SOLENOID ACTUATED CYLINDER DEACTIVATION VALVETRAIN FOR DYNAMIC SKIP FIRE

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Delphi Technologies

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Delphi Technologies

Project ID: ACS122
DE-EE0007811

Delphi Technologies

ACS122 Project Overview

Timeline

- **Project start: 01/01/2017**
- **Project end: 07/01/2019**
- **Percent complete: 35%**

Objectives

- Improve engine fuel efficiency by developing a production-feasible electrically actuated cylinder deactivation valvetrain which will enable internal combustion engines to operate more efficiently than what is possible with current hydraulic cylinder deactivation.
- The project is expected to enable the realization of 8% to 10% fuel economy improvement above stock operation in many 4-cylinder engine applications, while maintaining production-level noise, harshness, and vibration (NVH) targets and emissions.

Budget

- **Total project funding share**
  - DOE share: $1,736,338 (50%)
  - Delphi share: $1,736,338 (50%)
- **Budget Period Funding**
  - BP1 2017 DOE Funding : $678,605
  - BP2 2018 DOE Funding : $822,853
  - BP3 2019 DOE Funding : $234,880

Partners

- Delphi - Project Lead
- Tula Technology – Dynamic Skip Fire Cylinder deactivation algorithms

Relevance and Project Objectives

- Relevance:
  - The Enabling Technologies for Engine and Powertrain Systems subprogram supports the mission of the Vehicle Technologies Program to develop more energy-efficient and environmentally friendly technologies for highway transportation vehicles.
  - This project directly relates to the goal of:
    - Addressing 'existing barriers and limitations that inhibit using advanced technologies on a mass market basis to address national energy concerns'.
- Project Goal
  - The project will develop, implement and demonstrate an electrically actuated valvetrain system capable of meeting requirements for Dynamic Skip Fire combustion. The project targets 8-10% fuel economy improvement over a modern highly efficient downsized turbo direct injected engine

This project supports the Vehicle Technologies Program's goal to address existing barriers and limitations that inhibit using advanced technologies on a mass market basis to address national energy concerns

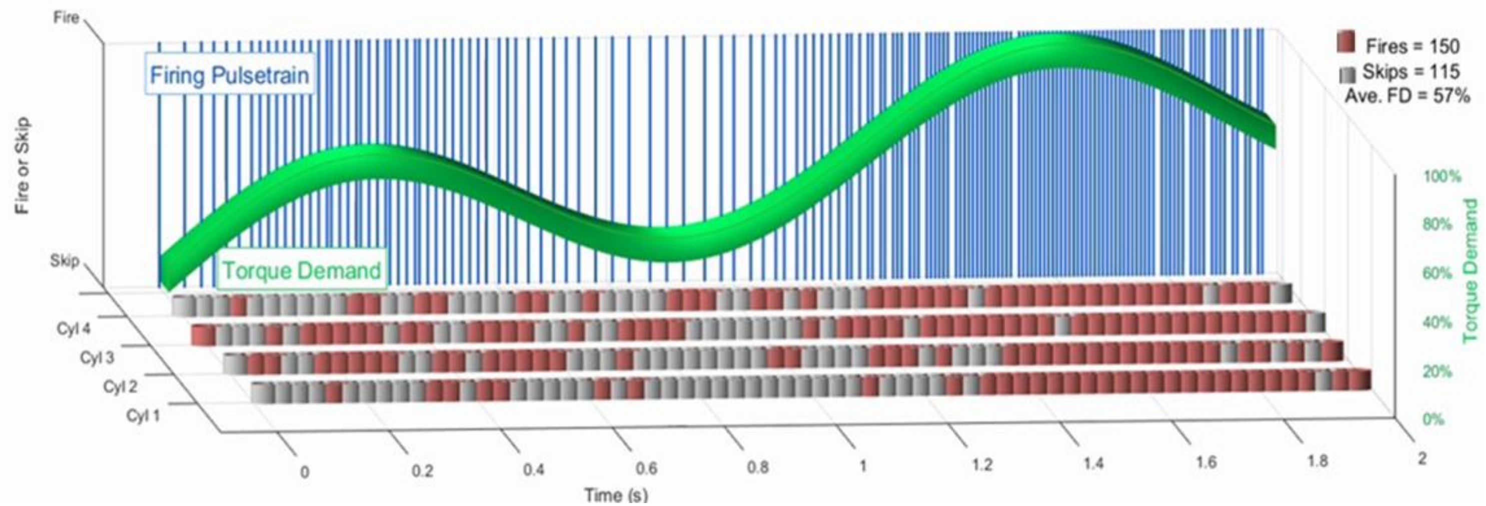
Relevance and Project Objectives – cont.

- Project Objective:
  - Design a solenoid actuated cylinder deactivation system for a broadly implemented overhead cam valvetrain architecture that maximizes potential Dynamic Skip Fire (DSF) fuel economy benefit and allows widespread implementation of DSF combustion strategy
- Objectives: (JAN 2017 – DEC 2017)
  - Complete engine simulation to define operating conditions and establish system requirements for optimized FE benefit
  - Design and evaluate solenoid actuated concepts and select a single concept for engine builds
  - Define control hardware and software requirements
  - Complete hardware design in order to integrate DSF system into an existing production cylinder head with minimal modifications

Project hardware and software designed with focus for rapid commercialization of this technology on engines that use popular SAE type 2 valvetrain architecture

Approach / Strategy
Dynamic Skip Fire Overview

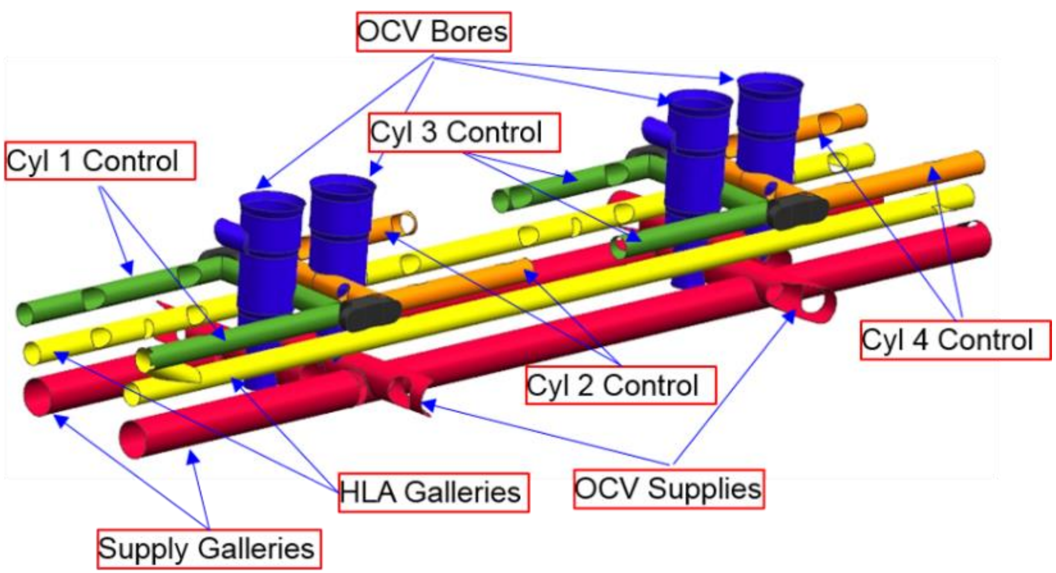
- This project employs a unique cylinder deactivation strategy called Dynamic Skip Fire (DSF)
  - Decision to “Fire” or “Skip” is made before each cylinder event depending on engine torque demand plus noise & vibration considerations
  - Enabled by individual cylinder deactivation
  - The resulting “firing density” is continuously variable between 0% and 100%



Continuously optimizes engine operation as conditions change to reduce pumping losses and improve combustion thermodynamics

Approach / Strategy
Reasoning for Electric Actuation

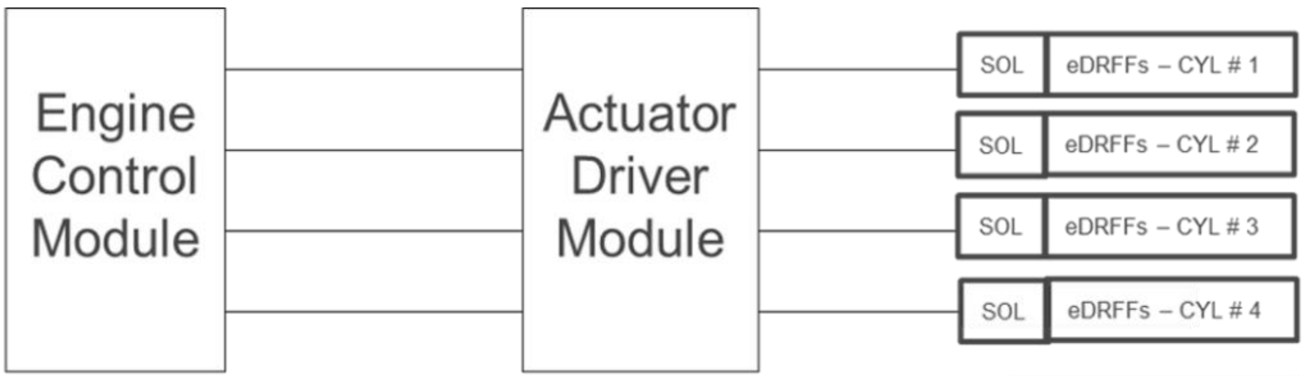
- *Successful commercialization of Dynamic Skip Fire combustion strategy is dependent on developing valvetrain hardware that minimizes OEM engine integration modifications while maximizing the potential operating window*
  - Applying hydraulic actuation from current fixed cylinder deactivation systems results in complex hydraulic circuitry which can be difficult to integrate.



Four independent hydraulic control circuits must be isolated from each other while being packaged into a cylinder head with is already cramped with spark plug tubes, valve springs, fuel injectors, and overhead cams

Approach / Strategy
Integrated System Approach

- Develop a fully integrated DSF system
  - Engine control module (ECM) with DSF calibration
  - Actuator driver module (ADM)
  - Solenoid mounting module with wiring
  - Direct acting solenoid
  - Switchable roller finger follower



Approach / Strategy: Milestones

- *Milestones and go/no-go's for 2017 – 2018 budget periods*

Milestone	Type	Description	Anticipated Quarter	Status
Engine simulation complete	Technical	Engine simulation is completed for selected 4-cylinder turbocharged engine	Q2 2017	Complete
Actuator concept(s)	Technical	Actuation concepts are narrowed down using simulation and available cylinder	Q3 2017	Complete
Control	Technical	The control hardware and software	Q2 2017	Complete
System Space Compatability	Go/No Go	Confirm selected valve deactivation mechanism and actuators fit within	Q4 2017	Complete
Demonstrate actuator control	Technical	Demonstrate functionality and interaction of ECM modifications and ADMs to control actuators and execute deactivation	Q3 2018	
Confirm operation of deactivation system	Technical	Demonstrate robust actuation and switching speed on a motored cylinder head stand, independent of oil	Q3 2018	
Baseline dyno engine	Technical	Document steady state fuel economy and emissions of the baseline engine	Q4 2018	
Control system functionality	Go/No Go	Confirm deactivation system meets modeled switching speed requirements on motored cylinder head and effectively	Q4 2018	

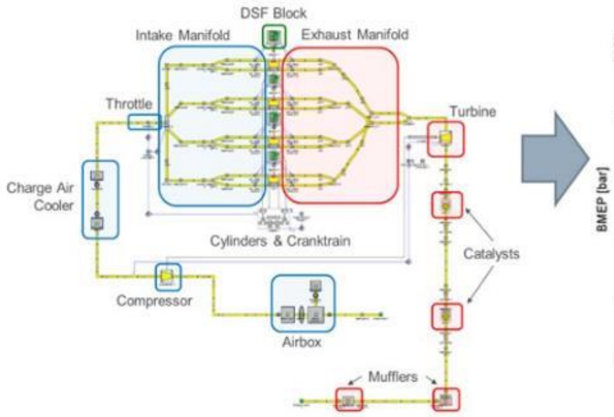
Any proposed future work is subject to change based on funding levels.

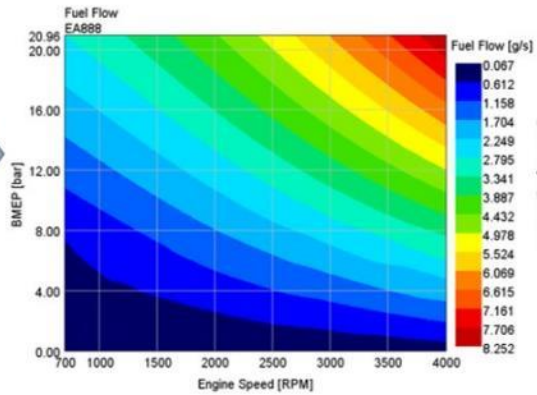
Technical Accomplishments and Progress: Overview

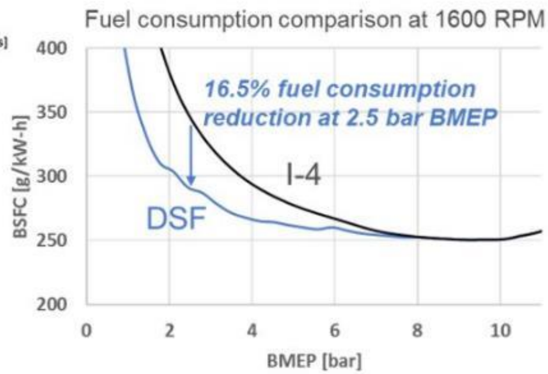
- Performed engine simulation to predict fuel economy benefit and establish system requirements
- Generated and evaluated various valvetrain concepts to select final design
- Performed analysis and testing to develop final design for technology demonstration engine build
- Developed system model to optimize response and establish Actuator Driver Module (ADM) requirements
- Completed system packaging into VW EA888 head
- Designed ADM architecture and defined wiring harness
- Determined Engine Management System (EMS) strategy and ECM interface with ADM

Technical Accomplishments and Progress: Engine simulation

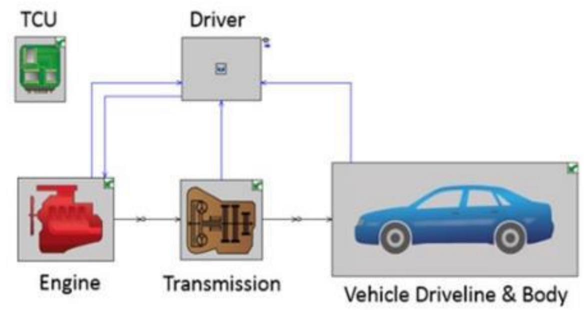
- 1.8-liter 4-cyl EA888 engine model developed and calibrated to measurements
- Fuel maps created for all-cylinder and DSF operation





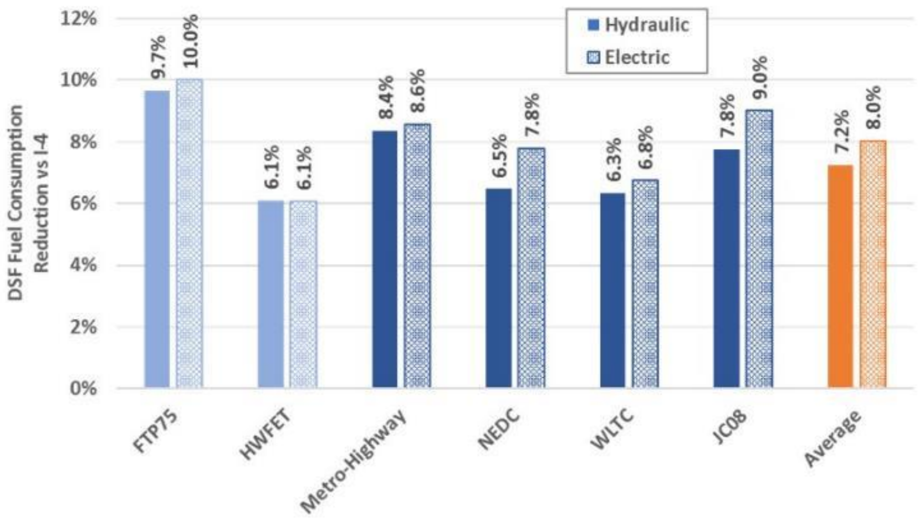


- Fuel maps incorporated into VW Jetta vehicle model
- Drive cycle simulations carried out to evaluate fuel consumption benefit due to DSF



Technical Accomplishments and Progress: Engine simulation

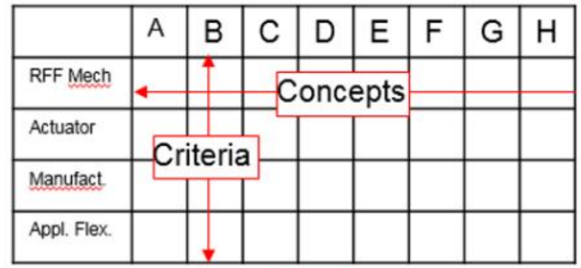
- Shifting to direct solenoid actuation from hydraulic actuation provides the following advantages
  - Reduces oil pump pressure and flow requirements
  - Larger operating envelope due to fast consistent switching response that is no longer sensitive to oil pressure, oil temperature (viscosity), and oil aeration related variation



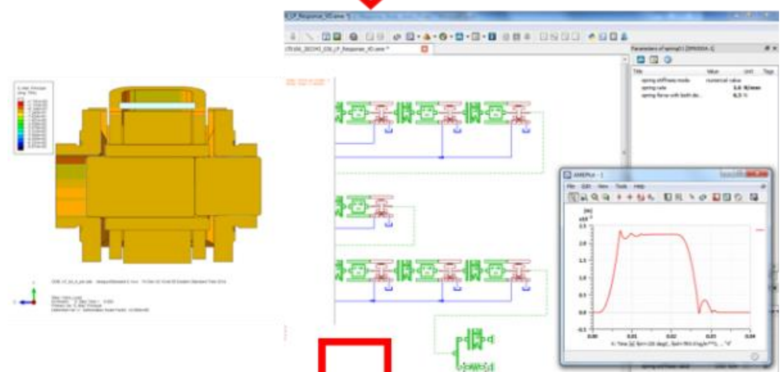
Independence from oil temperature and pressure requirements lead to earlier DSF enablement for cold-start driving cycles and larger fuel consumption reduction

Technical Accomplishments and Progress: Concept Selection

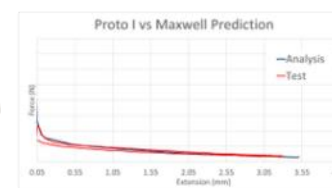
- **Several (22) concepts generated**



- **Analysis performed to select primary concepts**



- **Probe test hardware built to further evaluate concepts**



- **Completed final concept selection**

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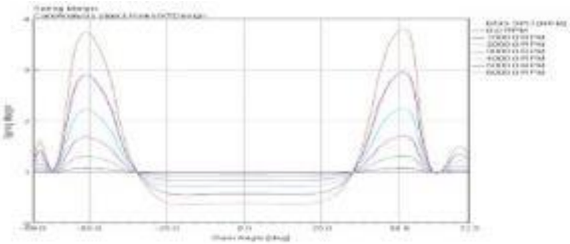
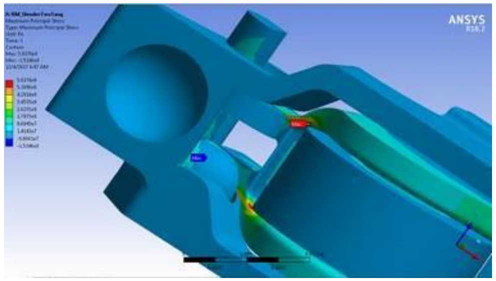
Technical Accomplishments and Progress: Concurrent Final Design Development Analysis

- Valvetrain Development
  - Dynamic analysis - used to optimize geometry & profiles and predict forces

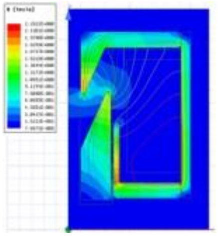


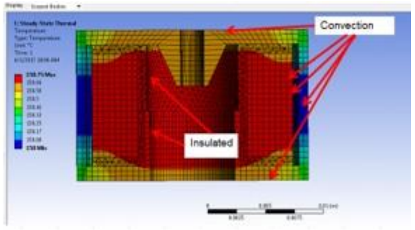
  - FEA analysis – used to optimize mass and evaluate stress and stiffness



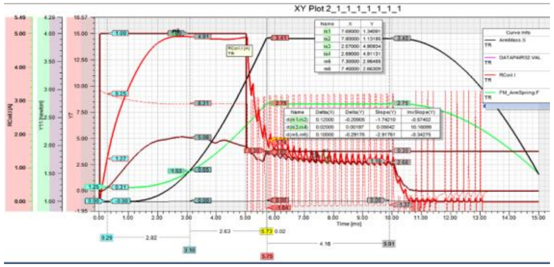
  - Tolerance analysis – used to optimize design for mass and stiffness and ensure proper function and clearances

- Actuation Development
  - Magnetic modeling – used to optimize solenoid design and meet packaging





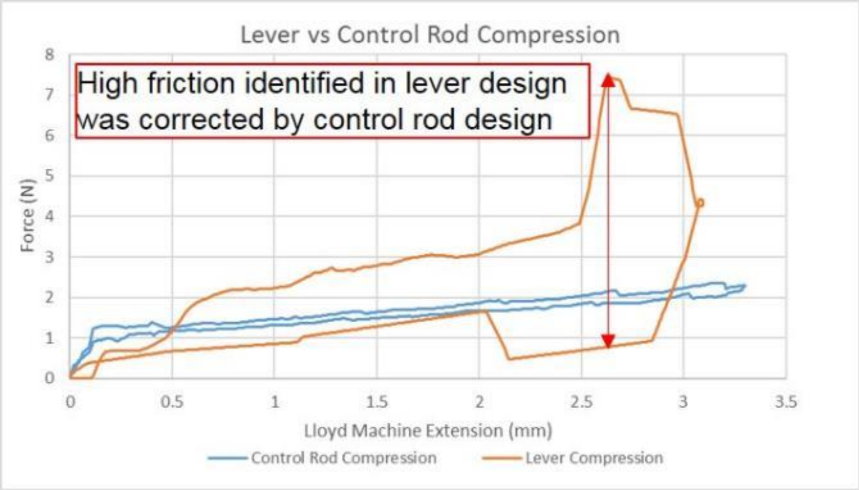
  - System response modeling – used for system optimization and ensure switching response requirements are met



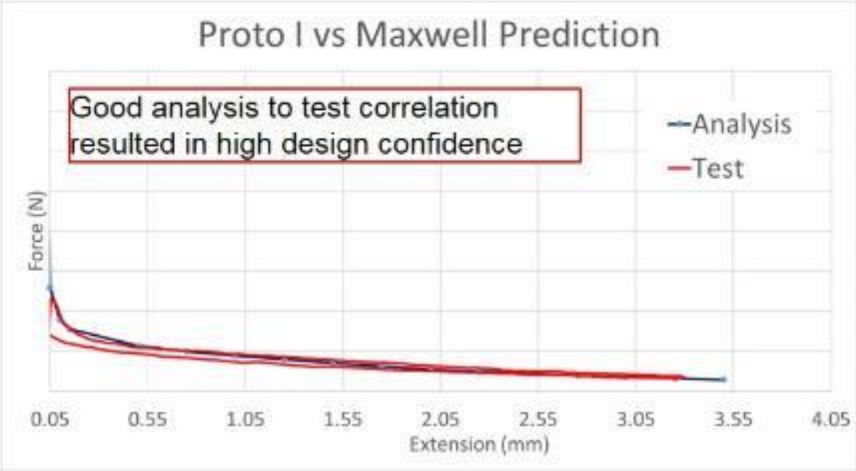
  - Tolerance analysis – used to ensure proper function while reducing cost

Technical Accomplishments and Progress: Concurrent Final Design Development Testing

- Valvetrain Development
  - Locking mechanism response

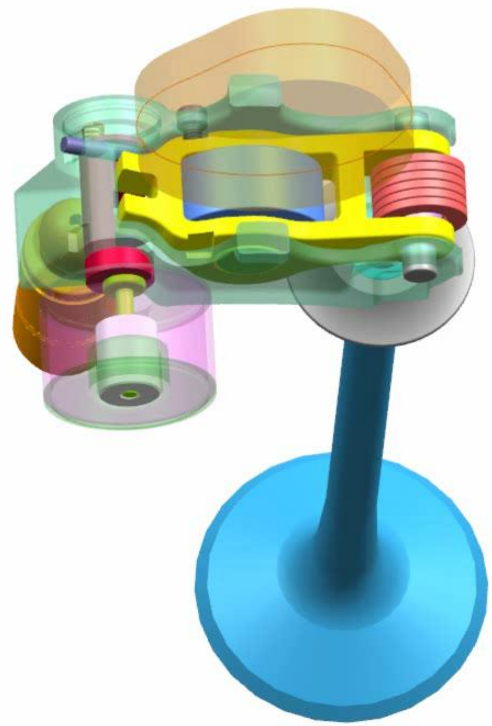


- Actuation Development
  - Solenoid response



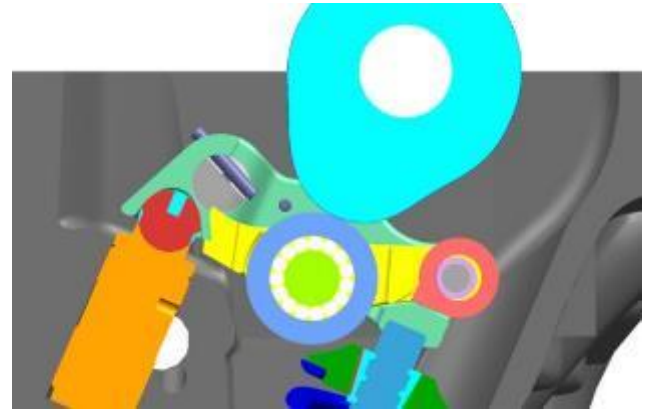
Technical Accomplishments and Progress: Final Design

- Final concepts evaluated on key performance and cost criteria as well as packaging flexibility and use of known low risk mechanisms
- Selected concept utilizes a solenoid acting directly on the lockpin of a switchable roller finger follower



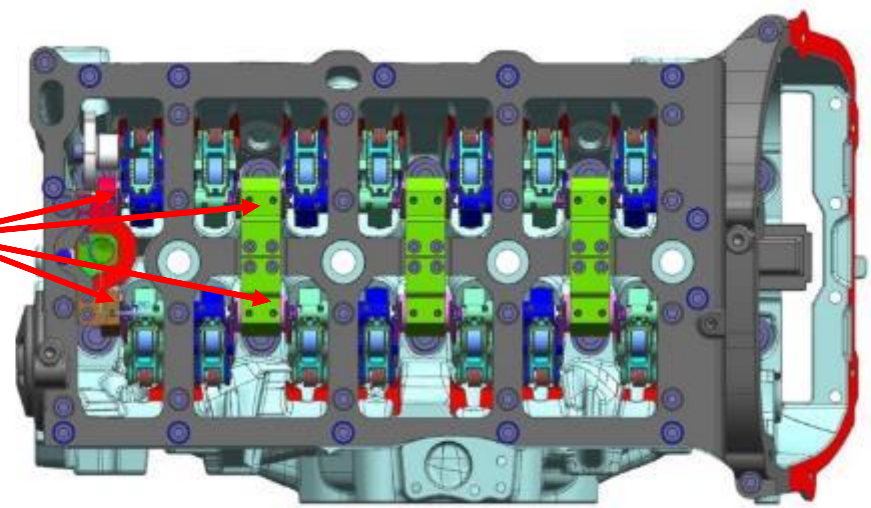
Technical Accomplishments and Progress: System Packaging – Go / No Go (passed)

- Evaluated switchable roller finger follower clearance including deactivated mode



- Designed upper cam bearing carrier to mount solenoids

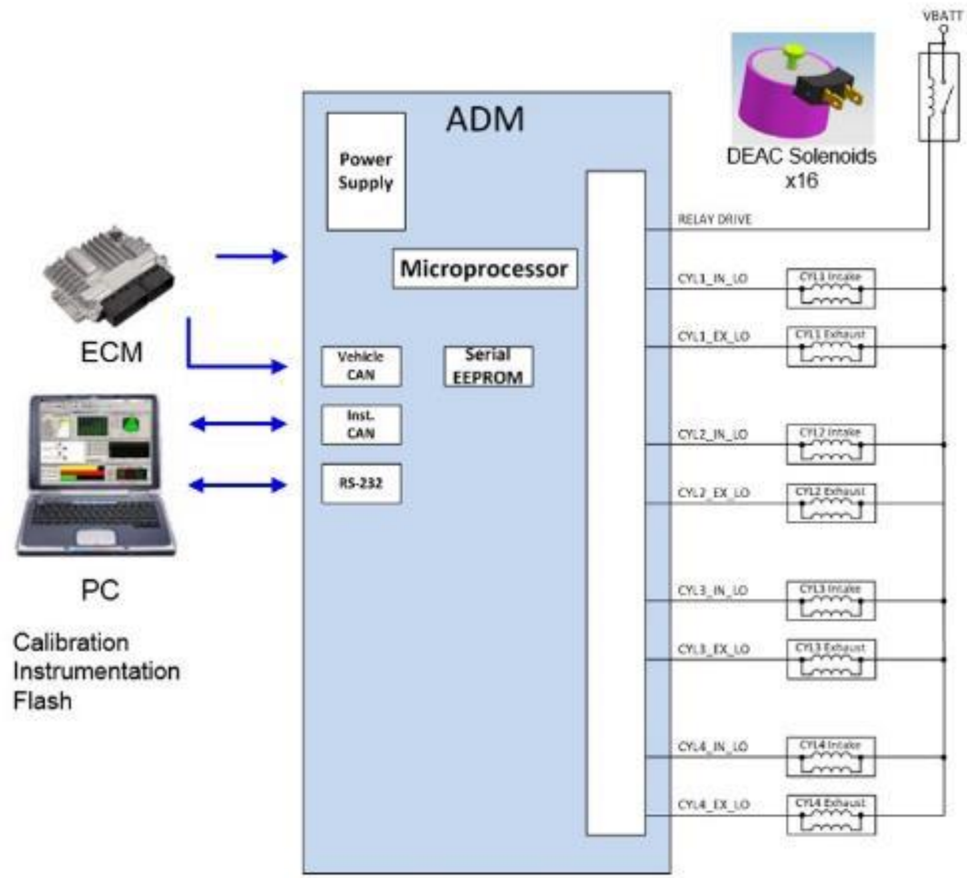
Solenoids are inside the brackets



- Project passed Go / No Go review Q4 2017

Technical Accomplishments and Progress: ADM Architecture

- Actuator Driver Module (ADM) requirements defined
- Several solenoid drive strategies evaluated
- Final ADM concept selected and developed
  - Circuit board assembly completed
  - Test bench set up
- Hardware / software integration completed
  - Debug completed – all functions checked
  - Solenoid control verified on bench
- ECM up-integration (future) is technically feasible



Responses to Previous Year Reviewers' Comments Collaboration and Coordination with Other Institutions

- This project was not presented at last years AMR so no comments are available – our project team looks forward to your feedback this year.

Collaboration and Coordination with Other Institutions

Delphi Technologies

- Cylinder deactivation hardware
- Engine control hardware and software
- Engine calibration and dyno testing

Delphi Technologies

Rochester, NY
Kokomo, IN
Troy, MI

Tula Technology Inc.

- Dynamic Skip Fire Cylinder deactivation algorithm development and calibration
- Engine and vehicle simulation

TULA

San Jose, CA
Plymouth, MI

Remaining Challenges and Barriers Proposed Future Research – Next Steps

- **Remaining Challenges and Barriers**
  - Demonstrate new hardware design durability with high cycle requirements for Dynamic Skip Fire
  - Address production implementation concerns including cylinder head stack up issues
  - Demonstrate fuel economy

- **Proposed Future Research – Next Steps**
  - Complete system hardware build
  - Test system performance and durability
  - Build up dyno engine
  - Complete calibration and document fuel economy benefits

Any proposed future work is subject to change based on funding levels.

Summary

- Excellent progress has been made over the past year
- Cross functional team of experts has been gathered to develop full system
- Engine and vehicle level simulation completed leading to system requirements
- Valvetrain hardware concepts were evaluated and final selection was completed, designed for packaging constraints, and detailed for build
- Engine control and hardware driver requirements established, solutions designed, and prototypes built and tested
- Future Work for Calendar Year 2018:
  - Complete valvetrain hardware build and confirmation testing (performance & durability)
  - Establish baseline engine fuel economy
  - Implement hardware and controls onto a firing engine

Any proposed future work is subject to change based on funding levels.


Thank you to the
Department of Energy for
supporting this project.

Technical Backup Slides

Project ID: ACE094
DE-EE0006839

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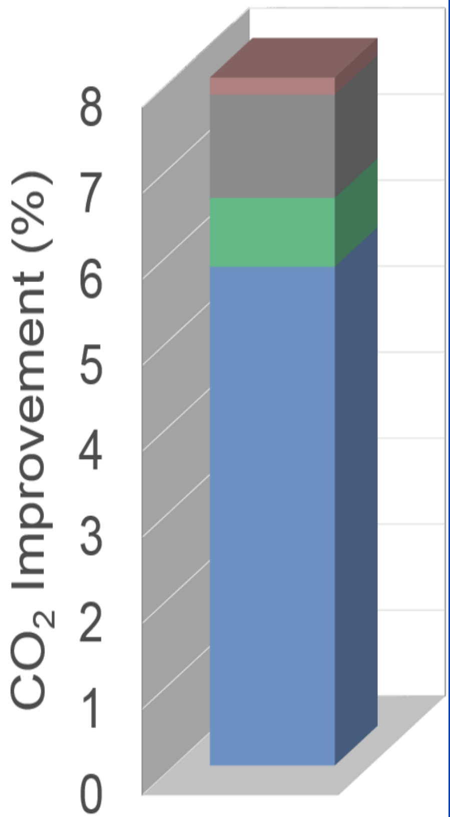
Approach / Strategy
Sources of Fuel Economy Improvement



- Fast Torque Control
  - Immediate torque reductions without spark retard
  - Improved time-to-torque response due to higher MAP
- Deceleration Cylinder Cut Off (DCCO)
  - Eliminates catalyst saturation with O_2 and associated refuel
- Improvements in Combustion
  - Higher cylinder loads improves burn rate and reduces misfire
  - Firing combustion stability improved dramatically
- Reduction in pumping losses

Approach / Strategy
Background – hydraulically actuated system