# Optimization of Direct-Injection $H_2$ Combustion Engine Performance, Efficiency, and Emissions

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Project ID: ACE009

# Overview

## Timeline

- Project start: FY2005
- Project end: FY2011

## Barriers

- Lack of understanding of hydrogen as an engine fuel, especially with DI
- Lack of hydrogen simulation tools and durable hydrogen injectors
- Lack of actual emissions data on future combustion engines

## Budget

- Funding in FY10: 500k$
- Funding in FY11: 400k$
- Funding in FY12: N/A

## Partners

- Industrial partners: Ford, Westport
- Collaborators: Sandia and Lawrence Livermore National Laboratories
- International team members: BMW, Graz University of Technology, Ghent University

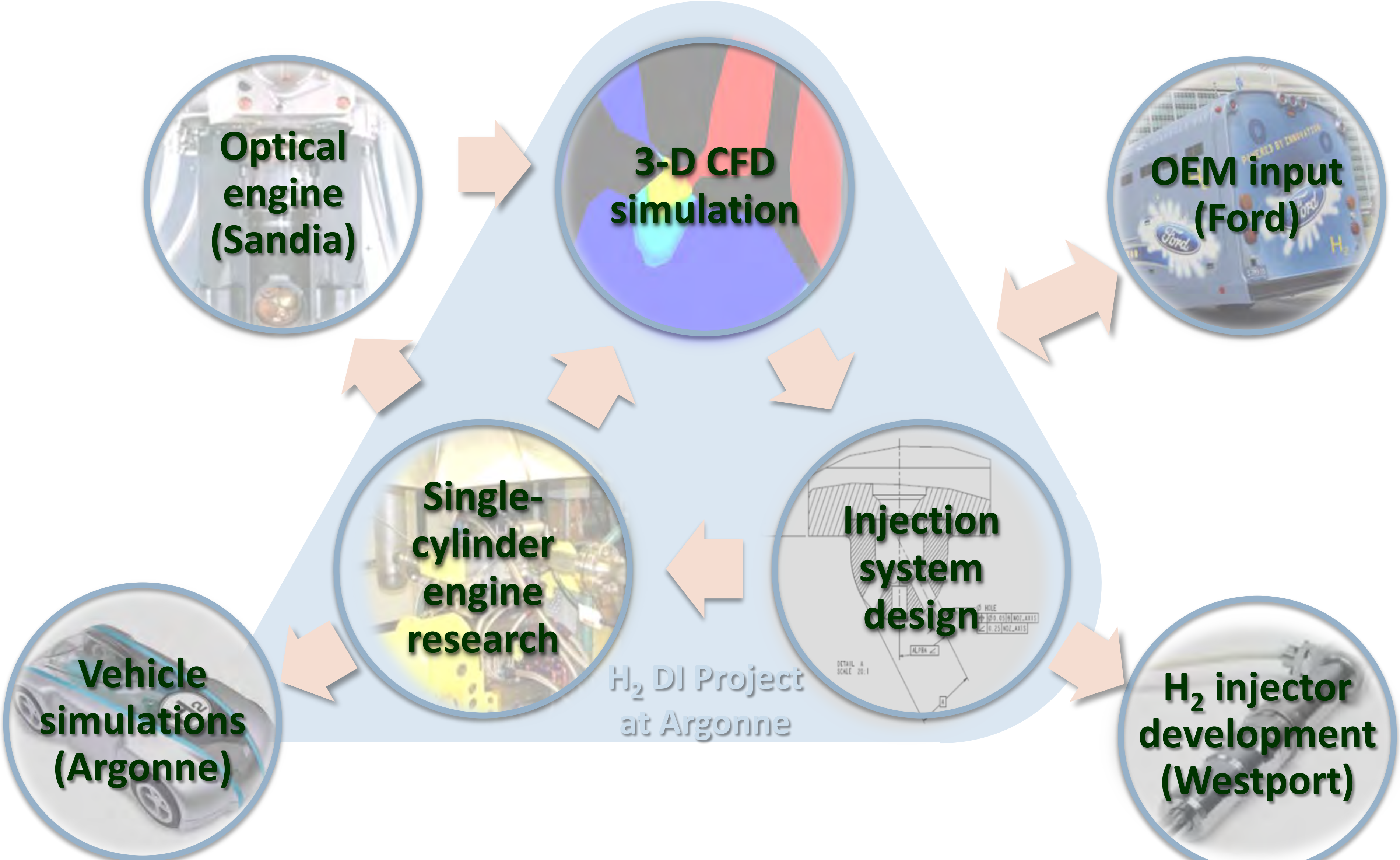
# Objectives – Project relevance

- Provide a clean and efficient, readily available tool for utilization of hydrogen as an energy carrier
- Overcome the trade-off between engine efficiency and NOx emissions in hydrogen direct injection (DI) operation to reach DOEs 2010 efficiency goals (45% peak, 31% at 1500 RPM 2 bar BMEP) with minimal emissions penalty (Tier 2, Bin 5 or better)
- Develop simulation capabilities to predict efficiency potential and emissions of advanced hydrogen combustion systems
- Assess the impact of injector nozzle geometry in combination with injection strategy and develop optimized configurations
- Estimate drive-cycle fuel economy and emissions based on single-cylinder engine efficiency and emissions maps

# Milestones

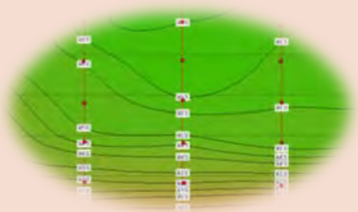
- Improved 3-D CFD simulation results validated against optical results from Sandia National Laboratories (05/2010)
- Advanced nozzles developed using 3-D simulation (07/2010)
- Assessment of advanced injector nozzle designs using experiments and simulation completed (11/2010)
- Full engine mapping and drive-cycle fuel economy and emissions estimates completed with simulated turbocharging (03/2011)
- Next generation of optimized injector nozzles manufactured based on 3-D CFD simulation results (04/2011)
- Further optimized engine efficiency and emissions map available for vehicle level simulations (07/2011)

# Approach – Integration and collaboration

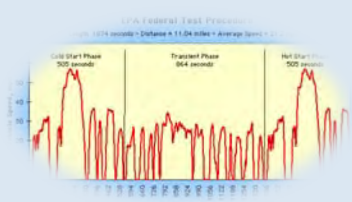


# Technical accomplishments
## Overview

- **Development of efficiency-optimized direct injection combustion system**
  - Application of validated simulation
  - Experimental benchmarking

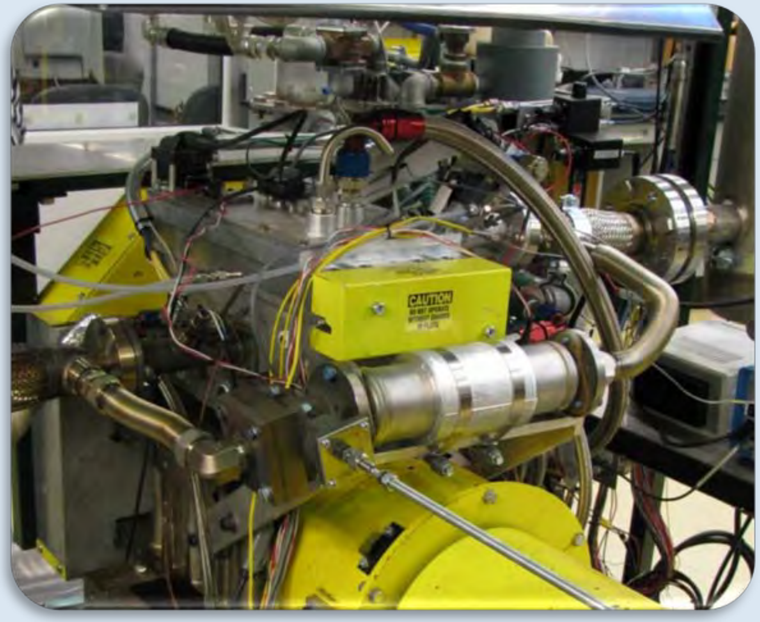


- **Full mapping of optimized $H_2$ DI combustion system**
  - Measurement of single-cylinder maps
  - Development of multi-cylinder maps

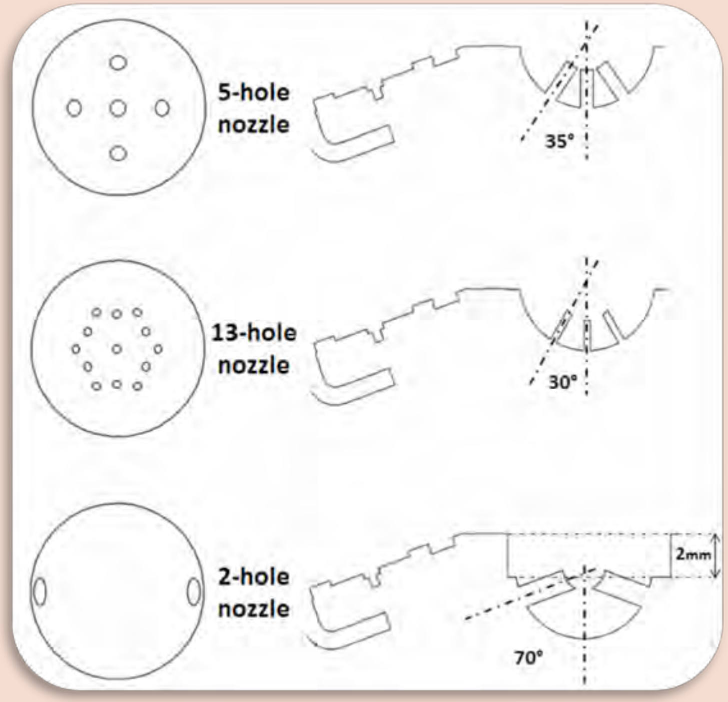


- **Estimation of drive-cycle results**
  - Drive-cycle fuel economy and NOx emissions based on steady-state maps
  - Result assessment versus DOE targets

# Efficiency-optimized combustion system
## Engine and injection system

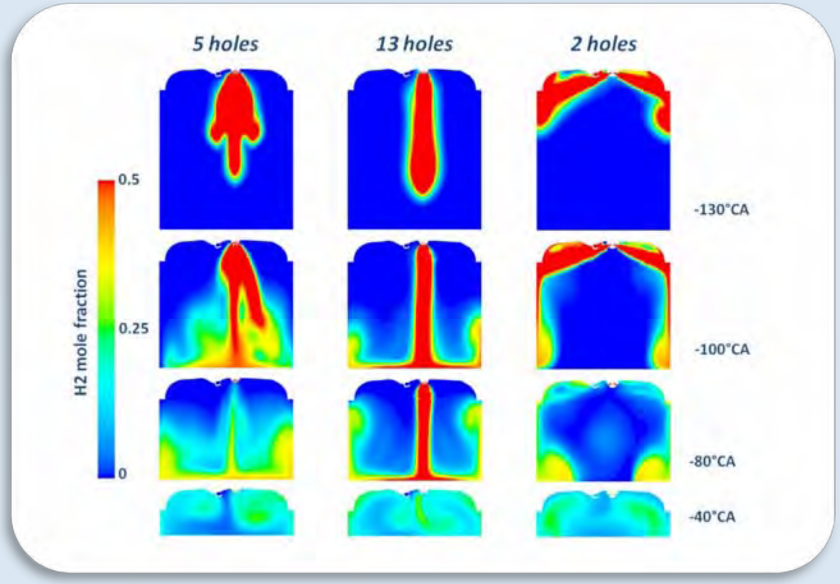


- **Optimized engine geometry**
  - Efficiency-optimized bore/stroke ratio (89 mm/105.8 mm stroke)
  - Increased compression ratio (12.9:1)

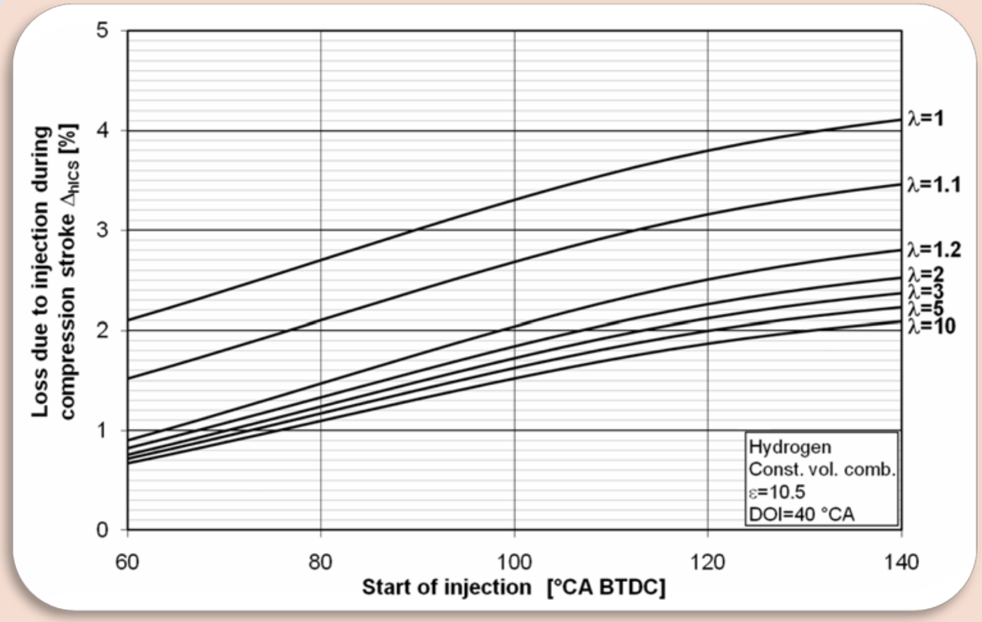



- **Upgraded injection system**
  - Fast-acting Piezo injectors
  - 3D-CFD simulation-aided injection strategy development

# Efficiency-optimized combustion system
## Simulation-guided development

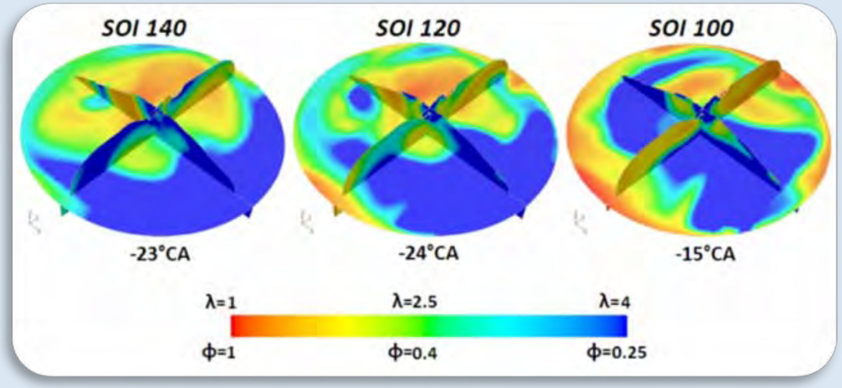



- **Influence of nozzle design**
  - Significantly influences jet penetration pattern and mixture formation
  - Jet-to-jet interaction must be considered

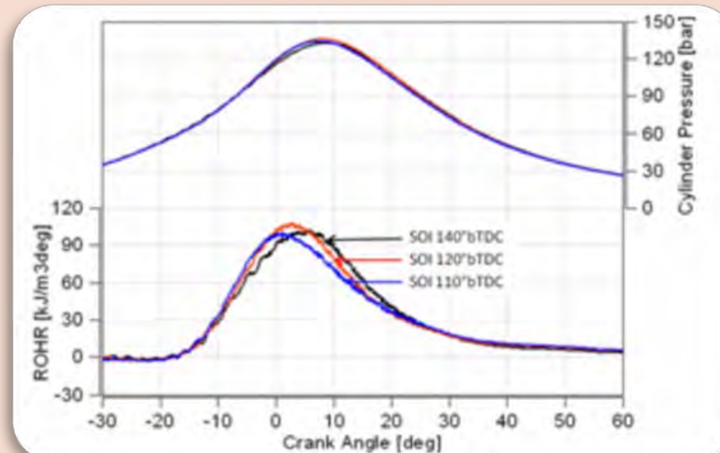



- **Influence of injection strategy**
  - Start of injection (SOI) influences stratification
  - Later injection desirable to reduce compression work

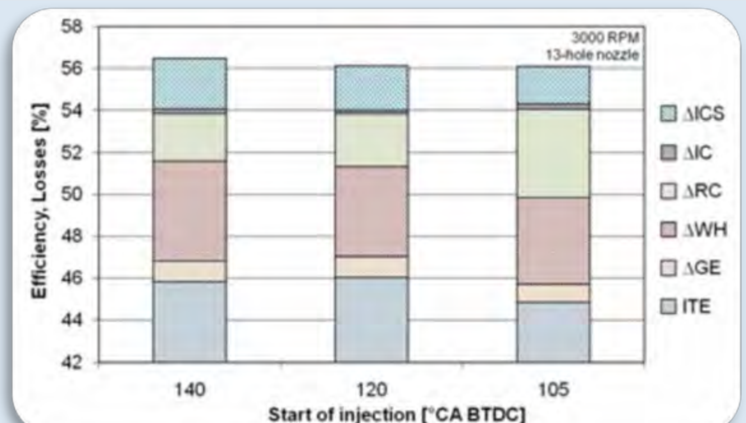
# Efficiency-optimized combustion system
## Experimental/analytical assessment




- **3D-CFD simulation provides**
  - Details on mixture distribution
  - Information on ignitability

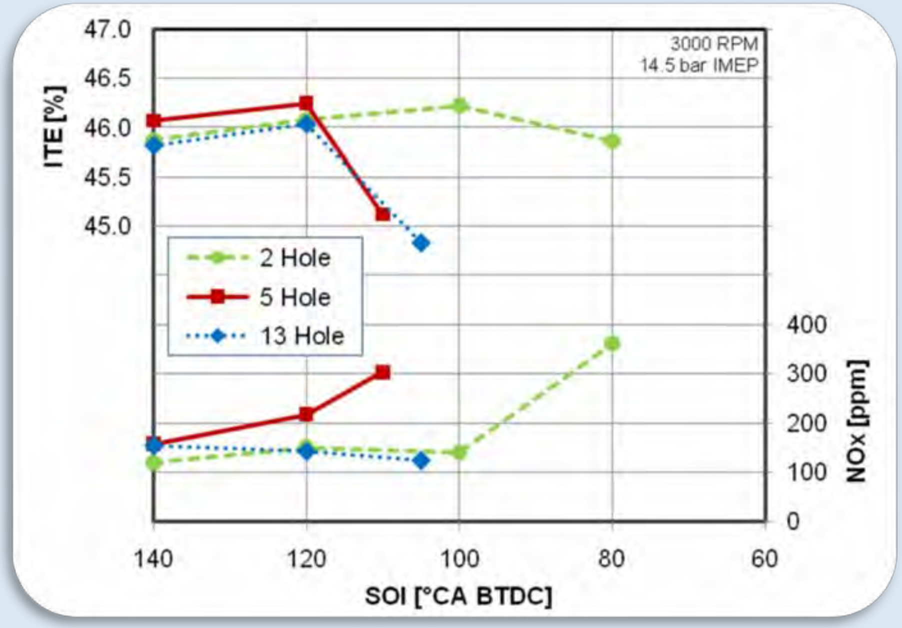



- **Experiments provide**
  - Pressure traces and related info
  - Fuel consumption information



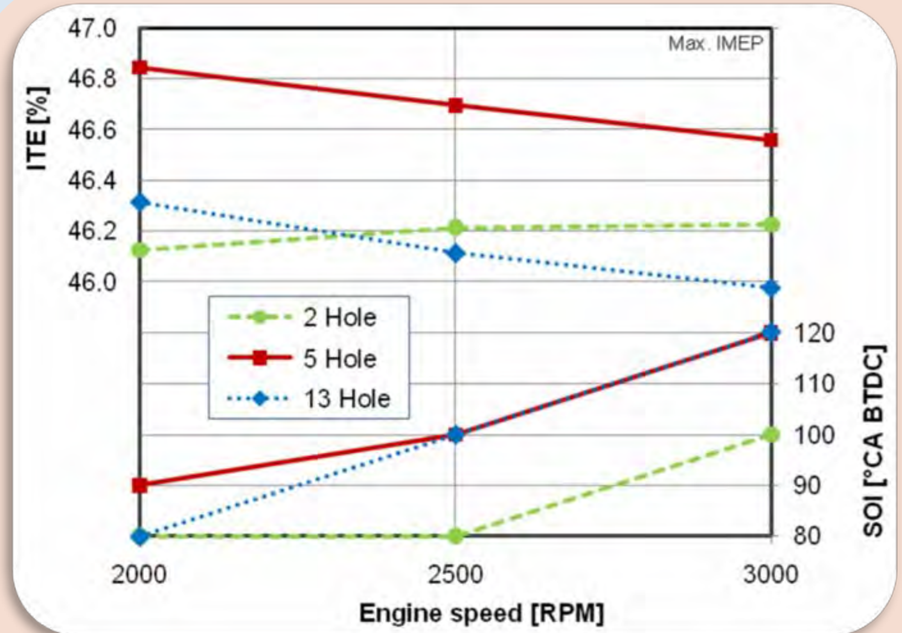

- **Loss analysis provides**
  - Information on individual losses
  - Details on areas for improvement

# Efficiency-optimized combustion system
## Experimental/analytical assessment




- **Nozzle design influences**
  - Peak efficiency
  - Combustion stability at later SOI
  - NOx emissions

- **Lower engine speed**
  - Enables later SOI
  - Increases efficiencies (5 and 13-hole nozzle)



# Conclusions for efficiency optimization
## Major influencing factors

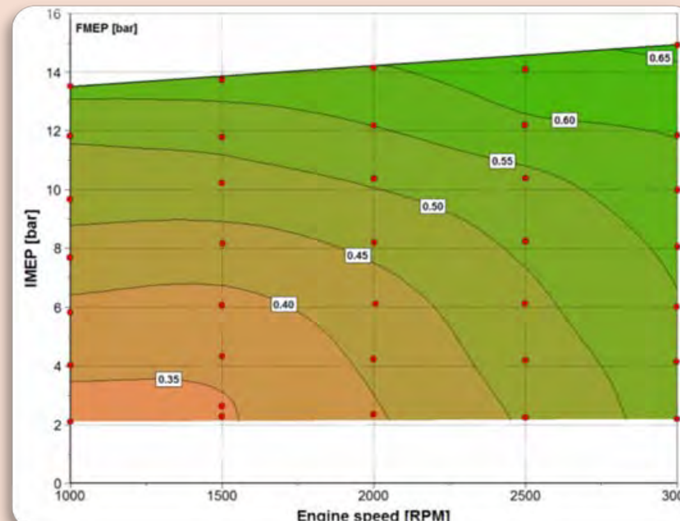
- **Engine geometry**
  - Increased compression ratio (high knock resistance with lean mixtures)
  - Increased engine stroke (higher flame speeds, reduced quenching distance)
- **Injection system**
  - Delayed **S**tart **O**f **I**njection (reduced compression work)
  - Optimized injector nozzle (influenced by geometry and SOI)
- **In-cylinder temperature reduction measures (optional)**
  - Exhaust gas recirculation
  - Water injection

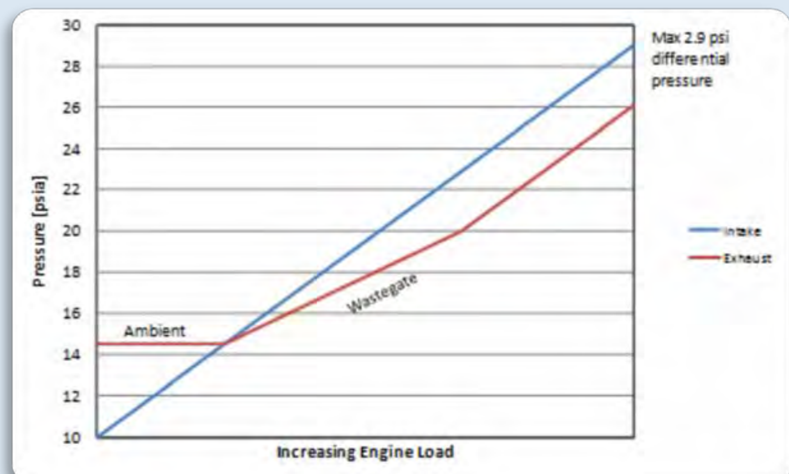
➲ **Mixture stratification for peak efficiency**
  - Target
    - Hydrogen-rich mixture around spark plug
    - Lean mixtures close to combustion chamber walls
  - Challenges
    - Engine geometry and injection system are interdependent
    - Stratification influences emissions characteristics

# Full mapping of optimized DI combustion system
## Assumptions for multi-cylinder estimates


- **Injection strategy**
  - 4-hole nozzle at 100 bar pressure
  - SOI as late as possible

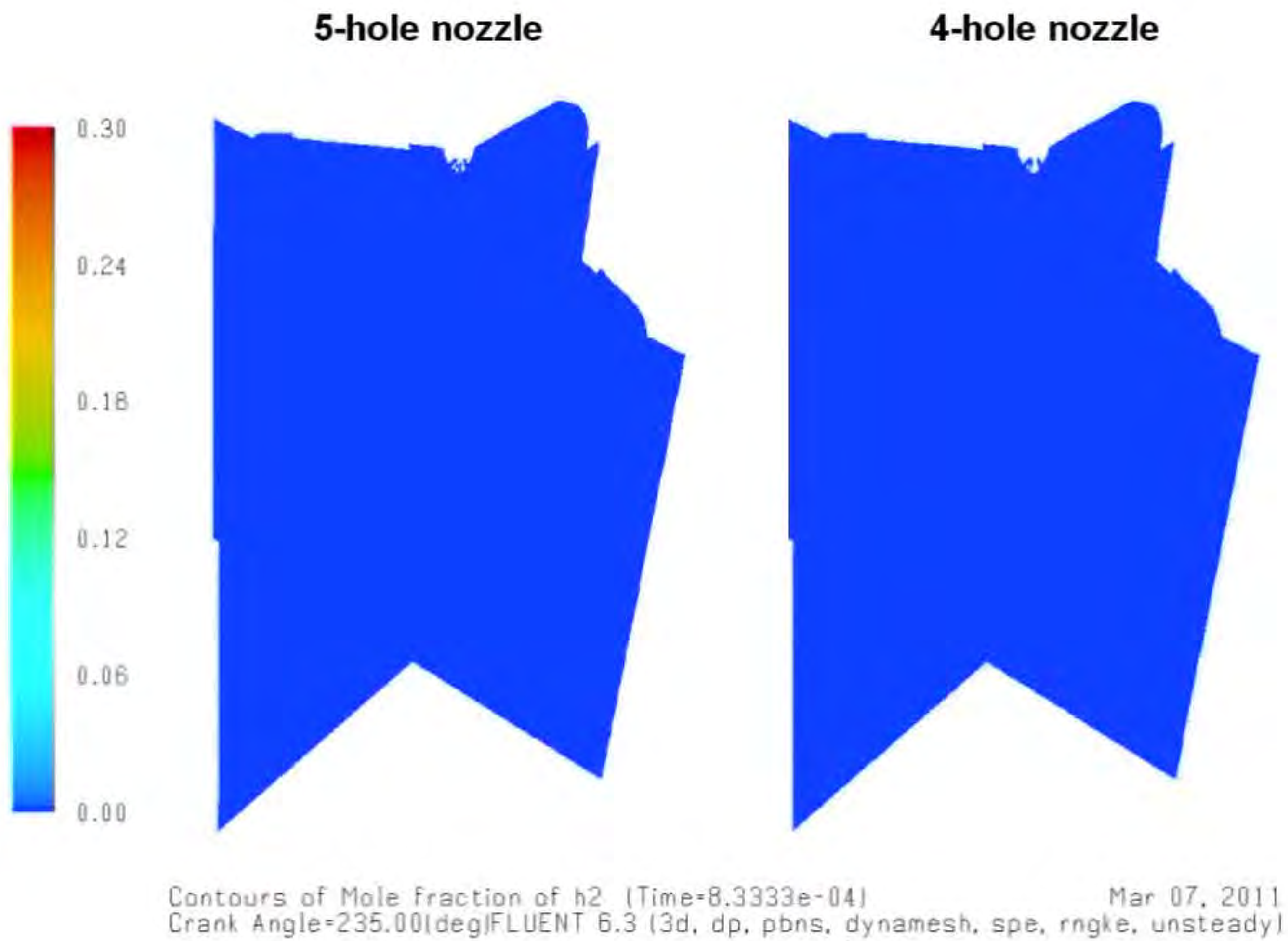
- **Engine friction**
  - Values derived from measurement on multi-cylinder engine



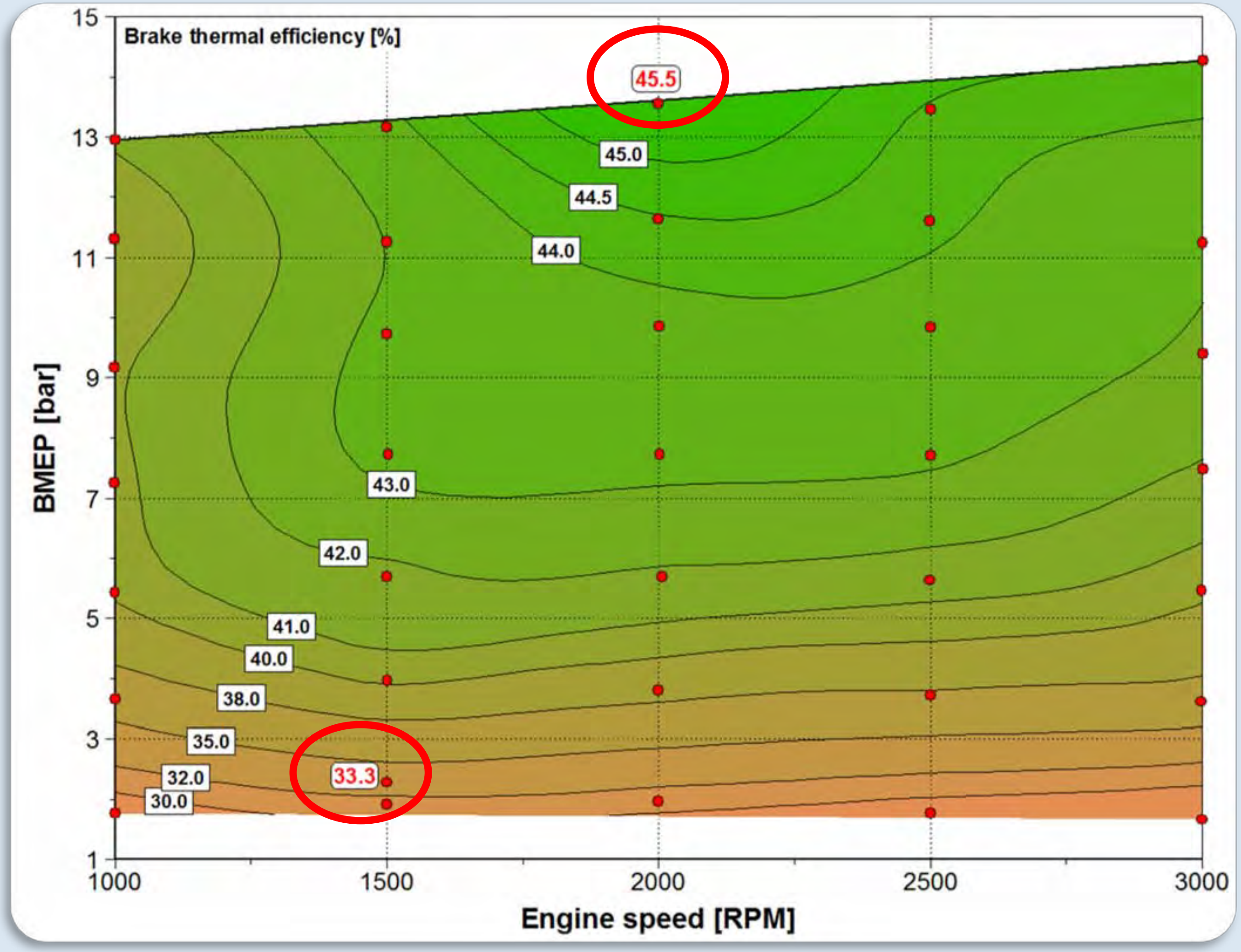




- **Turbo-charger performance**
  - Derived from results of turbo-charged multi-cylinder hydrogen PFI engine

# Full mapping of optimized DI combustion system
## Implementation of design criteria in improved nozzle design

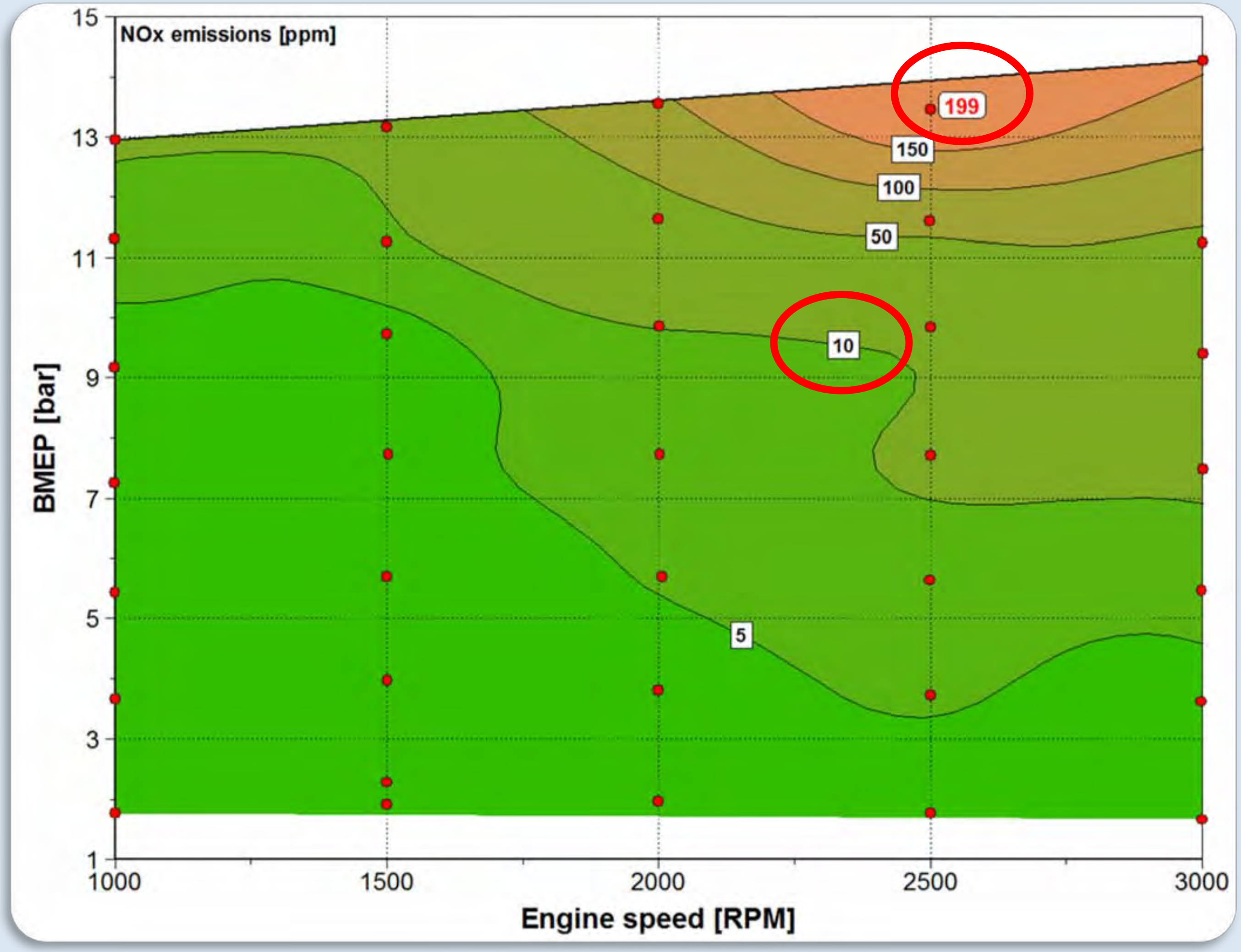


# Full mapping of optimized DI combustion system
## Brake thermal efficiency results




- **Peak BTE**
  - Target: 45%
  - **Actual: 45.5%**
- **BTE at WWMP**
  - Target: 31%
  - **Actual: 33.3%**
- **Performance**
  - **14.3 bar BMEP**

# Full mapping of optimized DI combustion system
## NOx emissions results




- **Emissions**
  - Peak around 200 ppm
  - Major areas below 10 ppm
  - Drive-cycle targets need to be estimated

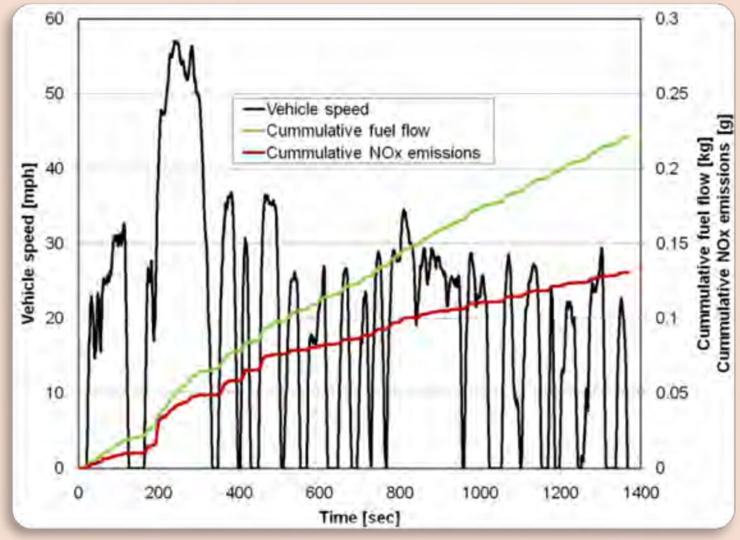
# Estimation of drive-cycle results
# Vehicle assumptions

## Midsize sedan

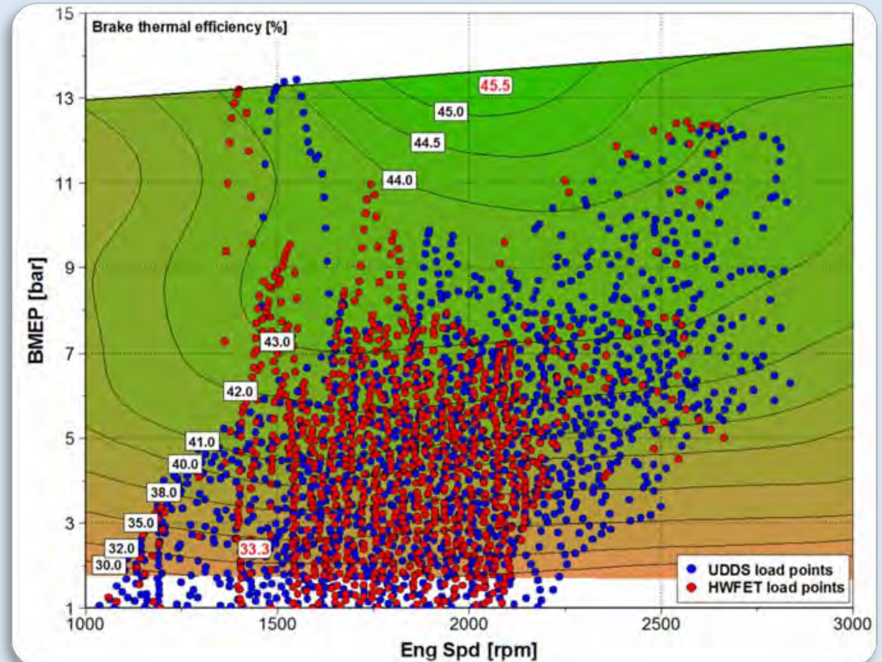
- Vehicle weight: 1553 kg
- Displacement: 3.0L
- Conventional powertrain
- 5-speed automatic transmission

## Drive-cycles

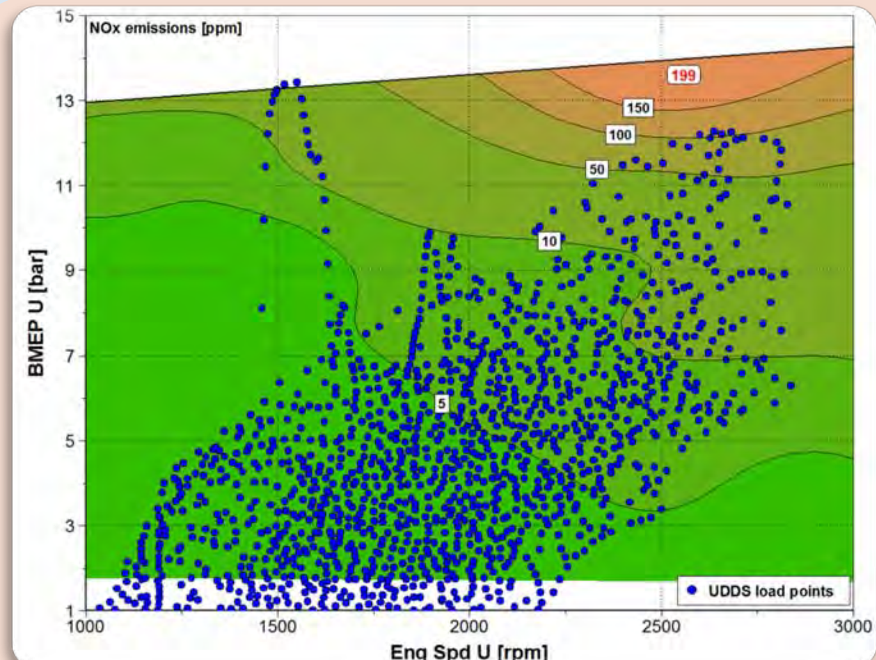
- Emissions: UDDS cycle
- Fuel economy: UDDS cycle (cold start corr.)
  HWFET cycle
  combined/unadjusted



# Estimation of drive-cycle results
# Fuel economy and emissions

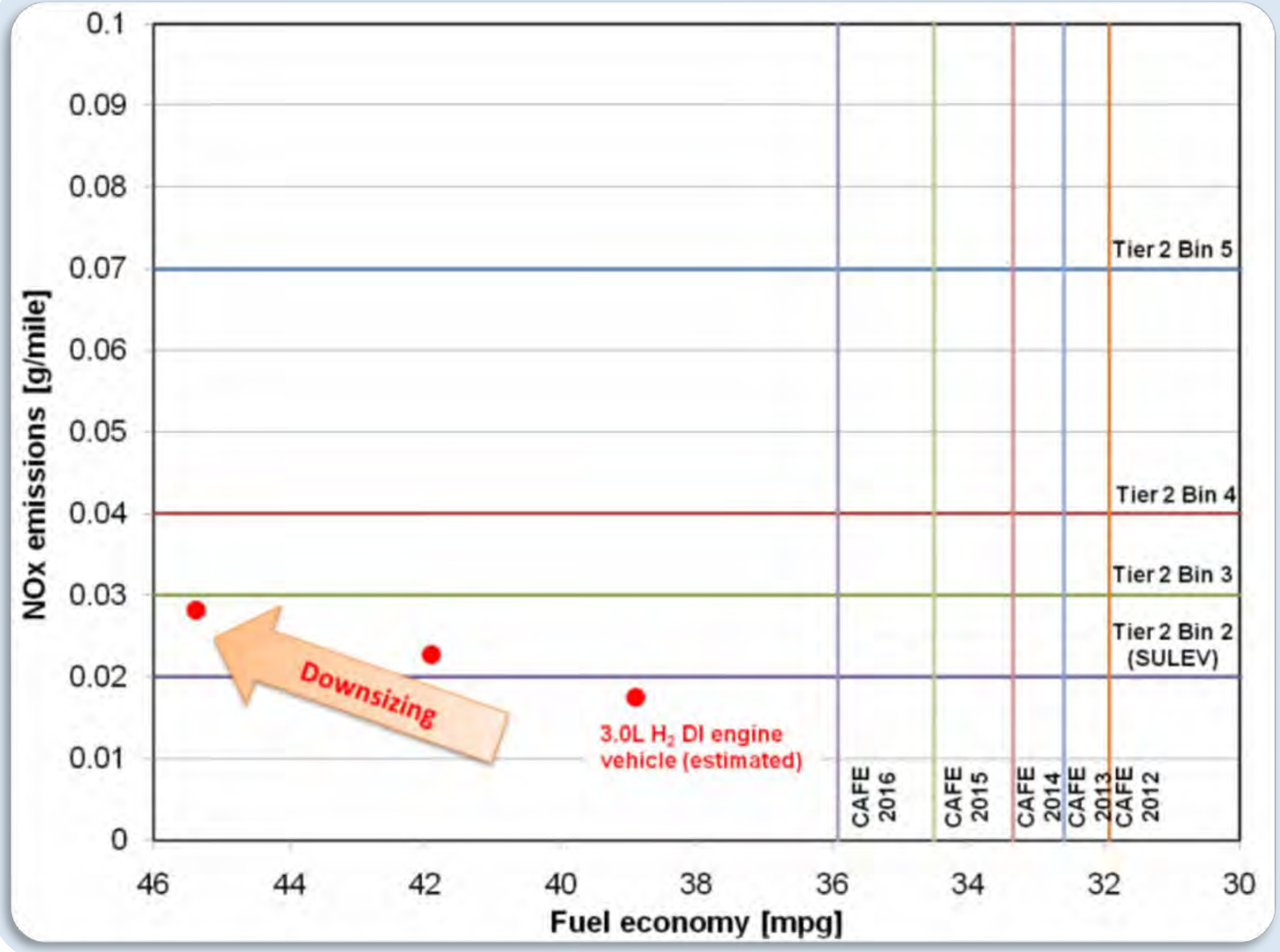



- **Fuel economy (unadjusted)**
  - City: 32.4 mpg
  - Highway: 51.5 mpg
  - **Combined: 38.9 mpg**




- **Emissions**
  - DOE target: Tier 2 Bin 5 0.07 g/mile
  - **Actual: 0.017 g/mile**

# Estimation of drive-cycle results
# Fuel economy and emissions




- **$H_2$ DI engine vehicle exceeds 2016 CAFE target at Tier 2 Bin 2 (SULEV) emissions levels without aftertreatment**
- **Further potential for fuel economy improvement with engine downsizing**

# Collaboration and coordination

- **Guidance and support from Ford Motor Company**
  - Input on test plan and activities
  - In-kind support (engine hardware)
- **Collaboration with Sandia National Laboratories**
  - Coordination of investigated operating conditions
  - Optical results used for validation of 3D-CFD simulation
- **Contract with Westport Innovations Inc.**
  - Subcontract to supply Piezo injectors, drivers and fabricate nozzles
- **Collaboration/coordination**
  - Injection simulation: Lawrence Livermore National Laboratory
  - Data analysis/joint publications: Ghent University
  - Progress updates/joint publications: BMW and Graz University of Technology

# Future work

- **Optimize mixture formation and combustion**
  - Develop and benchmark optimized injector designs using the integrated approach of 3D-CFD optimization and experimental assessment
  - Establish optimized engine efficiency and emissions maps
  - Estimate drive-cycle fuel economy and emissions results
- **Assess impact of compression ratio and surface/volume ratio**
  - Use analytical tools combined with simulation and experiments to isolate these interrelated effects
  - Derive basic design guidelines
- **Document and archive project findings**
  - Summarize and publish major project milestones and findings
  - Provide input and know-how to related projects on gaseous fuels

# Summary

- 'Optimization of Direct-Injection $H_2$ Combustion Engine Performance, Efficiency, and Emissions' project is focused on
  - providing a clean and efficient, readily available tool for utilization of hydrogen as an energy carrier
  - achieving 45% brake thermal efficiency with minimal NOx emissions
- Major accomplishments in FY2011 include
  - 3D-CFD simulation established as powerful tool for efficient optimization
  - Demonstrated 45.5% peak brake thermal efficiency and 33.3% at WWMP and power density superior to current gasoline engines (14.3 bar BMEP)
  - Demonstrated drive-cycle NOx emissions of 0.017 g/mile (below SULEV)
  - **Achieved and exceeded major DOE targets**
- Future work includes
  - Simulation and assessment of next generation combustion system
  - Assess geometry interdependencies and derive guidelines
  - Transfer know-how to related project areas on gaseous fuels