

---

## II.C.1 Variable Valve Actuation

Jeffrey Gutterman  
Delphi Automotive Systems  
5725 Delphi Drive  
Troy, MI 48098-2815

DOE Technology Development Manager:  
Roland Gravel

NETL Project Manager: John Jason Conley

Subcontractor:  
Electricore Inc.  
27943 Smyth Dr., Suite 105  
Valencia, CA 91355

### Objectives

- Develop an optimal, cost-effective, diesel variable valve actuation (VVA) system for advanced low temperature diesel combustion processes.
- Build and demonstrate a mechanism for the diesel variable valve actuation system.

### Accomplishments

- Received engine model and requirements and prepared mechanism design layout.
- Initiated and completed literature study to further the comprehension of advanced mode diesel combustion (AMDC)/VVA requirements.
- Initiated and completed detailed engine selection matrix.
- Completed benchmarking study on competing technologies.
- Determined resultant mechanism valve profiles and worked with OEM to identify differences.
- Prepared system requirements document based upon all available data.
- Developed production type carrier for ease of engine assembly and application to other engines.
- Identified design interferences with original equipment manufacturer (OEM) engine and proposed possible solutions.
- Submitted provisional patents covering the VVA mechanism.

### Introduction

The project objective is to develop and demonstrate an optimal, cost-effective diesel variable valve actuation (VVA) system for advanced, low temperature combustion processes. Flexible control of the valve event is a significant enabler for advanced mode diesel combustion (AMDC). It is an essential factor in the control of the species and thermodynamic conditions for the combustion cycle. VVA is expected to enable expanding the operating load and speed range of AMDC. It is also a potential tool for enhancing the effectiveness of aftertreatment catalysts. Thus, viable VVA technology is expected to help in reducing the penalty in fuel consumption related to extremely low emission standards.

Delphi Corporation has major manufacturing and product development and applied R&D expertise in the valve train area. Historical R&D experience includes the development of fully variable electro-hydraulic valve train on research engines as well as several generations of mechanical VVA for gasoline systems.

### Approach

Delphi utilized a milestone approach in the development of the VVA mechanism including:

- Identify preliminary functional requirements
- Identification of the target engine
- Building the engine model
- Calibration of the engine model
- Definition of representative points in the drive cycle
- Literature study and competitive analysis
- Develop detailed VVA functional requirements
- Identification of optimal valve lift profiles to maximize fuel economy
- Identification of required mechanism analysis tools
- Selection of the candidate VVA system

### Results

Significant focus for FY 2006 was placed on the establishment of an evaluation matrix of the current state-of-the-art of VVA technologies and systems that may be applicable to AMDC technology. During this year Delphi completed the engine evaluation matrix and selected the diesel engine to be used for Phase 1 and Phase 2 of the project. After evaluating more than 25 engines based upon the criteria developed by the design team, the engine was selected.

As part of the research effort during FY 2006, significant literature studies were completed in order to determine preliminary requirements required for engine selection. More than 100 research papers were studied and summarized to verify that the approach is viable.

The Delphi literature study indicates three potential valve motion solutions which include: variable lift, variable duration at fixed lift, and a combination of variable lift and duration as indicated in Figure 1.

	Intake	Exhaust	
I	Cont. VVA, w/o Phaser	Conventional valve train	System complexity
II	Cont. VVA, w/ Phaser	Conventional valve train	
III	Cont. VVA, w/o Phaser	2-step VVA, w/ Phaser	
IV	Cont. VVA, w/ Phaser	2-step VVA, w/ Phaser	
V	Cont. VVA, w/o Phaser	Cont. VVA, w/o Phaser	
VI	Cont. VVA, w/o Phaser	Cont. VVA, w/ Phaser	
VII	Cont. VVA, w/ Phaser	Cont. VVA, w/ Phaser	

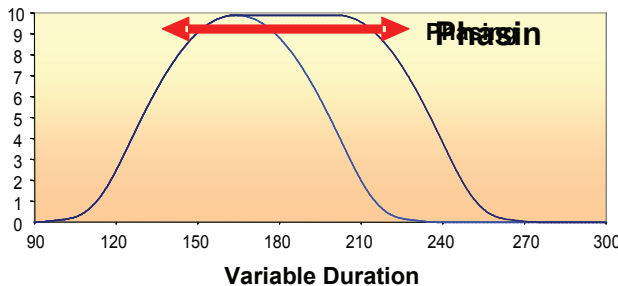
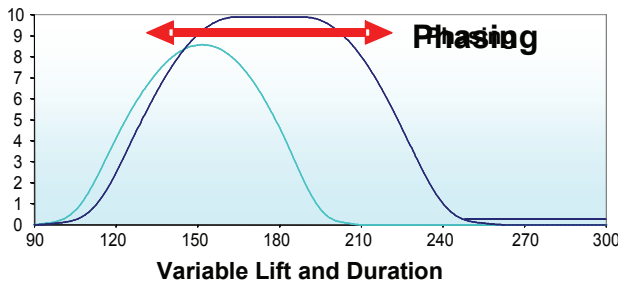
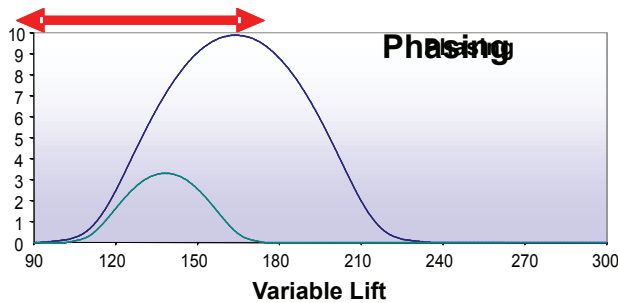


FIGURE 1. Potential Valve Motion Solutions

Lift profiles specific to the engine have been determined by Delphi and the OEM based upon significant dynamometer testing. These profiles are being used to develop the variable valve mechanism.

The engine selection matrix was populated and the candidate engine selected based upon an internal weighting system. Certain factors such as valve train type and availability of controller software were considered critical to the success of the project and thus were valued highly. Valve trains were classified into five main types as shown in Figure 2. Type 2 and Type 3 valve trains are preferred due to flexibility and ease in packaging.

More than 25 engines were evaluated based upon the specific criteria developed for the VVA project. During this period three separate meetings were held with the selected OEM to determine system specifications and verify the applicability of the Delphi mechanism to the OEM engine application. The OEM supplied desired lift profiles determined from more than two years of engine dynamometer testing. This data has enabled Delphi to quickly develop an actuation system that meets the requirements of this project.

The VVA mechanism is part of a programmable valve train system for an internal combustion engine. Control of the VVA will be from a powertrain control module (PCM) through the actuator, via the VVA control shaft. The actuator will be controlled by a pulse width modulated (PWM) drive signal in response to a positional command. A throttle position sensor (TPS) style potentiometer shall be mounted on one end of the control shaft. The sensor will be used for feedback to the closed loop PID-type positional control software in the PCM.

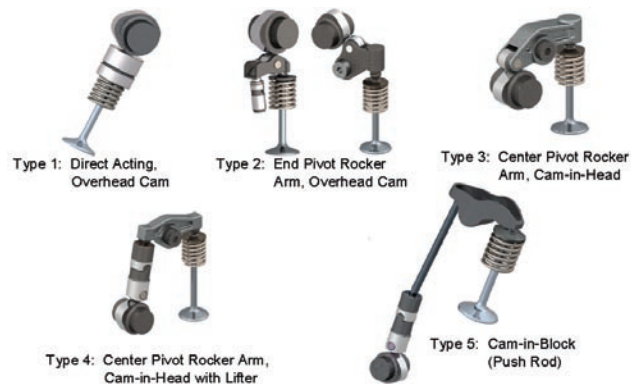


FIGURE 2. Valve Train Types

### Conclusions and Future Directions

- Phase I VVA objectives have been met.
- Evaluate new dual cam designs that will address all engine performance requirements.
- Develop detailed packaging designs on the engine that address injector interference, cylinder head height and width, cradle bearing cap penetration into the cylinder head and other packaging issues.
- Complete baseline valve train kinematic/dynamic analysis for both intake and exhaust valve train.
- Set up cylinder head model.
- Build VVA hardware.
- Demonstrate and document VVA mechanism.

### Special Recognitions & Awards/Patents Issued

Provisional patents submitted:

1. System for Continuously Varying Engine Valve Duration
2. Continuously Variable Valve Actuation System

---

## II.C.2 Low-Cost Fast-Response Actuator for Variable Compression Ratio Engines

Charles Mendler  
Envera LLC  
7 Millside Lane  
Mill Valley, CA 94941

DOE Technology Development Manager:  
Roland Gravel

NETL Project Manager: John Jason Conley

### Introduction

Several VCR mechanism concepts have been advanced since U.S. Patent Number 5,819,702 was issued to Charles Mendler in 1998 and SAAB disclosed its VCR engine [1,2,3,4,5,6,7,8]. Since then research conducted by the U.S. Department of Energy, the European Commission – Research, automobile manufacturers, and engine engineering firms have found that fuel economy can be improved by about 30% with VCR, boosting and engine down-sizing [3,4,9,10]. Analysis conducted by Envera in 2004 indicates VCR can provide fuel economy gains larger than 30% through optimized conventional combustion and/or homogeneous charge compression ignition (HCCI). GM and others estimate that HCCI combustion offers the potential for improving gasoline fuel economy by about 25% [11]. Down-sizing and HCCI technologies can be combined for very significant gains in fuel economy.

With respect to large trucks, future 2010 on-highway and 2014 Tier 4b regulations mandate ultra-low NOx and PM emissions. VCR technology enables improved control and performance of HCCI combustion diesel engines. VCR HCCI engines hold potential for significantly reducing emissions and improving efficiency from these diesel engines.

The first high-performance Envera VCR mechanism was built for the former Partnership for a New Generation of Vehicles (PNGV) program. The engine attained efficiency goals and continues to be used for research at Oak Ridge National Laboratory (ORNL). The engine is now going into its 6<sup>th</sup> year of service, a testament to the engines robustness and durability.

A peak engine efficiency of 35% was required for attaining the 80 mile per gallon PNGV fuel economy target. The ability to attain peak engine efficiency over 38% in a production VCR engine was demonstrated by Envera in November 2002 [12].

Equally significant, computer modeling conducted in 2004 by Envera for DOE/ORNL showed high efficiency for the gasoline VCR engine at light power levels [13]. High efficiency at light power levels is required for attaining high fuel economy because vehicles are operated at these light power levels most of the time. The computer modeling indicated that the gasoline VCR engine with conventional spark-ignition (SI) combustion can attain an efficiency of 25.6% at 2 bar bmep and 2,000 rpm. Recent analysis by Envera

### Objective

#### Phase I

- Design, build and bench test a proof of concept variable compression ratio (VCR) actuator system.
- Optimize the actuator system where practical within the scope of Phase I funding.

#### Phase II

- Optimize the actuator control system.
- Installation of existing VCR engine in mule vehicle.
- Test the VCR actuator system in a mule vehicle & demonstrate low-cost, fast-response and mass production practicality.

### Accomplishments

- Hydraulic pressures in the actuator system were reduced by 86% through system optimization. The reduction in pressure significantly relaxes the demands that will be placed on the hydraulic system and enables cost to be reduced.
- A test rig was designed and is currently being built for bench testing the hydraulic actuator system.

### Future Directions

- Optimize the actuator control system.
- Installation of existing VCR engine in mule vehicle.
- Test the VCR actuator system in a mule vehicle & demonstrate low-cost, fast-response and mass production practicality.

indicates an efficiency of 28.3% may be attainable for the SI gasoline VCR engine at 2 bar bmep and 2,000 rpm. For comparison, DOE reported in May 2006 a compression ignition direct injection (CIDI) engine efficiency of 27% at 2 bar bmep and 1,500 rpm [14]. The production Mercedes A170 common-rail CIDI turbo-Diesel attains a fuel efficiency of about 24.1% at 2 bar bmep and 2,000 rpm.

The data indicates that spark ignition (SI) gasoline VCR engines can attain about the same light-load efficiency as CIDI Diesel engines of equal displacement. This high-efficiency SI VCR combustion technology can be combined with down-sizing for very significant gains in fuel economy. These SI engines can also be operated on alternative fuels such as ethanol and butanol derived from switch grass, and can attain low tail-pipe emission levels using proven catalytic converter technology.

It is quite possible that VCR could also raise the efficiency of the CIDI engine. Envera built a VCR Mercedes A170 for ORNL and successfully tested the engine in 2006. It is anticipated that ORNL will use the engine for research in the areas of HCCI combustion; conventional combustion efficiency optimization, and alternative fuels. CIDI engines can be down-sized, but to a smaller degree than gasoline engines because they have a lower maximum engine speed and require higher air flow to minimize emissions.

Several VCR mechanisms have now been proposed and prototyped with U.S. and European Government funding in addition to funding from automotive and diesel manufacturers and engine research firms. The Envera VCR mechanism remains a leading production candidate. The latest generation Envera VCR mechanisms is about 75% lighter than first generation PNGV hardware, can be packaged inside the oil pan of existing engine blocks, and has robust valve chain and power take-off systems.

The current DOE/NETL/Envera effort is directed towards reducing system cost and providing a fast actuator response. The technology has three main cost areas; the VCR mechanism; the actuator system for adjusting compression ratio; and the super or turbocharging hardware.

The Envera VCR mechanism comprises an eccentric carrier that holds the crankshaft of the engine. Pivoting of the eccentric carrier raises and lowers the crankshaft relative to the engine's cylinder head, and adjusts engine compression ratio. The Envera VCR eccentric carrier presently has a low cost.

A hydraulic actuator system is used to pivot the eccentric carrier. The current effort is directed towards reducing the cost of the actuator system and providing a fast actuator response.

## Approach

The current effort is directed towards the development of the actuator used for adjusting the pivot angle of the eccentric carrier. Development goals include low cost and a fast response. At the beginning of the NETL program mechanical loading on the VCR eccentric carrier and hydraulic system were evaluated using:

ProEngineer Wildfire 2.0	Part and mechanism assembly
MDO Extension	Dynamic force analysis
GTPower	Gas force on the piston (prior data)
Origin 7.5	Data conversion

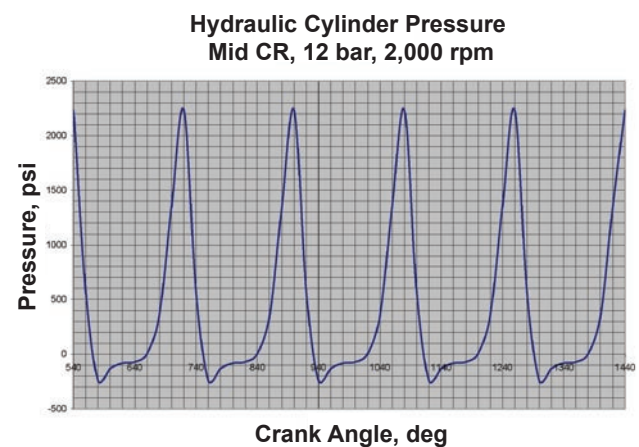
Dynamic loads were modeled at five conditions:

2,000 rpm	4 bar bmep	Low CR
2,000 rpm	4 bar bmep	Mid CR
2,000 rpm	12 bar bmep	Mid CR
6,000 rpm	4 bar bmep	Mid CR
6,000 rpm	12 bar bmep	Mid CR

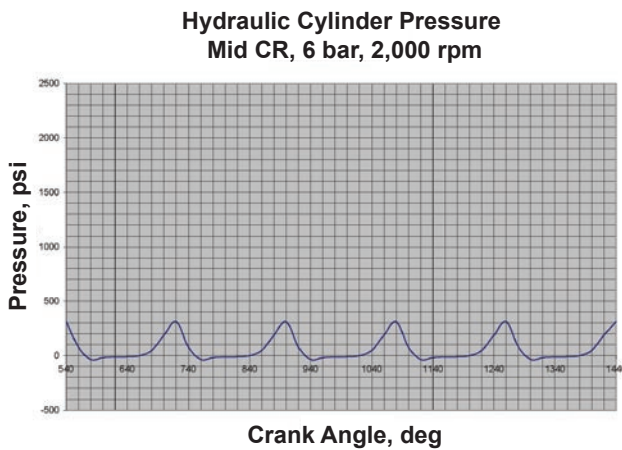
## Results

The 2,000 rpm, 12 bar bmep condition causes the highest loading on the hydraulic system. Figure 1 shows a maximum hydraulic pressure inside the hydraulic cylinder of about 2,250 psi. At higher engine speeds the loads are reversing and peak loads smaller due to the inertial effects of the piston.

As can be seen in Figure 1, the hydraulic cylinder pressure is under 400 psi for 2/3<sup>ths</sup> of the crank angle rotation.



**FIGURE 1.** Base case hydraulic cylinder pressure vs. crank angle at mid compression ratio. Peak hydraulic cylinder pressure is approximately 2,250 psi.



**FIGURE 2.** Optimized system hydraulic cylinder pressure vs. crank angle at mid compression ratio. Peak hydraulic cylinder pressure is approximately 314 psi.

The analysis showed a peak hydraulic pressure larger than desirable, but the lower range pressures generally reasonable. Envera pursued reducing the size of the hydraulic pressure spikes through system optimization. Through this effort peak hydraulic pressures have now been reduced to an estimated 314 psi, an 86 percent reduction in peak pressure. This reduction in peak pressure is a huge improvement. Figure 2 shows the estimated hydraulic cylinder pressure of the newly optimized hydraulic system.

A test rig was designed for evaluating actuator system response under load. The system is currently being assembled. Testing will take place at the end of the current project's Phase I.

## Conclusion

- During Phase I of the project hydraulic pressures in the actuator system were reduced by 86% through system optimization. The reduction in pressure will significantly relax the demands placed on the hydraulic actuator system.
- Down-sized gasoline VCR engines having optimized combustion can provide very large fuel economy benefits, and attain low tail-pipe emission levels using proven catalytic converter technology. The SI VCR engine can be operated on alternative fuels such as ethanol and butanol derived from switch grass.

## References

1. Mendler, Charles (ENVERA): High Efficiency Vehicle and Engine, US Patent Number 5,819,702, October 13, 1998.
2. Drangel, H., Olofsson, E., and Reinmann, R.(SAAB): Variable Compression (SVC) and the Combustion Control (SCC) – Two Ways to Improve Fuel Economy and Still Comply with World-Wide Emissions Requirements, SAE Paper 2002-01-0996, 2002.
3. Automotive Engineering International (SAAB), pages 54-57, SAE, April 2001.
4. Automotive Engineer (SAAB), page 36, December 2000.
5. FEV Spectrum, Issue 22, February 2003.
6. Yapici, K. I. (FEV), US Patent No. 6,588,384 B2, July 8, 2003.
7. Moteki, K. et al. (NISSAN): A study of a Variable Compression Ratio System with Multi-Link Mechanism, SAE paper 2003-01-0921, 2003.
8. Automotive Engineering International (NISSAN), pages 76-78, SAE September 2003.
9. Gravel, R., and Mendler, C.(DOE, ENVERA): Variable Compression Ration (VCR) Engine, OAAAT Accomplishments, [www.eere.energy.gov/vehiclesandfuels/pdfs/success/vcr3\\_29\\_01.pdf](http://www.eere.energy.gov/vehiclesandfuels/pdfs/success/vcr3_29_01.pdf)
10. European Commission, Community Research, Variable Compression Ratio Technology for CO2 Reduction of Gasoline Engine Passenger Cars, [europa.eu.int/comm/research/conferences/2002/pdf/presspacks/1-1-vcr\\_en.pdf](http://europa.eu.int/comm/research/conferences/2002/pdf/presspacks/1-1-vcr_en.pdf)
11. Natj, Paul (GM): The Wall Street Journal Online and on page B1, Autos: Car Makers Seek New Spark In Gas Engines, September 28, 2004.
12. Mendler, Charles (ENVERA): Variable Compression Ratio Engine, DOE FY 2003 Advanced Combustion Technologies Annual Report, US Department of Energy, 2003.
13. Mendler, Charles (ENVERA): Variable Compression Ratio Engine, DOE FY 2004 Advanced Combustion Technologies Annual Report, US Department of Energy, 2004.
14. Advanced Combustion and Emission Control Technical Roadmap for Light-Duty Powertrains, US Department of Energy, May 2006.

