Advancement of Gasoline Direct Injection Compression Ignition (GDCI) for US 2025 CAFE and Tier3 Emissions

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Auburn Hills, MI USA

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Motivation and Industry Challenge

• Stringent CAFE and CO2 targets with US Tier 3 emissions laws
• Changing demand for diesel and gasoline fuels worldwide
• Need efficient and clean engines operating on gasoline-like fuels

### Fuel Economy
(United States)

<table>
<thead>
<tr>
<th>Year</th>
<th>CAFE Target (MPG)</th>
<th>CO₂ Target (gCO₂/mile)</th>
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<tbody>
<tr>
<td>2011</td>
<td>27.6</td>
<td>322</td>
</tr>
<tr>
<td>2016</td>
<td>35.3</td>
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<tr>
<td>2025</td>
<td>54.5</td>
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Top Goals for Future Internal Comb. Engines

• Ultra high fuel efficiency
  • Target: 200 g/kWh (42% thermal efficiency)
  • Responsible use of non-renewable fossil fuels
  • High well-to-wheel (WTW) fuel efficiency

• Minimize GHG emissions for life cycle of vehicle
  • Includes CO2 emissions to process the fuel, manufacture vehicle, and combust fuel

• Ultra low criteria emissions both on cycle & off cycle (US Tier3-Bin30)
  • NOx, HC, PM, CO, CH2O
Three Main GDCI Programs at Delphi

<table>
<thead>
<tr>
<th>Organization</th>
<th>Duration</th>
<th>Description</th>
<th>Collaborators</th>
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<tbody>
<tr>
<td>US Dept of Energy</td>
<td>4-Year</td>
<td>Develop GDCI Powertrain and Demonstrate 35% improved FE with Tier3-B30 Emissions in a practical vehicle</td>
<td>ORNL, Umicore, Univ of Wisconsin-Madison</td>
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<tr>
<td>Saudi Aramco</td>
<td>3-Year</td>
<td>Study Fuel Effects and Low Octane Fuels on GDCI Combustion</td>
<td>Saudi Aramco</td>
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<tr>
<td>ARPA-E (DOE)</td>
<td>3-Year</td>
<td>Combine Opposed-Piston engine technology with GDCI for best-in-class fuel efficiency</td>
<td>Achates Power, Argonne National Labs</td>
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</table>

Delphi is partnered with leading industry experts to develop and commercialize GDCI technology
Contents

- GDCI Concept
- Combustion System
- Injection System and Sprays
- Engine Test Results
- Emissions and Aftertreatment
- Summary
GDCI Combines the Best of Diesel & SI Technology

- A new low-temp combustion process for Partially-Premixed CI
- Gasoline that vaporizes & partially mixes at low injection pressure
- High CR with late multiple injections (similar to diesel)
- High effic. & low NOx, PM over wide speed-load range
GDCI Engine Concept

- Gasoline Partially Premixed CI
- Fuel Injection
  - Central Mounted, Multiple-Late Injection, GDi-like injection pressures
- Valvetrain – cont.-var. mechanical (exhaust rebreathing)
- Adv EMS – Cyl.-Pres.-Based Control
- No classic SI Knock or Preignition
- Down-sized, down-speeded, & boosted
- High CR, Lean, Unthrottled

Addressing all loss mechanisms for internal combustion engines
• 1, 2, or 3 injections on Intake and Compression Strokes

• Complete injection & partial mixing prior to start-of-comb. (PPCI)

• “Stratify”: robust ignition and controlled heat release

• “Burn in the Box”: heat release below \( \Phi=1.2, \ 1200 < T < 2300 \text{ K} \)

Simultaneously low NOx, PM, and CO is possible
Gen3 GDCI Combustion System

- “Wetless” concept for low smoke
  - Inject at any SOI without wall wetting
  - Wide spray angle matched to bowl
- Long stroke S/B=1.28 increases TDC clr space for late injections (D=2.22 liters)
- Zero swirl & squish for min. heat losses

- GCR: 16:1 (compression)
- Fast Intake Air Heating
- Cylinder Pressure Sensing
- Integral air-gap insulated exhaust manifold
- Pre-turbo catalyst (PTC)
Gen3 GDCI Injection System

- Centrally-mounted, GDi Injectors with high injection rate
  - 350+ bar injection pressure
- Fuel pump driven by Intake Cam
- Sprays developed for fast atomization without wetting
Combustion System Development

- **Goal:** “wetless” combustion system for minimal smoke emissions
- **Optimize** spray and piston bowl design for both **early** and **late** injections
- **Preinjections** on intake stroke create premixed charge (PHI floor)
- **Last injection** late on compression stroke controls ignition; determines smoke and NOx emissions

**CFD tools used extensively for spray development**
CFD Simulation of Injection Process

- Plot shows injected fuel and vapor mass as function of time for SOI -45 to -25
- Injection period: 7 CAD (<0.6 ms)
- Very fast vaporization is observed, especially for late injections when cylinder gas temp. and pres. are high
- High cylinder gas temp. and pres. for late injections greatly reduce liquid penetration
  - Major factor to reduce wall wetting
Simulation Results: 3 Spray Angles

- Spray angle is a key factor in comb. system design
- Plots show piston and liner fuel mass as function of time for three spray angles (115, 125, 130 deg included)
- For spray angle 115, fuel wetting occurs for a range of SOI. Wetting persists at TDC and during combustion.
- For spray angle 125, fuel wetting is reduced
- For spray angle 130 and SOI later than -45, the injection process is “wetless”
- Conclude: wider spray angles of ~130 deg are preferred with Gen3 piston
Spray Chamber Testing (UW-Madison)

- High Pressure & Temperature Chamber at UW-Madison (Ghandhi & Oakley)
  - Non-reacting, flow-through type chamber
  - Multi-plume configuration
  - Plume oriented normal to axis of view

- Objectives: Characterize injectors, validate spray models
Backlit & Schlieren Images; Drop Size Measurement

- Liquid & Vapor penetration (Q=25mm³, 200bar)
- Low liquid penetration for higher chamber pressures
- Very small drop size (SMD) measured along spray plume (100bar)
Typical Combustion (1000rpm-3bar IMEP)

- Single Injection with exhaust rebreathing (SOI=40 btdc)
- Start-of-Combustion near TDC
- Low PMEP – rebreathing during intake stroke
- Stable, low-temperature combustion with good Texh

Measured PcyI and Heat Release

PV Diagram

PMEP = 3 kPa
BSFC - 1500 rpm Load Sweep

- BSFC significantly improved relative to Gen1 and Gen2 engines
- Low BSFC over a wide load range where the vehicle operates on drive cycle
- Near target: 200 g/kWh (~42% brake thermal efficiency)
- Exceptional light-load BSFC
- Small BSFC difference (~2%) attributed to aftertreatment system, which oxidizes unburned fuel prior to LP EGR system

<table>
<thead>
<tr>
<th>Load (kPa)</th>
<th>NOx (g/kWh)</th>
<th>FSN</th>
<th>COV IMEP</th>
<th>Noise %</th>
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</thead>
<tbody>
<tr>
<td>190</td>
<td>&lt;0.6</td>
<td>&lt;0.15</td>
<td>&lt;3%</td>
<td>&lt;12%</td>
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<td>&lt;0.15</td>
<td>&lt;3%</td>
<td>&lt;12%</td>
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<tr>
<td>210</td>
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<td>250</td>
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<td>&lt;0.15</td>
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<tr>
<td>260</td>
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<td>280</td>
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<tr>
<td>290</td>
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<td>&lt;0.15</td>
<td>&lt;3%</td>
<td>&lt;12%</td>
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Target 200 g/kWh
Gen3 Active ATS
Gen3 Inert ATS

205 g/kWh
BSFC Benchmarking: 1500rpm-6bar IMEP

- GDI is approx. 22% more efficient than SIDI turbo engine
- Approx. 11% more efficient than a leading 2.0L EU diesel
- Approx. 11% more efficient than 1.8L Atkinson engine (3rd Gen. Prius)

GDI has excellent part-load fuel economy relative to class leading turbo SI and diesel engines.
Reduced Smoke Emissions - 1500 rpm-11bar IMEP

- Smoke characteristic typically depends on injection timing
- Gen3 combustion system exhibits greatly reduced smoke
  - Attributed to “wetless” combustion system
- Strong injection pressure dependency for Gen3
  - Enables GDCI late injection with low smoke
- Further smoke reduction expected with latest injectors and sprays

![Graph showing typical SOI window and smoke limits for Gen2 and Gen3 systems.](image)
Emissions Challenges for Low-Temp Comb.

• Very challenging to achieve Tier3-Bin30 with low-temp combustion
• Low-temperature combustion equates to low-temperature exhaust
• Engine out NOx and smoke are very low; HC and CO are SI-like
• Commercially viable technology must achieve very low TP emissions both on-cycle and off-cycle including high load.
• Clean EGR flows are imperative for good engine health (sticky components, compressor degradation, cooler fouling)
Gen3 Aftertreatment System (ATS) for Tier3- Bin30

- **Heat conservation**: compact, integral, air-gap insulated, exh. manifold
- **HC/CO**: Pre-turbo Cat w fast lightoff, HC Trap, GOC
- **Particulates**: catalyzed, passive GPF for off-cycle
- **EGR feed stream post GPF**
- **NOx**: close-coupled SCR system with urea evaporator
Packaging: Gen3 Aftertreatment for T3B30

- Packaging is very compact for D-class passenger car
- Emphasis on heat conservation, short ducts, low space velocities
- Using Daimler SCR evaporator – good urea mixing and SCR temps
Close-Coupled SCR System (Gen3 GDCI)

- 3D & 1D simulations used to develop dosing strategies
- 300 C needed for high NOx conversion efficiency
- Tier3-Bin30 NOx target may be achievable depending on light-off strategy
  - Testing needed

3D Simulation – Urea Dosing

1D Simulation – NOx Conversion

- 300 C needed for high NOx conversion efficiency
- Tier3-Bin30 NOx target may be achievable depending on light-off strategy
- Testing needed
Smoke Emissions – 1500rpm Load Sweep

- Low engine out (EO) smoke over low-to-medium loads
- A small gasoline particulate filter (GPF) exhibits high trapping efficiency (1.35L)
- TP smoke <0.02 over load range
- Testing planned to characterize particle size and number
- Overall, very good trapping efficiency for small particles.
NOx and Exhaust Temp. – 1500rpm Load Sweep

- Low EO NOx over low-to-medium load range (<0.6 g/kWh limit)
- SCR temp exceeds the critical 300 C at most operating conditions for high NOx conv. efficiency.
  - SCR testing not yet completed
- Texh at PTC and GOC exceeds 300 C, even at low loads
- Texh increases with load; expected maximum <500 C.
Reasonable EO HC over low-to-medium load range

TP NMHC are below target (10 ppm) at light-to-moderate loads; increasing above targets at higher loads

Future tests:
- Low-temp. oxidation catalyst
- Cold start tests
Summary – Gen3 GDCI

• GDCI technology is evolving with very stringent requirements for fuel efficiency, CO2 emissions, and criteria emissions.

• Preliminary dynamometer tests show:
  • BSFC ~205 g/kWh for a wide load range
  • Smoke was greatly reduced, especially for late SOI (“wetless” injection process)

• While very challenging, preliminary Texh & emissions data indicate good potential to meet Tier3-Bin30 targets

• More testing and engine calibration is needed ahead of vehicle implementation
Acknowledgements

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Questions?