AMR 2016
NETL/DOE Award No. DE-EE0005981

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

June 9, 2016

Charles Mendler, ENVERA	PD/PI
David Genise, EATON	Program Manager & PI
Austin Zurface, EATON	Valvetrain

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

ENVERA LLC
Mill Valley, California
Tel. 415 381-0560

Project ID
ACE092

Overview

Timeline

Start date	April 11, 2013
End date	September 30, 2017
Percent complete[1]	
Time	62%
Budget	52%

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 12/31/15 $ 1,085,483

Partners

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

Project Lead

ENVERA LLC

1. Thru December 31, 2015

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.*

<u>Relevance to the VT-Office Program Plan</u>:

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	Complete
Durability testing, PTO	Go/No-go	Q2/2016	
Crankcase castings	Milestone	Q4/2015	Complete
Crankcase Machining	Milestone	Q2/2016	
Engine assembly	Go/No-go	Q2/2016	

Technological Approach

Approach for attaining high mileage

- Combine aggressive engine down-sizing with high-efficiency Atkinson cycle technology.

Approach for maximizing power and torque, e.g., Enabling technologies for aggressive engine down-sizing

- VCR
- Cam profile switching
- Advanced boosting

Compression Ratio Values

High CR needed for Atkinson Cycle efficiency

Low CR needed for multiple reasons:

Minimum compression ratio 8.2:1

A low compression ratio is needed for:

- Preventing detonation (knock)
- Limiting the rate of pressure rise to minimize combustion harshness
- Reducing turbocharger lag (Time-to-torque)
- Increasing boost pressure and engine torque at low engine rpm

Introduction

Approach for attaining low criteria emissions

- Lambda 1 fuel/air mixtures used with 3-way catalytic converter technology for low HC, CO and NOx emissions.

Proven strategies to be employed.
Gasoline & alternative spark-ignition fuels.

AMR Presentations 2014 & 2015	Chrysler*	Ford**	Envera
Light load BSFC 5.25 bar bmep @ 2000 rpm	~250	~245	234 est.
Power Maximum kW/L	56.3	80	118 est.

*AMR 2014/15: Results - Performance, pg. 6. Engine Efficiency, bsfc, pg. 9
**AMR 2014/15: Attributes and Architecture, pg. 7. Fuel consumption, pg. 13. Ford data interpolated by Envera.

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

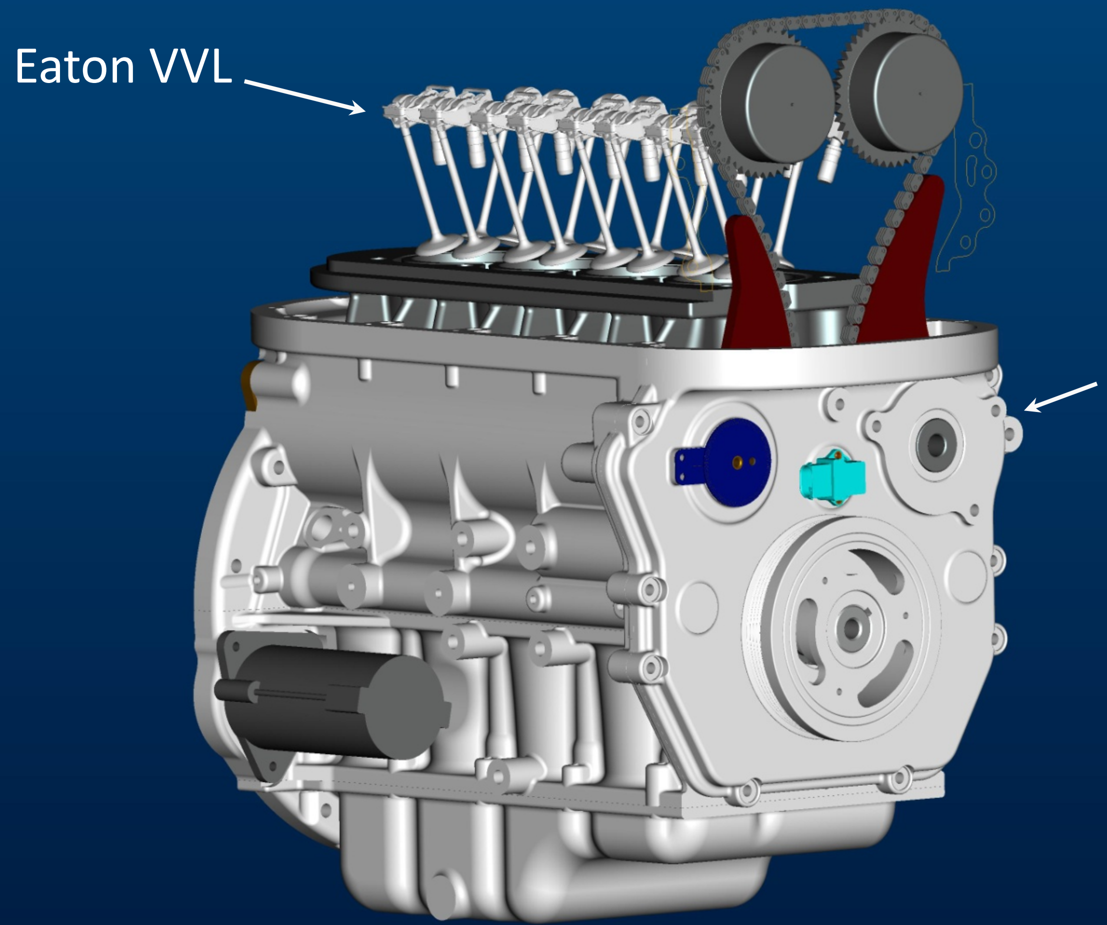
Phase 3
Engine Calibration / Milestone Testing

- ECU / Engine testing and development
- Mechanical systems validation assessment / reporting
- GT-Power / GT-Suite: BSFC & MPG projections
- "Value engineering" as needed for achieving Targets

Envera VCR Engine 2.0

2.4L Engine Build

Envera VCR 2.0



VCR actuator mounting pad, position sensor, and optional dial.

~Stock engine length and width.

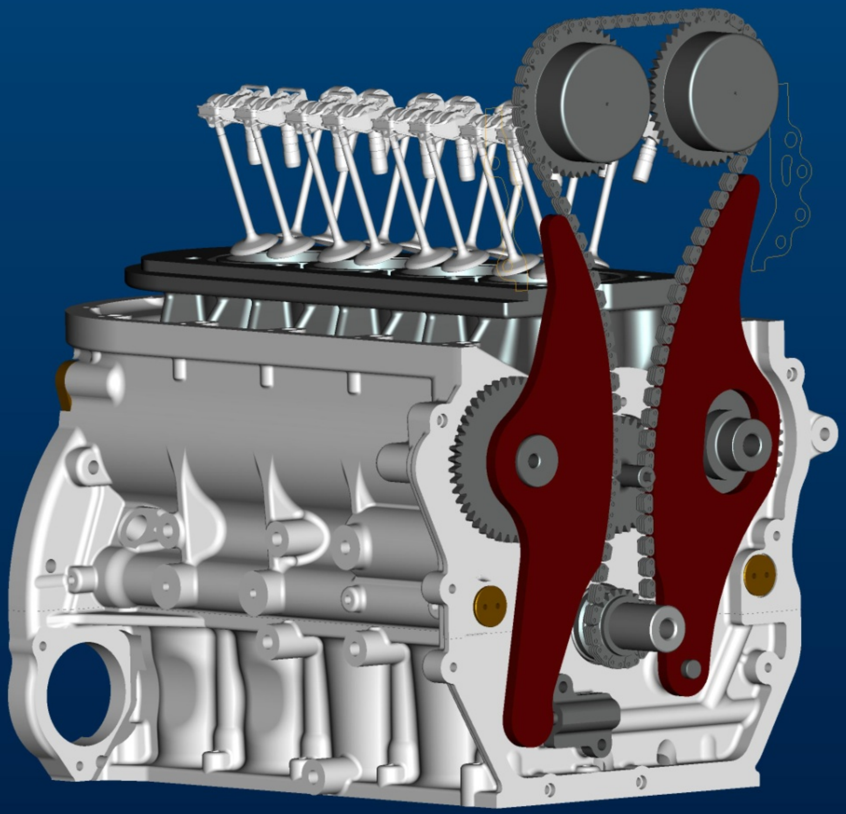
Valve chain, front pulley and transmission can retain stock location.

Much narrower than V6.

Scheduled build completion date for all parts shown: Mid 2016

Envera VCR 2.0

High CR



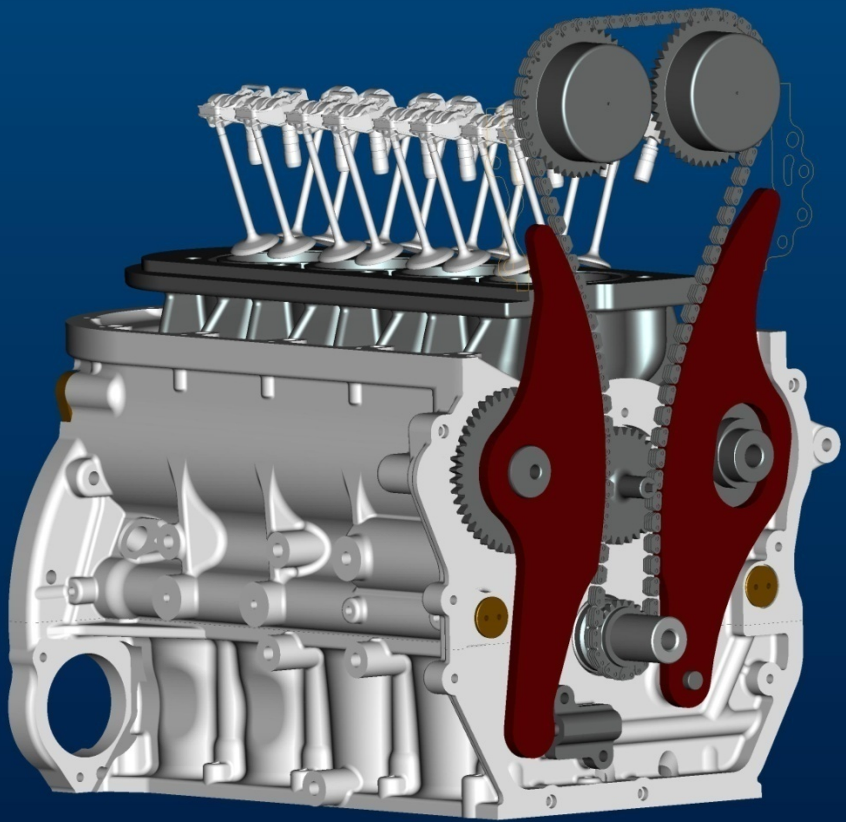
The control shafts position the chain guides

The cam timing can change with change of CR. OE options include:

- Advance of timing
- Retard of timing or
- No change at all.

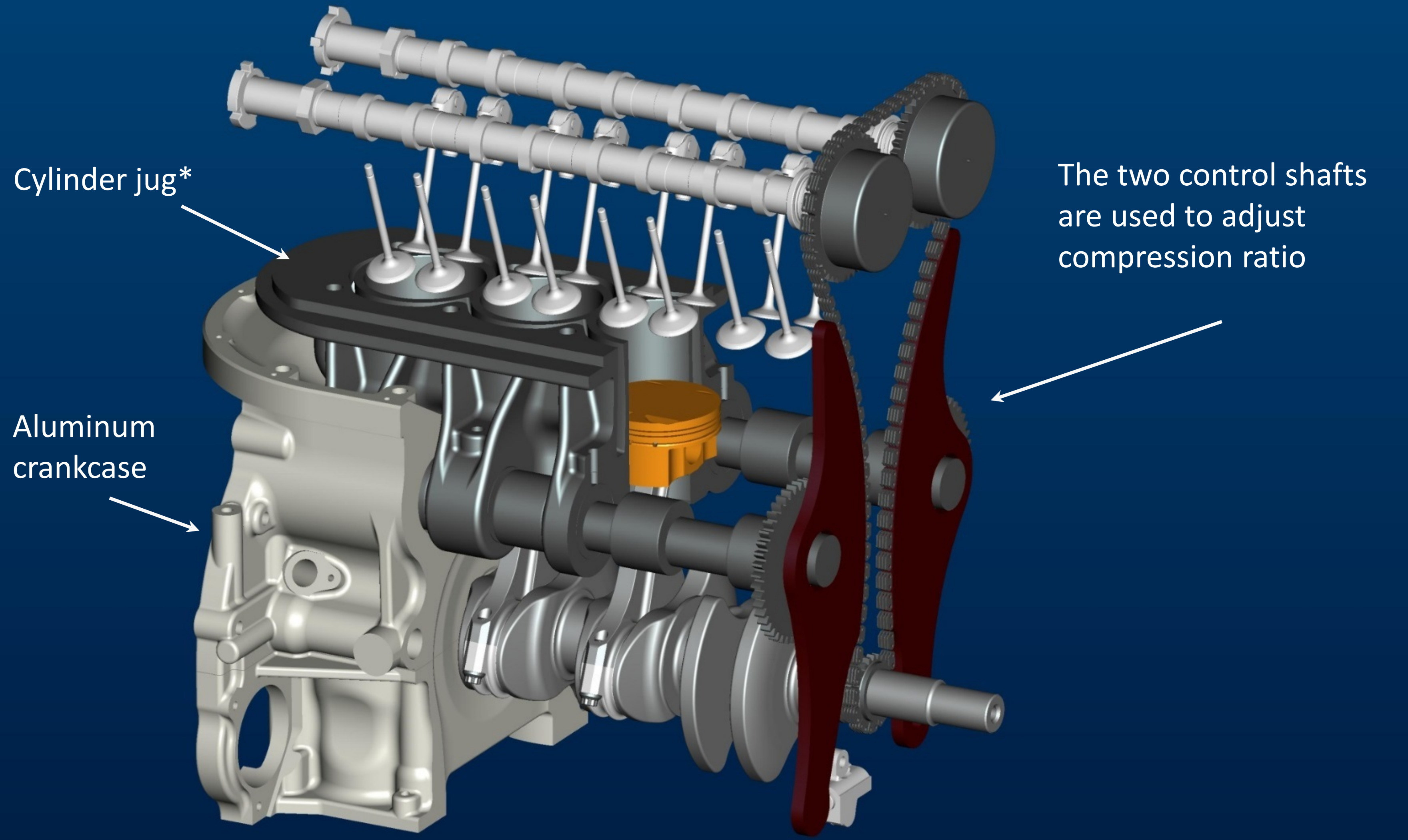
Envera VCR 2.0

Low CR



Camshaft chain drive friction is about the same as non-VCR engines.

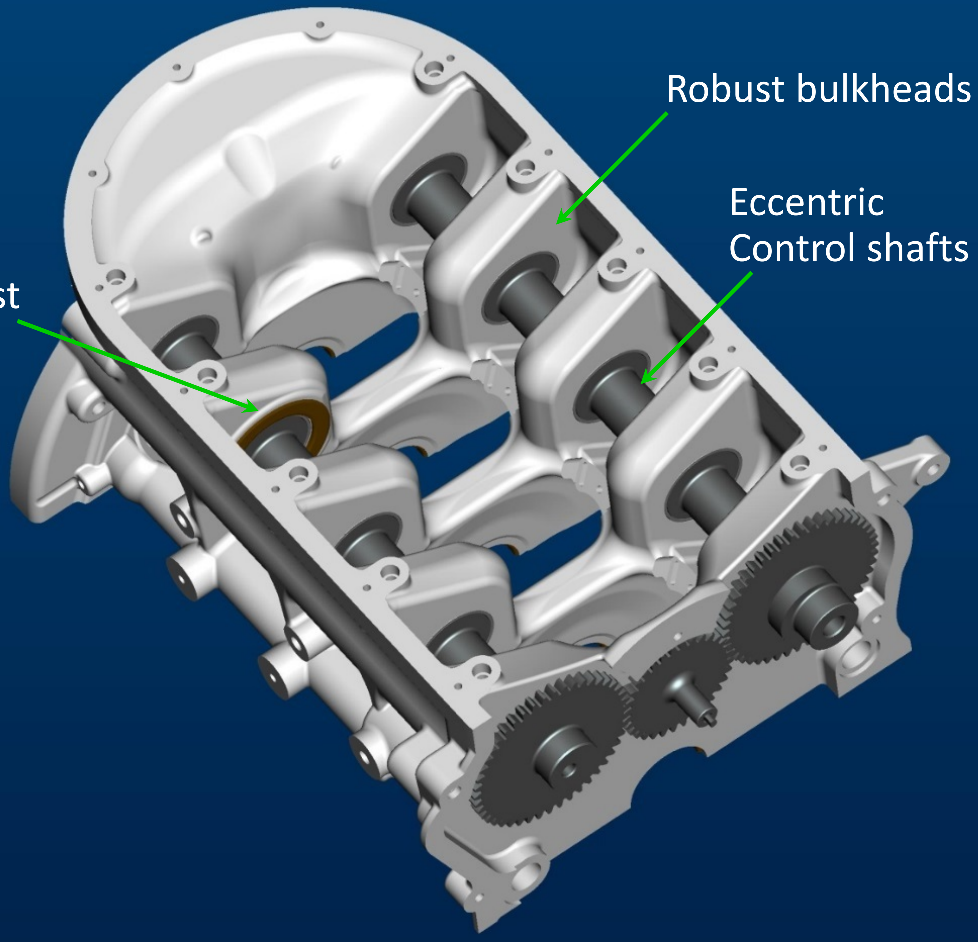
Envera VCR 2.0



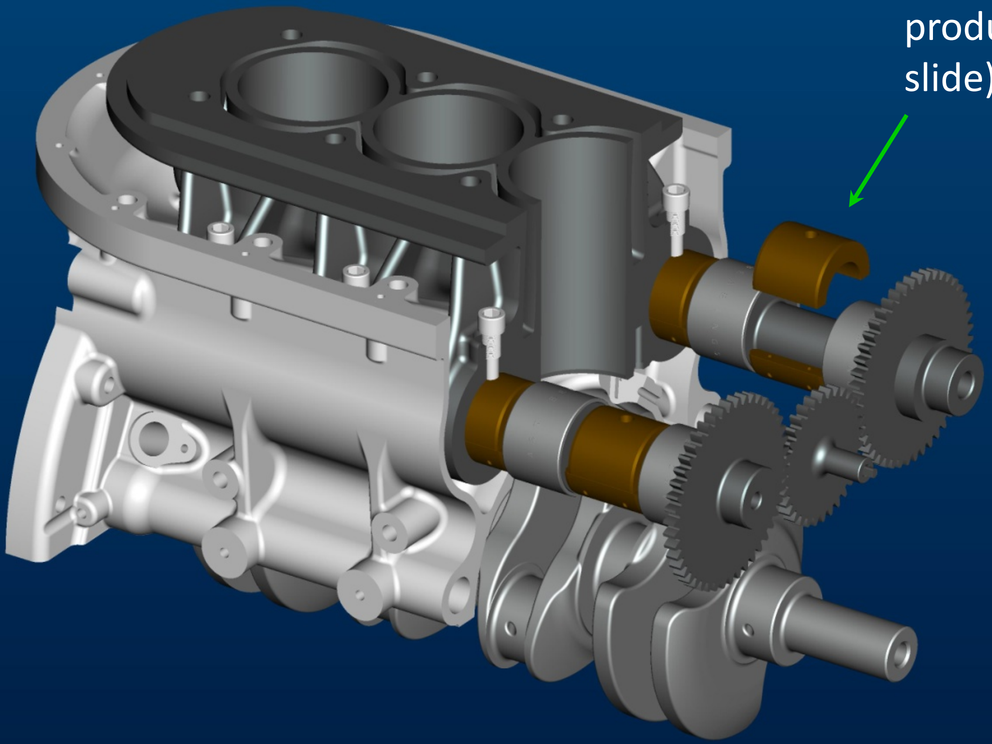
*Aluminum cylinder jug with cast in place liners for production. Iron jug for first prototype.

Envera VCR 2.0

Upper crankcase



Envera VCR 2.0



Assembled bushings for prototype.

Shrink-fit bushings for production. (See backup slide)

Envera VCR 2.0

Internal engine friction loss:

- No change in valve chain friction.
- VCR actuator power is minimal. Combustion forces are used for a rapid reduction in compression ratio. Compression ratio is increased “slowly” (over a number of seconds) to minimize actuator power.

Internal engine friction is about the same as a non-VCR engine.

Combustion chamber design:

- A small bore to stroke ratio is used to achieve a thicker, more compact combustion chamber volume.
- Deep valve pockets are not required, because the VCR lowers the piston at times when a large valve overlap is needed. *Only small pockets needed.*

Combustion chamber form looks good for the GM 2.5L Ecotec engine build.

Compression Ratio Values

High compression ratio:

Maximum compression ratio	17.5:1
Bore/Stroke ratio	0.9
BSFC projection 100 Nm 2000 rpm	~235 g/kWh*

High compression ratio engines need a small bore to stroke ratio for minimizing combustion chamber surface area and minimizing heat loss.

Increasing CR from 16.5 to 17.5 requires an additional VCR travel of only 0.38mm (0.015 inch). The higher CR value will be used because it will return higher efficiency with no real down side to the engine design.

*Lambda 1 with no external EGR. Lower BSFC values can be attained with external EGR.

Compression Ratio Values

VCR Mechanical Travel:

The VCR mechanism needs to provide a mechanical travel range of about 8.0 mm.

ENVERA 2.4L VCR Engine				
VCR Travel Needed			**Build 1**	**Build 2**
Bore		mm	88.50	88.50
Stroke, S		mm	97.50	97.50
Bore/Stroke			0.908	0.908
Cylinder displacement		cc	599.8	599.8
Cylinders			4	4
Engine displacement		L	2399	2399
CR				
	Max		17.50	17.50
	Min		8.22	8.00
Chamber volume, d				
	Max CR	cc	36.35	36.35
	Min CR	cc	83.07	85.68
Change in volume		cc	46.72	49.33
VCR Travel, T		mm	**7.6**	**8.0**

Eaton Variable Valve Lift

Eaton VVL Rocker Arm

Optimized

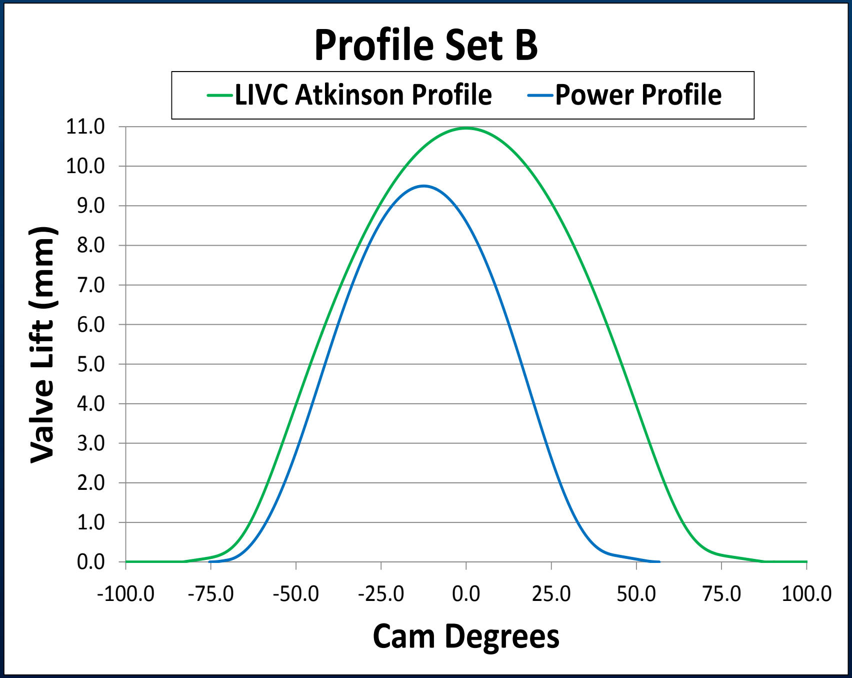
- Multiple valve lift profiles
- The VVL rocker arm to 6800rpm

Results

- VVL performance meets requirements
- Exhaust SRFF meets requirements

Status

- Fabricating cylinder head, cams, and VVL rocker arm hardware

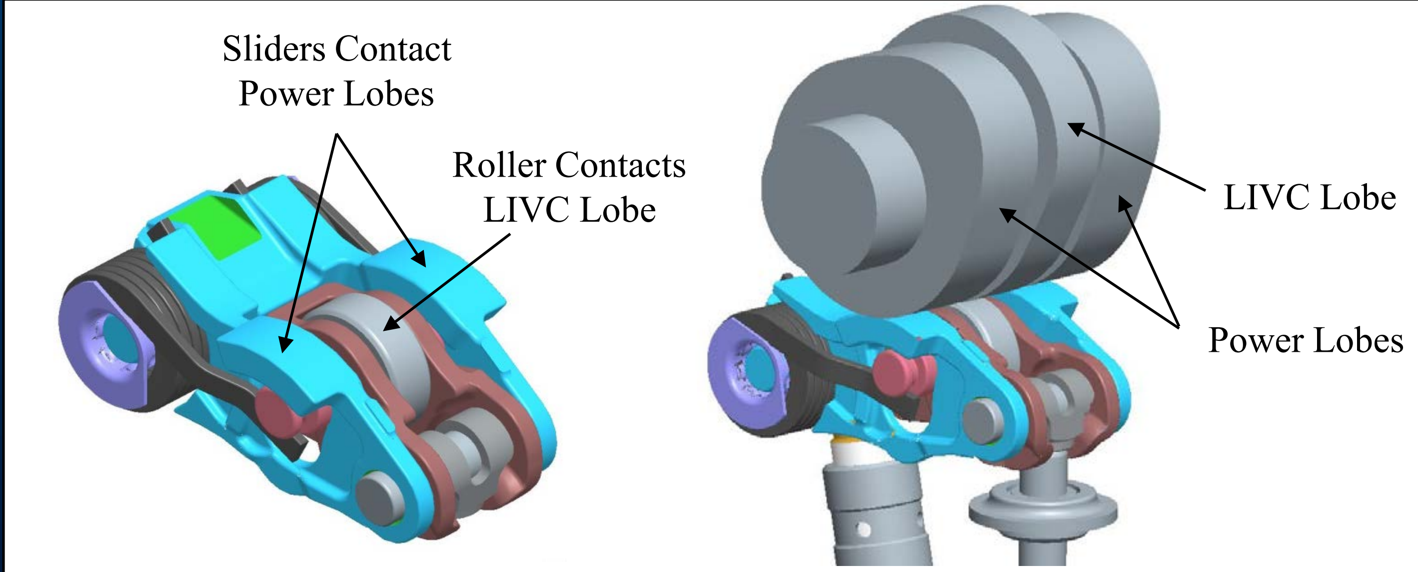


Eaton Variable Valve Lift

Phase 3 Optimization – *Under review*

Over-all fuel economy can be increased by using the roller follower for the Atkinson Cycle, and the slider contacts only for power and torque.

The current build uses sliding contact for the Atkinson Cycle. The roller follower Atkinson design is shown below.



LIVC Low Friction Rocker Arm For Atkinson Cycle Operation

Development Progress

Development Progress for VCR 2.0

ENVERA VCR PROTOTYPE ENGINE			I / PHASE II / PHASE III
TIME LINE			BUDGET PERIOD 1 / BP 2
CALANDAR TIMELINE			2013, 2014, 2015, 2016, 2017
Timing dependent on DOE/NETL award and kick-off meeting			Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3
PHASE II		**VCR PROTOTYPE ENGINE BUILD**	
Task 8		VCR Crankcase Design and Engineering	
	Subtask 8.1	CAD/FEA: Cranktrain and VCR Cradle	
	Subtask 8.2	CAD/FEA: Crankcase with Bedplate	Complete
	Subtask 8.3	Thermal-CFD: Cooling circuit	
	Subtask 8.4	CAD: Front Cover, Oil pan, remaining Components	
Task 9		Engine Build	
	Subtask 9.1	Procure Crankshaft, Pistons and Connecting Rods	
	Subtask 9.2	Rapid Prototype Castings	
	Subtask 9.3	Machine Castings and Other Components	
	Subtask 9.4	Purchase Components	
	Subtask 9.5	Engine Pre/Assembly and Functionality Checks	
Task 10		Advanced Supercharger	
	Subtask 10.1	Design and Engineering	
	Subtask 10.2	Hardware Prototyped	
	Subtask 10.3	I/O Controls Specification	
Task 11		Valve actuation	
	Subtask 11.1	Design and Engineering	
	Subtask 11.2	Hardware Prototyped	
	Subtask 11.3	Sensor installation	
	Subtask 11.4	I/O Controls Specification	
Task 12		Engine Management Advanced Set-up	
Task 13		Required DOE Reporting, meetings, presentations	
PHASE III		**ENGINE AND VEHICLE VALIDATION TESTING**	
Task 14		Engine Management and CV Calibration	
	Subtask 14.1	Engine Management and Base Calibration	
	Subtask 14.2	GTPower development / New Cams	
	Subtask 14.3	Calibration / Engine BSFC Map Produced	
Task 15		Test Vehicle Simulation	
Task 16		Cylinderhead Advanced Development	
Task 17		Valve actuation development	
Task 18		Value Engineering	
Task 19		Required DOE Reporting, meetings, presentations	

Progress for VCR 2.0

Development Status Summary:

- General design of the VCR 2.0 Engine has been completed.
- Completion of crankcase and cylinder jug general machining, crankshaft connecting rods and other major components scheduled for June 2016.
- Engine assembly with Envera and Eaton components is scheduled for mid 2016.

Progress for VCR 2.0

Outstanding Progress for VCR 2.0:

- DOE Grants authorization to proceed with VCR 2.0 August 2015
- Crankcase casting release December 2015

Casting release within 6 months of VCR 2.0 receiving DOE green light*!*

Progress for VCR 2.0

Phase III

- The VCR engine will undergo engine dynamometer testing in Phase III.
- Engine testing will focus on selected rpm/bmep load points. A leading goal is to establish calibration settings for minimum bsfc at 100 Nm load 2000 rpm. GTPower will be used for optimizing engine efficiency during real time engine dynamometer testing, and for post-testing optimization.
- Eaton will develop a second set of cams for its switchable rocker arms. These cams will be developed using the combustion data and GTPower modeling. The VCR engine will then be retested with the new cams.
- High-load testing will also be conducted to validate the VCR 2.0 mechanism.

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

AMR Reviewer comments from 2015

1. “VCR is a very relevant efficiency technology concept”

2. Mechanism and actuator friction needs to be considered.

   Low friction is a key selling point for the Envera VCR 2.0. Valve chain and FEAD friction is essentially unchanged from stock, and rapid reduction of CR is actuated by combustion forces.

3. The combustion chamber shape will be poor due to the high CR requirement.

   Deep valve pockets are not required because a large valve overlap is only required during low CR conditions. VCR lowers the piston 7.6 mm, and eliminates the possibility of piston to valve strike.

Previous Reviewer Comments

AMR Reviewer comments from 2015 *Continued*

4. Data is needed to support efficiency and performance projections

   Testing as planned in Phase 3 of the program.

5. There is no OE or Tier 1 involvement.

   The Eaton Corporation is a major Tier 1

6. A combustion controls partner is needed.

   Down-selection of the Phase 3 testing location and technical support will take place in Q4 2016.

Summary

Summary:

- Large reductions in CO_2 can be attained with VCR technology.
- Criteria emission standards (HC, NOx, CO, Particulate) for gasoline VCR engines are attainable using proven 3-way catalytic converter technology.
- The Envera VCR mechanism has several benefits:
  - A large enough VCR travel distance (+7.6mm)
  - Robust structure for supporting ~30 bar bmep loads
  - Minimal friction loss penalty
  - Approximately stock engine size (can fit into existing engine bays)
  - Stock cylinder heads can be used with the Envera VCR crankcase
  - Low cost high-volume production
  - Good match with production transmissions. 7000 rpm design speed. "Down-speeding" not required.

Thank you

US Department of Energy
National Energy Technology Laboratory

Cost share Partners and Program Donors:

- Envera LLC
- Eaton Corporation
- Gamma Technologies
- EngSim Corporation
- ADEM LLC
- BHJ Dynamics, Inc.

Charles Mendler
ENVERA LLC
Tel. 415-381-0560
CMendler@VCREngine.com

Technical Backup Slides

Envera VCR 2.0 – Backup Slide

Earlier version shown

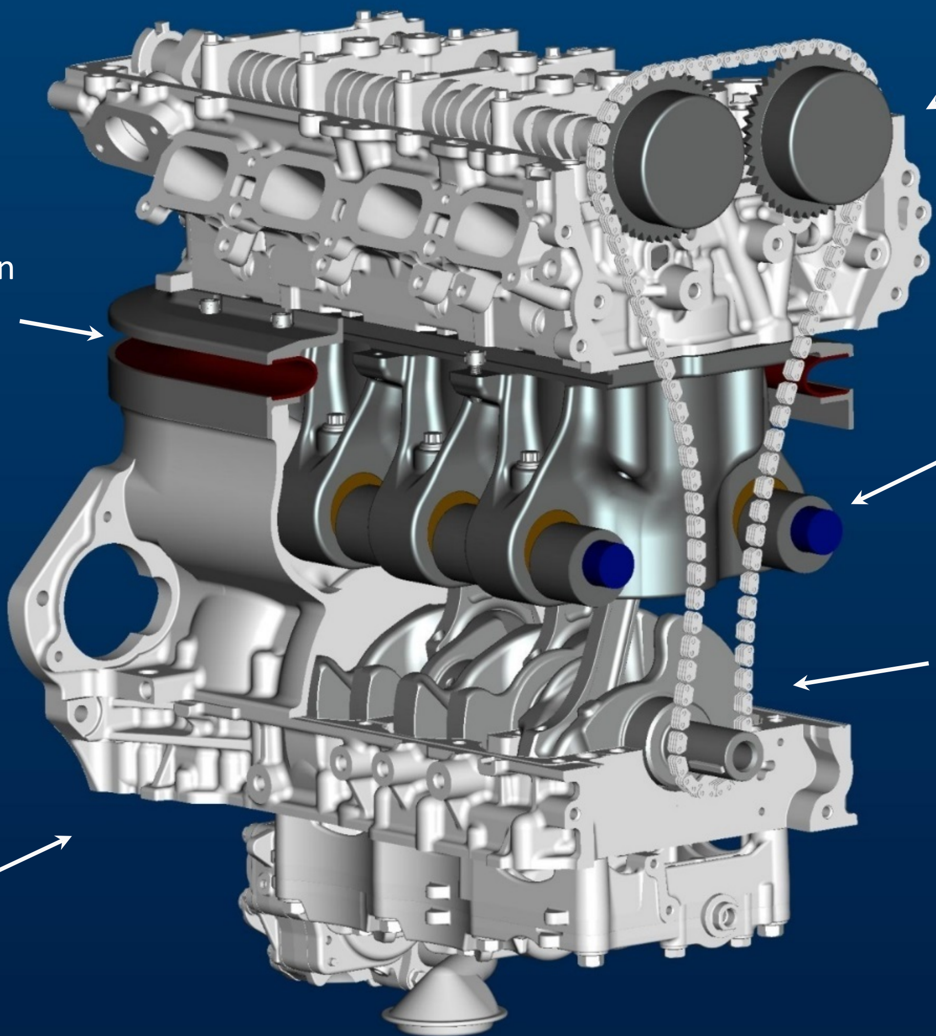
Nitrile gasket:

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.

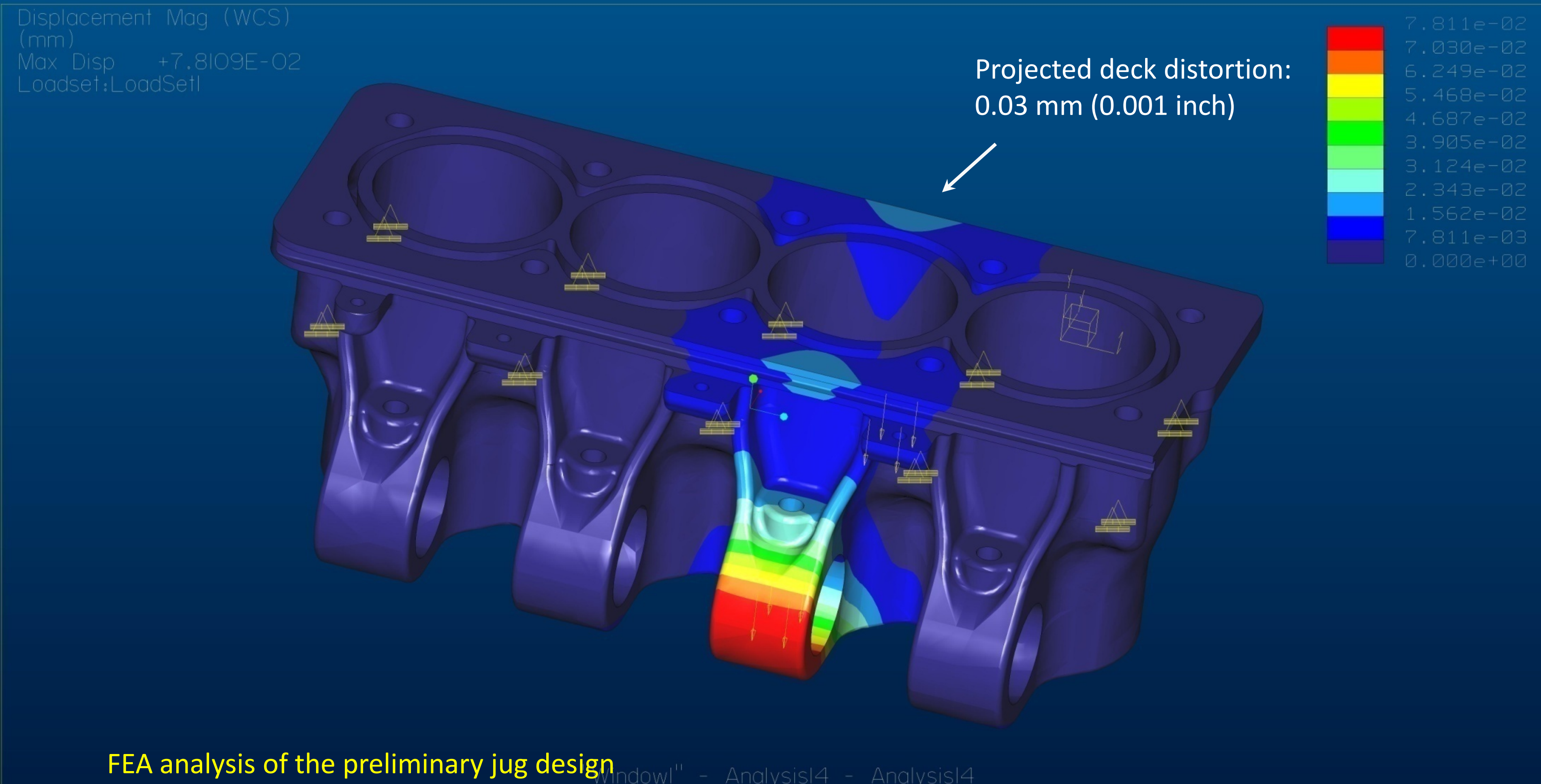


Stock cylinder head with Eaton VVL & Atkinson cycle cams

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.

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.