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

ACE090

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High-dilution SGDI project overview

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Summary

Timeline

- Project began in 2011
- Activities evolve to address changing DOE & industry needs

Barriers (MYPP 2.3.1 A, D)

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

Budget

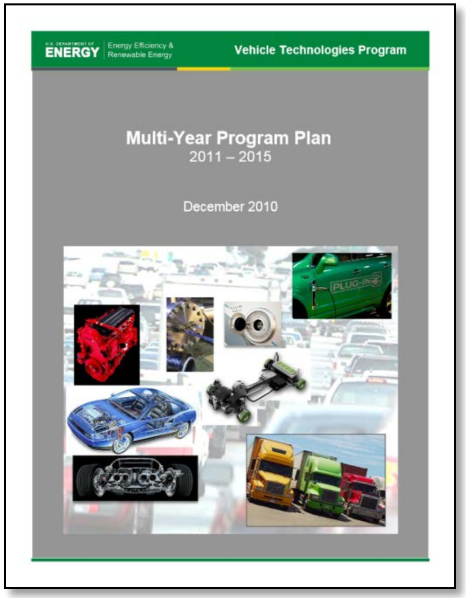
- FY 2013: $400k
- FY 2014: $300k

Partners/Interactions

- Industry Collaborators
  - Bosch
  - National Instruments
- 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 EGR dilution limit to enable greater efficiency gains with boosted downsizing, leading to increased vehicle fuel economy
- FY 13-14 Objectives
  - Characterize cyclic variability for external EGR operation
  - Evaluate effects of varying engine control inputs
  - 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
09/2013	Evaluate effects of varying engine control inputs, including fuel injection timing and cam timing, on high-dilution combustion stability	Completed
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	On Track
09/2014	Demonstrate potential of next-cycle control on combustion stability and engine efficiency and effectiveness for dilution limit extension	On Track

Advanced controls use deterministic behavior to reduce cyclic variability

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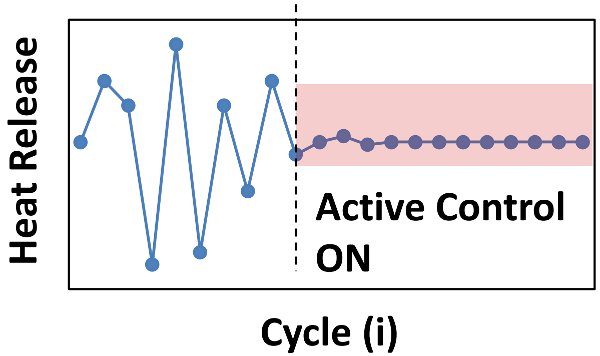
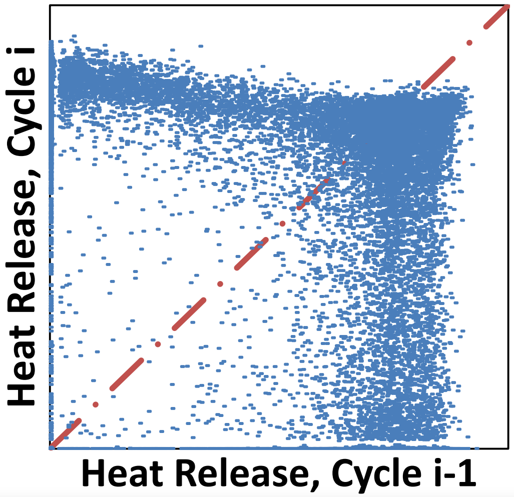
- Combustion instabilities at the dilution limit have deterministic structure combined with stochastic noise

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"



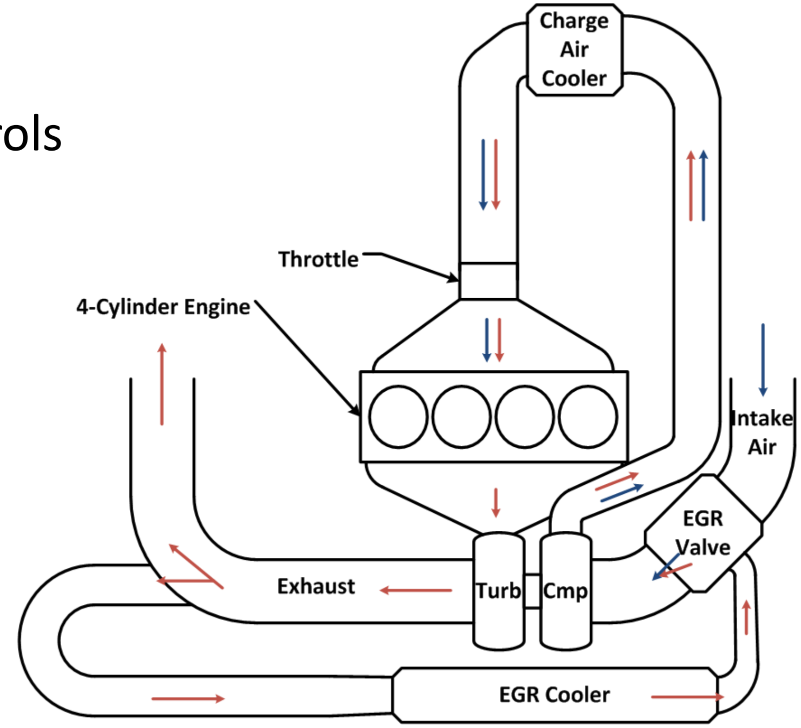


Experimental platform: 4-cylinder GDI engine with cooled EGR

- 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	



Accomplishments—Overview

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- Evaluated analysis methods for identifying deterministic components of variations
  - Validated analysis tools for identifying trajectories
  - Estimated potential improvement with control
- Elucidated the effects of external EGR loop geometry
  - Distinguished between short time-constant and long time-constant behavior
- Upgraded engine control system to allow next-cycle control
  - Control strategies currently being developed and implemented

SAE International

Analysis of Cyclic Variability of Heat Release for High-EGR GDI Engine Operation with Observations on Implications for Effective Control

Brian Kaul, Robert Wagner and Johney Green
Oak Ridge National Laboratory

SAE INTERNATIONAL

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Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion

Brian C. Kaul, Charles E.A. Finney, Robert M. Wagner, and Michelle L. Edwards
Oak Ridge National Lab.

ABSTRACT

Operation of spark-ignition (SI) engines with high levels of charge dilution through exhaust gas recirculation (EGR) achieves significant efficiency gains while maintaining stoichiometric operation for compatibility with three-way catalysts. Dilution levels, however, are limited by cyclic variability-including significant numbers of misfires-that becomes significant with increasing dilution. This variability has been shown to have both stochastic and deterministic components. Stochastic effects include turbulence, mixing variations, and the like, while the deterministic effect is primarily due to the nonlinear dependence of flame propagation rates and ignition characteristics on the charge composition, which is influenced by the composition of residual gases from prior cycles.

The dynamics of operation with an external EGR loop differ substantially from those of dilute operation without external recirculation, both in time-scale and cylinder-synchronization effects, especially when misfires are encountered. This paper examines these differences and the implications for prior-cycle-based control strategies.

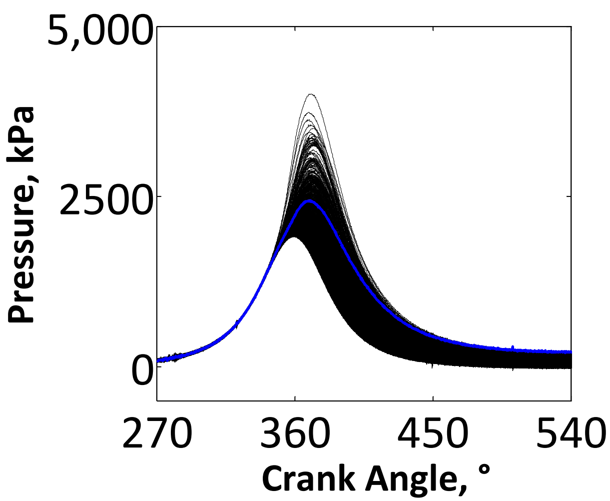
CITATION: Kaul, B., Finney, C., Wagner, R., and Edwards, M., "Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion," *SAE Int. J. Engines* 7(2):2014, doi:10.4271/2014-01-1236.

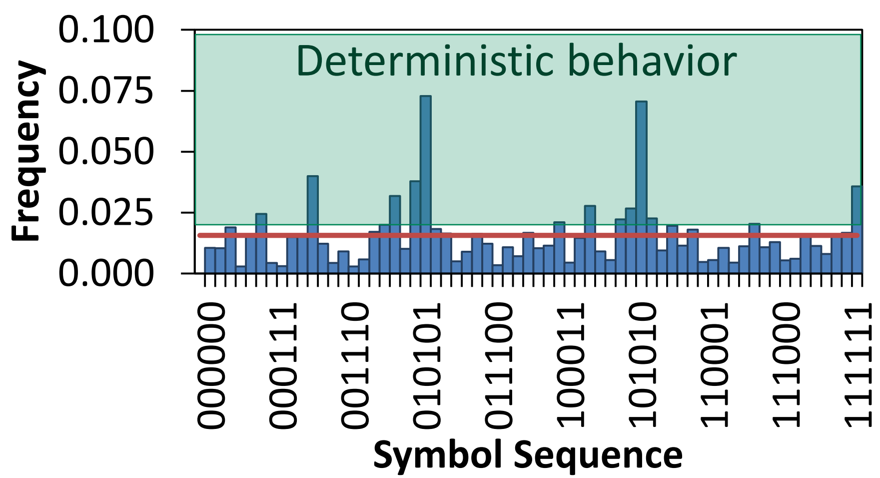
INTRODUCTION

Symbol-sequence statistics analysis finds order in chaos

ACCOMPLISHMENTS (2/6)

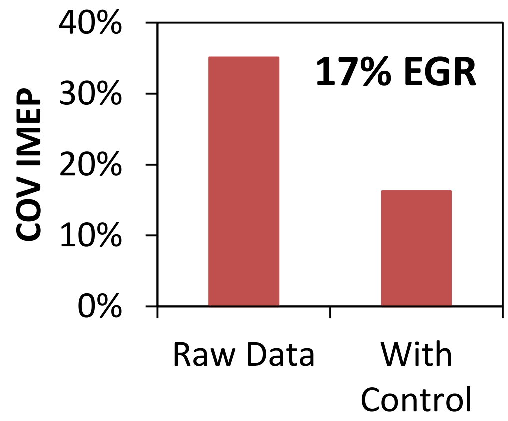
- Symbolization of chaotic time series data
  - Discretize data and identify patterns of recurring sequences
  - Enables automated identification of recurring, non-random trajectories
  - Robust even for low-quality or noisy input data
- Developed method of optimizing symbolization parameters for control purposes using modified Shannon entropy

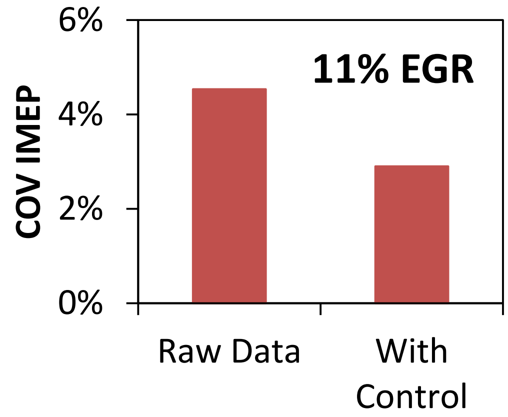




Effective control would enable operation at the "edge of stability"

- Estimation of potential controller effectiveness:
  - Identify cycles that are part of frequently occurring patterns in symbol sequence analysis
  - Remove these cycles and recalculate statistics such as COV and mean IMEP based on "filtered" data
- Effective controls will yield higher thermal efficiency and reduced COV



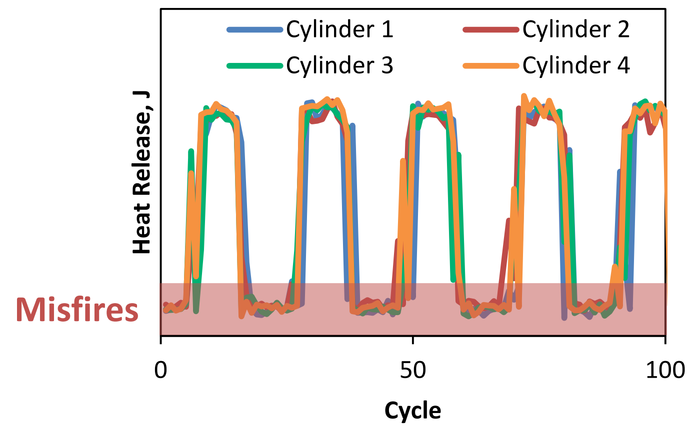


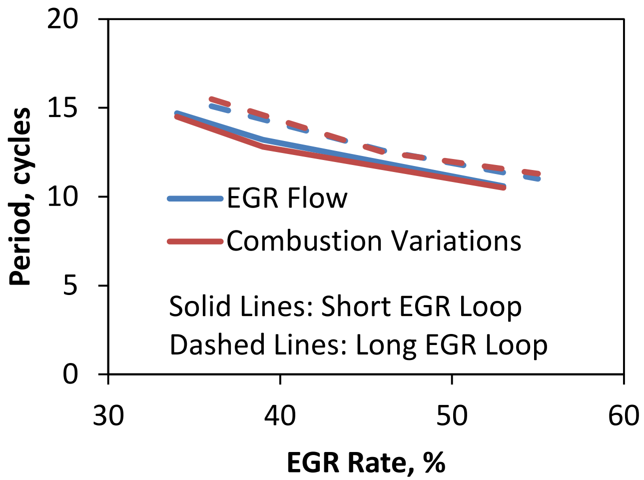
Indicates that symbol sequence analysis methods are well-suited for use in active controls to reduce COV and enable operation at the edge of stability

Long time-constant combustion instabilities were also found to occur with high-EGR operation

- Combustion instabilities at very high EGR rates have unique structure
  - Alternates between high-quality combustion and misfires
  - Long time-scale (~10s of cycles) variations in addition to previously observed short time-scale (~1 cycle) effects
- Varied EGR loop length
  - Period of combustion variations tracks closely with calculated EGR flow time
- Operated engine at extreme EGR levels to elucidate effects
  - Misfires are easier to detect than subtle changes

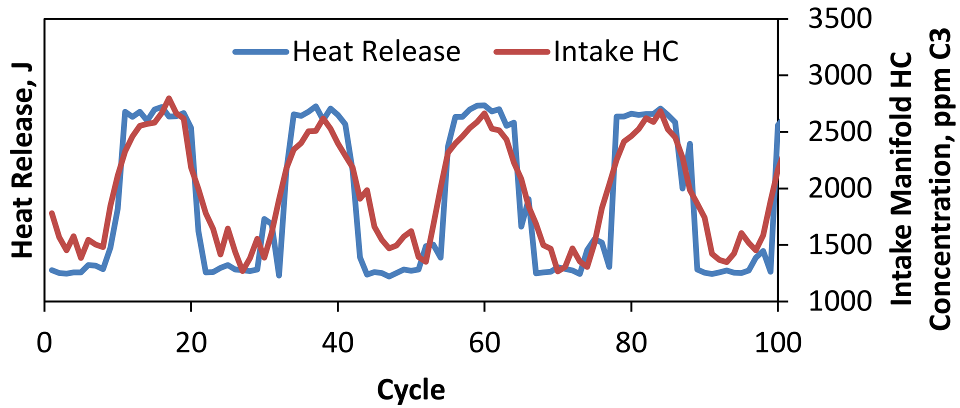
Same physical transport phenomena are present for more moderate EGR rates without misfires

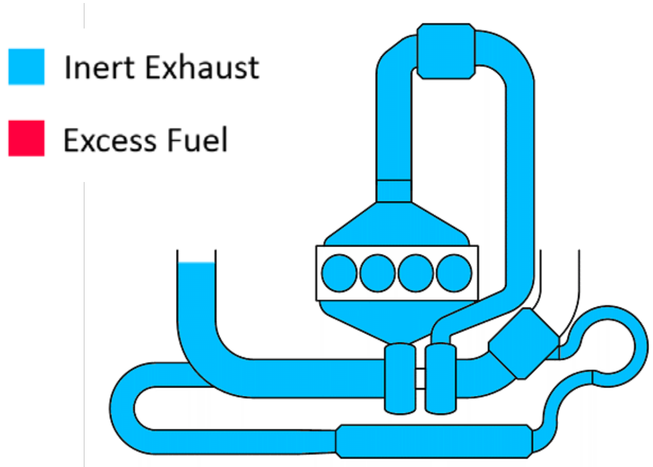




Long-period instabilities are driven by EGR flow recirculation time

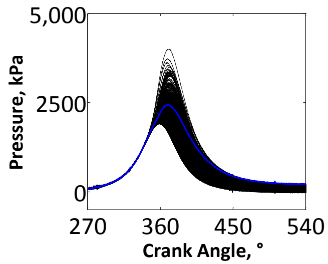
- External EGR loop feedback dominates over internal residuals
  - Period of oscillations (~1s) is due to flow through EGR loop
  - Recirculated exhaust from misfire cycles provides extra fuel and air
  - Recirculated exhaust from high-energy cycles provides only inert diluent
- Intake HC concentration measurement verifies that EGR composition is the feedback mechanism

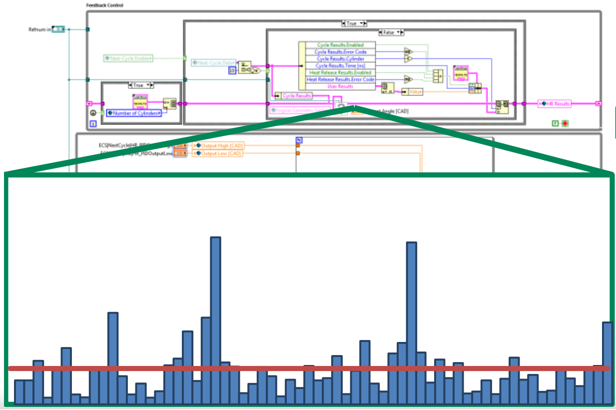


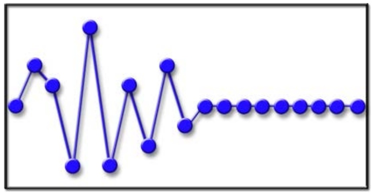


Next-cycle control being implemented: on-track to meet Q3 milestone

- Automatic cylinder-to-cylinder balancing
  - Cycle cumulative heat release (via fuel mass)
  - Combustion phasing (CA50, via spark timing)
  - Functionality demonstrated in March 2014
- Next-cycle controls to reduce COV
  - Use symbolic analysis to detect impending undesirable dynamical trajectories based on prior-cycle results
  - Adjust fuel quantity to push system back to stable operation
  - Include EGR flow rate effects







Reviewer comments from FY 2013

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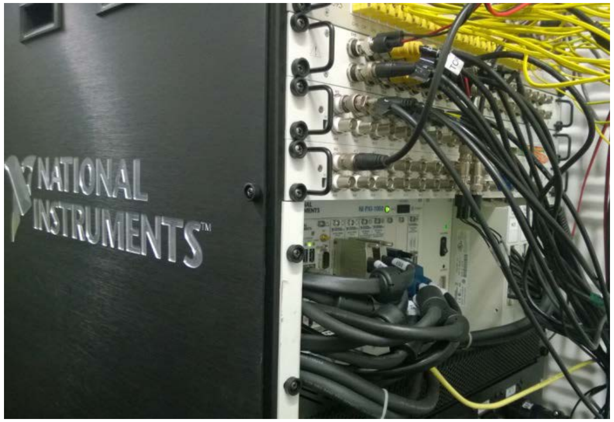
This project has not been previously reviewed

Collaborations

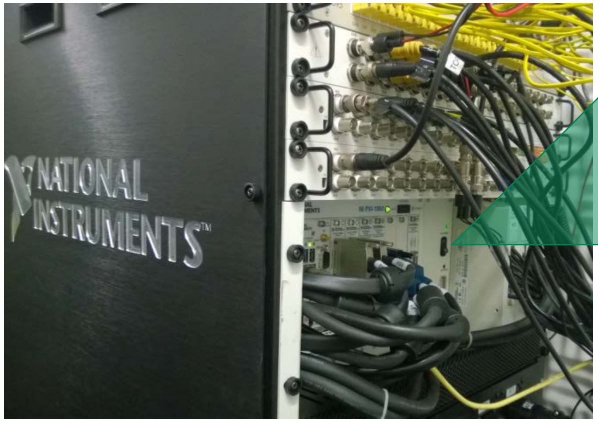
- Robert Bosch LLC
  - Customized engine for FFV optimization in previous DOE program
  - Provided engine and ECU with calibration-level access
  - Support of engine controls

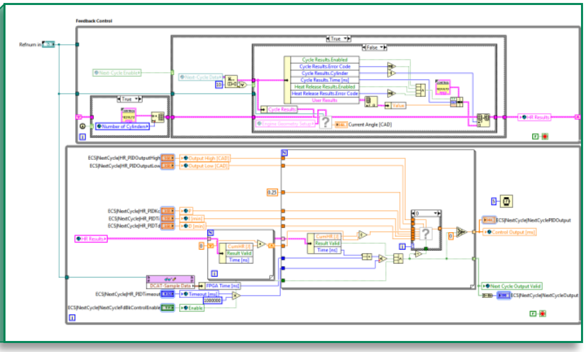
- National Instruments Powertrain Controls (Drivven)
  - Support of next-cycle and same-cycle controls development
  - In talks to exchange data



Remaining Challenges and Barriers

- Need to demonstrate next-cycle control of engine
  - Establish effectiveness for controlling COV
  - Determine resulting efficiency gains
- Need to address differing dynamics of lean-burn vs external EGR
- Need to refine and improve control strategies
  - Initial demonstration will be at a single steady-state condition
  - Initial strategy relies on online learning period





Future Work

- FY 2014
  - Finish implementation of next-cycle controls
  - Determine impact on COV and efficiency
- FY 2015
  - Continue development of next-cycle control strategies
    - Improve strategies for high-EGR operation
    - Evaluate application to lean-burn GDI
    - Demonstrate dilution limit extension
  - 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

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Relevance

- Cooled EGR enables significant fuel efficiency gains with boosted downsizing, 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

- Demonstrated potential for improvement in COV and efficiency using symbol sequence statistics
  - Developed method for optimizing symbolization parameters
- Elucidated effects of EGR recirculation time on long-period combustion variations
  - Identified long time-constant variations that occur along with previously known short-timescale effects
- Implemented next-cycle capable control system on engine

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"

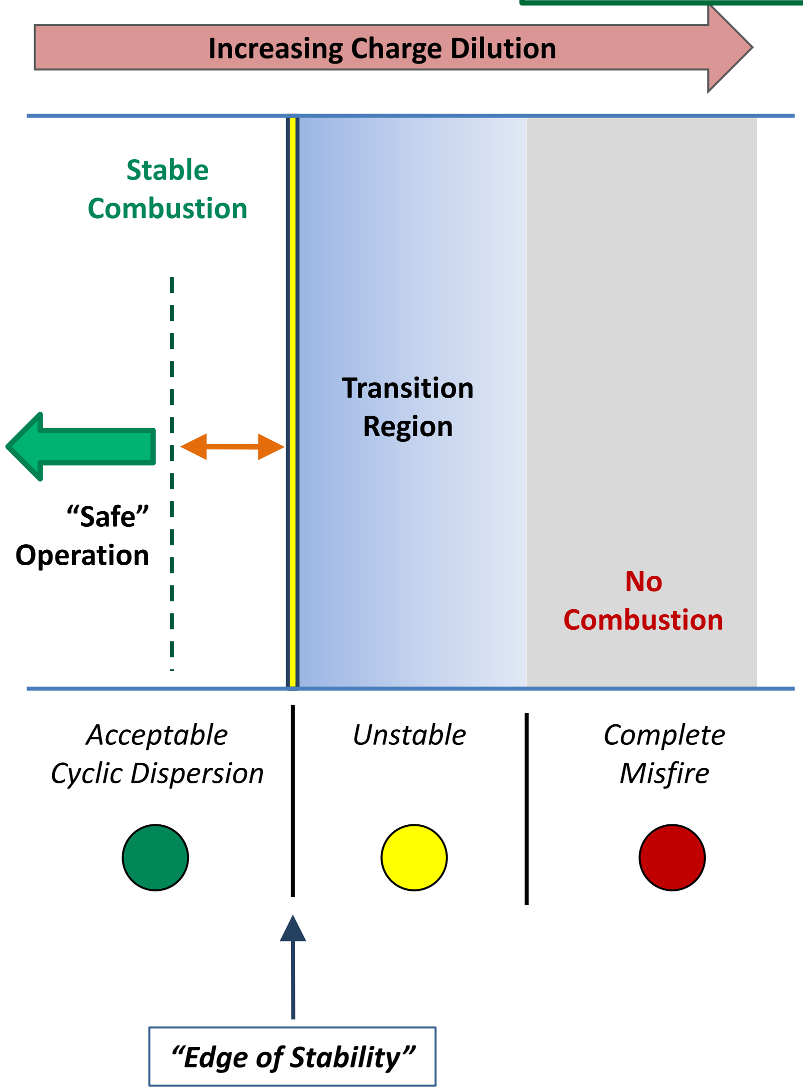
Technical Back-Up Slides

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

TECHNICAL BACKUP 1

- Practical implementations operate well away from the edge of stability to avoid unintended excursions
- Driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes
  - Very nonlinear relationship
  - Deterministic mechanisms act as nonlinear amplifier to stochastic variations
- Instabilities may be "short" or "long" timescale
  - "Short" refers to a few successive cycles
  - "Long" refers to 10s-100s successive cycles

➡ Improved control requires an improved understanding of instability mechanisms



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

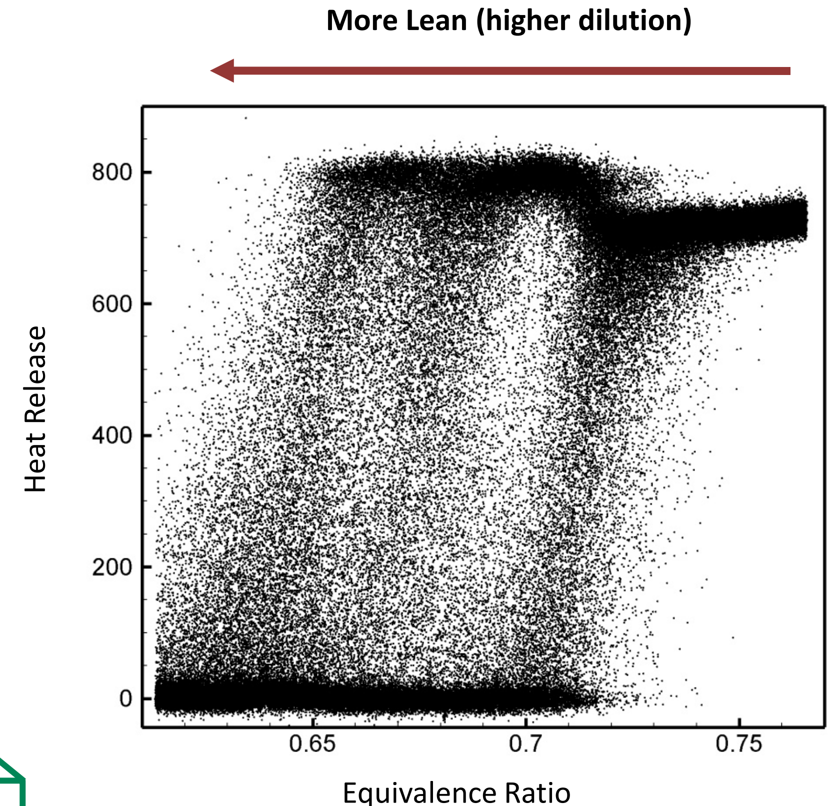
$$S_L = S_{L0}\left(\frac{T_u}{T_0}\right)^{\alpha}\left(\frac{P}{P_0}\right)^{\beta}\left(1-2.1Y_{dil}\right)$$

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

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

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

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



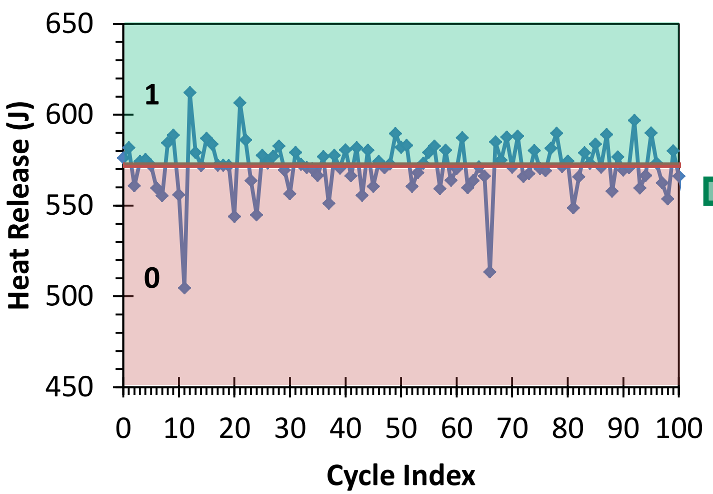
Experimental Data

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.

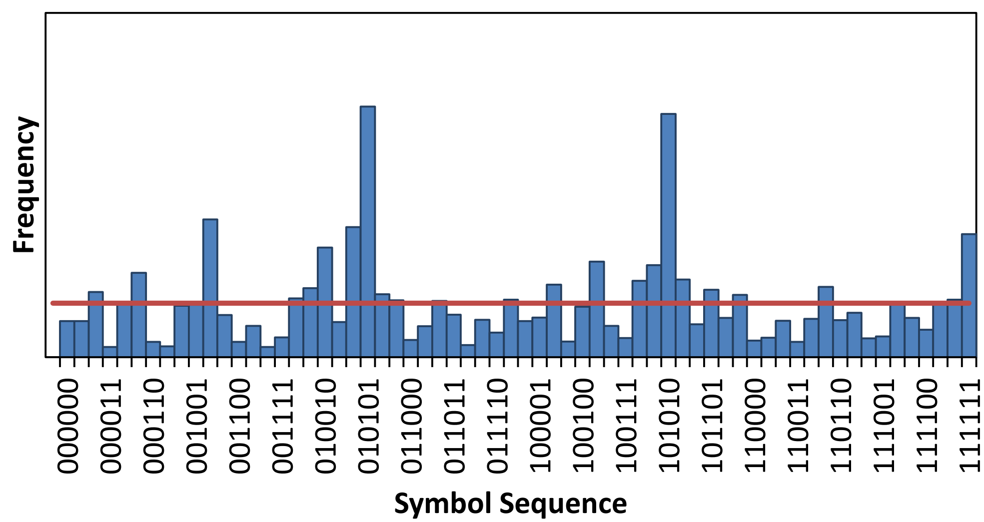
Symbol sequence analysis method

TECHNICAL BACKUP 3

- Procedure:
  - Partition time series data into discrete bins
  - Consider sequences of a specified number of cycles
  - Identify patterns of sequences that recur frequently
- Advantage: algorithmically identify recurring, non-random patterns in noisy data



Partitioning example: in this case, data are discretized into binary partitions (0,1). More partitions can be used for higher resolution.



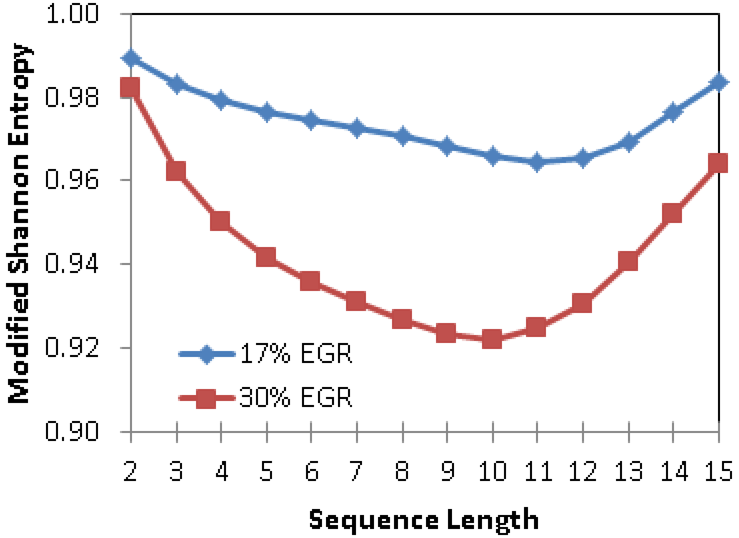
Symbol sequence histogram using 2 partitions and sequence length of 6 (optimal for this data). Red line indicates expected value for random data.

Modified Shannon entropy allows optimization of parameters for symbolic analysis

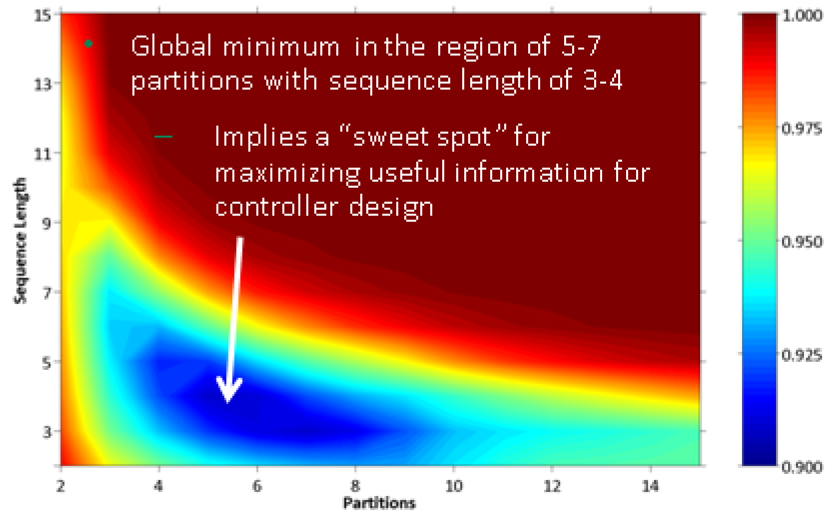
- Modified Shannon entropy
  - Measure of information availability
  - Minimum corresponds to greatest determinism

$$H_{s,m} = -\frac{1}{\log n_{seq}} \sum_k p_k \log p_k$$

n_{seq} = # of sequences
p_k = probability of sequence k occurring



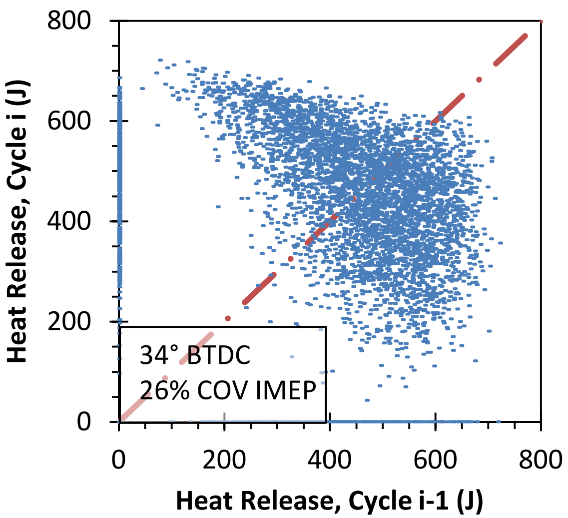
Modified Shannon entropy variation with sequence length using 2 partitions

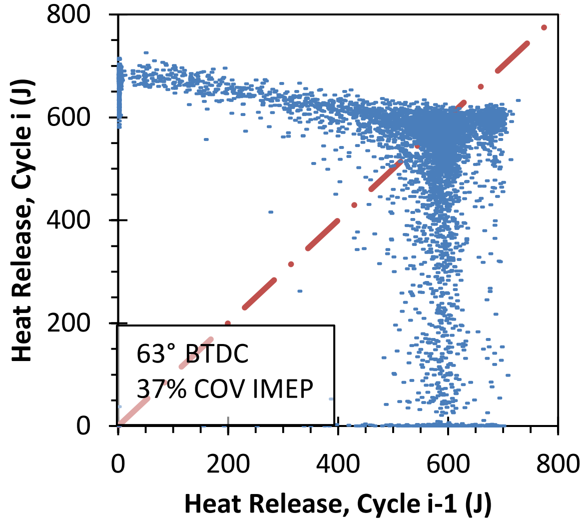


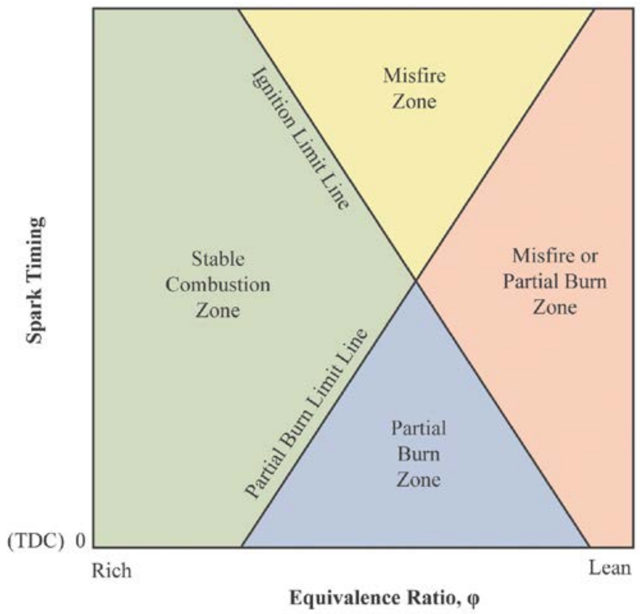
Modified Shannon entropy variation with number of partitions and sequence length

Ignition timing affects COV qualitatively

- For retarded timing, high degree of spread in heat release is evident (many partial burns)
- More advanced timing tightens up the map and yields higher average BMEP, at the cost of additional misfires







Heat release return maps of cycle i vs. cycle i-1. Time asymmetry (about 45¢ diagonal) indicates determinism.

Engine operation at nominal 2000 rpm, 4 bar BMEP operation with 22% EGR and ignition timings of 34¢ and 63¢ BTDC.

Zones of stable and unstable operation in lean mixtures. The vertical axis indicates spark advance from TDC.