2011 DOE Vehicle Technologies Program Review

Advanced Combustion Concepts - Enabling Systems and Solutions (ACCESS) for High Efficiency Light Duty Vehicles

Arlington, Virginia
May 13th, 2011

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Advanced Systems Engineering
Gasoline Systems, Robert Bosch LLC

Contract: DE-EE0003533
Project ID: ACE066

"This presentation does not include any confidential material"`

- **Project Overview**
- **Relevance**
- **Approach**
- **Collaboration and Coordination**
- **Accomplishments and Future Work**
- **Summary**

2011 DOE Merit Review – ACCESS – Overview

Budget

$24,556,737 – Total Project Budget

- $11,953,784 – DOE Funding
- $12,602,954 – Partner Funding

$9,987,412 – Phase I
$7,441,808 – Phase II
$7,127,518 – Phase III

Barriers

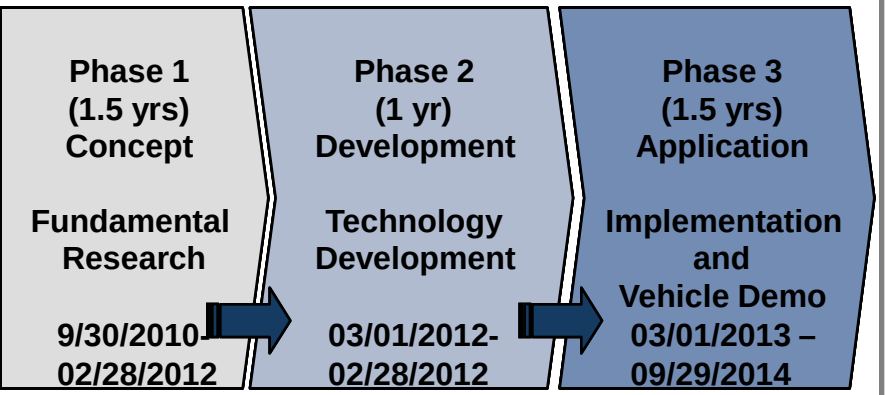
Barriers

- Fuel efficiency as key market driver
- Stringent emission requirements
- System cost of advanced combustion

Targets

- 30% fuel efficiency improvement
- SULEV emissions capability
- Commercially viable system solution

Timeline



Partners

- US Department of Energy
- Robert Bosch LLC
- AVL
- University of Michigan, Ann Arbor
- Stanford University
- Emitec

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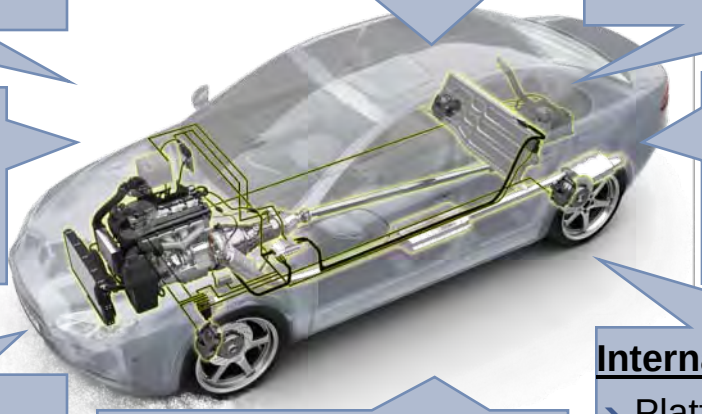
Major Market Drivers of Automotive Powertrain World Wide

Fuel economy and CO_2
- W-EU: 130g CO_2/km in 2012
- US CAFE: 34.1 mpg in 2016
- ww: volatile crude oil prices

Cost
- For entry level mobility
- Cost of Ownership
- Cost Effectiveness

Emissions & Diagnosis
- EU6
- NAFTA SULEV, PZEV, LEVIII
- CARB OBD II



Fun to drive
- Power output
- Low end torque
- Response time

Quality and Safety
- Reliability
- Robustness
- ISO26262

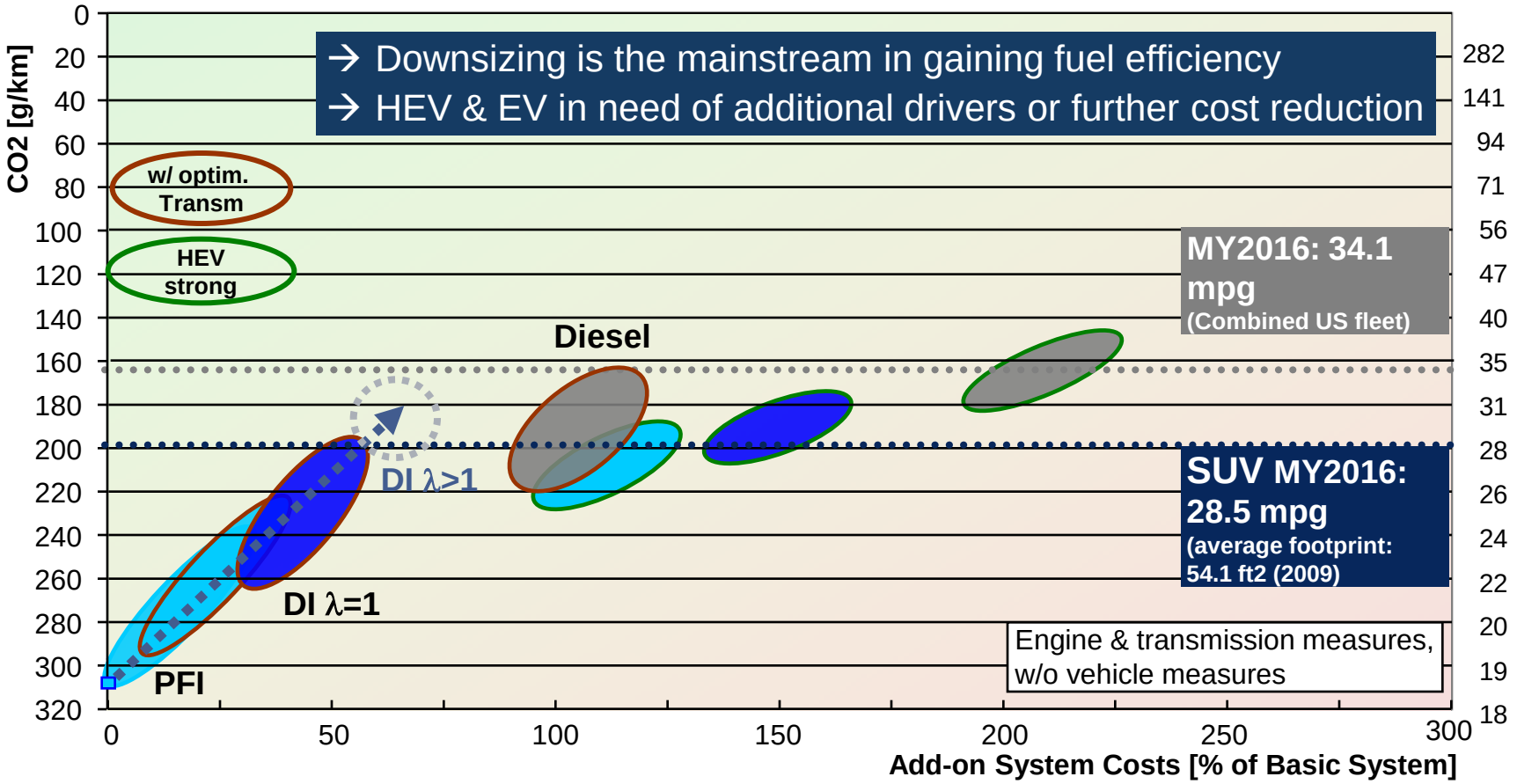
Driving comfort
- Noise, vibration, harshness
- Shift & launch quality
- Easy driving

Brand building
- Brand Identity & -value
- Image, e.g. Innovation

Internationalization
- Platforms (few, flexible)
- Modules
- Purchasing (global)
- Fuel quality differences

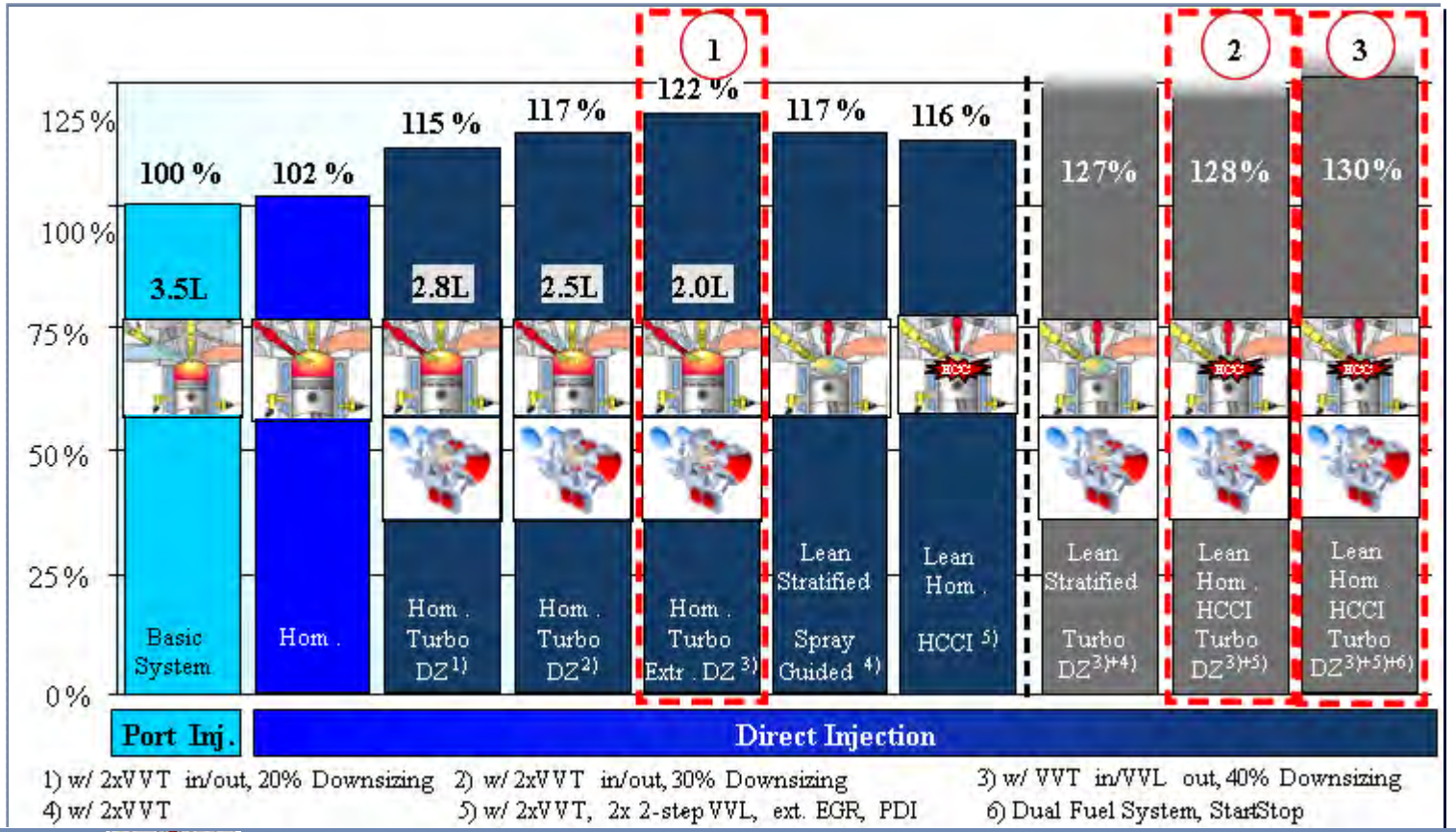
→ Costs and fuel economy currently are worldwide the most important market drivers. Emissions and diagnosis are mandatory requirements.

Bridging the Technology Gap



Basic system: SUV class (2300 kg); 4.0 l (8 cyl.) PFI; λ=1; CO_2 308 g/km

Advanced Combustion Concept – Homogenous Charge Compression Ignition (HCCI)



→Homogenous pre-mixture of air, fuel & residuals
→Controlled auto-ignition and flameless combustion

Overall Project Objectives

- Baseline Powertrain: 3.6L V6, PFI, 6 Speed
- Target Powertrain: 2.0L I4, DI, Turbo, 6 Speed –Multi Mode Combustion SI/HCCI
- 30% Fuel Economy Improvement Compared to Baseline
- SULEV Emissions Capability
- By mid 2014 commercially viable, production feasible, system solution

Annual Objectives – DOE kick off Oct 1, 2010 – March 2011

- Establish team structure and project management processes
- Validate boosted HCCI concept with Experimental and Simulation data
- Complete Prototype I engine design and initiate HW procurement
- Initiate Modeling, Systems and Controls development activities

Phase 2 Go/No Go Decision

- Modeling, simulation, or test results of selected technologies indicate technical feasibility of achieving project goals.
- The cost benefit analysis shows that the project is on a specific path to deliver a commercially viable engine and vehicle system.

Project Timeline

	Phase 1 Concept 2010 – 2011	Phase 2 Development 2012	Phase 3 Application 2013 – 2014
Engine Design •EMS design & build Bosch •Engine design & build AVL	•EMS System Concept and Lay -out •Engine / Vehicle Simulations •HW Design and Procurement •Prototype 1 Engine Builds	•Final HW Proposal •Final System Layout •Prototype 2 Builds	•Engine Upgrades & Maintenance
Combustion Development •Combustion Modeling AVL / UofM •Combustion Development AVL / UofM	•Physics Based Combustion Models •1cyl / 4cyl Base Combustion Data •System Lay -out and Sizing	•HCCI/SI Combustion •Combustion Mode Parameterization	•Combustion Model Updates
Combustion System •Combustion System Bosch / UofM •Combustion Simulations Bosch/Stanford	•CFD based Combustion Models •1cyl Combustion Investigations •Multi Mode Combustion Concepts	•CFD Model Updates •Multi Fuel Concepts •Dual Fuel System •1cyl Investigations	•Advanced Combustion Investigation •Advanced Bio -Fuel Concepts •Extreme High Compression Ratios
Controls •Control Oriented Models Bosch / UofM •Control Concepts Bosch / UofM	•Control Oriented Models •Control Concept – Mode Switching •Control Concept – Air / Fuel Path •Control Concept – Sub-Systems	•Model Validation •Experimental Control Concepts •Subsystem Application	•Final Control Concepts •Vehicle Level Controls •Calibration of Controls Parameters
Emissions Development •Emission System Emitec / Bosch •Emission Components Emitec	•3-Way SULEV Catalyst Design •Emission Simulations •After Treatment System Layout	•3-Way Catalyst Build •Lean NoX Trap Design	•Lean After Treatment Concept •Vehicle level Emission Development •Drive-cycle Emission Tests
Vehicle Development •Vehicle Integration Bosch •System Application Bosch	•Base Vehicle Simulations •Vehicle Communications	•Vehicle Integration •SI Mode Calibration	•Vehicle Level Development •HCCI Mode Calibration •Chassis Dynamometer •Drive Cycle Testing and Demo

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Multi Mode Combustion System

• Spark Ignited (SI) Combustion with High Compression Ratio and High Boost assisted with cooled external Exhaust Gas Recirculation (EGR)

• Homogenous Charge Compression Ignition (HCCI) with Boost, and Fueling strategies for operation range extension

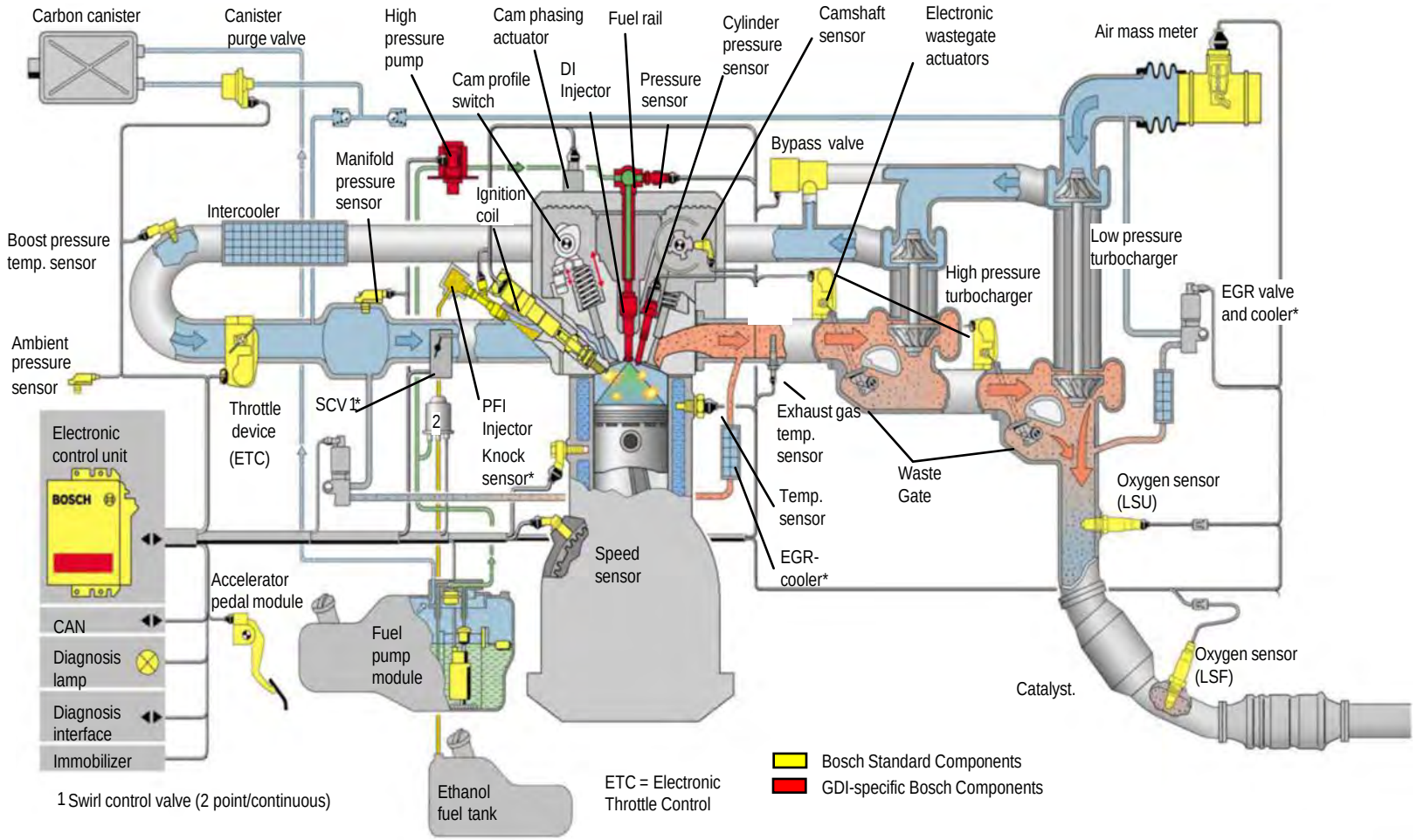
Enabling System Configuration

• Port assisted Direction Injection (PDI) – Dual injection system for combining the benefits of Port Fuel Injection (PFI) and Direct Injection (DI), and enabling Dual Fuel System approach for high compression ratios and extreme downsizing on boosted engines

• Multi-Hole Direct Injection with Individual Nozzle Geometry design for improved mixture preparation and combustion efficiency

• Start-Stop and Thermal Management Systems to eliminate fuel consumption at idling conditions and enhance engine warm-up behavior

Multi Mode Combustion System Configuration



Multi Mode Combustion System Configuration

Customized Engine Management (ECU)

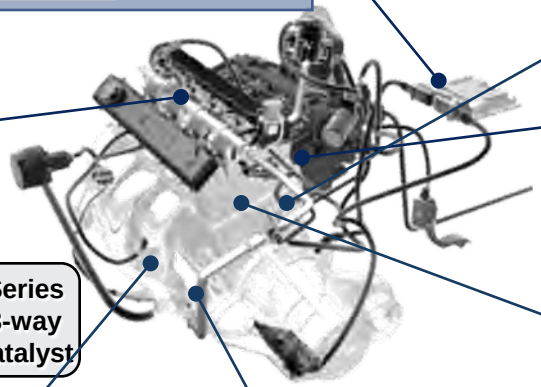
- Novel combustion algorithms
- Model based control

In-Cylinder Pressure Sensing

- Direct combustion feedback
- Closed loop control

Customized Injection

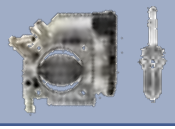
- Solenoid Multi-Hole
- Central mount
- Split injection
- Small quantities
- Variable hole size



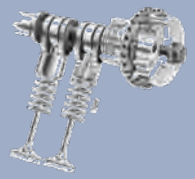
Series 3-way catalyst

Throttling and Ignition

- Stabilizing strategies
- HCCI map extension



Variable Valve Actuation



- 2x Var. phasing (CamPhasers)
- 2x Var. lift (TwinLift or cont. var.)
- Fast and accurate actuation

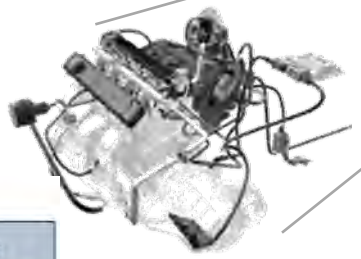
Turbo-charging

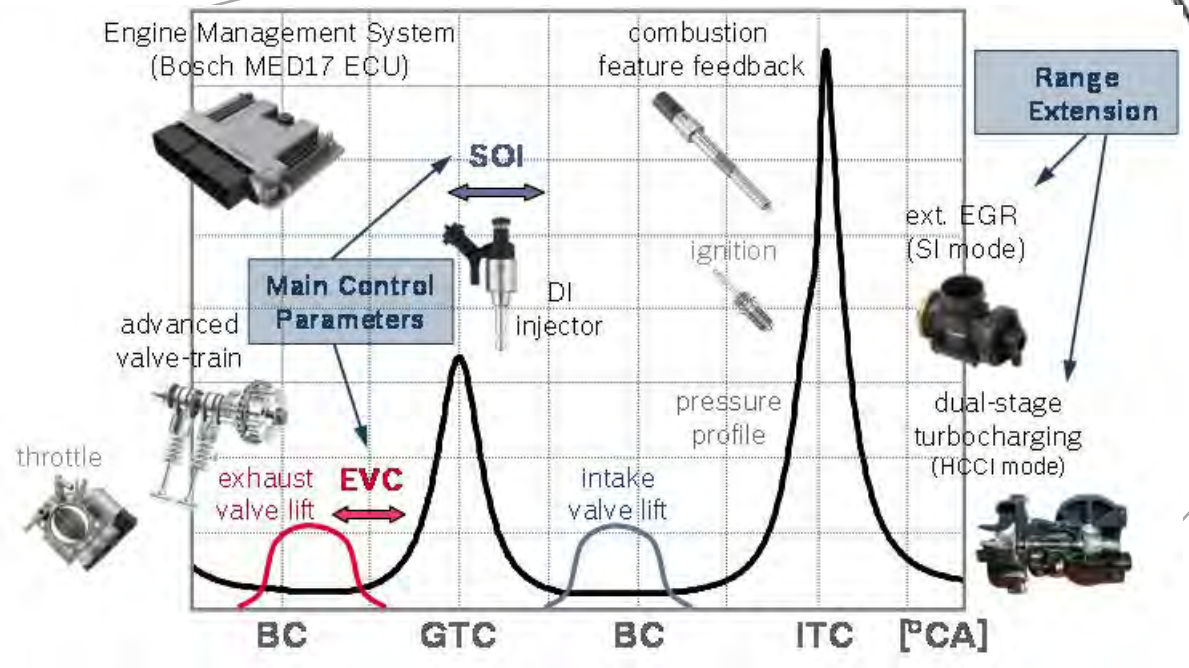
- 2-stage system
- HCCI map extension

External EGR System

- EGR control
- EGR cooling
- Map extension

Enabling System for Multi Mode Combustion





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ACCESS Project Organization

US Department of Energy

- Project / Contract Management
- Technical Merit / Milestone Reviews

Steering Committee

- Project Scope Definition
- Technical Merit / Milestone Reviews

Robert Bosch LLC - Sub
Research and Technology Center (RTC)

- HCCI and Bio Fuels Thermodynamics
- Combustion Modeling and Simulations
- HCCI Engine Controls

Robert Bosch LLC - Prime
Gasoline Systems (GS)

- Project Lead
- Engine Management System Concept
- Engine Controls & Application

AVL - Sub
Powertrain Engineering

- Engine & Vehicle Simulations
- HCCI Combustion System Research
- HCCI Engine Design and Development

Stanford University - Sub

- HCCI and Bio Fuels Thermodynamics
- Combustion Modeling and Simulations
- Single Cylinder Engine Operation

University of Michigan - Sub
Advanced Powertrain Controls Laboratory

- Control Oriented Models
-HCCI / SIDI Engine Controls
- Engine Sub -System Controls

Emitec - Sub

- After-Treatment System and Simulation
-3-Way Catalyst Development
- Lean NOx After-Treatment Development

Chevron Energy Technology Company
External Support

- Fuel Property Consultation
-Fuel Samples for Combustion Testing

University of Michigan - Sub
Walter E. Lay Automotive Laboratory

- Physics Based Combustion Modeling
-Combustion Development & Testing
-Single / Multi Cylinder Engine Research

US OEM's

- Information Exchange
- Technology Alignment

ACCESS Project Organization

Robert Bosch LLC
Research and Technology Center (RTC)

David Cook	**– Co- PI - CFD Simulations**
Joel Oudart	**– Advanced Combustion & Biofuels**
Nalin Chatuverdi	– Modeling and Controls
Aleksander Kojic	– Controls
Nikhil Ravi	– Controls

Robert Bosch LLC
Gasoline Systems (GS)

Hakan Yilmaz	**– PI**
Li Jiang	**– Co -PI** – Engine Controls
Roland Herynek	**– Co - PI** – System
Carrie Morton	– Project Management
Jeff Sterniak	– Combustion Concept
A. Fuchsbauer	– Software Architecture
Julien Vanier	– System Integration
Alan Mond	– System Concept
Adrian Brdarski	– System Hardware
Andre Kulzer	– Thermodynamics

AVL
Powertrain Engineering

Jennifer Wheeler	**– Co -PI** – Combustion
Dusan Polovina	**– Co -PI** – Combustion
Roger Faber	– Project Management
Vasile Frasinel	– Design
Ken Kernyo	– Design
Kevin Roth	– Calibration
Chris Erhardt	– Engine Assembly & Dyno

Stanford University

Heinz Pitsch	**– Co -PI** – CFD Simulations
Mittal Varun	– CFD Simulations
Eric Doran	– CFD Simulations
Chris Edwards	– Thermodynamics
Julie Blumreiter	– Thermodynamics
Ben Kessel	– Thermodynamics

University of Michigan, Ann Arbor
Advanced Powertrain Controls Laboratory

Anna Stefanopoulou	**– Co – PI – Engine Controls**
Eric Hellström	– Research Fellow – Engine Controls
Phillip Bonkoski	– Air Path Modelling / Controls
Patrick Gorzelic	– Combustion Mode Switching
Shyam Jade	– Combustion Modelling / Controls
Jacob Larimore	– Combustion Mode Switching

Emitec

Ulrich Pfahl	**– Co -PI** – After -Treatment
Jan Kramer	**– Co -PI** – After -Treatment
Markus Downey	– System Application

Chevron Energy Technology Company
(ETC)

– Technical Consultation
– Advisory and Information Exchange

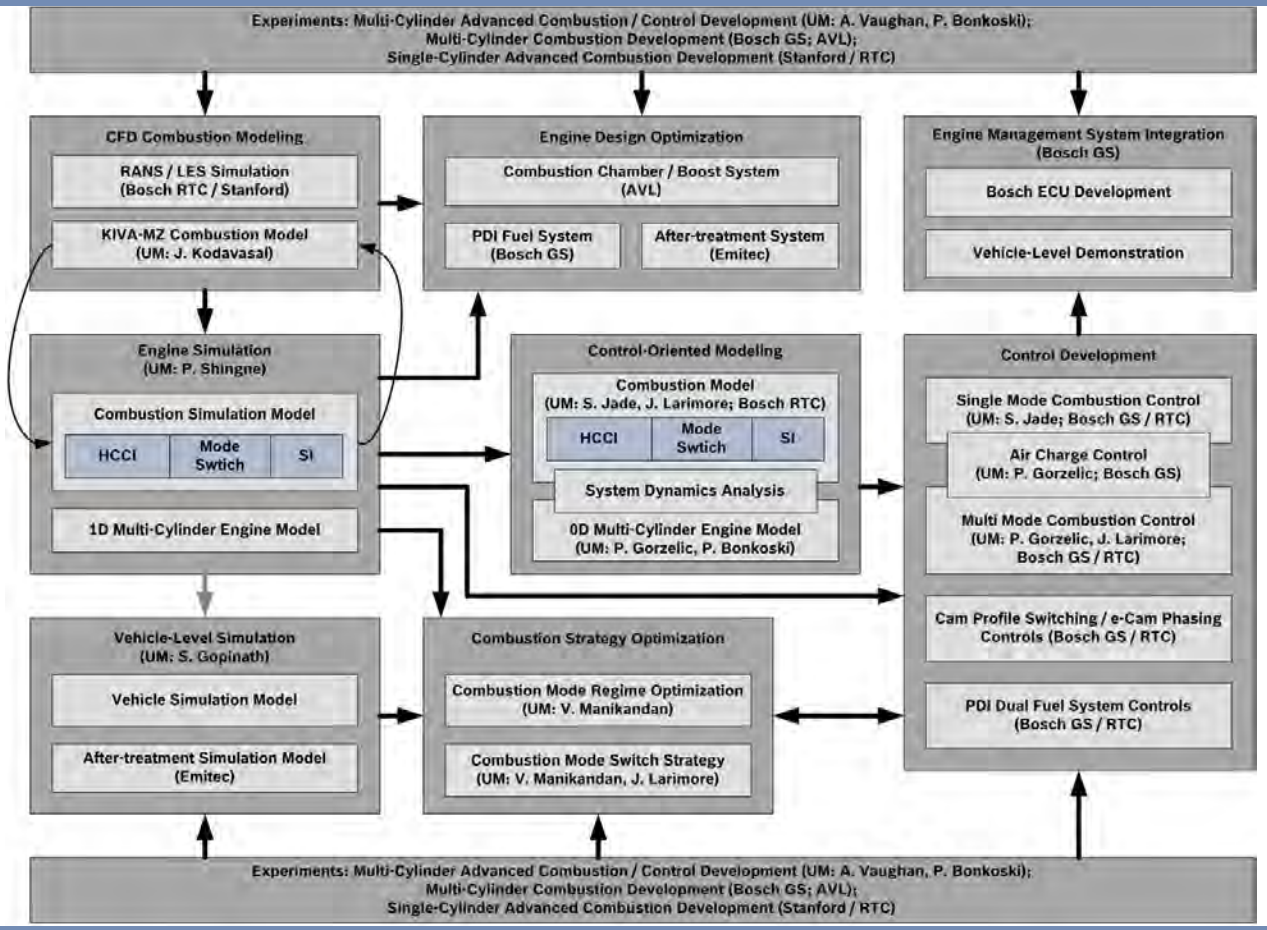
University of Michigan, Ann Arbor
Walter E. Lay Automotive Laboratory

Dennis Assanis	**– Co -PI** – Combustion
Aris Babajimopoulos	– Combustion Simulation
George Lavoie	– Combustion Research
Stani Bohac	– Experimental Research
Srinath Gopinath	– Multi-Mode Operation Optimization
Janardhan Kodavasal	– Chemical Kinetics Modelling
Prasad Shingne	– 1D Engine Simulation
Adam Vaughan	– Experimental Research
Vijai Manikandan	– Multi-Mode Operation Optimization

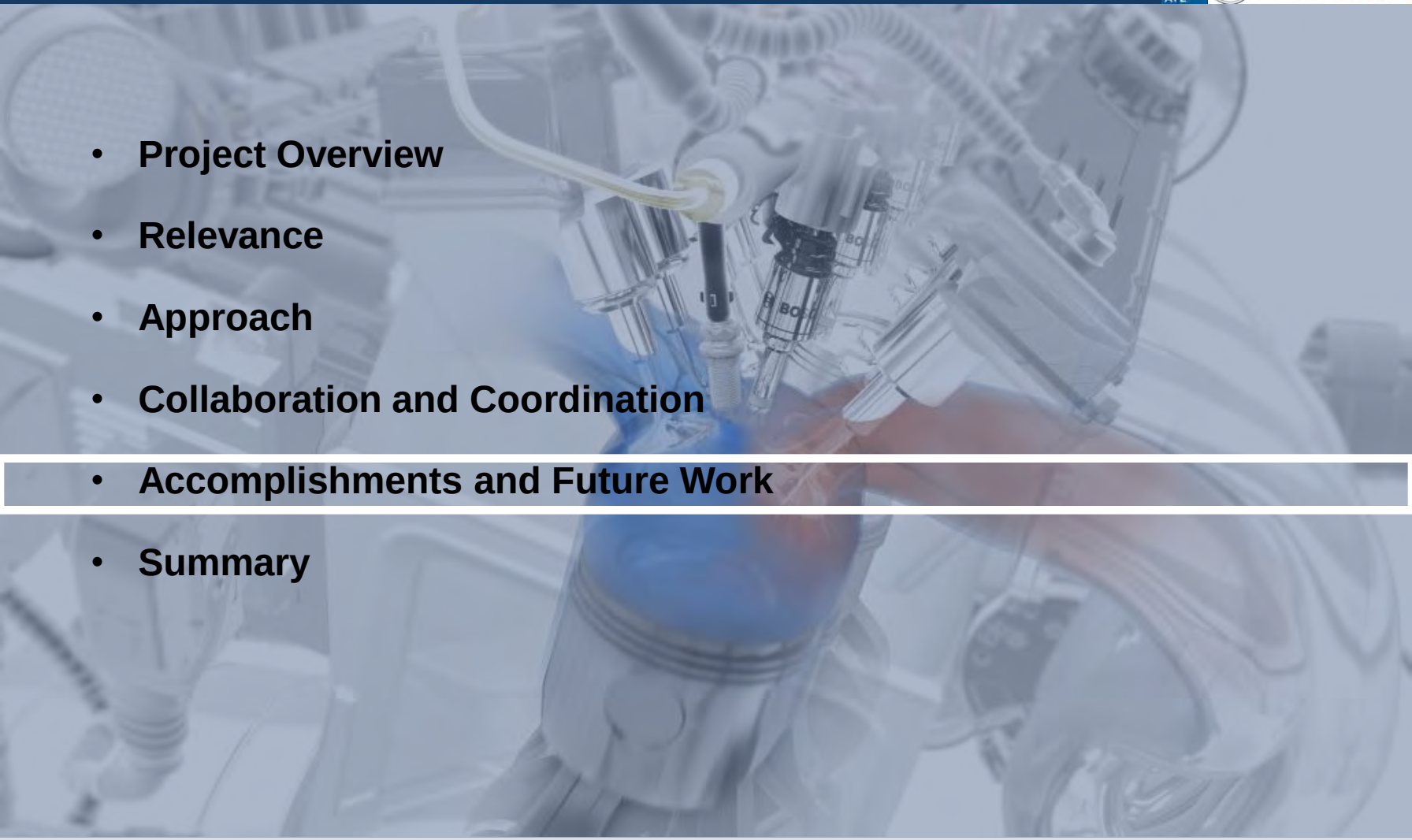
US OEMs

– Information Exchange
– Technology Alignment

Consortium Partner Roles and Interactions



→ Effective coordination of information and data flow based on roles and responsibilities



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Competence and Project Management

Establish Team Structure

- ✓ Project Teaming Agreement
- ✓ Full team in place, roles defined
  - 14 PhD Students
  - 4 Faculty Members, 3 Post Docs
  - 15+ Industry Staff
- ✓ HCCI Center of Competency Transfer from Bosch Germany to Bosch North America
- ✓ Comprehensive training for all students and team members by the research team from Bosch, Germany

Project Management Plan

- ✓ Communication plans
- ✓ President level – Industry Executive steering committee established
  - 3 quarterly review meetings
- ✓ Monthly Cockpit Charts
- ✓ Risk Management Plan
- ✓ Reporting templates & data collection standards in use
- ✓ Web based filing structure and data exchange to enhance collaboration

→ Project team and management structure are in place and fully active!

35+ Researchers and Staff from Industry and Academia!

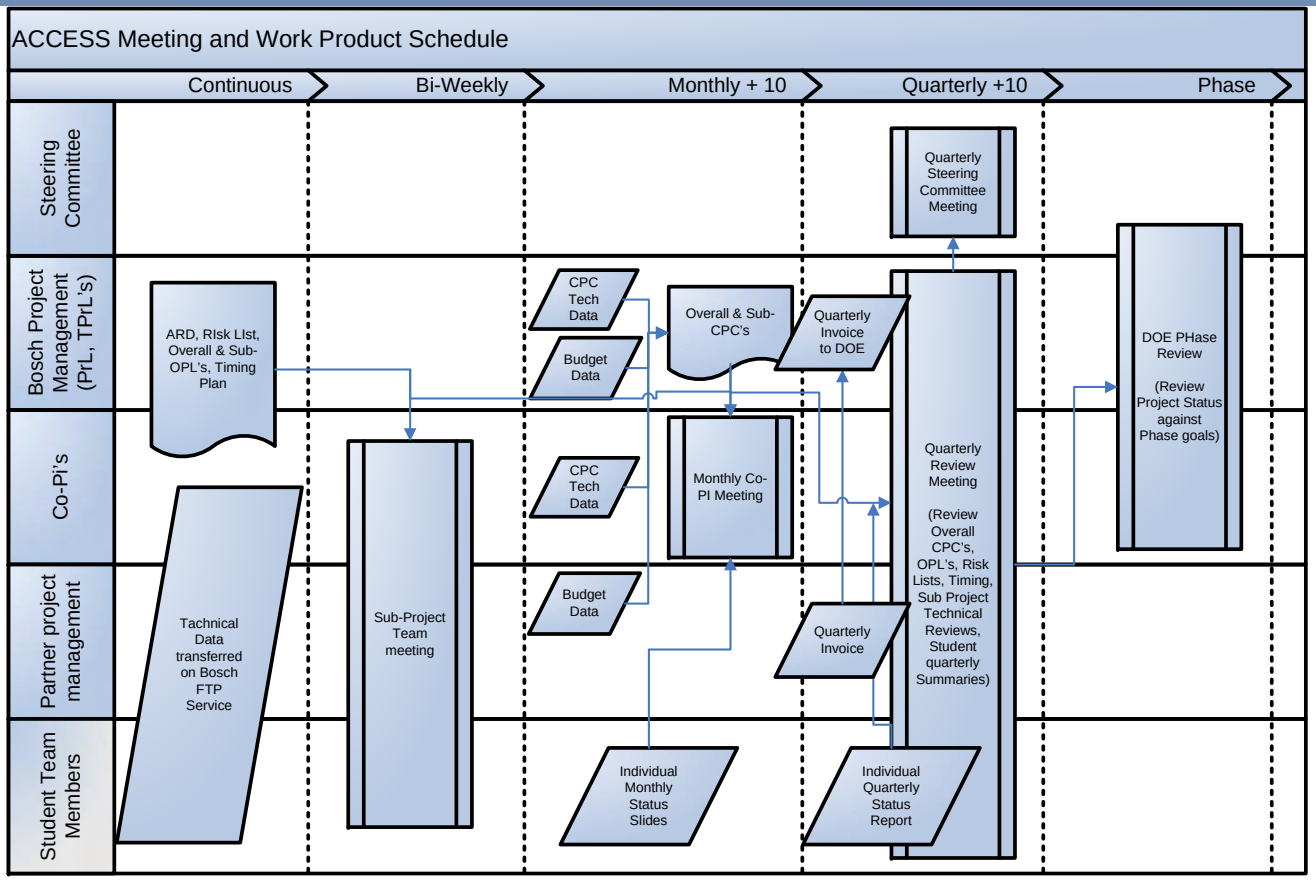
UofM & Bosch

AVL & Bosch

UofM & Bosch

Stanford & Bosch

Consortium Meeting and Reporting

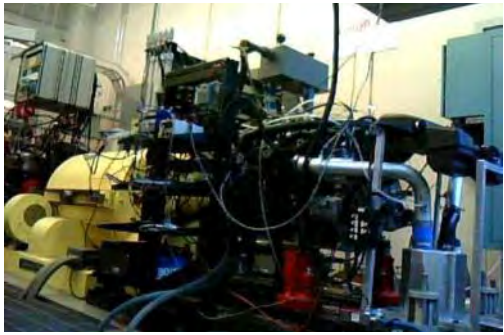


→ Overall alignment and control of project status and target achievements
→ Comprehensive project management to minimize administrative burden on researchers

Engine Test Cells at University Partners

- Single-cylinder research engine lab with Fully Flexible Valve Actuation (FFVA) at Stanford operational
- Multi-cylinder engine lab at University of Michigan operational with support of Bosch
- State-of-the-art multi-cylinder transient engine dynamometer ordered; will be commissioned at University of Michigan in August 2011
- Resident Bosch engineers at both universities

Stanford University

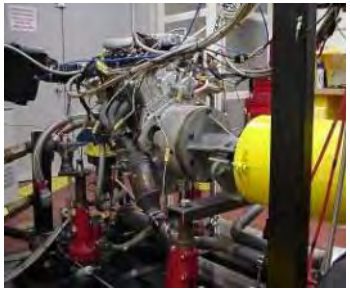


University of Michigan

Engine Test Cells at Industry Partners

- HCCI combustion development and parameterization at AVL test cell
- SI development and calibration at Bosch test cell
- All experimental set-ups will have same Engine HW and Engine Management System
- Open data sharing among partners and test cells

AVL test cell



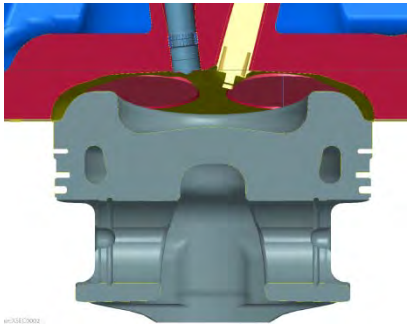
Bosch test cell

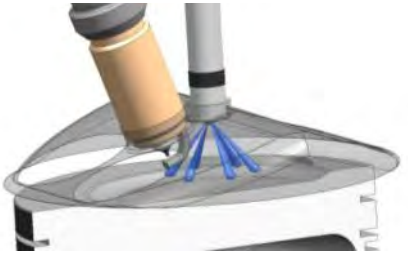
→ Industry support enables University researchers to focus on innovation

Prototype 1 Engine Design (AVL, Bosch)

- Target Multi Mode Combustion Engine will be based on GM Ecotec 2.0 L DI Turbo platform
- All Base Engine HW design and improvements for target engine configuration in progress, lead by AVL
- All Engine Management System design and improvements for target system configuration in progress, lead by Bosch
- All Aftertreatment System design and improvements for emission concept in progress, lead by Emitec

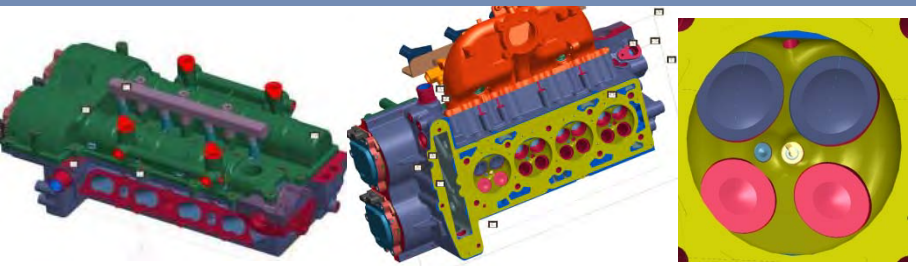
Combustion and Spray Optimization





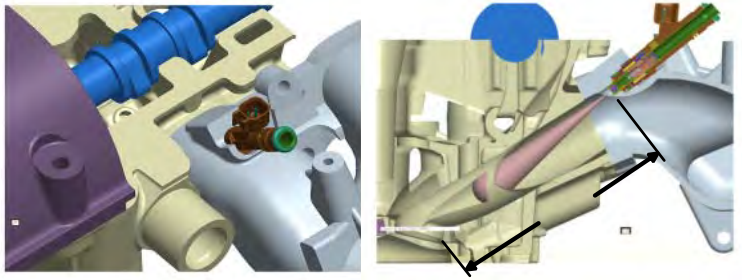
Combustion chamber, piston crown and injection spray designs for Prototype 1 engine are completed

Cylinder Head with Central Mount Injection



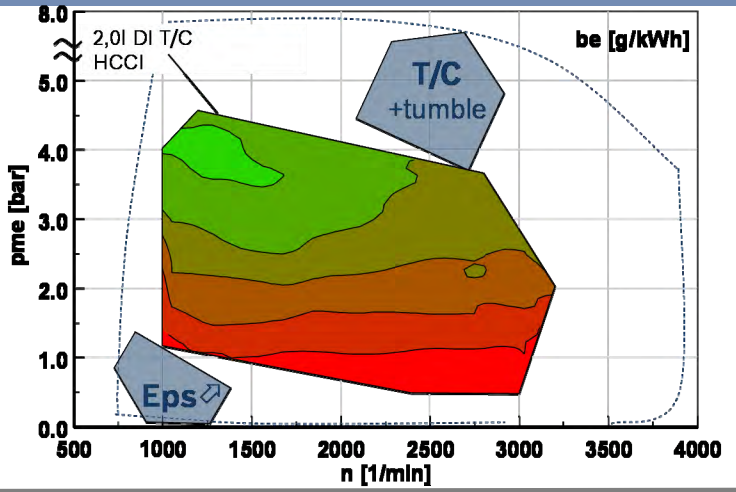
Cylinder Head Design for Central Mount Direct Injection and Variable Valve Actuation is completed

Dual Injection Design DI + PFI

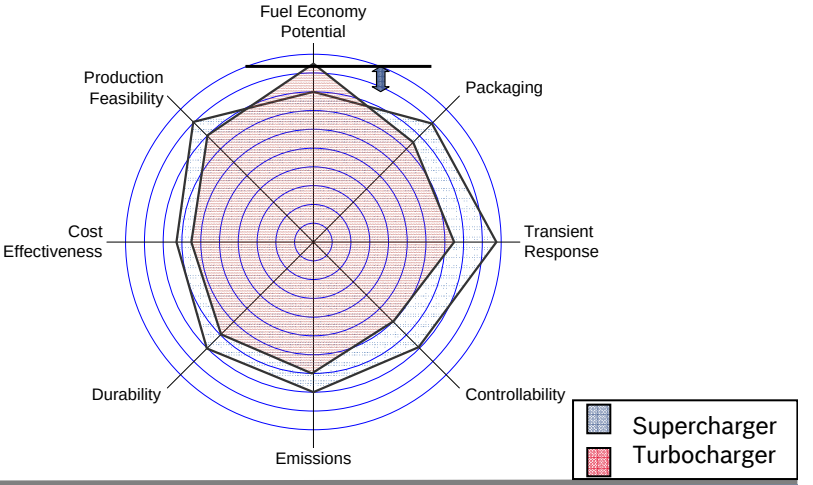


Dual Injection System design with DI + PFI is completed

HCCI Range Extension w/ Boosting



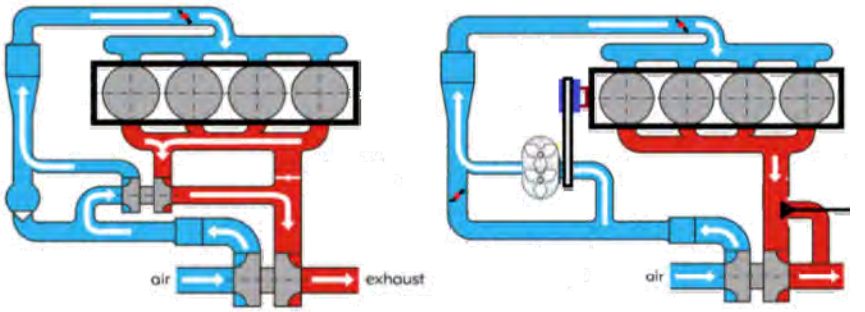
Turbo Charger vs. Super Charger



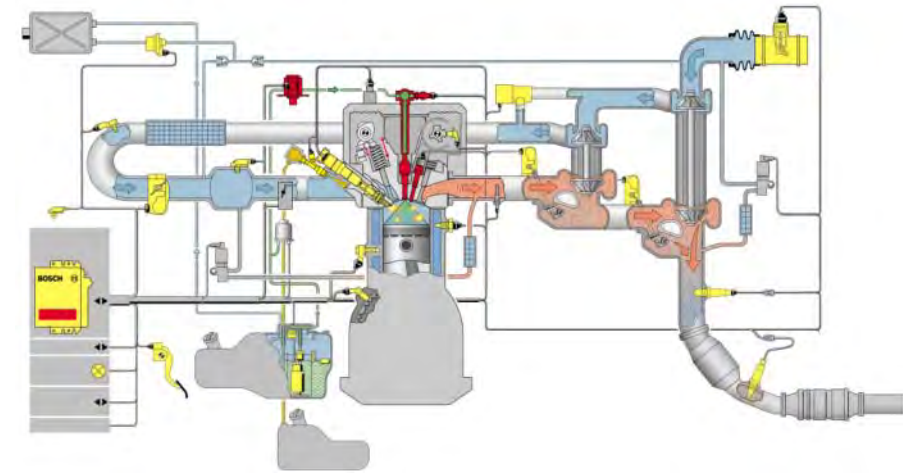
Accomplishments

- Simulations of dual-stage boosting in GT Power completed
- Experimental data from Boosted HCCI Mule engine was used for simulation validation
- Comprehensive analysis of boosting system options was performed

T/c + T/c vs. S/c + T/c Configuration



Overview – Combustion System



Approach

- High fidelity combustion model for fundamental multi-mode combustion
- Engine HW design and procurement
- Transient dynamometer experiments
- After-treatment simulation
- Vehicle simulation and verification

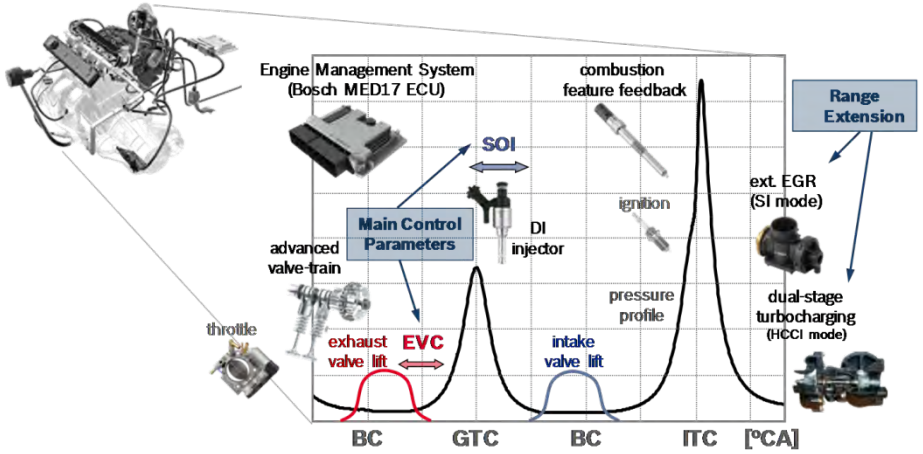
Accomplishments

- Engine design for Prototype level 1 completed
- Boosted HCCI experiment is setup for data collection at University of Michigan
- Vehicle + Engine simulation in progress
- Transient dynamometer ordered for University of Michigan

Future Work

- Build Prototype I engines
- Combustion development and validation of Prototype I engine on transient dynamometer
- Parameterization of multi mode combustion
- Prototype level 2 updates and proof of combustion concept for vehicle readiness

Overview – Control System



Approach

- Simulation / Experiment based system dynamics and control sensitivity analysis
- Model-based combustion / air path control with cylinder pressure sensing feedback
- Engine-in-the-Loop (EIL) control algorithm validation via rapid prototyping techniques

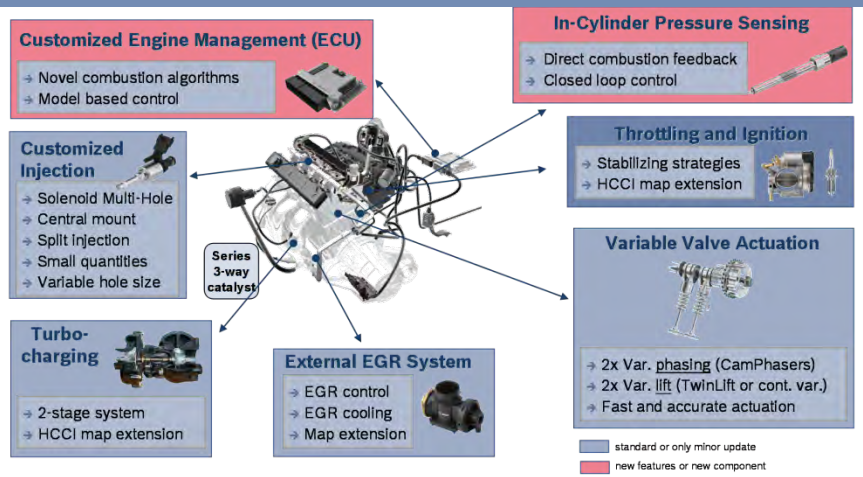
Accomplishments

- Control-oriented HCCI combustion model validated for low/part load and light boost
- Control-oriented air path model established for a single-stage turbocharged base configuration
- Dynamic analysis of the engine in progress
- Sub-system control development in progress

Future Work

- Validate charge estimation algorithm for target engine platform
- Validate sub-system / component controls
- Improve controls for HCCI & SI combustion and dual-stage turbo charging system
- Finalize control strategy architecture for a multi-mode combustion engine

Overview - Software Architecture



Approach

- Bosch Motronic engine control platform to be used for Engine and Vehicle level development with all sub-system and system level functions
- Engine Control Unit with integrated algorithms for multi mode combustion for production feasible proof of concept
- Common ECU platform for all partners' research

Accomplishments

- Prototype Engine Control Unit (ECU) to be used by the project is built with additional drivers
- Integrated ECU software for Mule engine, including base HCCI control algorithms
- Rapid-Prototyping hardware acquired and installed on test cell

Future Work

- Integration of new algorithms into ECU software to fulfill all requirements of Prototype I engine
  - New actuators: dual-stage boost system, variable valve lift (VVL) and electric variable valve timing (eVVT)
  - Multi-mode combustion: HCCI and SI

2011 DOE Merit Review – ACCESS – Accomplishments

Overview –Fundamental Combustion & Fuels

Approach

- Single cylinder research engine (SCRE) with Fully Flexible Variable Valve actuators (Stanford Univ.)
- Advanced combustion concept with bio fuel
- rCFD RANS to investigate extreme high and low load HCCI
- Development of rCFD LES method for engine simulation in SI and HCCI modes

Accomplishments

- Engine test bench operational with DI + PFI Injection, Fully Flexible VVA, Boost (<3000rpm)
- Baseline Steady state HCCI map in progress
- rCFD RANS Combustion model implemented, and first gas exchange simulation completed
- rCFD LES framework defined and flow bench simulation SCRE cyl. head in progress

Future Work

- Investigate low load HCCI w/ multiple injection
- Integration of a cooled compressed external EGR system and Prototype 1 cyl. head
- Validation of rCFD RANS and LES simulations using experimental and numerical data
- Implementation of rCFD LES Combustion model

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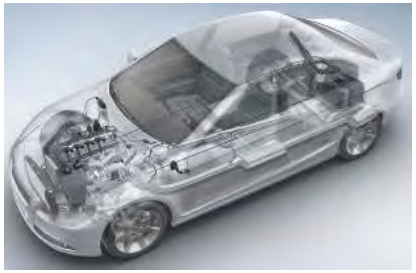
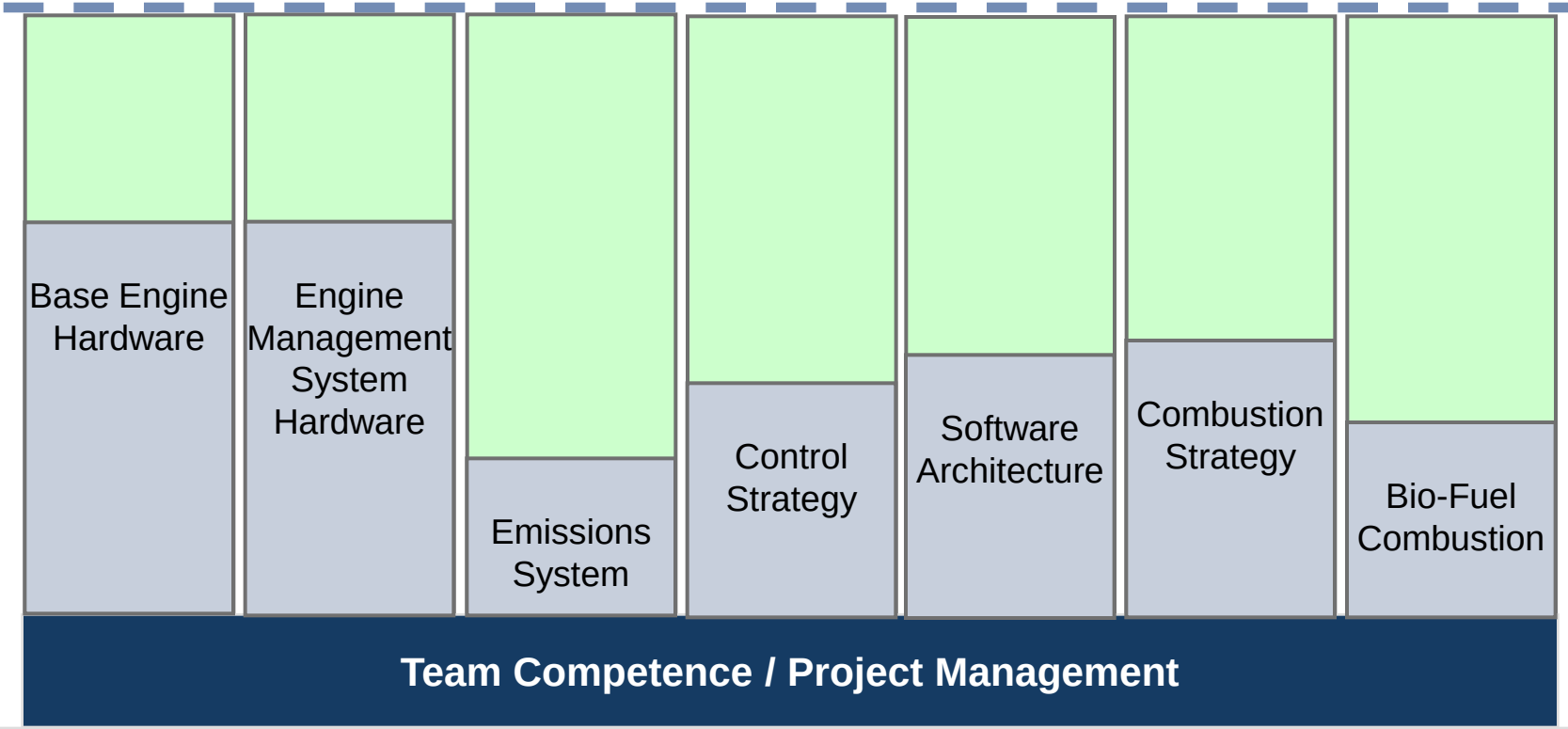


- 30% FE↑
- SULEV Capable
- Commercially Viable

Target



Questions?