Westport™ INNOVATIONS INC.

Advancing the shift of global commercial transportation to natural gas and hydrogen.

Development of a Robust Accelerometer-based Start of Combustion Sensing System

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This presentation does not contain any proprietary or confidential information

Outline

- Purpose of work
- Address Previous Review Comments (if applicable)
- Barriers
- Approach
- Performance Measures and Accomplishments
- Technology Transfer
- Publications/Patents
- Plans for Next Fiscal Year
- Summary

Purpose of Work

- A method to determine the Start of Combustion from knock sensors mounted on engine bearing caps was proven prior to the DoE funded work.
- The purpose of this DoE project is to improve the robustness of the solution method, through:
  - Compensation for engine-to-engine variations
  - Compensation for sensor-to-sensor variations

Advantages over Competing Technologies

- Non-Invasive
- Easy Installation
- Using Proven Hardware with High Durability
- Multiple Redundancy – High Robustness
- Low Cost
- Maintenance Free

Previous Review Comments

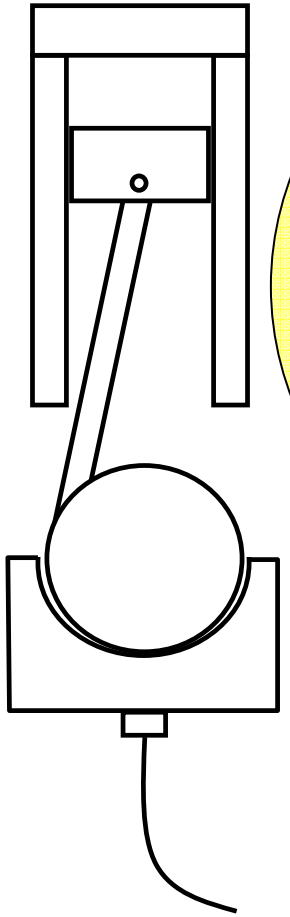
- First Merit Review for this program

Barriers

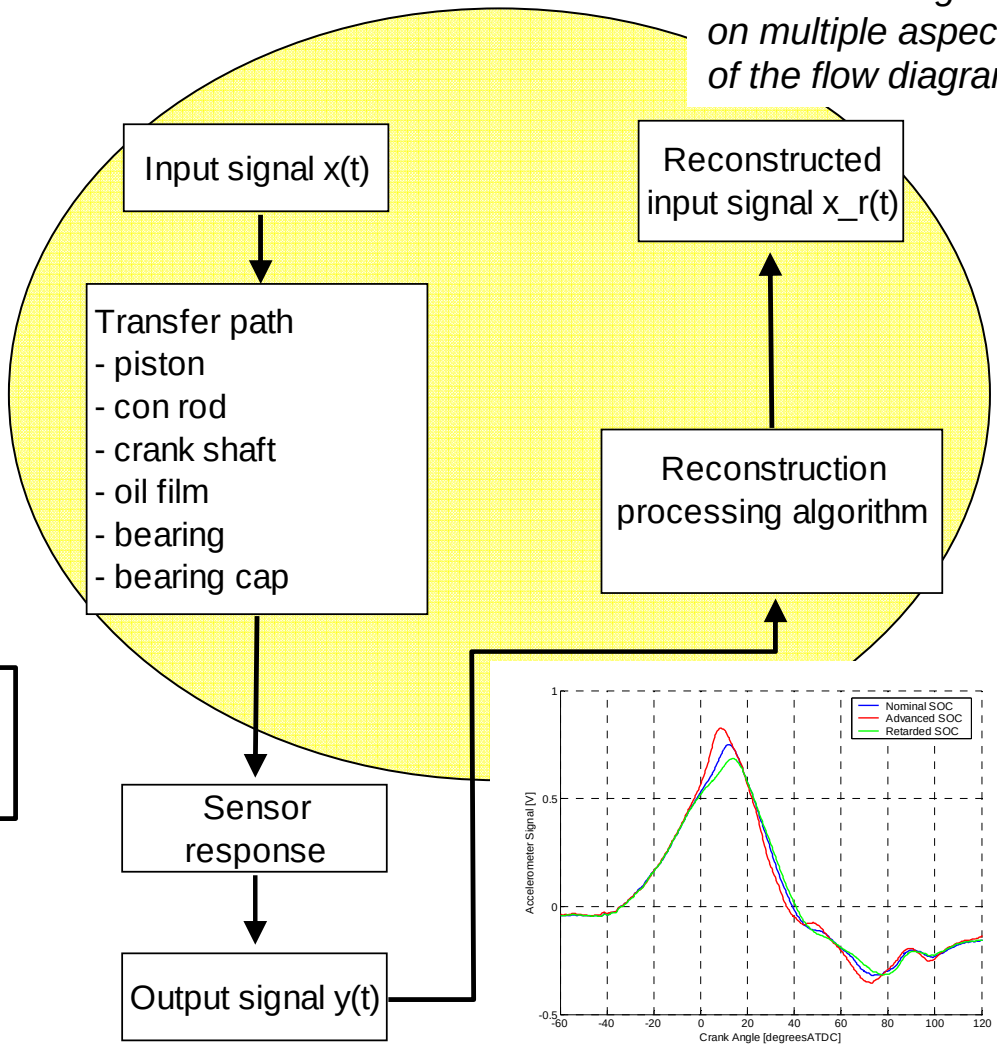
- Transfer path for signal from combustion chamber to bearing cap
- Non-linear transfer function between knock sensor signal and in-cylinder pressure
- Engine noise
- Robustness and accuracy of signal required for engine control
  - Sensor-to-sensor
  - Engine-to-engine
- Amount of information that can be predicted using the sensors

Approach:
Knock Sensors as Combustion Sensors

- **Idea**: reconstruct in-cylinder combustion event using knock sensors



Patent coverage on multiple aspects of the flow diagram



Performance Measures and Accomplishments

- Criterion for success was defined as:
  - SOC error standard deviation to be less than 0.5º CA, both engine-to-engine and sensor-to-sensor

- Accomplishments
  - Mean Engine-to-engine Variation 0.32℃A with 98.9% Confidence Level (3 Sigma)
  - Mean Sensor-to-sensor Variation 0.36℃A with 98.9% Confidence Level (3 Sigma)
  - Mean Total Error (1 Sigma) 0.19 ℃A – 0.41 ℃A

Technical Accomplishments – Cont.

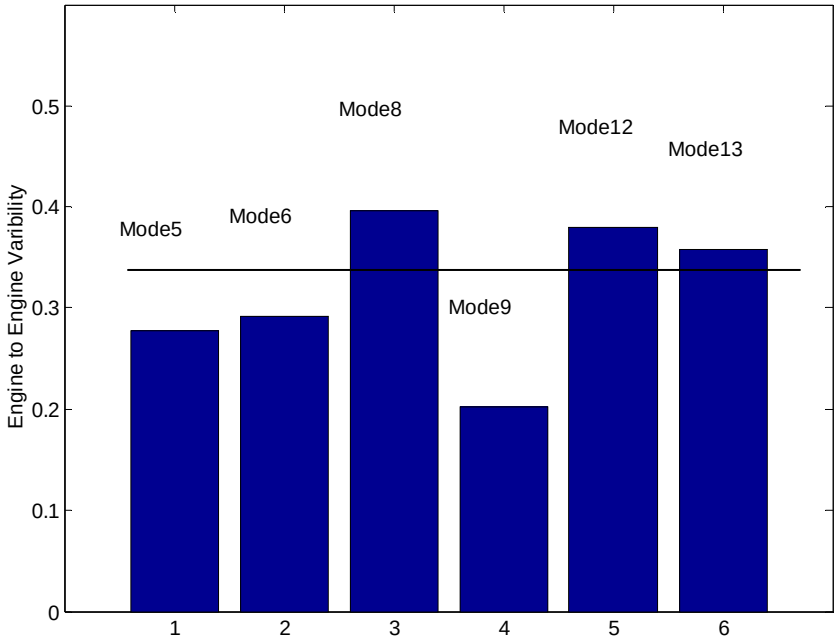
Accuracy

- 95%+ Accuracy on Identifying Misfired Cycles Over a Wide Range of Conditions
- Error (one standard deviation) in Peak Cylinder Pressure 4.5%
- Error (one standard deviation) in Peak Heat Release Rate 15%
- Error (one standard deviation) in IMEP 16%
- Reasonable agreement in 20%, 50% and 90% cumulative heat release timing
- Correct capture of heat release curve from multiple-pulse injections

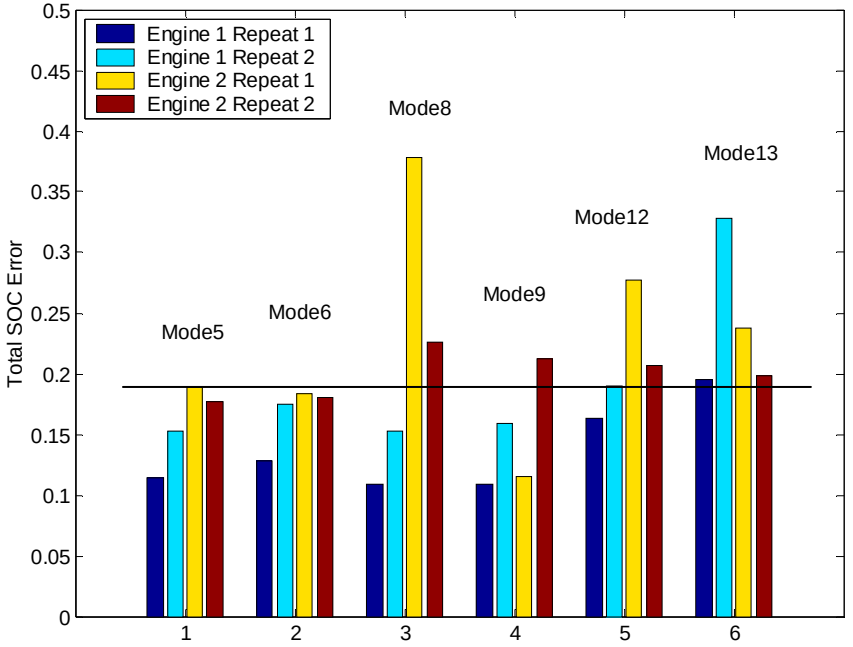
Robustness

- Algorithm developed for auto compensation for change in sensor properties
- Real-time auto calibration with no calibration table involved
- Multiple Redundancy

Total Error and E-to-E Variability



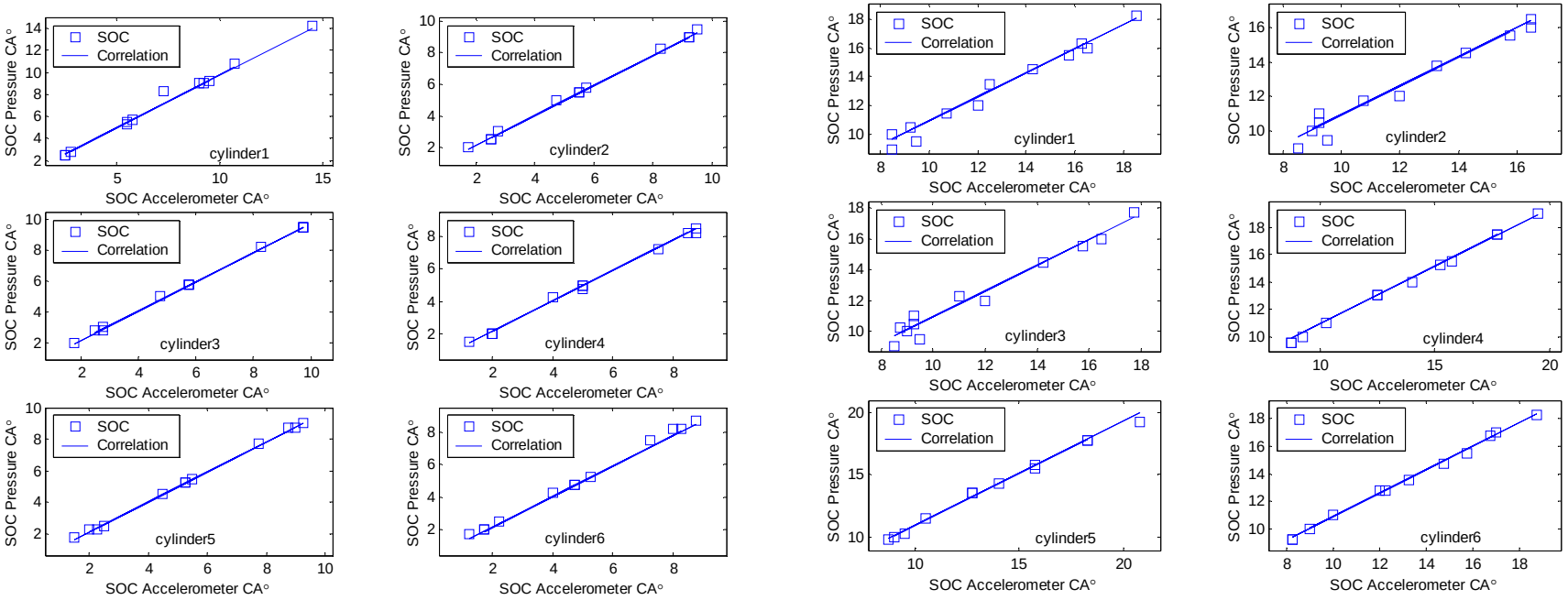
Engine-to-engine Variability from two ISB Engines – 0.32 °CA (3 σ)



Mean SOC Error 1 σ – 0.19 °CA

Cylinder-to-Cylinder Variation

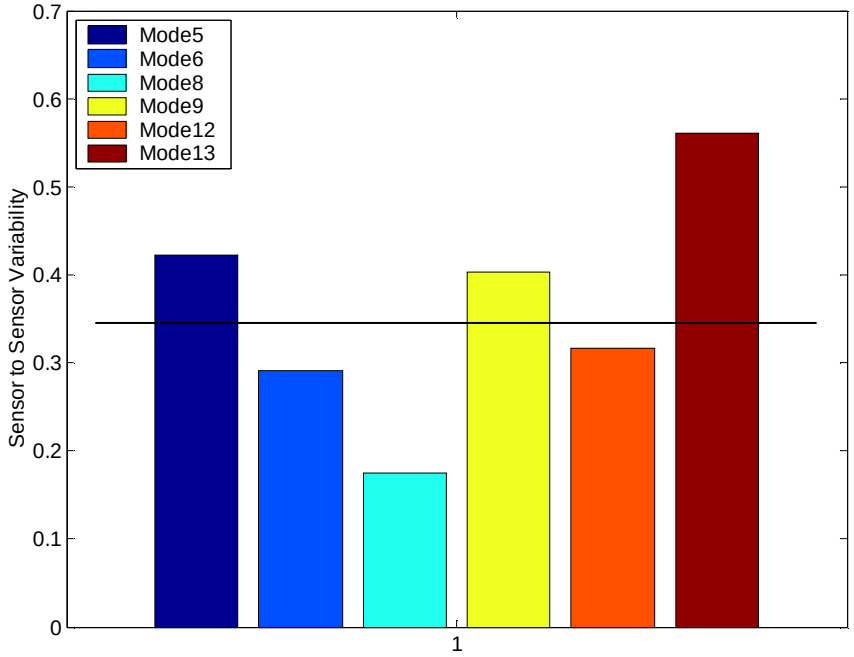
Engine 1 **Engine 2**



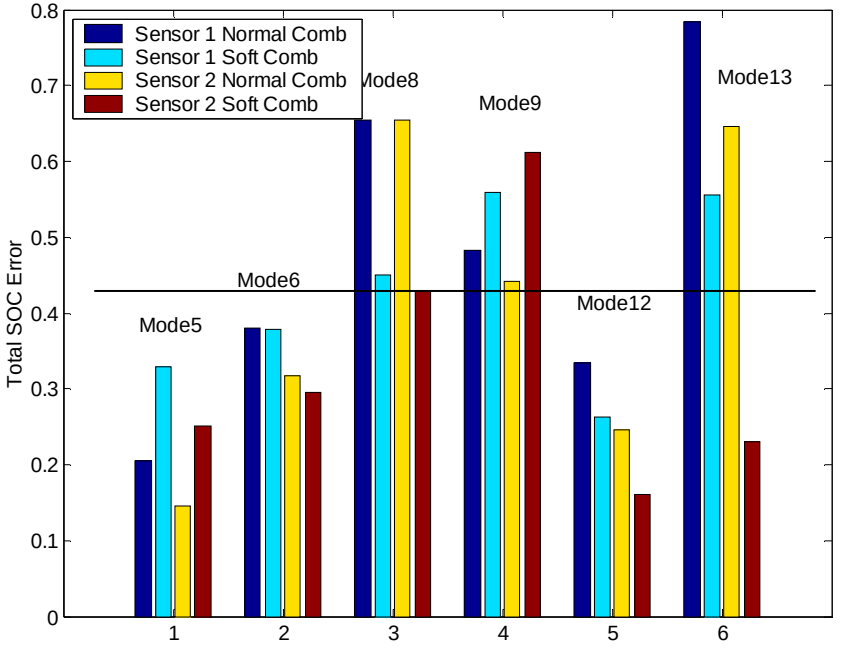
Comparison of Cylinder-to-cylinder Variation with Engine #1 (Left) and Engine #2 (Right)

Each Subplot Compares the Measured and Actual SOC for Each Cylinder with Correlation Developed from Engine #1

Sensor-to-Sensor Variability

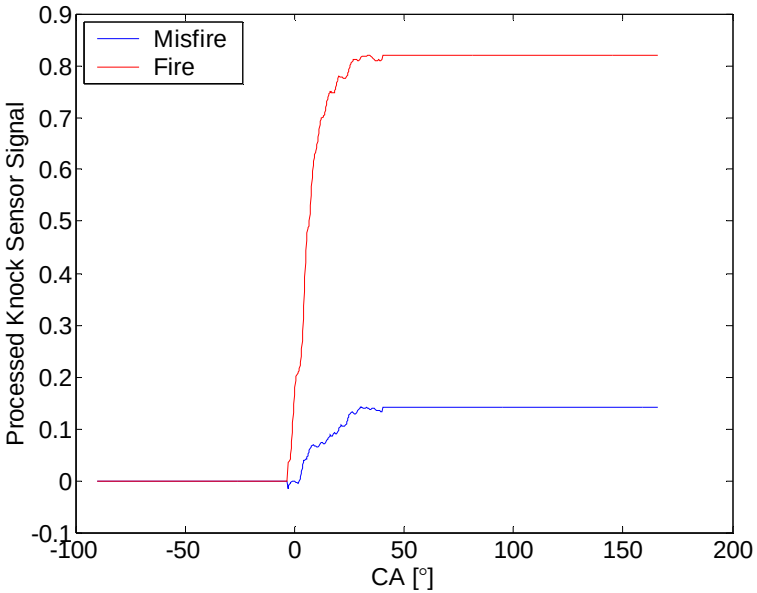


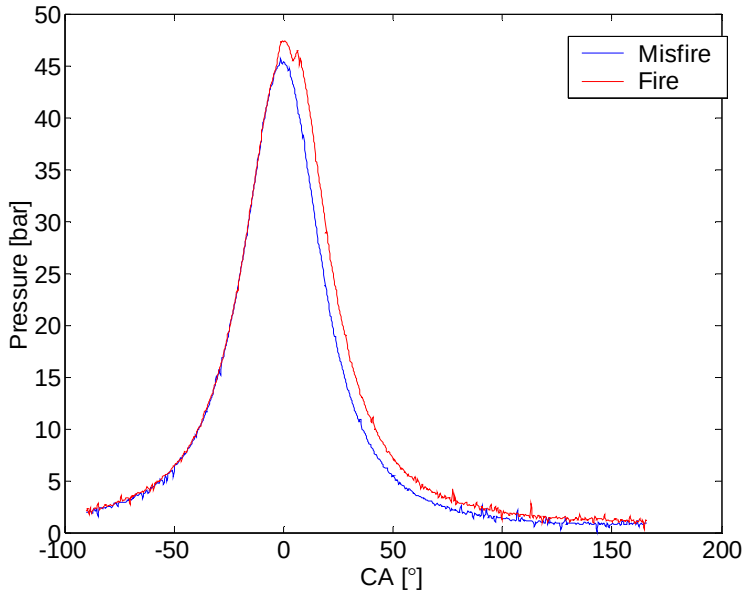
Mean Sensor-to-sensor Variability from two Sets of Siemens Knock Sensors 3 σ – 0.36 °CA



Mean SOC Error 1 σ – 0.41 °CA

Detecting Misfiring



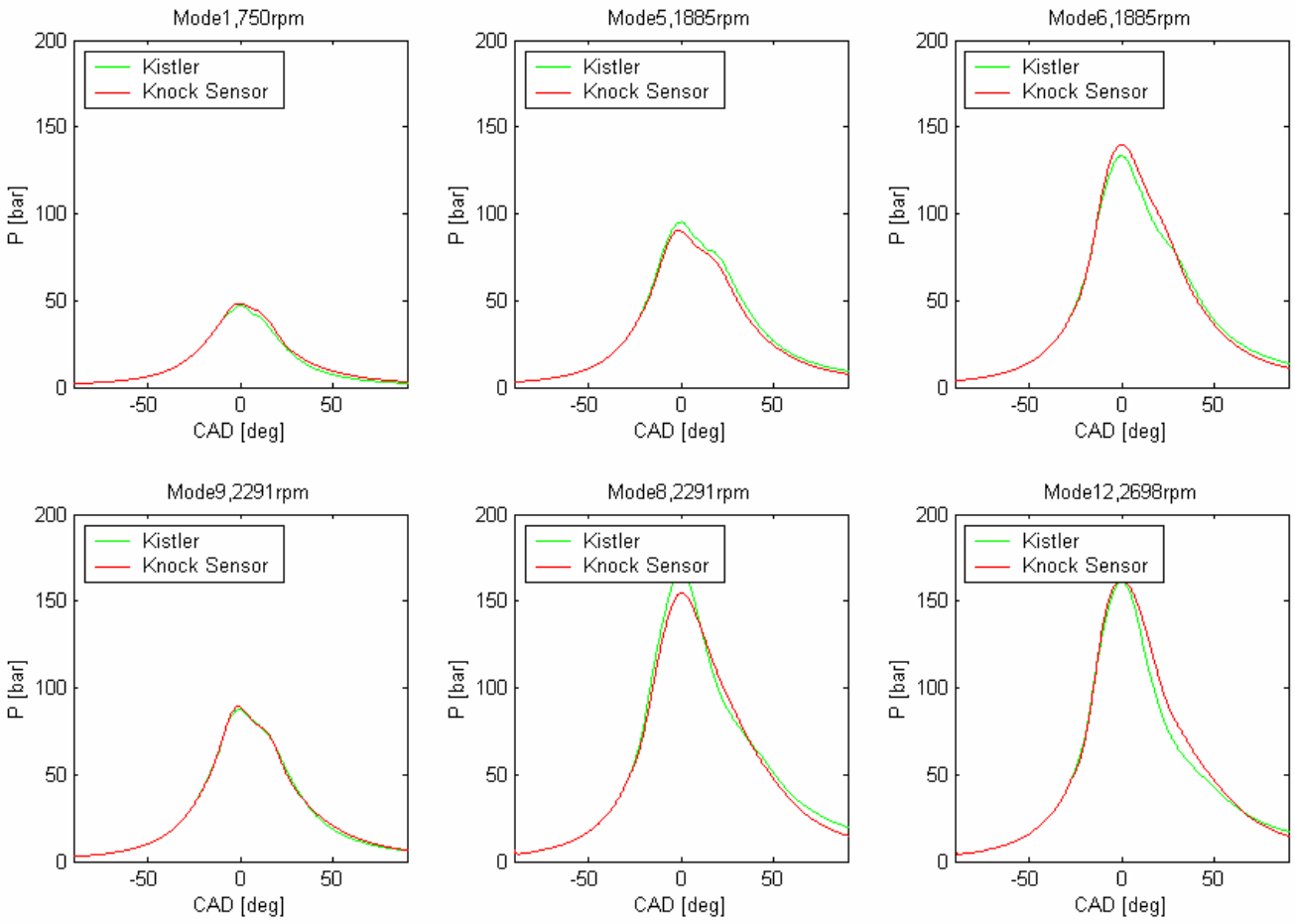


- 95%+ Accuracy for Identifying Misfired Cycles Under Various Operating Points Including Idle

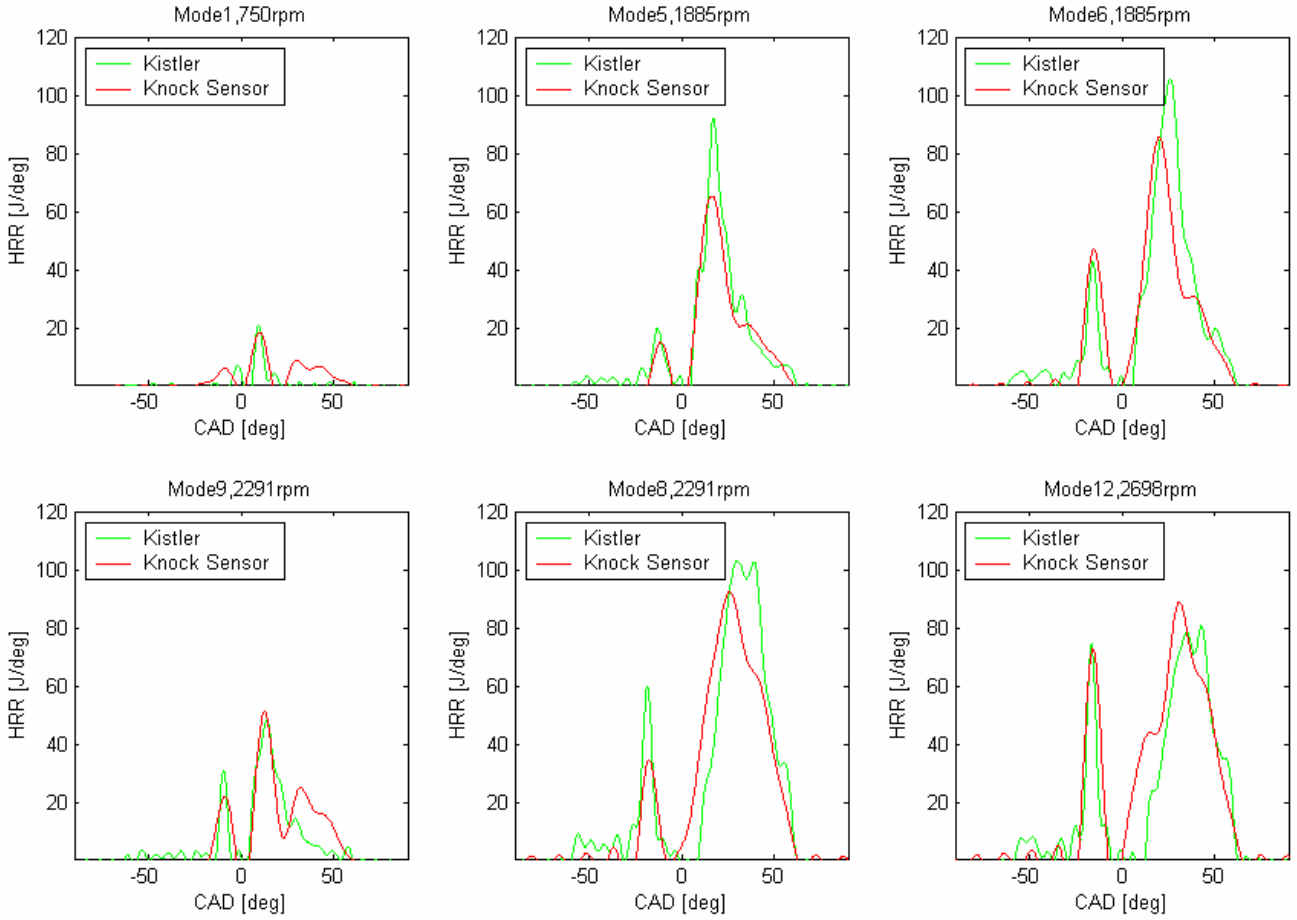
Progress

- Phase I was completed in July 2007
  - Originally scheduled to complete at the end of May 2007, but continuation application to extend Phase I by two months
  - Work completed approximately $40,000 under DoE budgeted amount
  - All tasks successfully completed for Phase I. Project continued into Phase II.
- Phase II started in August 2007.
  - Tested a charge amplifier and a buffer amplifier and verified that the buffer amplifier would be useful.
  - Engine testing for sensor-to-sensor variation work is now complete
  - Continued development of algorithm, with focus on sensor-to-sensor variation and also on obtaining as much information as possible from the signals

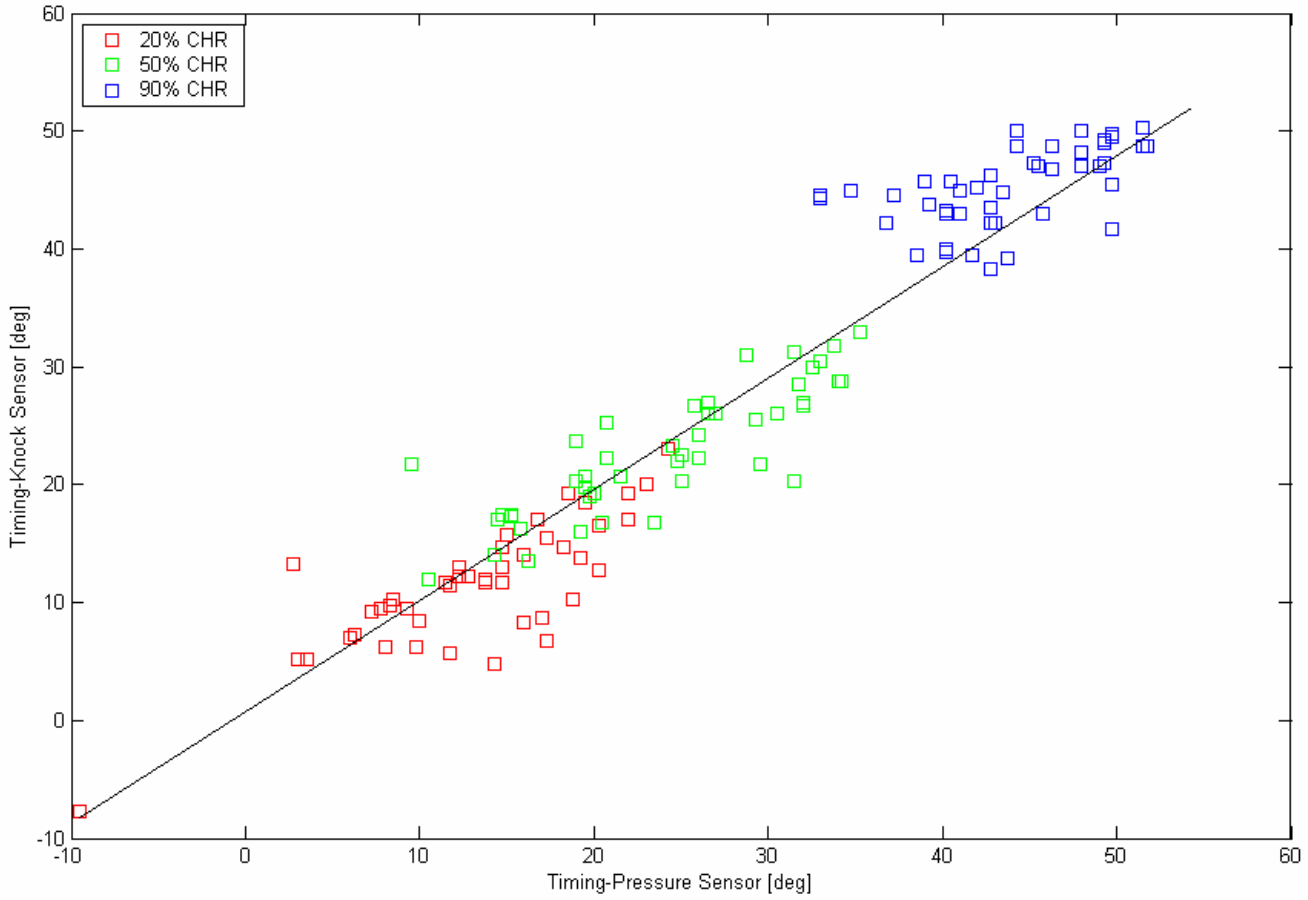
Work In Progress – Pressure Reconstruction



Work In Progress - Comparison of Heat Release Rate



Work In Progress - 20%, 50% and 90% Heat Release Timing



Technology Transfer

- In Active Contact with OEMs for Possible Licensing
- In Discussion with OEMs for Adopting Current Technology on Customer Platforms

Publications, Presentations, Patents

- **Presentations:**
  - DoE Diesel Cross-cut Meeting (November 8, 2007) – WebEx presentation
- **Patents filed before the Current DOE Contract:**
  - WP-PA2004012: US Patent No. 7,133,761, filed April 12, 2004
  - WP-PA2005081: US Patent No. 7,200,487, filed November 18, 2005
  - WP-PA2007009: US Patent Application 11/695,474, filed 2 April 2007 (relating to mounting methods and reducing signal noise for accelerometer sensors)
- **Patents filed during the Current DoE Contract:**
  - WP-PA2007028: Canadian Patent Application, filed 27 Nov. 2007 (relates to determining normal combustion characteristics from an accelerometer signal)
  - WP-PA2007029: Canadian Patent Application, filed 29 Nov. 2007 (relates to detecting misfiring)

Activity for Next Fiscal Year

- Continue Improvement of Robustness and Accuracy of Knock-Sensor Based Combustion Sensing Technology
- Demonstrate Close-loop Engine Control with Current Combustion Sensing Technology in Test Cell

Major Results Summary

- Mean Engine-to-engine Variation 0.32℃A with 98.9% Confidence Level (3 Sigma)
- Mean Sensor-to-sensor Variation 0.36℃A with 98.9% Confidence Level (3 Sigma)
- Mean Total Error (1 Sigma) 0.19 ℃A – 0.41 ℃A
- 95%+ Accuracy on Identifying Misfired Cycles Over a Wide Range of Conditions
- Research Grade Accelerometer Confirms Vertical Direction as Optimal Sensor Direction

Work In Progress

Accuracy

- Reasonable Agreement between Measured (Kistler) and Reconstructed (knock sensor) pressure and heat release rate
- Error (one standard deviation) in Peak Cylinder Pressure 4.5%
- Error (one standard deviation) in Peak Heat Release Rate 15%
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- Reasonable agreement in 20%, 50% and 90% cumulative heat release timing
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Robustness

- Algorithm developed for auto compensation for change in sensor properties
- Real-time auto calibration with no calibration table involved
- Multiple Redundancy

- Thank you for your attention!