Advanced Combustion Strategies for High Efficiency Engines of the 21st Century

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Estimated U.S. CO$_2$ Emissions in 2008:
~5815 Million Metric Tons

Source: LLNL 2010. Data is based on DOE/EIA-0573(2008), December 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon embodied in industrial and commercial products such as plastics is not shown. The flow of petroleum to electricity production includes both petroleum fuels and the plastics component of municipal solid waste. The combustion of biologically derived fuels is assumed to have zero net carbon emissions – lifecycle emissions associated with biofuels are accounted for in the Industrial and Commercial sectors. Emissions from U.S. Territories and international aviation and marine bunkers are not included. Totals may not equal sum of components due to independent rounding. LLNL-MI-411167
Estimated U.S. Energy Use in 2009:
~94.6 quadrillion BTUs

Source: LLNL 2010. Data is based on DOE/EIA-0384(2009), August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant “heat rate.” The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527
**DOE Vehicle Technologies Program Technical Targets**

**DOE Passenger Car Goals**: Increase peak engine efficiency from 34% to 45% and vehicle fuel economy by ~30% by 2016.
How Can We Improve Brake Thermal Efficiency ($\eta_b$)?

- $\eta_b$ is a product of two efficiencies:

$$\eta_b = \eta_m \eta_{i,n}$$

$$\eta_m = \frac{W_b}{W_{i,n}} : \text{Mechanical Efficiency}$$

$$\eta_{i,n} = \frac{W_{i,n}}{Q_{in}} : \text{Net Indicated Thermal Efficiency}$$

Hypothetical $\eta_m$ for a light duty engine

Reducing Displacement/Increasing Load

$\eta_{i,n}$ from fuel-air cycle simulation

Increasing Dilution
To identify potential high efficiency operating regions, GT-Power simulations were performed with a simple Wiebe function combustion model for a range of boost pressures

- 25°10-90 burn duration, CA50 at 10° ATDC

Family of curves represents operation at a given boost pressure for a range of $\Phi$

Regime of high efficiency operation ($0.4 < \Phi < 0.6$) combines:
- Dilute combustion
- Boosted operation
- High mechanical efficiency

Due to high levels of charge dilution, it is difficult to use the conventional spark ignited (SI) combustion mode in high efficiency regions (0.4 < Φ < 0.6).

HCCI on the other hand lacks flames and can run extremely dilute, but is load limited due to excessive combustion rates.

SACI (Spark Assisted Compression Ignition) combines both SI and HCCI combustion modes:
- Begins with spark ignited flame propagation
- Completed with auto-ignition

Images of SACI Combustion

Drive Cycle Simulations with Different Combustion Modes

- GT-Drive simulations of EPA UDDS (city) and HWFET (highway) drive cycles with maps from GT-Power simulations
  - 1490 kg vehicle
  - Peak torque and power maintained at 281 Nm, 161 kW
- The benefits of advanced combustion (HCCI + SACI) with boosting and downsizing appear to be relatively independent
  - Best results obtained by combining both strategies
- Fuel economy gains of up to 58% are possible relative to base

<table>
<thead>
<tr>
<th>CASE</th>
<th>Combustion Mode</th>
<th>Air Handling</th>
<th>Size</th>
<th>City/Hwy (mpg)</th>
<th>FE GAIN</th>
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<td>40.3</td>
<td>+58%</td>
</tr>
</tbody>
</table>

LTC (Low Temp. Comb.) Modes

SACI Combustion Experiments: UM FFVA Engine

- Engine Displacement: 550 cc
- Bore: 86 mm
- Stroke: 94.6 mm
- Connecting Rod Length: 152.2 mm
- Piston Pin Offset: 0.8 mm
- Compression Ratio: 12.5:1
- Number of Valves: 4
- Piston Shape: Shallow Bowl
- Fuel Type: Gasoline 87 (RON+MON)/2

**Sturman Hydraulic Valve System**
- Fully-flexible valve actuation (FFVA)
- Four valves actuated electro-hydraulically
- Variable lift, timing, duration
- Independently controlled
Internal EGR for Charge Dilution

- **Negative Valve Overlap (NVO)**
  - The exhaust valve is closed early during the exhaust displacement stroke and the intake valve is opened late during the intake stroke
    - This retains products from the previous cycle (internal residual)
  - Can control internal residual quantity from cycle to cycle
  - Internal residual fraction increases with more NVO
  - Varying internal residual changes compression temperature, which affects auto-ignition combustion phasing
Load Extension of LTC with SACI

- SAE 2011-01-1179 (Manofsky et al.)
  - Demonstrated control over burn rate and combustion phasing at various loads
  - Extended high load limit to ~7.5 bar IMEPₙ

![Graph showing SACI with Φ = 1 and HCCI with Φ < 1](image)
Current Study

- **Goals**
  - Examine methods for modifying heat release behavior at constant load and CA50
  - Control burn rate (CA 10-90) and combustion phasing (CA50) *independently*

- **Approach**
  - Change both variables (spark timing *AND* compression temperature) simultaneously
  - Temperature will affect flame propagation rate and timing of auto-ignition
  - Spark timing should compensate for the change in temperature, allowing constant CA50
Vary Spark and Compression Temperature at Constant CA50 (~8 dATDC) and Load (~6.5 bar IMEPn)

- **Strategy**
  - Constant fueling rate of 19 mg/cycle
  - Constant $\Phi = 1.0$, $\Phi' = \Phi (1 - \text{EGR}) \sim 0.62$
  - Constant intake temperature (45° C)
  - Vary temperature by trading off NVO and external EGR
  - Compensate for changes in combustion phasing with spark timing
Results

- Time of auto-ignition = maximum change in slope of rate of heat release
- Burn rate can be controlled at constant CA50 – addresses a major shortcoming of HCCI
Possible explanations

- As more mass is burned by the flame, less mass is available for auto-ignition.
- For a higher portion of flame based heat release, the mass consumed by auto-ignition is closer to the wall and has a higher temperature gradient.
Operational Constraints

As spark is advanced:
- More mass is consumed by the flame
- Less mass auto-ignites simultaneously
- Trends are opposite of what advancing spark alone gives
- Ringing intensity and NO\textsubscript{x} decreases
- COV of IMEP\textsubscript{n} increases
  - Caused by flame or auto-ignition?
Effect on Thermal Efficiency

- Thermal efficiency remains relatively constant despite changes in compression temperature and burn rate.
- At constant load, we can manipulate the combustion behavior (to reduce NO$_x$ and ringing) without negatively affecting thermal efficiency.
Conclusions and Future Work

- Thermodynamic and drive cycle simulations indicate that significant improvements in IC engine brake thermal efficiency can be made relative to conventional powertrains with downsized boosted combustion
  - Additional gains can be made by operation within the advanced combustion regime (HCCI + SACI combustion modes)
  - Additional measures will be required to meet future CAFE regulations – 54.5 mpg

- SACI combustion is one means of accessing the advanced combustion regime
  - This has been demonstrated for naturally aspirated operation
  - Future work will ideally focus on boosted, SACI combustion
Acknowledgements

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Thank You and Questions?

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Timing and Burn Duration Effects

- For reasonable burn durations, CA50 is more important to gross efficiency than burn duration.
- Unfortunately, brake efficiency does not scale with gross efficiency trends.
  - FMEP (speed) – nearly constant in these plots.
  - Relative friction becomes much more important at low load.
    - This causes the departure between gross and brake efficiencies and is a problem with low load operation.

The Effect of Gamma

- Gross efficiency improves with dilution
  - Low burned gas temperatures lead to higher gamma

![Graphs showing the effect of gamma on efficiency and temperatures](image-url)
Air vs. EGR Dilution

![Graph showing the comparison between Air Dilution and EGR Dilution. The graph plots Brake Efficiency (η) against BMEP (bar). The regions HCCI, ADV. COMB, and SI are highlighted. The curves represent different conditions: Air Dilution, EGR Dilution (Φ = 1), EIVC (SI; Φ = 1), and Throttled (SI; Φ = 1).]