R&D of Natural Gas D-EGR Engine for Improved On-Highway Efficiency

SOUTHWEST RESEARCH INSTITUTE®

Michael Kocsis
Sr. Research Engineer

21 February 2018

Acknowledgements

CALIFORNIA ENERGY COMMISSION

WOODWARD

SoCalGas A Sempra Energy utility®

Honeywell

Solicitation Purpose (GFO-16-507)

- California Energy Commission funded research to develop advanced engine efficiency improvement technologies for HD natural gas vehicles
  - Necessary to support California's air quality improvement and green house gas reduction initiatives
- Current natural gas engines are 10-20% less efficient compared to heavy duty diesel
  - Stoichiometric NG engines have potential for near zero NO_x emissions

SwRI's Solution

- SwRI proposed D-EGR on a Cummins ISX-12G engine combined with an advanced ignition system, charge motion development and high efficiency turbo as a potential solution
- Previous SwRI research
  - D-EGR IR project on ISX-12G
    - Showed D-EGR potential, but without efficiency improvement
    - Engine was dilution limited and could not run rich enough to gain benefit from hydrogen production
    - Did not take advantage of compression ratio increase possible with higher dilution levels
  - CARB Low NOx
    - Demonstrated 0.02 g/bhp-hr NO_x on ISX-12G
    - Slight efficiency penalty due to rich bias
      - Follow-on work project gained most of efficiency loss back
  - HEDGE
    - Engine was less dilution tolerant than expected
      - Combustion visualization showed early flame staying centered about spark plug

Project Goals and Objectives

- Goals:
  - 10% efficiency gain over base engine
  - 0.02 g/bhp-hr NO_x
- Objectives
  - Extend dilution limit through the use of advanced ignition systems
    - Rank ignition system performance benefit
  - Extend dilution limit through combustion system development
    - Swirl flow field not ideal for spark ignited combustion
  - Increase compression ratio
  - Reduce pumping work through optimization of turbocharger hardware and EGR delivery method

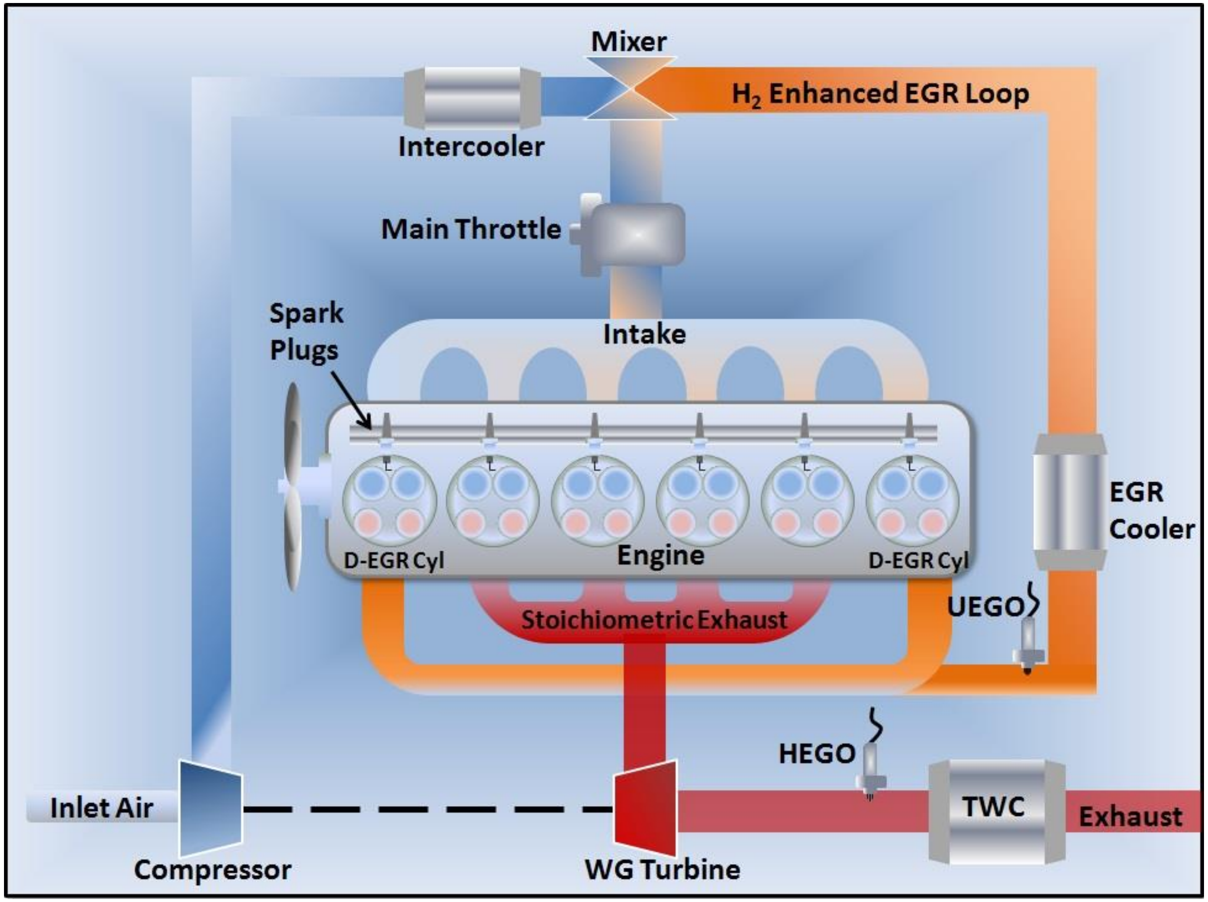
SwRI Design for Dilute Operation

- SwRI lessons learned through the years to extend dilution tolerance
  - High energy ignition systems
    - Faster 0-2% MFB reduced variability in the early flame kernel development
  - Improve burn-rates through chemical enhancement
    - H_2 has significant impact on 10-90% MFB
  - High level of TKE
    - High tumble ports
    - Low B/S ratio (<0.85)
  - High CR
    - Balance knock/stability limit

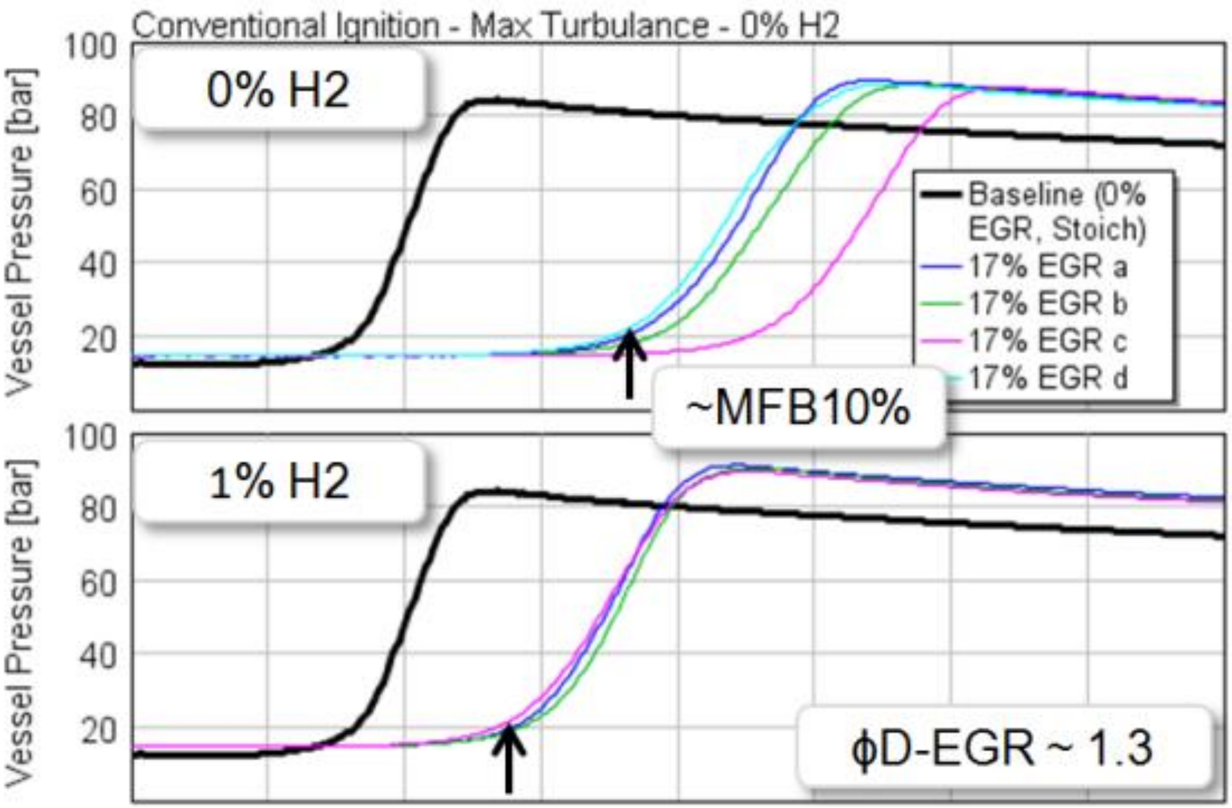
Challenge for NG engines converted from HD Diesel

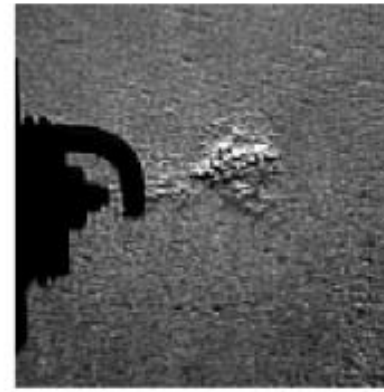
D-EGR on Natural Gas

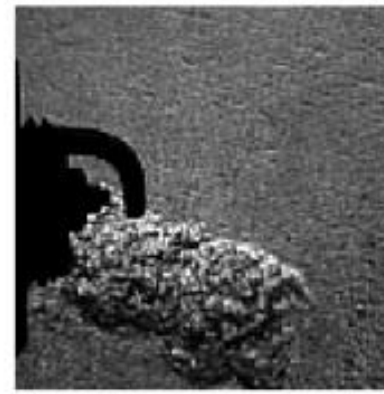
- Natural Gas D-EGR engine (6 cylinders)



Benefit of Reformate

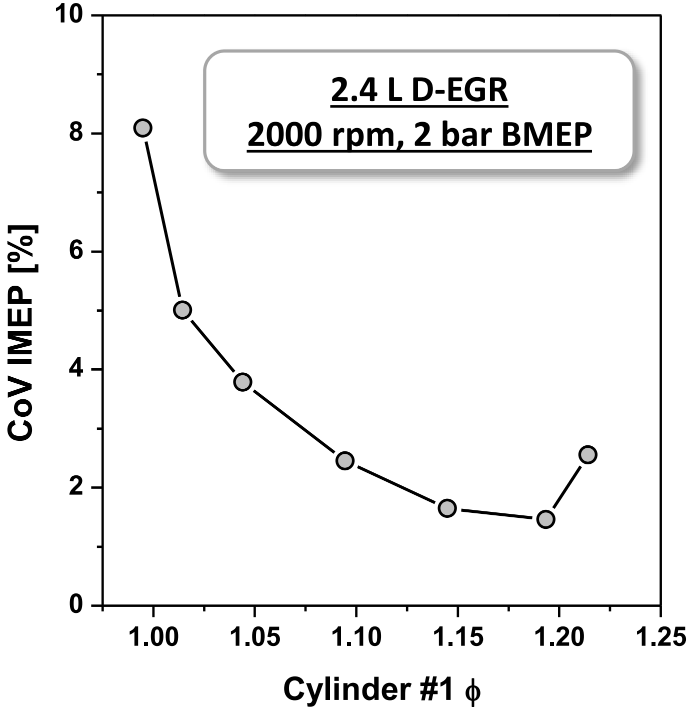


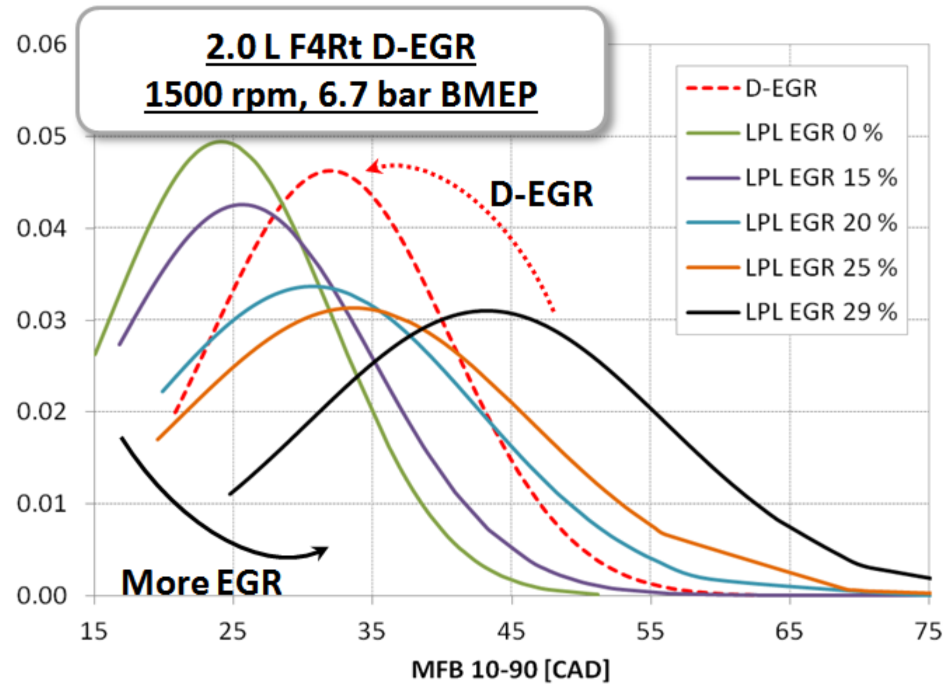




- Dilution tolerance enabled by 1% H_2 is significantly better than without H_2
  - EGR tolerance
  - Combustion stability
  - Combustion efficiency

Flame Speed and Stability with D-EGR





Reformate improves

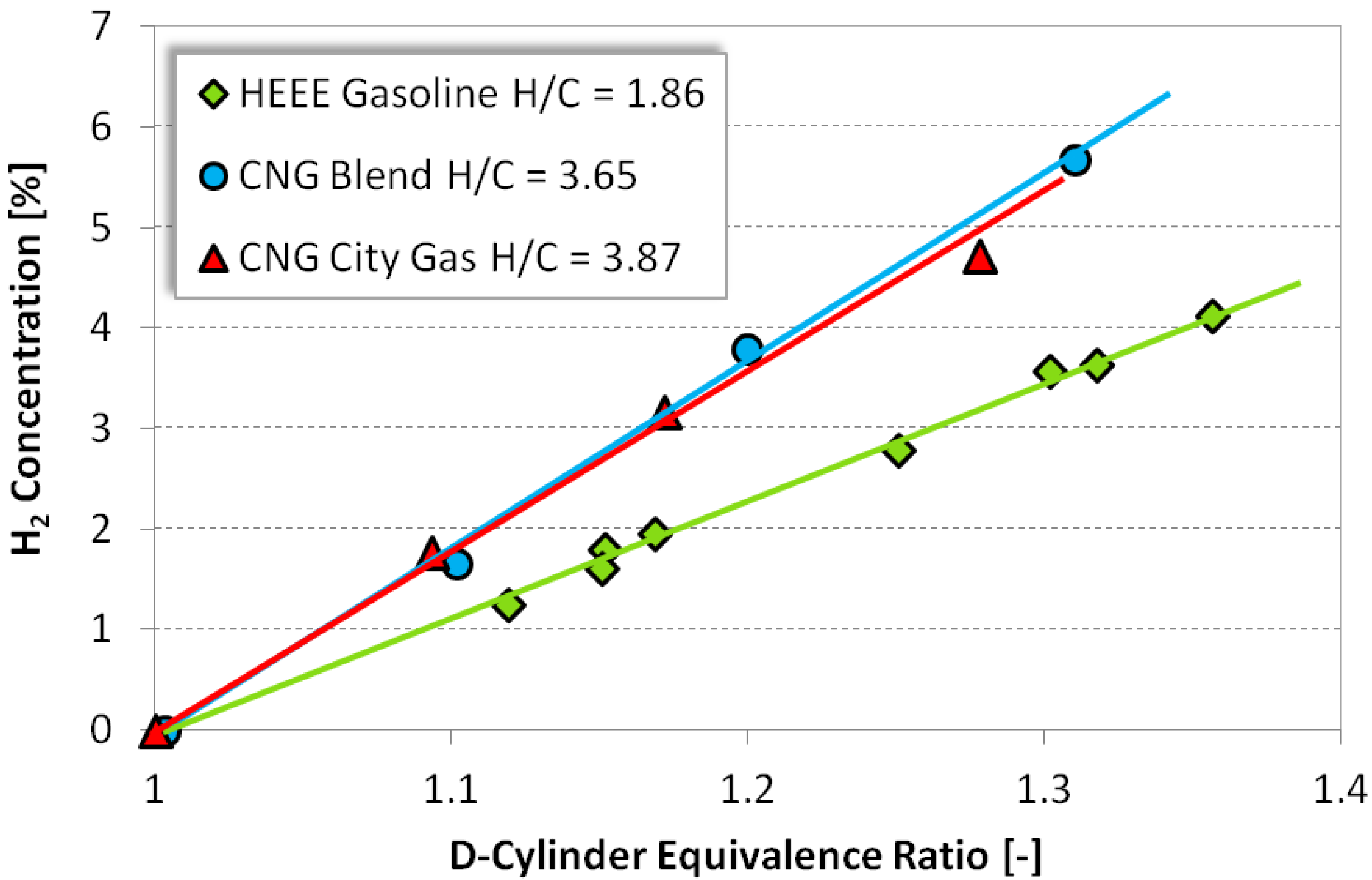
- Dilution tolerance
- Laminar flame speed
- Initial kernel formation

→

Result

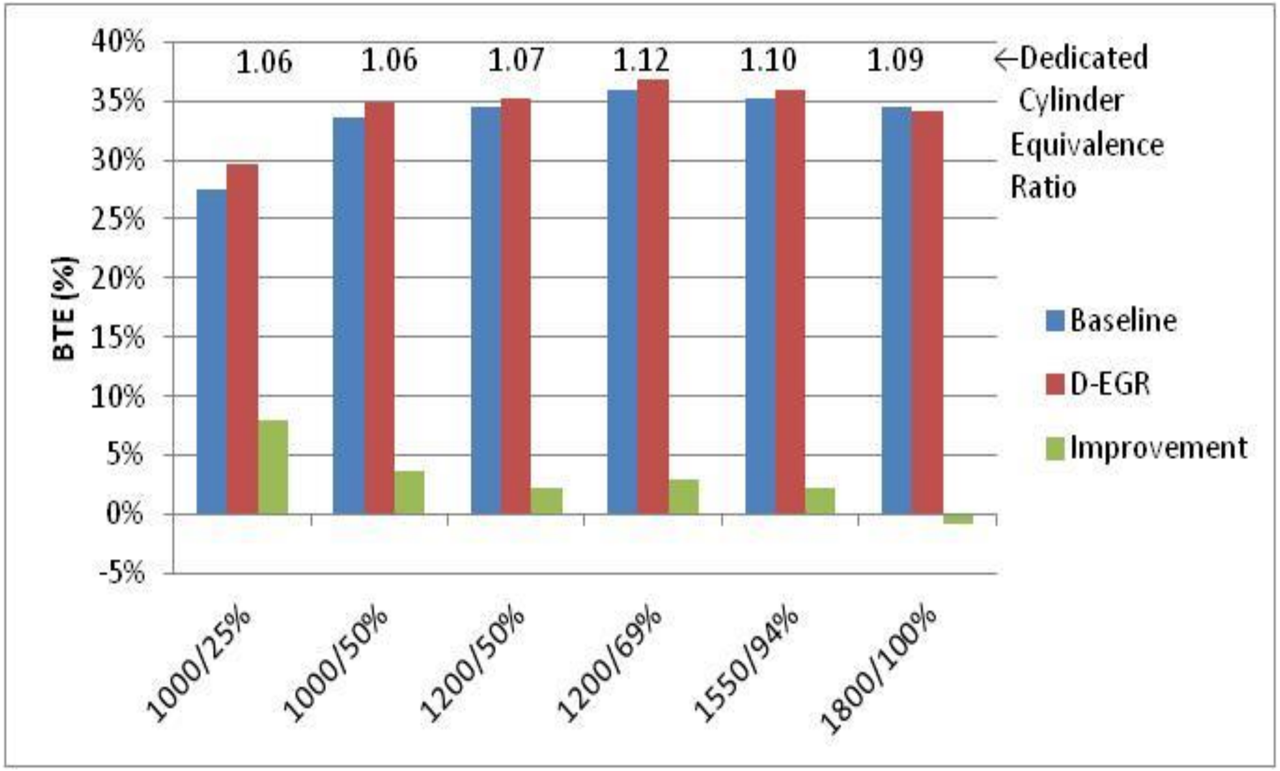
- Improved stability
- Improved robustness
- Improved η_{comb}

NG Hydrogen Potential

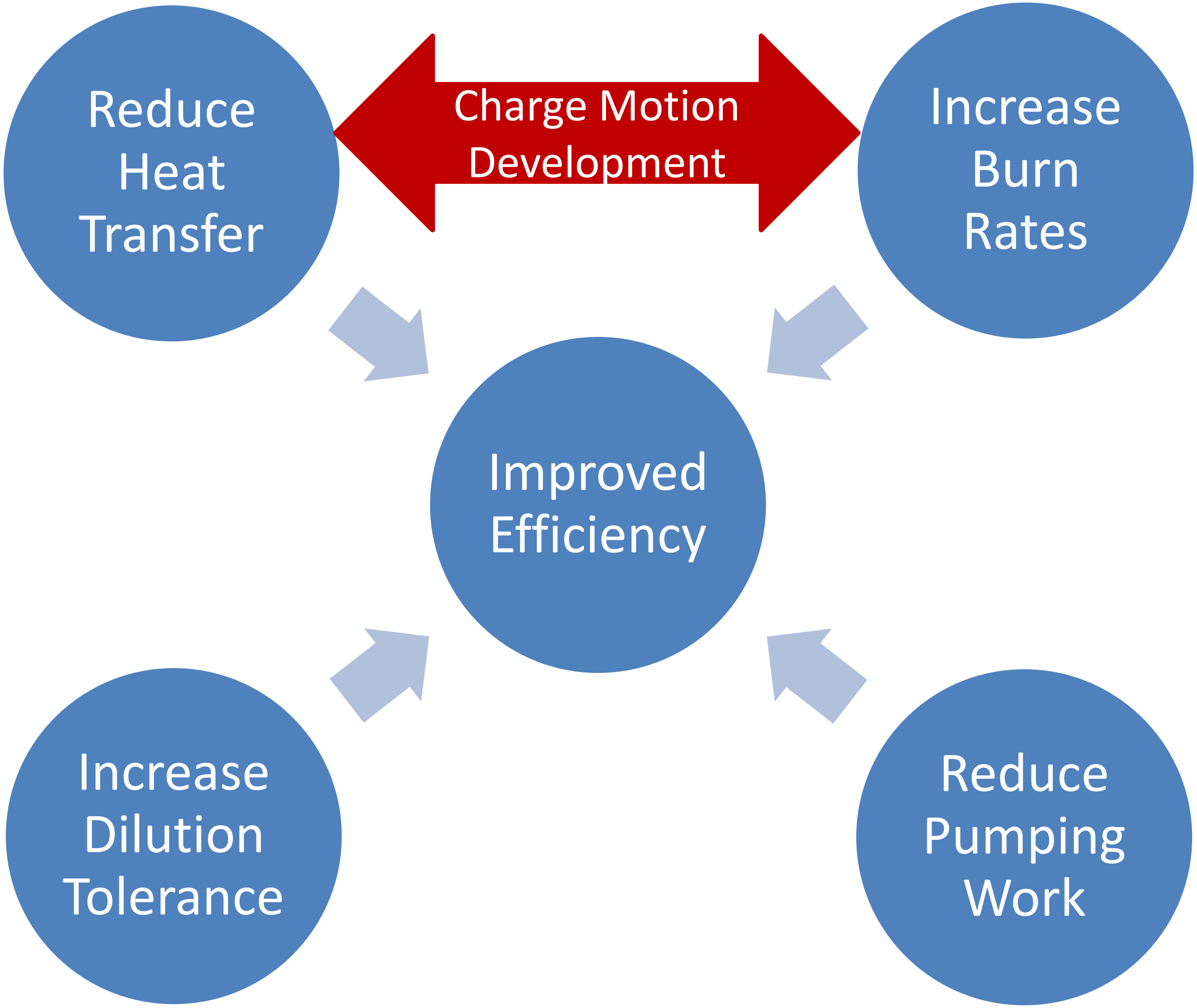


Previous SwRI Internal Research
HD NG D-EGR (ISX-12G)

- Efficiency gains were small
- **Dedicated cylinder equivalence ratio was lower than desired**
  - Limited by combustion stability with 33% EGR and rich operation

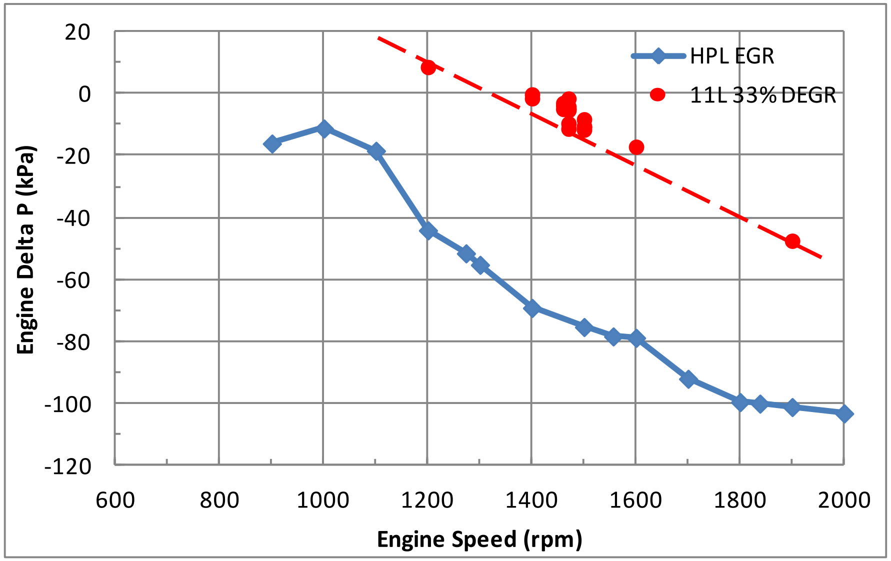


Project Plan



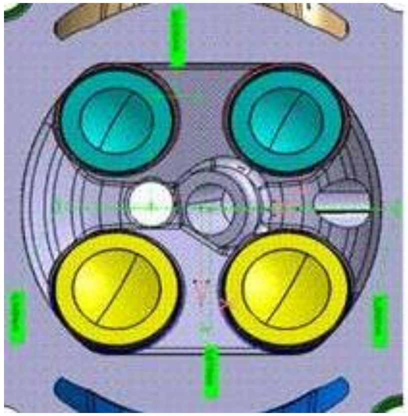
Potential Areas for Improvement

- Piston has large amounts of squish to generate turbulence needed for fast burn rates
  - Open bowl piston design will reduce heat transfer
    - Charge motion / ignition system needs to improve burn rates
- Turbo matching
  - D-EGR cylinders act as EGR pump; turbine does not need to be sized to provide the pressure ratio necessary to flow EGR



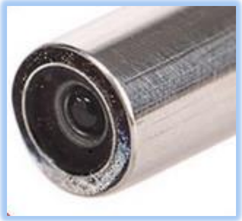
Charge Motion Development

- Acquire optical combustion data to calibrate baseline CFD model
- Refine port / piston design
  - Reduce swirl / Increase tumble
    - Limited by flat head design
  - Turbulent ignition system will reduce the required turbulence generated by combustion chamber
  - Objective is to have flame drift towards exhaust valve



Optical Combustion – LSPI Setup

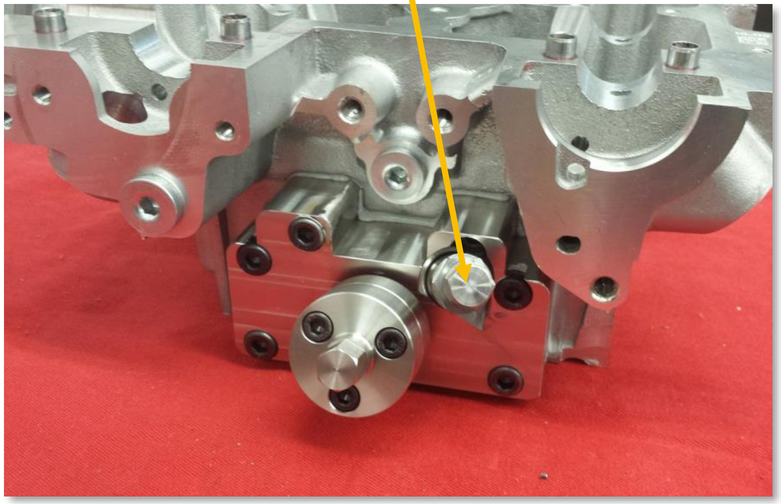
- Optical setup includes larger optics
  - ~1mm optics to ~5mm optics



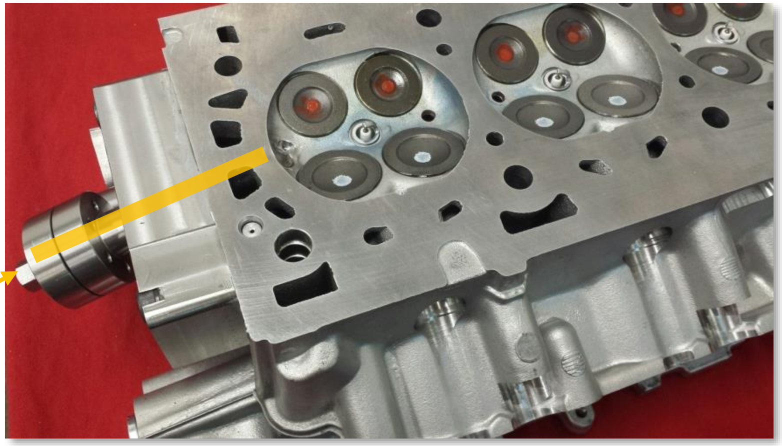
Typical configuration of a commercial borescope input optical lens. Size constrained by borescope design and cooling requirements

- Increased light throughput demonstrated compared to commercial borescope

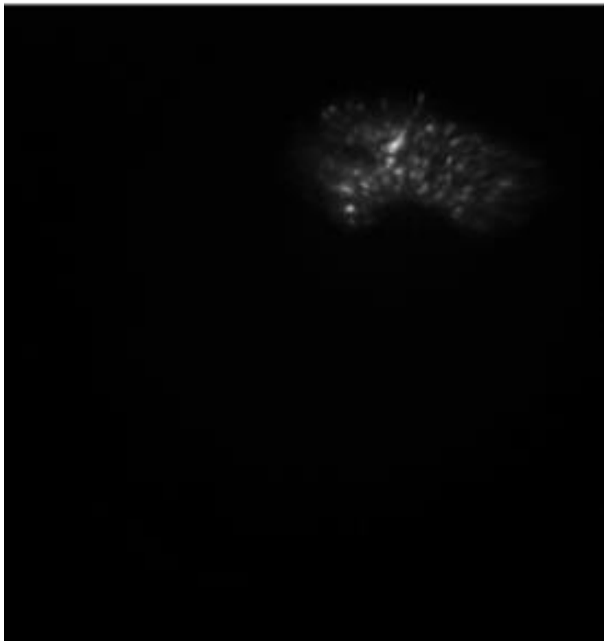
Port for Laser



A through hole in the cylinder head provides space for the updated borescope with larger optical components

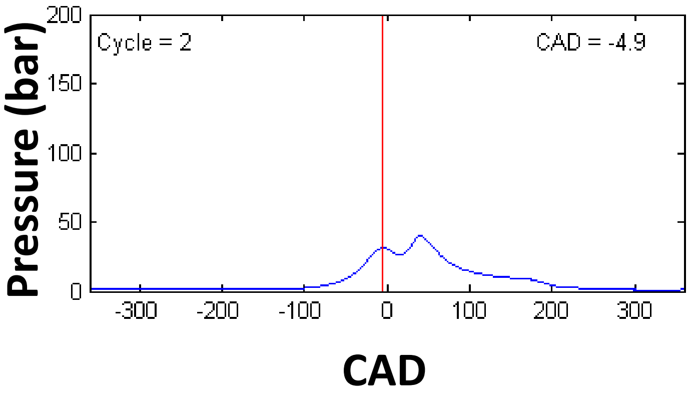


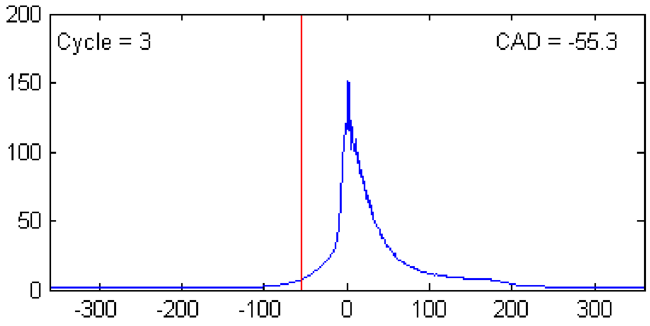
Optical Combustion - LSPI



Normal Combustion

LSPI Cycle





General Methods for Improving Ignition Systems

Reduce / overcome HT losses in the gap

- High power and/or high energy systems
- Long duration discharges (continuous or discontinuous)
- Volumetric devices
- Large gap spark plugs

Couple with the flow field

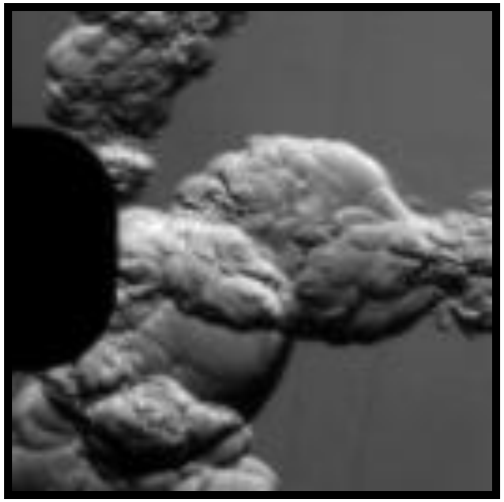
- Long duration discharges
- Indexed spark plugs or custom gaps

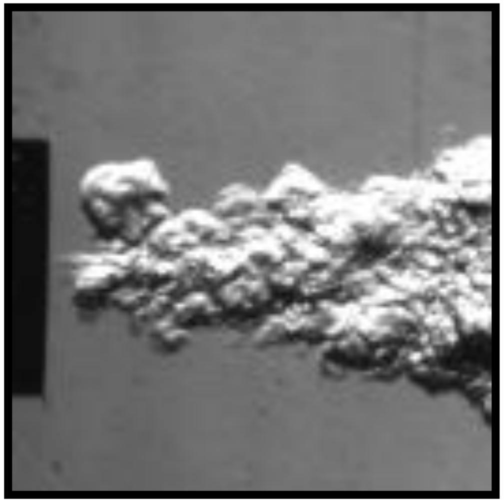
Improve robustness

- Repeatable events
- High power / high energy systems
- Jet or torch type systems
- Long duration discharges

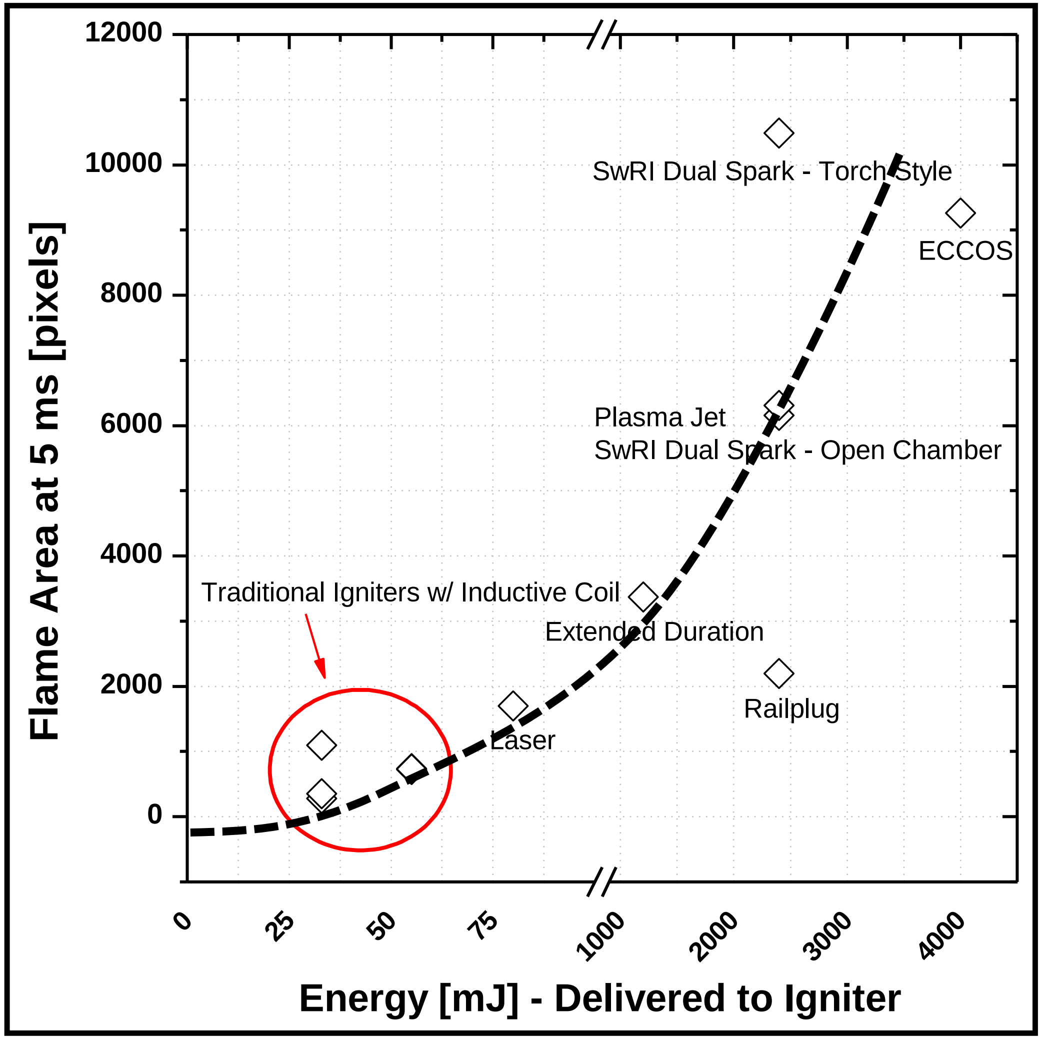
Technologies for Improved Ignition

- Spark plug hardware
  - Fine center electrodes
  - Large gaps
  - Design for low heat transfer plugs
- "Traditional" coil designs
  - Long duration, single discharge units
  - Multi-strike applications
  - Continuous discharge systems
    - DCO
    - Others as shown at IAV Ignition Conference
- Unique or non-traditional designs
  - Pre-chamber
    - Fuelled (with or without air)
    - Un-fuelled
  - RF discharge
    - Corona
  - Plasma jet
  - Railplug
  - Continuous discharge systems
    - A/C Ignition



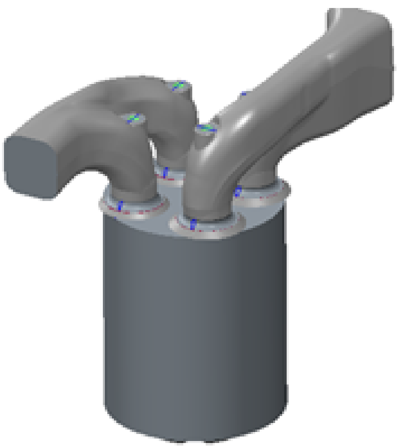


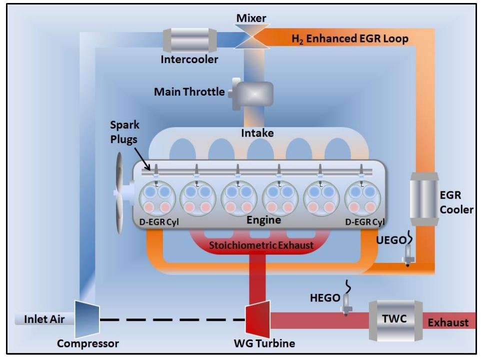
Advanced Ignition System Previous SwRI Evaluation

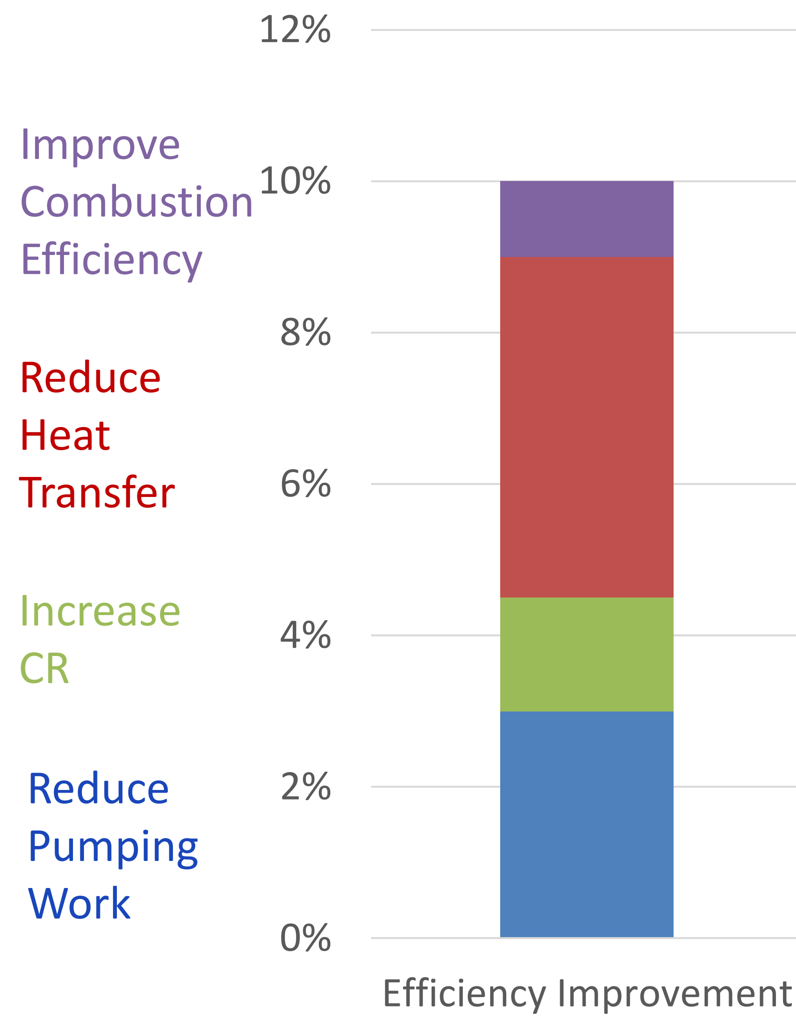


- Higher energy levels resulted in increased performance
  - High energy levels overcome heat transfer losses
- Large initial flame areas yielded significant improvements in flame development speed
  - Jet / torch style plugs yielded improved initial burn rate
- Increasing spark duration had a beneficial effect
- Dual fine wire design was the best of "traditional" igniters
- **Not all technologies transferred to engine**
  - Challenged by charge motion, scavenging, etc.

Areas of Improvement







Conclusions

- SwRI plans to take a systems level approach to improve losses at a fundamental level and increase overall efficiency by 10%
  - Improve combustion efficiency
    - H_2 from D-EGR operation
    - Reduces squish piston
  - Reduce heat transfer
    - Increased dilution tolerance via advanced ignition systems
    - Charge motion development
  - Increase CR
    - Increased dilution tolerance via advanced ignition systems and charge motion development
    - Increased burn rates via H_2 from D-EGR operation
    - Reduced back pressure from advanced turbocharger
  - Reduce pumping work
    - Advanced turbocharger
    - Reduced TKE from charge motion

Question and Answer

- Project Manager
  - Michael Kocsis
  - michael.kocsis@swri.org
  - (210) 522-3751

Southwest Research Institute®