AMR 2014
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High Efficiency VCR Engine with Variable Valve Actuation and new Supercharging Technology

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Project ID
ACE092

Overview

Timeline

Start date*	April 11, 2013
End date	October 31, 2016
Percent complete	
Time*	27.3%
Budget	18.6%

Budget

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

Expenditure of Government funds

Year ending 3/31/13	$ 29,732
Year ending 3/31/14	$359,693

* Kick-off meeting

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)*

Partners

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

Project Lead

ENVERA LLC

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: Kick-off – March 2015

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	Pass
GTPower modeling	Go/No-go	Q4/2014	On schedule
Base engine specifications	Milestone	Q2/2013	Complete
Crankcase CAD and FEA	Go/No-go	Q2/2014	On schedule
Crankcase castings	Milestone	Q2/2014	Q3/2014
Durability testing, PTO	Go/No-go	Q3/2014	On schedule
Crankcase Machining	Milestone	Q4/2014	On schedule
Engine assembly	Go/No-go	Q1/2015	Q2/2015

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.

Development Strategy

Phase 1

Feasibility analysis, including:

• VCR power takeoff coupling	Envera
• VVA operational range	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

Note: Phase 1 and 2 overlap for scheduling reasons.

Development Strategy

Phase 3
Engine Calibration / Milestone Testing

- ECU programming / calibration pre-sets
- Engine start-up / data capture for GTPower modeling *(Burn rate, COV)*
- GTPower modeling / new camshafts
- Steady-state engine calibration *(Limited range for budgetary reasons)*
- Transient software development as needed
- Mechanical systems validation assessment / reporting
- Engine installation in test vehicle
- Baseline FTP mileage testing
- "Value engineering" as needed for achieving Targets

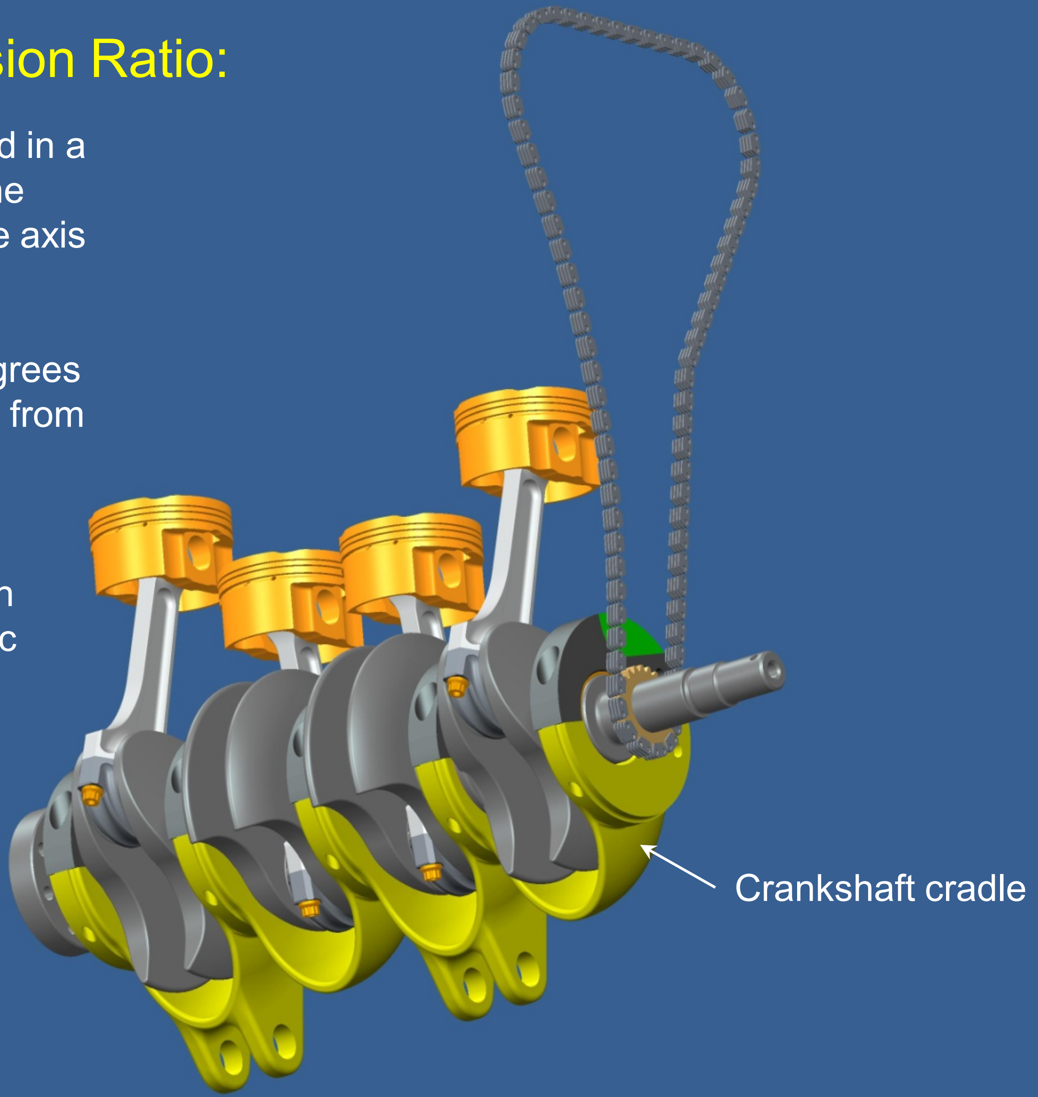
Accomplishments - VCR

Variable Compression Ratio:

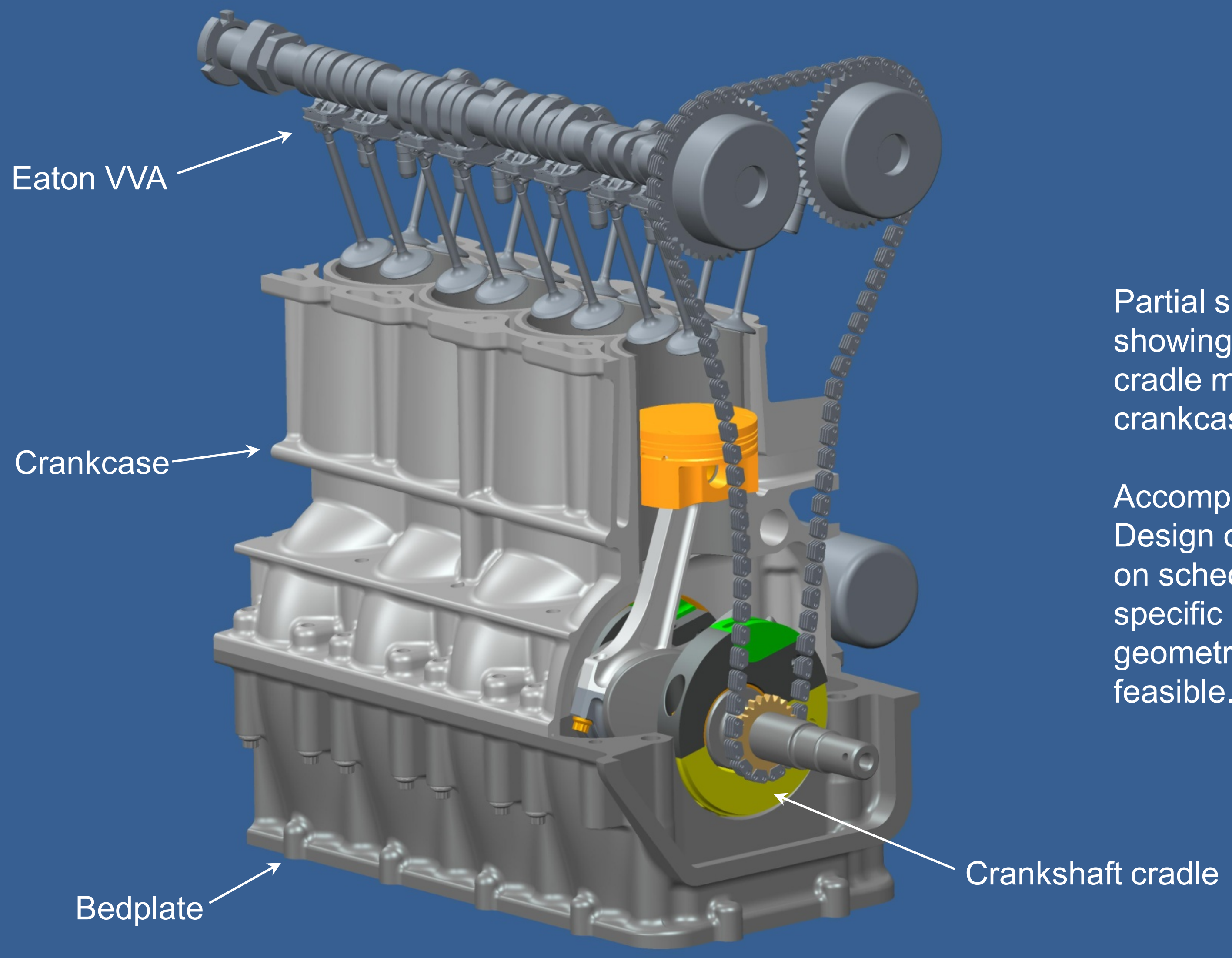
The crankshaft is mounted in a "crankshaft cradle" with the crankshaft axis and cradle axis offset by 13.5 mm.

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

Accomplishment:
Design complete of shown assembly. Engine-specific design and geometry determined feasible.



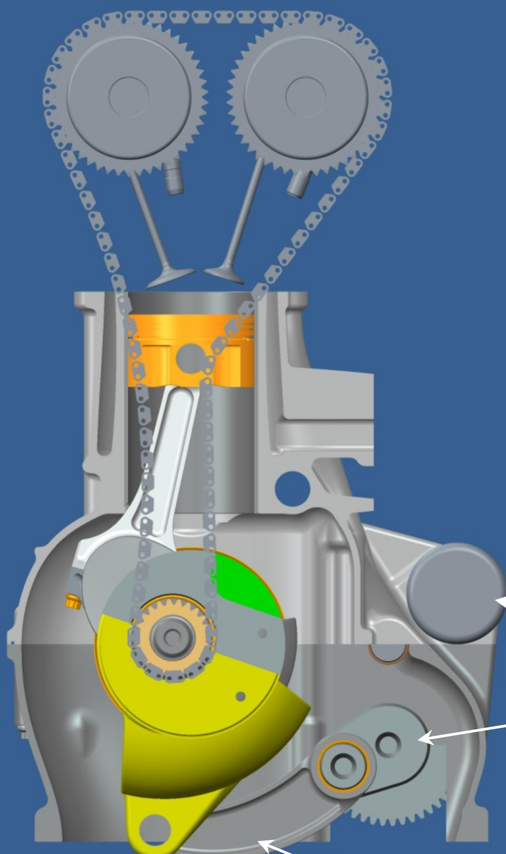
Accomplishments - VCR



Partial sectional view showing the crankshaft cradle mounted in the crankcase.

Accomplishment: Design of crankcase on schedule. Engine-specific design and geometry determined feasible.

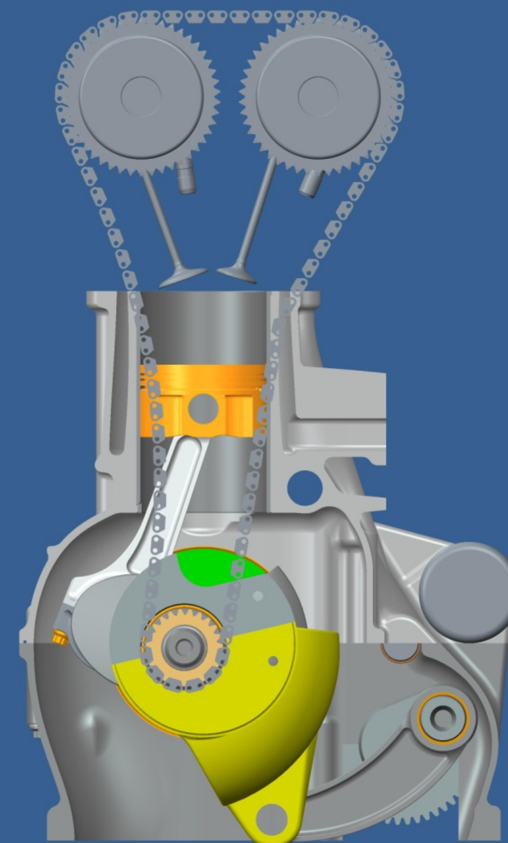
Accomplishments - VCR



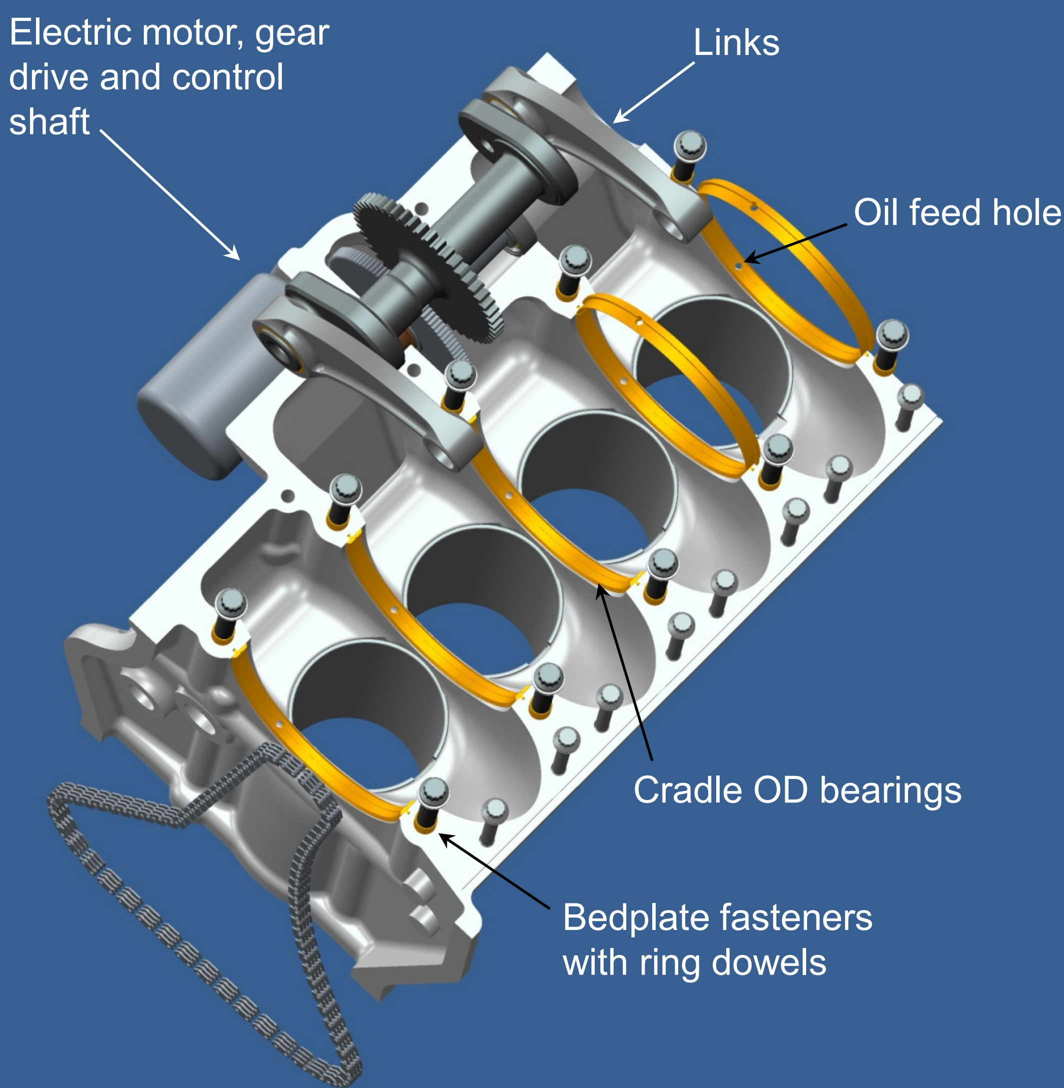
High compression ratio

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

Accomplishment:
Design of electric actuator system.


Low compression ratio

Accomplishments - VCR



The upper crankcase is shown with the crankshaft cradle removed. The crankshaft cradle is mounted in bronze bushings so that it can pivot for adjusting compression ratio.

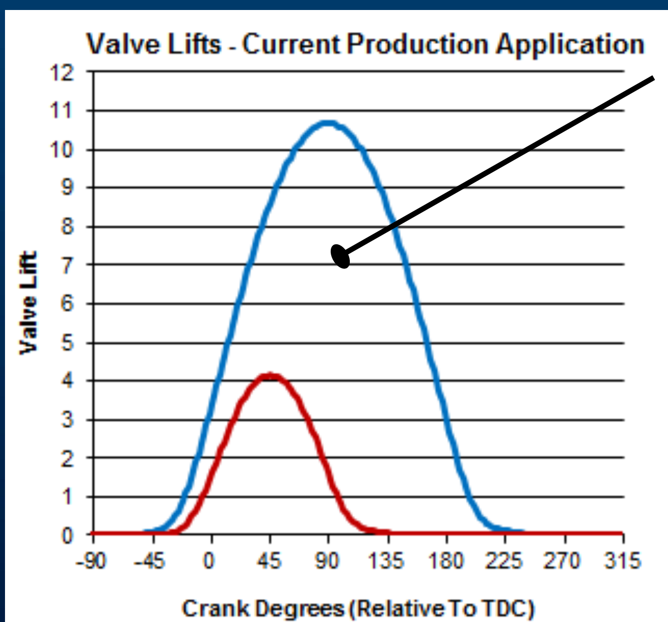
The power take-off coupling and valve chain dive have confidential design details, and are not shown.

Accomplishment:
Several design upgrades from earlier engine builds.

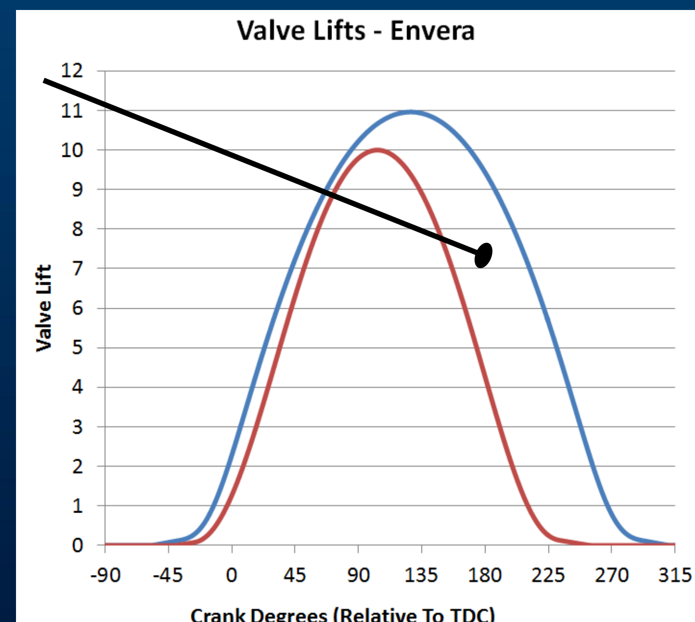
Accomplishments - VVA

Introduction:

Eaton began commercial production of the VVA mechanism for MY 2014 Early Intake Valve Closing (EIVC) systems. The Envera project VVA is to have Late Intake Valve Closing (LIVC) for a switchable Atkinson Cycle combustion strategy.



Lost Motion Area



EIEC

LIVC

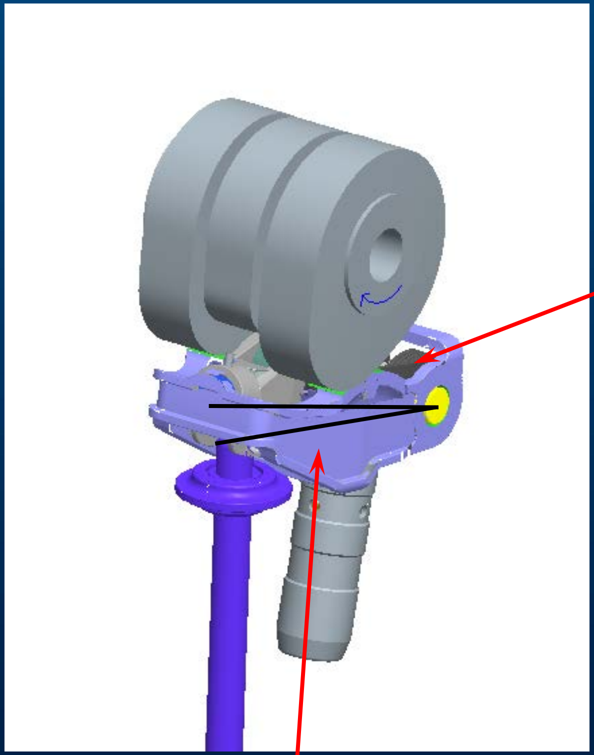
Accomplishments - VVA

Variable Valve Actuation
Late Intake Valve Closing Development

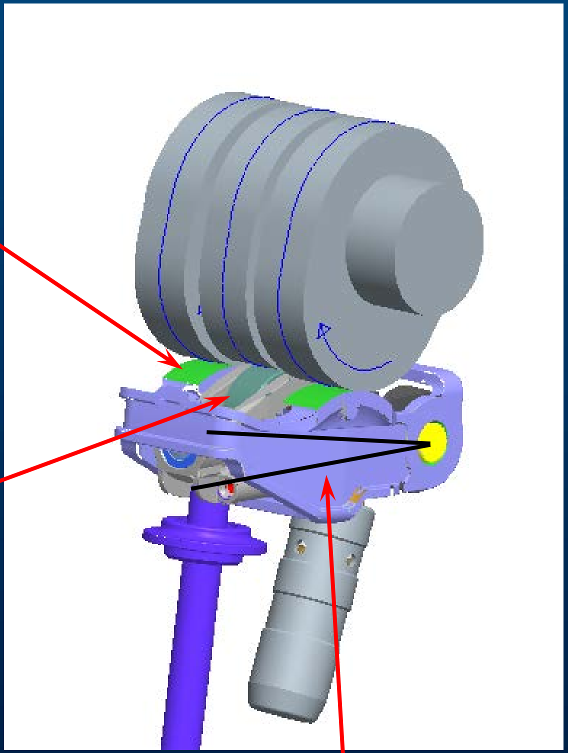
- Defined hardware requirements and risks of utilizing Switching Roller Finger Follower (SRFF) in Late Intake Valve Closing (LIVC) application.
- Analyzed lost motion requirements for the SRFF for the proposed LIVC events. Determined loads needed. Modified lost motion specifications to suit the application. Assessed durability of the lost motion springs.
- Analyzed load stresses on the SRFF for proposed LIVC events to determine suitability for durability of the sliding and rolling interface. Determined baseline hardware is suitable.

Accomplishments – VVA
Camshaft to SRFF Interface - Production EIVC to Envera LICV

Early Intake Valve Closing (EIVC)



Late Intake Valve Closing (LIVC)



Outer Arm contacts pair of outer lobes

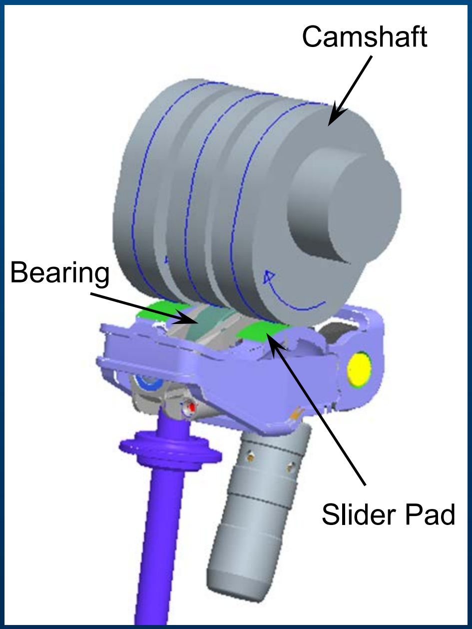
Torsion Springs create force to keep Outer Arm in contact with cam lobe

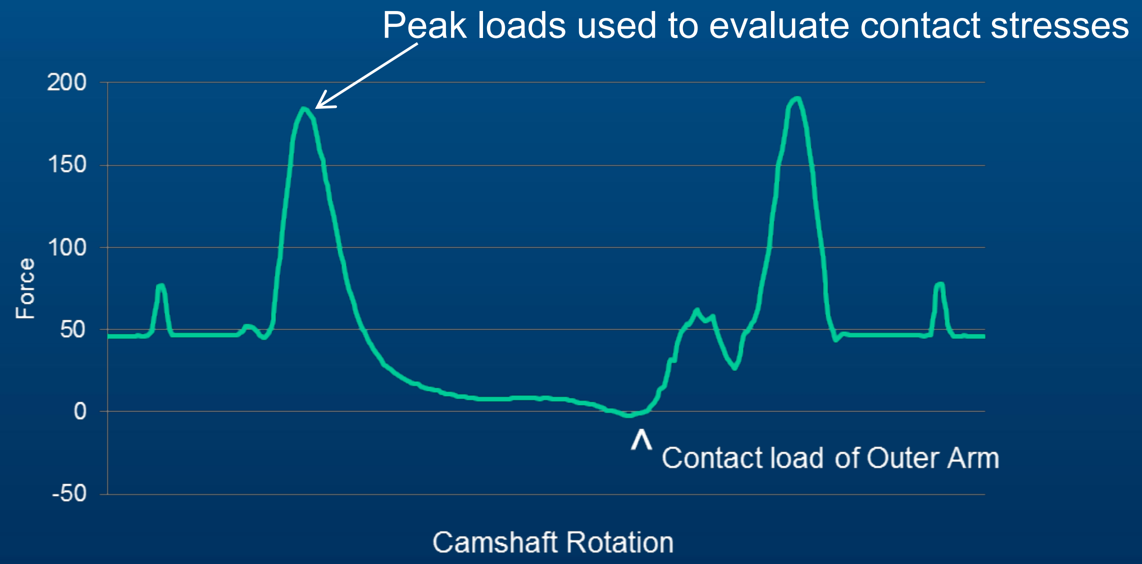
Inner Arm contacts inner lobe

Lost Motion between Inner and Outer Arm absorbed by Torsion Springs

Less Lost Motion absorbed, but higher load required to maintain Outer Arm contact

Accomplishments – VVA
LIVC Envera Application Analysis





Dynamic load curve example

Feasibility Analysis:

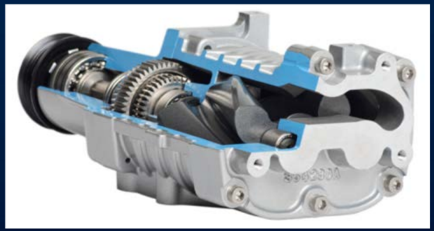
- Peak loads used to verify application stress acceptable for Eaton valvetrain standards for camshaft and SRFF bearing and slider pad.

- Contact load analysis of Outer Arm determined additional SRFF torsion spring load was required to meet Envera engine speed targets. Torsion spring life analysis of new spring design is acceptable to Eaton life targets.

Accomplishments - Supercharging

Advanced Supercharging:

- EATON provided supercharger maps to ENVERA for evaluating power and torque capabilities. Performance targets can be met with several boosting system options.
- GT Power modeling will be conducted to evaluate boosting system options based on predicted fuel economy and performance. Variable speed supercharger, supercharger-turbocharger combinations and other approaches will be considered.
- GT Power results will be used to select boosting hardware.
- In parallel to GT Power modeling, EATON is conducting CAD modeling of supercharger mounting options.



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 areas where collaboration will be pursued in the future is the engine management system (the engine control unit, ECU). ENVERA will explore collaboration opportunities in this and other areas later on in 2014/5.

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

Remaining Challenges/Barriers

VCR Power take-off coupling: *Confidential design not shown*

The feasibility of the power take-off coupling needs to be validated under dynamometer testing. This testing is currently scheduled and part of the program plan. The current contingency plan would result in an increase of engine length. While added length is undesirable, the added length is acceptable for the target markets: Pickup trucks and full-size vans.

Supercharging:

Needed boosting levels can be attained via a number of different technological pathways. The best approach has not yet been determined. GTPower computer modeling will be used to evaluate boosting options. GTPower modeling is currently scheduled for Q4 2014.

Variable Valve Actuation:

Analysis conducted by Eaton indicates that Atkinson and supercharging valve settings are feasible. An objective of the program is to demonstrate feasibility through engine testing.

Proposed Future Work: 2014 - Q1 2015

Variable Compression ratio:

• Durability testing of the VCR Power take-off coupling	Go/No-go
• VCR crankcase design completed with finite element analysis	Go/No-go
• Crankcase casting and machining	Milestone
• Engine assembly and inspection	Go/No-go

Variable Valve Actuation:

• GTPower modeling to optimize cam settings	
• Camshafts made	
• VVA fully integrated into cylinder head with optimized camshafts	Milestone

Supercharging:

• GTPower modeling to evaluate boosting options & Select option	Go/No-go
• Supercharger mounting and installation on the VCR engine	

Contingency and Options Assessment:

For the VCR power take-off-coupling, VVA, and boosting, contingency plans and/or options for improving on initial design approaches will be evaluated. *Invention disclosures have been made for Boosting & VVA.*

Summary

Summary:

- The current program is relevant to the DOE Vehicle-Technologies Office Multi-Year Program Plan. Advanced engine controls are being developed and combined with aggressive engine down-sizing to attain mileage gains consistent with VT-Office program targets.

- VCR, VVA and advanced boosting technology will enable the 4-cylinder engine to operate under the Atkinson Cycle most of the time for attaining high mileage, and provide V8-like performance on demand when needed.

- Envera and Eaton are collaborating on the engine development, with Envera developing the VCR engine build, and Eaton providing the VVA and supercharging.

- The program is on budget. Engine assembly is being delayed one quarter for GTPower modeling and evaluation of potential improvements.

Technical Backup Slides

Technical Backup Slide

Invention Disclosures:

Invention disclosures have been submitted to DOE for inventions conceived during performance of the program. These inventions could substantively improve the performance, and efficiency of the engine and relate to valve control and boosting.

GTPower modeling in 2014 will be used to assess potential gains, and support informed decision making on if and how these developments should be incorporated into the VCR engine. It's highly probable that some of the improvements will be incorporated into the engine.

Envera has and will continue to inform and discuss potential improvements with NETL and DOE management, and discuss any impacts on budget and schedule.

Technical Backup Slide

Feasibility Analysis: *Accomplishments*

Cam duration and timing values: The Eaton variable valve actuation mechanism provides two cam lobe settings. ENVERA provided target cam values to EATON for attaining high efficiency using the Atkinson Cycle at smaller engine power levels, and also cam values for attaining high power levels with supercharging. Through dynamic analysis EATON confirmed the feasibility of attaining both target values.

Supercharging: EATON provided supercharger maps to ENVERA for evaluating power and torque capabilities. Performance targets can be met, but which approach provides the best results has not yet been determined. GTPower modeling will be conducted in Q4/2014 to evaluate options in detail. It should be noted that Volvo recently announced that it will be offering a new 4-cylinder engine that combines supercharging and turbocharging. There are a few options on how to attain impressive boosting levels that will be evaluated.

VCR Mechanism: Several ENVERA VCR engines have been built, and none has experienced main bearing failure. Based on this track record, the core VCR mechanism is viewed as “Feasible”. The power take-off couple connects the core VCR engine and the transmission. In Q3 2014 ENVERA will conduct durability tests of the power take-off coupling in a separate single-cylinder research engine to establish feasibility.

Technical Backup Slide - VCR

Variable Compression Ratio: *Accomplishments*

The VCR crankcase will be mated to a donor cylinder head. The GM 2.5L cylinder head was chosen for the project based on projections of available power and torque capacity, and the ability to implement the Eaton VVA technology. Ideal bore and stroke dimensions are also attainable with the cylinder head.

A VCR crankcase is currently being designed by ENVERA to match fit the GM cylinder head. The crankcase deck carries over GM deck geometry to ensure reliable head gasket sealing (with use of open-deck geometry optional). Design of the crankcase is largely complete. Remaining design work includes the oil return drain-backs, bellhousing and front cover, motor mounts and accessory attachments. The crankcase will be cast in A356 aluminum. The VCR mechanism has been designed, and includes a number of improvements from earlier VCR engine builds.

- Clearances have been increased to reduce manufacturing tolerances and costs
- A new crankshaft cradle OD bearing design is being used to aid in assembly, and again reduce manufacturing cost
- Ring-dowels are used on all bedplate main fasteners
- An electric VCR actuator is now being used
- A stiffer crankshaft cradle design is being used
- An improve valve chain system is being used to take up slack during change of CR

Technical Backup Slide - Boosting

Boost pressure on demand:

- For a downsized 4-cylinder engine to provide the responsiveness of a larger V8, the turbo or supercharger needs to be responsive and efficient while providing the needed boost. This can also be challenging.

- Envera LLC and the Eaton Corporation are developing a boosting system for the VCR engine that provides both high boost levels and a fast response.

- The new boosting system will expand on the capabilities of Eaton's latest generation "TVS" supercharger series. Details for the advanced boosting systems are confidential at this time.

Technical Backup Slide – VVA+VCR

Variable Valve Actuation is not a substitute for VCR:

- While VVA is highly beneficial, it is not a desirable method for adjusting the engine compression ratio.
- VVA can adjust the “effective compression ratio” by adjusting the amount of air trapped in the cylinder.
- Trapping more air in the cylinder provides a higher effective compression ratio and more power. Trapping less air in the cylinder provides a lower effective compression ratio and less power.
- Unfortunately, the opposite compression ratio values are needed. A low compression ratio is needed at high power to avoid detonation, and a high compression ratio is needed at low power levels to provide higher engine efficiency.

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.

Technical Backup Slide

Technological Approach for Achieving Targets:

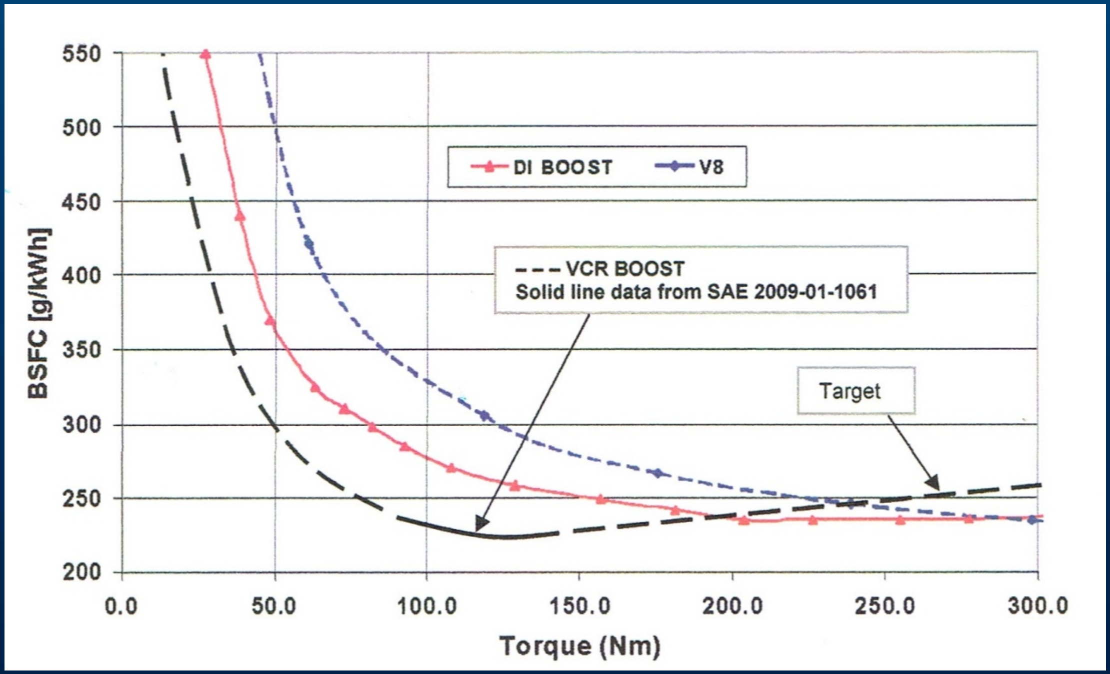
The VCR engine will achieve high efficiency using the Atkinson Cycle with an 18:1 compression ratio, combined with aggressive engine downsizing. Analysis indicates that the engine will be operated most of the time using the high-efficiency Atkinson Cycle.

Occasionally high power and torque values are needed. To attain high power levels:

- Advanced supercharging technology will be used to boost the engine and provide V8-like performance from only four cylinders.
- Valve events will be adjusted with the VVA to trap more air in the cylinders.
- Compression ratio will be lowered using the VCR to prevent detonation.

Technical Backup Slide

Fuel efficiency comparison:



Fuel efficiency comparison of a 5.7L V8, a 3.6L DI-Boost V6, and a 2.2L VCR Boost 4-cylinder engine (projected data/Target)