2011 DOE Vehicle Technologies Review
Gasoline Ultra Fuel Efficient Vehicle

ACE064
Merit Review DE-EE0003258

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Ultra Fuel Efficient Vehicle (UFEV) Project Overview

**Timeline**
- Project start: 9/1/2010
- Project end: 3/31/2014
- Percent complete: 50%

**Budget**
- Total project funding
  - DOE share $7,480,582 (50%)
  - Contractor share: $7,480,582 (50%)
- BP1 2010-2011 Funding: $2,788,205
- BP2 2011-2012 Funding: $2,837,265
- BP3 2012-2013 Funding: $1,169,418
- BP4 2013-2014 Funding: $685,693

**VT Programmatic Barrier**
- Improve the efficiency of light-duty engines for passenger vehicles through advanced combustion and minimization of thermal and parasitic losses.
- Project primarily addresses VT Program Barriers:
  - A: Advanced engine combustion regimes
  - D: Effective engine controls

**Partners**
- Delphi - Project Lead
- HATCI (Hyundai America Technical Center Inc.)
- WERC (Wisconsin Engine Research Consultants)
- Wayne State University
Ultra Fuel Efficient Vehicle (UFEV) Project Collaboration with Other Institutions

Detroit, Michigan

Henrietta, New York

Superior Township, Michigan

Auburn Hills, Michigan

Madison, Wisconsin

University of Wisconsin
Ultra Fuel Efficient Vehicle (UFEV) Project

Relevance

**Objective**

- Develop, implement and demonstrate fuel consumption reduction technologies with a partnership of universities, systems level OEM supplier and OEM.

- Targeted fuel economy improvement of > 30% vs. PFI baseline.
  - Improved internal combustion engine efficiency reduces GHG and emissions by reducing petroleum consumption.
  - Phase I of the project concentrates on fuel efficiency improvements using EMS, GDi, and advanced valvetrain products in combination with technologies to reduce friction and parasitic losses.
  - Phase 2 of the project will develop and demonstrate improved thermal efficiency from in-cylinder combustion with gasoline direct compression ignition (GDCI).
Ultra Fuel Efficient Vehicle (UFEV) Project

Project Milestones

**Phase I** - Friction, Parasitic and Pumping Loss Reduction Technologies

- June 2012: Vehicle Demo of Phase 1
- June 2012: Go / No Go Phase Review

**Phase II** - Gasoline Direct-Injection Compression Ignition

- March 2013: Go / No Go Phase Review
- March 2014: GDCI Project Vehicle Demonstration

Transfer Successful Technologies to GDCI Vehicle

*June 2012: Vehicle Demo*

*March 2014: Vehicle Demo*
Approach / Strategy
Project Hardware Plan

Phase 1
- Phase 1 Loss Reduction Vehicle
- Phase 1 Electronics & Controls Vehicle

Phase 2
- Phase 2 Vehicle Demo
- Phase 2 Vehicle
- Phase 2 Engine Development

GDCI SCE1
GDCI SCE2
GDCI multi cylinder
HCCI MCE

April 2010 to June 2012
Phase 1 Vehicle Demo
Applicable technologies
Phase 2 Vehicle Demo

May 18, 2012
Slide 6
Approach / Strategy
Phase 1 Vehicle 1 (Parasitic Loss Reduction Vehicle)

- 2011 Sonata 6MT, 2.4L GDI Theta II
- Technologies on Vehicle:
  - Camshaft Rollerization
    - ~1% for Rollerized Camshaft
  - Optimized Oil Pump
  - Crank Rollerization
    - ~3% for Rollerized Cranktrain
  - Engine Downspeeeding
    - 5000 RPM
    - Revised cam shafts
    - Coated Piston Rings
    - Low Tension Oil Control Rings
    - Coated Piston Skirt
    - ~3% improvement in vehicle level
  - Exhaust Thermal Management
    - ~1-2% exhaust heat recovery
  - Demonstrated on Hyundai Theta GDI engine in a 2011 Sonata
  - Cooled EGR
    - ~3% cooled EGR

*Targeted fuel economy improvement vs. PFI baseline vehicle shown in italics
Phase 1 Accomplishments: 
Project specific hardware and testing

**Vehicle Build and Integration of Technologies**

- The Phase 1 Parasitic loss demonstration vehicle has been assembled and is currently completing calibration and testing. The build at HATCI included; a new engine with roller bearing crank and cam shafts, cooled EGR, exhaust heat recovery system, down speeding (gear ratio, low tension oil control rings, reduced force chain tensioner, reduced flow oil pump...), low friction engine hardware (DLC coatings, roller chain, coated piston skirts...). Delphi also provided stand-alone controls for the exhaust heat recovery system and for the two step oil pump system.

![HATCI low friction technologies](image1)

![Delphi Heat Recovery and Friction Reduction Controls](image2)
Approach / Strategy
Phase 1 Vehicle 2 (Engine Management System)

- 2011 Sonata 6MT, 2.4L GDI Theta II
- Technologies on Vehicle:

![Diagram showing various components and improvements.]

Cooled EGR

Variable Valvetrain
~4% improvement in vehicle level

GDi Fuel System
1-3% improvement

GDi Injector

GDi Rail

Calibration

Stop / Start
• Micro Hybrid Stop / Start Controls

~3% improvement in vehicle level

EMS Control Algorithms

ECM
With Integrated GDi Controls

2 step

ePhaser Controls

ePhaser

Demonstrated on Hyundai Theta GDi engine in a 2011 Sonata

~4% improvement in vehicle level

~3% cooled EGR

*Targeted fuel economy improvement vs. PFI baseline vehicle shown in italics
Phase 1 Accomplishments: Project Specific Hardware and Testing

**Vehicle Build and Integration of Technologies**
- The Phase 1 demonstration vehicle has been completed and is currently being calibrated. The build included conversion from the production engine controller to a Delphi MT92 development engine controller, Delphi GDI fuel system, Delphi ePhasers, Delphi belt alternator starter system (BAS) and modifications to receive the HATCI 2-step head and cooled EGR.
The project was submitted with a mixed mode combustion strategy and evaluation of GDCI, HCCI and mode transition control were built into the project scope.

Strategy: Work to develop combustion technology and practical engine systems that permit full-time GDCI operation.

In SCE tests, GDCI combustion has demonstrated good performance across the speed-load range.
Accomplishments
Phase 2 HCCI Development at Delphi and WSU

- **HCCI engine construction and testing**
  - A project specific HCCI engine was constructed featuring advanced valvetrain, redesigned pistons, fuel injectors and controls systems.
  - Engine testing focused on optimizing injection and valvetrain strategies to extend the operating range of the HCCI operational envelope.
  - While HCCI has shown considerable benefits in terms of fuel consumption when compared to the baseline, GDCI technology has fuel consumption improvements plus superior emissions at loads and speeds that far exceed that of the HCCI domain.
  - Future work will focus on developing GDCI across a broad dynamic range and HCCI will not be explored further in this project.

- **Optical engine at Wayne State University - HCCI combustion**
  - Observe combustion initiation of compression auto ignition and improve understanding of combustion initiation processes
  - HCCI work on this project has concluded
Approach / Strategy
Phase 2 GDCI (Gasoline Direct injection Compression Ignition)

- 2011 Sonata 6MT, 2.0L GDI Theta Turbo
- Technologies on Vehicle:

GDCI Low Temperature Combustion Process and Controls

EMS Control Algorithms
Calibration
ECM
Boosting Systems
Charge Air Coolers

GDCI Optimized Valvetrain
GDi Pump
GDCI Optimized Injector
GDi Rail

Demonstrate on Hyundai Theta Turbo GDI engine in a 2011 Sonata

~25% targeted fuel economy improvement

Parasitic loss reduction technologies from Phase 1 (where applicable)
Approach / Strategy
GDCI Combines the Best of Diesel & SI Technology

- High compression ratio (CR) with late multiple injections (similar to diesel)
- Gasoline that vaporizes & mixes easily at low injection pressure
- A new low-temp combustion process for partially-premixed CI
- High efficiency with low NOx & PM over full speed-load range
Approach / Strategy
GDCI Engine Concept

- Gasoline Partially-Premixed CI (PPCI)
- Fuel Injection
  - Central Mounted
  - Multiple Late Injections
  - GDi-like injection pressures
- Valvetrain – continuously-variable mechanical
- Advanced Engine Controls
- No classic SI knock or pre-ignition
- Boosted and down-speeded
- High CR & lean for high thermal efficiency

References:
Kalghatgi (Shell) 2005-2010
Manente & Johansson (Lund) 2007-2011
Dempsey & Reitz 2011, Ra & Reitz 2009-11, Hanson & Reitz 2009 (ERC)
Sellnau (Delphi) SAE 2012, SAE 2011, Aachen 2011, Deer 2010
Accomplishments
Phase 2 GDCI (Gasoline Direct injection Compression Ignition)

- Conducted extensive single cylinder engine tests with advanced injectors, valvetrain and piston designs
- Conducted extensive FIRE & KIVA simulations of spray, mixing and combustion processes (performed at WERC and Delphi)
- Designed and fabricated new GDCI engine
  - Cylinder heads and enhanced engine block
  - Valvetrain systems
  - Injection systems
  - Boost & air control system
- Running new single cylinder and multi-cylinder engines on dynamometers
- Initiated advanced controls work
Injector Tests on Hydra Engine (1500-6bar)

- Injectors A, B, C, D, E were tested on Hydra SCE with M57 bowl
- Injector E performed best
  - $FSN \sim 0.01$ with 4.5% lower ISFC and no swirl

**Constraints**
- Noise < 85 dB
- Pinj < 500 bar
- ISNOx < 0.2 g/kWh

**Note:**
- GCR=16.2 for INJ A-D
- GCR=14.5 for INJ E
Injector Tests on Hydra Engine (1500-6bar)

- Exhaust Particle Size Distribution measured with TSI EEPS
- EEPS data confirming very low particulate emissions for injector E without swirl

Smoke vs ISFC

- Injector B, SR = 1.6
- Injector C, SR = 1.7
- Injector D, SR = 2.1
- Injector E, SR = 0.6

Particle Size Distrib (EEPS)

- Diesel Peak (Ref 30)
- INJ C, SR = 1.8
- INJ D, SR = 3
- INJ E, SR = 0.6
- HEPA

Accomplishments
Phase 2 GDCI (Gasoline Direct injection Compression Ignition)
Accomplishments
Phase 2 GDCI (Gasoline Direct injection Compression Ignition)

Engine Design, Analysis, & Fabrication

*Strong Delphi & HATCI collaboration for First GDCI engine*

- **Cylinder Head Design & Packaging**
- **Structural Analysis & CFD**
- **Cylinder Head Fabrication**
- **Enhanced Block & Analysis**
- **Piston Design & Fab**
Future Work
UFEV Project 2012-2013

- **Phase 1**
  - **Calibration**: Demonstration vehicles will finish calibration for fuel economy and emissions
  - **Vehicle Test**: Vehicle level testing and demonstration will be completed

- **Phase 2**
  - **SCE Testing**: Advanced injection and valvetrain strategies will be refined over the speed load range using a project specific head.
  - **Simulation**: A variety of simulation tools for injection and spray development, combustion system, and valvetrain systems will be applied to achieve minimum NOx and PM emissions.
  - **MCE Testing**: MCE testing will continue throughout the project in support of powertrain integration, component refinement, controls development and calibration
  - **Advanced Controls**: Advanced controls hardware and software will be developed using HIL Bench, simulation, and start cart, followed by transfer to the vehicle
Summary
Ultra Fuel Efficient Vehicle (UFEV) Project

- **Objective**
  - Develop, implement and demonstrate fuel consumption reduction technologies with a targeted fuel economy improvement of > 30% vs. PFI baseline.

- **Project**
  - The project team, with representation from universities, research, systems level automotive supplier and automotive OEM, has been assembled and tasked.
  - The project is on schedule and is meeting budget targets.

- **Phase 1**
  - Demonstration vehicle design and construction is complete. The demonstration vehicles are currently undergoing final calibration and testing.

- **Phase 2**
  - An HCCI multi-cylinder engine has been built and tested but HCCI combustion mode will not be required due to large operating range of GDCI.
  - SCE test results have demonstrated very low fuel consumption and emissions for GDCI, with the potential to not require lean NOx aftertreatment.
  - A new multi-cylinder GDCI engine has been designed and fabricated with new valvetrain and injection systems. Multiple test facilities are in use to integrate systems and calibrate ahead of vehicle demonstration.