Increased efficiency through gasoline engine downsizing

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Increased Efficiency through Gasoline Engine Downsizing

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Contents:

- Introduction
- Technologies for Downsizing
- Low-Speed Pre-Ignition
- LSPI Mechanisms
- Research
- Conclusion
Introduction

Technologies for Downsizing

Low-Speed Pre-Ignition

LSPI Mechanisms

Research

Conclusion
Worldwide CO2 emission fleet targets for new passenger cars and light trucks

<table>
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ACEA commitment
- EU LCV: 175g
- 34.1 mpg (combined)
- EU: 130g (120g)
- EU: 95g

New Discussions in US and WEU
- US
- EU

Target
- Vision/scenario

CAFE = Corporate Average Fuel Economy
PC = Passenger Cars
LT/LDT = Light Trucks (pick-ups, vans, SUVs)
MD(P)V = Medium Duty (Passenger) Vehicles
GHG = Greenhouse Gases
NHTSA = National Highway Transportation and Safety Administration
CARB = California Air Resources Board
mpg = miles per gallon
Technologies for Gasoline Engine Fuel Economy Improvement

• **Gasoline direct injection** (GDI) (Homogenous and stratified lean)
• **Exhaust gas recirculation** (EGR)
• **Variable valvetrains** (camshaft phasing, profile switching, variable lift and duration systems)
• **Controlled auto ignition** (CAI) or homogeneous charge compression ignition (HCCI)
• **Gasoline engine downsizing**
• **Friction reduction**, engine downspeed
Gasoline engine downsizing / downspeed: are processes whereby the speed / load operating point is shifted to a more efficient region through the reduction of engine capacity whilst maintaining the full load performance via pressure charging.
Downsizing reduces fuel consumption thanks to:

- **Pumping losses reduction:**
  - Less volume swept on each engine revolution;
  - Higher average load on driving cycle (higher average intake pressure).

- **Gases-to-wall heat transfer reduction:**
  - Reduced internal surface area;
  - Shorter flame travel distance (faster combustion >> reduced gases-wall heat exchange duration).

- **Friction losses reduction:**
  - Smaller moving parts.
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Turbocharging & Supercharging:

- Turbochargers use exhaust energy
- Not mechanically connected to the shaft
- Turbos are small and run at high speeds

- Superchargers use crankshaft energy
- Mechanically connected to the shaft
- Superchargers are large and run slow
Boosting System Schematics

A) Single Turbocharger

B) 2-Stage Turbocharger

C) Supercharger & Turbocharger

D) Electric Supercharger & Turbocharger

Graph:
- Torque vs. Engine Speed (rpm)
- Output

Legend:
- Torque
- Output
Steady State Full Load Curves with Different Boosting Systems

- **LP turbo only**: the low speed BMEP falls significantly below the target

- **2-stage turbocharger system**: achieving in excess of 23 bar BMEP at 1000rpm and reaching 30 bar BMEP by 2000rpm

- **Addition of the VTES**: also significantly improve the low speed BMEP
Transient Load Step with Different Boosting Systems

- **LP turbo only:** for reference
- **2-stage turbocharger system:** is clear to see, with an almost linear response of IMEP against time.
- **VTES and LP turbo:** is marked, with an almost step increase to 18 bar IMEP after about 0.35 seconds and at t = 1.0 second achieving 202% of the NA IMEP.

Transient load step performance (SAE 2009-01-1053)
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Low-Speed Pre-Ignition (LSPI)

• Several SI abnormal combustion, knock and pre-ignition, have been addressed with improved engine design and control schemes,
• A new mechanism, called **Low-Speed Pre-Ignition (LSPI)**, has become a consideration in the pursuit of engine downsizing and low speed, high specific power strategies and the implementation of an optimized turbocharged GDI engine with maximum efficiencies.

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**In-cylinder Pressure Curve of Super Knock** (SAE2012-01-1141)

**Typical LSPI Event with Multiple LSPI Engine Cycles** (SAE 2012-01-1148)
The Occurrence of LSPI

- The transition from normal combustion to Super Knock occurs suddenly with no warning.
- Once Super Knock occurs, it repeatedly appears for several cycles, and the number of cycles is variable.
- The maximum pressure of Super Knock is variable at each cycle.
- Normal combustion and Super Knock occur alternately.
- Super Knock always subsides without runaway.
- The causes of these characteristics are not clear.

In-cylinder pressure trend during Super Knock (SAE2012-01-1141)
The normal “spark ignition end–gas knock” phenomenon can at least be suppressed by retarding spark advance.

A LSPI event, however, following irregular ignition, is beyond the control of any actuator.

One potential cause for LSPI is ignition of fresh charge by hot in-cylinder components.

The mechanisms of pre-ignition particularly the effects of different fuels, are not fully understood.

Progress of a typical pre-ignition, false colour images. Top dead centre at 180 CAD, spark ignition at 185 CAD
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Engine Operating Condition vs. LSPI

Variations in engine operating conditions compared to Baseline case

Engine Operating Condition Effects on LSPI (SAE 2011-01-0342)

- engine control parameters: spark timing, manifold temperature, coolant temperature have a limited impact on the frequency at which LSPI occurs.
- two most dominant factors are engine load as governed by fuelling rate (energy flux) and in-cylinder air/fuel ratio.
Engine Fuelling Strategy vs. LSPI

LSPI Trends, PFI/GDI Ratio Sweep

LSPI Activity for PFI versus GDI
(SAE 2012-01-1148)
GDI Injection Timing vs. LSPI

GDI Injection Timing with Reference to Valve Lift Profile

GDI Injection Timing Effects on LSPI (SAE 2012-01-1148)
Fuel Compositional vs. LSPI

- Fuel chemical composition has a strong impact on the likelihood and intensity of LSPI.
- High aromatics increase the frequency of LSPI.
- Low aromatic blends reduced the frequency of LSPI.
- Low-aromatics fuel showed an increase tendency to auto-ignition and knock characterized by the presence of a low-temperature heat release regime prior to the main combustion phase.
Cooled-EGR vs. LSPI

- The combustion cooling and knock mitigating potentials of EGR,
- it was observed, that even small amounts of cooled EGR (6% to 10%) can significantly reduce the likelihood (frequency) as well as the intensity of LSPI.
Piston Design vs. LSPI

LSPI Test Results using Chamfered Pistons (SAE 2012-01-1148)

Test Conditions:
- Test Duration: 30,000 cycles
- Speed: 1250 rpm
- Load/BMEP: 12.4 bar
- MAT: 60°C
- Intake Cam Phasing: 33° bTDC
- Spark Time: ~4.0° bTDC
- Phi: 1.0
- Fuel Flow Rate: 13.6 kg/hr (582 MJ/hr)

Chamfered Piston Crown
Piston Crevices vs. LSPI

LSPI Frequency versus Piston Crown Geometry
(SAE 2012-01-1148)
Lubricant Oil vs. LSPI

- the type of base oils and additives in the engine oil have significant effects on LSPI frequency,
- the auto-ignition temperature of engine oil under high pressure correlates well with LSPI frequency.

LSPI Response to Calcium Content Level

(SAE 2012-01-1615)
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Pre-Ignition Mechanisms
Gasoline auto-ignites in a three-stage combustion and then could be defined a cool flame delay, a pre-ignition delay, and a final ignition delay, each represented by a heat release maximum.

Modeling result of the heat release for the gasoline surrogate, at an inlet temperature of 70°C, a compression ratio of 13.5 and an equivalence ratio of 0.462.
Modelling of Flame Speed using Combustion Kinetics, 1

- **Transient laminar burning velocity model**: consists of 0D thermo-model and a reduced combustion kinetics mechanism
- it requires minimum priori calculations and experimental data.
- includes **in-flame combustion calculations**, offering the potential for engine combustion and emission formation simulation.

Development of a H$_2$-Air flame at $\Phi=0.6$, 298K and 1bar. Measured flame radii are: 5.8, 12.1, 17.8, 23.9, 30.0, 35.0mm.

Variations of reactants mole fractions and temperature during H2-Air combustion at $\Phi=1.0$, 1000K and 1bar.
Comparisons of simulated unstretched laminar burning velocities and numerical correlations

Comparisons of transient stretched laminar flame speeds. Solid lines represents corresponding simulation results.
Lubricant Oil Droplets

- The release of lubricant oil droplets from the cylinder liner turned out to be the most probable explanation for the occurrence of pre-ignition.
- Cylinder liner wetting due to the lateral injector position

Spatial distribution of pre-ignition origins
Fuel Injection Modelling

Spray Simulation:

**PHYSICAL PROCESSES**
- Turbulent Flow
  - Primary Break-up
- Secondary Break-up
- Droplets
  - Vaporisation
- Combustion
- Soot Generation

**NUMERICAL MODELS**
- Turbulence
- Primary Atomisation
- Secondary Atomisation
- Droplet Collision
- Droplet Break-up
- Vaporisation
- Self Ignition
- Heat Release
- Chemical Kinetics
Phase Doppler Anemometry (PDA)

Two beam transmission optics

Small Droplet Flow

Twin receiver optics

Detector A

Detector B

Detector B Output

Detector A Output

Detector B Output

Detector A Output

Detector A Output

Phase Lag

Time

Detector A Output

Detector B Output

Detector A Output

Detector B Output

Detector A Output

Detector B Output

Detector A Output

Detector B Output

Detector A Output

Detector B Output
Measurement on injector centerline 18mm from tip
Droplet Flow Field and Dynamics

Droplet Size

Percent of Samples

D10 Mean Diameter = 9.8 um
D32 Sauter Mean Diameter = 20.4 um

Mean Droplet Size Increases

9.8 um

23.6 um

1440

Log

Samples

0
Fuel Spray Light Sheet Imaging System

- Laser Control Unit
- Engine Timing Unit
- Injector Driver Module
- Camera
- CPU
- Laser Sheet Optics
- UV Laser
- Digital Storage Scope
- Injector
- Delayed Trigger (1)
- Delayed Trigger (2)
- Engine Timing Unit
- Trigger
Fuel Spray Imaging:

- 1 bar Back Pressure
- 6 bar Back Pressure
- 12 bar Back Pressure
Optical Engine

- Bore: 80.5 mm
- Stroke: 88.2 mm
- Capacity: 0.45 litres
- Compression ratio: 10.5:1
- Number of valves: 4
- Maximum speed: 5000 rpm
  - Limited by Valve Train to 4000 rpm
- Homogeneous Direct Injection
  - Near vertical
- Liner: Fused silica
- Piston crown: Titanium
- Piston window: Sapphire
Conclusions

• Gasoline engine downsizing / downspeed shift the speed / load operating point to a more efficient region.
• Furthermore, downsizing reduces fuel consumption by reducing pumping losses, gases-to-wall heat transfer, and friction losses.
• Low-Speed Pre-Ignition (LSPI) forms a new challenge.
• Two most dominant factors of LSPI are:
  – engine load as governed by fuelling rate (energy flux) and,
  – in-cylinder air/fuel ratio.
• GDI reduces the tendency of LSPI, the injection timing has a significant effect.
• Fuel chemical composition has a impact on the frequency and intensity of LSPI.
• Cooled EGR reduces the frequency as well as the intensity of LSPI.
• Piston design and crevice volume all have significant effects.
• The auto-ignition temperature of lubricant correlates well with LSPI frequency.
• Flame modelling based on thermo-model and reduced combustion kinetics offers the potential of engine combustion and emission formation simulation.
• Phase doppler anemometry (PDA), fuel spray light sheet imaging, and optical engine together reveal the fuel spray, mixing, and provide direct characterise GDI, EGR, lubricant droplets inside cylinder, and evaluation of piston design and crevice volume.
Q & A

Thanks!