2014 DOE Annual Merit Review REGIS

2014 DOE Vehicle Technologies Program Review

Washington, D.C.
June 19th, 2014

Claus Schnabel (PI)

Award: DE-EE0005975
Project ID: ACE091

Sensors and Ignition
Gasoline Systems, Robert Bosch LLC

BOSCH

Project Overview

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

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

$1,781,072 – Actual expenditure (as of 12/2013)

- $1,096,084 – DOE Funding
- $684,988 – Partner Funding

$2,665,614 – Remaining (as of 12/2013)

- $1,653,916 – DOE Funding
- $1,011,698 – Partner Funding

Timeline

2013-Phase I **2014 -Phase 2**

cEGR Control Strategy

- Control
- Algorithm Development
- Validation

System Evaluation

- cEGR System Evaluation Requirements Sensor
- Demonstration of potential

Sensor Development

- Baseline Sensor Evaluation Design Development
- Design Development Validation
- Validation

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

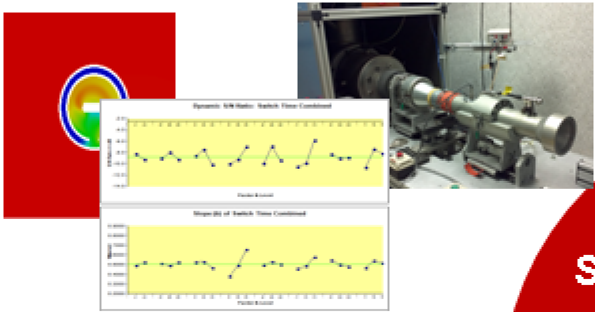
- cEGR enables improved fuel economy in most driving conditions (on and off cycle) supporting the mainstream trend of Downsizing
- Improvement of up to 5% in engine peak thermal efficiency
- Other future combustion technologies will utilize cEGR

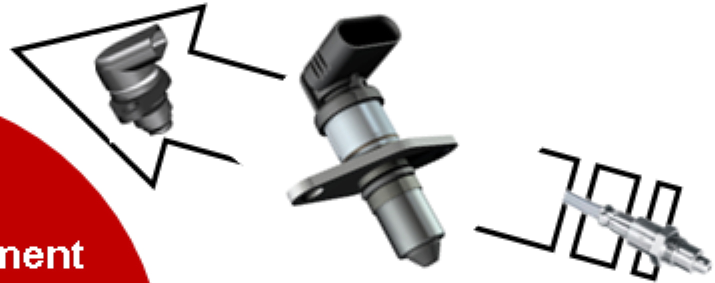
Relevance of IAO2

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

BOSCH

Approach - REGIS

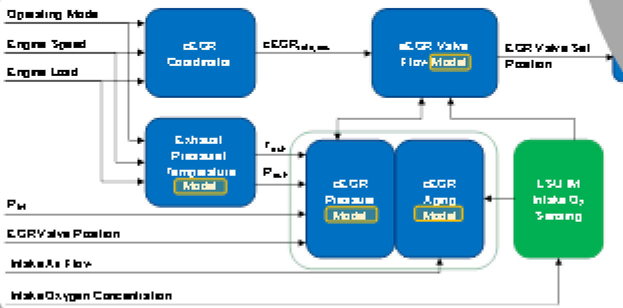


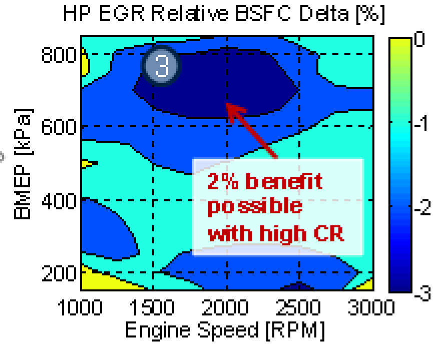


Sensor Development and Design

Controls & Software

System evaluation





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

BOSCH

Collaborators and Partners

BOSCH

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

Funded by DOE	2110 T USD
Own Funding	1582 T USD

CLEMSON UNIVERSITY

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

Funded by DOE	460 T USD
Own Funding	115 T USD

OAK RIDGE National Laboratory

- Advanced testing support
- Thermodynamics cEGR

Funded by DOE	180 T USD
Own Funding	0 T USD

Milestones & Summary of Technical Accomplishments

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

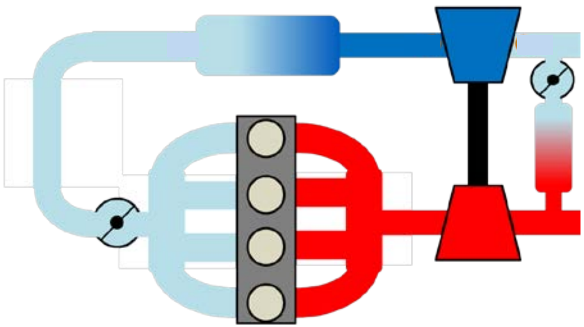
Control Development

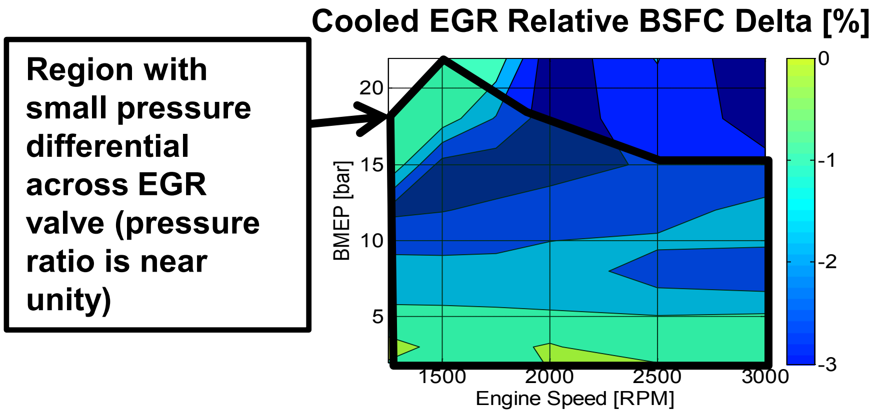
- ✓ EGR estimation algorithm development
- ➢ Control-oriented model for in-cylinder EGR prediction

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

IAO2 Motivation





Sensing Alternatives for EGR Determination

	IAO2	Δp
Accuracy (long term)	green	red
HW Robustness	yellow	green
Dynamic	yellow	green
Cost	yellow	green
Risk	yellow	green
Calibration effort	green	yellow

- Near unity pressure ratio over EGR valve in region with greatest impact on fuel economy
- Near unity pressure ratio with LP-EGR is challenging for flow modeling and controls with differential pressures sensor

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

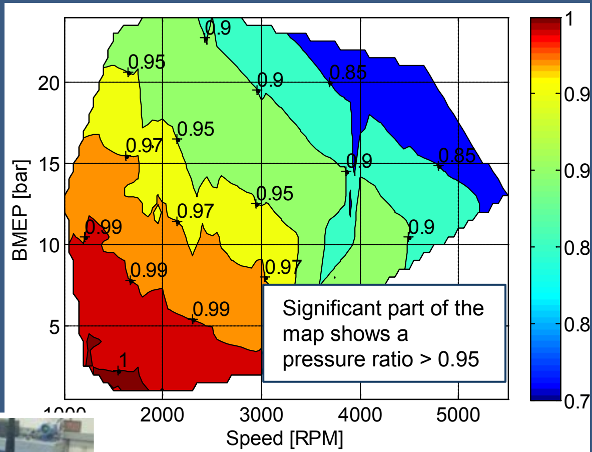
BOSCH

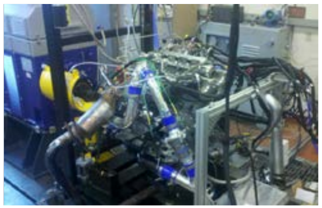
IAO2 Control Development

BOSCH

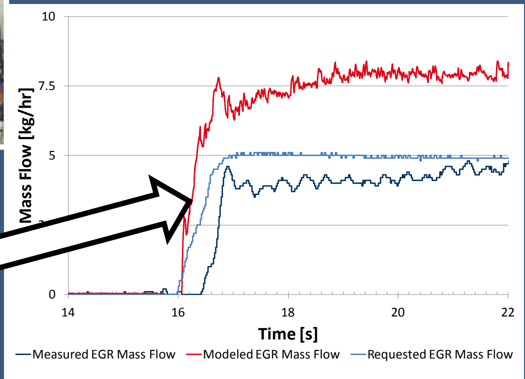
Low Δp challenge for system model

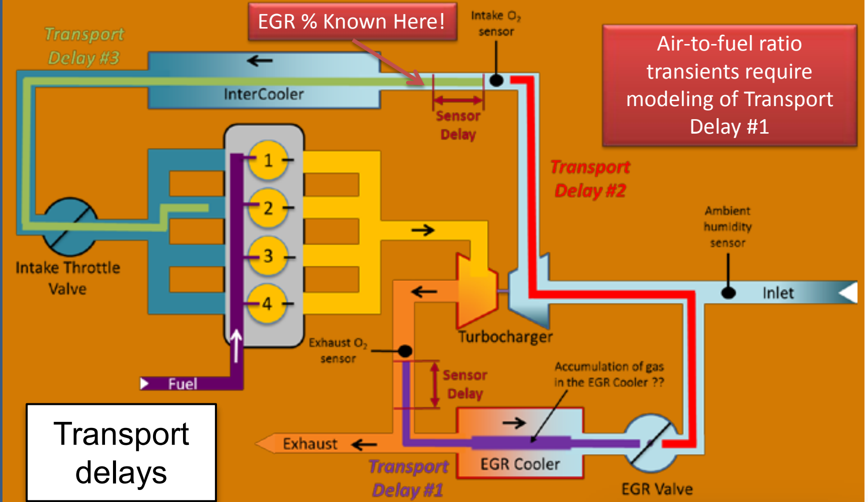
Long term accuracy major challenge

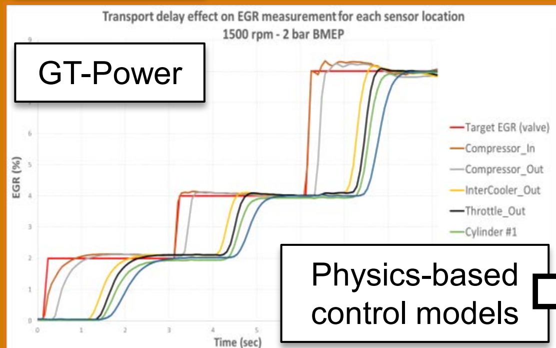




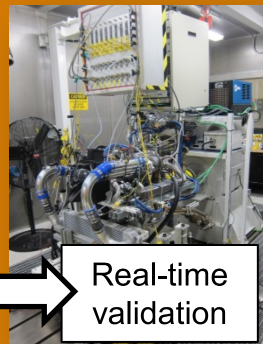
IAO2 able to close model gap







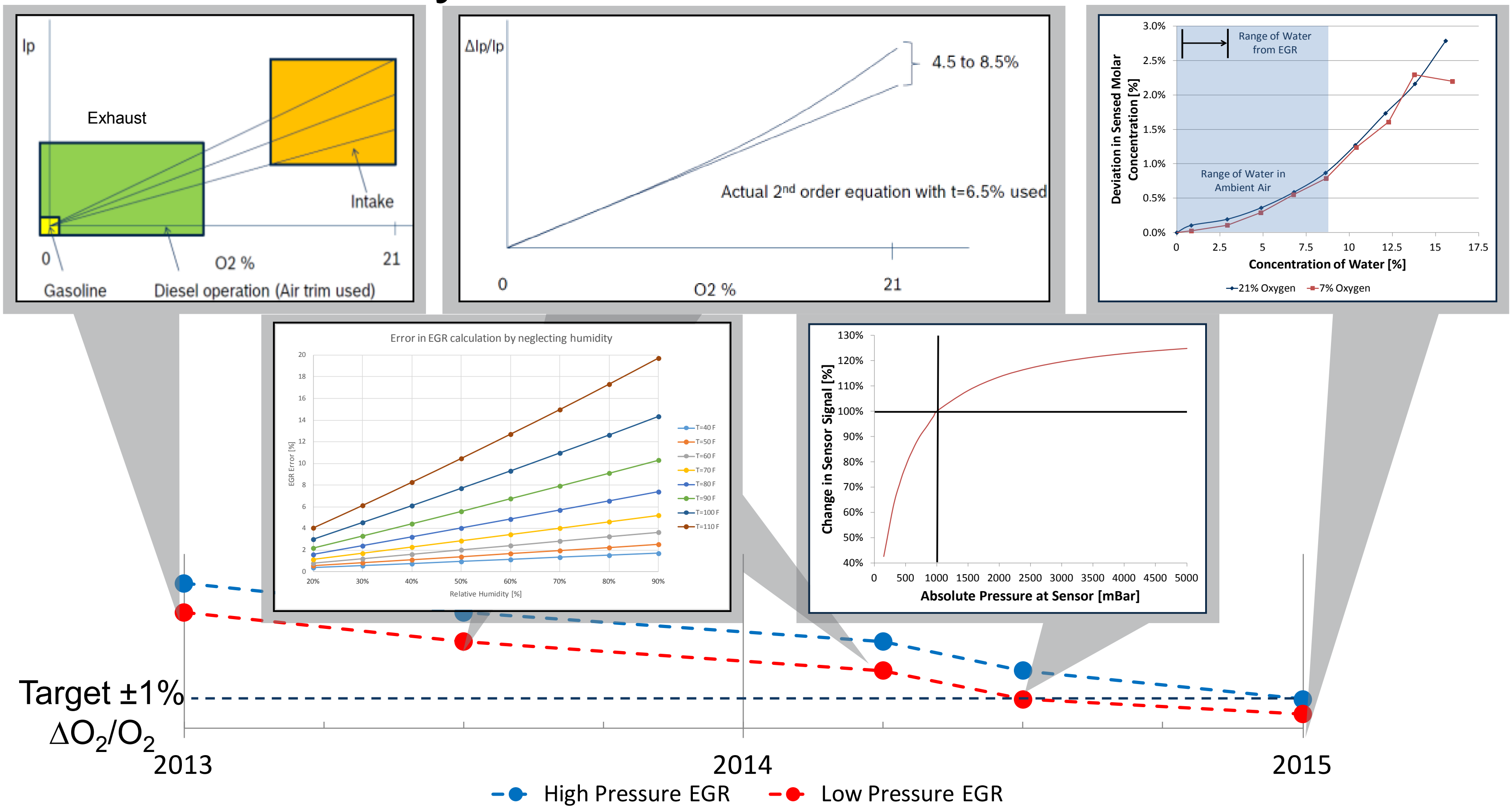
Physics-based control models



Real-time validation

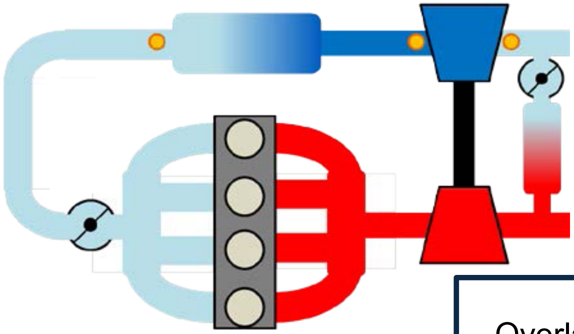
BOSCH

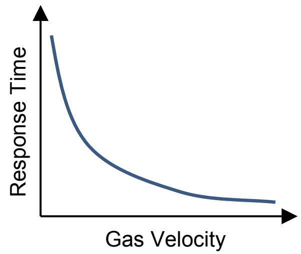
IAO2 Accuracy

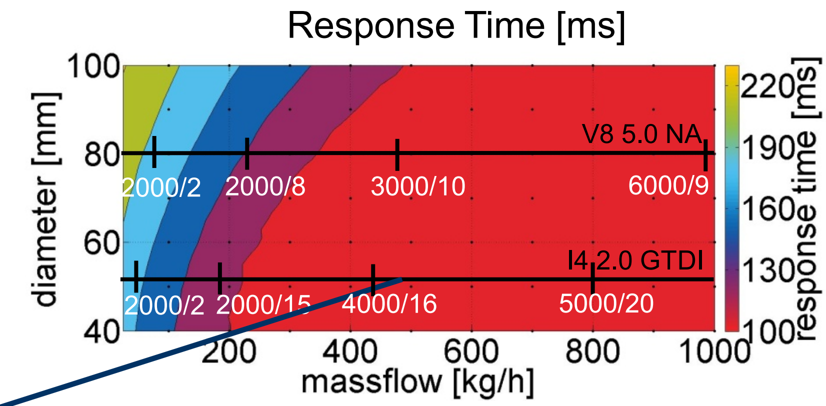


Multi-faceted approach needed to meet desired accuracy targets.

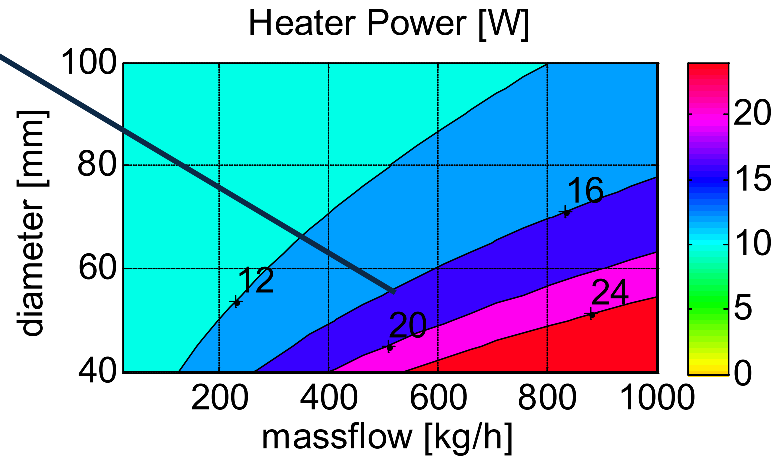
IAO2 Mounting Position







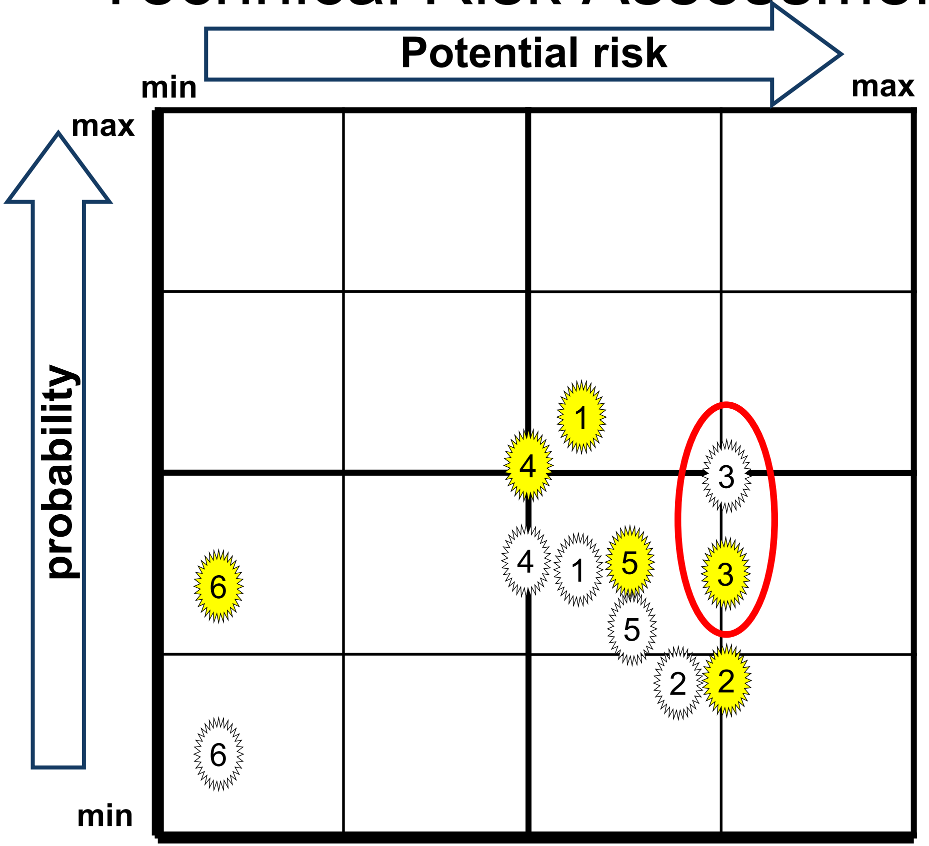
Overlapping regions where response time and heater power requirements are met



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

Technical Risk Assessment

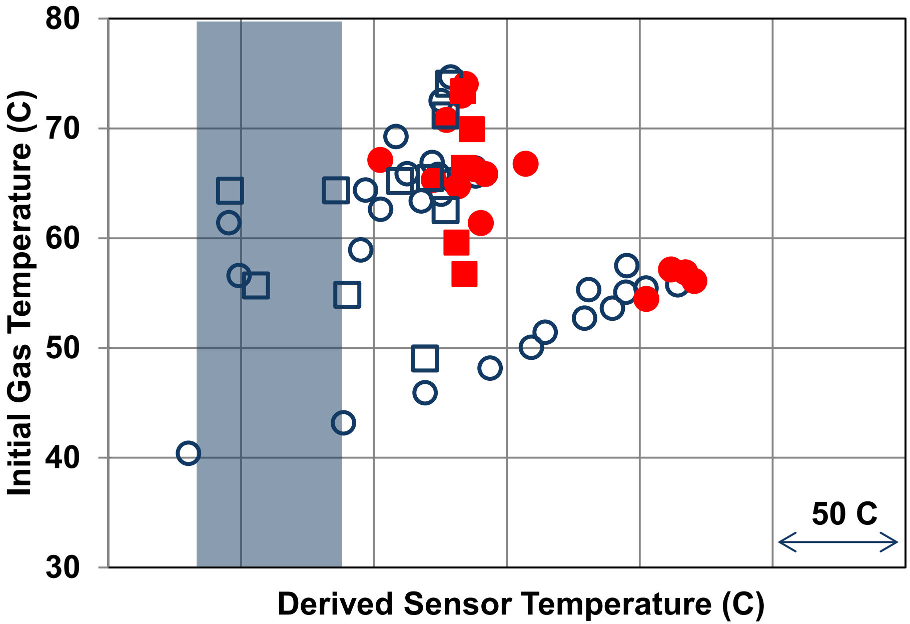


Technical / technology	
1	Sensor not robust for intake
2	Other methods for controlling EGR are better
3	Sensor can lead to ignition of intake gas
Development risk	
4	Sensor accuracy not sufficient
5	Sensor costs higher than estimated
Competencies / Know-how	
6	Unable to package sensor for intake

Start of Project today

Ignition of intake gas is key remaining risk after Phase 1

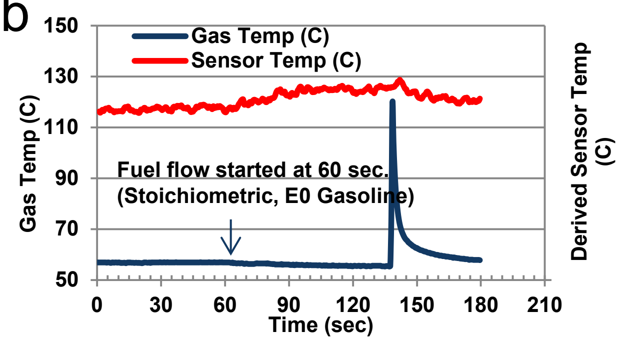
Ignition Study at Oak Ridge National Lab



Circles = E0 Gasoline
Square = 100% non-denatured ethanol

Blue, empty = no ignition (<10C Delta Gas T)
Red, filled = ignition (>10C Delta Gas T)

Temperature range of new sensor



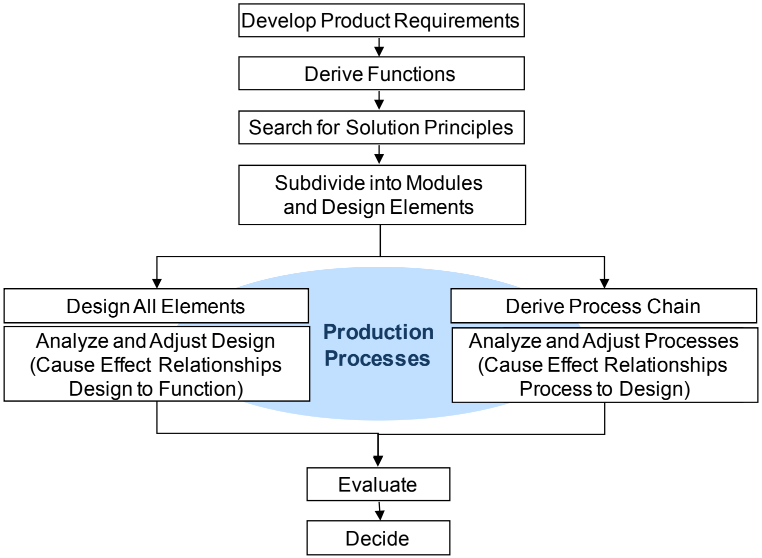
Result

- Ignition can occur at elevated gas temperatures and with aged sensor

Next Steps

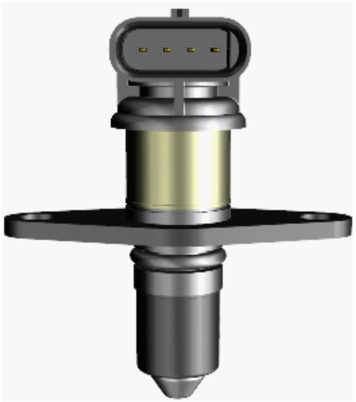
- FMEA
- Study to understand ignition risk for failure modes identified by FMEA
- Identify measures in sensor design to arrest flame kernels
- Propagate engine design with purge entry upstream of sensor for critical operation points

Choice of Sensor Concept



Number of concepts evaluated

- Contacting 25
- Housing 10
- Mounting 3
- Protection Tube 4



Sensor Concept:

- Use single cell wideband element
- Change to direct connector
- Find high commonality to existing production
- Optimize protection tube for intake application

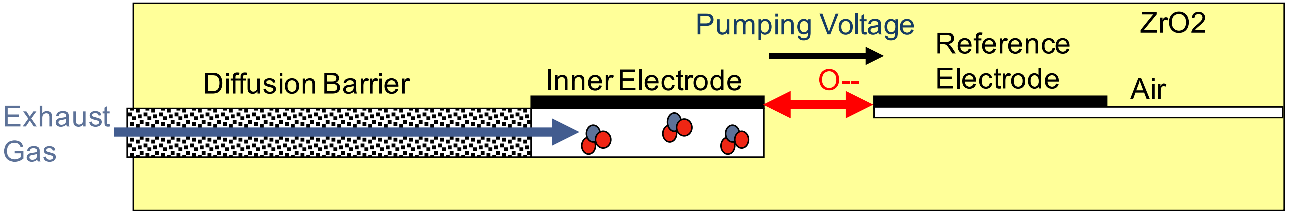
BOSCH

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

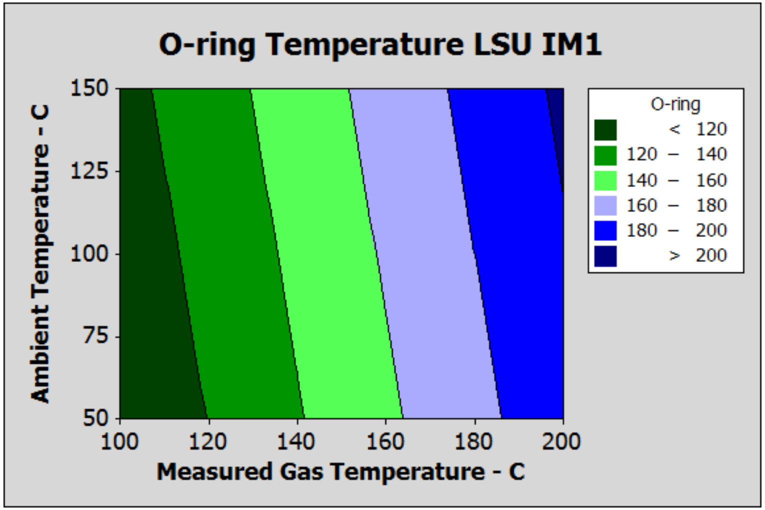
  Free choice of sensor connector

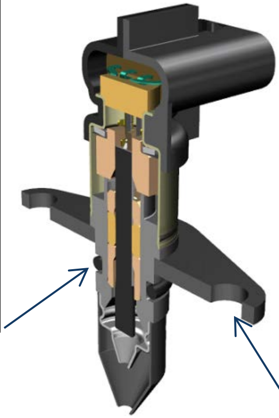
Coating for thermal shock protection



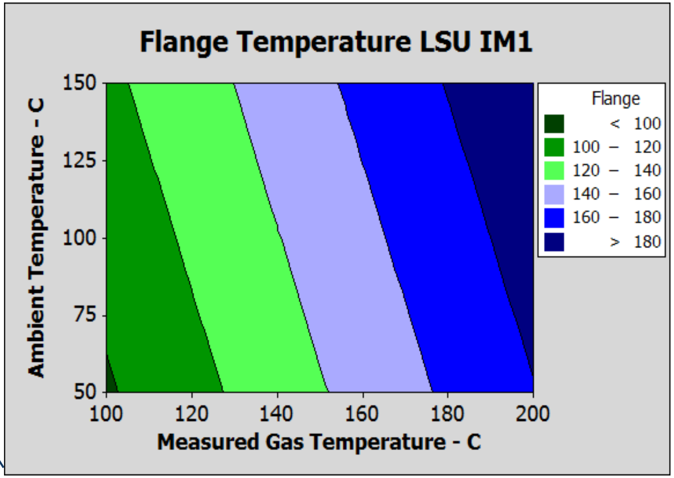
BOSCH

First Build Thermal Management





Thermal mapping at rated power conditions



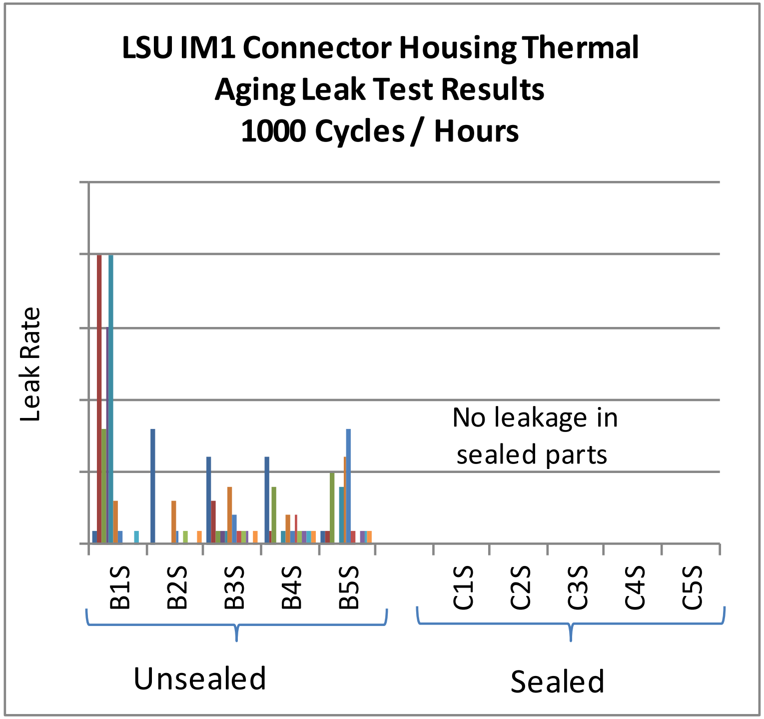
Results from thermal mapping of component

- Component temperatures are in acceptable range
- Recommendation for calibration derived

Development goal for first build robustness of plastic connector/ housing achieved

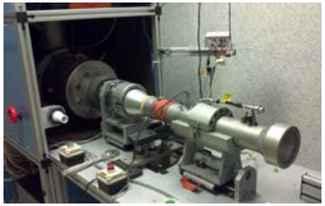
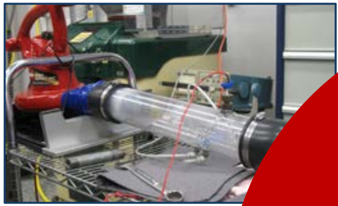
BOSCH

Validation Results of First Build



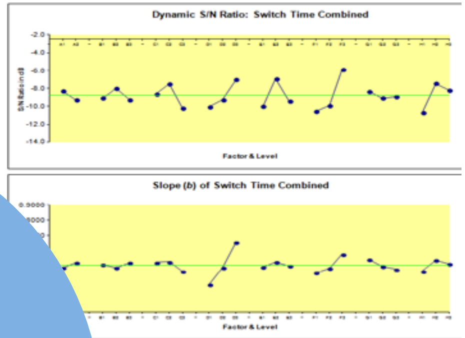
Sealing of plastic connector to metal housing after thermal aging achieved

Protection Tube Optimization - Tool Box

Flow bench

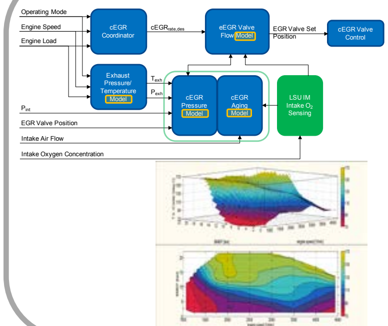
DFFS

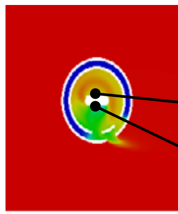


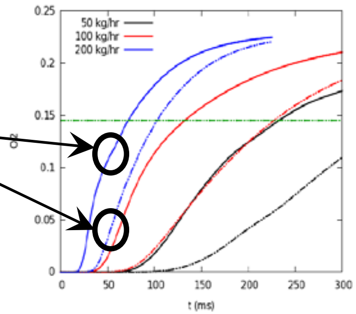
Requirements

Response Time
Heater Power Demand
Thermal Shock
Contamination

3-d CFD

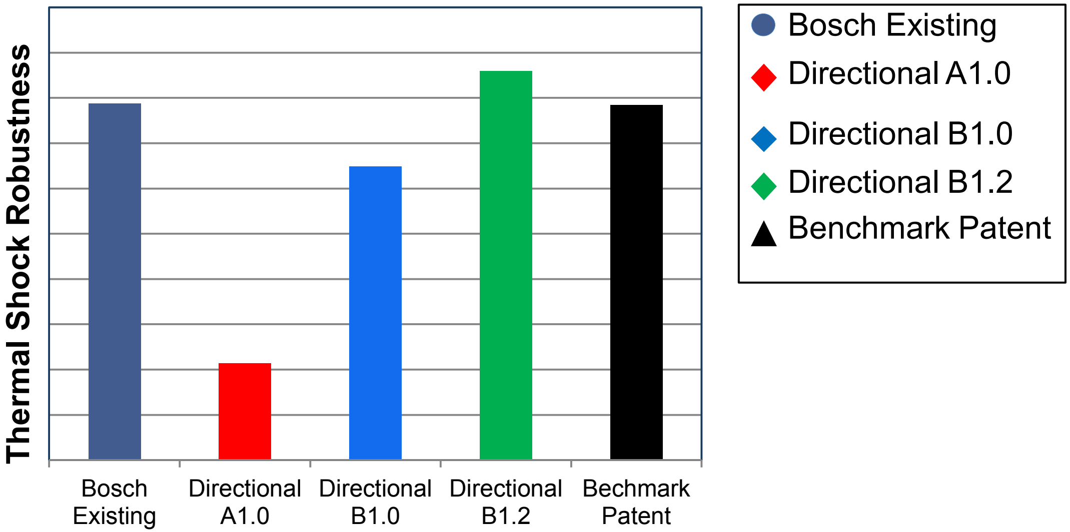


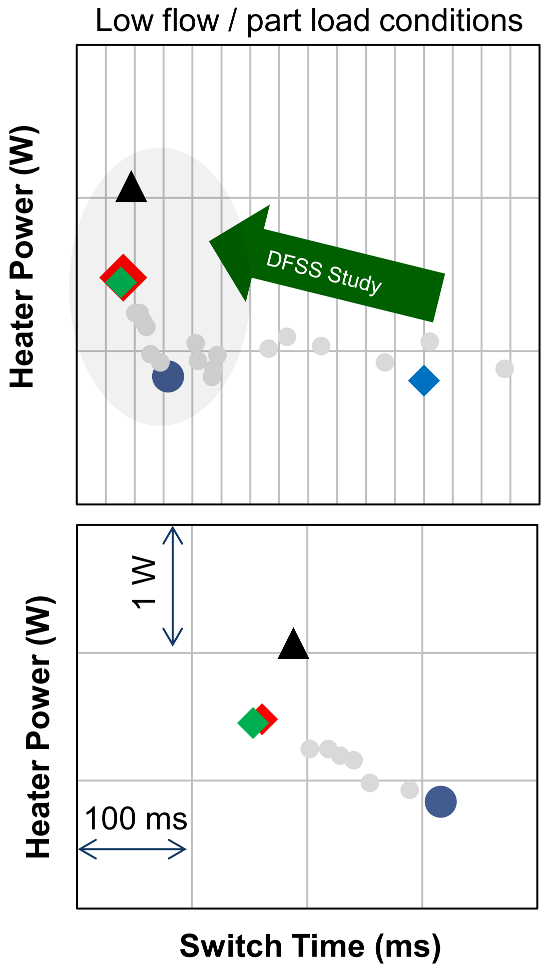




BOSCH

Protection Tube (PT) Optimization





Results from protection tube optimization

- PT performance has increased from optimization of feature parameters.

Target to exceed performance of benchmark patent was achieved.

Future Directions REGIS

Sensor Development

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

System Evaluation

- Understand risk in vehicle for ignition
- Understand signal off-set caused by HC’s found in intake during vehicle operation

Control Development

- Control-oriented model for in-cylinder EGR prediction

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

BOSCH

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

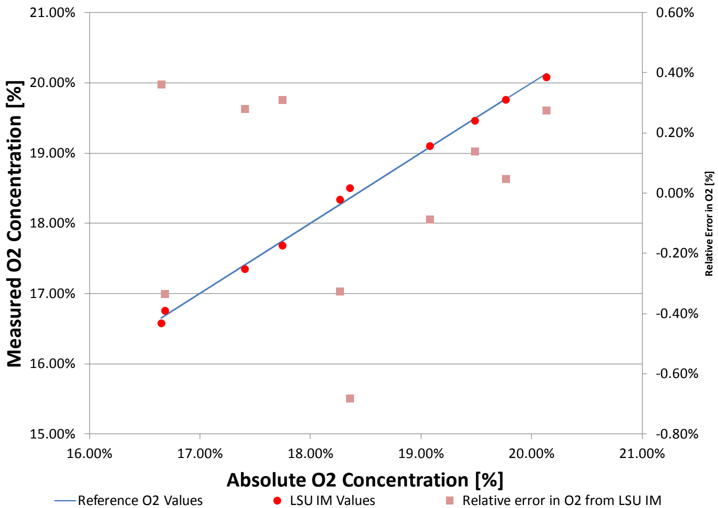
Future Work

- Develop and demonstrate sensor functional robustness over lifetime
- Investigate concept for 2nd generation IAO2 element
- Develop control-oriented model for in-cylinder EGR prediction
- Demonstrate sensing benefits

Technical Back Up slides

LSU IM Accuracy

High Accuracy Potential

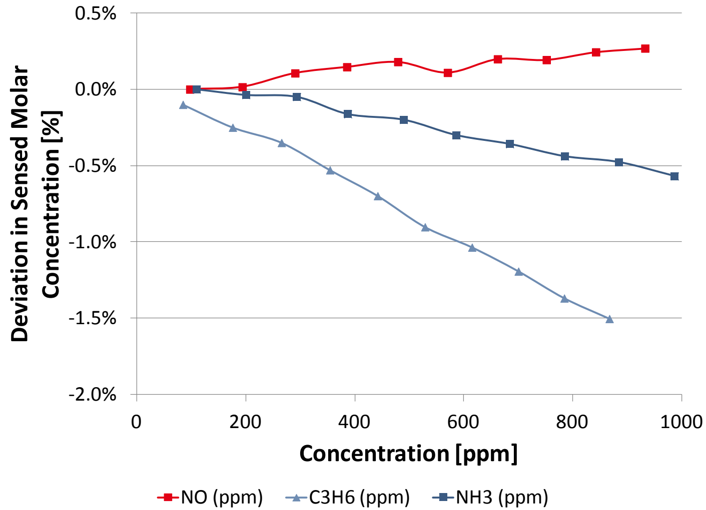


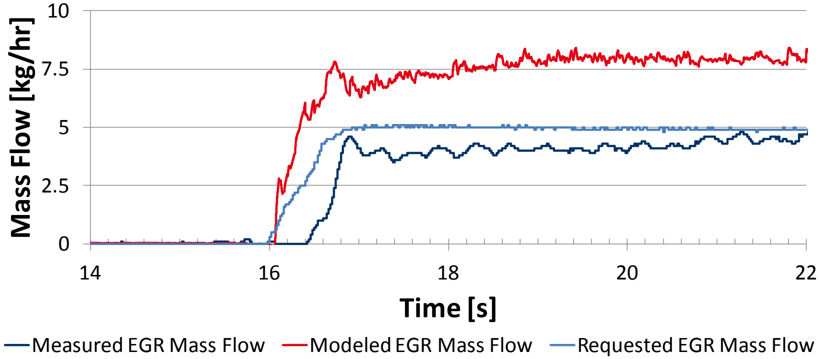
Ability to tolerate large errors in system metering

- Production part tolerance
- Aging of components
- Modeling errors in calibration

Long term adaptation possible over lifetime

Predictable Cross-Sensitivity





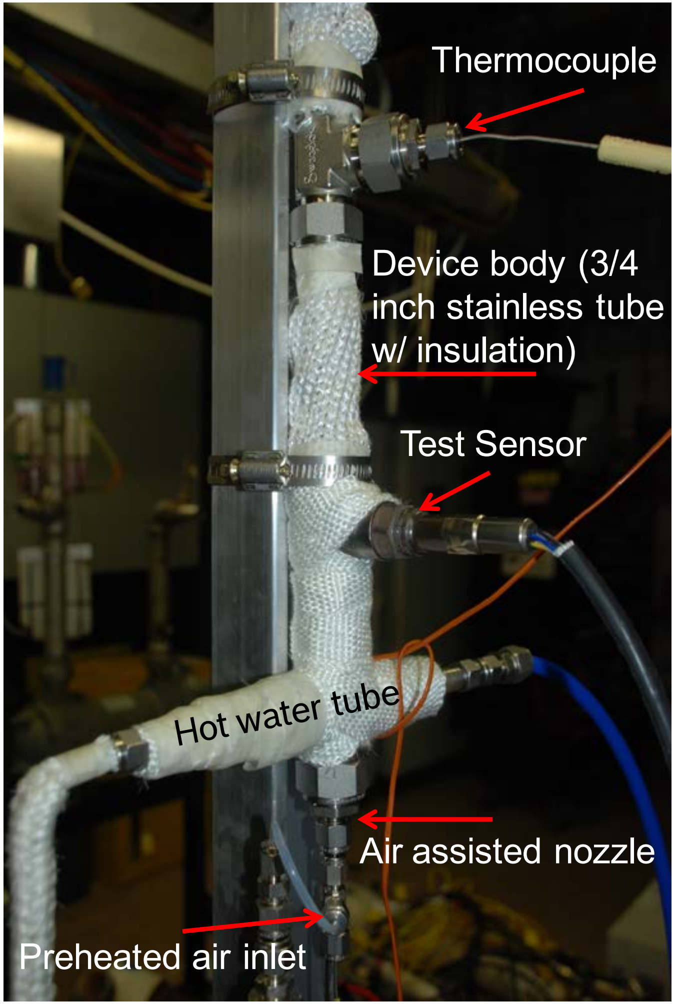
BOSCH

Ignition Study

- Introduce aerosolized fuel/air mixture to REGIS sensor
  - Fixed gas velocity (slow) ~1 m/s
  - Fixed air/fuel ratio (stoichiometric)
  - Fixed mixture temperature (50 -80 °C)
  - Two fuels: E10 gasoline blend plus E85 blend

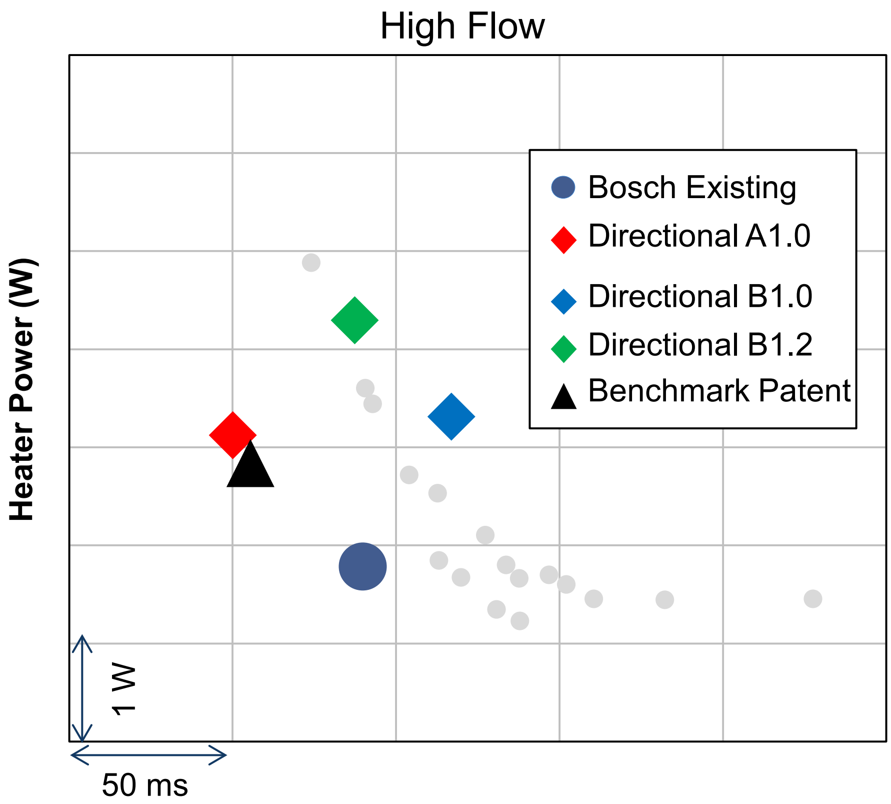
- Vary sensor element temperature
- Detect ignition with thermocouple measurement of gas temperature downstream of REGIS sensor

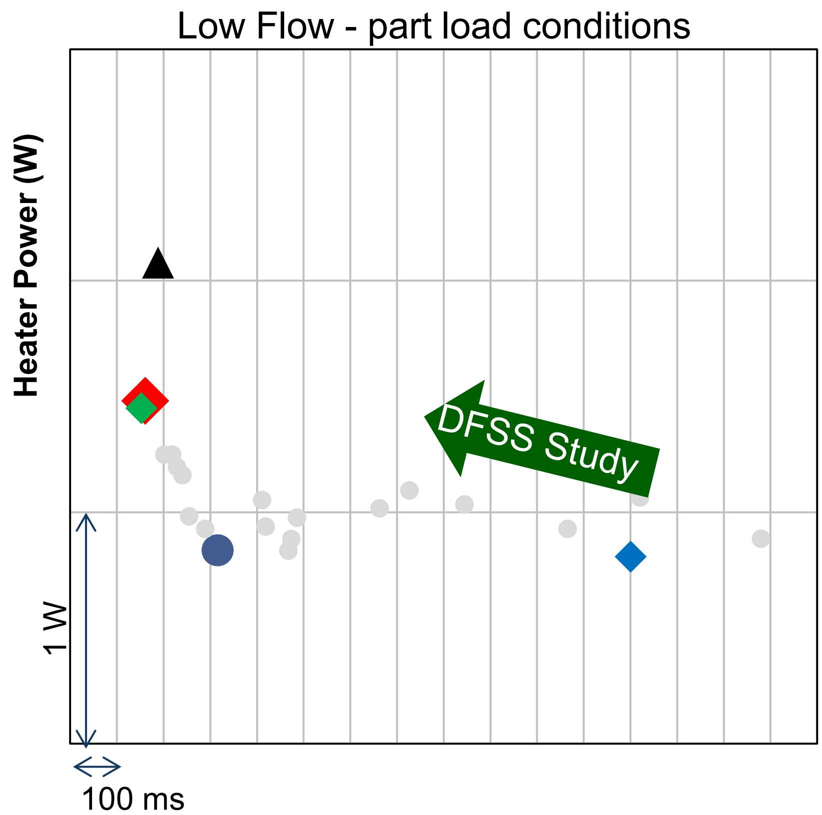
- Realization
  - Use of air assisted atomizer nozzle w/ preheated air
  - Air flow control using a mass flow controller
  - Fuel flow control using a syringe pump
  - Heating of air and surfaces around the injector to maximize fuel vaporization minimize condensation on surfaces



BOSCH

Protection Tube Optimization

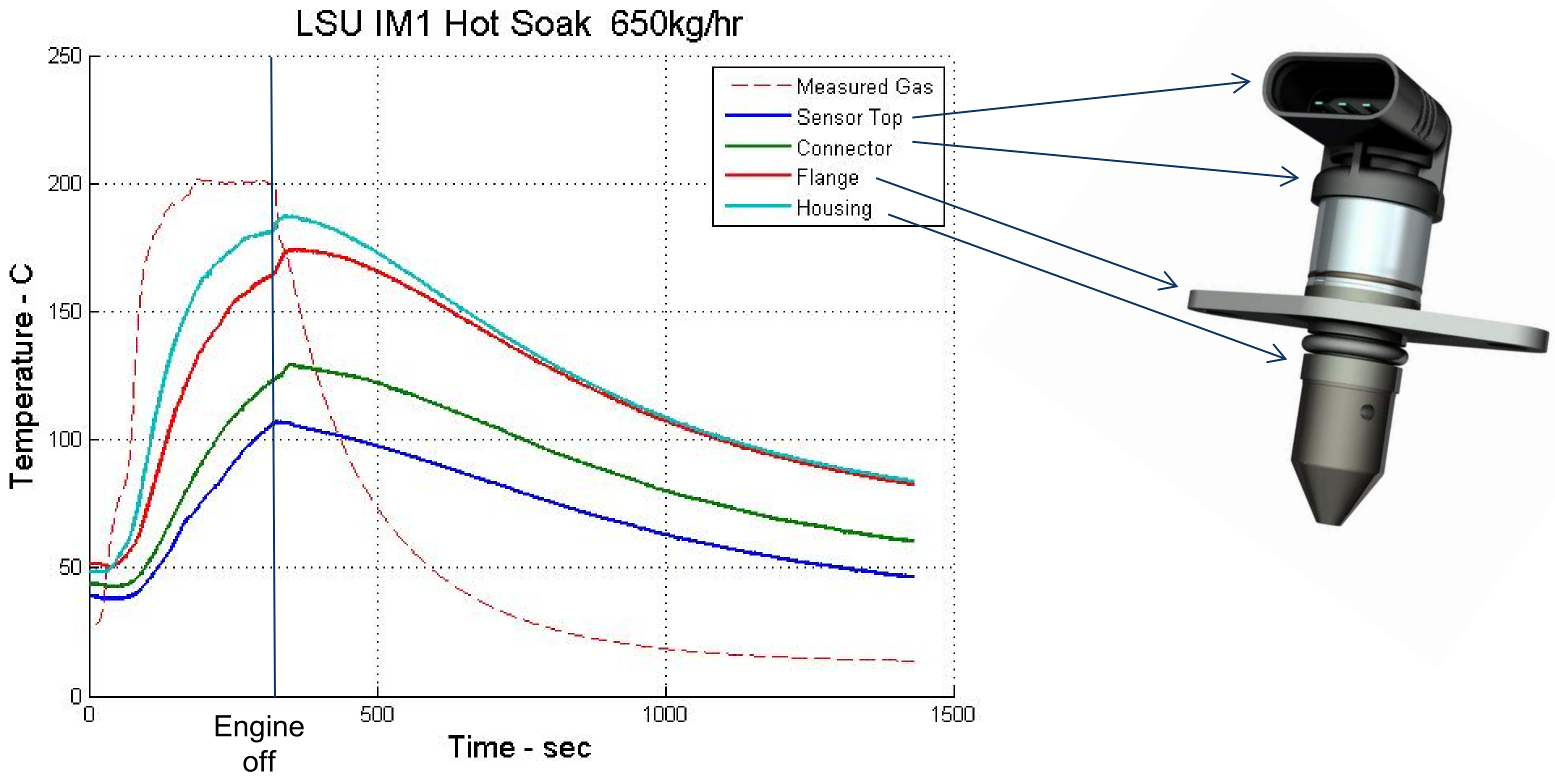




Protection tube optimization achieved targets for sensor performance in engine part and medium load conditions

BOSCH

First Build Thermal Management



Thermal mapping for hot soak showed component temperature in acceptable range

First Build and Validation

First build completed in December 2013

Mechanical Testing:
- Sine Vibration
- Wideband Vibration
- Vibrational Resonance
- Mechanical Shock
- Drop
- Pendulum Swing

Environmental Testing:
- Hot Soak
- Cold Soak
- Thermal Cycling
- Salt Water Submergence
- High Pressure Water Spray

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

Results:
- No design related failures

First build validation completed in April 2014

BOSCH