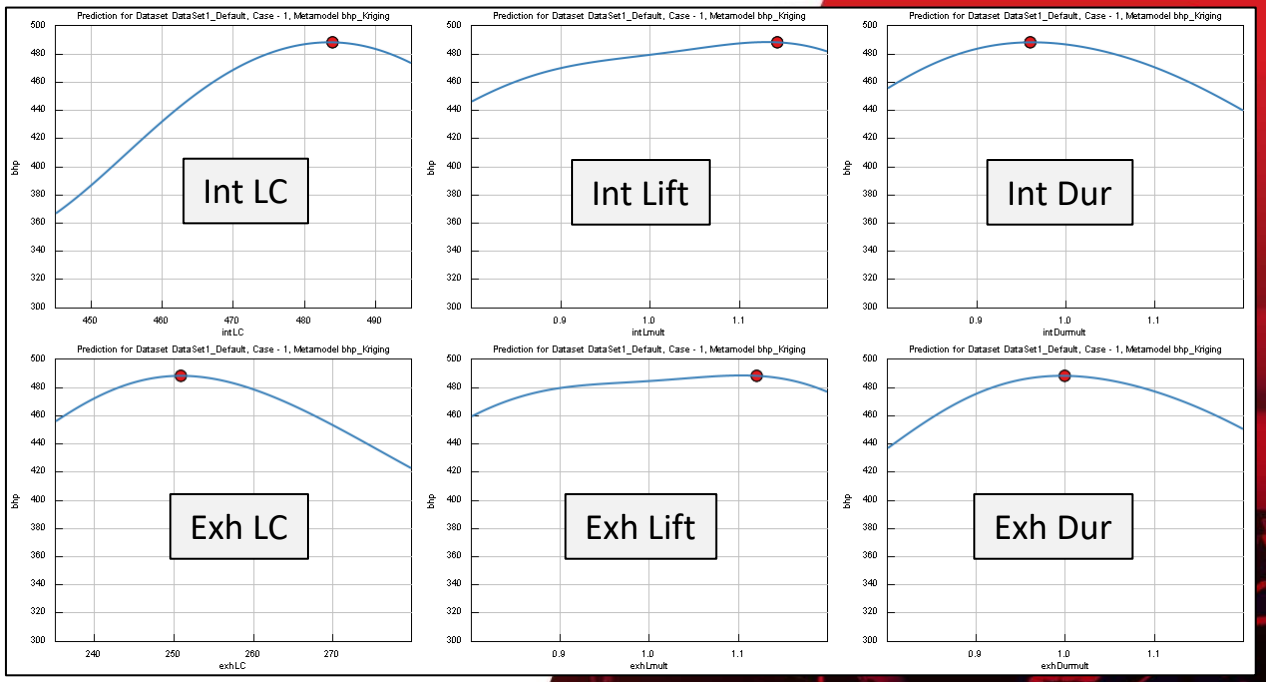
Using the Model for Cam Optimization

The Starting Point… Sweeping a Range of the Variables Shows Their Relative Sensitivities

Peak Power 6400 RPM - Baseline



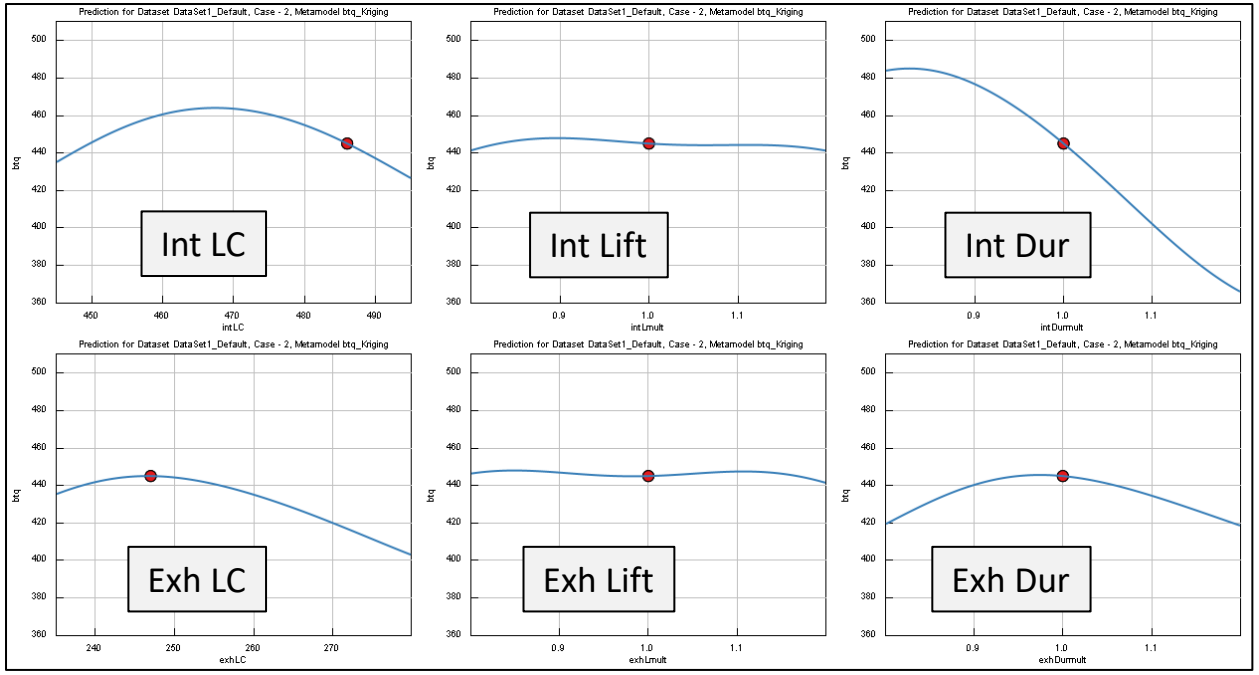
Peak Power 6400 RPM - Optimized



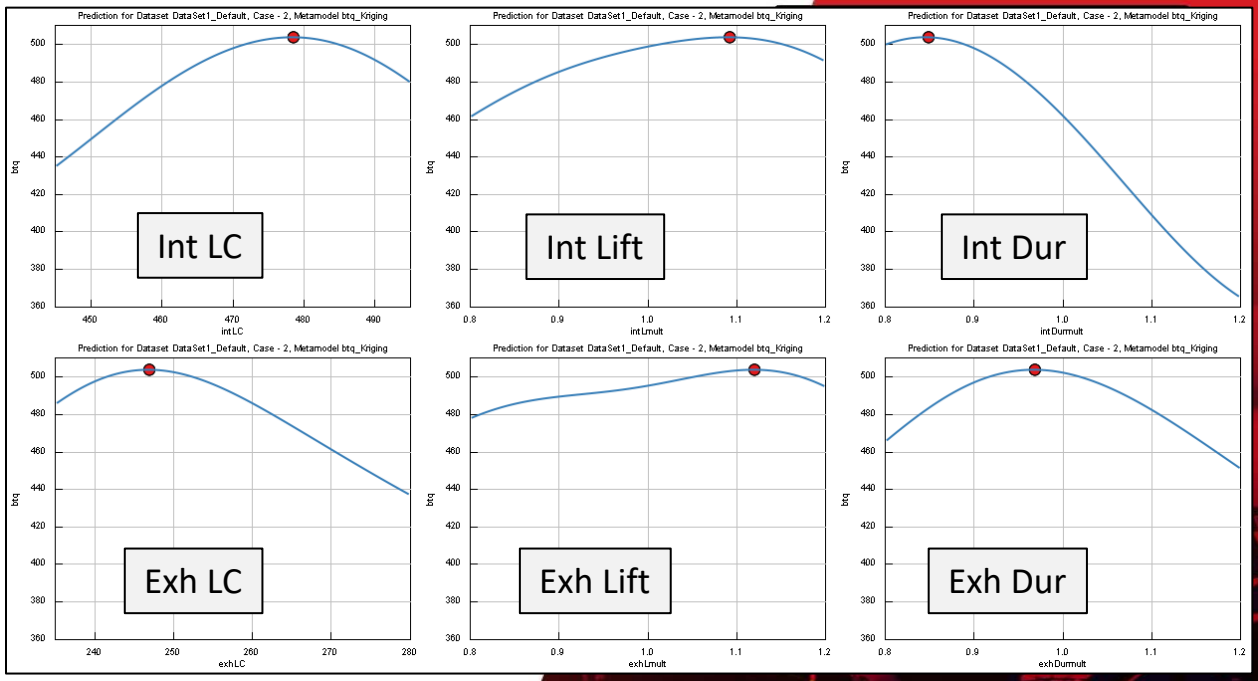
Using the Model for Cam Optimization

The Starting Point… Sweeping a Range of the Variables Shows Their Relative Sensitivities

Peak Torque 4800 RPM - Baseline



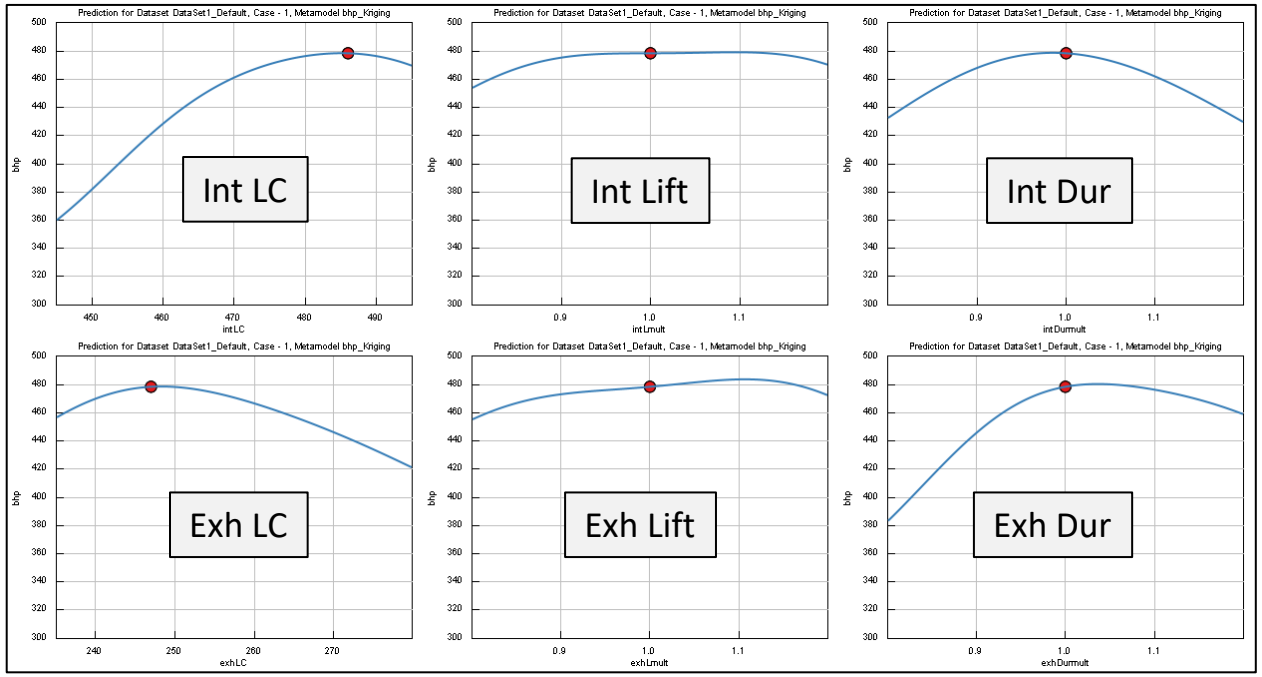
Peak Torque 4800 RPM - Optimized



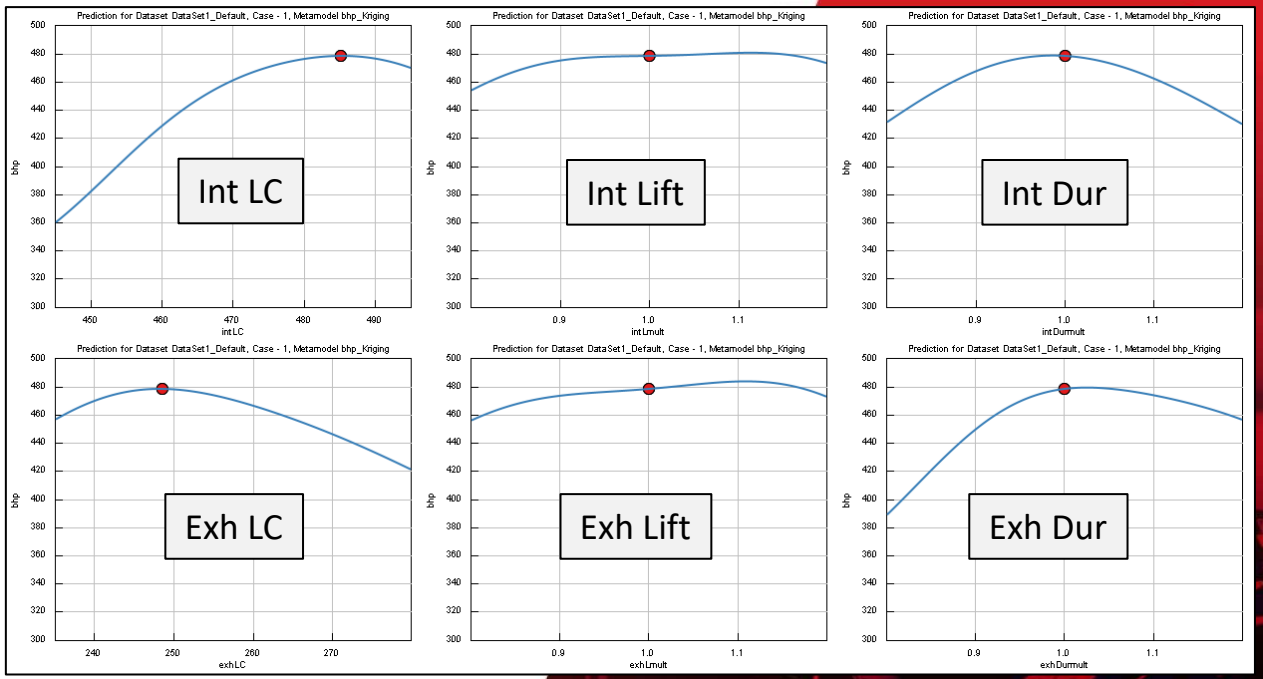
Using the Model for Cam Optimization

The Starting Point… Sweeping Timing Only and Fixing Lift and Duration

Peak Power 6400 RPM - Baseline



Peak Power 6400 RPM – Optimized for Timing Only



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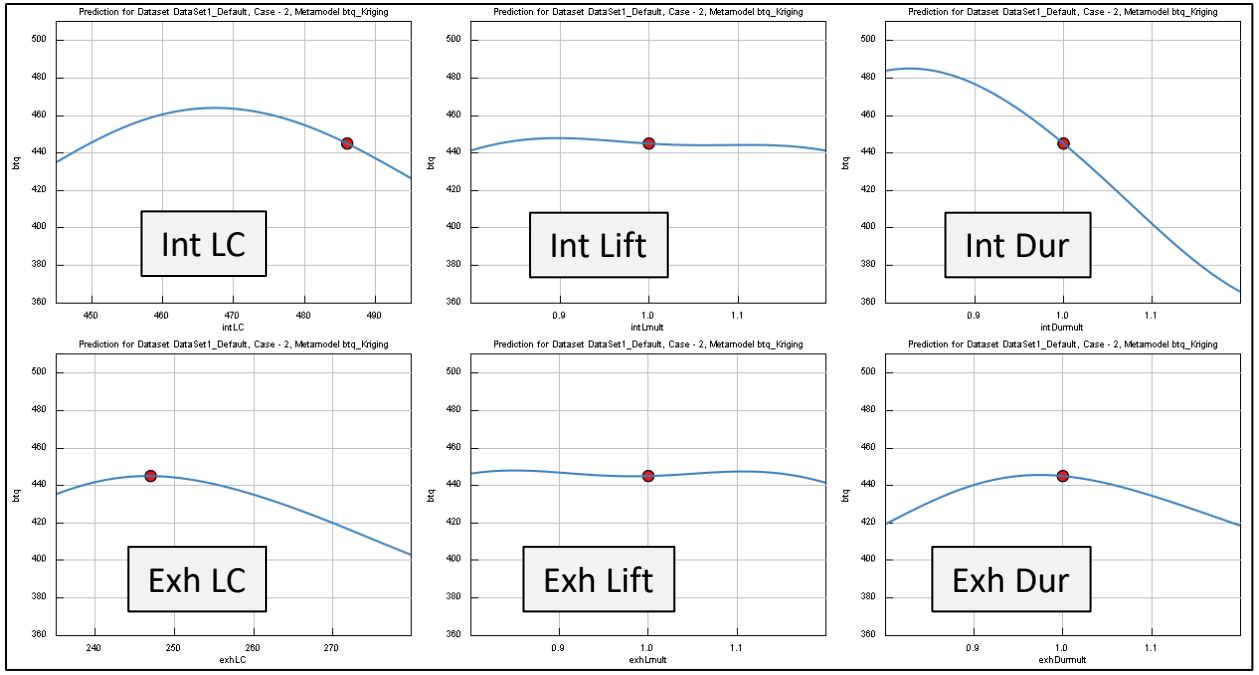
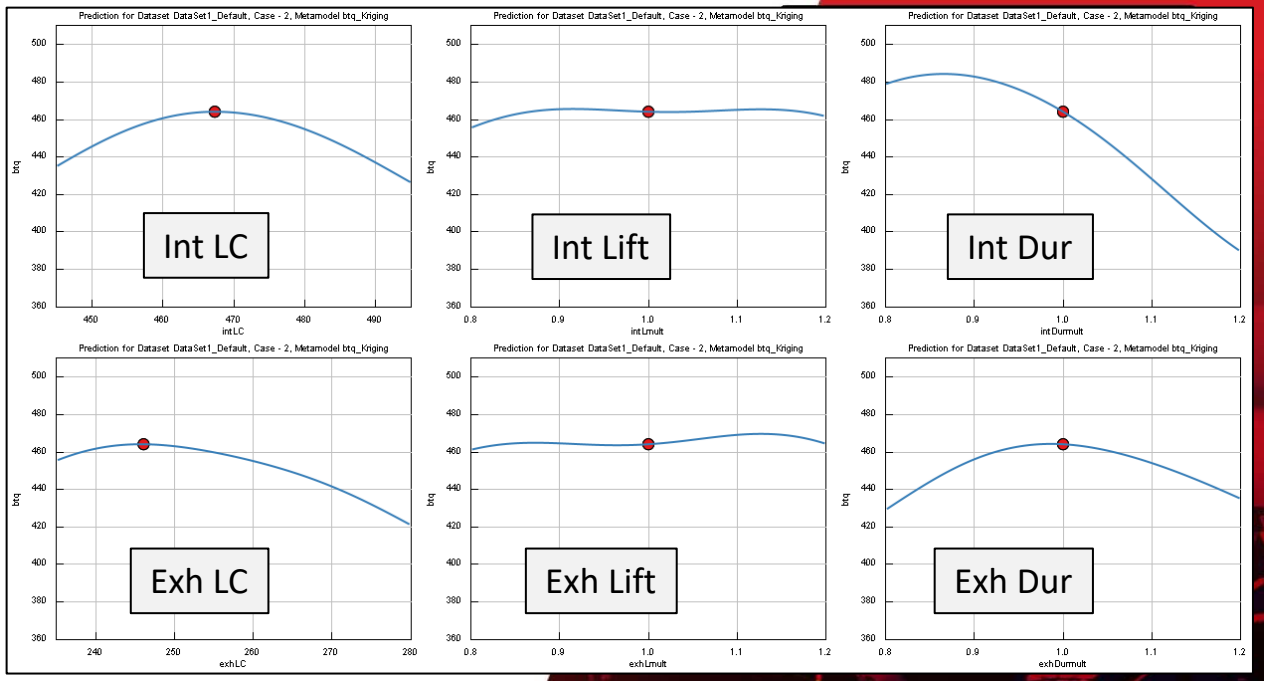
Using the Model for Cam Optimization

The Starting Point… Sweeping Timing Only and Fixing Lift and Duration

Peak Torque 4800 RPM - Baseline



Peak Torque 4800 RPM - Optimized



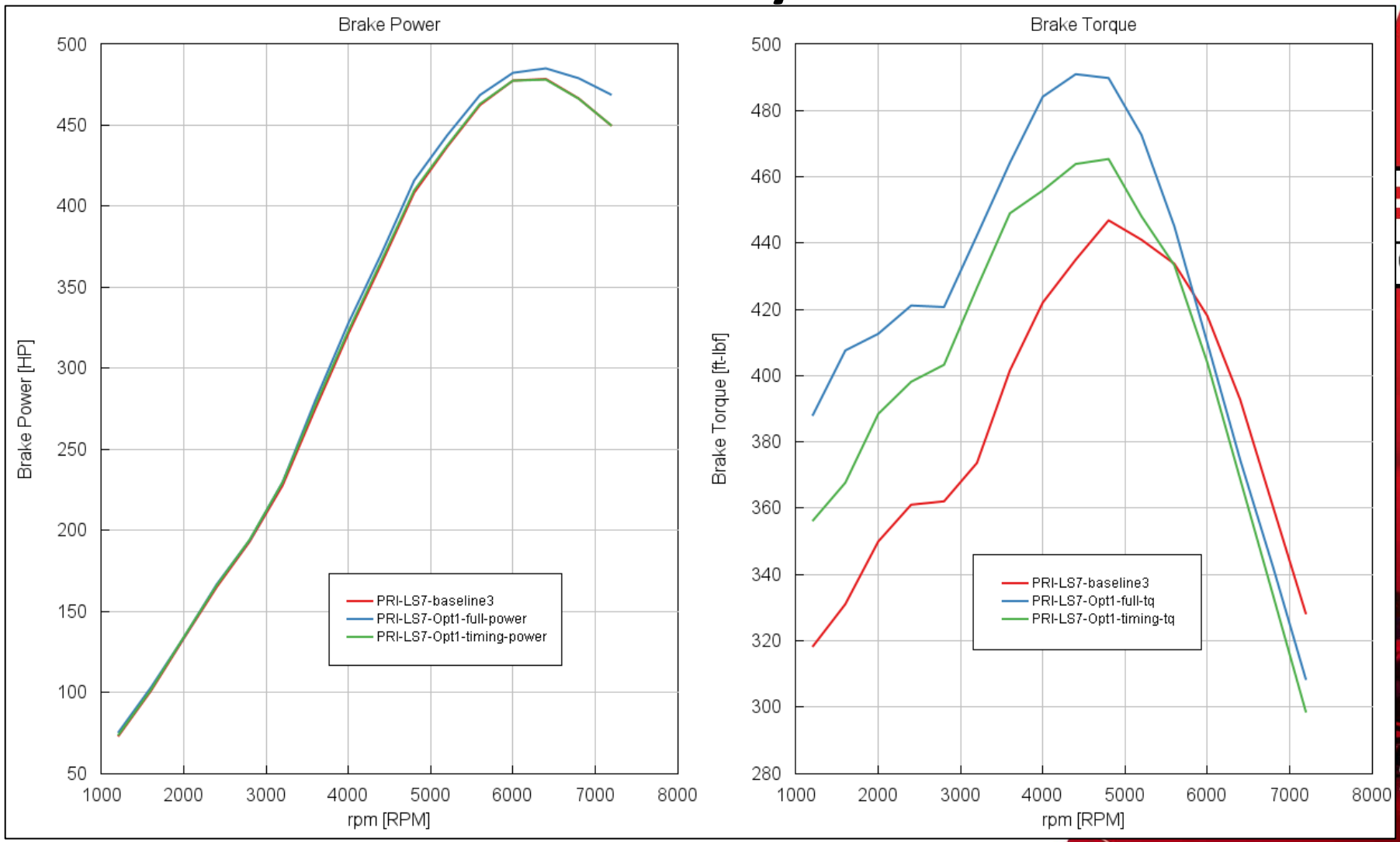
Using the Model for Cam Optimization

DOE Summary Results…

	Baseline	Full Optimized For Power	Full Optimized For Torque	Timing Only Optimized for Power	Timing Only Optimized for Torque
Parameter					
Intake LC, deg ATDCf	486	484	479	485	467
Intake Lift, multiplier	1.0	1.14	1.09	1.00	1.00
Intake Duration, multiplier	1.00	0.96	0.85	1.00	1.00
Exhaust LC, deg ATDCf	247	252	247	248	246
Exhaust Lift, multiplier	1.00	1.12	1.12	1.00	1.00
Exhaust Duration, multiplier	1.00	1.02	0.97	1.00	1.00
Power at 6400 RPM, Hp	478	488	-	478	-
Torque at 4800 RPM, Ft-Lbs	445	-	504	-	464
Design Direction From Intake Baseline	-	Advance LC, More Lift, Less Duration	Advance LC, More Lift, Less Duration	Slight Advance LC	Advance LC
Design Direction From Exhaust Baseline	-	Retard LC, More Lift, More Duration	Same LC, More Lift, Less Duration	Slight Retard LC	Slight Retard LC

Using the Model for Cam Optimization

DOE Summary Results…



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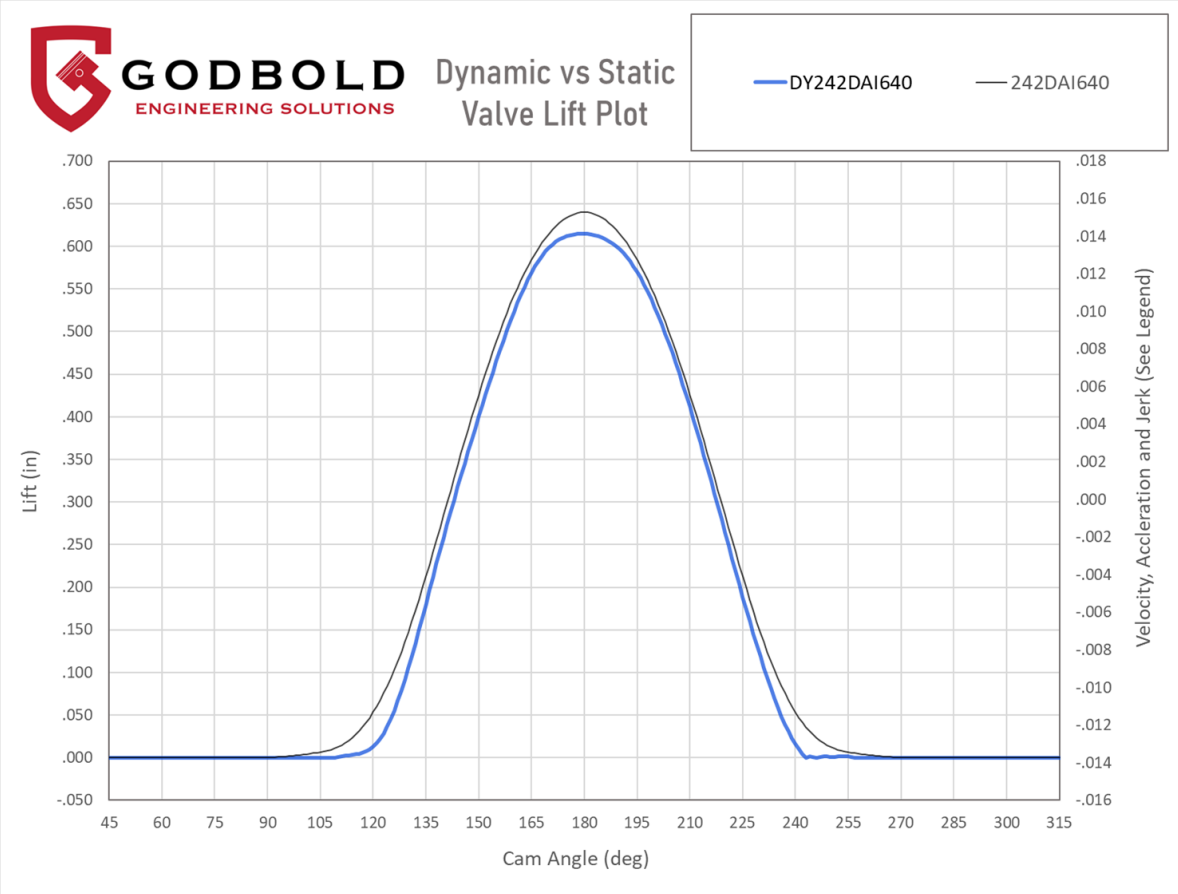
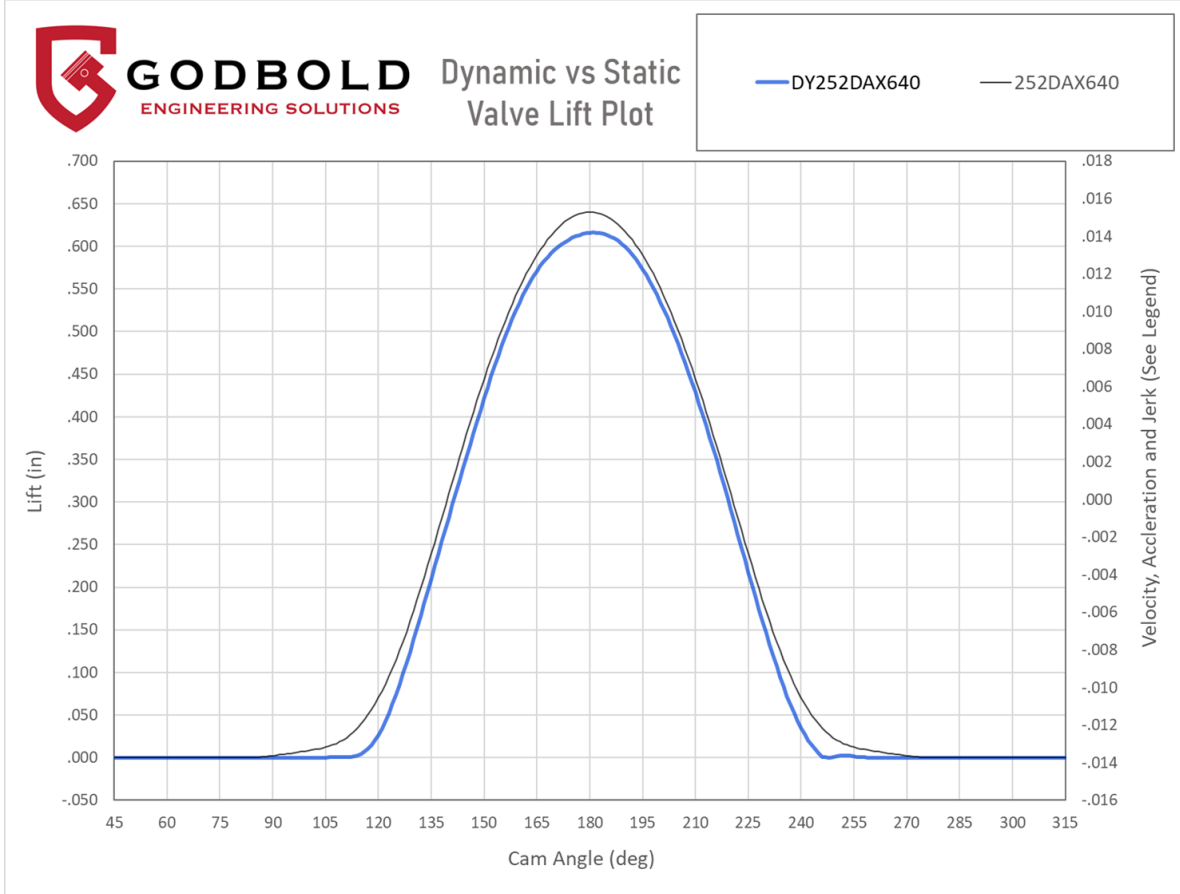
Using the Model for Cam Optimization

DOE Summary Results, But With Dynamic Lift …





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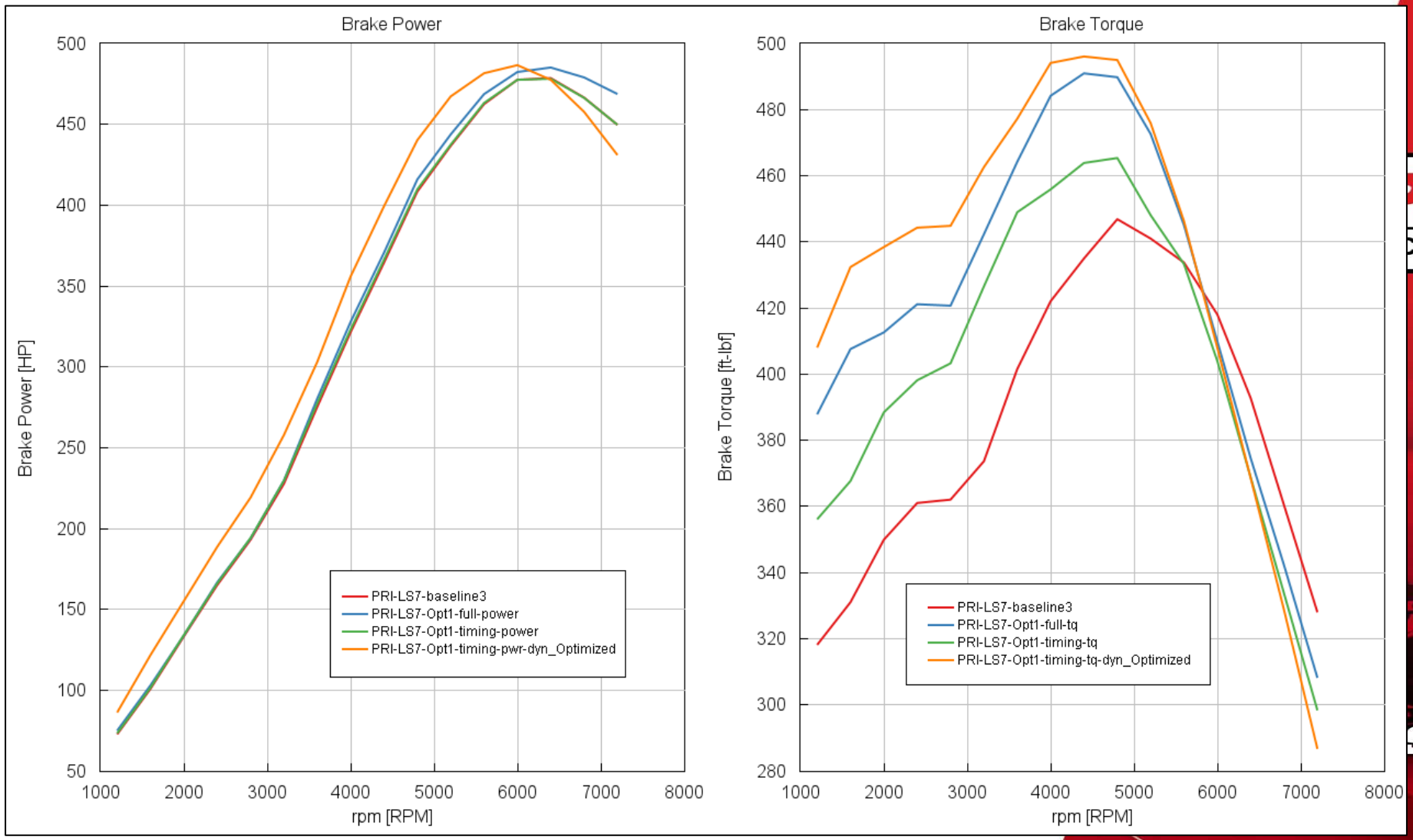
Using the Model for Cam Optimization

DOE Summary Results, But With Dynamic Lift …



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Using the Model for Cam Optimization

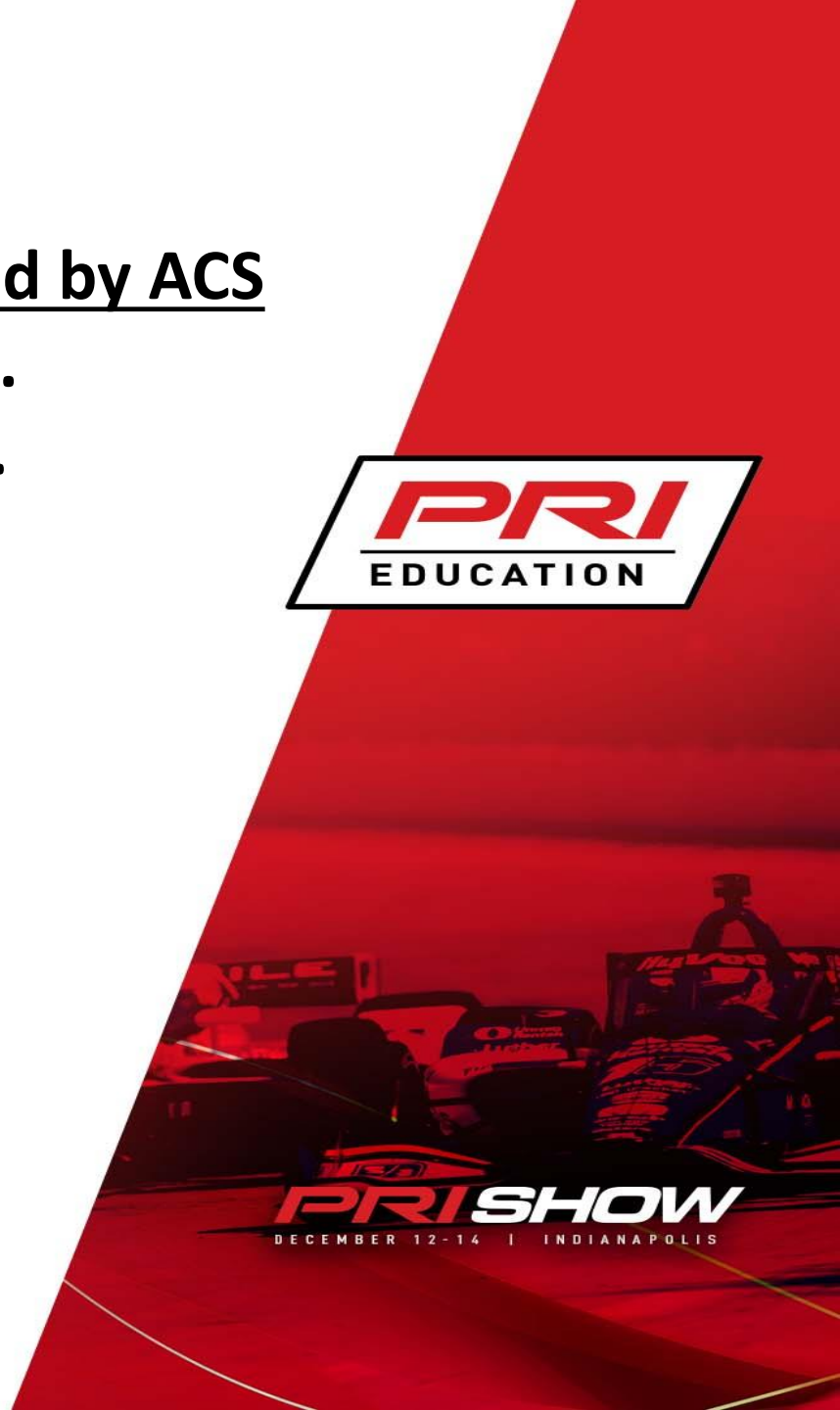
DOE Summary Results…

	Baseline	Full Optimized For Power	Full Optimized For Torque	Timing Only Optimized for Power (Dynamic)	Timing Only Optimized for Torque (Dynamic)
Parameter					
Intake LC, deg ATDCf	486	484	479	485 (481)	467 (467)
Intake Lift, multiplier	1.0	1.14	1.09	1.00	1.00
Intake Duration, multiplier	1.00	0.96	0.85	1.00	1.00
Exhaust LC, deg ATDCf	247	252	247	248 (251)	246 (248)
Exhaust Lift, multiplier	1.00	1.12	1.12	1.00	1.00
Exhaust Duration, multiplier	1.00	1.02	0.97	1.00	1.00
Power at 6400 RPM, Hp	478	488	-	478 (487)	-
Torque at 4800 RPM, Ft-Lbs	445	-	504	-	464 (496)
Design Direction From Intake Baseline	-	Advance LC, More Lift, Less Duration	Advance LC, More Lift, Less Duration	Slight Advance LC	Advance LC
Design Direction From Exhaust Baseline	-	Retard LC, More Lift, More Duration	Same LC, More Lift, Less Duration	Slight Retard LC	Slight Retard LC

Using the Results in Calibration

Typical Controllers and Tuning Solution Apps Used by ACS

- Motec M1 as a stand-alone for R&D and racing.
- ATI Vision software for tuning OEM controllers.
- Aftermarket tuning solutions.
  - ✓ HP Tuners.
  - ✓ Derive Systems – SCT.
  - ✓ Diablo CMR.
  - ✓ EFI Live.
  - ✓ EVC – WinOLS.
  - ✓ Others depending on the application.



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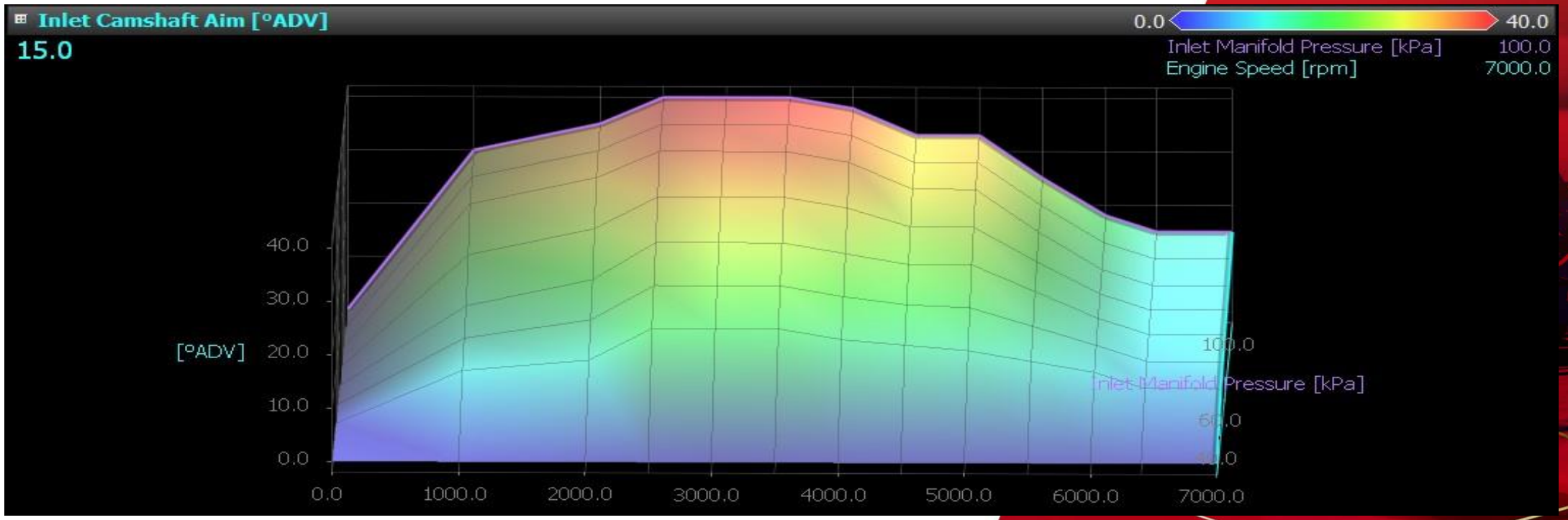
Using the Results in Calibration

Inlet Camshaft Aim [°ADV] 0.0 — 40.0

Engine Speed [rpm] × Inlet Manifold Pressure [kPa]

Inlet Manifold Pressure [kPa] \ Engine Speed [rpm]	0.0	1000.0	2000.0	2500.0	3000.0	3500.0	4000.0	4500.0	5000.0	5500.0	6000.0	6400.0	7000.0
100.0	0.0	30.0	35.0	40.0	40.0	40.0	38.0	33.0	33.0	25.0	18.0	15.0	15.0
90.0	0.0	28.5	33.5	38.5	38.5	38.5	36.5	31.5	31.5	23.5	16.5	13.5	13.5
80.0	0.0	27.0	32.0	37.0	37.0	37.0	35.0	30.0	30.0	22.0	15.0	12.0	12.0
70.0	0.0	21.0	26.0	32.0	32.0	32.0	30.0	26.5	26.5	20.0	14.0	11.0	11.0
60.0	0.0	15.0	20.0	27.0	27.0	27.0	25.0	23.0	23.0	18.0	13.0	10.0	10.0
50.0	0.0	12.5	16.0	22.5	22.5	22.5	20.5	19.0	18.5	15.0	11.5	8.5	8.5
40.0	0.0	10.0	12.0	18.0	18.0	18.0	16.0	15.0	14.0	12.0	10.0	7.0	7.0
20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0



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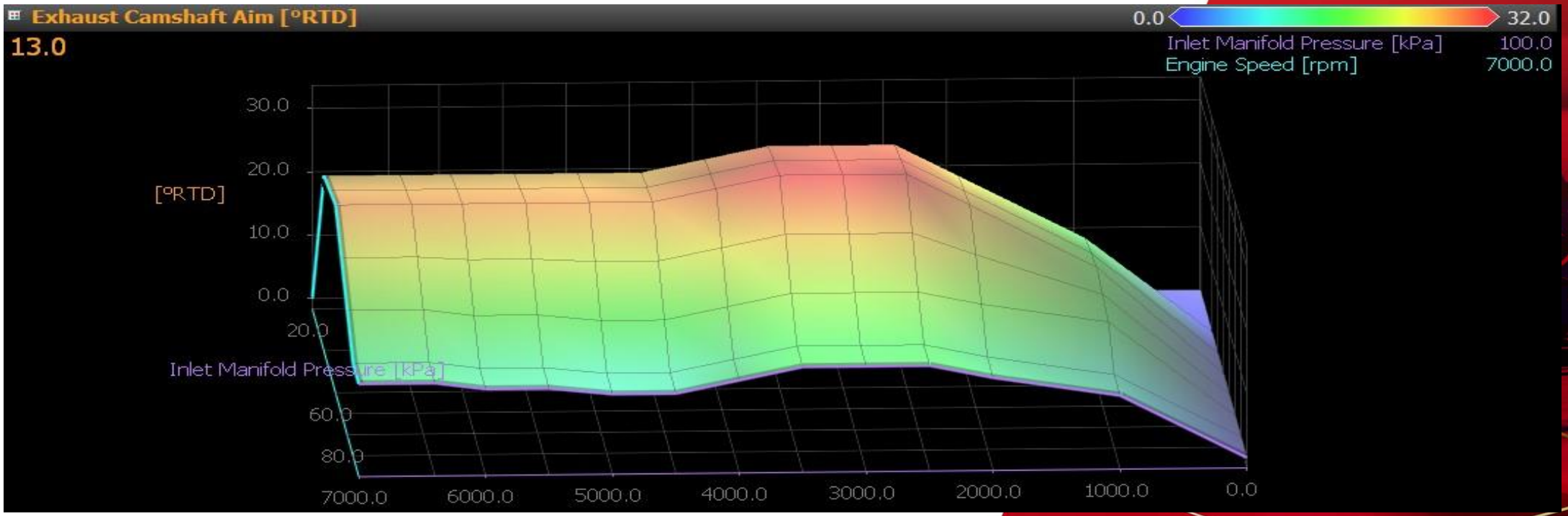
Using the Results in Calibration

Exhaust Camshaft Aim [°RTD] 0.0 – 32.0

Engine Speed [rpm]

Inlet Manifold Pressure [kPa]	0.0	1000.0	2000.0	2500.0	3000.0	3500.0	4000.0	4500.0	5000.0	5500.0	6000.0	6400.0	7000.0
100.0	0.0	10.0	13.0	15.0	15.0	15.0	13.0	11.0	11.0	12.0	12.0	13.0	13.0
90.0	0.0	10.0	13.0	15.0	15.0	15.0	13.0	11.0	11.0	12.0	12.0	13.0	13.0
80.0	0.0	15.0	18.0	20.0	20.0	20.0	18.0	16.0	16.0	17.0	17.0	18.0	18.0
70.0	0.0	16.0	22.5	26.0	26.0	26.0	24.0	22.0	22.0	22.5	22.5	23.0	23.0
60.0	0.0	17.0	27.0	32.0	32.0	32.0	30.0	28.0	28.0	28.0	28.0	28.0	28.0
50.0	0.0	16.0	26.0	31.0	31.0	31.0	29.0	27.0	27.0	27.0	27.0	27.0	27.0
40.0	0.0	15.0	25.0	30.0	30.0	30.0	28.0	26.0	26.0	26.0	26.0	26.0	26.0
20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0



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Using the Results in Calibration

Injector Phasing Should be Considered During Cam Phasing Calibration to Allow Ideal Combustion

Fuel Timing Primary [°BTDC] 200.0 600.0

Engine Speed [rpm]

Inlet Manifold Pressure [kPa]	0.0	500.0	1000.0	1500.0	2000.0	3000.0	4000.0	5000.0	6000.0	7000.0
100.0	290.0	290.0	290.0	295.0	295.0	300.0	300.0	310.0	330.0	330.0
90.0	290.0	290.0	290.0	295.0	295.0	300.0	300.0	310.0	330.0	330.0
80.0	290.0	290.0	290.0	295.0	295.0	300.0	300.0	310.0	330.0	330.0
70.0	285.0	285.0	285.0	290.0	290.0	295.0	295.0	305.0	325.0	325.0
60.0	285.0	285.0	285.0	290.0	290.0	295.0	295.0	305.0	325.0	325.0
50.0	280.0	280.0	280.0	285.0	285.0	290.0	290.0	300.0	320.0	320.0
40.0	280.0	280.0	280.0	285.0	285.0	290.0	290.0	300.0	320.0	320.0
20.0	280.0	280.0	280.0	285.0	285.0	290.0	290.0	300.0	320.0	320.0

Summary

- This demo shows how CAE tools like 1D multi-physics modeling can supplement prototyping and testing to save cost, time, and increase understanding of your engine development.
- This kind of DOE study most certainly can, and likely should, be expanded to include part load and fuel injection, and include outputs parameters such as residuals, emissions, valve to piston clearances, etc.
- Work with your cam profile designer to make sure you are realistic in your expectations and don’t forget about the effects of valvetrain dynamics on performance.
- These tools continue to evolve to be even more accurate, more comprehensive, easier to use, and faster.

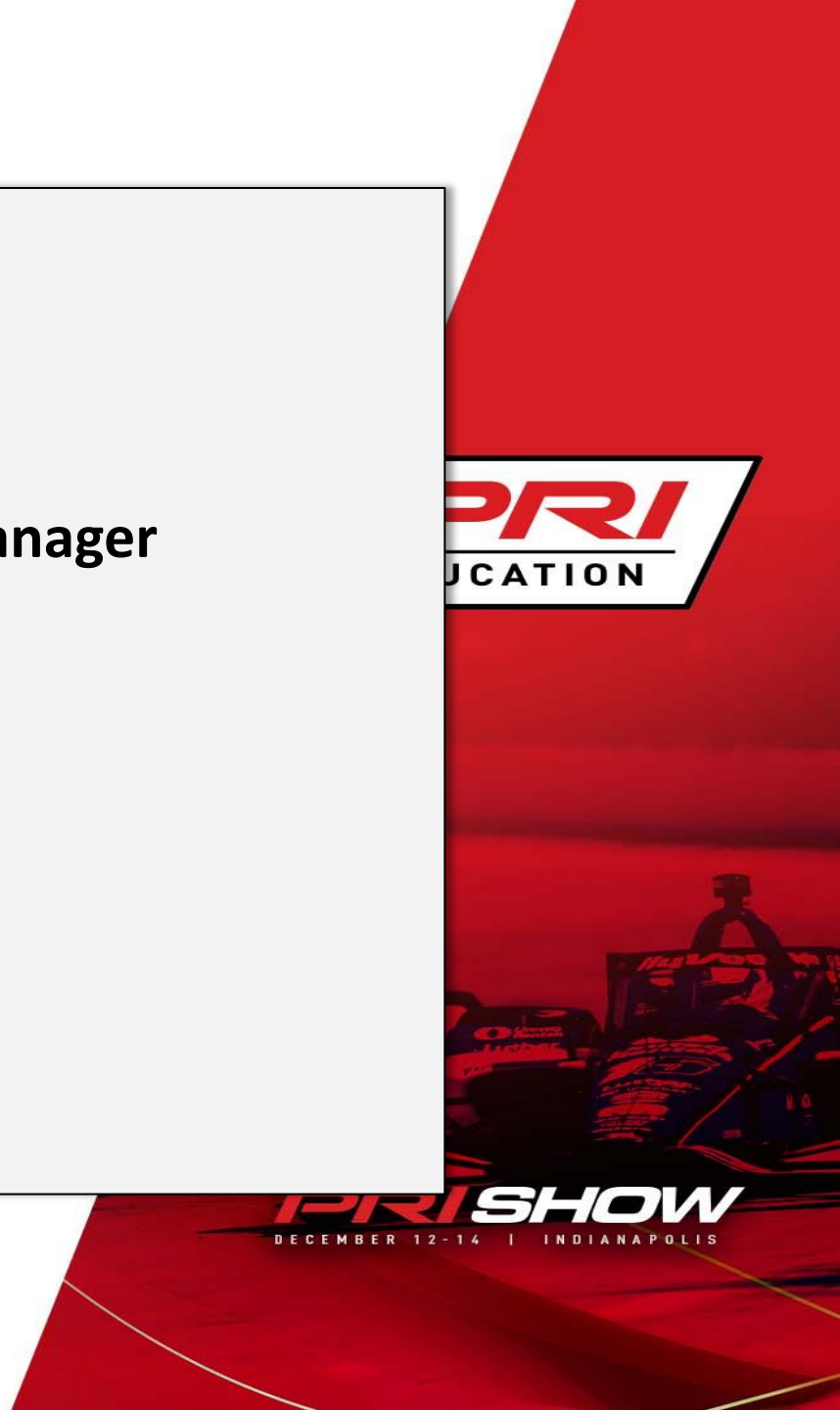
Contacts

- **Dan Agnew, Simulation Engineer**
  Ph: 248-765-1821
  Email: dagnew@automotivecs.com

- **Steven Ruiz, Calibration and Compliance Manager**
  Ph: 310-995-2151
  Email: sruiz@automotivecs.com

- **Rob Simons, President**
  Ph: 949-439-0865
  Email: rsimons@automotivecs.com

- **Web: www.AutomotiveCS.com**



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