Achieving High-Loads with HCCI & Partially Stratified Low-Temperature Gasoline Combustion (LTGC)

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CRC Advanced Fuel and Engine Efficiency Workshop
Baltimore, MD  February 25 – 26, 2014

Sponsor:
U.S. DOE, Office of Vehicle Technologies
Program Managers: Gurpreet Singh and Leo Breton
Motivation and Objectives

- Global demand for transportation fuels is increasing and CO₂ emissions from transportation is a major source of GHG
- Improved engine efficiency is an important part of the path forward.
- Critical that both gasoline-like & diesel-like fuels be used efficiently.
  - Current diesel engines are very efficient, but gasoline (light-fuel) engines are not.
- Low-temperature gasoline combustion (LTGC) has the potential to provide high efficiencies with very low NOx and PM emissions at a reasonable cost.
  - LTGC ⇒ HCCI, partially stratified variants of HCCI, spark-assisted HCCI, etc.
- Historically, the limited max. load of LTGC has impeded its implementation.

Objectives:
- Summarize recent work showing that properly applied, intake boosting can substantially increase loads achievable with LTGC/HCCI ⇒ diesel levels.
- Show how partial fuel stratification (PFS) can provide further performance improvements in the high-load range.
**Premixed Fueling**

**Good LTGC Operating Conditions**
- Ringing Intensity ≤ 5 MW/m²
- $\eta_{\text{combust}} > 96\%$, higher loads >98%
- NO$_x$ and Soot < US 2010 Limits
- COV of IMEP < 2%

**Cummins B**
0.98 liter / cyl.

All data are at 1200 rpm
LTGC High-Load Limits

- Naturally aspirated – max. load ~5 bar IMEP ⇒ knock/stability limit.
- Intake boosting offers potential for higher loads ⇒ maintain dilution needed for high eff. & low NO\textsubscript{X}.
- CA50 control is critical
  - Boosting enhances autoignition.
  - Increased load with boost requires more CA50 retard to avoid knocking.
- Reduce T\textsubscript{in} from 130°C at P\textsubscript{in} = 1 bar to 60°C, then add EGR to further slow autoignition.
- Allows a large increase in fueling ⇒ Max. IMEP\textsubscript{g} = 16.3 bar at P\textsubscript{in} = 3.25 bar for regular 87-AKI gasoline (zero ethanol).
- Load limited by max. P\textsubscript{cylinder} ~ 155 bar. ⇒ Estimate IMEP\textsubscript{g} = 20 bar for P\textsubscript{cyl} = 200 bar.
- Substantial CA50 retard with good stability is key to controlling knock with boost.
CA50 Retard and Stability

- Stability depends on $dT/d\theta$ prior to onset of main combustion.
- $dT/d\theta$ increases with intake boost.
  - Allows more retard with good stability.
- Compare HRR curves $\Rightarrow$ aligned by peak HRR & normalized by total HR.
- Shows that the cause is increased ITHR (intermediate-temperature heat release) at higher boost.
  - Increases greatly $P_{in} = 100 - 180$ kPa, $T_{in}$ is reduced from 130 $\rightarrow$ 60°C.
  - Little change for $P_{in} > 180$, $T_{in} = 60$°C.
- Increased ITHR due to both $\uparrow P_{in} \& \downarrow T_{in}$

More details in SAE 2010-01-1086
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- Increased ITHR due to both \( \uparrow P_{in} \) & \( \downarrow T_{in} \)

More details in SAE 2010-01-1086
High-Load Limit – Premixed (PM)

- Gasoline reactivity increases w/ boost ⇒ use EGR to control CA50.
- **E0**, 87-AKI: O₂ limited for \( P_{in} \geq 2.6 \) bar ⇒ Load limit = 16.3 bar IMEP₉.
- Blending with ethanol significantly reduces EGR requirement with boost.
  - More air in charge ⇒ higher fueling.
- **E10**, 90.5 AKI: O₂ limited, \( P_{in} \geq 2.8 \) bar ⇒ Load limit = 18.1 bar IMEP₉.
- **E20**, 93-AKI: O₂ limited, \( P_{in} \geq 3.6 \) bar ⇒ Load limit = 20.0 bar IMEP₉.
- **CF-E0**, 93-AKI: O₂ limited \( P_{in} \geq 2.7 \) bar ⇒ Load limit = 17.7 bar IMEP₉.
- At boost, CF-E0 behaves more like E0 or E10 ⇒ Despite AKI like E20.
- Ringing \( \leq 5 \), ultra-low NOₓ & soot.
- High-loads limited by \( P_{max} < 155 \) bar.
Controlling the HRR with Partial Fuel Stratification (PFS)

- PFS is effective for controlling HRR, but has two requirements:
  1) Fuel autoig. must be \( \phi \)-sensitive
  2) Appropriate \( \phi \)-distribution

- Gasoline \( \phi \)-sensitive with boost.
  \( \Rightarrow \) Ethanol is not \( \Rightarrow \) Correlates w/ ITHR

- Sequential autoignition slows HR.
  \( \Rightarrow \) Higher load and/or adv. CA50 w/ \( R \leq 5 \).

- **Std. PFS**: premix 80-90% + late DI.
- **Early-DI PFS**: inject all fuel at 60°CA.
  - Images show not completely mixed.
  - Allows \( T_{in} = 30^\circ C \) \( \Rightarrow \) high \( \rho \), less EGR, less heat transfer loss, and higher \( \gamma \).
Benefits of PFS, $P_{in} = 2.4$ bar

- With boost, fuel autoignition becomes $\phi$-sensitive.
  - PFS reduces HRR & PRR.
    - Allows significant CA50 advance, or higher load at same CA50
      → with Ringing $\leq 5$ MW/m$^2$.
- **E10:**
  - Std. PFS (PM + ~9%DI) very effective for increasing T-E & load vs. PM.
    > Increases max. load compared to PM.
  - Early-DI PFS further increases T-E.
    > Lower $T_{in}$ ⇒ less heat loss & higher $\gamma$.
    > CA50 only slightly more advanced.
- **CF-E0:** Like E10, Early-DI increases T-E and max. load compared to PM.
  - Max. load increased to 15.2 bar.

- For both fuels, PFS significantly improves T-E and increases max. load.
High-Load Limit – PM and PFS

- PFS fueling $\Rightarrow$ higher loads than PreMixed (PM) for the same boost.
  - **Std.-PFS** increases Max. Load at intermediate boost ($T_{in} = 60^\circ C$).
    > No increase at higher $P_{in}$ because $O_2$ limited.
  - **Early-DI PFS** allows $T_{in} = 30^\circ C$ $\Rightarrow$ less EGR required ($> O_2$), more charge mass.
    > Substantial increase in Max. Load for $P_{in} \geq 2.4$ bar.

- **CF-E0, Early-DI** $\Rightarrow$ IMEP$_g$ = 19.4 bar @ $P_{in} = 3.0$ bar v. 3.45 bar for E20.

For all boosted data, NO$_x$ $\leq$ 10% of US 2010 and Smoke is not detectable.
Summary and Conclusions

- Intake boosting allows significantly higher loads with LTGC/HCCI.
  - Use EGR and reduced $T_{\text{in}}$ to control autoignition timing.
  - No knock, very good stability, high efficiency, and ultra-low $\text{NO}_x$.

- Key to this success is the ability to substantially retard combustion phasing $\Rightarrow$ CA50 to 379°CA (19°aTDC) with very good stability.
  - Possible because the ITHR increases significantly with boost.

- Ethanol blending to E10 or E20 reduces EGR required at high boost leaving more oxygen available for combustion.
  $\Rightarrow$ Increased max. load from 16.3 bar $\text{IMEP}_g$ for E0 to **20.0 $\text{IMEP}_g$ bar for E20**.

- Std. PFS effective for increasing T-E and max. loads at intermediate $P_{\text{in}}$.
  - For E0, at $P_{\text{in}} = 2.0$ bar, max. load increased from 11.4 to 13.0 bar $\text{IMEP}_g$.

- Early-DI PFS combined with reduced $T_{\text{in}} = 30^\circ\text{C}$ allows a substantial increases T-E and max. load for higher $P_{\text{in}}$.
  - Reached **19.4 bar $\text{IMEP}_g$ at $P_{\text{in}} = 3$ bar vs. $P_{\text{in}} = 3.45$ bar for premixed with E20**.

- High loads match/exceed those of production diesel version of this engine.
  - Limited by max. allowable cylinder-head pressure.