AMR 2015

NETL/DOE Award No. DE-EE0005981

High Efficiency VCR Engine with Variable Valve Actuation and new Supercharging Technology

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Project ID ACE092

Overview

Timeline

Start date[1]	April 11, 2013
End date[2]	December 31, 2017
Percent complete	
Time	37%
Budget	33%

Barriers & Targets

Vehicle-Technology Office Multi-Year Program Plan

Relevant Barriers from VT-Office Program Plan:

- Lack of effective engine controls to improve MPG
- Consumer appeal *(MPG + Performance)*

Relevant Targets from VT-Office Program Plan:

- Part-load brake thermal efficiency of 31%
- Over 25% fuel economy improvement – SI Engines
- *(Future R&D: Enhanced alternative fuel capability)*

Budget

Total funding	$ 2,784,127
Government	$ 2,212,469
Contractor share	$ 571,658

Expenditure of Government funds

Year ending 12/31/14 $733,571

Partners

Eaton Corporation
Contributing relevant advanced technology R&D as a cost-share partner

Project Lead

ENVERA LLC

1. Kick-off meeting
2. Includes no-cost time extension

Relevance

Research and Development Focus Areas:

Variable Compression Ratio (VCR)	*Approx. 8.5:1 to 18:1*
Variable Valve Actuation (VVA)	*Atkinson cycle and Supercharging settings*
Advanced Supercharging	*High “launch” torque & low “stand-by” losses*
Systems integration	

Objectives

40% better mileage than V8 powered van or pickup truck without compromising performance. *GMC Sierra 1500 baseline.*

Relevance to the VT-Office Program Plan:

Advanced engine controls are being developed including VCR, VVA and boosting to attain high part-load brake thermal efficiency, and exceed VT-Office Program Plan mileage targets, while concurrently providing power and torque values needed for consumer appeal.

Milestones: Budget Period 1

Description	Milestone/ Go/No-go	Month/year	Status:
Feasibility analysis			
VCR	Milestone	Q2/2013	Complete
Valvetrain	Milestone	Q2/2013	Complete
Boosting			
Preliminary	Milestone	Q2/2013	Complete
GTPower modeling	Go/No-go	Q4/2014	Complete
Base engine specifications	Milestone	Q2/2013	Complete
Crankcase CAD and FEA	Go/No-go	Q3/2015	
Durability testing, PTO	Go/No-go	Q3/2015	
Crankcase castings	Milestone	Q4/2015	
Crankcase Machining	Milestone	Q1/2016	
Engine assembly	Go/No-go	Q1/2016	

Technological Approach

Atkinson Cycle for high efficiency:

The VCR engine employs the Atkinson cycle to attain high efficiency. The intake valves are closed late, and mechanical compression ratio is increased up to 18:1 during part-load conditions. The Atkinson cycle will be used most of the time to attain high mileage values.

Boosted Otto Cycle for high power:

The VCR engine is supercharged to attain 360 hp and V8-like driving responsiveness. Mechanical compression ratio is reduced to ~8.5 to prevent engine detonation. Valve timing and duration is adjusted for maximum torque at low engine speeds.

The supercharger is clutched out most of the time to maximize fuel economy.

Development Strategy

Phase 1
Feasibility analysis, including:

• Variable compression ratio, VCR	Envera
• Variable valve actuation, VVA	Envera/Eaton
• Advanced boosting feasibility	Envera/Eaton
• GTPower computer modeling	Envera

Phase 2
Engine design / analysis / build

• VCR crankcase	Envera
• VVA, cylinder head, pressure sensing	Eaton
• Supercharging	Eaton
• Engine assembly	Envera

Phase 3
Engine Calibration / Milestone Testing

• ECU / Engine testing and development	
• Mechanical systems validation assessment/reporting	Envera/Eaton
• GT-Power / GT-Suite: BSFC & MPG projections	EngSim/Envera
• “Value engineering” as needed for achieving Targets	Envera

Accomplishments - GTPower

GTPower Projections

Power, torque and BSFC values were projected using GTPower modeling software. EngSim Corporation conducted the GTPower modeling. Envera and Eaton provided input data for the assessment.

Major findings of the study include:

- An Eaton TVS supercharger with high-speed clutch will provide power and torque values needed for the NETL/DOE program.
  440 Nm @ 2500 rpm
- Part load efficiency is projected to be within reach of the program target value. *234 g/kWh at 100 Nm @2000 rpm vs. target of 230 g/kWh*
- Best part load efficiency occurs with moderate exhaust gas residual values. *Unexpected finding: Best results with only 12% dilution.*

Accomplishments - GTPower

GTPower Part-load BSFC Projections – 5.25 bar BMEP, 2000 rpm

		BMEP, Bar	Torque, Nm	BSFC, g/kWh
NETL Program Target			100	230
Envera VCR Projections		5.25	100	234
Toyota	*SAE 2009-01-1061**	5.25	75.1	228
Ford	*AMR June 19, 2014**	5.25	94.5	~245
Chrysler	*AMR June 19, 2014**	5.25	100	~250

Power and Torque Projections

		Displacement, L	Power, kW	kW/L
NETL Program Target		2.4	270**	112.5
Envera VCR Projections		2.4	283	118
Toyota	*SAE 2009-01-1061**	1.7978	73 @ 5200 rpm	40.6
Ford	*AMR June 19, 2014**	2.260	181 @ 6000 rpm	80
Chrysler	*AMR June 19, 2014**	2.4	129 @ 5200 rpm	53.5

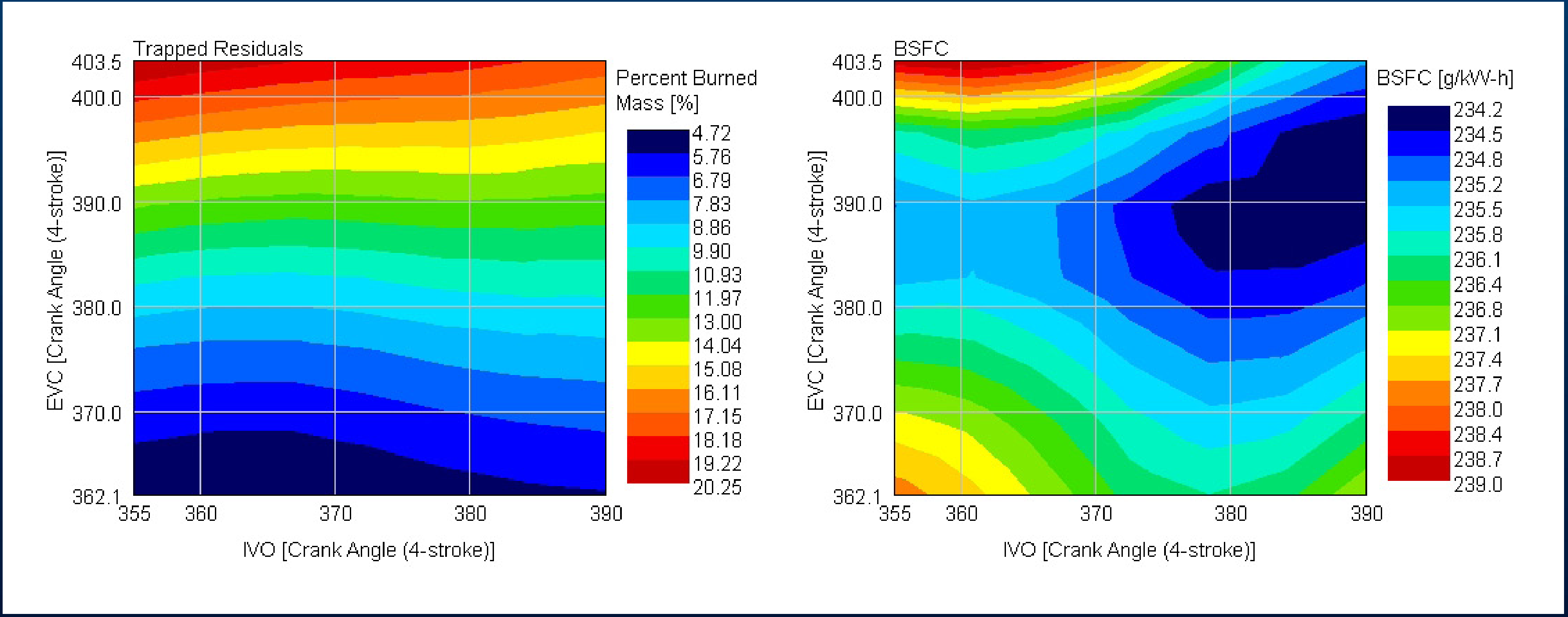
* See backup slide for references

**Minimum contract obligation: 210 kW

Accomplishments - GTPower

Near-conventional EGR dilution values provide best results

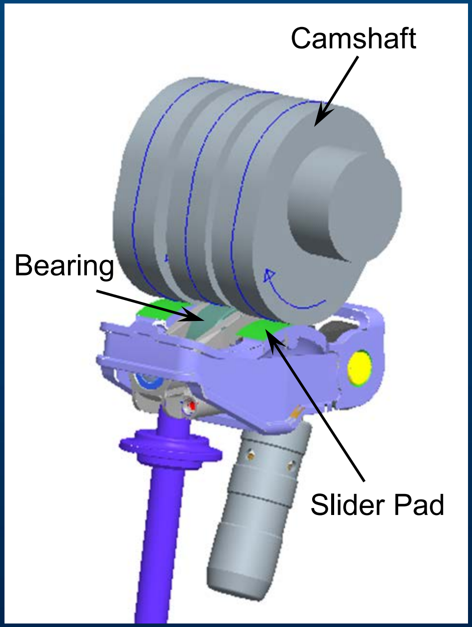
Best part load efficiency occurred with an internal EGR dilution value of only 12%. This finding indicates that the Atkinson cycle with moderate dilution values may provide an easier pathway to attaining high efficiency than low temperature combustion an extreme-dilution approaches.



100 Nm, 2000 rpm, 18:1 CR

Accomplishments – VVA

LIVC Envera Application Analysis



Eaton's Variable Valve Actuation Mechanism (VVA):

- Eaton's VVA technology was introduced in MY 2014 GM 2.5L 4-cylinder engines.

  The VVA provides an additional early intake valve closing (EIVC) cam setting.

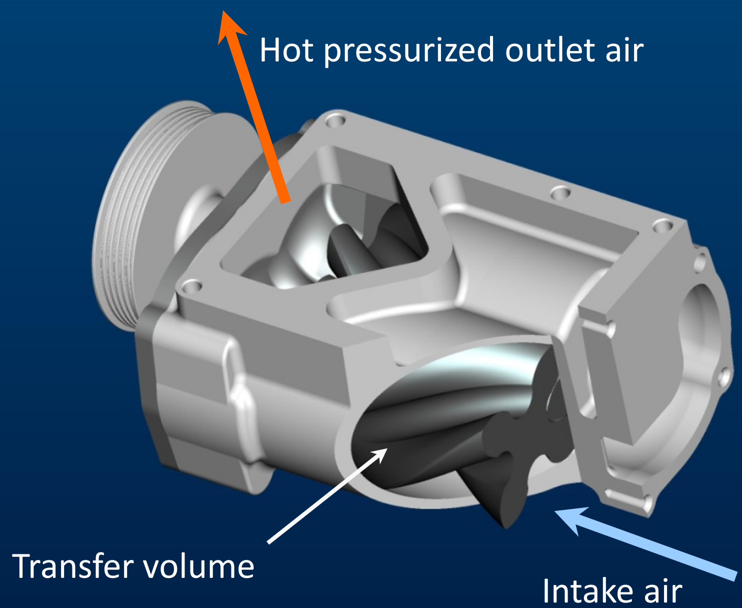
- In the Envera engine, late intake valve closing (LIVC) is used to achieve the Atkinson cycle.

- Analysis by Eaton of the VVA mechanism indicates that Envera cam settings for efficiency, power and torque are attainable with the Eaton VVA mechanism.

Accomplishments - Supercharging

Supercharging

The following slides describe new cooling technology for a supercharger. The cooling technology enables the pressure ratio of the supercharger to be significantly increased. This is the first public disclosure of the technology.



Conventional supercharger:

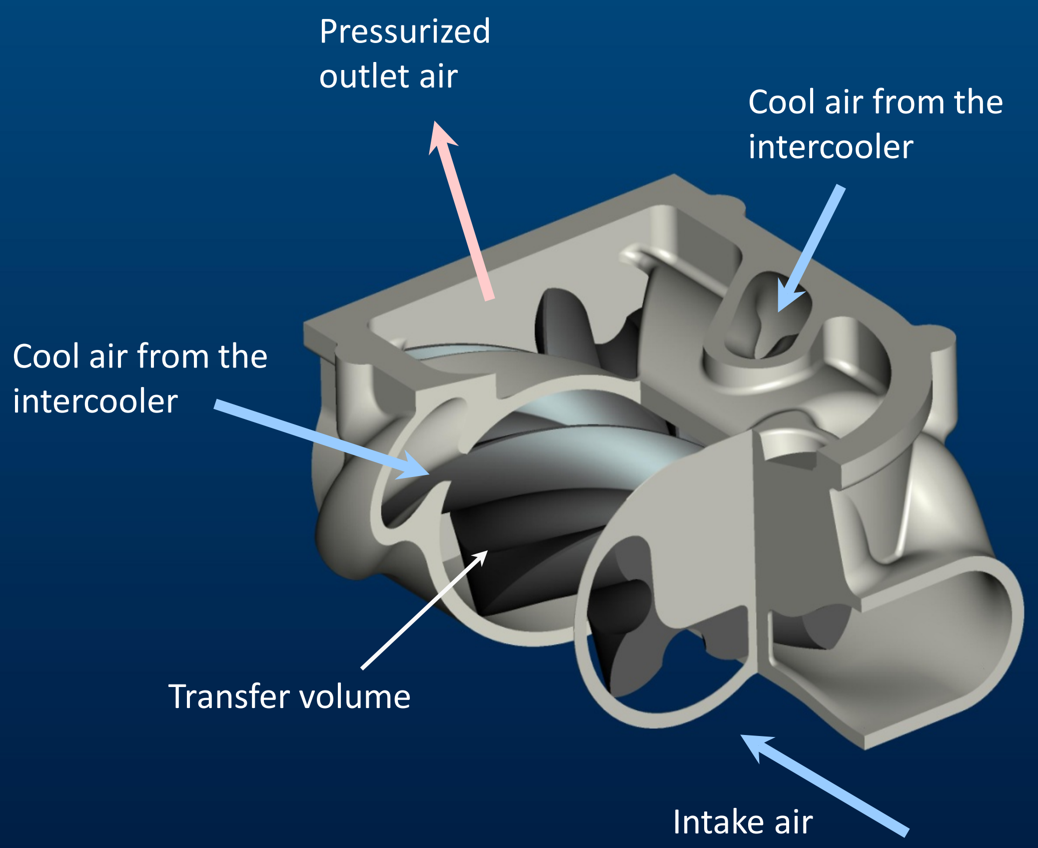
In the position shown, the transfer volume is fully enclosed and contains air at inlet pressure.

As the rotor turns clockwise, the transfer volume opens into the high-pressure outlet manifold. When this occurs, the hot outlet gas blows back into the transfer volume.

The rotors continue to turn pushing the air into the outlet manifold.

Accomplishments - Supercharging

Supercharger with new cooling technology



Eaton TVS 1320 Rotor set

Cooled supercharger:

With the new cooled supercharger, the transfer volume is filled with cool air from the intercooler, instead of hot blow-back air from the outlet manifold. The transfer volume is pressurized with cool air from the intercooler instead of hot blow-back air.

With the new cooling technology, the supercharger can deliver higher pressures without over heating.

Patent pending: Envera LLC

Accomplishments - Supercharging

Supercharging the Envera 2.4L VCR Engine

- Supercharging provides a relatively “flat” torque curve, and largely eliminates “turbo lag”. These qualities are beneficial for aggressively downsized engines.
- GTPower projections of 440 Nm torque at 2500 rpm were with a conventional supercharger pressure ratio of 2.5.
- The new supercharging technology is expected to have a significantly higher pressure ratio capability. Testing is needed to quantify the PR capability.
- A clutch is used to disengage the supercharger during most driving conditions. The supercharger is clutched out to minimize “standby losses” and maximize fuel economy.

Accomplishments - VCR

VCR Mechanism Assessment - *Evaluation Findings*

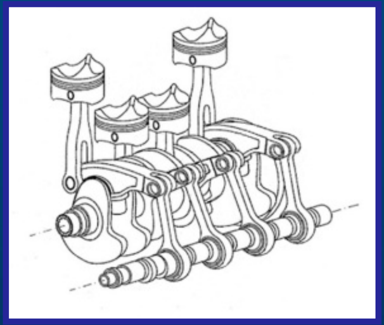
During the 2014 AMR, reviewers recommended Envera assess other VCR concepts. Review criteria are provided in the backup slides. Evaluation findings are as follows:

VCR Pistons and Connecting rods	The CR range is probably not large enough for spark-ignition gasoline engines. FEV's con rod has a 1.42 mm range, and Honda's VCR piston has a 3.5 mm range.* 7.0 mm is desired for an 8.7 to 18:1 CR range having a bore to stroke ratio under 0.95. High reciprocating mass values is a major concern, especially for VCR mechanisms designed for 150 to 200 hp/L loads. Internal engine friction loss is a concern for the Honda piston.*
MCE-5 approach	Cost of all-new technology & engine factories is a significant concern. Existing manufacturing investments / factories can't easily be leveraged. BSFC data indicates friction losses may be somewhat higher.

Accomplishments - VCR

VCR Mechanism Assessment - *Evaluation Findings*

Nissan / VW



Interesting concept.

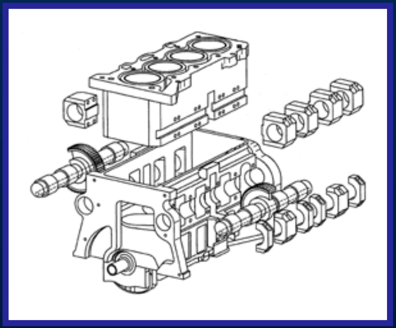
Robustness at 150 to 200 hp/L is a concern. Will the added mass needed for attaining high power levels compromise the design? Complex RD&D.

Envera

Robust: No piston, main bearing or connecting rod bearing failures in an Envera VCR engine.

Engine length is increased.

Toyota

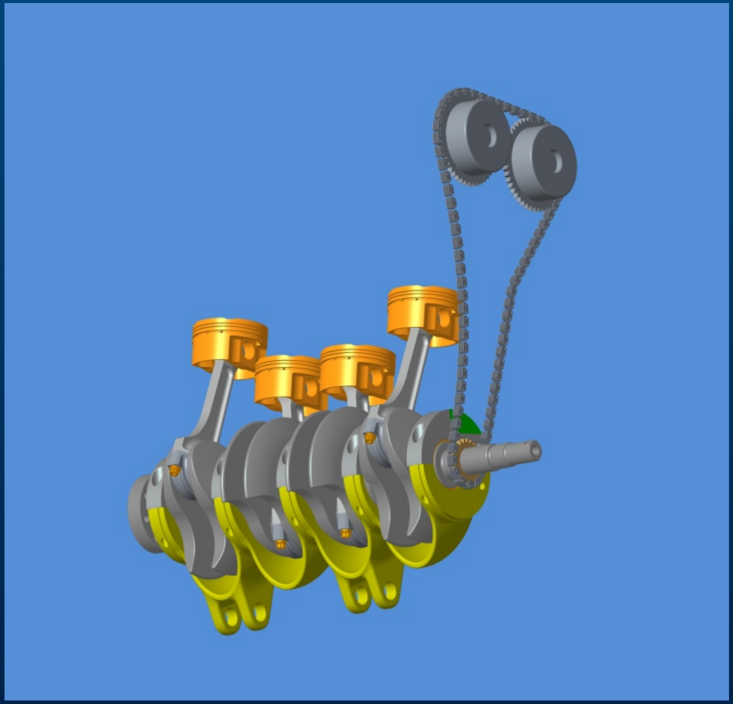


Fail-safe cranktrain: Mainstream technology is used. Low friction values a plus.

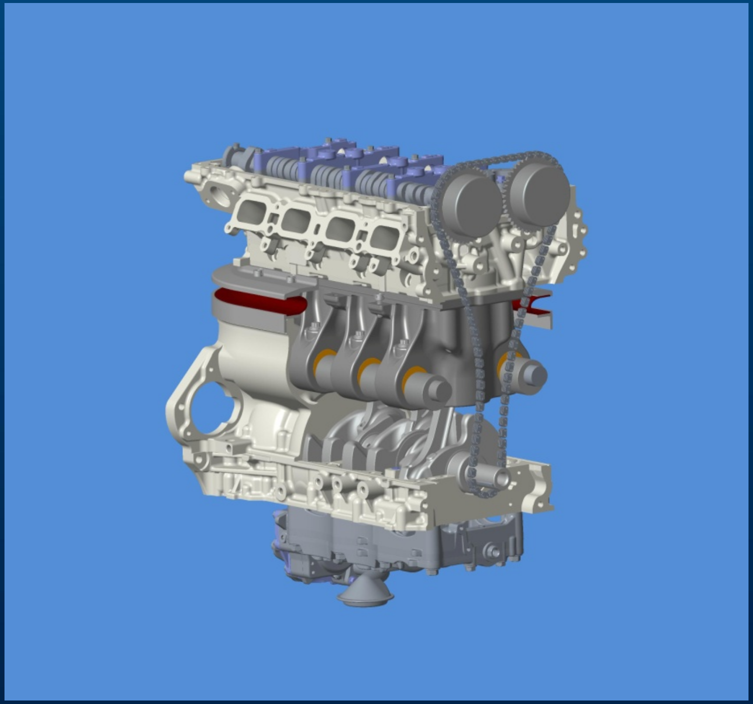
The cylinder jug and crankcase have too many bearing caps, that compromise robustness, cost and size.

Accomplishments - VCR

Two Envera VCR Options



VCR 1.0 - Primary R&D Pathway



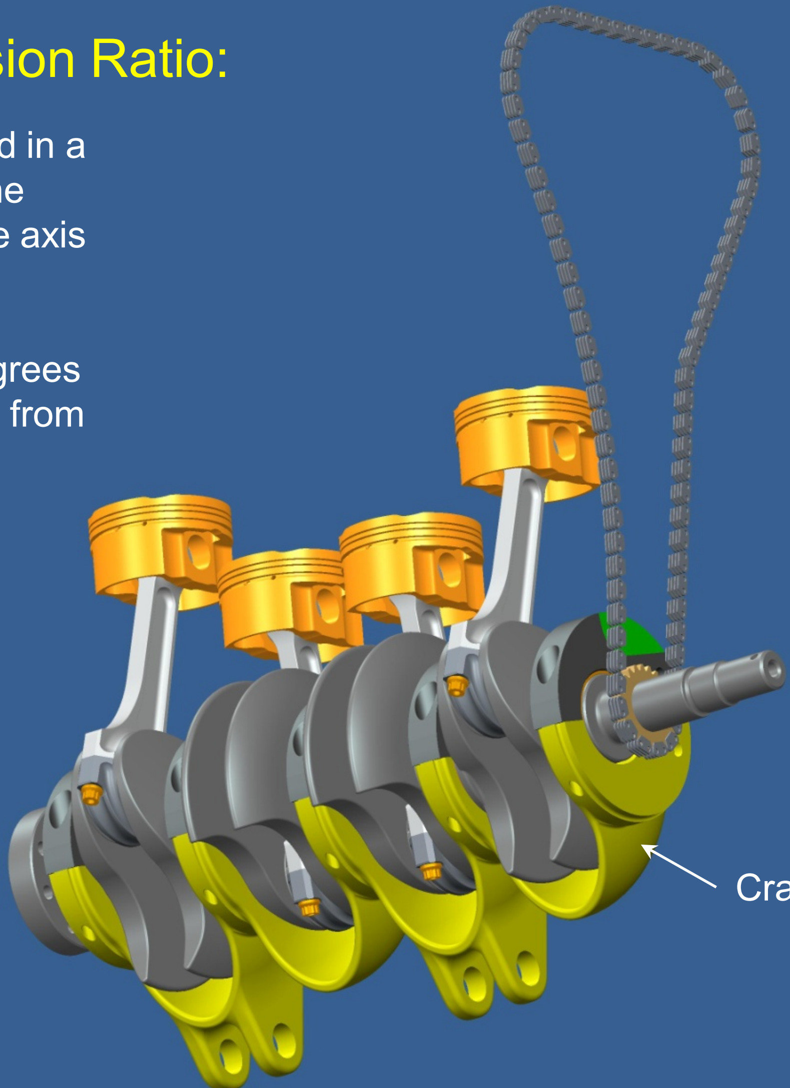
VCR 2.0 – Under Consideration

VCR 1.0

Variable Compression Ratio:

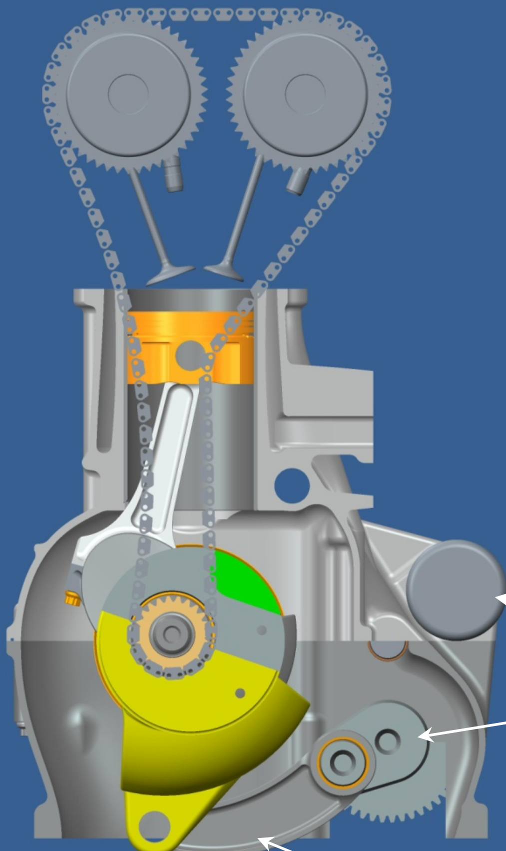
The crankshaft is mounted in a "crankshaft cradle" with the crankshaft axis and cradle axis offset by 13.5 mm.

Pivoting the cradle 32 degrees adjusts compression ratio from 8.5:1 to 18.6:1.

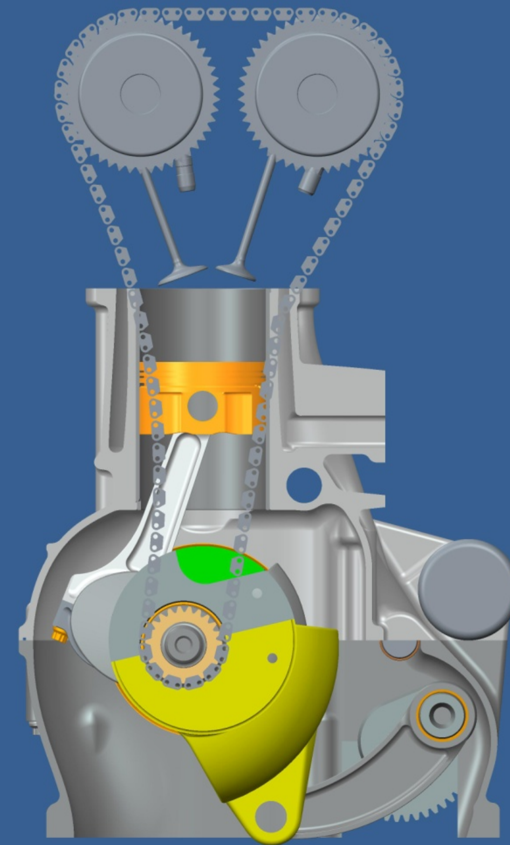


VCR 1.0

An electric motor rotates a control shaft to adjust CR. Steel links connect the control shaft and cradle.



High compression ratio

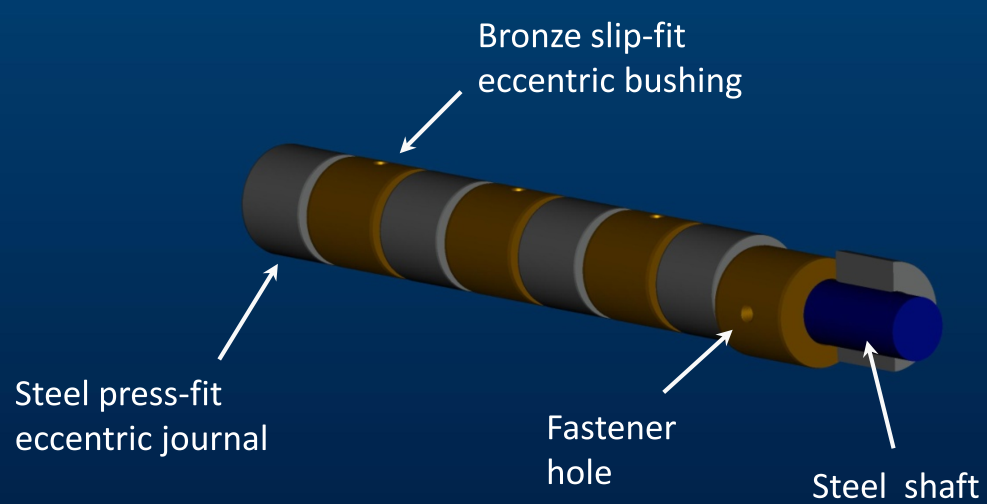


Low compression ratio

VCR 2.0

ENVERA's upgrade of the Toyota VCR

This is a first public disclosure of Envera's upgrade to the Toyota VCR system. The new Envera technology includes preassembled control shafts. With the preassembled control shafts, removable bearing caps are no longer needed on the crankcase and cylinder jug. *Lower cost and higher strength.*



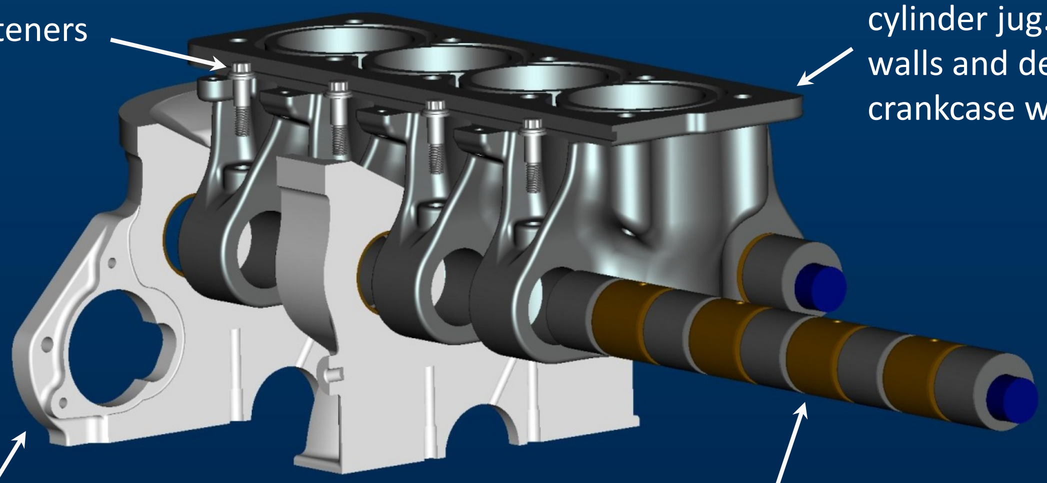
Control shaft assembly:

The control shaft is assembled by press fitting a steel eccentric onto the steel shaft, then sliding on an eccentric bronze bushing and then pressing on another steel eccentric until the shaft is fully assembled.

VCR 2.0

Envera VCR 2.0 engine assembly

The preassembled control shaft slides into bearing sockets formed in the crankcase and cylinder jug. Fasteners are installed in the cylinder jug to lock the eccentric bushings in place in the cylinder jug. The crankcase is shown in partial sectional view.



Envera VCR 2.0

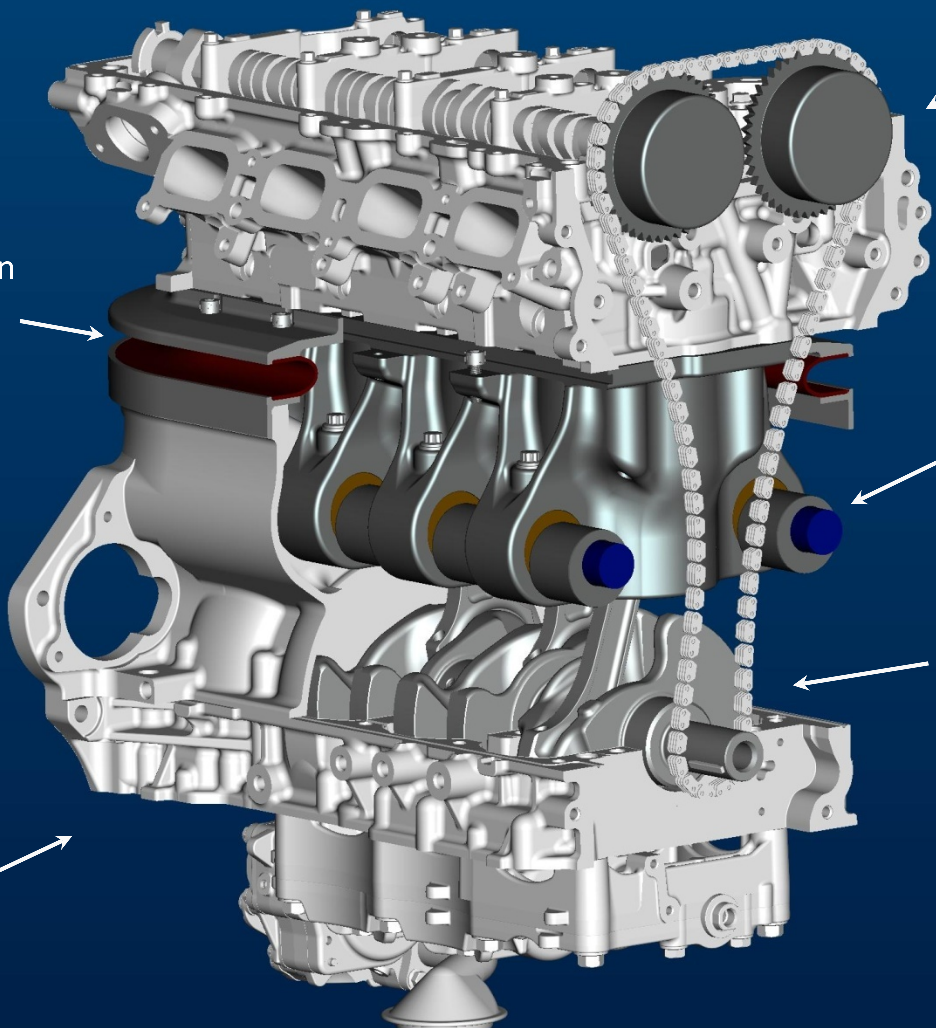
Nitrile gasket:

The Nitrile curtain is bonded to steel flanges. The bond is stronger than the curtain.

Affordable: Low-volume production quote of $42 each on order of 10,000 pieces.

~Stock engine length:

Stock bedplate and crankshaft. Stock starter motor and bell housing flange.



Stock cylinder head with Eaton VVL & Atkinson cycle cams

Rotating the control shafts adjusts compression ratio from 8.5:1 to 18:1

The VCR mechanism doesn’t add mass to the cranktrain. High engine speeds and loads attainable with conventional and reliable cranktrain technology.

Collaboration

Collaboration:

Eaton is currently collaborating with ENVERA on the project as a subcontractor. Eaton is contributing relevant advanced technology R&D as a cost-share partner. Eaton R&D development areas include the VVA and boosting.

Future Directions:

A key area where collaboration will be pursued in the future is the engine management system. ENVERA is currently discussing collaboration opportunities in this and other areas.

We welcome interest from the OEs, component manufacturers, and other R&D organizations.

Patent references

Companies sighting Envera / Mendler patents – Partial listing:

BorgWarner	Caterpillar
Cummins	Daimler Chrysler
DENSO	FEV
Ford	GE
GM	Hitachi
Honda	INA
Izuzu	MTU
Nissan	Pinnacle / Cleeves
Polaris	Suzuki
Toyota	Visteon
VW	Yamaha

There's interest in what we're doing

Previous Reviewer Comments

Engine dynamometer testing instead of vehicle-level testing

A number of reviewers commented on the “daunting” challenges of system integration for both engine optimization and vehicle testing.

In view of reviewer comments, the program plan has been modified to eliminate in-vehicle testing, and instead focus resource on engine dynamometer development. GT-Suite will now be used to project vehicle mileage potential instead of in-vehicle testing. The program timeline has also been extended to provide additional time for development.

VCR Mechanism assessment

A number of reviewers recommended that other VCR mechanisms be evaluated. A review was conducted, and is presented in this briefing.

Proposed Future Work: 2015 - Q1 2016

Variable Compression ratio:

- Durability testing of the VCR Power take-off coupling
- VCR crankcase design completed with finite element analysis
- VCR 1.0 or VCR 2.0 down selection
- Crankcase casting and machining
- Engine assembly and inspection

Variable Valve Actuation:

- VVA fully integrated into cylinder head with optimized camshafts

Supercharging:

- Final assessment and go/no-go of supercharger cooling technology
- Supercharger & intake system procurement and installation

Engine management

- Engine management system selection & advanced ECU development

Summary

Summary:

- GTPower projections indicate that part load efficiency, low-speed torque and high speed power targets are achievable. Projected values are:
  - 234 g/kWh 5.25 bar bmep @ 2000 rpm *100 Nm load point*
  - 440 Nm @ 2500 rpm
  - 118 kW/L @ 6000 rpm

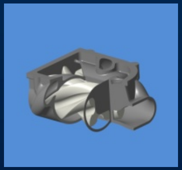
- New supercharging technology is presented that holds promise for significantly increasing supercharger pressure ratio.

  The higher pressure ratios will enhance the performance of aggressively downsized engines both with and without VCR.

- Design objective: VCR variant of a current production engine.

  An all new VCR mechanism is presented. The new mechanism has a large CR range (8.5 to 18:1), a 200 kW/L load capacity, and a near-stock engine length.

Thank you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Technical Backup Slides

Accomplishments - VCR

VCR Mechanism Review - *Evaluation Criteria*

During the 2014 AMR, reviewers recommended Envera assess other VCR concepts. OEs are considering a number of VCR mechanism options. A consensus has not been reached on which mechanism is best. While many factors need to be considered in such a review, Envera has identified seven key evaluation criteria:

1. Robustness at 150 to 200 HP/L: The VCR mechanism must be robust enough to support high power levels that can be expected in 5 to 10 years.

2. CR Range of at least 9.5 to 15, and preferably 8.5 to 18: Higher boost pressures in the future will necessitate lower CR values, and the Atkinson Cycle has an ideal “expansion ratio” of about 1:18 at light engine load.

3. Typical engine speed and vibration levels: VCR mechanisms can add reciprocating mass to the engine, especially when designed to accommodate 150 to 200 hp/L power levels. The increased inertial forces can increase vibration and and/or necessitate a reduction in engine speed. Increased inertial forces can also lead to larger bearing sizes and increased internal friction losses.

Accomplishments - VCR

VCR Mechanism Review - *Evaluation Criteria*

4. Engine Length: When replacing a V6 or V8 engine with an in-line VCR 4-cylinder engine, engine length needs to closely match stock for passenger cars, but may be longer for light-duty trucks which typically have longer engine bays. Engine width is less of a concern unless the in-line VCR engine is wider than the V engine it replaces.
5. Friction: Internal engine friction losses must be minimized. VCR mechanisms that don't increase internal engine friction losses are at an advantage.
6. VCR Control: The VCR needs to be controlled by the central engine management system to accommodate a broad range of operating and environmental conditions. A fully variable VCR is desirable for both maximizing efficiency and for transient engine performance.
7. Cost: The ideal scenario from a manufacturers perspective is a VCR variant of a current production engine, with minimum changes to the production line. The manufacturer does not want to abandon invested costs in manufacturing plants. Objectively the new VCR technology can be integrated into the existing production facility. From a corporate perspective, the question is "Can implementation expand economically across multiple product lines."

Backup Slide

Reference Engine Data

Toyota

Kawamoto, N., et al. Toyota Motor Company: Development of New 1.8-Liter Engine for Hybrid Vehicles, SAE Paper No. 2009-01-1061, pub 2009.

Table 1 and Figure 5.

Ford

Weaver, C., Ford Research and Advanced Engineering: Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development, DOE Annual Merit Review, Project ID ACE065, pub June 19, 2014.

Attributes and Architecture, page 7
Fuel consumption, page 13. Ford data interpolated by Envera.

FEV

Spectrum Issue 52, May 2014.
VCR range in millimeters, page 4

Backup Slide

Reference Engine Data, Continued

Chrysler

Reese, R. Chrysler: A MultiAir / MultiFuel Approach to Enhancing Engine System Efficiency, DOE Annual Merit Review, Project ID ACE062, pub June 19, 2014.

Results – Performance, page 6
Engine Efficiency, BSFC, page 9

MCE-5

MCE-5 VCRi: Pushing back the fuel consumption reduction limits
http://www.mce-5.com/english/pop_up/resultats_cles/Key_results.html

BSFC map, page 4

Honda

Kadota, M., et al: Advanced Control System of a Variable Compression Ratio (VCR) Engine with Dual Piston Mechanism, SAE 2009-01-1063.

Figure 2	Undersized piston pin bosses for the intake stroke
Figure 17	Mechanical friction losses equal in size to compression ratio benefits?

Approach

Downsizing with VCR:

- Engine downsizing is viewed by US and foreign automobile manufacturers as one of the best options for improving fuel economy.
- While this strategy has already demonstrated a degree of success, downsizing and fuel economy gains are currently limited.
- With new variable compression ratio, valve actuation and supercharging technologies however, the degree of engine downsizing and fuel economy improvement can be greatly increased.
- A small variable compression ratio (VCR) engine has the potential to return significantly higher vehicle fuel economy while also providing high power.

Approach

Downsizing with VCR:

- To meet torque and power requirements, a smaller engine needs to do more work per stroke.
- This is typically accomplished by boosting the incoming charge with either a turbo or supercharger so that more energy is present in the cylinder per stroke to do the work.
- With current production engines the degree of engine boosting (which correlates to downsizing) is limited by detonation (combustion knock) at high boost levels.

Approach

Downsizing with VCR:

- VCR technology eliminates the limitation of engine knock at high load levels by reducing compression ratio to ~8.5:1 (or whatever level is appropriate) when high boost pressures are needed.

- By reducing the compression ratio during high load demand periods there is increased volume in the cylinder at top dead center (TDC) which allows more charge (or energy) to enter the cylinder without increasing the peak pressure. Cylinder pressure is thus kept below the level at which the engine would begin to knock.

- When loads on the engine are low the compression ratio can be raised (to as much as 18:1) providing high engine efficiency using the Atkinson Cycle.

- High fuel economy values will be achieved in pickup trucks, utility vans and other larger vehicles by using a small 4-cylinder engine that operates under the high-efficiency Atkinson Cycle most of the time. High torque and power levels will be achieved on demand using advanced boosting, VCR and variable valve actuation.

Technical Backup Slide – VVA+VCR

Combining Variable Valve Actuation and VCR:

- VCR is unique in its ability to provide the correct compression ratio when needed.
- Unlike VVA systems, the Envera VCR mechanism adjusts the physical size of the combustion chamber and is able to provide the ideal compression ratio settings at all power levels.
- The best solution is to combine VCR and VVA.
- With this approach much higher efficiencies are attained at low load by increasing the mechanical compression ratio with VCR, reducing pumping losses with VVA, and operating the engine using the high-efficiency Atkinson cycle.

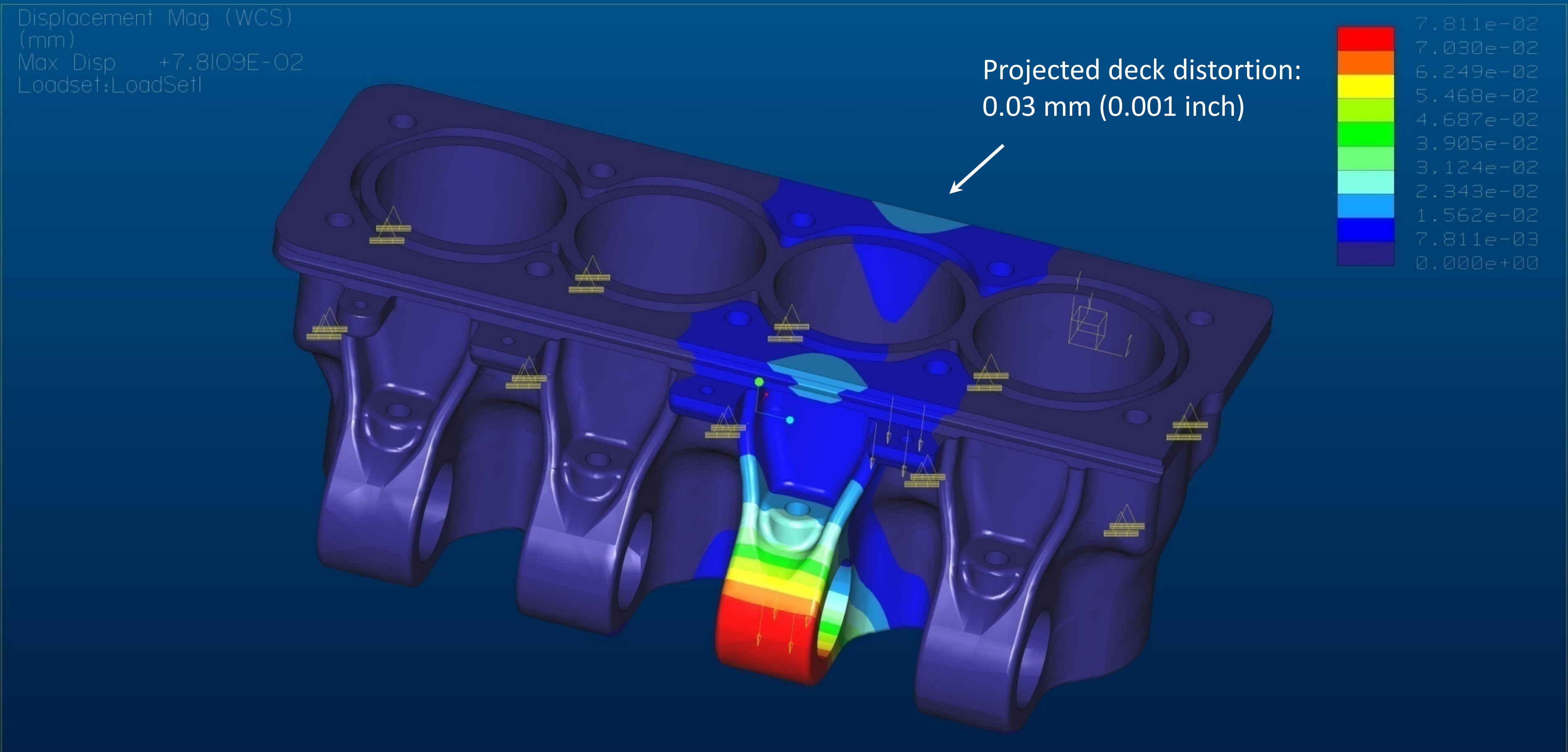
Technical Backup Slide – VVA+VCR

Combining Variable Valve Actuation and VCR:

- Attaining high power output is also important for improving fuel economy, because increased power output permits large engines to be replaced with smaller engines that return higher efficiency under most driving conditions.

- High power output levels are attained by boosting the engine, adjusting the valve settings to trap as much intake air as possible in the engine cylinders, and reducing compression ratio with the VCR to avoid detonation.

Finite Element Analysis



FEA analysis of the preliminary jug design

Use of iron provides a stiff deck and sturdy cylinder walls for highly boosted engines.

Use of aluminum with cast in place liners under development.