Advanced Flex-Fuel Systems

US Department of Energy & Bosch Gasoline Systems
Collaborative Research on Advanced Flex Fuel Systems

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Advanced Flex-Fuel Systems

AGENDA:

- US Market and Powertrain Technology Overview
  - Fuel Economy → CAFÉ 2016
  - Engine Technologies → Turbo Charging & Gasoline Direct Injection
- Advance Flex Fuel System Project and Proposed Concepts
  - Project Overview → Partnership and Targets
  - Fuel Efficiency → Engine HW and System Optimization
  - Ethanol Detection → In-Cylinder Pressure Sensor Utilization
  - Model Based Controls → Reduced Calibration Effort
  - Emissions → DI Start and Emission System Concept
- Questions

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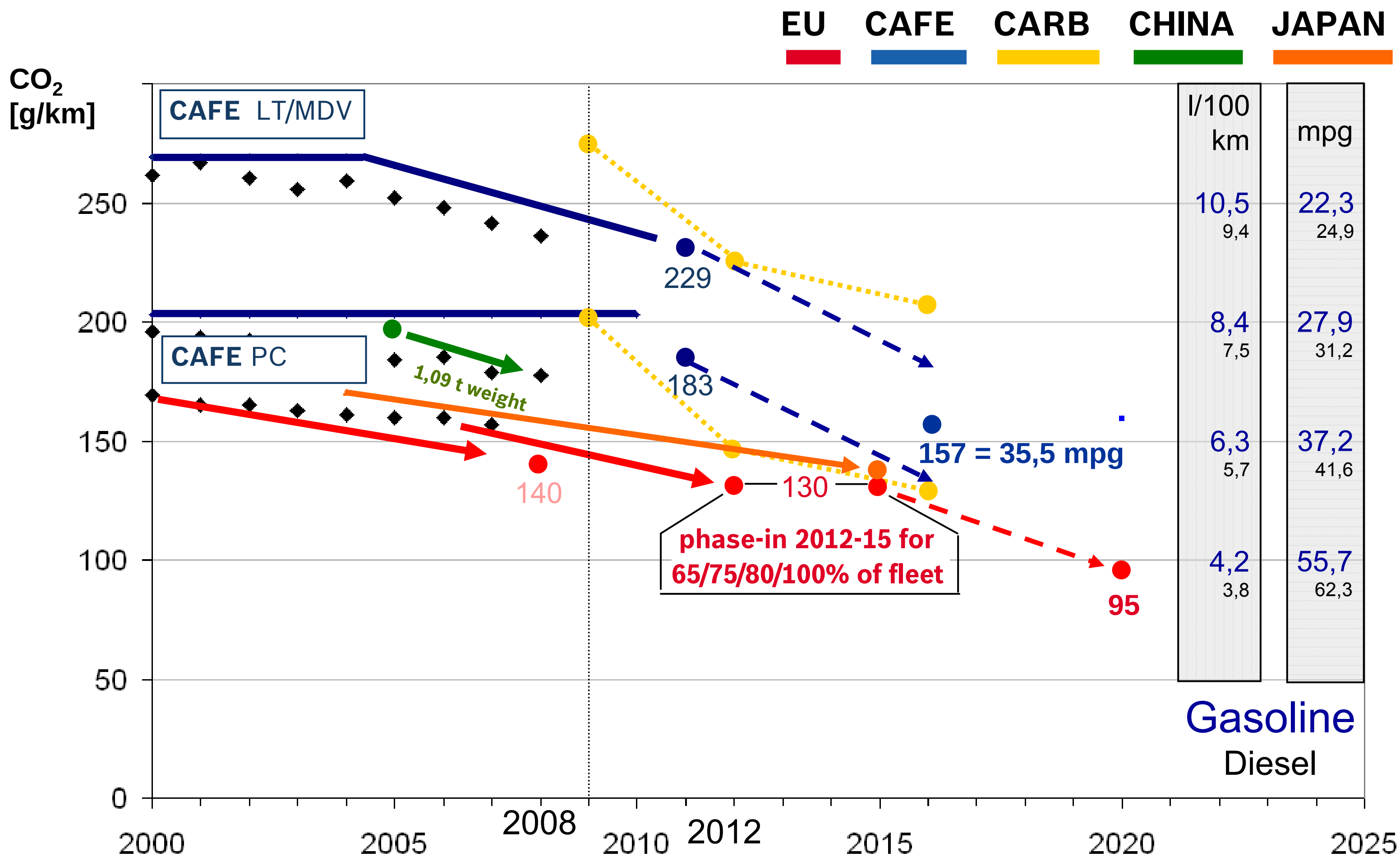

CAFE = Corporate Average Fuel Economy PC = Passenger Cars, LT / LDT = Light Trucks (pick-ups, vans, SUVs), MD(P)V = Medium Duty (Passenger) Vehicles GHG = Greenhouse Gases
NHTSA = National Highway Transportation and Safety Administration CARB = California Air Ressources Board mpg = miles per gallon China weight based limits (here for 1,09 tons curb weight)
CAFE data NHTSA report October 2006 EU data for ACEA (Association des Constructeurs Européens d'Automobiles) 6th EU Report 24.8.2006, for MY05 and 06 from T&E 2006 / 2007

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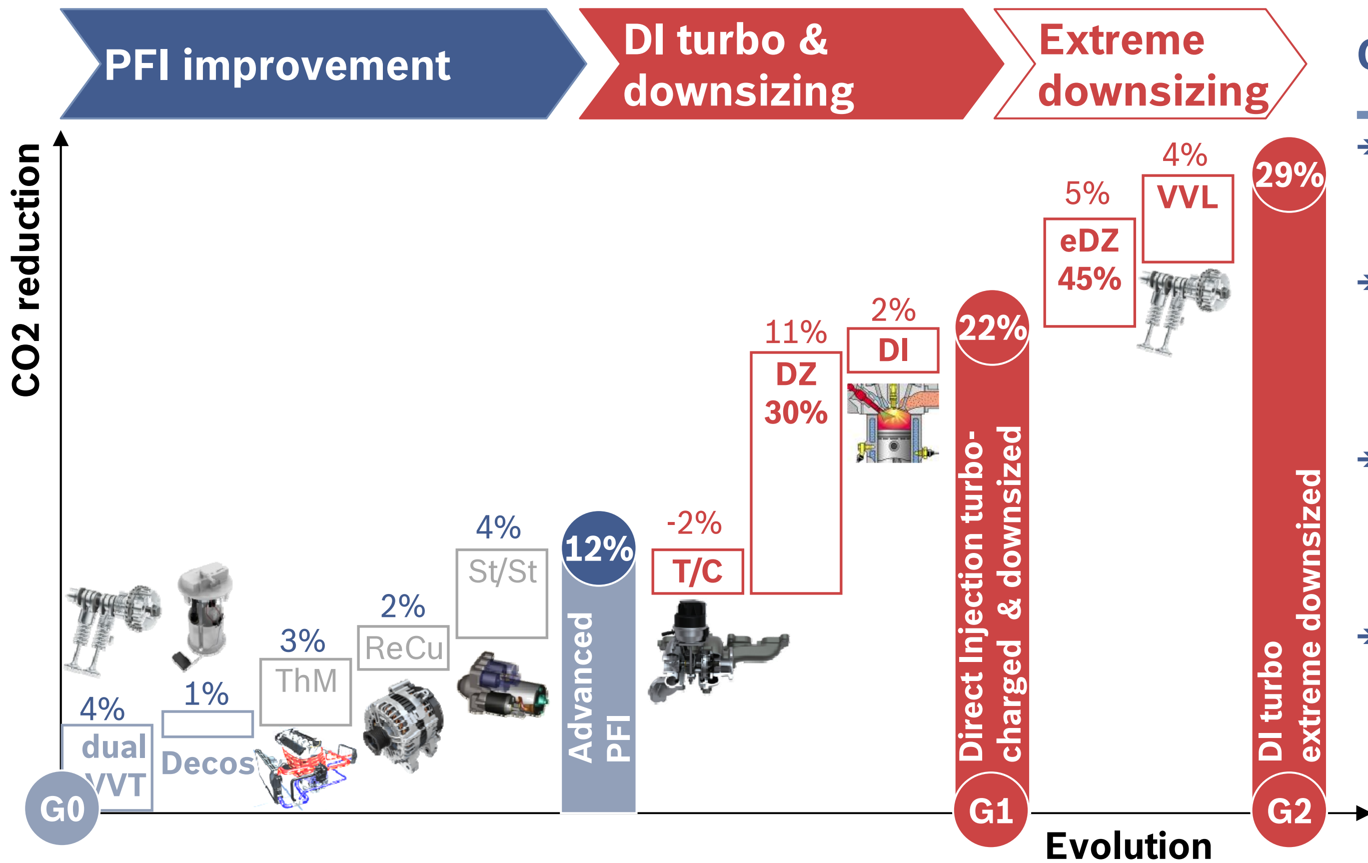
Synergistic CO2 Reduction Measures for Gasoline Engines



COMMENTS

- %-value is reduction potential for stand-alone measures.
- Combination of measures w/ negative synergies cause of part-redundancies
- Turbocharger (T/C) w/o additional measures leads to losses by lower compression.
- Extreme downsizing (eDZ) includes effect on cylinder reduction 4→3

CC

Reference base: CC vehicle, 1400 kg, 100 kW, MT, G0=2.0L PFI, NEDC driving cycle
PFI=port fuel injection | DZ=downsizing | T/C = turbocharger | Thm=Thermal management | St/St=Start/Stop System

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Fuel Properties – Gasoline vs. Ethanol

Properties	Unit	Gasoline	Ethanol
Heat of Combustion (Calorific Value)	MJ/kg-fuel	**42.5**	**26.8**
	MJ/kg-air	**2.90**	**2.98**
Air-Fuel Ratio	-	**14.8**	**9.0**
Boiling Temperature	°C	**25…215**	**78**
Evaporation Enthalpy	kJ/kg-fuel	**380…500**	**845**
Octane	RON	**>91**	**111**

Dielectric Constant	-	**2.0**	**24.0**

Benefits / Drawbacks

- Requires Higher Injection Quantity up to 35%
- Cold start critical below -10°C (E85)
- Produces more water, Retarded Cat warm up
- More wall wetting
- More oil contamination

\+ More Power / Higher Efficiency due to stronger air charge cooling

\+ High Knock Limit

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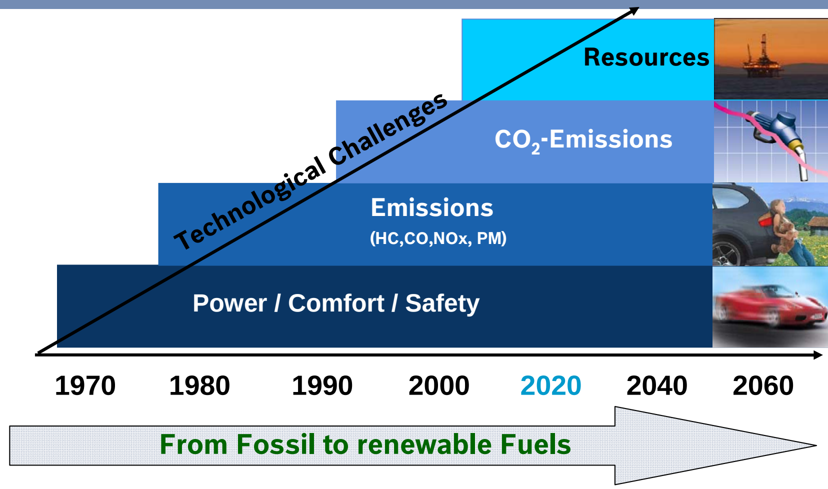
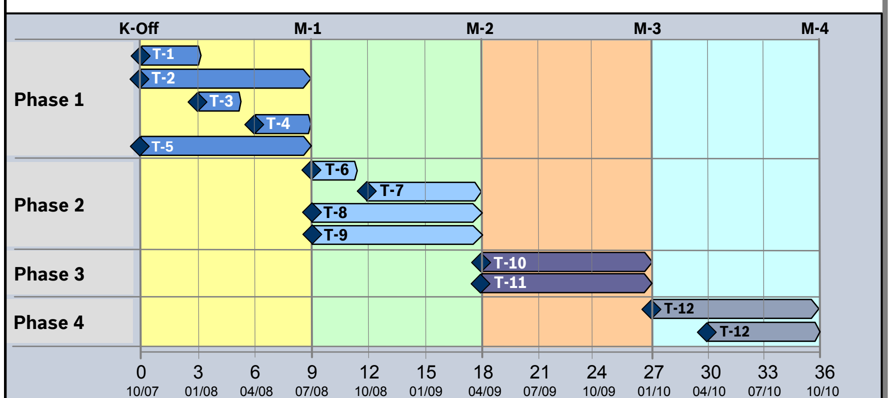
Advanced FFV (Project size 3.6M USD)



Project Targets

- Targets
  - 10+% fuel efficiency improvement with E85
  - Adv. controls to reduce FFV development effort
  - Ethanol learning via in-cylinder pressure sensor

Timeline



Partners

- US Department of Energy
- Robert Bosch LLC
- Ricardo, Inc
- University of Michigan, Ann Arbor

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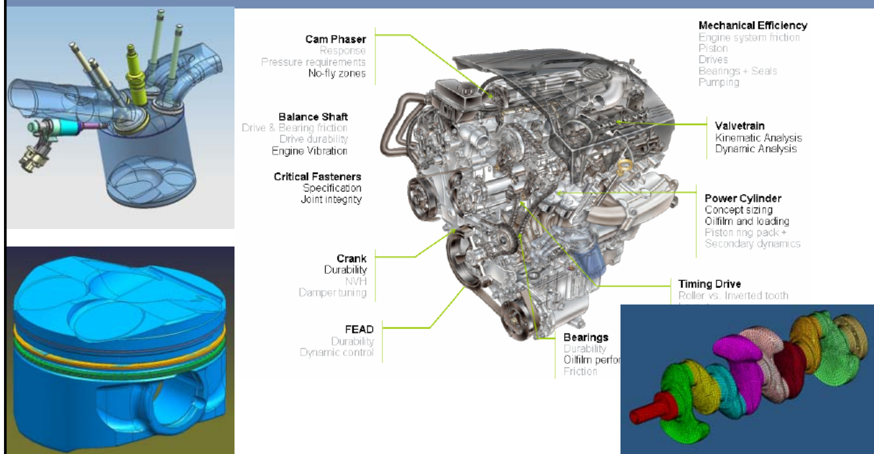
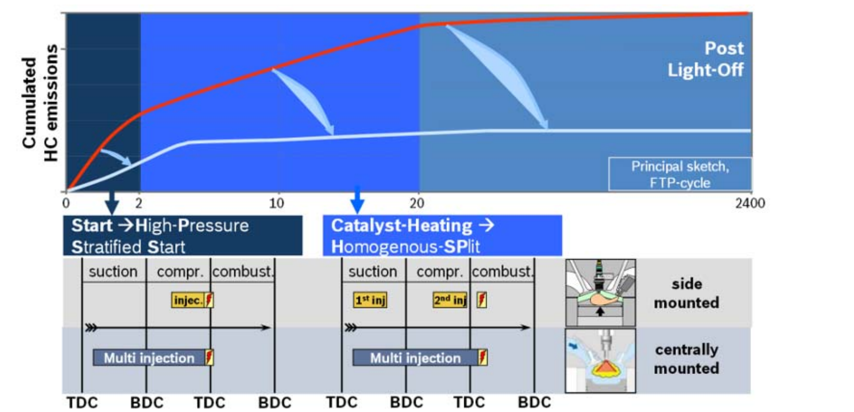
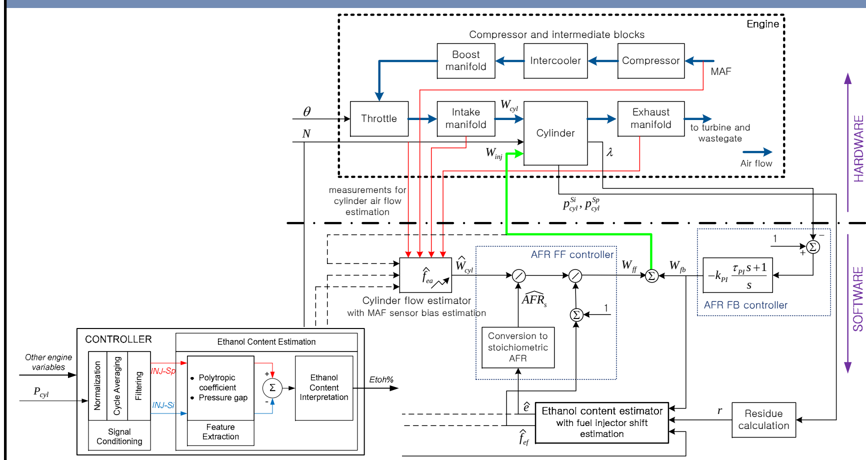
Engine Optimization for Gasoline & Ethanol



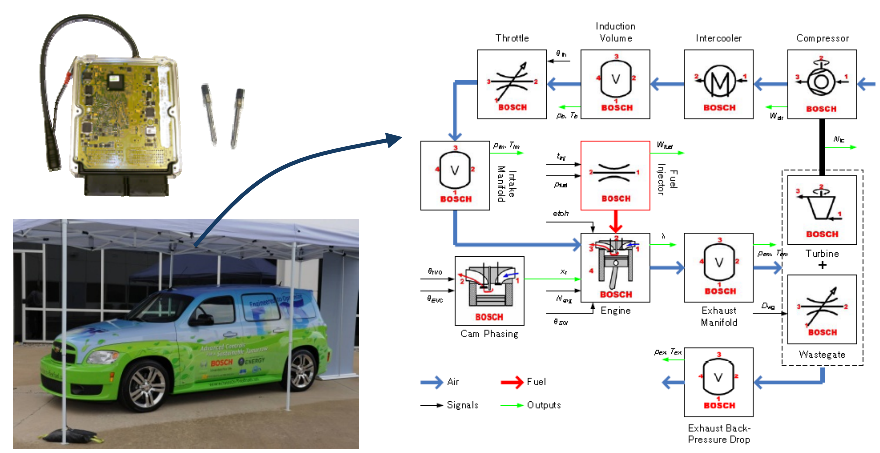
DI System Concept for Emissions



Ethanol Detection via PS-C



Model Based Controls via PS-C



Advanced Flex Fuel Engine Configuration

- **Goal**:
  - Optimized engine design for improved combustion performance
  - Hardware structural robustness for all fuel blends
  - Minimized fuel economy penalty due to increased ethanol content
  - Enhanced performance through exploitation of fuel properties

- **Barriers**:
  - Engine hardware
    - peak cylinder pressure capability restricts E85 performance
    - volumetric compression optimized for gasoline only
    - additional NVH measures necessary for E85 combustion
  - Engine management system
    - Fuel system pressure not sufficient for high ethanol content
    - Injection dynamic flow rate optimized for gasoline
    - Boost / VVT systems require optimization for ethanol

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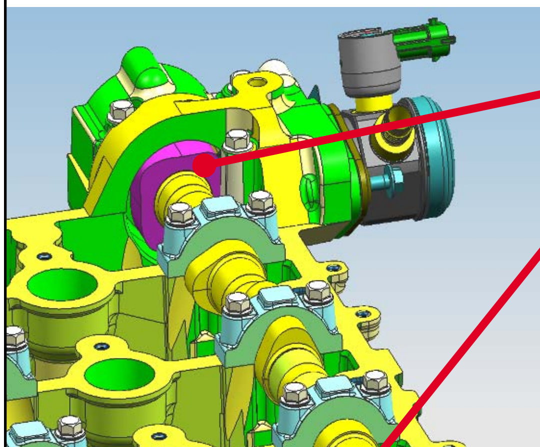
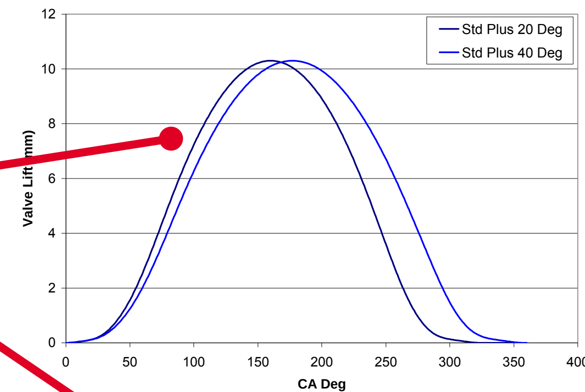
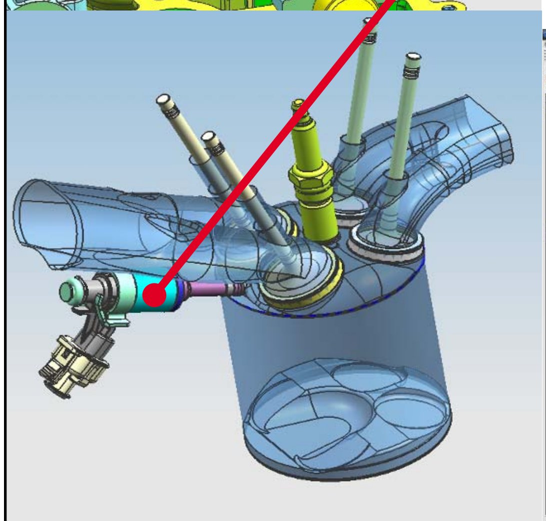
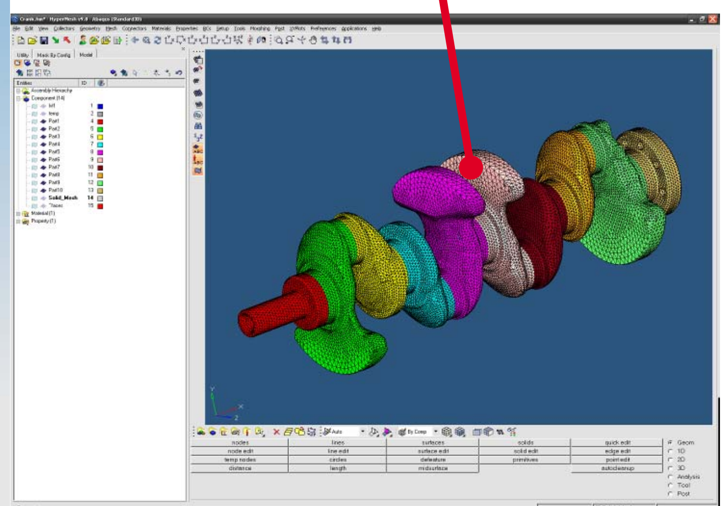
Advanced Flex Fuel Engine Configuration

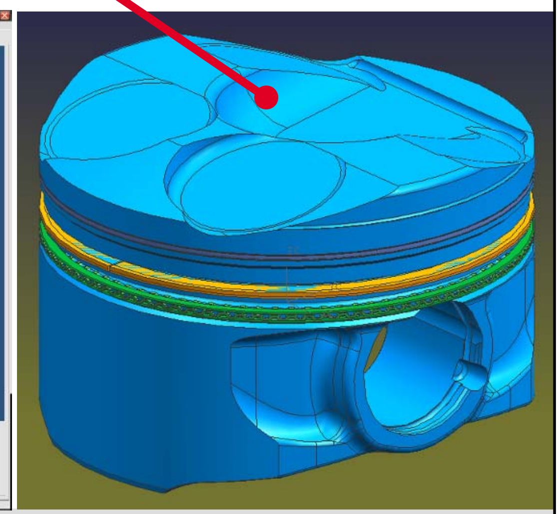


- Larger Fuel Pump
- Revised Fuel Spray
- Late Intake Valve Closing
- High Compression Ratio
- Revised Piston Bowl
- 130 Bar Pmax



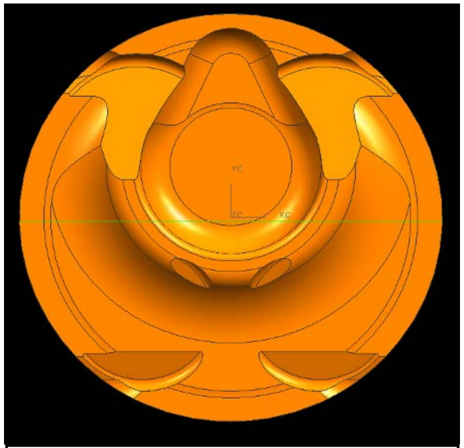






Advanced Flex Fuel Engine Configuration

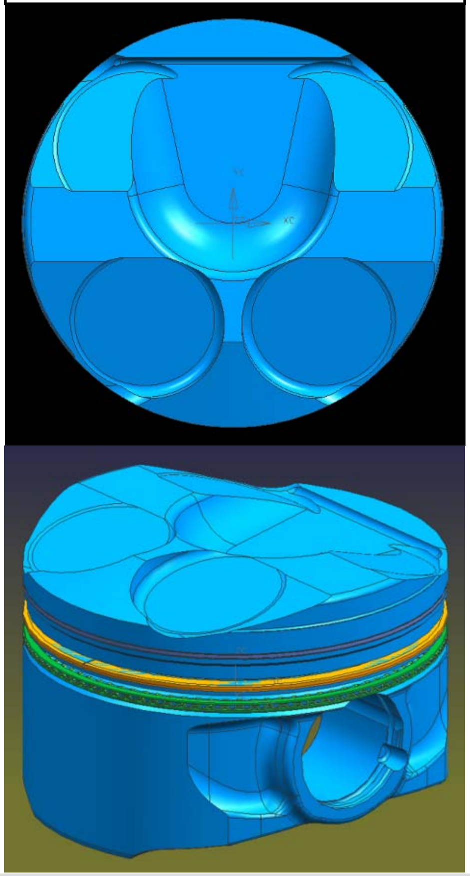
- **Approach:** Engine Design Optimization
  - Increased compression ratio: 9.25:1 → 10.7:1



Ecotec LNF Design

Flex-Fuel Optimized Design

Flex-Fuel Optimized Design



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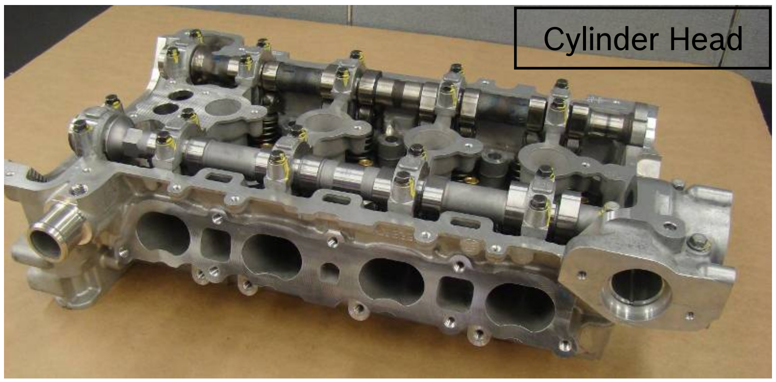
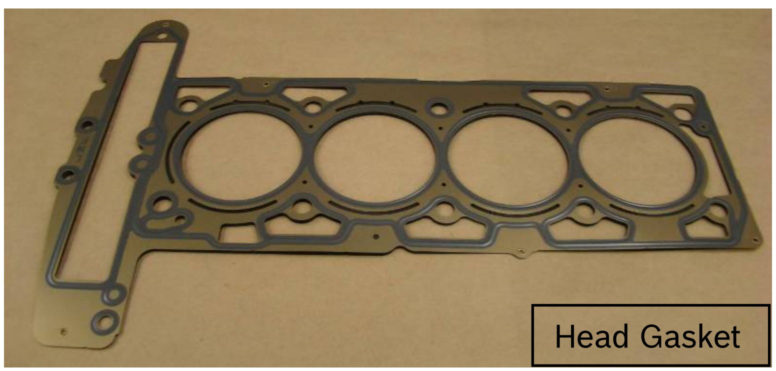
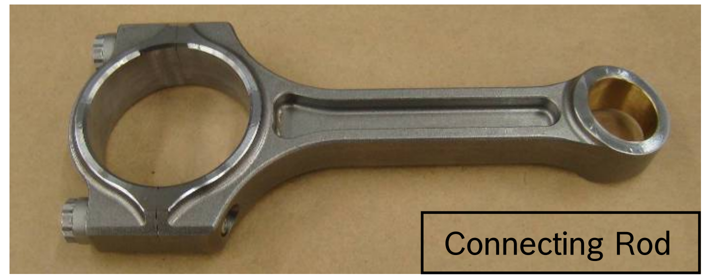
Advanced Flex Fuel Engine Configuration

➔ **Approach:** Engine Design Optimization
- Increased maximum cylinder pressure: 100bar → 130bar


Cylinder Head


Head Gasket


Connecting Rod


Rod Bearings


Crank Damper Washer


Piston Pin

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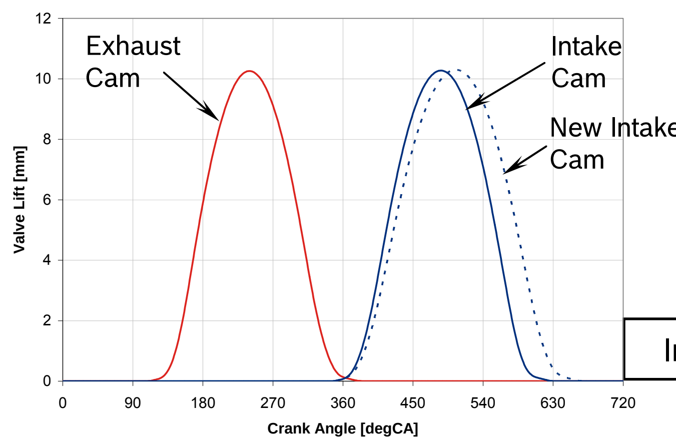
Advanced Flex Fuel Engine Configuration

- **Approach:** Engine Design Optimization
  - Late Intake Valve Closing (LIVC) strategy
    - intake cam profile with extended open duration of 37degCA
    - intake cam phaser with increased authority of 60degCA

Intake Cam Phaser

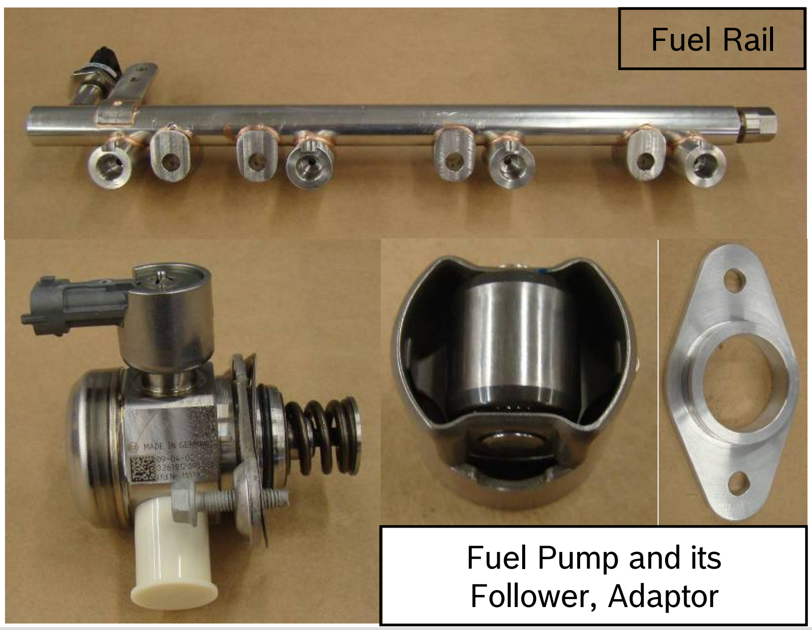
Intake Camshaft

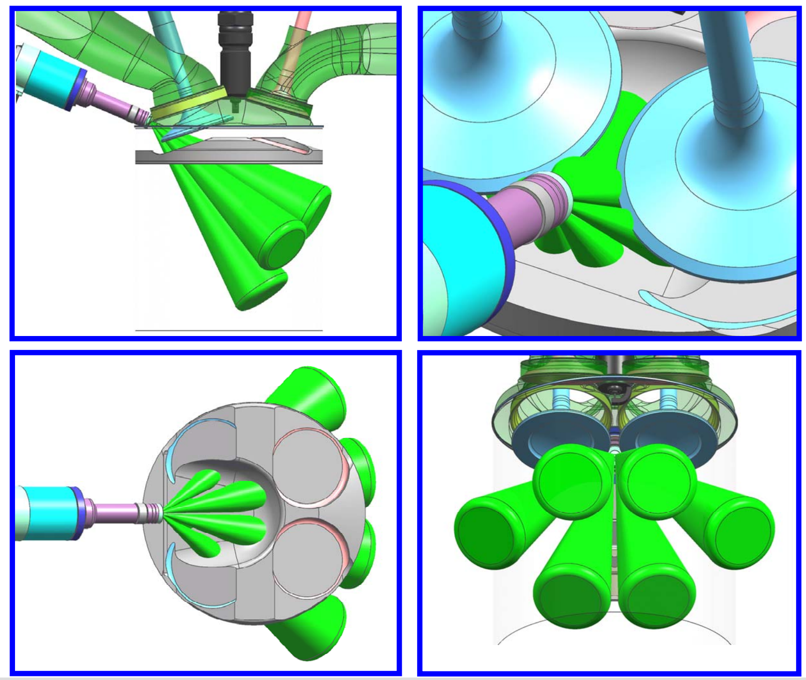


Intake Cam Profile

Advanced Flex Fuel Engine Configuration

- **Approach:** Fuel System Adaptation
  - Increased operating pressure in the direct injection system: 150bar → 200bar
  - Increased capability in the fuel pump: 3-lobe, 0.9cc/rev → 4-lobe, 1.1cc/rev
  - Decreased fuel rail volume: 135cc → 66cc
  - Optimized spray pattern





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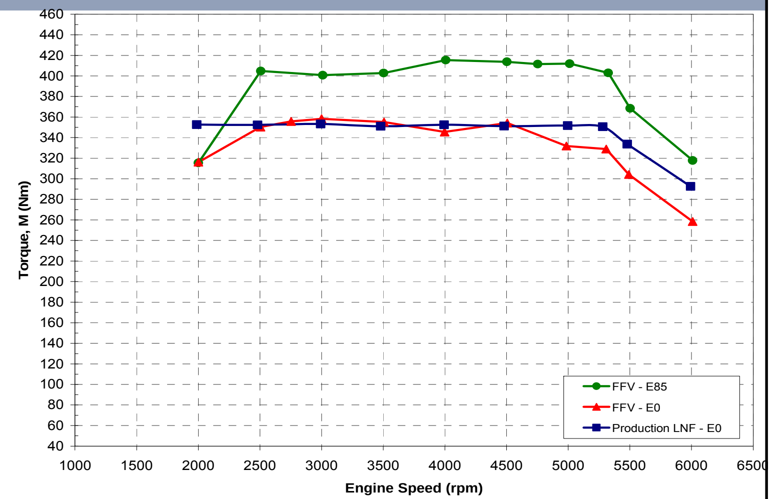
Advanced Flex Fuel Engine Configuration

- **Conclusions**: Fuel Efficiency Improvement
  - Increased compression ratio + LIVC
  - Advanced multi-variable calibration
  - Optimized transmission shift pattern
  - Optimized final drive ratio

	Fuel	FTP Fuel Economy [mpg]		Delta	Highway Cycle Fuel Economy [mpg]		Delta
		2.9 FDR*	4.05 FDR*		2.9 FDR*	4.05 FDR*	
FFV	E85	21.59	19.37	10.3%	32.36	28.47	12.0%
FFV	E0	29.83	27.02	9.4%	44.62	39.62	11.2%



		2008 HHR SS (LNF) Published Data E0	LNF E85/E0	FFV E85	FFV E0
Final Drive Ratio	--	4.05	2.90	2.90	2.90
0-30 mph	s		3.07	2.96	3.38
0-60 mph	s	6.2	6.75	6.13	7.16
0-100 mph	s	15.1	16.00	13.87	16.82
1/4 mile	s	14.8	15.18	14.63	15.61
1/4 mile	mph	99	97.65	102.74	96.50
Max. Power	HP	260	256	300	234
Max. Torque	ft-lbs	260	260	307	264

Emission Concept

- **Goal**:
  - Achieve ULEV emission levels with all fuel blends E0..E85
  - Define potential path to reach SULEV
  - Optimized combustion design for different fuels
  - No additional after-treatment system complexity

- **Barriers**:
  - Cold starts with E85
    - significantly higher ethanol injection quantity resulting in increased HC
    - delayed catalyst heating due to higher water concentration
  - Increased wall wetting and oil contamination with increased ethanol content
    - increased HC emissions and smoke

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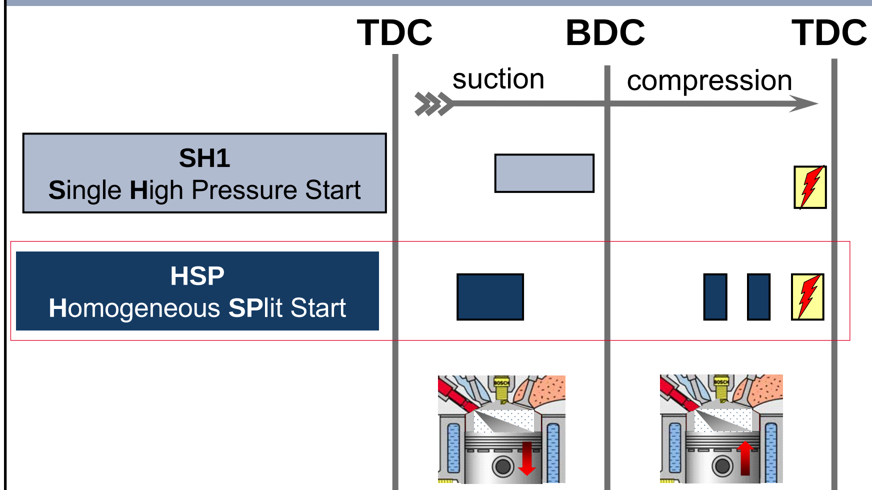
Cold Start Strategy

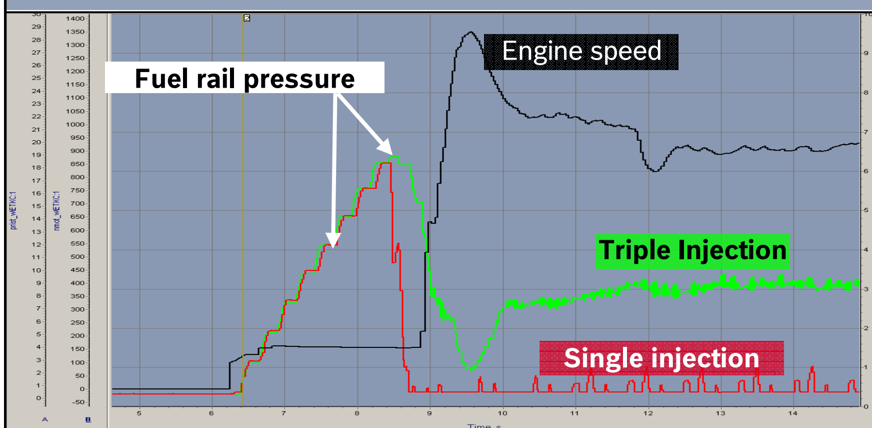


Platform

- 2.0L Turbo DI (LNF)
- ECU MED17 Platform
- E85 Class III Fuel (E70)
- 3 lobe HP pump

MY09 Chevy HHR Turbo

Results



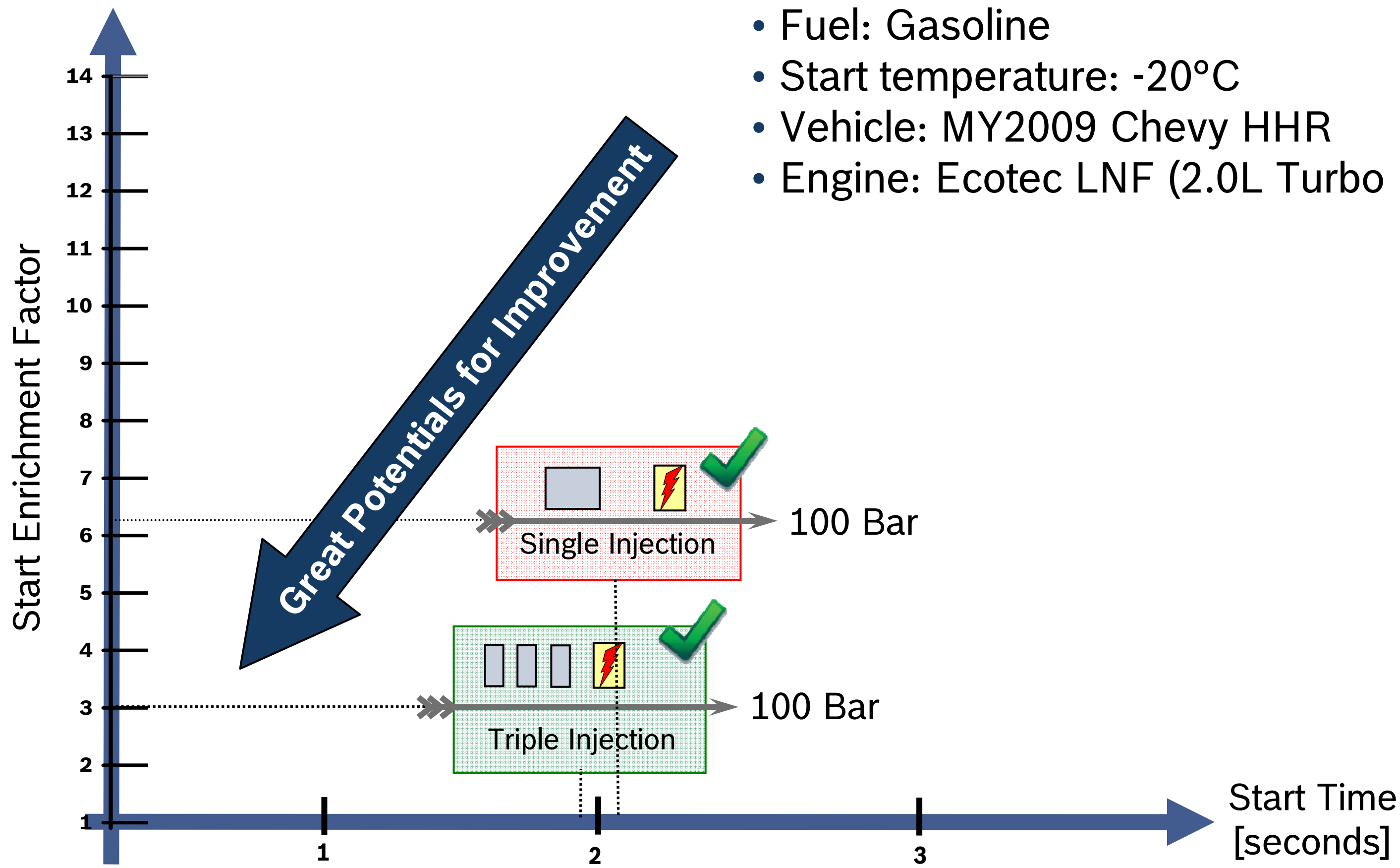
Conclusion

<u>Start Pressure</u>	<u>→ 180 Bar</u>	<u>100 Bar</u>
Start	→ ✔	✔
Temperature	→ -20°C	-20°C
Start Time	→ 3 sec	1.8 sec
Start Fuel Factor	→ 4.2 (same as E0 single injection)	5.3

Cold Start Strategy

→ **Results:** Multiple Injection Strategy at Cold Start

- Fuel: Gasoline
- Start temperature: -20°C
- Vehicle: MY2009 Chevy HHR
- Engine: Ecotec LNF (2.0L Turbo DI)



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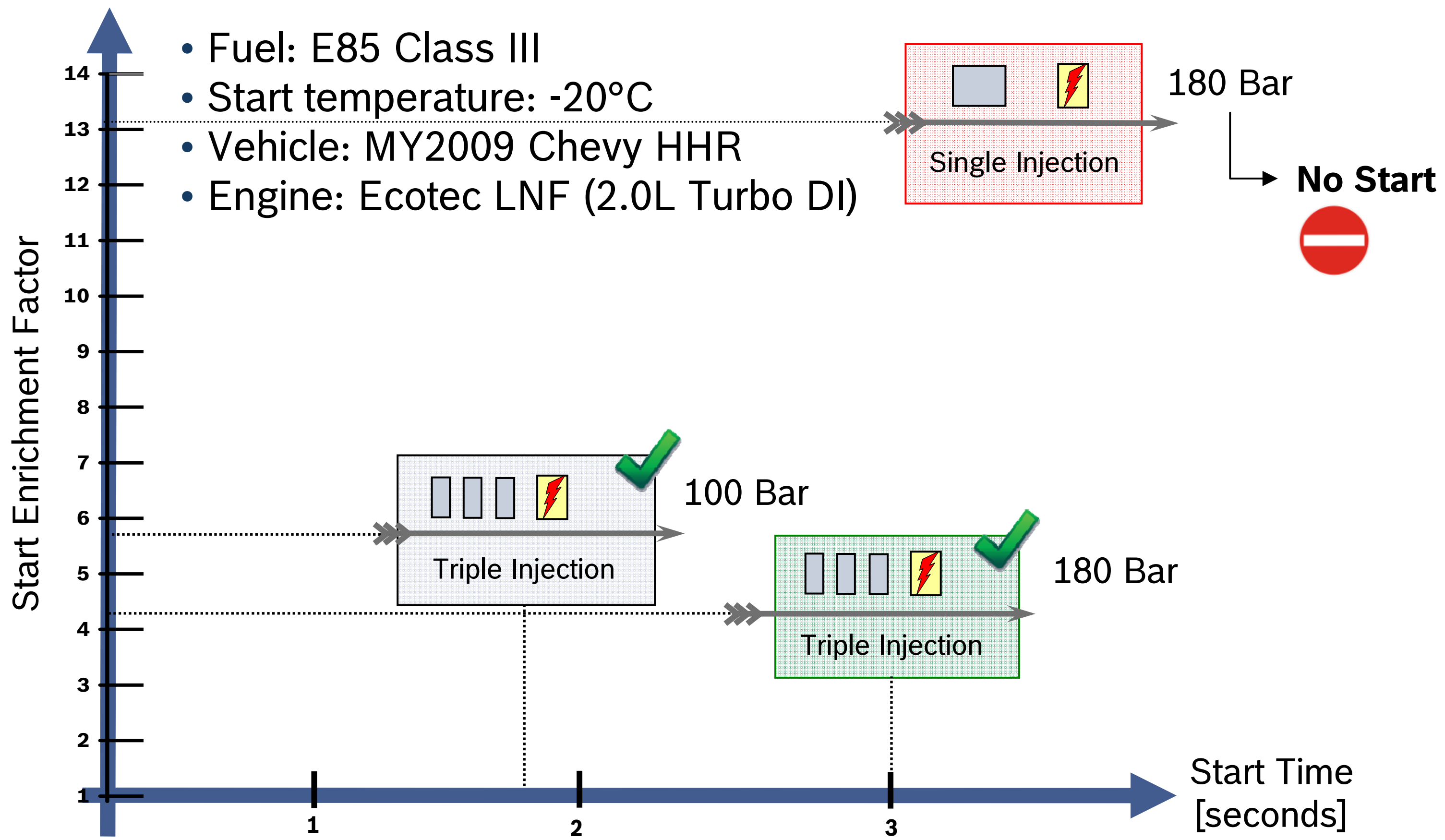
Cold Start Strategy

→ **Results:** Multiple Injection Strategy at Cold Start

- Fuel: E85 Class III
- Start temperature: -20°C
- Vehicle: MY2009 Chevy HHR
- Engine: Ecotec LNF (2.0L Turbo DI)



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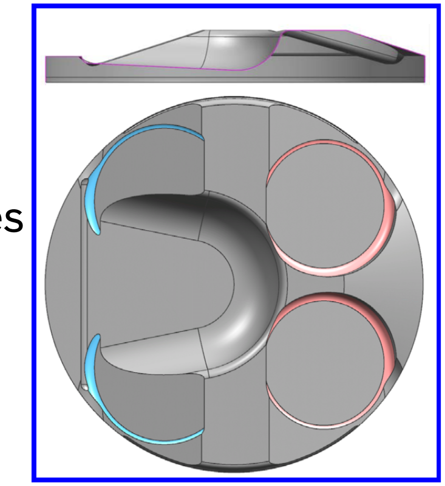
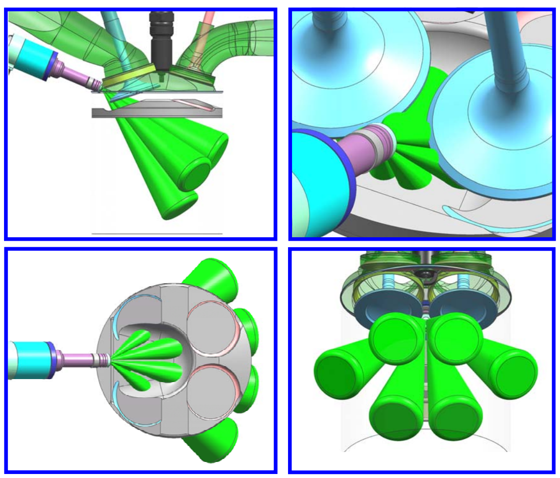
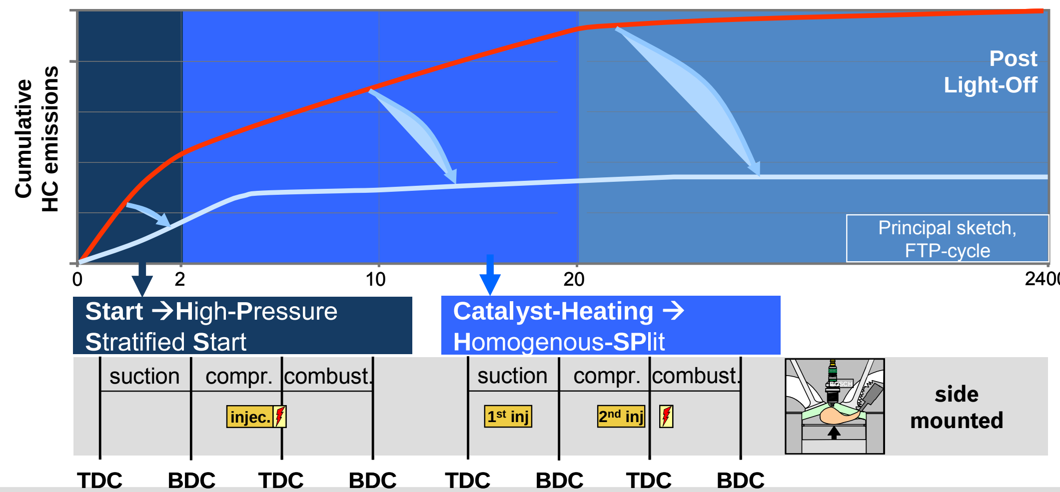
Emission Concept

- **Approach:** Piston Bowl Design for HC Reduction
  - Increased bowl width for improved air/fuel mixture
  - Optimized fuel spray deflection angles
  - Smoother surface transitions & decreased crevice volumes
- **Approach:** Injector Design and Injection Strategies
  - Spray targeting for fuel mixture preparation
  - High Pressure Stratified Start
  - Homogenous Split Injection for Catalyst Heating







Emission Concept

Conclusion:

- ULEV level Emissions reached with NMHC
- SULEV level Emissions reached with CO and NOx

Cat	Test - Fuel	NMHC [g/mile]	CO [g/mile]	NOX [g/mile]	CO2 [g/mile]
SULEV	20C FTP - E0	0.034	0.489	0.028	345
SULEV	20C FTP - E85	0.029	0.246	0.029	349
SULEV	20C FTP - E77	0.021	0.281	0.010	333

	NMHC [g/mile]	CO [g/mile]	NOX [g/mile]
California ULEV Standard	0.055	2.10	0.070
California SULEV Standard	0.010	1	0.02

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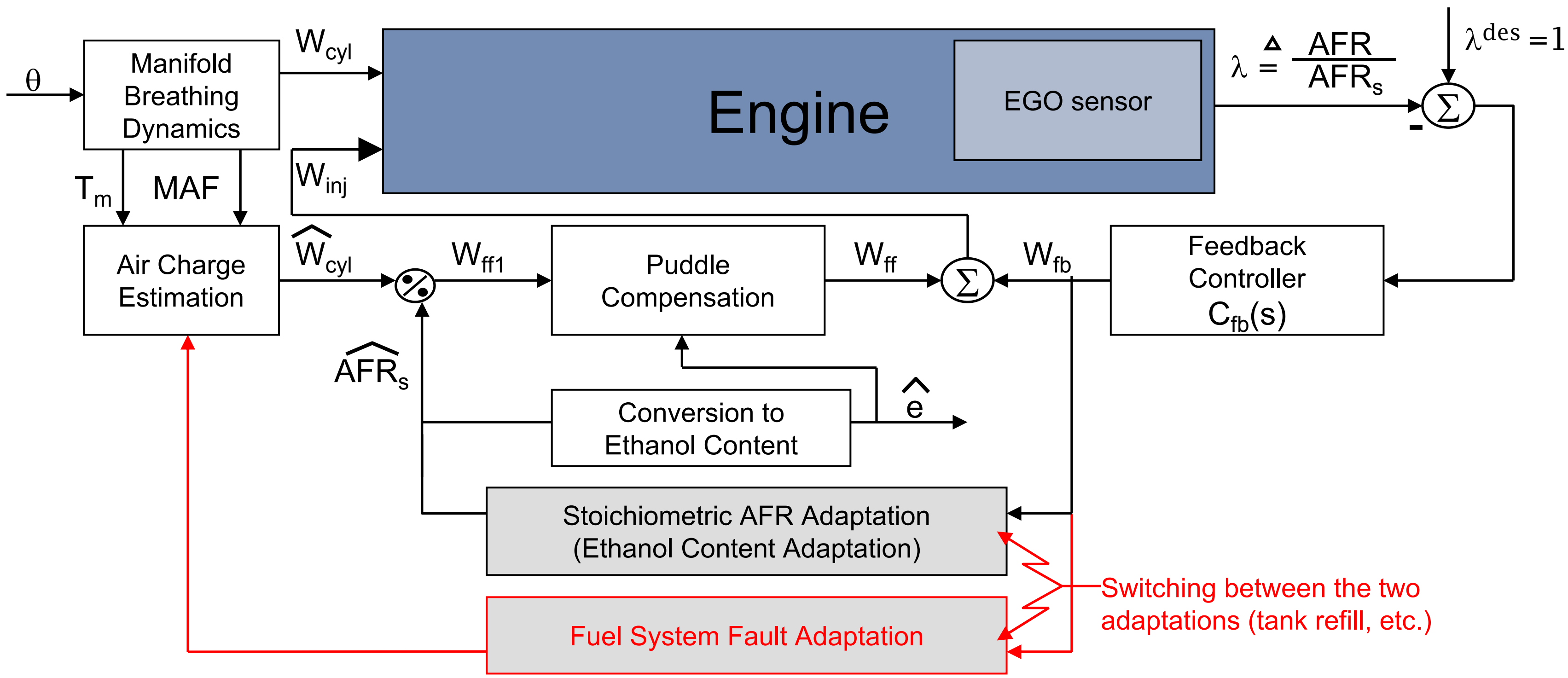
Ethanol Detection Strategy

- **Goal**:
  - Develop a systematic approach to achieve an accurate, robust, and fast ethanol content estimation for engine performance optimization, even in the presence of component aging and sensor drifts

- **Barriers**:
  - Direct measurement from Ethanol sensor on fuel line
    - ✗ additional cost and system complexity
  - Indirect estimation by Exhaust Gas Oxygen (EGO) sensor
    - ✗ sensitive to mass airflow sensor drift and fuel system failures
    - ✗ requires coordination of fuel system and ethanol content adaptation
  - Indirect estimation by Cylinder Pressure Sensor (PS-C):
    - ✗ robustness and accuracy has not been addressed for combustion and heat release based detection

Ethanol Detection Strategy

- **Approach:** Ethanol Detection via A/F Ratio using EGO sensor
  - Ethanol content and fuel system fault adaptation depends on the same λ signal
  - Error accumulates in estimated ethanol content due to the switching approach

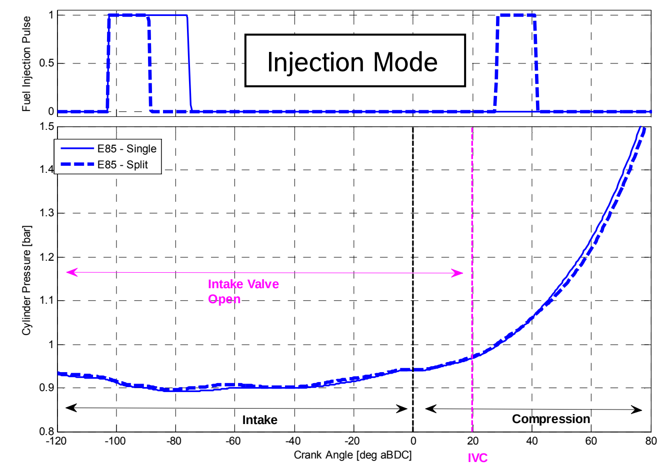


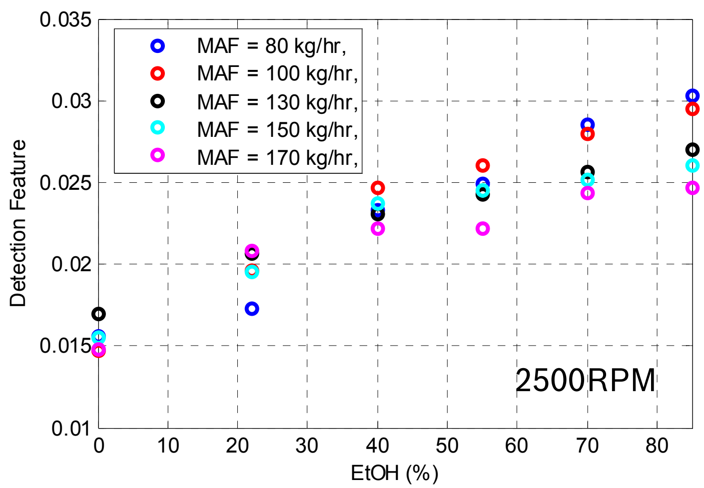
Ethanol Detection Strategy

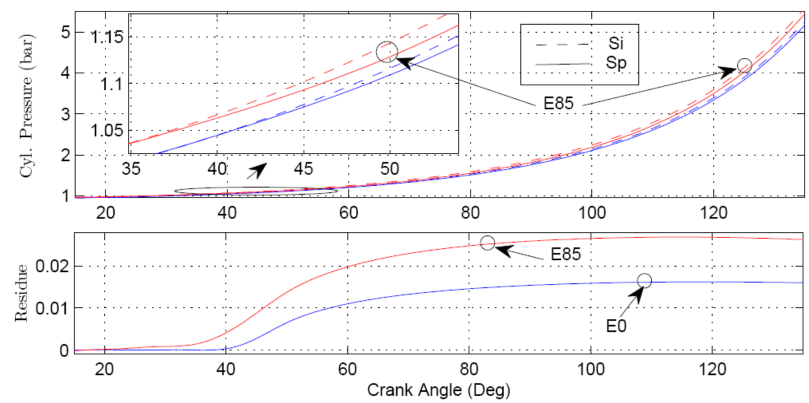
- **Approach**: Latent Heat of Vaporization (LHV) Based Features
- Injection Mode: switching between Single and Split injections
- Extracted Features
  - Residue: $Rsd(k) = \ln(p_0^{Si}(k)/p_0^{Sp}(k))$
  - Detection Feature:

$$r_{LHV} = \frac{\sum_{k=k_1}^{k_2} Rsd(k)}{k_2 - k_1 + 1}$$

  - Principles: Charge cooling effects, captured by r_{LHV}, increases with ethanol fuel content

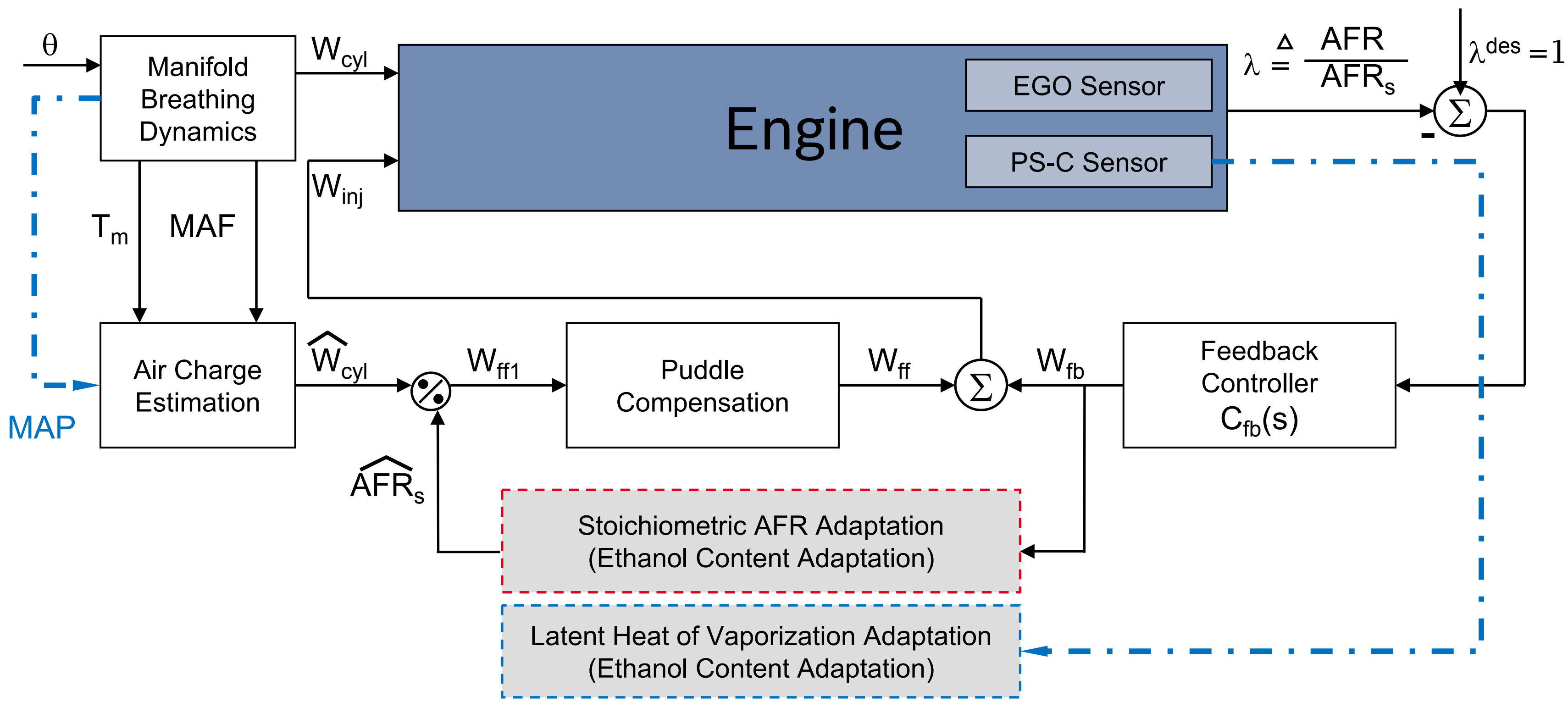






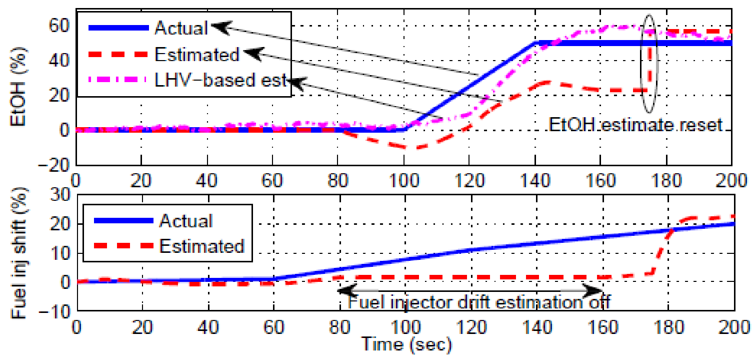
Ethanol Detection Strategy

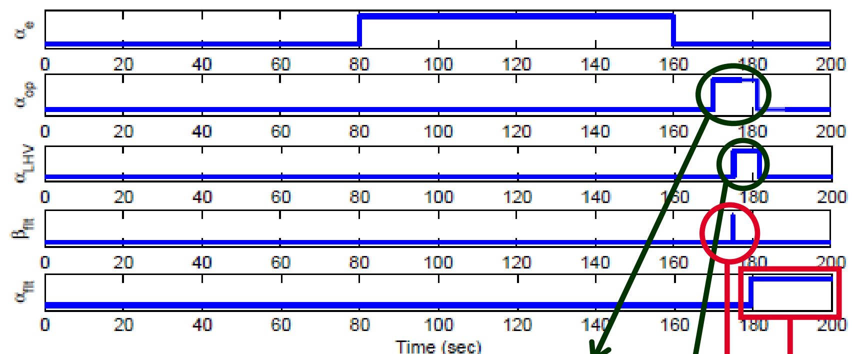
- **Approach**: Ethanol Detection using AFR and LHV Based Features
  - MAF Sensor Error: Estimated MAF using Manifold Absolute Pressure (MAP) Sensor
  - Fuel Injector Drift: Estimated EtOH using Cylinder Pressure Sensor

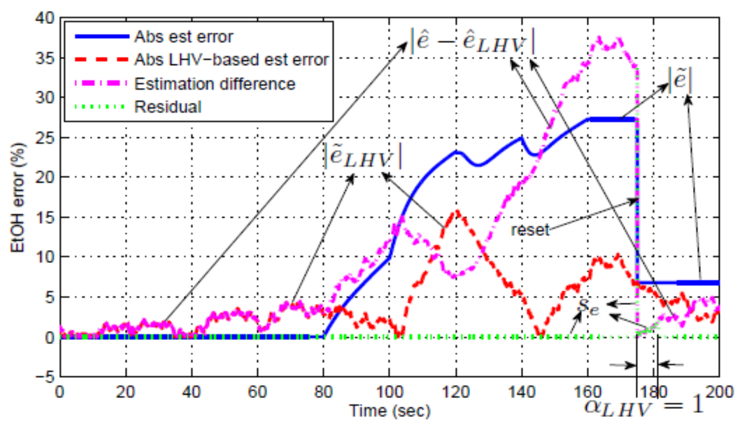


Ethanol Detection Strategy

- **Results**: Ethanol Detection using LHV and AFR Based Features
  - Simulated Case: MAF sensor bias (5%) + fuel ethanol content change (0 → 50EtOH%) + fuel injector drift (0 → 20%) under varying engine operation conditions







Current operation point is within the identified regime for generating LH V-based detection features

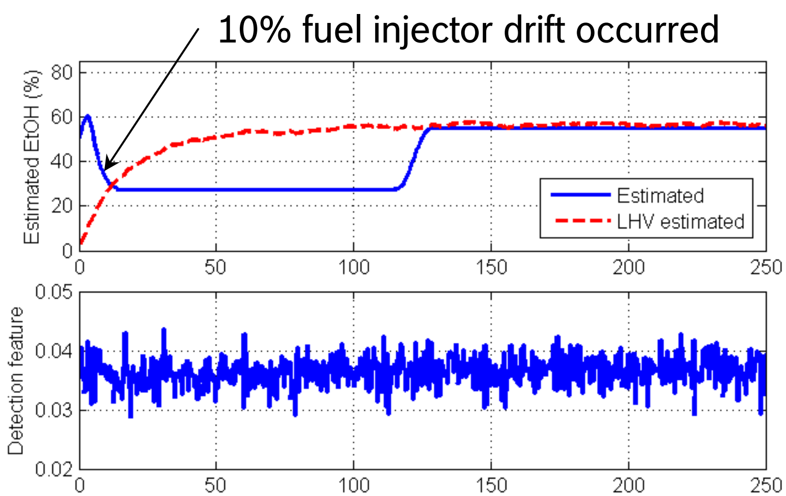
The generated LHV-based feature is reliable for ethanol content adaptation

Reset triggered

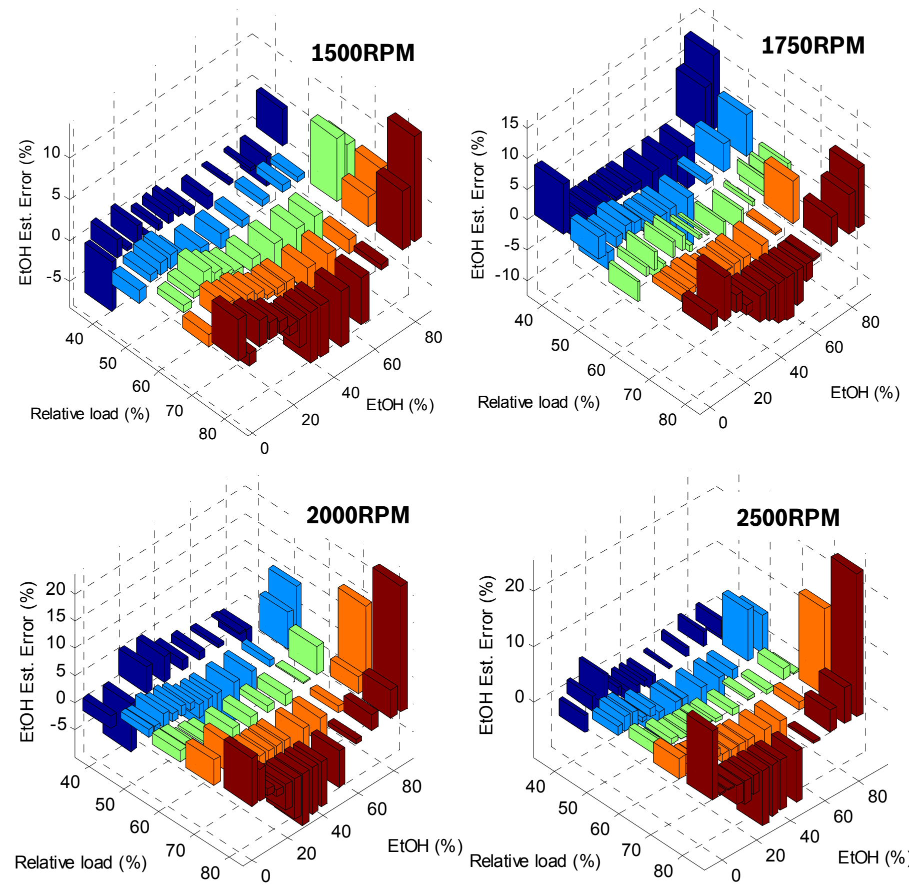
Fuel injector fault reported

Ethanol Detection Strategy

- **Experimental Results**:
  - Steady-State Estimation: frequently visited operation conditions ranging from 1500-2500RPM
  - Simulated Case: 10% fuel injector drift introduced via rapid prototyping at engine dynamometer → detected by the LHV based feature



Steady-State Ethanol Detection



Control Strategy

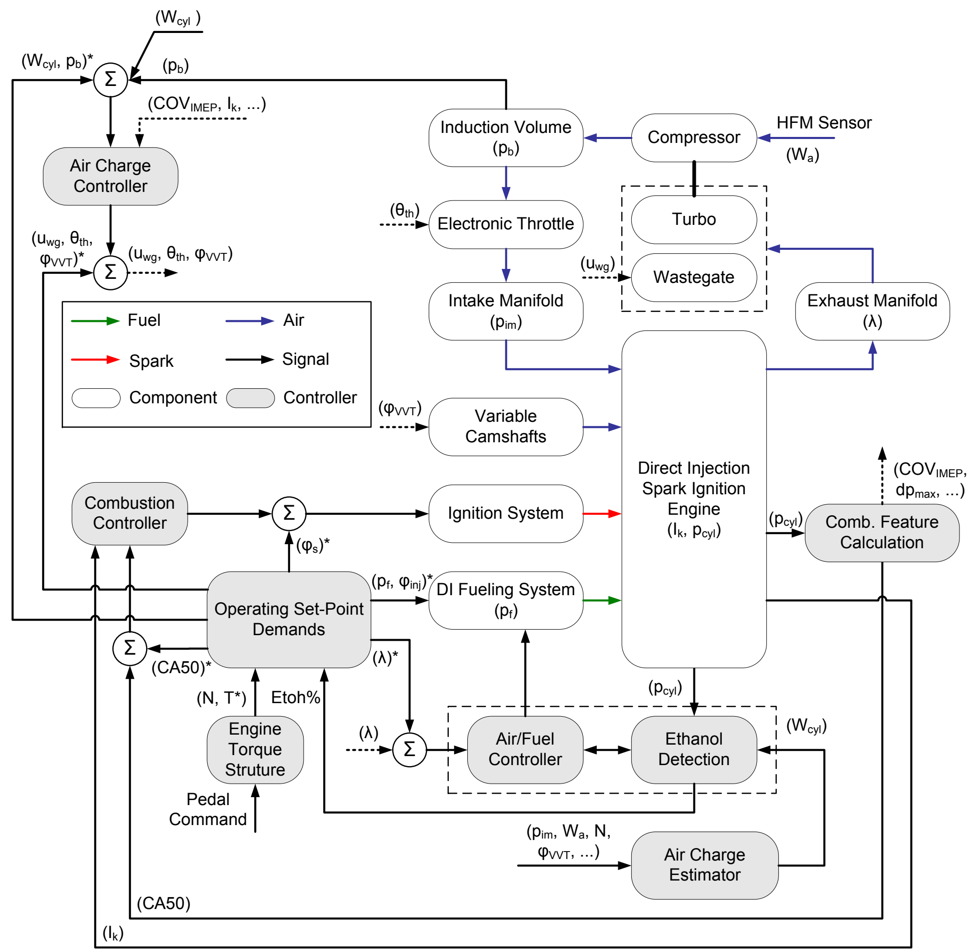
- **Goal**:
  - Optimized engine controls for all fuel blends
  - Robust and fast adaptation of engine control parameters
  - Minimum additional calibration effort

- **Barriers**:
  - Current engine controllers adjust the spark and fuel injection timing, variable valve timing and boost in a feed-forward manner
    - ✗ significant additional calibration efforts for different fuel blends
    - ✗ deviation from optimal calibration due to interpolation inaccuracies
    - ✗ lack of coordinated control of air path during speed/load transients

Control Strategy

➔ **Approach:**

- Closed-loop combustion control via spark angle using cylinder pressure feedback
- Optimize set-point values of key engine control variables (e.g. spark angle, VVT) to adapt ethanol combustion



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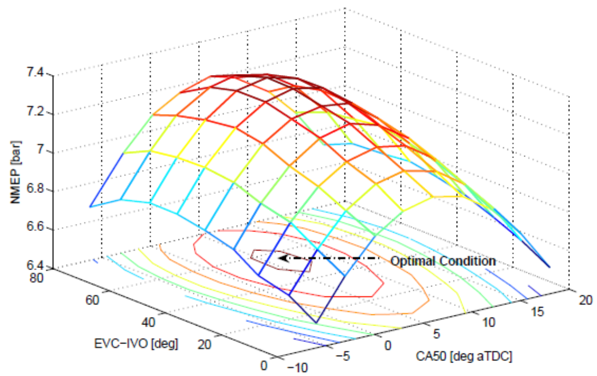
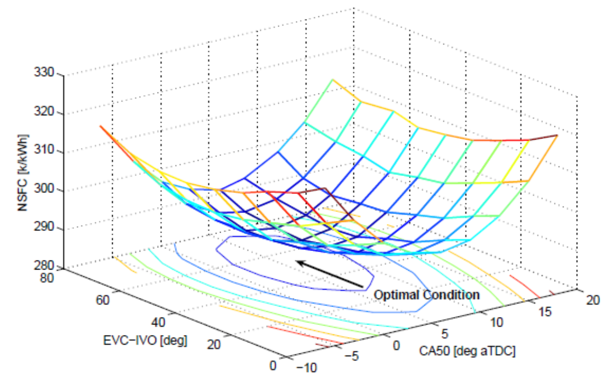
Control Strategy

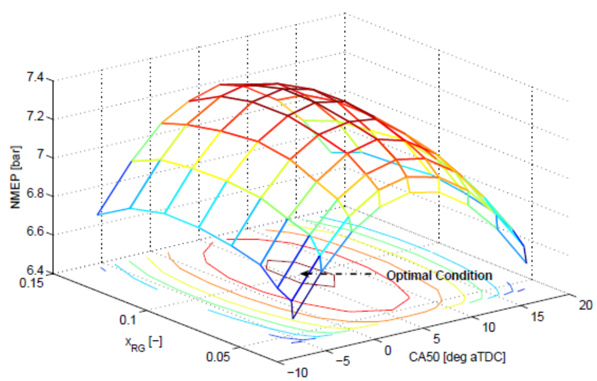
➔ **Result:** Engine Air/Fuel Path Dynamics + Combustion Modeling – Stochastic



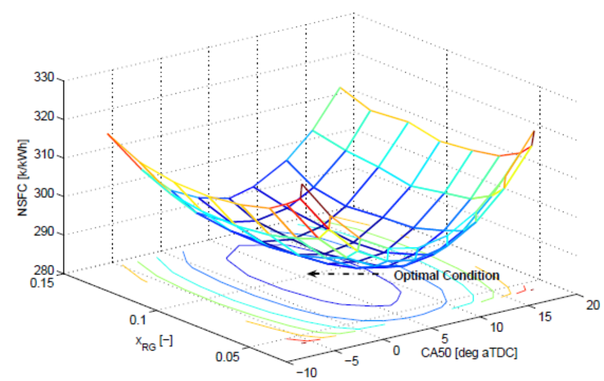
(a) NMEP vs. VVT vs. θ_{CA50}



(b) NSFC vs. VVT vs. θ_{CA50}



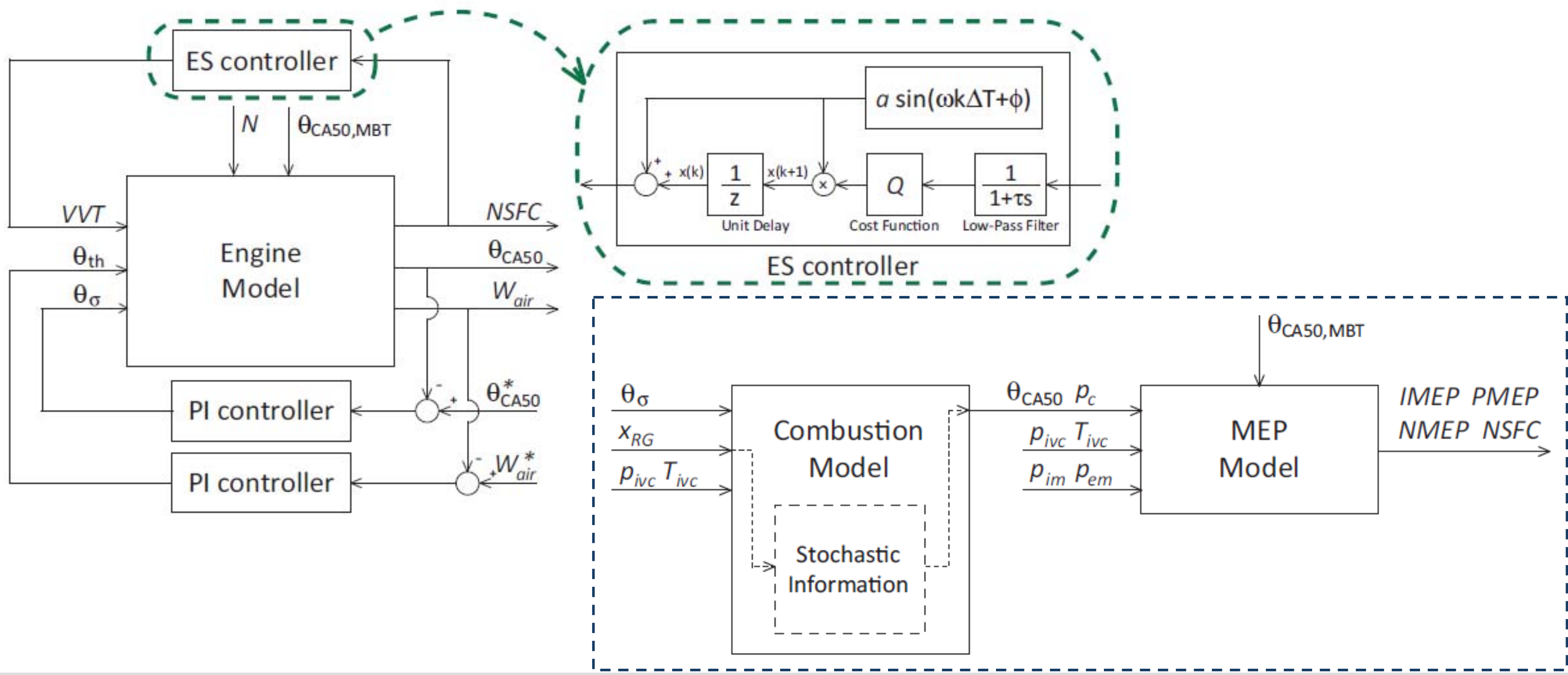
(c) NMEP vs. x_{RG} vs. θ_{CA50}



(d) NSFC vs. x_{RG} vs. θ_{CA50}

Control Strategy

- **Approach:**
  - Closed-Loop Combustion Control Via Spark Advanced using Cylinder Pressure Feedback
  - MBT spark timing optimization for Ethanol Fuels using Extremum Seeking

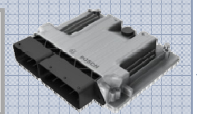


Advanced Flex-Fuel Systems

Advanced Flex Fuel System Configuration

Customized Engine Management (ECU)

- Model based controls
- Fuel property detection

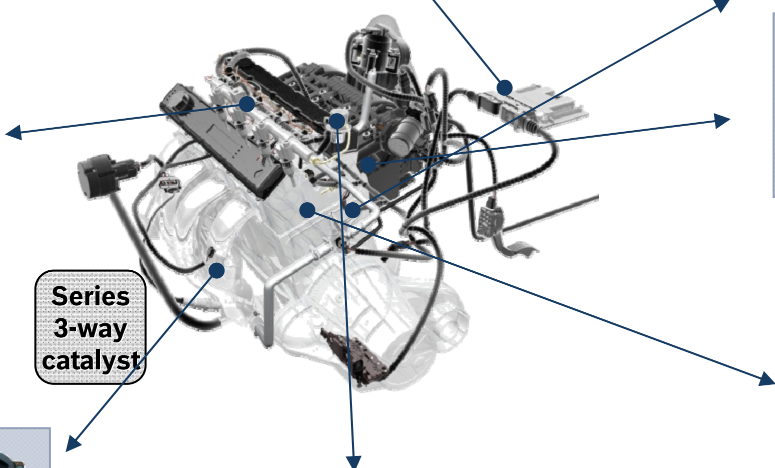


In-Cylinder Pressure Sensing

- Direct combustion feedback
- Ethanol detection

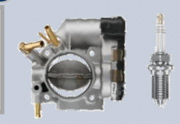
Customized Injection

- Solenoid MHI
- Side/Central mount
- Split injection
- Dynamic flow rate

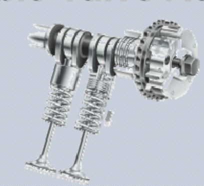


Throttling and Ignition

- High energy coils
- Transient torque



Variable Valve Actuation



- 2xVVT via Cam phasing
- Extended phase authority

Turbo-charging

- Standard turbo charger

High Pressure Pump

- Stainless Steel
- High flow range

BOSCH

Advanced Flex-Fuel Systems

Thank You!