An Overview of Gasoline Direct Injection

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Gasoline Direct Injection

Changing “The Rules”
Why GDI?

- **Fuel is injected under high pressure directly into the combustion chamber.**
  - Allows the precise control of charge stratification vital to ignite ultra-lean air / fuel mixtures.

- **Direct injection has less need for a Throttle.**
  - Eliminates pumping loss associated with drawing air around a conventional engine's butterfly valve.
**GDI vs PFI**

**PFI**
- 2875 Measurements for Calibration.
- Lambda Closed-Loop Control.
- TWC and Rich/Lean Cycle.

**GDI**
- 12,000,000 Measurements. (Engine Mapping)
- 40% More Computer Functions.
- High Pressure Pump, Injectors, Valves, and Fuel Rail.
- High Pressure & Exhaust Temperature Sensors
- NOx Storage Catalyst
GDI Advantage & Disadvantage

Advantages
- 25% Improvement in Fuel Economy
- 12–15% Reduction in Emissions
- Higher Compression

Disadvantages
- High Cost
- More Components
- NOx Storage Catalyst Required.
- Complex Strategies.
- Possibly Six Operating Modes.
Compression Ratios

- Higher Compression
- Turbo Charging
- Knock?
  - Gas Injected Just Before Ignition.
  - Less Time for Knock.
  - Colder Fuel at Ignition.
  - Tighter Controls.
  - Higher Compression Ratios and Boost Pressures.
  - Better MPG and Higher HP.
General Specifications

- **Fuel Pressure** = 500–2900 psi. (high side)
- **Injector Opening Voltage** = 50–90V Capacitor Kick
- **Injector ON time** = As little as 400μs. @ Idle
- **Transfer Fuel Pressure** = 50–60 psi.
Terminology

- **Stratified**
  - Fuel/Air Mixture is Rich around Spark Plug Only, Remaining Mixture in Cylinder is Lean.

- **Stratified Cold Start**
  - Retarded Ignition Timing, Increases Exhaust Temp, Faster Catalyst Warm-up.

- **Homogeneous**
  - Air and Fuel are Equally Mixed in Cylinder.
SI Engine Efficiency

81/100 km fuel consumption
S.I. engine in MVEG test cycle

- Effective work at power train: 13%
- Friction, additional consumers: 10%
- Pumping losses: 15%
- Non-ideal combustion, heat loss at chamber wall: 7%
- Losses caused by $\lambda = 1$: 45%

Losses of ideal process

Courtesy of Robert Bosch LLC.
Fuel Savings Comparison

Compact car, MVEG test cycle

- Exhaust gas recirculation: 3-4%
- Thermomangement: 3-5%
- Ideal stop: 5-7%
- Homogeneous lean: 6-8%
- Variable valve lift: 6-7%
- Gasoline direct injection: 10-15%

Theoretical potential: 25%

Courtesy of Robert Bosch LLC.
Enlarged NOx Catalyst

- EGR: Reduction of NOx engine out emission
- Pre-Catalyst: HC oxidation at lean burn, three way conversion at $\lambda = 1$
- NOx-Catalyst without oxygen storage
- LSF: Trim control at $\lambda = 1$, monitoring of catalyst
- Temperature Sensor: Operation conditions of NOx-adsorber, monitoring of pre-catalyst
- LSU: $\lambda$-control, control of catalyst regeneration, torque monitoring

Courtesy of Robert Bosch LLC.
NOx Regeneration

Regeneration during 100 s at 650 °C

8 h operation with 150 ppm sulphur

Courtesy of Robert Bosch LLC.
Different Spray Guide Designs

Wall guided, Swirl

Wall guided, Tumble

Spray guided

Courtesy of Robert Bosch LLC.
Tumble Concept Animation
Wall Guided Burn Concept - Swirl

Swirl Concept Animation
Pulse Width Times

Port injection

GDI

Injection pulse width in msec

Fuel amount

0.4  3.5  5  20

WOT

Idle

Courtesy of Robert Bosch LLC.
64 V capacitor discharge for initial injector opening.

.9ms (907μs) 2007 Volkswagen GTI 2L. Turbo

52 V Spike
Injectors Waveforms @Idle

2006 VW Passat 2.0T

Courtesy of Robert Bosch LLC.
Spray Patterns @ Pressures

10 MPa
1450 PSI

4 MPa
580 PSI

tv = 2.0 ms

\[ p_k = 100 \text{ kPa} \]
\[ p_k = 300 \text{ kPa} \]
\[ p_k = 560 \text{ kPa} \]

Courtesy of Robert Bosch LLC.
Vaporizing Fuel @ 10Mpa

Chronological jet development of a spin valve

Jet angle: 60°  steady flow: 15cm³/s  material: n-Heptan  system pressure: 10 MPa  environment: standard atmosphere

Courtesy of Robert Bosch LLC.
GDI System Overview

ETC = Electronic Throttle Control
1) intake and exhaust camshaft
2) ECU with integrated ambient pressure sensor

Bosch components specifically for DI

Source: Robert Bosch GmbH

Courtesy of Robert Bosch LLC.
Current Manufactures

- Audi
- Bosch GDI – Manifold Charge Valve
- Delphi
- Ford EcoBoost System – Turbo Charging
- General Motors
- Lexus – Hybrid Design (PFI & GDI)
- Mazda
- Mitsubishi
- ?????
Delphi System

Operating pressure 120 bar to 200 bar. (1740–2900 psi)

Single-piston design.

200 bar w/No Bounce

< .2 ms Between Multiple Injections Capability
Ford EcoBoost

- 500K Cars/Year Next Five Years
- 3.5L = 340 HP/ 340 lb.–ft Torque
- 2 – 5 MPG over 4.6L
- 150 – 200 lb. Lighter
- Less Fuel Less CO2
GM High Pressure Fuel System

- High pressure pump is driven off the camshaft (2150 psi, 140 bar)
- Fuel pressure regulator valve
- Rail-mounted fuel pressure sensor
- Integral pressure relief valve incorporated in HDP5 HP Pump

Courtesy of Robert Bosch LLC.
GM SIDI 3.6L

Mechanical One (1) Cylinder HIGH-Pressure Fuel Pump and Fuel Pressure Regulator Solenoid (FPR) w/Integral Pressure Relief Valve

Exhaust Camshaft (Bank 2)

Fuel Pressure Sensor

Pressure Tap

Courtesy of General Motors Corp
GM SIDI 3.6L

• 1 of 6 GM engines will be SIDI

• Features:
  1. Polymer-coated piston skirts
  2. 11.3–to–1 compression ratio.
  3. Closed-coupled catalytic converters.
  4. Fuel Pressure = Idle 35bar (508psi) to 120bar (1740 psi)
GM SIDI 3.6L

FPR:

- Spring pressure opened
- ECM provides PWM B+ (high side driver) and ground.
- Camshaft and crankshaft position sensor inputs synchronize the FRP regulator with the position of the eccentric on the camshaft.
- Fuel Pressure Regulation
  - FPR is held open for a portion of each piston stroke displacing fuel back into low pressure side.
- GM Service Manual is telling that story.
Cut-Away of HDP5

Pressure damper
Limp home valve
Outlet
Outlet Valve
Piston
Control Valve
Inlet Valve
Seal

Courtesy of Robert Bosch LLC.
Port Injectors

Direct Injectors
**Lexus: Port and Direct Injectors**

**In-cylinder Injectors:**

Pulsed–Timed individually to intake or compression stroke.

**Port injectors:**

Pulsed simultaneously, grouped, or sequentially according to operating conditions.

**Operating Modes**

- SFI D-4S Fuel Injection
  - Combines direct injection and port injection
  - Injection Operation
  - Feed Pump
  - High Pressure Fuel Injector
  - Delivery Pipe
  - Port Injector
  - EDU
  - ECM

**Fuel Systems**

- Warm-up (Stratified Combustion)
- Intake (Port Injection)
- Intake (Direct Injection)

- Normal Operation (Homogeneous Combustion)
- Intake (Port Injection)
- Intake (Direct Injection)
- Compression (Direct Injection)
Lexus 2 Modes of Operation

- **Stratified:**
  - Area around spark plug is richer than rest of cylinder.

- **Homogeneous:**
  - Fuel and Air are mixed throughout the cylinder.
Stratified Mode

- **Exhaust Stroke**: Fuel Injected into Intake Port.

- **Intake Stroke**: Homogeneous Mix Enters Cylinder.

- **Compression Stroke**: Fuel Injected into Cylinder Just Prior to TDC

- **Ignition**: Fuel is Directed by Piston Contour Around Spark Plug. Rich Mix Easily Ignites to Burn Lean Mix in Rest of Cylinder.
Homogeneous Mode

- **Exhaust Stroke:**
  - Fuel Injected in Intake Port.

- **Intake Stroke:**
  - Homogeneous Mix Enters Plus Fuel is Directly Injected as Homogeneous Mix Enter Cylinder for Mix Correction.
  - Utilizes Heat Evaporation of Cooler Fuel = Higher Efficiency /Power.

- **Compression Stroke:**
  - Mixture is Compressed.
High Pressure Fuel Pump and Electronic Pressure Regulator

3.5 to 4.5 MPa (508 to 653 psi)
Electric In–Tank Transfer Pump

Computer Controls Spill Valve Open Duration.

Longer open Time =

More gas Pushed Back into Intake Line =

Less Pressure
PWM of FPR to Cam Position

[Diagram showing the operation of a plunger lift with suction, inactive, and pressure rise phases.]

Plunger Lift

[Suction] [Inactive] [Pressure Rise]

Solenoid Spill Valve

(Valve Closed) (Valve Open) (Valve Closed)

Valve Closing Timing Control

Fuel Inlet

Check Valve (60kPa)

Pump Cam (Intake Camshaft)

[Inactive]

Return

To Delivery Pipe

[Pressure Increase]
Lexus SFI D-4S
Three Speed Fuel Pump Control

196 to 588 kPa
(28 to 85 psi)
Mitsubishi Start-Stop System

- Smart Idle Stop System (SISS)
  - Restart in 0.35 seconds (1/2 time of electric motor)
  - 10% fuel savings.
  - No Electric Motor.
  - Uses Direct Injection + Spark
SISS: Different Concepts

System operation

Forward operation

Reverse operation

Beginning of engine restart

Compression-stroke cylinder

Expansion-stroke cylinder

Reverse operation

Compression-stroke cylinder

Expansion-stroke cylinder

Start of forward operation

Compression-stroke cylinder

Expansion-stroke cylinder

Mazda's elegantly simple SISS stop-start relies on precise crank-angle sensing, injection, and ignition control.

Fuel is injected into compression-stroke cylinder

Ignition of fuel in compression-stroke cylinder causes reverse rotation

Ignition of fuel in expansion-stroke cylinder causes forward rotation that results in engine restart

Courtesy of Green Car Congress

Courtesy of Automotive Engineering
Mitsubishi

- **Two-Stage Combustion**
  - Late combustion fuel injection for catalytic warm-up
  - Exhaust gas temperature 700°C (1300°F).
- **Stratified Slight Lean Combustion**
  - Started few seconds after Two-Stage.
  - Immediate CO oxidation reaction.
  - Prevents CO poisoning.
Mazda DSIS 2.3L

Shared with Ford Escape, Focus, and Ranger.

Shaped Intake Ports
• Low Restrictions
• Wall Guided Swirl
GM SIDI Fuel Pressure Relief

- **W/O Scan Tool:** WAIT at LEAST 2 hours after the engine has been run, before removing the high pressure fuel line.

- **Use Scan Tool:**
  - Command the low pressure fuel pump relay OFF.
  - Start the vehicle and allow the engine to idle until the engine stops. (20–30 seconds)
  - Using the scan tool, verify that there is little to no fuel pressure.
Six Operating Modes
1. Homogeneous
2. Homogeneous Lean
3. Stratified
4. Homogeneous Stratified
5. Homogeneous Knock Protection
6. Stratified Catalysts Heating
## Bosch Injection Timing Chart

### Injection Timing of Operating Modes

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Exhaust open</th>
<th>Intake open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manifold injection</td>
<td></td>
<td></td>
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<tr>
<td>Homogeneous</td>
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<tr>
<td>Homogeneous lean</td>
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<tr>
<td>Stratified</td>
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<tr>
<td>Homogeneous stratified</td>
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<tr>
<td>Homogeneous knock protection</td>
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<tr>
<td>Stratified catalyst heating</td>
<td></td>
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</tbody>
</table>

- **PFI**
- **6 Operating Modes**

Courtesy of Robert Bosch LLC.
Homogeneous Mode

- 14.7–1
- Throttle Controlled.
- Single Injection
- Even Mixture Across Chamber
- Used for High Torque/High Speed
Homogeneous Lean Mode

- Smooth Switch (Stratified/Homogeneous)
- Throttle Controlled
- Charge Motion Valve Closed
- Lambda > 1 (excess air)
- Single Injection
- Less Fuel Consumption
- Some Torque/Speed Loss
Stratified Mode

- Throttle Valve is Wide Open
- Charge Motion Valve Closed
  - Ram–Air Swirl Effect
- Injection Just Before Spark
  - Lean Combustion
- Occurs Only Around Plug
  - Low Cylinder Wall Heat Loss

Disadvantages
- Limited Torque/Speed
- Soot Formation & Short Mixture Prep Time.

Advantage
- 20% Fuel Conservation = Less Emissions
Homogeneous Stratified Mode

- Throttle Opening Charge Motion Valve Closing
- Double Injection
  - 1 on Intake Stroke & 1 on Compression Stroke
- Lean Mix w/Rich Mix Around Spark Plug
  - Rich mix burns Lean mix
- Advantages:
  - Smooths Switch Between Modes
  - Decreases Emissions w/Smooth Torque
  - Less Fuel than Homogeneous Lean Mode
  - Lower Emissions than Stratified Mode

Courtesy of Robert Bosch LLC.
Homogeneous Knock Protection Mode

- Charge Motion Valve Open
- Increases Knock Limit at Lower RPMs
  - Useful at full load
- 2 Injections
  - 1 on Intake (homogeneous lean)
  - 1 on Combustion (target desired Lambda)
- Combustion Injection Lowers Mix Temp
- Lowers Need for Retarding Timing
- Lowers Emissions & Fuel Consumption

Courtesy of Robert Bosch LLC.
Stratified Catalyst Heating Mode

- Charge Motion Valve Closed.
- Fast Warm-Up of Catalyst System
  - Pre-catalyst & NOx Catalyst.
- 2 Injections
  - 1 just before combustion (stratified mode).
  - 1 just after combustion (heats exhaust).
- Used to De-Sulfurize NOx Catalyst
  - 1200°– 1300° F.
Questions?

Website: http://www.siucautomotive.com/autoindex.html

Pictures, Illustrations and Animations
Courtesy of Ford, Mazda, Mitsubishi, Toyota, GM, and Robert Bosch LLC.