High-Dilution Stoichiometric Gasoline Direct-Injection (SGDI) Combustion Control Development

Project ID # ACE090

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Advanced Combustion Engines R&D
Vehicle Technologies Office
U.S. Department of Energy

2015 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review
June 10, 2015

ORNL is managed by UT-Battelle
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High-dilution SGDI project overview

Timeline

- Evolution of a project that began in 2011
- Current trajectory began in 2013

Barriers (MYPP §2.3.1 A, D)

- Lack of fundamental knowledge of advanced engine combustion regimes
- Lack of effective engine controls

Budget

- FY 2014: $300k
- FY 2015: $200k

Partners/Interactions

- Collaborations
  - Bosch
  - National Instruments
  - Argonne National Laboratory
- Regular status reports to DOE

Objective: Develop advanced control strategies to extend SI dilution limits

- Project Objective
  - Address barriers to the VTO goal of improving light-duty vehicle fuel economy by developing control strategies that enable high-efficiency, high-dilution, gasoline direct-injection (GDI) engine operation
  - Extend dilution limit to enable greater efficiency gains in modern GDI engines, leading to increased vehicle fuel economy
- FY 14-15 Objectives
  - Characterize cyclic variability for external EGR operation
  - Evaluate effects of data quality on symbol-sequence analysis
  - Develop next-cycle control methodology to reduce cyclic variability
  - Implement next-cycle controls on engine and evaluate efficacy

Goal of Advanced Combustion Engines R&D

"By 2015, improve the fuel economy of light-duty gasoline vehicles by 25 percent and of light-duty diesel vehicles by 40 percent, compared to the baseline 2009 gasoline vehicle." (MYPP 2011-2015 §2.3.1)

All tracked milestones have been completed or are on-track

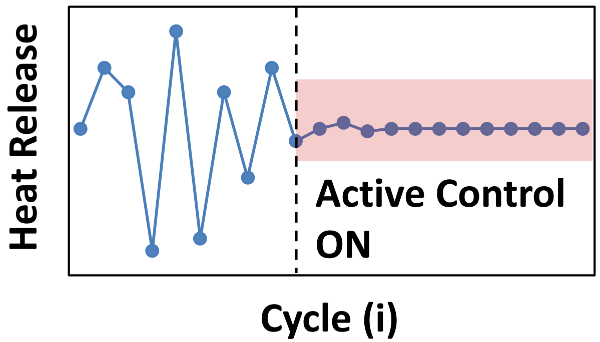
Month/Year	Milestone	Status
12/2013	Characterize sensitivity of control parameters on data sampling rate and quality	Completed
03/2014	Demonstrate automatic cylinder balancing which will be integrated with next-cycle control in future milestone	Completed
06/2014	Demonstrate next-cycle control of engine based on prior-cycle events	Completed
09/2014	Demonstrate potential of next-cycle control on combustion stability, engine efficiency, and dilution limit extension	Completed
06/2015	Demonstrate impact of combined control strategies on EGR dilution limit extension	On Track
09/2015	Demonstrate applicability of next-cycle control strategy to homogeneous lean combustion	On Track

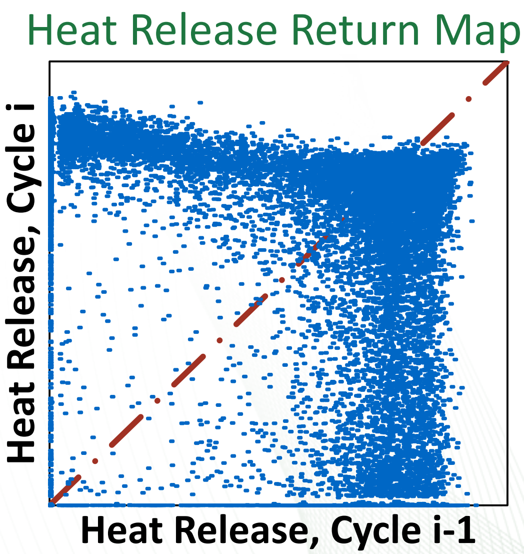
Advanced controls use deterministic behavior to reduce cyclic variability

- Combustion instabilities at the dilution limit have deterministic structure combined with stochastic noise

Determinism implies controllability

- Leverage ORNL's extensive background in identifying dynamical structure in noisy and chaotic time series
- Utilize tools from nonlinear dynamics and information theory to predict and control deterministic variations
- Enable operation at the "edge of stability"





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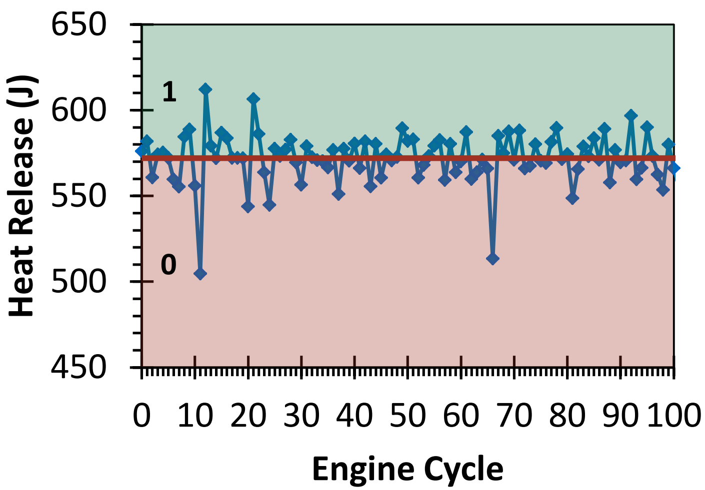
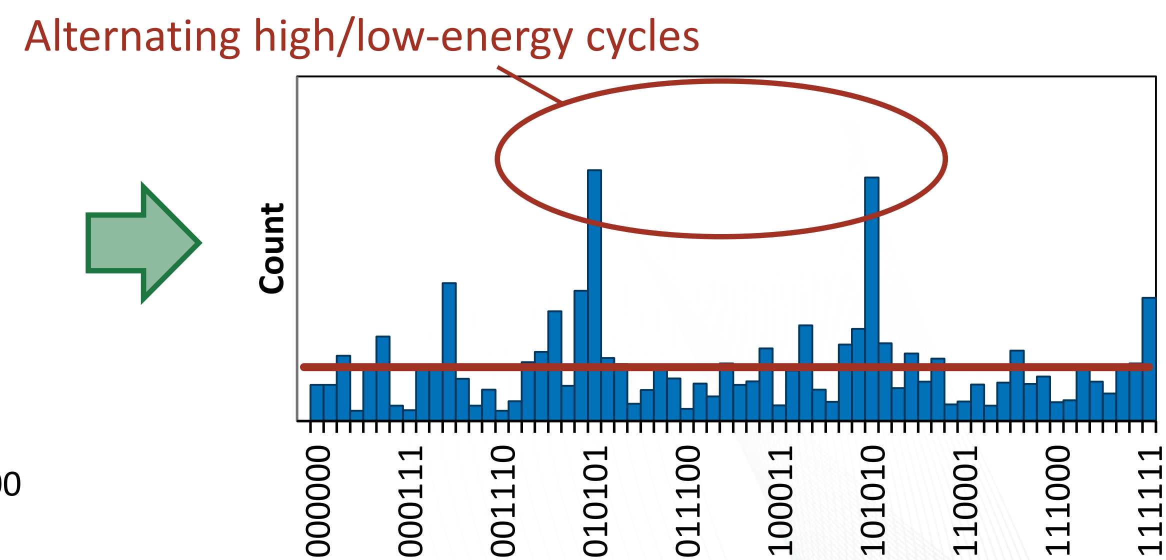
Symbol-sequence statistics analysis finds order in chaos

APPROACH (2/3)

- Method:
  - Partition data into discrete bins
    - Each bin is labeled with a “symbol” or “letter”
  - Identify sequences of a given number of cycles
    - These symbol sequences can be thought of as “words” made up of the symbolic “letters”
  - Detect patterns by identifying words that occur frequently
- This information will be used to enable online control of cyclic variability



Example time series with binary symbol partition



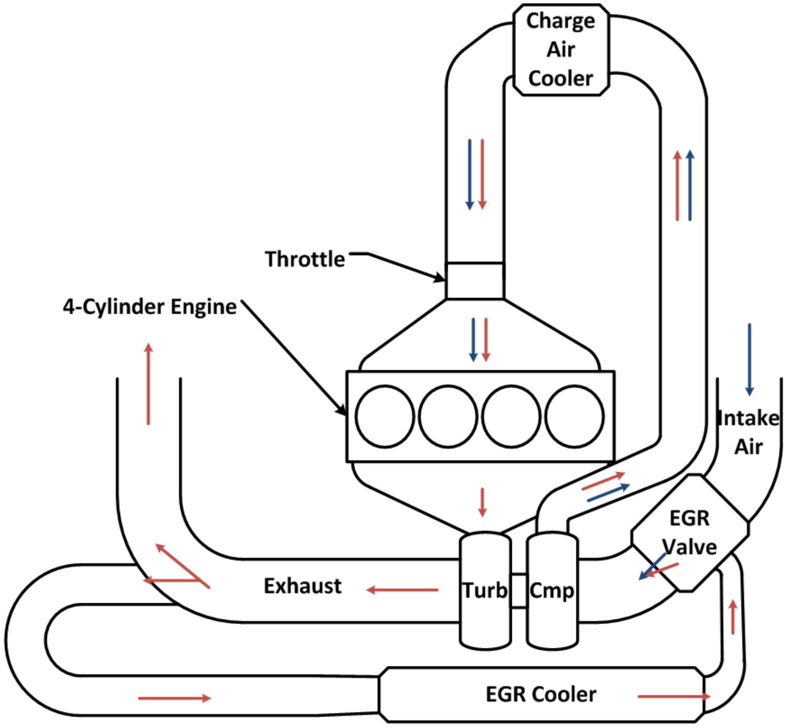
Symbol sequence histogram with 2 symbolic letters and a word length of 6

Experimental platform: 4-cylinder GDI engine with cooled EGR

- GM LNF 2.0L turbocharged GDI engine
  - Modified by Bosch for DOE FFV optimization program
  - Outfitted by ORNL with external cooled EGR loop
- NI (Drivven) Engine Controller
  - Allows fully customizable engine controls
  - Capable of next-cycle or same-cycle controls

Engine Specifications

	Stock	Modified
Bore	86 mm	
Stroke	86 mm	
Compression ratio	9.50:1	10.67:1
Ignition coil energy	80 mJ	100 mJ
Maximum cylinder P	100 bar	130 bar
Induction	Turbocharged	
Fuel system	Wall-guided GDI	



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Accomplishments—Overview

- Built further understanding of cycle-to-cycle dynamics: needed to develop effective control strategies
  - Ability to use production-viable sensors: data quality study
  - Effects of control parameters
    - Spark re-strike study
    - Collaborated with Argonne National Laboratory on study of effects of control perturbations on dilute combustion
- Implemented initial symbol-sequence-based control strategy on the engine
  - Control strategies currently being refined and improved based on information gained
  - Adapting symbol-sequence analysis method to account for dual feedback timescale with external EGR loop and build symbolic words based on appropriate feedback cycle history

PHILOSOPHICAL TRANSACTIONS A

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Characterizing dilute combustion instabilities in a multi-cylinder spark-ignited engine using symbolic analysis

SAE INTERNATIONAL

Effects of Data Quality Reduction on Feedback Metrics for Advanced Combustion Control

2014-01-2707
Published 10/13/2014

Brian C. Kaul, Benjamin J. Lawler, Charles E.A. Finney, Michelle L. Edwards, and Robert M. Wagner
Oak Ridge National Laboratory

CITATION: Kaul, B., Lawler, B., Finney, C., Edwards, M. et al., "Effects of Data Quality Reduction on Feedback Metrics for Advanced Combustion Control," SAE Technical Paper 2014-01-2707, 2014, doi:10.4271/2014-01-2707.

Abstract

Advances in engine controls and sensor technology are making advanced, direct, high-speed control of engine combustion more feasible. Control of combustion rate and phasing in low-temperature combustion regimes and active control of cyclic variability in dilute SI combustion are being pursued in laboratory environments with high-quality data acquisition systems, using metrics calculated from in-cylinder pressure. In order to implement these advanced combustion controls in production, lower-quality data will need to be tolerated even if indicated pressure sensors become available. This paper examines the effects of several data quality issues, including phase shifting (incorrect TDC location), reduced data resolution, pressure pegging errors, and random noise on calculated combustion metrics that are used for control feedback.

Symbolic data analysis is an effective technique for identifying underlying patterns in noisy data, and has been applied to cyclic variability of dilute SI combustion, identifying deterministic effects that underlie the stochastic variations that are present. These techniques form a basis for current attempts to implement active next-cycle control of cyclic variability for dilution limit extension, and their effectiveness is evaluated in the presence of the reduced-quality data.

The results indicate that IMEP and cumulative heat release are the most sensitive combustion metrics, showing the strongest trends with TDC offset and encoder resolution. While these combustion metrics show sensitivities to data quality issues, the symbol sequence statistics were always able to identify the correct deterministic trajectories in cycle-to-cycle variations, proving that production sensors provide data of sufficient quality for control methods based on symbol sequence statistics.

Introduction

Implementation of the many advanced combustion strategies being developed to meet increasingly stringent fuel efficiency and emissions standards will require equally advanced combustion controls, which will likely rely on in-cylinder pressure data for feedback of combustion quality. Automotive-grade sensing [1, 2] and control systems [3, 4] are now available and undergoing continued development. Other inputs such as crankshaft rotational speed [5, 6] or knock sensor data [7] are also being used to estimate cylinder pressure data. For any of these techniques, it will be necessary for real-time control strategies to be robust while using data that is of lower quality than can be obtained with laboratory-grade equipment.

Davis and Patterson [8] have previously analyzed the effects of TDC offset and pegging errors on IMEP and other calculated metrics. They and others (e.g. [9, 10]) have also quantified the effects of thermal shock on IMEP and associated metrics. Maurya and Agarwal [11] evaluated the effects of measurement errors, on various parameters including cumulative heat release rate and IMEP for HCCI combustion, and found significant errors, especially due to incorrect phasing (TDC offset). These studies have focused primarily on maximizing data quality for accuracy of combustion characterization.

Corti, et al. [12] and Antonopoulos and Hountalas [13] have also evaluated the errors due to use of time-based pressure sampling for control purposes and developed algorithms to account for the effect of crankshaft accelerations and reduce the associated errors in IMEP calculations, which could help to address one of the major sources of error.

Many advanced combustion modes, including highly dilute SI combustion (both lean [14, 15, 16] and EGR [17, 18, 19]), HCCI combustion [20], and spark-assisted HCCI combustion [21, 22, 23], have been shown to exhibit not only stochastic behavior, but also deterministic effects, at their stability limits. This has significant implications for the controllability of these

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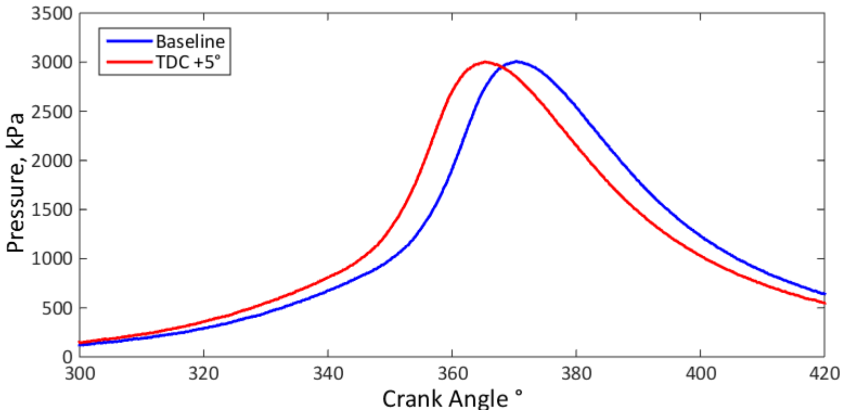
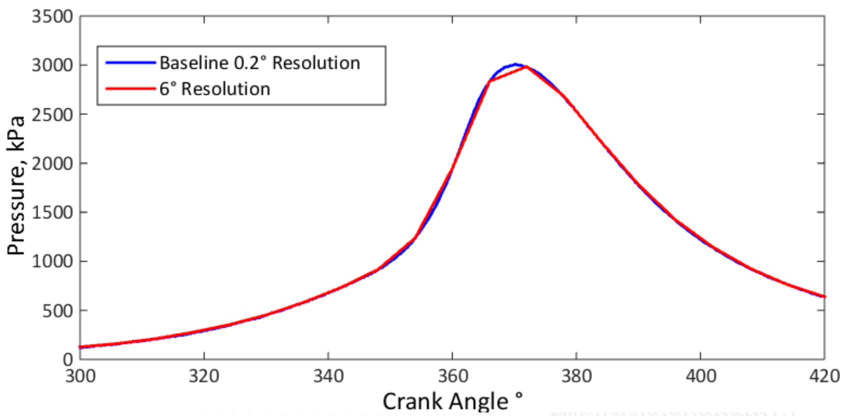
Laboratory-quality data is unlikely to be available in production: how does this impact advanced controls?

ACCOMPLISHMENTS (2/7)

- Effects of data quality reduction were evaluated in post-processing
- Data from two operating conditions considered:
  - Low-COV: 2000 rpm, 4 bar BMEP, ϕ = 1 (COV = 1.7%) — General trends
  - High-COV: 2000 rpm, 4 bar BMEP, ϕ = 0.7 (COV = 37.7%) — Symbolic analysis
- Errors imposed on cylinder pressure data
  - TDC offset, Pegging offset, Reduced crank-angle resolution, Random noise
- Metrics evaluated
  - IMEP, Cumulative heat release (HR), Peak pressure, CA10/50/90, Max pressure rise rate (MPRR)





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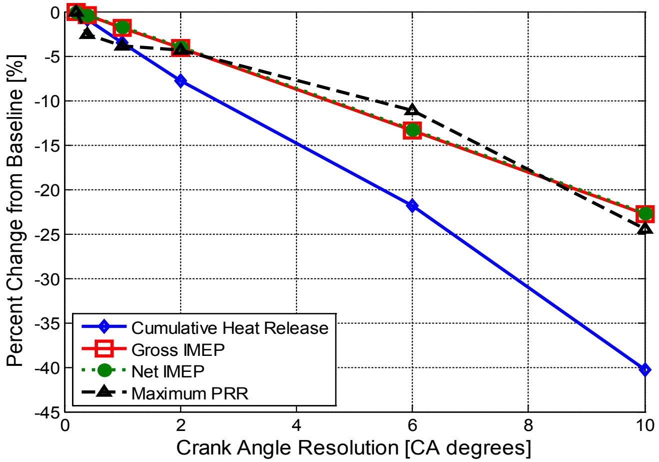
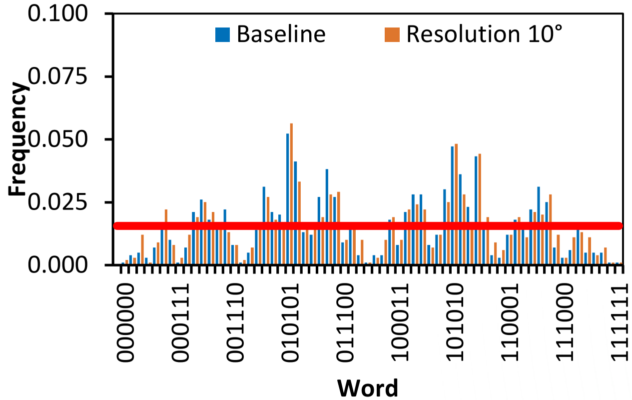
Symbol sequence analysis is effective even with poor-quality data

ACCOMPLISHMENTS (3/7)

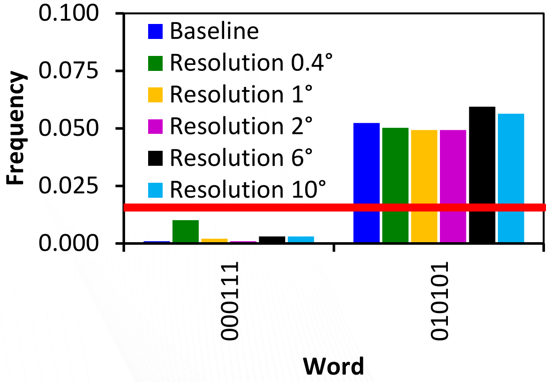
- Data quality reduction has significant impact on combustion metrics, e.g.
  - TDC offset: 4.5% error in IMEP per °CA
  - Reduced resolution: 2.2% error in IMEP and 3.8% error in HR per 1° resolution
- Symbol sequence analysis is robust even when analyzing time series of these erroneous metrics
  - Overall structure of histogram unchanged
  - Individual words also detected with similar frequency



Effect of reduced resolution on HR, IMEP, and MPRR; ensemble-averaged



Symbol sequence histograms of HR for unmodified baseline (0.2°) and 10° encoder resolution



Frequency of occurrence of example symbolic words with reduced resolution

Kaul BC, Lawler BJ, Finney CEA, Edwards ML, Wagner RM, "Effects of Data Quality Reduction on Feedback Metrics for Advanced Combustion Control," SAE Technical Paper 2014-01-2707, 2014, doi:10.4271/2014-01-2707.

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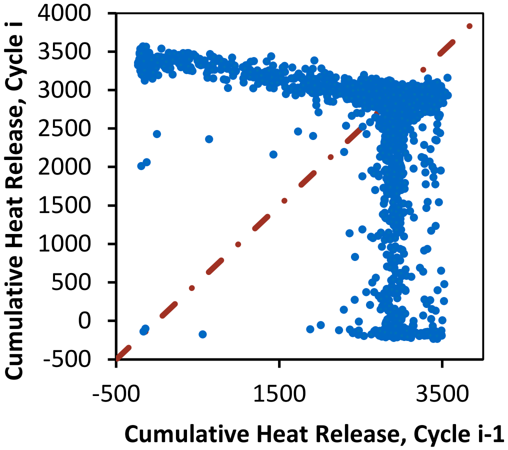
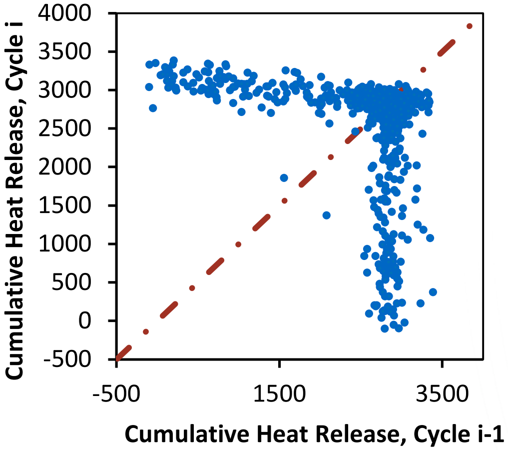
Multiple spark strategy can qualitatively change cyclic dynamics

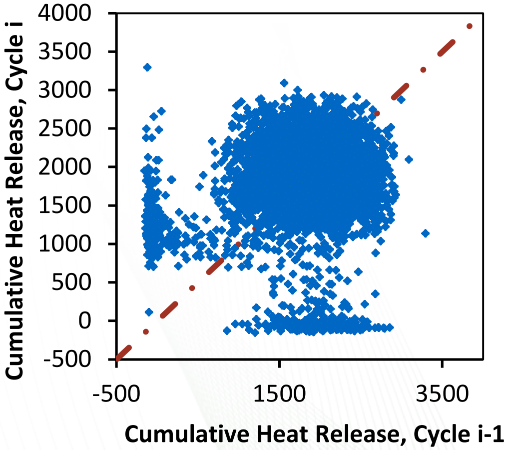
- Adding a restrike spark helps reduce misfire events
  - Converts misfires to partial burns
  - Impact initially grows with restrike delay
- After some threshold, retarding the restrike further is counter-productive
  - Increased COV and misfires
  - Collapse of deterministic structure – largely stochastic variations
  - Unclear so far whether cause is inherent in late restrike or due to increased variability in timing due to constant time restrike delay in ms rather than crank angle



Heat release return map; 20% EGR
Main spark 70° BTDC; No Restrike



Heat release return map
Restrike ~20° BTDC

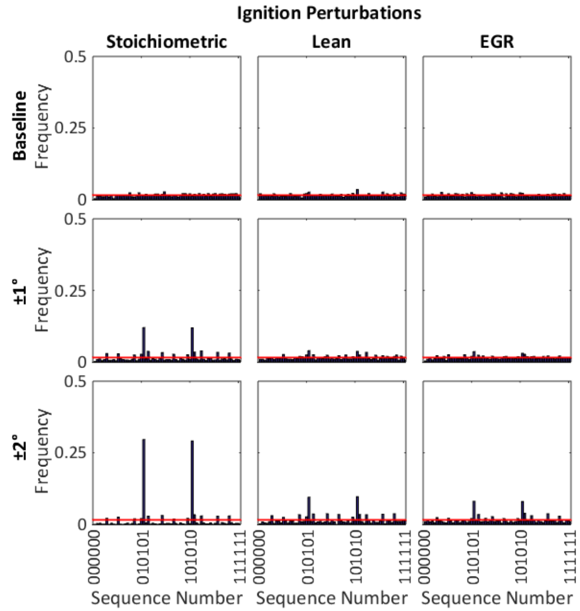


Heat release return map
Restrike ~0° BTDC

Effects of cycle-to-cycle perturbations of ignition timing and fuel quantity vary with dilution

ACCOMPLISHMENTS (5/7)

- Experiments at ANL perturbing ignition timing (±*x*°) and injection quantity (±*x*%) every-other-cycle
- Analysis at ORNL using nonlinear dynamics tools
  - Effects of ignition perturbations are suppressed by dilution
    - Longer burn duration necessitates earlier spark timing
    - Less sensitivity to small changes in this region
  - Effects of injection perturbations are amplified for lean operation
    - Ignition and flame propagation properties nonlinearly dependent on mixture composition for dilute combustion
    - Next-cycle feedback from residual fraction is predominant for lean operation – synchronous with perturbations
    - For EGR operation, dominant feedback is longer-timescale due to external EGR loop – not synchronous with perturbations



Symbol sequence analysis of 50% MFB location for ignition perturbation at baseline conditions as well as lean (λ=1.6) and 21% EGR dilute operation

Wallner T, Kaul BC, Sevik JM, Scarcelli R, Wagner RM. “Effects of Ignition and Injection Perturbation under Lean and Dilute GDI Engine Operation,” SAE Technical Paper 2015-01-1871. To be presented at the JSAE/SAE 2015 International Powertrain, Fuels, and Lubricants Meeting, September 1-4 2015, Kyoto, Japan.

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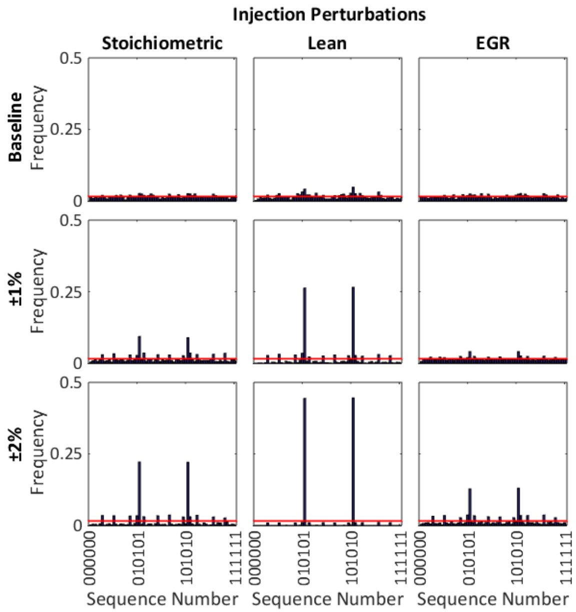
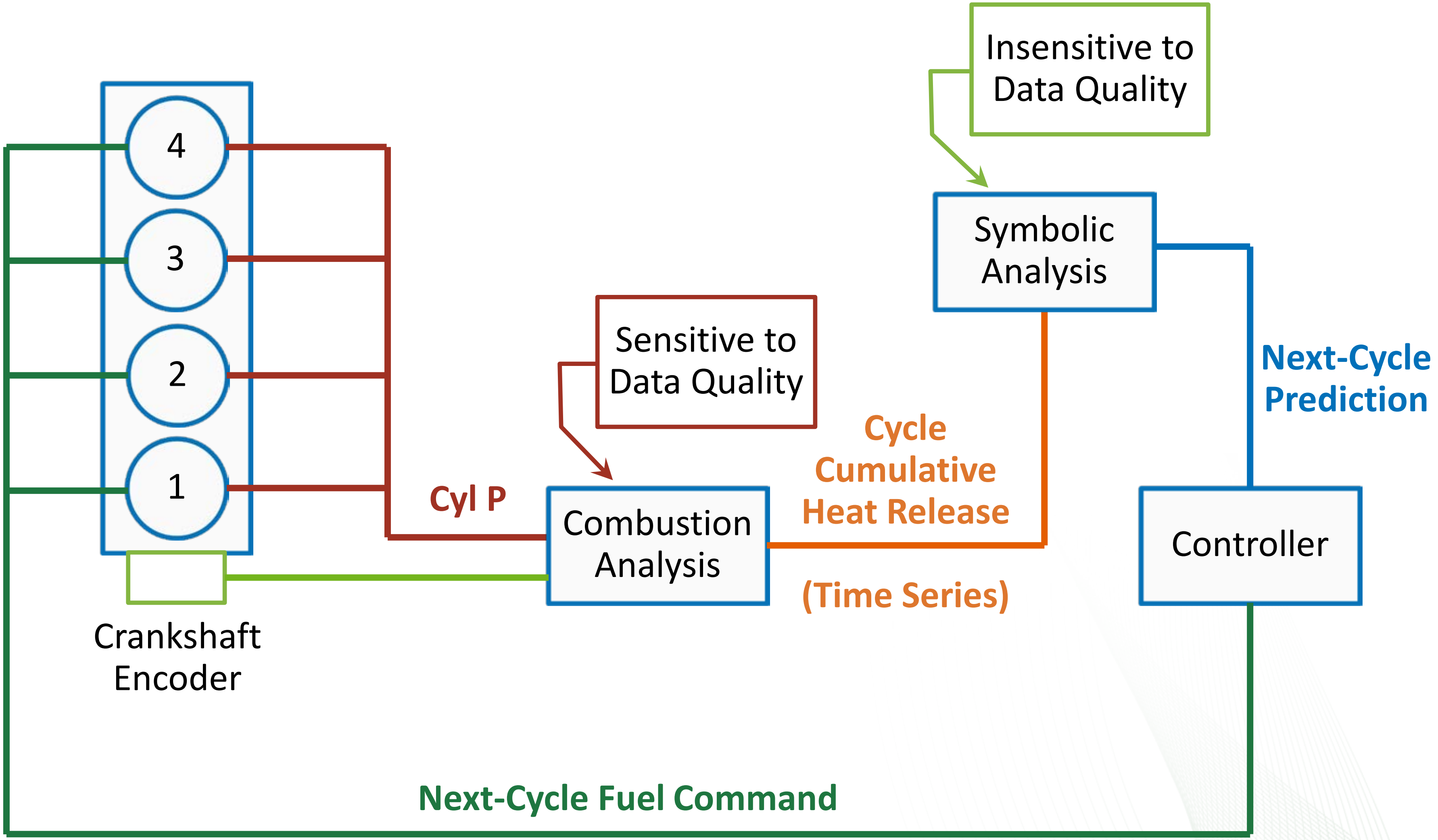


Symbol sequence analysis of cumulative heat release for injection perturbation at baseline conditions as well as lean (λ=1.6) and 21% EGR dilute operation

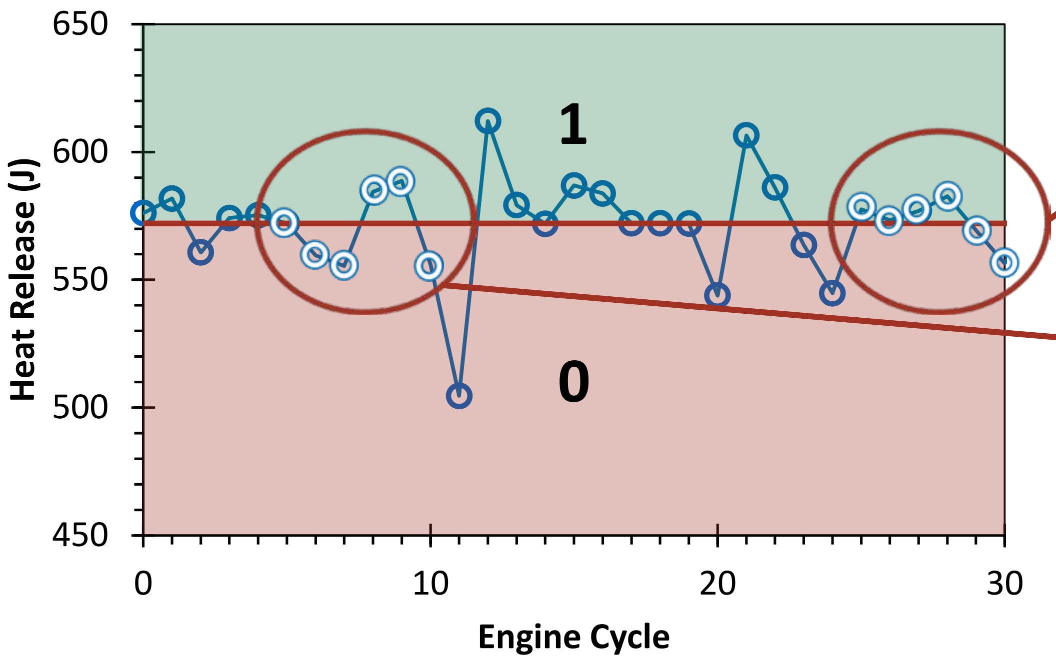
Wallner T, Kaul BC, Sevik JM, Scarcelli R, Wagner RM. “Effects of Ignition and Injection Perturbation under Lean and Dilute GDI Engine Operation,” SAE Technical Paper 2015-01-1871. To be presented at the JSAE/SAE 2015 International Powertrain, Fuels, and Lubricants Meeting, September 1-4 2015, Kyoto, Japan.

Next-cycle control strategy: use symbol sequence analysis to correct undesirable trajectories



Symbol sequence method has been modified for dual-timescale feedback

ACCOMPLISHMENTS (7/7)



Time series of cumulative heat release

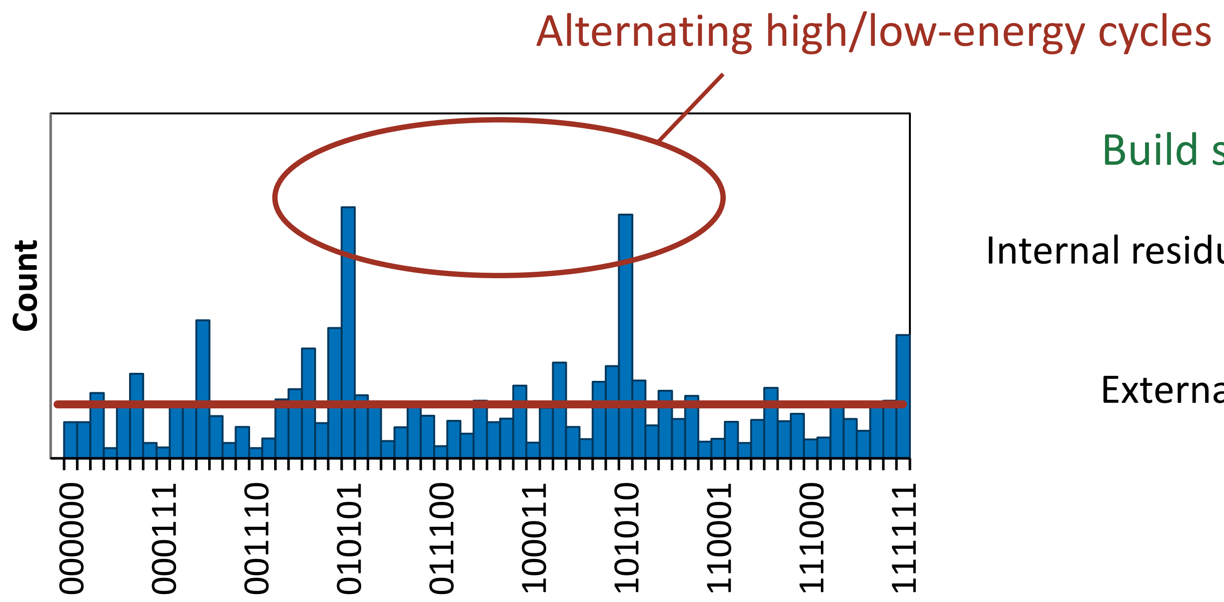
Build symbolic "words"

Internal residual: Prior-cycle dominant
111100

External EGR: Delayed feedback
000110

Symbol sequence method has been modified for dual-timescale feedback

ACCOMPLISHMENTS (7/7)



Build symbolic "words"

Internal residual: Prior-cycle dominant

111100

External EGR: Delayed feedback

000110

Recurring patterns indicate deterministic trajectories

- Initial results indicated method not sufficiently effective when building symbolic words for a single cylinder
- Need to modify to incorporate multi-cylinder feedback history, accounting for firing order (currently in progress)

Reviewer comments from FY 2014

Positive comments

*"The reviewer **exclaimed** that it was about time someone did this work. The reviewer remarked that it was an exciting chance to do something about the stability limit."*

"The reviewer noted good progress by the project team on a difficult problem. The project team has created a good test bed and the necessary infrastructure to do some great work."

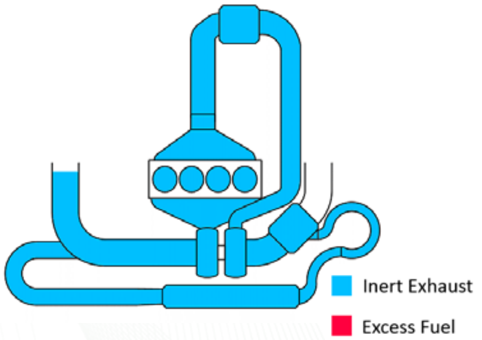
Responses to reviewer comments/suggestions

Reviewers inquired whether cylinder pressure was required for optimal control, and inquired if crankshaft speed or some other feedback mechanism could be used.

We believe crankshaft speed or other metrics would be suitable: results of a data quality study motivated by this question are included here and were published earlier this FY, and there is an existing patent (Ford & ORNL, #5,921,221) based on earlier lean combustion work that utilized crankshaft acceleration.

Reviewers expressed a desire to see more collaborations, especially from an OEM's controls experts.

This project has received general directional input from industry via presentations at the ACEC Tech Team and such forums, but we would welcome more direct OEM involvement.



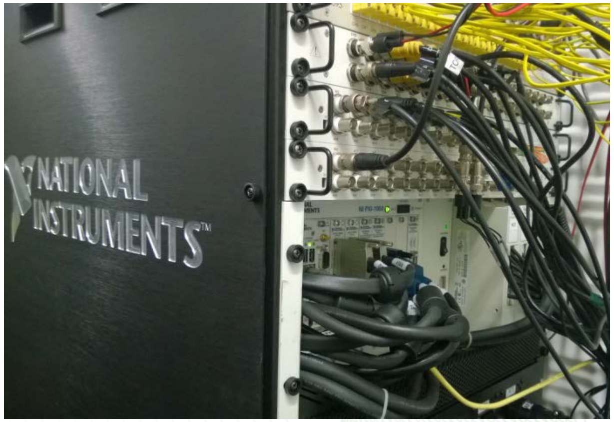
Reviewers asked whether the EGR path length results are as applicable at more moderate EGR rates with low COV or only for the extreme case with misfires.

This is a good question, and one we are currently working to answer. Experiments using fast EGR sensing technology developed in a separate ORNL project (Partridge # ACE077) are currently underway to determine the extent to which the temporal resolution of combustion products is maintained at more moderate EGR levels where misfires do not occur.

Reviewer comments paraphrased from 2014 AMR report

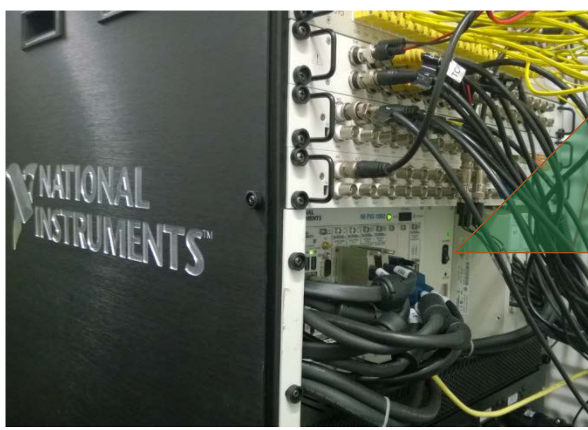
Collaborations

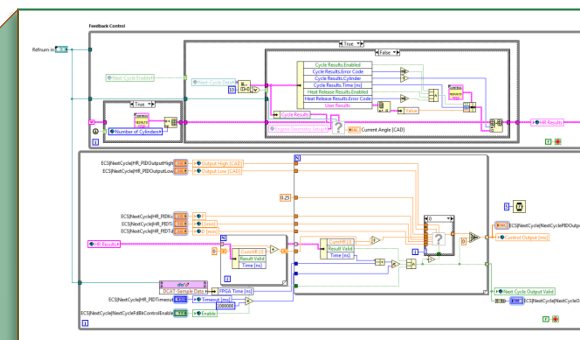
- National Instruments Powertrain Controls (Drivven)
  - Support of next-cycle and same-cycle controls development
  - In talks to exchange data and collaborate on joint publications
- Argonne National Laboratory
  - Collaboration on analysis of effects of control perturbations in dilute SI combustion
  - Joint paper to be published later this FY
- Robert Bosch LLC
  - High-compression GDI engine customized in previous DOE program
  - Provided engine and ECU with calibration-level access
- ORNL–Cummins Combustion CRADA
  - High-resolution EGR measurements



Remaining Challenges and Barriers

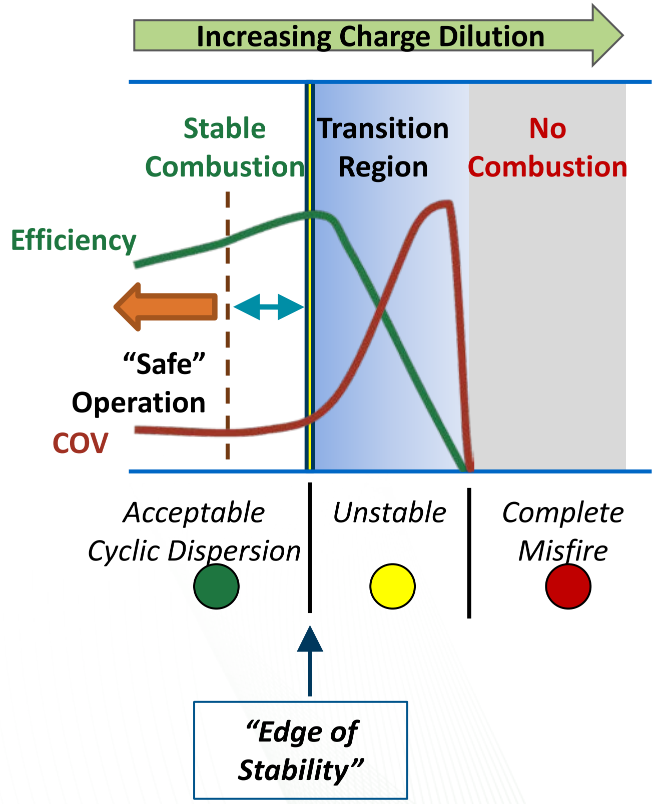
- Need to improve prediction for external EGR
  - Interleaved multi-cylinder, multi-timescale symbolic words
  - Model-based prediction
- Need to refine and improve control strategies
  - Determine efficacy of enhanced symbol-sequence based control
  - Integrate online model-based control
  - Determine efficacy at “edge of stability”
  - Extend to transient operation
- Evaluate applicability to lean-burn GDI





Future Work (3-Year Plan Reviewed by ACEC Tech Team 9/11/2014)

- Remainder of FY 2015
  - Evaluate EGR feedback dynamics for moderate EGR levels (no misfires)
  - Continue development of next-cycle control strategies
    - Improve strategies for high-EGR operation
    - Evaluate application to lean-burn GDI
    - Demonstrate dilution limit extension
- FY 2016
  - Development of low-order models for improved prediction
    - Extension of prior ORNL efforts for lean combustion to high-EGR operation
    - Informed by results from ORNL HPC work (Edwards # ACE017)
  - Continued next-cycle control strategy development
- FY 2017
  - Evaluate potential for same-cycle control strategies
    - Detect and correct for misfires or slow burns during combustion
    - Possible future applications for other combustion modes at the edge of stability
  - Plans will evolve based on FY 15-16 results



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Summary

Relevance

- Dilute combustion enables significant fuel efficiency gains in modern SI engines, but is limited by cyclic variability

Approach

- Use tools from nonlinear dynamics and information theory to take advantage of deterministic effects and develop active control strategies that bring order out of chaos, reducing cyclic variability and extending practical dilution limits

Accomplishments

- Built further understanding of cycle-to-cycle dynamics that will be used to develop improved control strategies
- Implemented initial symbol-sequence-based control strategy on the engine
- Adapted symbol-sequence analysis method to account for dual feedback timescale with external EGR loop

Collaborations

- Collaborating with industry on high-EGR control system development

Future Work

- Implementing next-cycle control strategies to enable operation on the “edge of stability”


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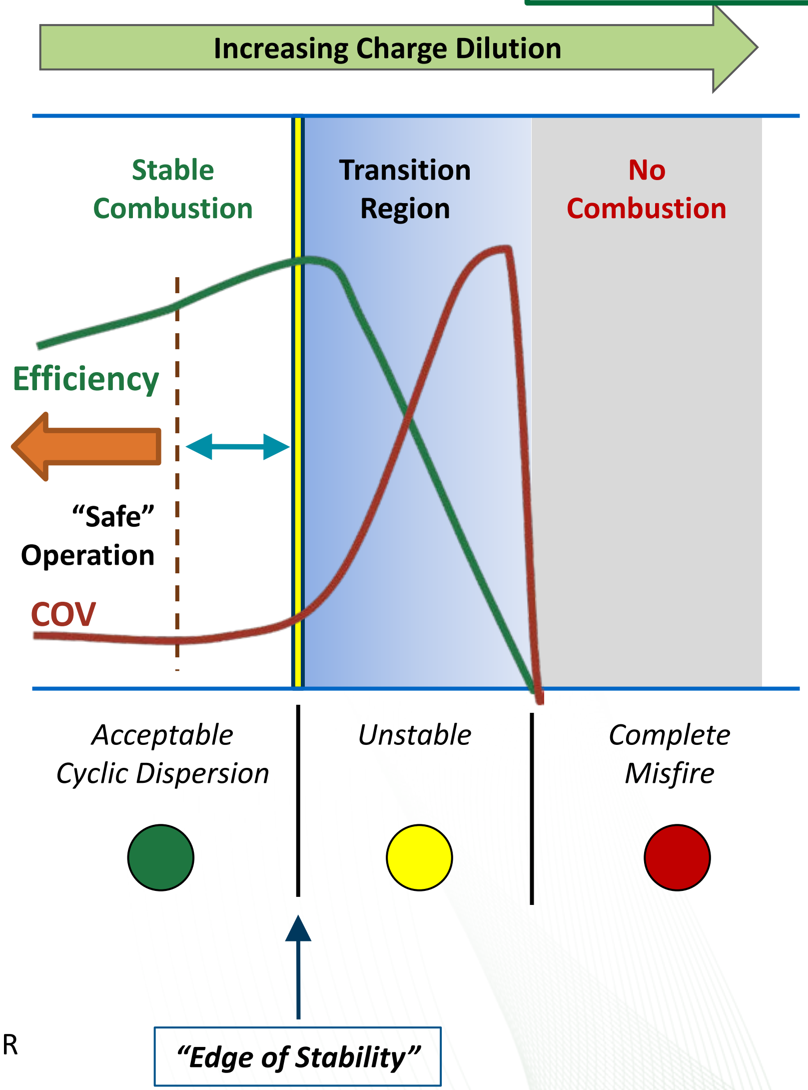
Technical Back-Up Slides

Simple representation of the onset of cycle-to-cycle instabilities

TECHNICAL BACKUP 1

- Driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes
- Instabilities may be "short" or "long"[1] timescale
  - "Short" refers to a few successive cycles
  - "Long" refers to 10s-100s successive cycles
- Practical implementations operate well away from the edge of stability to avoid unintended excursions
- Advanced controls could enable operation at the "edge of stability"
  - Requires a detailed understanding of instability mechanisms



[1] Kaul BC, Finney CE, Wagner RM, Edwards ML. "Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion," SAE Int. J. Engines. 2014; 7(2), doi:10.4271/2014-01-1236.

Nonlinear dependence of combustion on composition causes chaotic behavior

Technical Backup 2

- Flame speed dependence on ϕ is highly nonlinear
  - System is very sensitive to small variations in composition
  - Can take advantage of this to enable active control

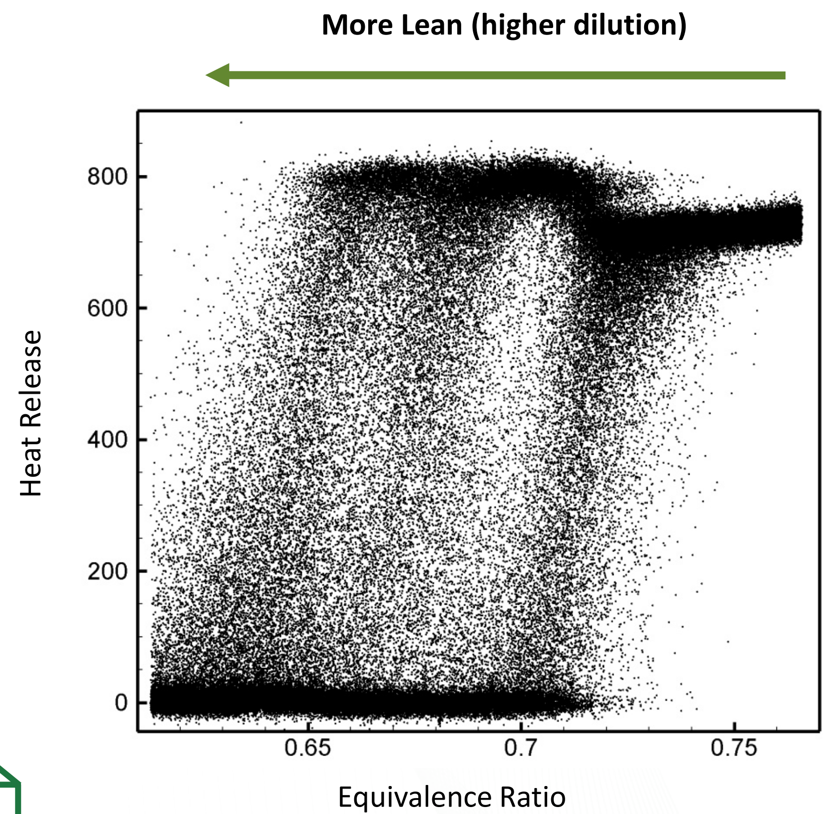
$$S_L = S_{L0}\left(\frac{T_u}{T_0}\right)^{\alpha}\left(\frac{P}{P_0}\right)^{\beta}\left(1-2.1Y_{dil}\right)$$

$$S_{L0} = B_M + B_2\left(\Phi - \Phi_M\right)^2$$

$$\alpha = 2.18 - 0.8\left(\Phi - 1\right)$$

$$\beta = -0.16 + 0.22\left(\Phi - 1\right)$$

Reference: B. C. Kaul, "Addressing Nonlinear Combustion Instabilities in Highly Dilute Spark Ignition Engine Operation", PhD Dissertation, Missouri University of Science and Technology, 2008.



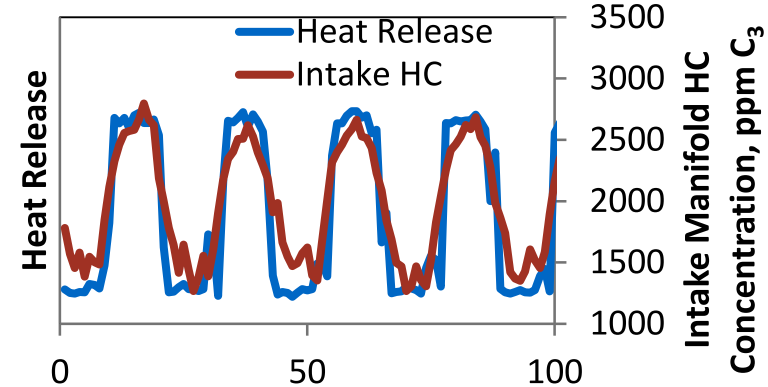
Experimental Data

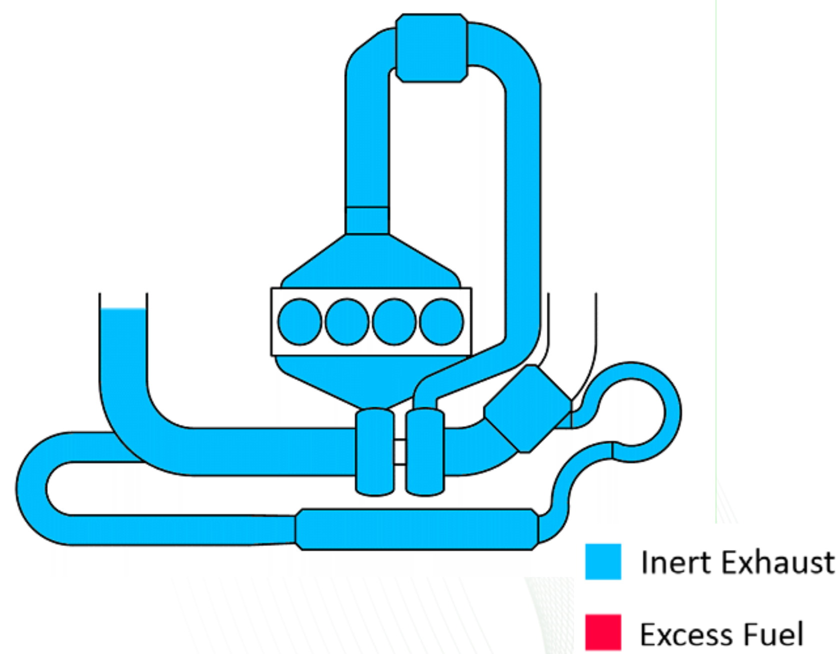
Reference: R. M. Wagner, J. A. Drallmeier, and C. S. Daw, "Characterization of Lean Combustion Instability in Premixed Charge Spark Ignition Engines", International Journal of Engine Research, 1, No. 4, pp. 301-320, 2001.

Long time-constant combustion instabilities observed for high-EGR operation

TECHNICAL BACKUP 3

- Combustion instabilities
  - Alternates between high-quality combustion and misfires
  - Period on the order of 10s of cycles
  - Variations synchronized across all 4 cylinders
- External EGR loop feedback dominates over internal residuals
  - Period of oscillations is due to flow through EGR loop
  - Recirculated exhaust from misfire cycles provides extra fuel and air
  - Recirculated exhaust from high-energy cycles provides only inert diluent





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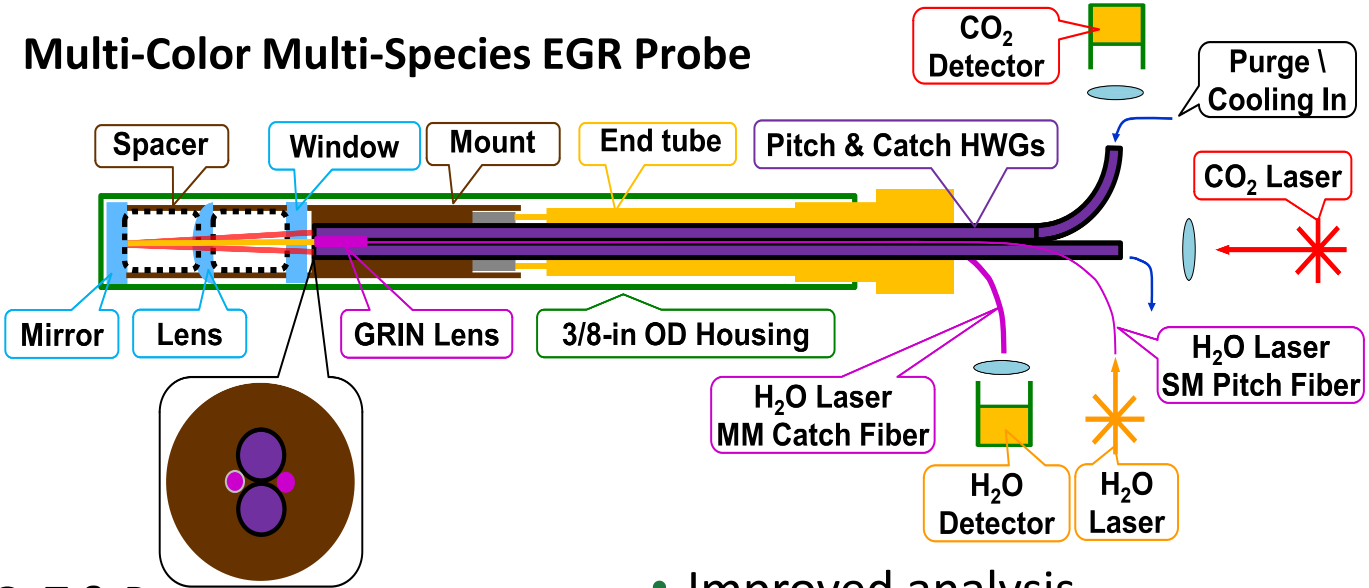
Fast EGR Measurement Probe

TECHNICAL BACKUP 4

Multi-Color Multi-Species EGR Probe



- Measures CO_2, H_2O, T & P
- Leverages ORNL–Cummins CRADA & SuperTruck
  - CRADA
    - Original EGR Probe development
  - SuperTruck
    - H_2O diagnostic development at Purdue
  - CRADA & SuperTruck
    - 4-probe multi-plex system
    - Combined CO_2–H_2O probe instrument

- Improved analysis
  - Iterative baseline fit
  - Absorption profile fit to theory (vs. integration & calibration-factors)
  - Shifted-sawtooth laser ramp for real-time background subtraction
  - Improved wavelength calibration
  - 5kHz rate (200µs, 2.4° CA at 2k RPM)

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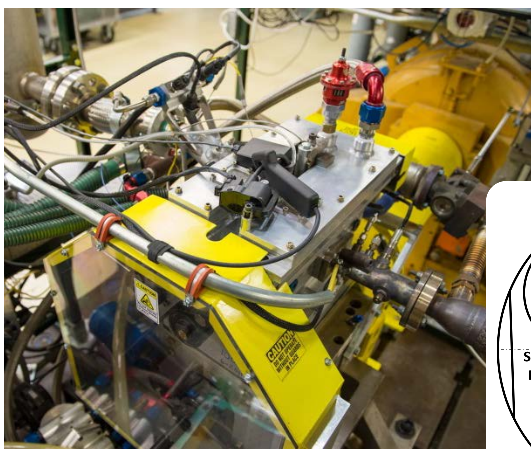
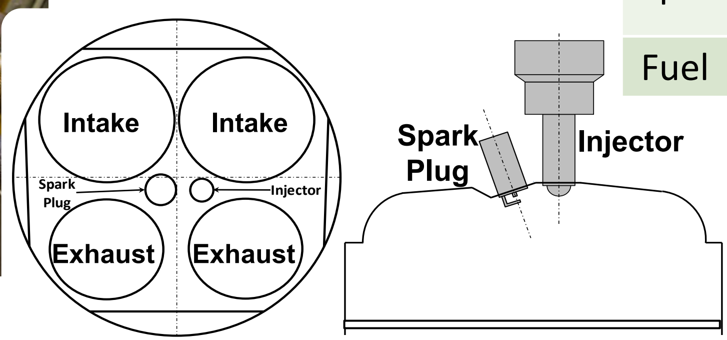
ANL Single-Cylinder Engine Setup for Perturbation Experiments

TECHNICAL BACKUP 5

- 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

GDI Engine Specifications	
Displacement	0.626 L
Bore/Stroke	89/100.6 mm
Compression Ratio	12.1
Intake Valve MOP	100 °CA ATDC
Exhaust Valve MOP	255 °CA ATDC
GDI Injector	6 hole, solenoid
Injection pressure	150 bar
Spark Plug	NGK-R dual fine wire, 0.7 mm gap
Fuel	EPA Tier II EEE





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