Gasoline Engine Performance and Emissions
Future Technologies and Optimization

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- Fuel Economy Trends and Drivers – USA and Europe
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- Optimization of Advanced Gasoline Combustion Systems
  - Example: Optimization of a CAI enabled flexible valvetrain engine
- Summary and Conclusions
Fuel Economy Trends and Drivers – USA and Europe

- Significant improvements since 1995:
  - Increased diesel fleet (25% to 45% in last 5 years)
  - Some improved gasoline engines
- 2002 & 2003 data shows levelling off
- Diesels near saturation
- Emissions legislation limiting dieselization
- Increased pressure for improved fuel economy
  - CO₂ legislation? stricter CAFE? High Fuel Prices?

Further improvements in gasoline powertrain efficiency will be required that are cost effective and attractive to consumers

Production Advanced Gasoline Technologies

**Stratified Charge SIDI**
- Failed to deliver fuel economy promise
- Work continues on central injection (2nd generation)
- NOx challenge difficult to overcome in US

**Homogeneous \(\lambda=1\) SIDI**
- Fuel economy, emissions & performance benefits
- Synergies with many other technologies
- Less complicated/expensive than stratified, lower risk

**Cylinder Deactivation**
- Fuel economy potential similar to Stratified SIDI
- Relatively easy and inexpensive to implement
- Particularly suitable for OHV engines
- Easier to apply to V8 than V6 engines
- Advanced NVH technologies required for full benefit

**Continuously Variable Cam Phasing**
- Most widely adopted advanced gasoline technology?
- Fuel economy, emissions & performance benefits
- Best benefits are from dual independent phasing
- Phaser speed/controls can limit benefits

**Fully Mechanical VVA**
- Unthrottled operation, throttled across intake valve
- Potential friction reduction from reduced valve lift
- Complex mechanical system
- Only in production with BMW

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Baseline: V8 PFI Gasoline Engine Without EGR, Cost of $2,000, 500,000 units p.a.

<table>
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<th>Cost Benefit vs HSDI</th>
<th>Better</th>
<th>Worse</th>
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<td>Full VVA PFI</td>
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Emissions and performance benefits must also be considered
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Lean Boost DI (LBDI)

- Control Octane requirement by
  - direct injection
  - lean operation at full load
  - enables high compression ratio
- Stratified operation at part load
- Fuel economy approaching diesel
- Lower cost and weight
- Real world fuel economy benefit
Lean Boost DI demonstrator has delivered downsizing benefits - Fully lean operation at all conditions delivers the fuel economy of a diesel with gasoline NVH and lower cost

- LBDI delivers fuel economy through downsizing, boosting & lean operation with high compression ratio
- Octane requirement controlled by:
  - direct injection
  - lean operation at full load
  - stratified lean DI operation at part load

1.1l LBDI maximises hardware value:
- Higher power than 1.6 l (+5%)
- Higher torque than 1.6 l (+20%)
- Higher economy NEDC >20% better
  - 132 g/km EUDC CO₂
- Matched or better acceleration
- Economy over wide operating range
Uses cooled EGR as a dilutant to reduce octane requirement

Enables high CR boosted operation

Lambda=1 operation with Three-way Catalyst

Cost penalty 30%

Fuel economy benefit 12%

Technical risk medium/high
DI Gasoline 2 / 4 Stroke Switching Concept improves efficiency through extreme downsizing – 2 stroke operation provides enhanced low speed torque

- Very high low speed torque - 220 Nm/litre
- Ultimate fun to drive (torque and revs)
- HCCI at part load?
- LNT required for 2 stroke mode only

(not required for typical urban or motorway driving)
Cost/FE Benefit Trade-off Advanced Gasoline Technologies

Baseline: V8 PFI Gasoline Engine Without EGR, Cost of $2,000, 500,000 units p.a.

Emissions and performance benefits must also be considered

Downsizing technologies offer the greatest fuel economy potential
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Increased variability requires a mathematical optimisation technique
– DoE provides an efficient, robust analytical solution

- New powertrain configurations have increased challenges in optimisation:
  - More variables
  - More interactions
  - More non-linear responses
  - More emphasis on robustness

- Design of Experiments can create a “virtual” engine or powertrain and reduce experimental work leading to:
  - Shorter development times
  - Better, more robust solutions
  - Increased engineering understanding

- DoE is now essential for many engine development and calibration tasks

- Two requisites for successful DoE
  - Good tools, especially for modeling and optimisation
  - Intelligent implementation of DoE process
    - Planning ⇒ Design ⇒ Testing ⇒ Modeling ⇒ Validation ⇒ Optimisation
Example – Optimisation of a Controlled Auto Ignition enabled gasoline engine using a flexible valve train providing variable lift & phasing on intake & exhaust

BMW Valvetronic system applied to intake and exhaust system on 4 cylinder engine
A Design-of-Experiments (DoE) approach using Stochastic Process Modelling (SPM) and optimiser tools identified variable settings for best fuel economy

- **Variables**
  - Inlet valve phasing (IVP)
  - Exhaust valve phasing (EVP)
  - Inlet valve lift (IVL)
  - Exhaust valve lift (EVL)
  - Manifold air pressure (MAP)

- **Responses Modelled**
  - BMEP
  - Fuel consumption
  - HC
  - NOx
  - CO
  - COV (Net IMEP) (stability)
  - 50% Mass Fraction Burned
  - Ignition to 10% MFB
  - 10 – 90 % MFB
  - PMEP
  - Optimum spark timing (MBT)

- Data sets obtained for inlet valve throttled, load ranges 1000-3500 rev/min with inlet throttle wide open.
  - Control variables IVP, EVP, IVL, EVL, MAP
Comparison of model output and measured data shows good correlation – Data shown at minimum fuel consumption

**2000 rev/min throttled**

- DoE model - Max lift - variable inlet and exhaust phase - throttled unconstrained optimum BSFC
- Validation test data

**2000 rev/min valve lift controlled**

- DoE model - variable inlet and exhaust lift and phase - unconstrained optimum BSFC
- Validation test results

**1000 rev/min valve lift controlled**

- DoE model - variable inlet and exhaust lift and phase - unconstrained optimum BSFC
- Validation test results

**3500 rev/min valve lift controlled**

- DoE model - variable inlet and exhaust lift and phase - unconstrained optimum BSFC
- Validation test results
Validated optimum settings show that CAI combustion provides significant BSFC gains compared with normal SI operation. Results shown for 2000 rev/min load range. VCP = Variable Cam Phasing, VVL = Variable Valve Lift.

Baseline – fixed maximum lift and variable inlet and exhaust cam phasing

Variable inlet and exhaust phasing and lift – SI operation

Variable inlet and exhaust phasing and lift – CAI operation

BSFC [g/kWh]

BMEP [bar]
Typical pressure/volume characteristics for CAI operation show recompression in exhaust stroke

- Negative valve overlap creates recompression cycle
- Recompression largely reversible
- Higher trapped mass due to high residuals – higher pressures
- Lower losses across intake valve – reduced throttling due to high residuals
CAI combustion provides significant BSFC gains compared with normal SI operation mainly due to pumping work reduction. Results shown for 2000 rev/min load range.

VCP=Variable Cam Phasing  VVL=Variable Valve Lift

Fuel Consumption benefit versus Dual VCP

Dual VCP + Dual VVL with SI combustion

Dual VCP + Dual VVL with CAI combustion

-1.0 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

PMEP [bar]

BMEP [bar]