Low Emissions IC Engine Development at Ford Motor Company

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Powertrain Research and Advanced Engineering

ERC Symposium
University of Wisconsin at Madison

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Presentation Overview

- **Emission Standards Evolution**
- PZEV PFI/DI Engine Development
- Electric-Gasoline Hybrid Vehicle
- HCCI Engine Development
- H2ICE Engine Development
- Summary
HC Emission Standards

Evolution of Hydrocarbon Emission Standards - USA

HC REDUCED BY 96%

98% ADDITIONAL REDUCTION

99.9% REDUCTION OVERALL

1966-1993

Hydrocarbons (grams per mile @ 50K)

HC Emission Standards

Ford Motor Company

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NOx Emission Standards

Evolution of Nitrogen Oxide Emission Standards  USA

NOx REDUCED BY 90%

1st NOx STANDARD C/H 110 MODE FTP

99.5% REDUCTION OVERALL

95% ADDITIONAL REDUCTION

CAABase TLEV LEV ULEV ULEV II SULEV

0.4 50%

0.2 75%

0.05 60%

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National Medal of Technology

- Haren Gandhi wins for his work in automotive exhaust catalyst technology
- Ford executives salute Gandhi's breakthrough accomplishment
- Today's automobiles are more than 96 percent cleaner – due in part to Gandhi's efforts
- First time ever that auto industry researcher has been awarded Medal of Technology
- Past winners include Bill Gates, Steve Wozniak, and Edwin Land of Polaroid
IC Engine Technology Roadmap

Gasoline

Cost Effective

Diesel

Limited By Emissions Constraints

Performance
Fuel Economy
Emissions

Time
Gasoline IC Engine Technology Spectrum

Now

PFI

FE, P

DI

FE, P

Future

Boosted/Downsizing

Fixed Cam

FE, P

Cam lift/phasing

FE, E

HCCI

High EGR

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Emissions Example

- Minimize emissions before Cat light-off
- Minimize time to Cat light-off
- Maximize Cat efficiency (AFR Control)
PZEV with Improved Aftertreatment

DISI enables late ignition for improved CC catalyst light-off.

Detroit Diesel Allison

Close Couple Catalyst

UEGO

Cast Iron Exhaust Manifold

Intake UCT (Cont. Variable)

Fine Spray Fuel Injector

Continuously Variable CMCV

High Speed Starter

HEGO

Underbody Catalyst

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PZEV PFI Engine: Improved AFR Control

Injector Targeting Process

MESIM CFD Injector Targeting

Four Puddle Fuel Evaporation Model

Simulated S_Type98 Transient Test

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Injector Targeting Optimization for AFR Control

Tricky Spots

Injector Rotation

Injector Up/Down offset

Cone Angle

Angle between Cones

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Injector Targeting Optimization for AFR Control

Nominal Design

Worst Case

AFR Response Nominal Vs Worst Case

Time=0.00 msec.
Direct Injection Engine For Low Emissions
Reducing Smoke at Part-Load Operation

DI Engine

60 deg Injector

70 deg Injector

Computed Piston Wetting History

Measured Engine Smoke Number

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Ford Focus PZEV
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Hybrid Vehicle Technology – Ford Hybrid Escape

2005 North American Truck of the Year

- High FE vehicle at low emission levels
- Fuel efficient driving
- Regenerative braking captures over 90% of braking energy on EPA city cycle

2.3 L Atkinson Engine
E-CVT

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HCCI Combustion System Concept

Requirements:
- Homogenization
- Temperature of ~1100 K
- Cycle-to-cycle control parameter

Spark Ignition (Gasoline)
Spark Ignition Wall Guided (Spray Guided) Stratified (Gasoline)
Homogeneous Charge Compression Ignition (HCCI) (Gasoline & Diesel)
Compression Ignition (Diesel)

Low temperature combustion…

Flame Propagation
Kinetics
Diffusion
Gasoline HCCI Technology

Controlled Auto Ignition (CAI)

Optimized Kinetics Process (OKP)

Negative Valve Overlap and pilot fuel injection is the key for controlled ignition timing

Intake air heating & fast intake T control
HCCI Significantly Reduces CO₂ Emission

1500 rpm Engine Speed

NSFC (g/kWh) vs NMEP (bar)

- AVL CSI (HCCI)
- PFI CAI (HCCI)
- PFI
- OKP (HCCI)
- Diesel

Throttling points:
- (85 kPa)
- (70 kPa)
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Why Hydrogen Internal Combustion Engine?

- Ford Motor Company is dedicated to the realization of Fuel Cell powertrains in mass produced consumer vehicles.
- Fuel cell powertrains are not ready for mass production in the near term.
- H$_2$ICE is regarded as a transition or “bridging” strategy to stimulate the hydrogen infrastructure, and related hydrogen technologies:
  - On-board hydrogen fuel storage
  - Hydrogen Fuel dispensing
  - Hydrogen safety sensors
## H2 Focus Breaks SULEV NOx Barrier

<table>
<thead>
<tr>
<th></th>
<th>NOx (g/mi)</th>
<th>CO (g/mi)</th>
<th>NMHC (g/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SULEV Standard</td>
<td>0.02</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>H₂ICE – Test 1</td>
<td>&lt;= 0.02</td>
<td>0.0036</td>
<td>0.006</td>
</tr>
<tr>
<td>H₂ICE – Test 2</td>
<td>&lt;= 0.02</td>
<td>0.00317</td>
<td>0.008</td>
</tr>
</tbody>
</table>
Hydrogen DI Provides Further Opportunities

- Power density improvement
  - Air is not displaced by H2 during intake stroke
- Elimination of backfire
  - H2 injection after intake valve closing
- Higher CR & improved thermal efficiency opportunity due to charge cooling
- Optimized injection strategy may provide:
  - Reduced pre-ignition tendency
  - Reduced NOx
  - Increased fuel efficiency (less unburned H2)
# Volumetric Efficiency Comparison

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gasoline PFI</th>
<th>H2 PFI</th>
<th>H2 Cryogenic PFI</th>
<th>H2 DI</th>
<th>H2 PFI Positive Displacement Supercharger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol. Effy.</td>
<td>Base</td>
<td>70%</td>
<td>~115% (Source: HyICE)</td>
<td>102%</td>
<td>125+%</td>
</tr>
</tbody>
</table>
CFD-Based Engine Upfront Design Methodology

- **Modeling**
  - Up-front Design Optimization

- **Design**

- **Thermo Engine**
  - Design Evaluation/Confirmation

- **Optical Engine**
  - Models/Design Validation

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Injector Included Angle Optimization

\[
\begin{array}{ccccc}
\text{t (ms)} & 60^\circ & 90^\circ & 120^\circ & 150^\circ \\
0.5 & & & & \\
1.0 & & & & \\
2.0 & & & & \\
3.0 & & & & \\
\end{array}
\]

Included angles

Cutting plane

A/F

\[
\begin{array}{cccc}
60 & 45 & 30 & 15 \\
\end{array}
\]
Summary

- Ford has been recognized among the leaders in environmental stewardship.

- Ford will continue developing a spectrum of vehicle technologies to meet and/or exceed environmental regulations and customers needs.