High Efficiency GDI Engine Research with Emphasis on Ignition Systems

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Overview

Timeline
- Project start: FY 2013
- Project end: ongoing

Budget
- Funding in FY13: $400k
- Funding in FY14: $350k

Barriers
Robust lean-burn and EGR-diluted combustion technology and controls, especially relevant to the growing trend of boosting and down-sizing engines...
- Limited lean and EGR-diluted operating range
- Lack of systematic assessment of ignition systems and their potential in combination with lean/dilute combustion
- Absence of robust modeling tools

Partners
- Ford (engine hardware)
- Altronic, LLC. (DEIS ignition system)
- CSU, Seaforth, LLC. (laser ignition)
- Sandia Natl Lab (optical engine data)
Dilute combustion in advanced gasoline SI engines offers the greatest potential for decreasing petroleum consumption, since gasoline is the most widely produced and used fuel in the US — a trend expected to continue for the foreseeable future\(^1\).

For the US market, dilute combustion currently translates to stoichiometric operation with ever increasing EGR levels.

Honda R&D recently published lean-burn efficiency data (33.7 to 39.9% ITE at 1500RPM 5 bar IMEP, AFR 14 to 30, 2000 ppm to 30 ppm NOx)\(^2\).

Recent developments in Pumped Solid State Lasers show promise for integration in automotive Spark Ignition (SI) engine applications.
Maximize efficiency benefits and minimize NOx emissions from automotive GDI engines

- Broaden the lean and EGR-dilute operating range
- Investigate ignition systems systematically and determine compatibility with lean/dilute combustion
- Provide robust modeling tools for rapidly screening proposed designs based on sound metrics
### Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2013</td>
<td>Upgrade to spray-guided DI configuration</td>
<td>Complete</td>
</tr>
<tr>
<td>June 2013</td>
<td>Ranking of ignition systems</td>
<td>Complete</td>
</tr>
<tr>
<td>Sept 2013</td>
<td>Cyclic variability study with dilute operation</td>
<td>Complete</td>
</tr>
<tr>
<td>Dec 2013</td>
<td>Evaluation of advanced spark-based ignition systems</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2014</td>
<td>Meet with Sandia to coordinate collaboration on ignition system projects</td>
<td>Initiated/ongoing</td>
</tr>
<tr>
<td>June 2014</td>
<td>Determine applicability of RANS based 3D simulation approach for flame propagation and combustion stability under dilute (lean/EGR) operating conditions</td>
<td>On schedule</td>
</tr>
<tr>
<td>Sept 2014</td>
<td>Finalize assessment of laser ignition potential</td>
<td>On schedule</td>
</tr>
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</table>
Approach
Organizational Integration

High-Efficiency GDI Engine Project

- OEM input
- Sandia National Laboratories
- 3-D CFD simulation
- Single-cylinder engine research
- Ignition system analysis
- Ignition system developers

High Efficiency GDI Engine Research with Emphasis on Ignition Systems
Technical accomplishments
Advanced RANS + multi-cycle simulations

- Cyclic differences in turbulent scales deliver variable charge motion
- Charge motion affects combustion
- Combustion affects gas-exchange

Compounded effect of in-cylinder flow on flame propagation and vice versa

This is a RANS approach with similar results to LES....
Can this approach be useful for combustion stability assessment?

- Initial test - LEAN (λ = 1.5)
- No inhomogeneities (PFI)
- Conventional spark system
  Different intake geometry (OPEN/CLOSE swirl plate)
- 10 consecutive cycles (the 1st cycle is discarded)
- Trends in variation of simulation consistent with measured COV

The only difference between the two cases is the intake flow
Technical accomplishments
Analysis of Cyclic Variability

- Variability relative to position
  - Increased ignition delay and combustion duration result in increased COV_{IMEP}
- Within natural cyclic variability
  - Late combustion phasing results in reduced efficiency

- Control parameter sensitivity
  - Induced perturbation on a cyclic basis
  - Ignition timing & relative air/fuel ratio
- Higher COV_{IMEP} with injection variability
- Fast efficiency decay with ignition variation
  - Ignition delay is a critical time of early flame kernel development

- Alternative Ignition Concepts!

![Graph showing indicated efficiency vs COV_{IMEP} for different EGR levels and injection perturbations.](https://via.placeholder.com/150)
Technical accomplishments
Alternative Spark-Based Ignition

- Several ignition concepts in one platform (Altronic - Directed Energy Ignition System)
- Ignition Energy
  - 75 mJ & 150 mJ (nominal)
- Alternative Ignition Profiles
  - Sustained Arc & Multi-Spark

- Differentiating ignition strategies
  - 20-25% EGR → high COV_{IMEP}
- Relative COV_{IMEP} improvement
  1. Higher energy alternative profiles
  2. Lower energy alternative profiles
  3. Conventional profile
- Alternative profiles more effective at reducing variation than increased energy
Technical accomplishments
Modeling Alternative Ignition Profiles

- **GDI cases with high EGR (18%)**
  - L-shaped energy transfer adapted to the ignition characteristics
  - DEIS 1 mimics conventional spark systems (75 mJ, single pulse)
  - DEIS 4 has higher energy (150 mJ, single pulse)
  - DEIS 6 has 150 mJ and multiple (5) pulses

- Can our RANS approach capture stability trends?
  - Current results are up to 10 cycles (1st cycle is discarded)
  - The only difference between the operations is the ignition profile (except for baseline)
  - Numerical pressure variations well correlate with experimental trends

<table>
<thead>
<tr>
<th>EGR 0%</th>
<th>Product. Spark</th>
<th>75 mJ</th>
<th>Measured COV = 2%</th>
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</thead>
<tbody>
<tr>
<td>EGR 18%</td>
<td>Single pulse</td>
<td>75 mJ</td>
<td>Measured COV = 8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 mJ</td>
<td>Measured COV = 7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Measured COV = 4%</td>
</tr>
</tbody>
</table>
Technical accomplishments
Ignition and Cyclic Variability

- What causes higher variability in flame propagation?
  - Charge motion variability
  - Additional contribution of mixture distribution (GDI)
  - Combustion has an effect on next gas-exchange phase
  - PFI cases show similar variations and the charge motion was the driver

  Significant impact of charge motion (especially in the near-spark region)

- How do multiple pulses reduce variability?
  - Higher energy increases the low-high amplitude
  - Gradual energy release reduces amplitude of variations because of reduced dependence on charge motion
Technical Accomplishments
Laser Ignition

- **Free-Air Delivered Laser**
  - Internal collaboration
  - Quantel USA (a.k.a Big Sky Lasers)
    - 532 nm green
    - 60 mJ/pulse
    - 7-10 ns pulse width

- **Fiber Optic Delivered Laser**
  - Collaboration with Colorado State University and Seaforth, LLC
  - Successful engine firing

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High Efficiency GDI Engine Research with Emphasis on Ignition Systems
Technical Accomplishments
Free-Air Delivered Laser

- **Improved combustion stability**

  - Higher rate of heat release
  - Flame kernel isolation from head
  - Opportunity for optimizing ignition location (CFD input)
  - Potential for multiple ignition locations

- **Higher rate of heat release**
  - 66.2 mJ Single
  - 70.9 mJ Sustained Arc
  - 67.8 mJ Multi-Spark
  - 131.4 mJ Single
  - 135.3 mJ Sustained Arc
  - 145.3 mJ Multi-Spark
  - 40 mJ Laser

- **Sweep of EGR Dilution**

  - 1500 RPM 5.6 bar IMEP
  - Indicated Efficiency
  - COV IMEP

- **Heat Release in EGR Operation**

  - 1500 RPM 5.6 bar IMEP 19.5% EGR
Responses to Previous Year Reviewers’ Comments

- ...an optical dimension would make this project more valuable and provide more in-depth insights.

  ✓ The team has established a collaboration with Sandia National Laboratories (Isaac Ekoto) for optical engine data specifically related to this project. Optical data will support the CFD effort to characterize the fundamental processes of ignition and flame kernel development with alternative ignition systems.

- ...laser ignition systems applied to smaller engines could be considered new.

  ✓ The team has evaluated alternative spark based ignition which serve as a point of reference for continued alternative ignition studies. Laser ignition has been implemented and provides a pathway for more novel laser ignition concepts.

- Reviewer was not clear what new fundamental learning will result from this work.

  ✓ The CFD approach is very fundamental, delivering insight into the mixture and turbulence especially in close proximity to ignition and how it relates to the flame kernel development. Cyclic variability has been rigorously characterized and the analysis is a framework in which to experimentally evaluate performance improvements with alternative ignition concepts.
Collaboration with Other Institutions

- **Ignition system developers**
  - Altronic, LLC: DEIS ignition system
  - CSU, Seaforth, LLC: Fiber-coupled laser ignition system (SBIR)

- **Sandia National Laboratories**
  - Fundamental ignition/combustion optical analysis

- **U.S. DRIVE Advanced Combustion & Emissions Control Tech Team**
  - Coordination and update presentations

- **In-kind Support from Ford Motor Company**
  - Engine hardware
  - Injection equipment

- **Argonne internal collaboration**
  - Benefit from extensive laser ignition expertise at DERC
  - Numerical Simulations run on Blues Cluster at LCRC
Remaining Challenges and Barriers

- A comprehensive understanding of cycle to cycle feedback mechanisms for gasoline combustion is needed to maximize efficiency specifically in dilute operation.
- Fundamental understanding and predictive simulation capabilities of cyclic variability are in their infancy.
- Simplified ignition models are likely not able to correctly represent advanced ignition modes/systems.
- Benefits of advanced ignition systems in combination with extreme dilution are not well understood.
Proposed Future Work

- Develop advanced RANS approach as a means to determine combustion stability and benchmark against LES simulations
- Continue evaluation of advanced ignition systems including laser ignition with focus on combustion stability and fundamental interactions
- Develop alternative ignition models to correctly represent advanced ignition systems in predictive simulations
- Investigate ignition/flow interactions and validate against optical results from Sandia National Laboratories
Summary

- Characterized fundamental combustion stability trade-offs as a function of dilution level (lean/EGR)
- Assessed the effect of sustained and multi-spark modes for different energy levels
- Identified promising approach to predicting cyclic variability using advanced RANS simulations
- Successfully implemented and demonstrated laser ignition system on single-cylinder research engine platform
Technical Back-Up Slides
Engine Setup
State-of-the art GDI Engine

- Typical SI combustion chamber design
  - 140° pent roof head, flat piston top, central spark plug and injector
- External high pressure gasoline pump
  - Up to 200 bar injection pressure

High Speed Secondary Coil Voltage
- ~1 nanosecond breakdown phase
- 2.4 kV in-cylinder breakdown
- Up to 40 kV measurement

Simultaneous Current Measurement
- Enables high fidelity power measurements to quantify ignition energy

GDI Engine Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>0.626 L</td>
</tr>
<tr>
<td>Bore/Stroke</td>
<td>89/100.6 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>12.1</td>
</tr>
<tr>
<td>Intake Valve MOP</td>
<td>100 °CA ATDC</td>
</tr>
<tr>
<td>Exhaust Valve MOP</td>
<td>255 °CA ATDC</td>
</tr>
<tr>
<td>GDI Injector</td>
<td>6 hole, solenoid</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>150 bar</td>
</tr>
<tr>
<td>Spark Plug</td>
<td>NGK-R dual fine wire, 0.7 mm gap</td>
</tr>
<tr>
<td>Fuel</td>
<td>EPA Tier II EEE</td>
</tr>
</tbody>
</table>
Control Parameter Sensitivity
Baseline for Perturbation Cases

- Combustion Phasing
  - 7.5 °CA is optimal
  - Early and late phasing both decrease efficiency and increase COV_{IMEP}

- Relative Air/Fuel Ratio
  - $\lambda < 1$ not only decreases efficiency but also COV_{IMEP}
  - $\lambda > 1$ improves efficiency but with greater COV_{IMEP}

Simulation Details

CFD features

CONVERGE™ from Convergent Science, Inc.

- Orthogonal grid with advanced refinement algorithm
  - Base grid = 4 mm
  - Fixed Embedding where needed (chamber, valve seats, spark-plug)
  - AMR based on Temperature and Velocity gradients
  - **Cell size during combustion = 0.125 mm (spark) – 0.5 mm (flame)**
  - High accuracy with reasonably small grids (1,200,000 cells maximum)
  - One cycle simulated in 36-48 hrs on 24-64 cores

- **2nd order accuracy for the momentum equation (central scheme)**

- RANS approach, k-ε RNG model for turbulence

- **Energy deposition model (L-type, 0.5 mm sphere)**

- **Direct Chemistry (Arrhenius + detailed chemistry)** → No turbulent sub-grid term in the reaction rate

- Multi-zone model to speed up the calculations involving kinetics
Simulation Details

Effect of grid resolution on cyclic variability

**CONVENTIONAL**
**NO AMR** (adaptive mesh refinement)
Grid resolution:
- Spark1 0.25mm
- Spark2 0.5mm
- Flame 1mm
- Flow 1mm
- Cylinder 1mm

**ADVANCED**
**WITH AMR**
Grid resolution:
- Spark1 0.12mm
- Spark2 0.25mm
- Flame 0.5mm
- Flow 0.5mm
- Cylinder 1mm

Conventional RANS (low mesh resolution - no AMR) does not deliver significant fluctuation of numerical results but needs a turbulent sub-grid term (TCI) to simulate combustion properly.
Simulation Details

CFD Model Validation

- Lean and EGR dilute SI combustion
  - Reliable mechanism (LLNL-lowP) and fine mesh are needed*
  - Flame propagation and interaction with the flow well described even using Direct Chemistry*
- Effect of intake flow on combustion
  - Importance of near-spark flow
  - Tumble preferred over swirl
- Validation against engine data
  - Numerical results show no convergence of pressure traces
- RANS with low numerical diffusion
  - Difference in turbulent scales due to the effect of each cycle on the next → **Low numerical diffusion does not damp out the variability in large structures from cycle to cycle**

**Multi-cycle simulations and qualitative validation against 500 cycles**

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* Scarcelli, R., Matthias, N., and Wallner, T., 2013-24-0029