3-Cylinder Turbocharged Gasoline Direct Injection: A High Value Solution for Euro VI Emissions

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Outline

- Global Emissions and CO₂ Challenges
- Technology Overview for 3-Cyl Boosted GDi Engines
- Value Analysis
- Summary and Conclusions
The Emission Legislation Global Drive

Global emission legislation are evolving toward fuel neutral standards, with emerging countries adopting European legislation.

- **China (nationwide)**
- **India (nationwide)**
- **USA (federal)**
- **Europe**

### Emissions Standards

- **Euro 2/BSII**
- **Euro 3/BSIII**
- **Euro 4?**
- **Euro 4** (w/o OBD)
- **Euro 5**
- **Euro 5+**
- **Euro 6**

### NOx Emissions Standards (mg/km)

- **NEDC Cycle**
  - **Euro 4**: 250
  - **Euro 5 / 5+**: 180
  - **Euro 6**: 80

- **FTP Cycle**
  - **Tier 2 Bin 8**: 124
  - **Tier 2 Bin 5**: 43

**NOx relief is disappearing for EU diesel engines**
CO₂ Regulations Globally Introduced

Powertrain/Vehicles will change significantly:
- Dramatic Downsize and Boost ➔ 3-cyl. Turbo GDi
- Hybrids/Electrification required to meet future targets
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Fuel Economy Benefits from Engine Boosting
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Downsizing and Downspeeding

- Reduced Engine Displacement and Decreased Engine Speed Increase Engine Load for Reduce Fuel Consumption
  - Good low end torque is essential

\[
P = f(B \cdot V \cdot N)
\]

\[
B1 \cdot V1 \cdot N = B2 \cdot V2 \cdot N
\]

\[
P = f(B \cdot V \cdot N)
\]

\[
B1 \cdot N1 = B2 \cdot N2
\]

Delphi Powertrain
Gasoline Direct Injection is a Key Enabler to Improve Low End Torque in Boosted Engines

- Improved Volumetric Efficiency
  - Direct injection with cam phasing allows scavenging with fresh air to reduce residual gas fraction
- Reduced knock propensity
  - In-cylinder fuel vaporization reduces charge temperature
- Improved combustion phasing
  - Charge motion increases burn rate

Greater than 18bar achievable at 1000rpm with GDi.
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Benefits

- Fuel economy improvement
  - 9-15% for homogeneous systems
  - 15-21% for stratified systems
- Improved fuel control and rapid catalyst light-off with split-injection during cold start
- Increased power and responsiveness
Gasoline Direct Injection
Boosted Engine System Mechanization
Gasoline Direct Injection
Boosted Engine System Mechanization
System Features

- Inwardly-opening, multi-hole GDi Injectors, fuel rail and engine-driven high pressure fuel pump
- Injection during the intake stroke focused on complete vaporization and mixing of fuel and air
- Stoichiometric operation allows emissions control via traditional 3-way exhaust catalyst
Gasoline Direct Injection Homogeneous Systems

◆ System Features
- Inwardly-opening, multi-hole GDi Injectors, fuel rail and engine-driven high pressure fuel pump
- Injection during the intake stroke focused on complete vaporization and mixing of fuel and air
- Stoichiometric operation allows emissions control via traditional 3-way exhaust catalyst

◆ Key Requirements
- Operation at fuel pressures up to 200 bar
- Injector packaging for cylinder side mount and central mount
- Spray generation for good vaporization and mixing without wetting in-cylinder surfaces
- Good linear flow range
Gasoline Direct Injection
Stratified Systems

System Features
- Outwardly-opening, hollow-cone GDi Injectors, fuel rail and engine-driven high pressure fuel pump
- Central mount injector near spark plug
- Injection during the compression stroke for careful placement of fuel mixture in space and time
Gasoline Direct Injection Stratified Systems

- **System Features**
  - Outwardly-opening, hollow-cone GDi Injectors, fuel rail and engine-driven high pressure fuel pump
  - Central mount injector near spark plug
  - Injection during the compression stroke for careful placement of fuel mixture in space and time

- **Key Requirements**
  - Operation at fuel pressures up to 200 bar
  - Well-atomized and well-placed stratified mixture under engine conditions
  - Multiple injections to confine the fuel mixture
  - High linear flow range
3 Cylinder Engine Analysis
Comparison with 4 Cylinder

- 3 Cylinder Engine Offers Improved Engine Breathing at Full Load
  - Reduced firing frequency increases scavenging for improved full load torque

![Graph showing pressure at valves](image)

- Area of Valve Overlap
- 1500rpm, Full Load
- L4, mono scroll
- L4, twin scroll

(Simulation AVL BOOST)
3 Cylinder Engine Analysis
Comparison with 4 Cylinder

- 3 Cylinder Engine Offers Improved Engine Breathing at Full Load
  - Reduced firing frequency increases scavenging for improved full load torque

- 3 Cylinder Engine Provides Reduced Fuel Consumption and Emissions
  - Reduced heat transfer surface area
  - Reduced quench layer and crevices
  - Lower friction

Source: Weinowski et al. (FEV) 2009 Vienna Motor Symposium

Source: Heil et al. (Daimler) 2002 Vienna Motor Symposium
3 Cylinder Engine Analysis
Comparison with 4 Cylinder

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- 3 Cylinder Engine Increases NVH
  - Unbalanced 1st and 2nd order torque pulses require counterbalancing
  - Results in slight friction increase

Overall Conclusion: 3 Cylinder Engine is the Preferred Configuration for Displacements < 1.5L

Source: Colltman et al. SAE 2008-01-0138 (SABRE Engine)
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Comparison 1.6lt - 4cyl vs. 1.2lt - 3cyl.

No electrification considered

Better

4cyl. MPFI EU4, 1160

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Delphi Powertrain
Comparison 1.6lt - 4cyl vs. 1.2lt - 3cyl.

- No electrification considered
- 4cyl. Diesel EU4
- 4cyl. MPFI EU4, 1160kg
- 25€/%
- 50€/%

OEM - On Cost [Euro]

CO2 Reduction [%]
Comparison 1.6lt - 4cyl vs. 1.2lt - 3cyl.

- No electrification considered
- 25Euro/%
- 50Euro/%
- 3cyl. Diesel EU6 (with SCR)
- 4cyl. Diesel EU6 (with DeNOx)
- 4cyl. MPFI EU4
- 1.6lt - 4cyl. Diesel EU4
- 1160kg

OEM - On Cost [Euro]

DELPHI
3 Cylinder Engine Value Analysis

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Delphi Powertrain
Comparison 1.6lt - 4cyl vs. 1.2lt - 3cyl.

No electrification considered

3 Cylinder Engine Value Analysis

Delphi Powertrain
Comparison 1.6lt - 4cyl vs. 1.2lt - 3cyl.

No electrification considered

4cyl. GDi TCI EU6
3cyl. GDi TCI 2 step EU6
3cyl. GDi TCI stratified EU6
4cyl. GDi TCI EU6

25Euro/%

3cyl. Diesel EU6 (with SCR)
3cyl. Diesel EU6 (with DeNOx)
4cyl. Diesel EU6 (with SCR)

50Euro/%

4cyl. MPFI EU4, 1160kg

CO2 Reduction [%]

OEM - On Cost [Euro]
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Summary and Conclusions

- Global CO2 Regulations Will Require Substantial Engine Downsizing and Hybridization

- Significant Reduction in Euro 6 Standards Makes Diesel NOx Emissions Compliance More Challenging and Expensive
  - Global rollout expected and viable

- Gasoline Direct Injection Systems Enable Excellent Low End Torque and Responsiveness in Downsized, Boosted Engines

- 3-Cylinder Gasoline Direct Injection Engines Offer Similar Value in CO2 Reduction Capability (Euros / % CO2 Reduction) at a Significantly Lower On-Cost
  - Particularly Attractive for Compact / Sub-compact Vehicle Customers