2015 DOE Vehicle Technologies Program Review

Washington, D.C.
June 11, 2015

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Award: DE-EE0005975
Project ID: ACE091

Sensors and Ignition
Robert Bosch LLC

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Project Overview REGIS

Target & Barriers

Target is to develop an Intake Air Oxygen (IAO2) sensor which directly and accurately measures the oxygen concentration in the intake manifold and demonstrate its potential.

Barriers are
- Inadequate data on requirements and risks concerning sensing with IAO2
- Control Strategies utilizing IAO2 sensing

Partners

US Department of Energy

Robert Bosch LLC

Clemson University

Oak Ridge National Lab

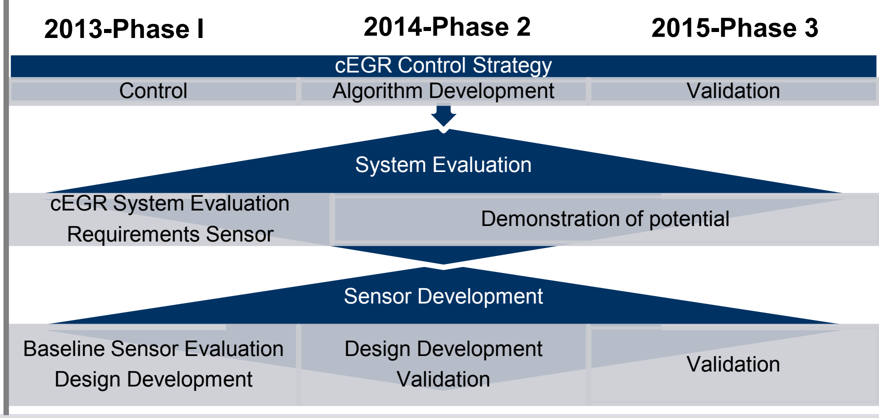
Budget

$4,446,686 – Total Project Budget
- $2,750,000 – DOE Funding
- $1,696,686 – Partner Funding

$4,137,184 – Actual expenditure (as of 03/2015)
- $2,506,501 – DOE Funding
- $1,630,683 – Partner Funding

$ 309,502 – Remaining (as of 03/2015)
- $ 243,499 – DOE Funding
- $ 66,003 – Partner Funding

Timeline



Objectives and Relevance

Objectives

- Develop an Intake Air Oxygen (IAO2) sensor which directly and accurately measures the oxygen concentration in the intake manifold
- Demonstrate the potential of the sensor in combination with system adaptation and cEGR control strategies in a target engine application

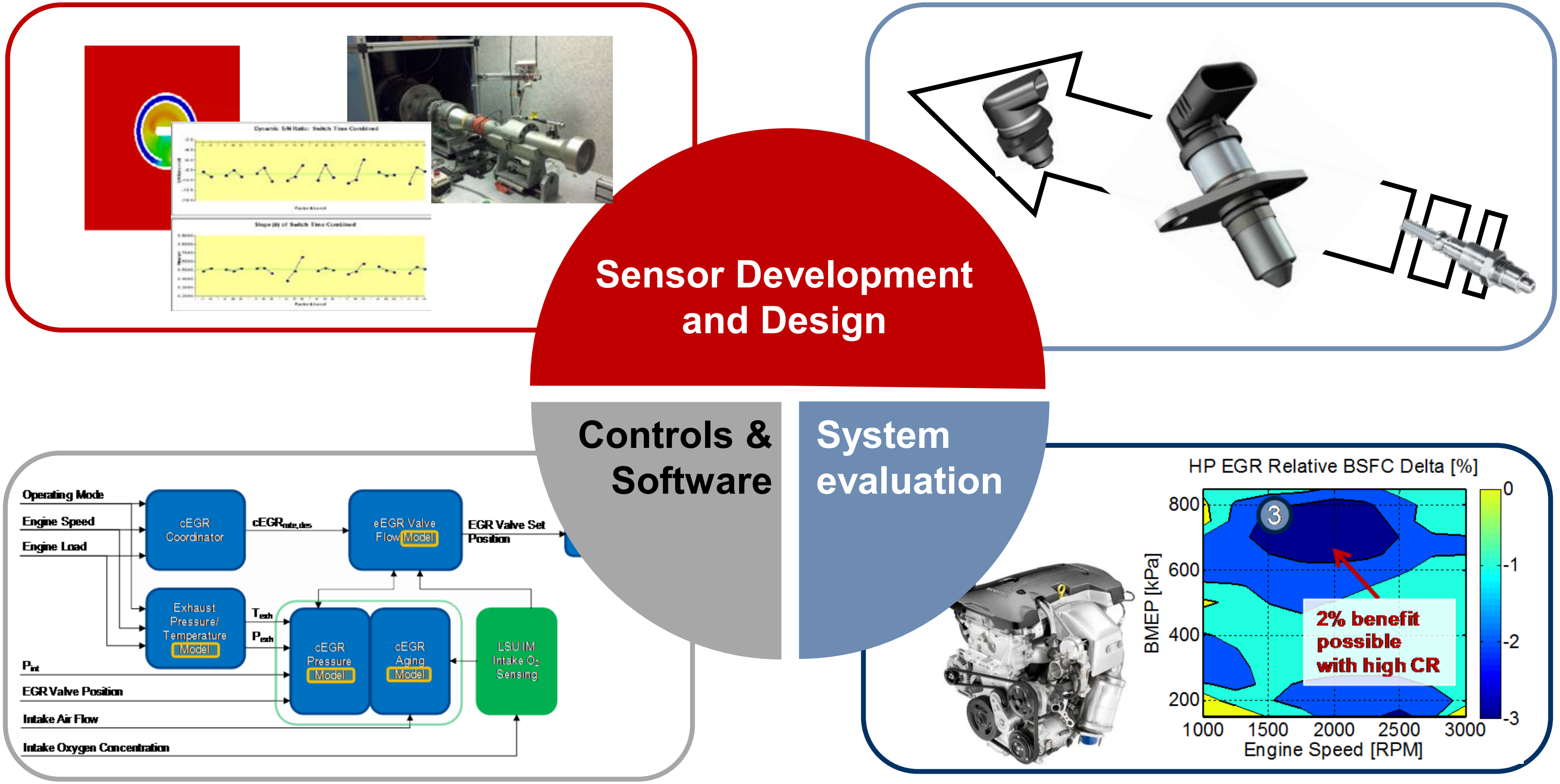
Relevance of cEGR

- cEGR enables improved fuel economy in most driving conditions (on and off cycle) supporting the mainstream trend of Downsizing
- Improvement of up to 5% in engine peak thermal efficiency
- Other future combustion technologies will utilize cEGR

Relevance of IAO2

- IA02 aims at providing a significant improvement in control accuracy of cEGR to maximize the fuel economy potential of the system

Approach - REGIS



Development of an IAO2 sensor for EGR control and demonstration of benefits

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Collaborators and Partners

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- Derivation of requirements
- Development and Validation Sensor
- Built of Sensor Prototypes
- Validation Control Strategy

Funded by DOE	2,140 T USD
Own Funding	1,582 T USD

CLEMSON UNIVERSITY

- System level evaluation cEGR
- Control Development
- Proof of Potential

Funded by DOE 430 T USD
Own Funding 115 T USD

OAK RIDGE National Laboratory

- Advanced testing support
- Thermodynamics cEGR

Funded by DOE	180 T USD
OwnFunding	0 T USD

Milestones & Summary of Technical Accomplishments

black: completed 2013
white: completed 2014

Sensor Development

- ✓ Baseline sensor characterization
- ✓ Improve sensor mounting and ECU connector design; build prototypes
- ✓ Sensor development for functional robustness over lifetime; build prototypes
- ✓ Concept for 2nd generation IAO2 element

System Evaluation

- ✓ Baseline system characterization (engine testing and simulation)
- ✓ Assessment of system risks and requirements for sensor (intake conditions, controls)
- ✓ Investigate impact of sensor location on sensor performance and requirements

Control Development

- ✓ EGR estimation algorithm development
- ✓ Control-oriented model for in-cylinder EGR prediction

Demonstration of sensing benefits

- ✓ Engine simulation to demonstrate sensor benefits
- Demonstration of improved sensor functionality and robustness
- Demonstration of potential for fuel economy improvement and emissions performance with IAO2 compared to a model-based EGR control strategy using rapid prototyping

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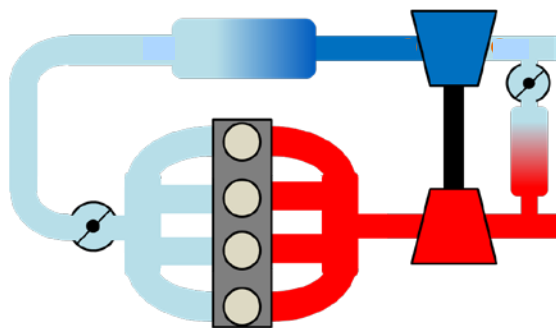
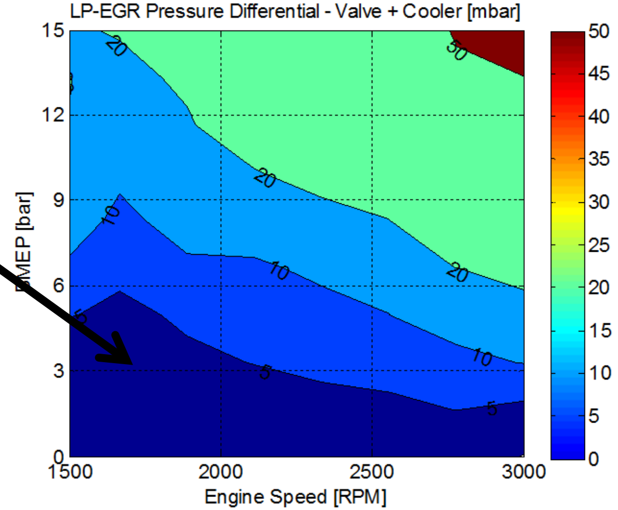
IAO2 Motivation



Significant portion of drive cycle operating area with small pressure differential across EGR valve and cooler (< 5 mbar)



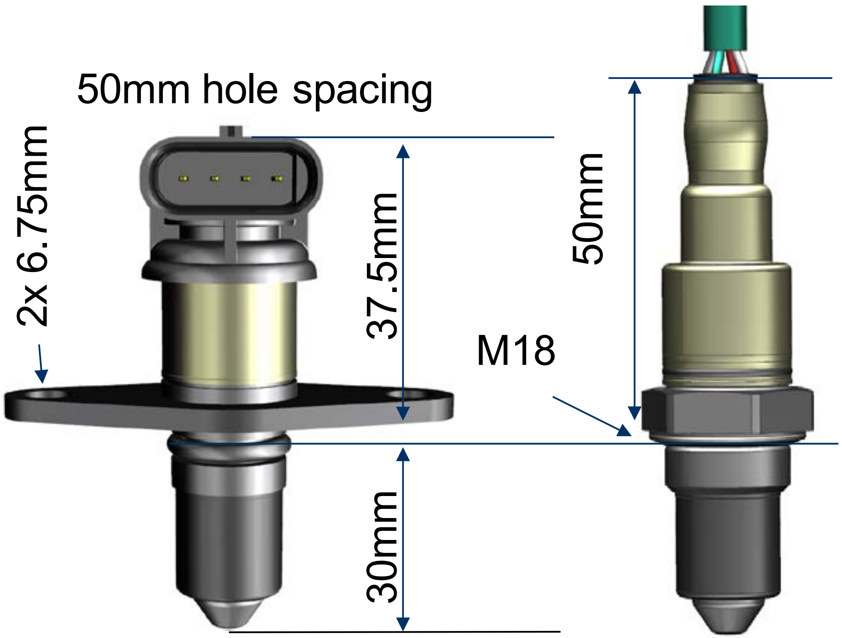
Sensing Alternatives for EGR Determination

	IAO2	Δp
Accuracy over lifetime		
HW Robustness		
Dynamic		
Cost		
Risk		
Calibration effort		

- Elevated EGR rates required even at part load to achieve high EGR rates at high load due to air charge system dynamics
- Near unity pressure ratio with LP-EGR at low flows is challenging for flow modeling and controls with differential pressure sensor

IAO2 is a key enabler for maximizing the benefits of LP cooled EGR

LSU IM1 comparison to LSU 5.1 (diesel exhaust sensor)



LSU IM1 primary application is LP cEGR Gasoline and Diesel application

Project was launched with focus on Gasoline applications

Requirements for HP EGR applications are considered but not decision drivers

LSU IM1 concept:

- **Use of single cell wideband element (LSU 5.1 element)**
- **High communality to existing production**
- **Change to direct connector**
- **Optimize PT for intake application**
- **Directional PT to achieve better trade-offs**

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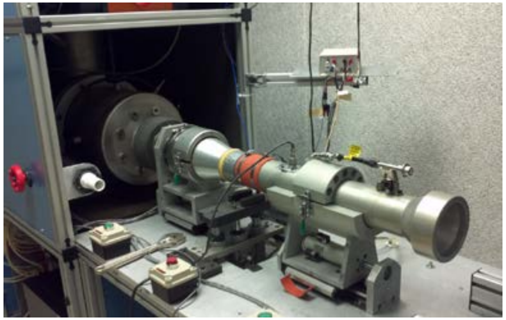
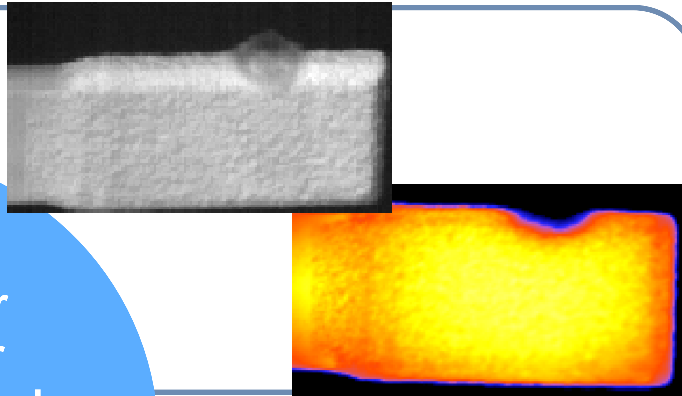
PT Optimization Parameters

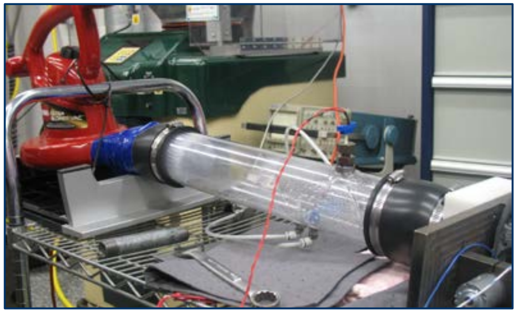


Response Time

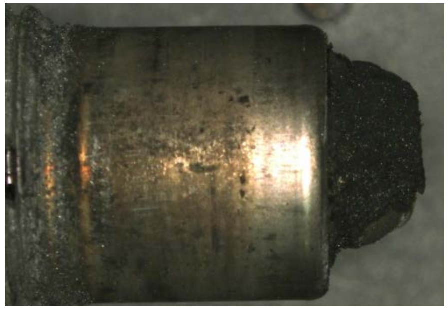
Heater Power Demand



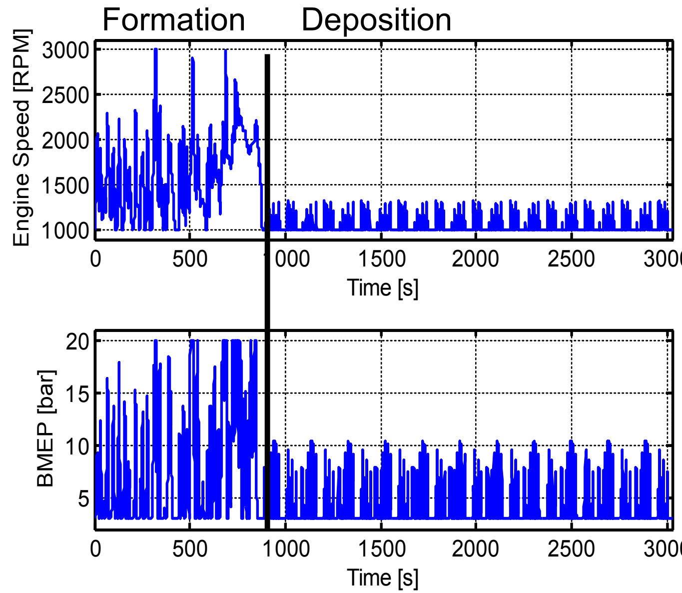
Robustness Thermal Shock



Robustness Soot and other con-taminants



IAO2 fouling robustness test

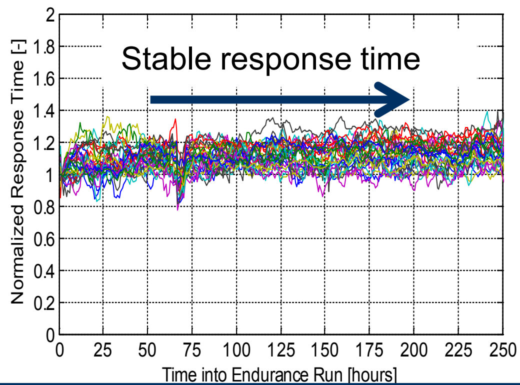


Soot robustness test cycle

- *Phase 1:* Bosch reference "Aggressive" PN generation cycle
- *Phase 2:* Low flow velocity cycle to "bake on" particulate matter
- Automated in-situ response time test with intake N2 purge each cycle
- Continuous 24/7 automated running
- 25 sensors tested with 14 different protection tubes for 250 hours

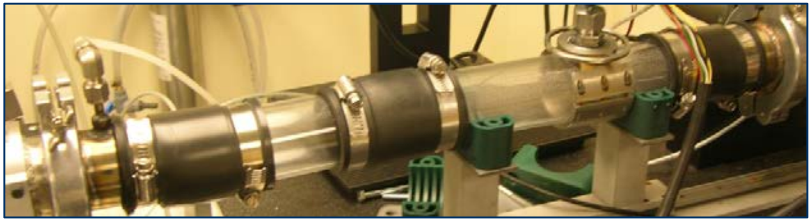
Test Calibration Parameters

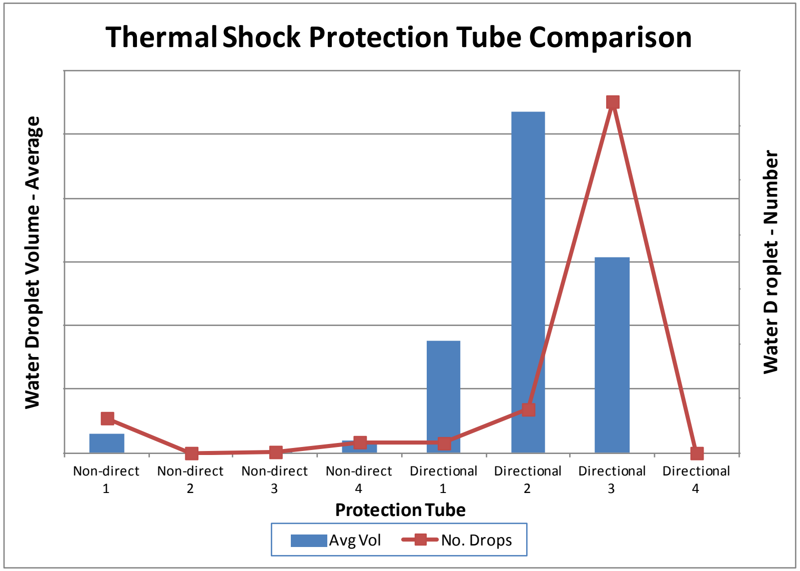
- 10 to >25% eEGR commanded over entire engine map
- High particulates induced by modified injection timing



Stable T63 response time observed over entire test independent of protection tube design

Thermal Shock Testing





Test Method

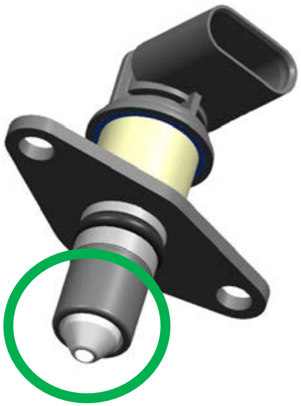
- New test method uses Bosch liquid sensor to detect size and number of water droplets impacting sensor element
- Previous test method used sensor signal to evaluate the signal to noise ratio based on the cooling effect of water entering protection tube

Results

- Benchmarking of directional and non directional designs
- Good thermal shock results are possible with non-directional and directional protection tubes

High Thermal Shock Protection with a variety of directional and non directional designs

Example of Protective Tube evaluation

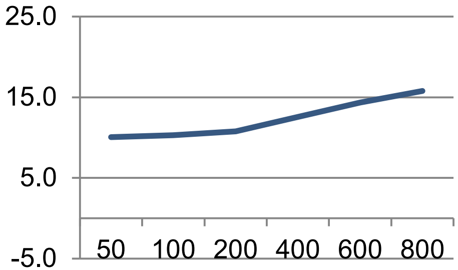


Selection criteria

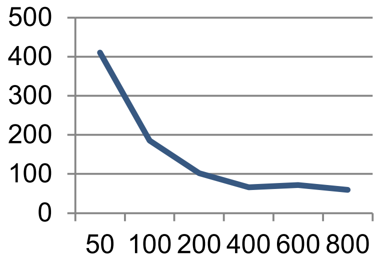
- Switch time
- Heater power demand
- Water thermal shock resistance
- Soot durability

Example shown is a projection tube of current production and proven in the field

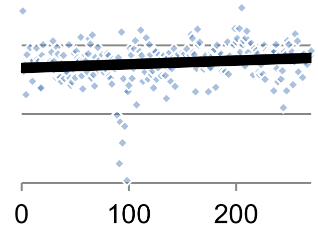
Heater Power Demand



Switch Time



Soot Durability



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Second Build and Validation

Second Build completed in September 2014

Mechanical Testing:
- Sine Vibration
- Wideband Vibration

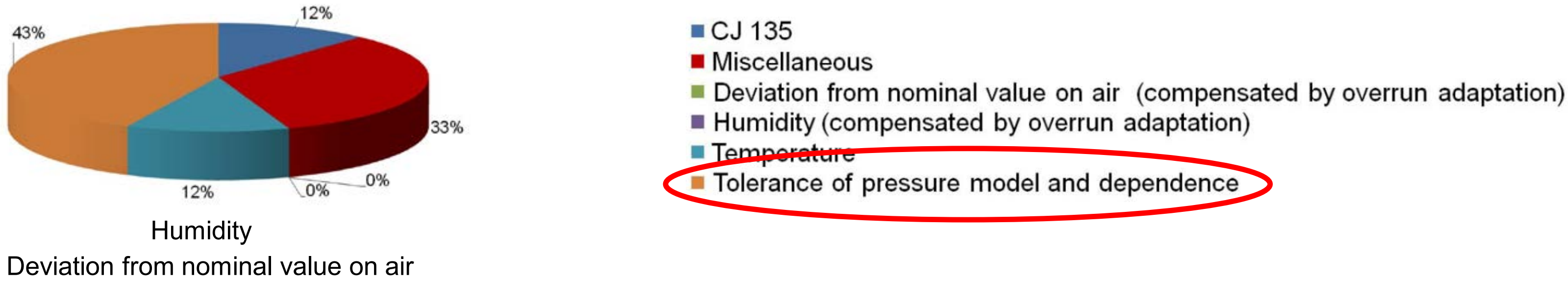
Environmental Testing:
- Thermal Cycling
- Salt Water Submergence

Purpose proof of robustness against environment:
- Ensure sealing of components
- Mechanical robustness of external and internal connections
- Pre- and post- functionality of sensor

Results: No Design related failures

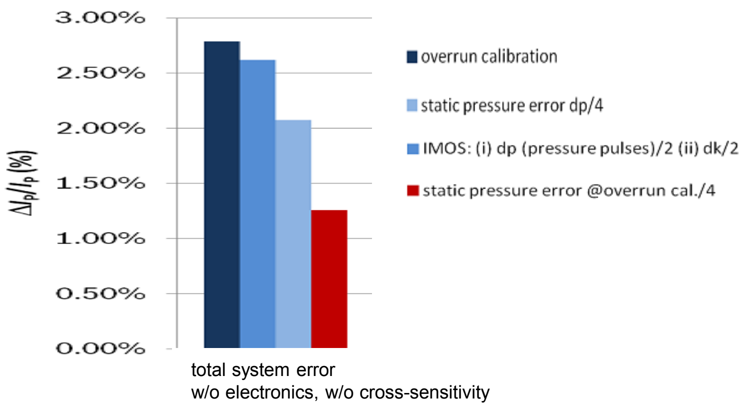
IAO2 Accuracy

Contributors of exhaust oxygen sensor LSU5.1 tolerance ± 3.5% @ λ=2.4:



Reduced tolerances for IAO2 sensor by improved pressure compensation:

- Online pressure measurement
- Pressure compensated air trimming
- Sensor specific k-value adaption
- Reduced pressure pulses



- Improved pressure compensation strategy established
- Accuracy target of +/- 2% ΔO2/O2 can be reached
- To check: Cross-sensitivities will have an impact on the accuracy depending on operating mode

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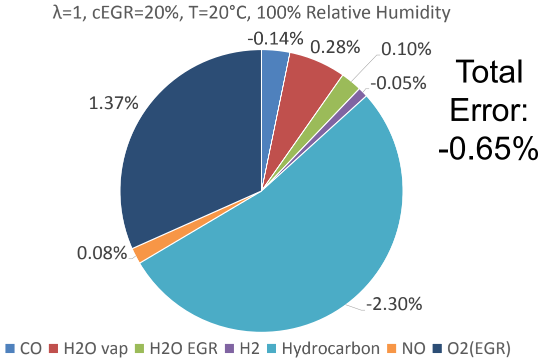
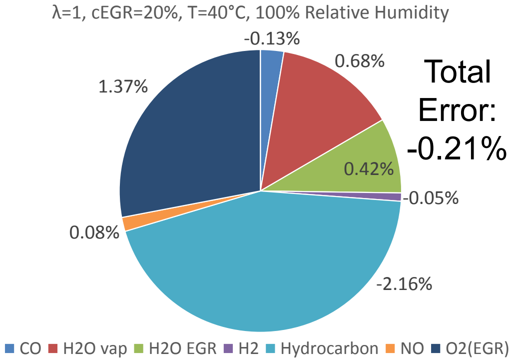
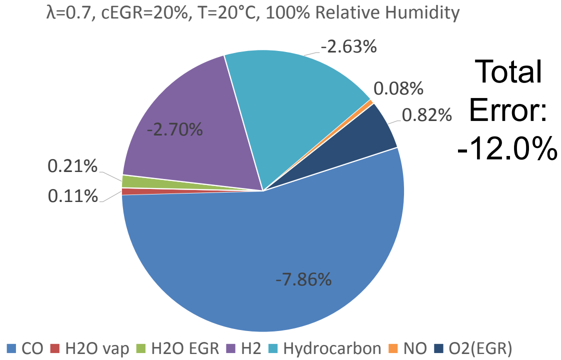
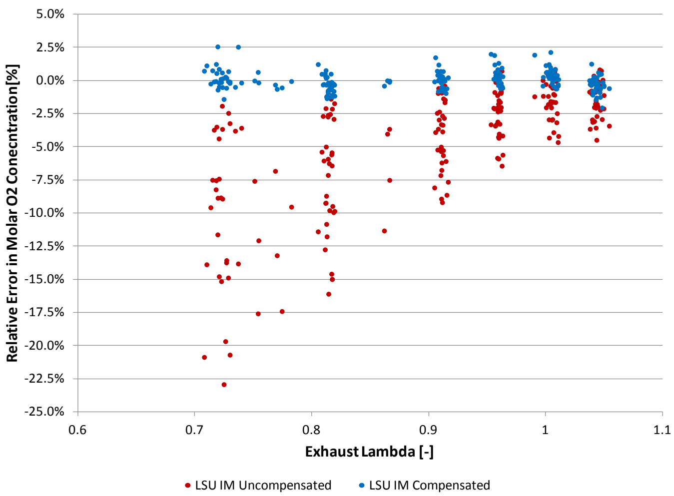
Accuracy

Cross Sensitivities Resulting from Exhaust λ Deviations









- Various exhaust species have a significant effect on the LSU IM’s signal, especially at rich conditions
  - Previous testing by ORNL and modeling of the exhaust species at engine operating points shows the total error this generates
- Using this data and measurements from the LTG engine the errors were reduced from >23% at extreme operating conditions to ±2.5% at all conditions

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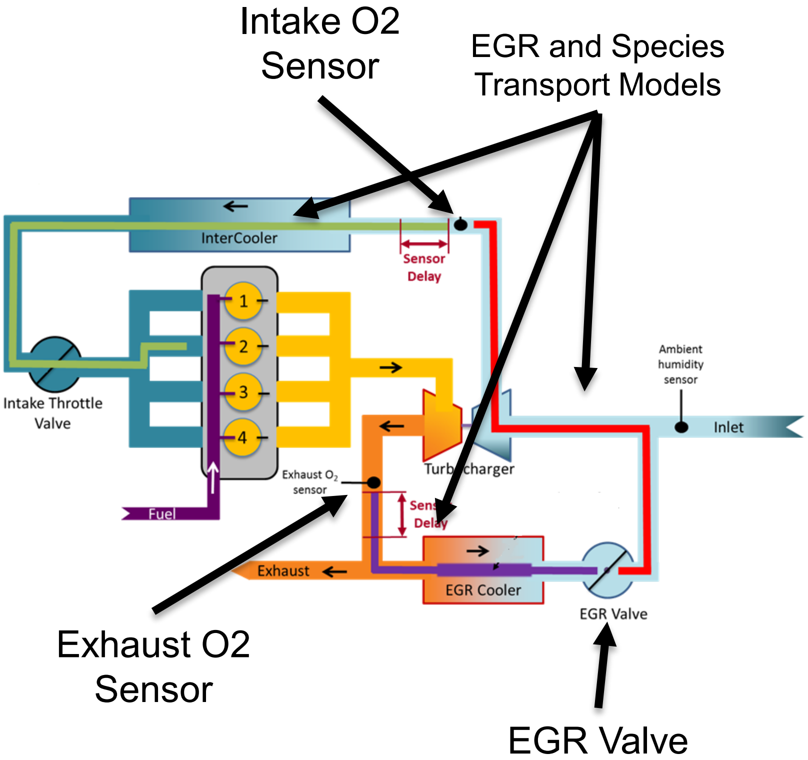
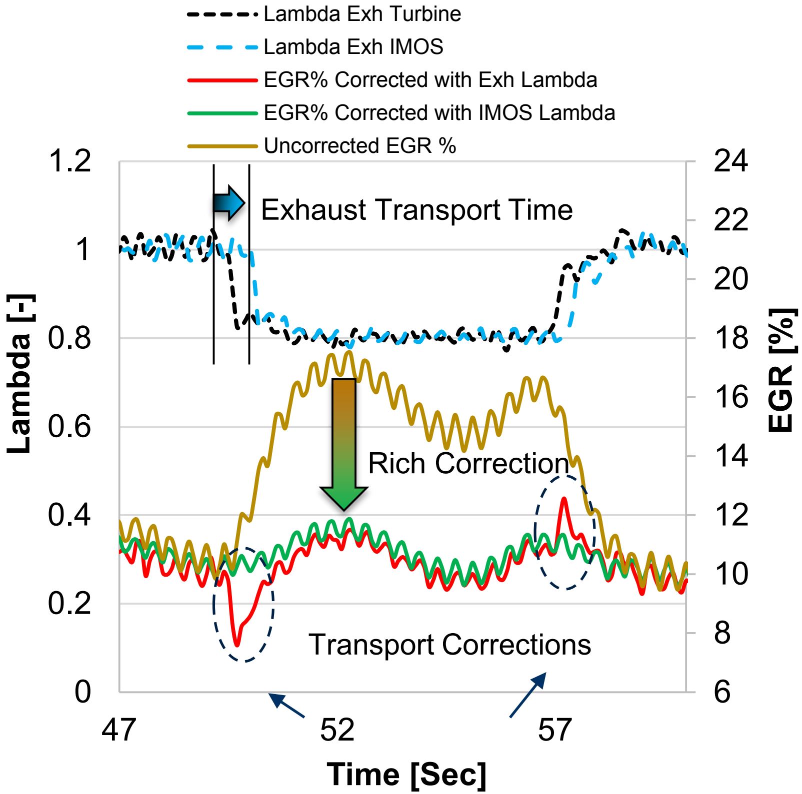
Controls



Real time testing at Clemson University has validated EGR correction and transport sub-systems



EGR transport and sensor correction control models are validated

Phase 2 objectives for sensor correction and transport delay are complete

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Controls

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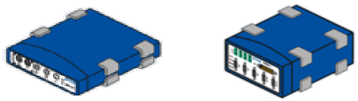
ETAS Rapid Control Prototyping



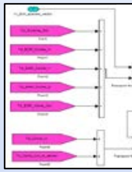
Real-time Engine Testing

Low pressure EGR control system

Phase 2

Transport models (completed)

IMOS signal correction (in final validation)



$$t_{delay} = \frac{L\,P\,A}{R\,T\,\dot{m}}$$

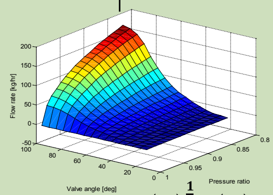
IMOS sensitivity

Engine out emissions prediction

Phase 3

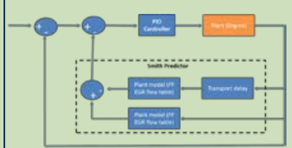
EGR and Exhaust flow models (on-going)

EGR Valve Control (on-going)



$$\dot{m}_{th} = \frac{C_D\,A_{th}\,p_0}{\sqrt{R\,T_o}}\left(\frac{p_T}{p_0}\right)^{\frac{1}{\gamma}}\Psi\left(\frac{p_T}{p_0}\right)$$

Adaptive Control



Control models will be delivered to Bosch during phase 3 for ECU integration

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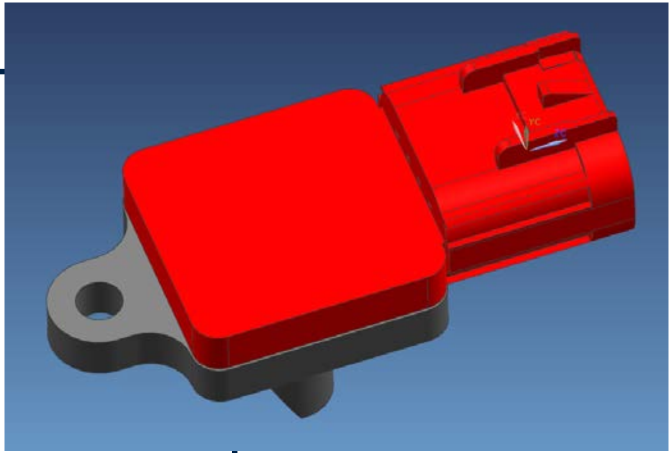
Concept: Second Generation Sensor



- Potential to measure multiple species
- Newly designed measurement concept
- High water load robustness
- Stable in lean conditions
- Low pressure dependency
- No humidity dependency
- Lower heater power optimized for intake manifolds
- Stabilized sensor temperature at high, cold flow rates
- Flexibility regarding protection tube design
- Two single cell sensors: 8 wire sensor concept
- Free choice of sensor connector

Future Directions REGIS

Sensor Development

- Develop and demonstrate sensor functional robustness over lifetime
- Investigate concept for 2nd generation IAO2 element

Demonstration of sensing benefits

- Demonstration of improved sensor functionality and robustness
- Demonstration of potential for fuel economy improvement and emissions performance achieved with IAO2 compared to a model-based EGR control strategy using rapid prototyping

Summary REGIS

Relevance of Intake Air Oxygen (IAO2) sensing

- Directly and accurately measures the oxygen concentration in the intake manifold
- Enables accurate and robust EGR control for future engine concepts utilizing cEGR

Approach

- Develop requirements
- Design sensor solutions
- Develop robust cEGR controls

Tools

- Targeted engines
- Flow benches
- Simulation studies

Technical Accomplishments

- ✓ Developed and demonstrated improved sensor mounting and ECU connector design
- ✓ Identified sensor design for improved thermal shock robustness and response time
- ✓ Assessed system risks and requirements for sensor (intake conditions, controls)
- ✓ Identified sensor location for best sensor performance and cEGR control
- ✓ Developed cEGR estimation algorithm
- ✓ Develop control-oriented model for in-cylinder EGR prediction

Future Work

- Develop and demonstrate sensor functional robustness over lifetime
- Investigate concept for 2nd generation IAO2 element
- Demonstrate sensing benefits

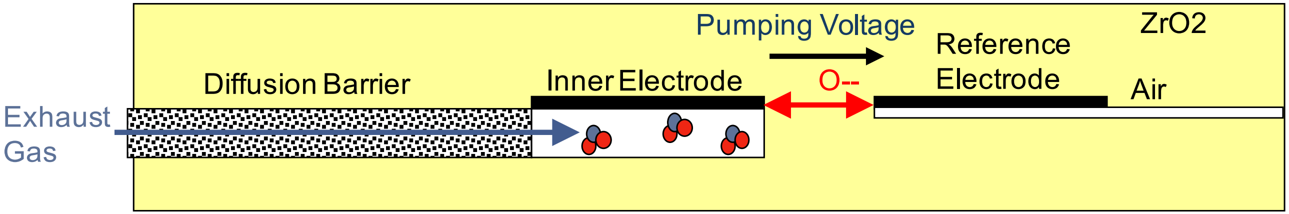
Technical Back Up slides

Choice of Sensing Element

- High water load robustness
- Stable in lean conditions
- Low pressure dependency
- High soot robustness (optimized for Diesel engines)
- Strong heater optimized for Diesel engines
- Stabilized sensor temperature at high, cold flow rates
- Flexibility regarding protection tube design
- Single cell sensor : Compact 4 wire sensor concept

  Free choice of sensor connector

Coating for thermal shock protection



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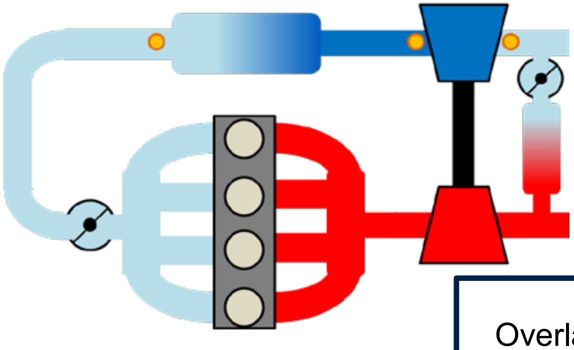
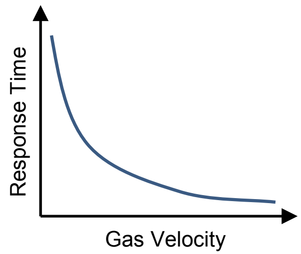
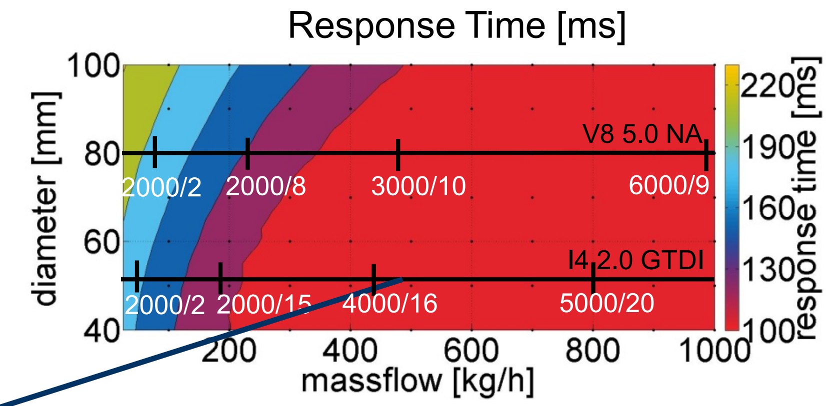
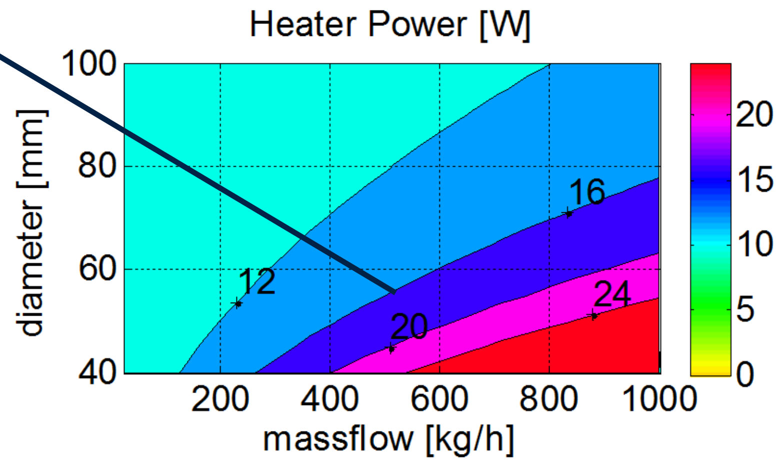
IAO2 Mounting Position







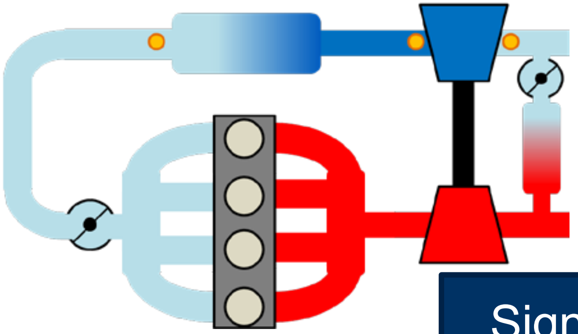
Overlapping regions where response time and heater power requirements are met



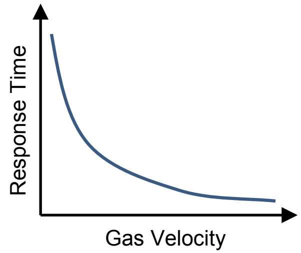
Location	LP EGR		
	Pre-Compressor	Post-Compressor	Post-Charge Air Cooler
Durability			
Function			

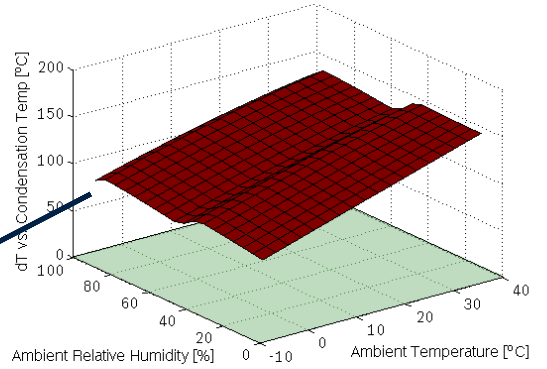
IAO2 mounting post-compressor is the best solution for durability, functionality and power consumption

IAO2 Mounting Position



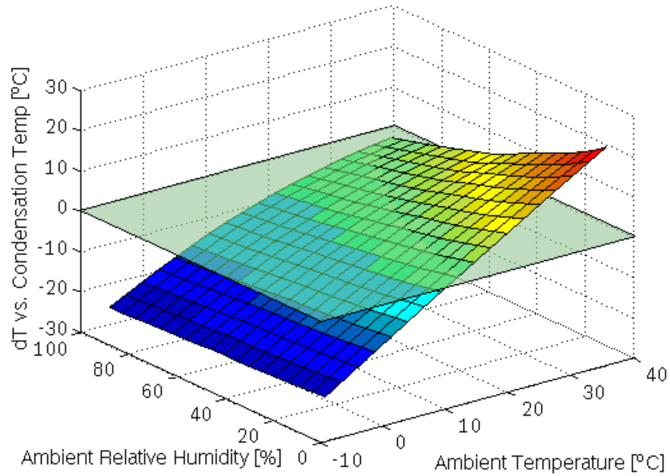
Sensor Location





Significant margin to condensation conditions only for Pre-CAC position

Location	LP EGR		
	Pre-Compressor	Post-Compressor	Post-Charge Air Cooler
Durability			
Function			



IAO2 mounting post-compressor is the best solution for durability, functionality and power consumption

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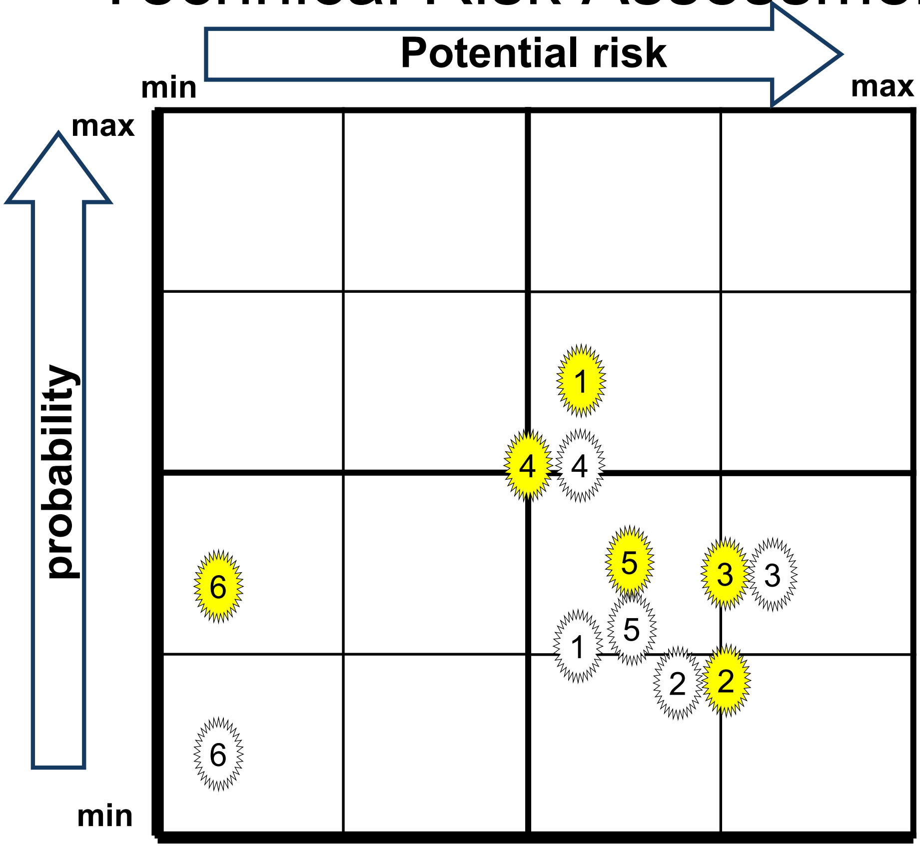
Technical Risk Assessment



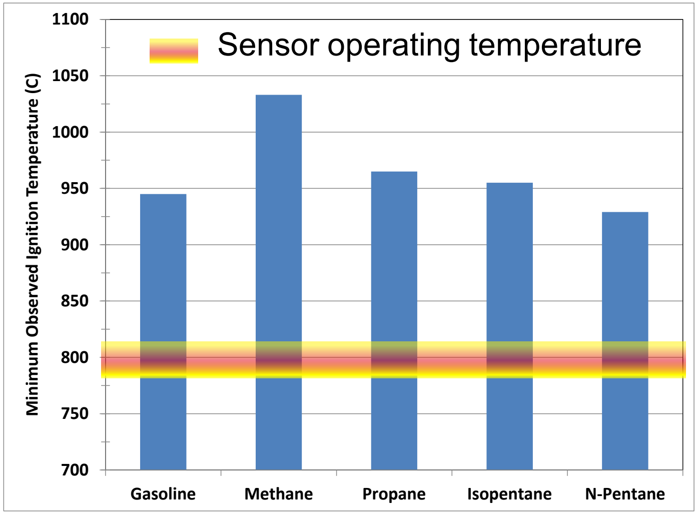
Technical / technology	
1	Sensor not robust for intake
2	Other methods for controlling EGR are better
3	Sensor can lead to ignition of intake gas
Development risk	
4	Sensor accuracy not sufficient
5	Sensor costs higher than estimated
Competencies / Know-how	
6	Unable to package sensor for intake

HC Cross Sensitivity in Gasoline Applications remain a challenge

Assessment of Ignition Risk

Eliminate the very low ignition risk by one of the following strategies:

- **Temp. control and heater diagnostic**
  Check sensor heater power demand with engine operating conditions
- **Define purge conditions**
  Avoid explosive mixtures by avoiding purging during tip-out (check valves in tank purge lines after tip-out)
- **Define mounting position**
  Mounting of LSU-IM1 before throttle in case of T/C -systems



Minimum observed ignition temperature 929degC at worst case conditions:
- Stoichiometric mixtures
- Low flow conditions
- Direct exposure to the hot ceramic element

- An ignition is very unlikely and if with minor impact on the intake manifold (loss in boost due to intake manifold damage)
- Elimination of the low ignition risk possible by simple application rules
- No LSU IM1 design adjustments necessary to eliminate ignition risk