Low-Temperature Gasoline Combustion for High-Efficiency Medium- and Heavy-Duty Engines

Project ID: ACE157

John E. Dec
and Dario Lopez-Pintor
Sandia National Laboratories

June 4, 2020 – 12:00 p.m.

U.S. DOE, Office of Vehicle Technologies
Annual Merit Review and Peer Evaluation

Program Managers: Gurpreet Singh & Michael Weismiller

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- Project start date: October 1, 2018
- Project end date: September 30, 2021
- Percent complete: 53%

Barriers

- Development of combustion systems that achieve high thermal efficiency while limiting emissions
- Inadequate understanding of combustion and simulation for new combustion regimes, such HCCI and LTC
- Develop new LTC regimes for their potential efficiency gains and emissions reduction.
- Develop advanced fuel-injection and control strategies high-efficiency LTC.
- Improved low-load operation and combustion efficiency for LTC engines

Budget

- Project funded by DOE/OVT:
- FY19 – $470k
- FY20 – $450k

Partners / Collaborators

- Project Lead: SNL ⇒ John E. Dec
- Advanced Engine Combustion MOU:
  15 industrial partners, 6 national labs, several universities
- Cummins – Engine Hardware
- GM – GDI fuel-injection hardware
- HATCI – Hyundai-Kia America Tech. Center

  (3 industrial partners)
- LLNL – Kinetic Modeling
- ANL – Data analysis

  (2 national labs)
- SUNY-Stony Brook – CFD modeling
- Clemson Univ. – CFD modeling
- Univ. of Connecticut – Skeletal kinetic mech.

  (3 universities)
- Collaborations with DOE Co-Optima and PACE programs

Relevance

- For Medium- and Heavy-Duty (MD/HD) applications, new engines are needed that can achieve significantly higher thermal efficiencies (TE)
  - Reduce fuel costs and the CO_2 footprint
  - Engine-out emissions must be low to minimize the burden on aftertreatment
- **Low-Temperature Gasoline Combustion (LTGC)** offers strong potential to increase the efficiencies of MD/HD engines above those of diesel engines with very low engine-out NOx & PM
  - Gasoline is often considerably less expensive than diesel fuel in the US due to high global demand for diesel
  - **LTGC could significantly reduce operating costs ⇒ higher efficiencies, lower fuel prices, less DEF**
- **SNL-LTGC project focuses on:** understanding LTGC fundamentals, then applying this knowledge to develop methods that can overcome the barriers limiting the application of these advanced engines
- During FY20, substantial progress has been made on overcoming many barriers, including:
  - Controlling LTGC operation over the load/speed map
  - Increasing efficiency while maintaining very low NOx and PM emissions
  - Achieving good low-load combustion efficiency
  - Extending high-load and high-speed limits with good stability

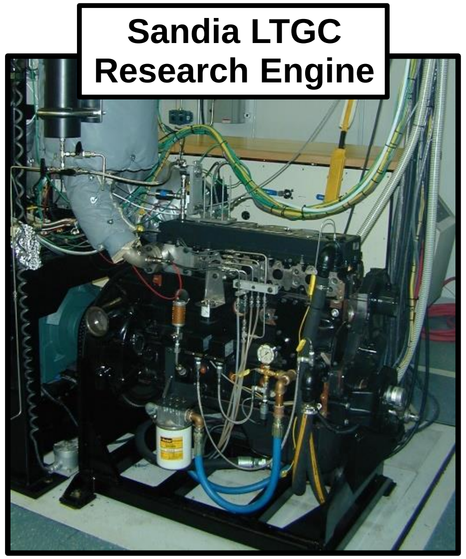
- Apply these techniques to demonstrate LTGC operation over wide portions of the load/speed map with high efficiencies

Milestones

Date Due	Description	Status
3/31/2020	Complete initial study of fuel-stratification techniques to obtain good low-load LTGC performance without significant charge heating using gasoline additized with ignition improver	Complete
6/30/2020	Determine the potential of controlled mixture stratification, produced by multiple fuel-injections, to provide next-cycle combustion-phasing control of LTGC using additized gasoline	On Track

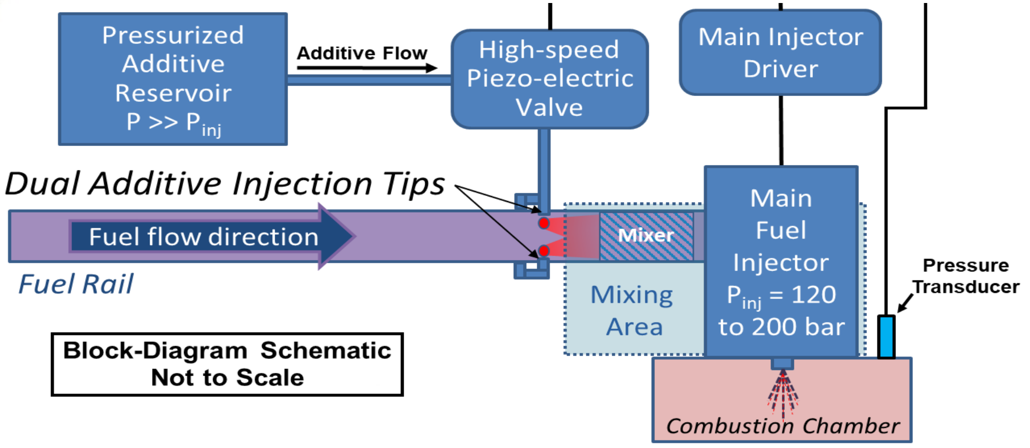
Approach

- **SNL LTGC method** ⇒ kinetically controlled compression ignition (CI) of a dilute charge with well-controlled, low-to-moderate fuel stratification
  - Stratification can vary kinetic rates of autoignition if the fuel is sufficiently ϕ-sensitive
  - Provides many advantages, e.g. higher loads, higher efficiencies, better low-load performance
- LTGC has major advantages for low NOx & PM vs. injection-timing control LTC methods
- Extend this LTGC method by using additive-mixing fuel injection (AMFI)
  1) Combustion-timing control
  2) Can eliminate the need for charge heating ⇒ simplifies design & greatly increases TE
  3) Increases the fuel's ϕ-sensitivity ⇒ allows greater benefit from stratification techniques



- AMFI system meters a very small amount of ignition-enhancing additive into the fuel each engine cycle to adjust its autoignition reactivity ⇒ inherently fast response (hardware under development)
  - Use 2-ethyl hexyl nitrate (EHN) ⇒ inexpensive common diesel fuel ignition improver
  - Requires only 0.01 – 0.5 mm^3 per cycle. For MD, estimate ~2 gallons for 8,000 miles (cost ~$20/gallon)
- Acquire data in the SNL all-metal LTGC research engine ⇒ based on Cummins ISB 5.9 L MD engine
  - Current study uses CR = 16:1 (vs. 14:1 previously) ⇒ increases TE and improves operation over the map
- CHEMKIN modeling for fundamentals & to guide experiments ⇒ effects of fuel, ϕ, NOx, EGR, EHN, etc.
- Working with two universities on LES-CFD modeling, and optical-engine experiments are planned, with the goal of better optimizing stratification at the various conditions where it is used

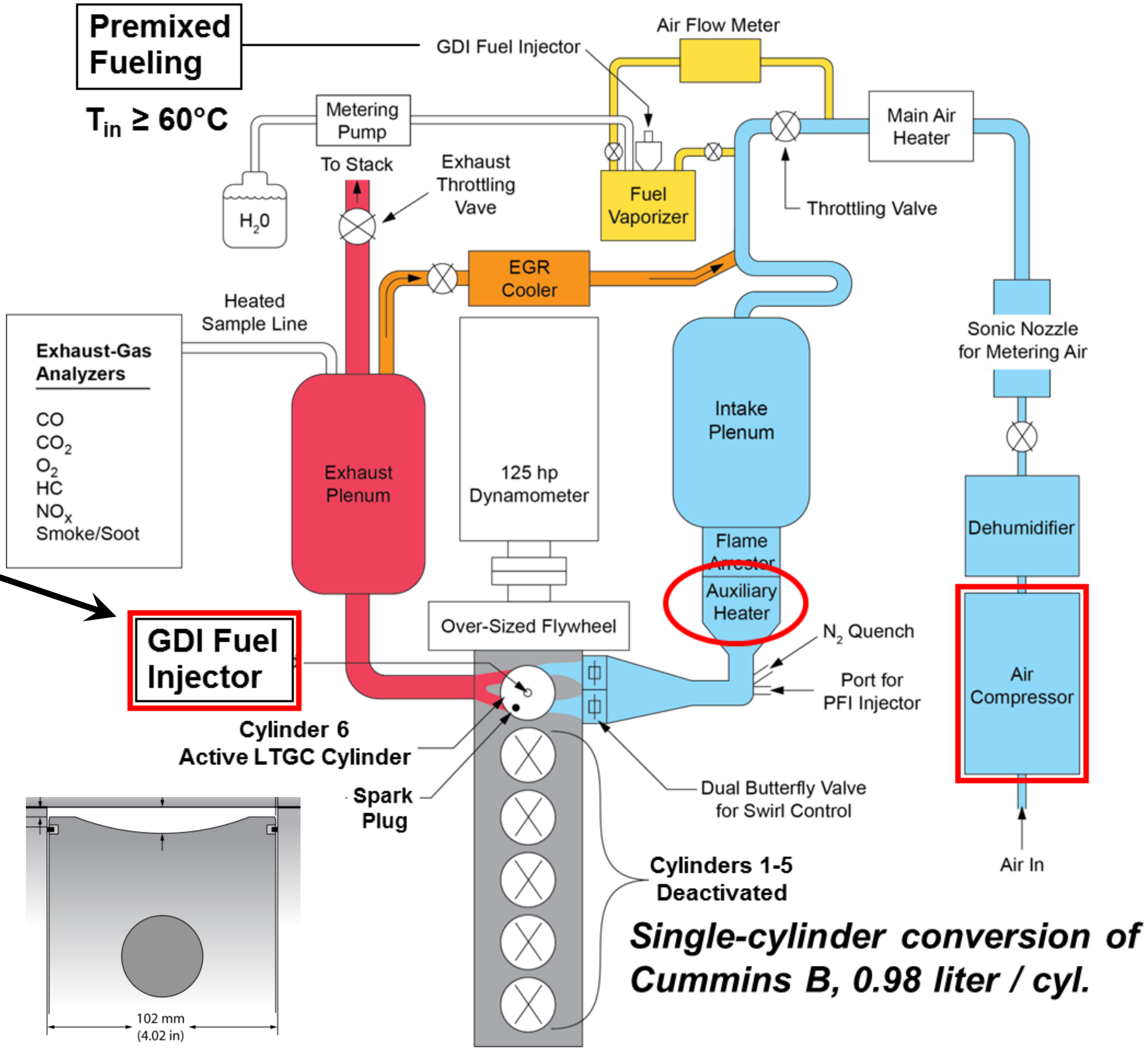
LTGC – AMFI Engine Facility



AMFI System – feeds into GDI fuel injector

Fuel: RD5-87-2A, Reg E10, 92.3 RON, 88.4 AKI
GDI injector, Bosch HDEV 5.1, 8-hole, 90°
P-injection = 120 bar
Speeds = 600 - 2400 rpm

- **Data are only minimally optimized**
- **Significant scope for improvement**
  ⇒ Injection strategies
  ⇒ Increased Injection pressures
  ⇒ Optimized spray pattern



Single-cylinder conversion of Cummins B, 0.98 liter / cyl.

CR = 16 piston

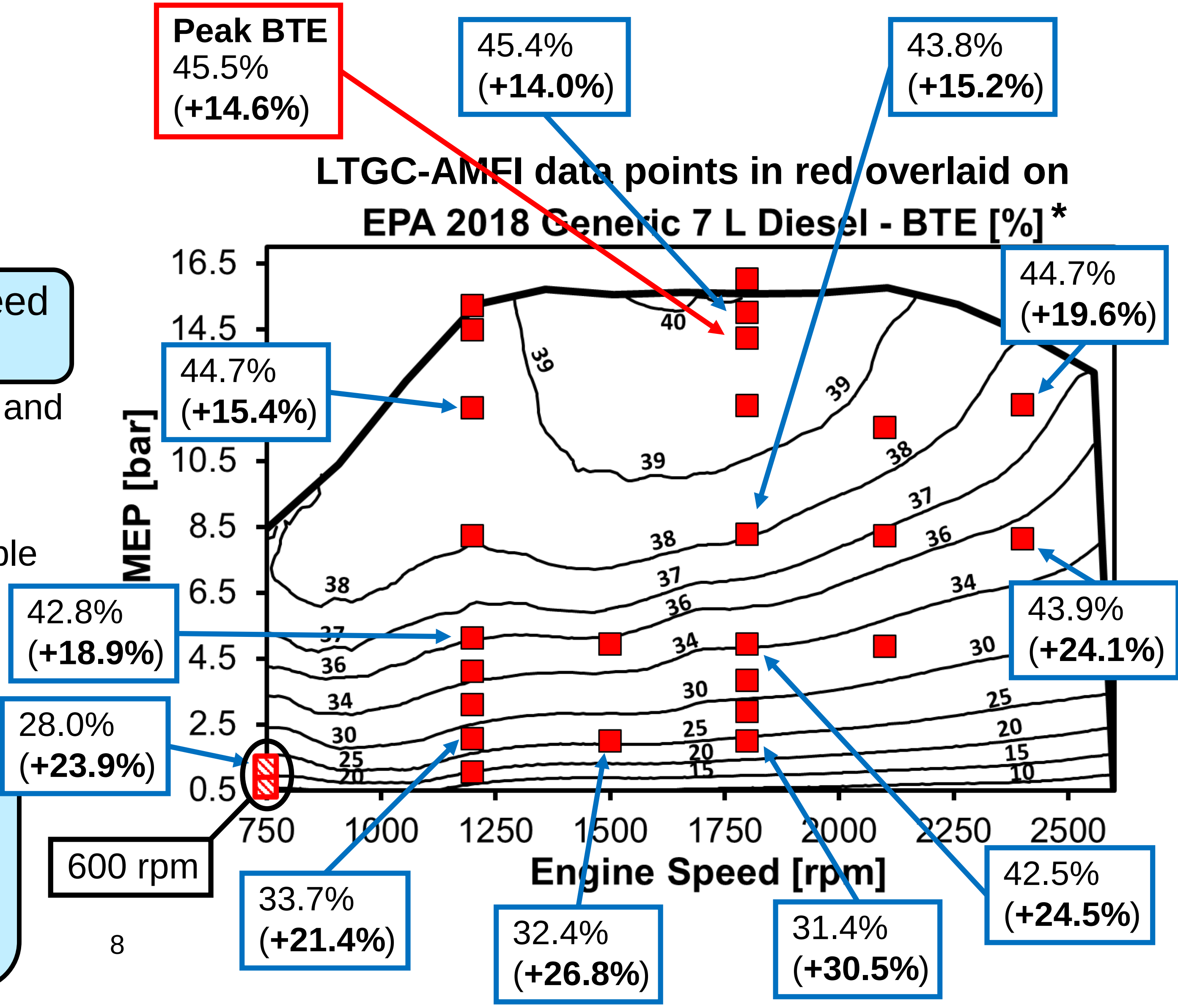
Overview of Accomplishments

<u>Overarching objective</u>: **achieve well-controlled high-efficiency LTGC over the operating map**

- Based on analysis, increased geometric CR to 16:1 (vs. 14:1 used previously) for higher TE
- This also greatly improved performance:
  - Substantially reduced the amount of additive required/consumed
  - **Facilitated AMFI operation w/o heating (T_{in} = 40°C)** ⇒ Low T_{in} also increased TE (higher γ & less heat transfer)
- Developed techniques for good operation at: 1) low loads, 2) high-loads and 3) high speeds
  - Investigated injection strategies to minimize NOx formation and EHN consumption and achieve good combustion efficiency (CE) and good combustion stability
- With these techniques and CR = 16, the LTGC-AMFI the system worked extremely well ⇒ Easily operating from low idle to fairly high loads and speeds **using regular E10 gasoline**
- The following slides compare the Brake Thermal Efficiency (**BTE**) and Brake Specific Fuel Consumption (**BSFC**) of the LTGC-AMFI engine with that of:
  1) EPA Generic 7-liter diesel engine (closest to our 5.9 liter)
  2) Two typical MD diesels on the market today ⇒ called "MD-diesel A" and "MD-diesel B"
  3) EPA Generic 15-liter HD diesel engines
- BTE and BSFC computed by correcting indicated values for pumping work, friction, and turbocharger losses ⇒ using models provided by GM

LTGC-AMFI Operation vs. EPA Generic 7 L Diesel

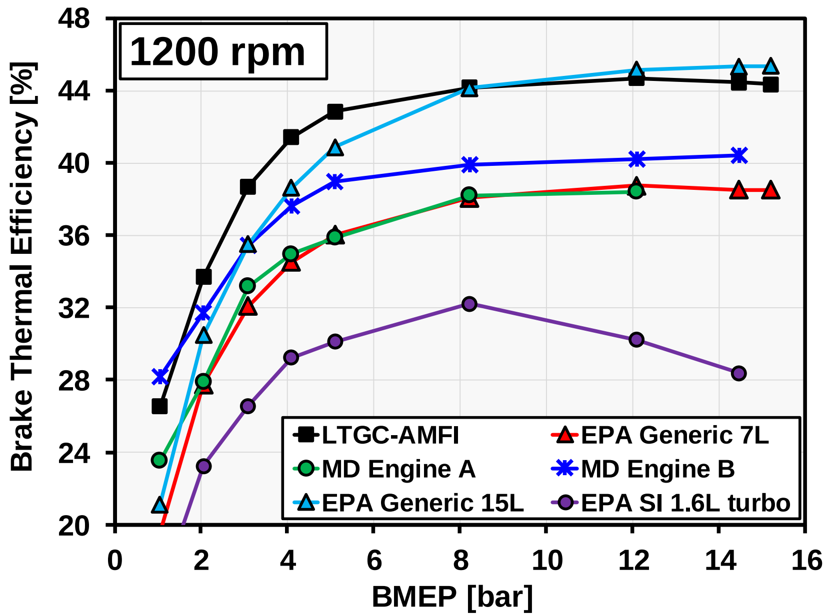
- Using LTGC-AMFI with various stratification and operating strategies, obtained good performance over a wide range of conditions
  - Loads: Idle to BMEP = 16.3 bar
  - Speeds: 600 – 2400 rpm
- LTGC-AMFI can operate over the entire load-speed map of the EPA Generic 7 L diesel ⇒ see figure
  - Data acquisition was limited by other commitments and shutdown due to COVID-19
  - Higher loads and speeds are possible
  - Operation in regions between these points is possible
- Operation down to idle easily achieved ⇒ discussed in detail in later slide.
- BTEs for LTGC are very high ⇒ substantially higher than EPA Generic 7 L diesel
  - **Peak BTE = 45.5%**
  - **14% higher near peak BTE**
  - **20–30% higher at lower loads & higher speeds**

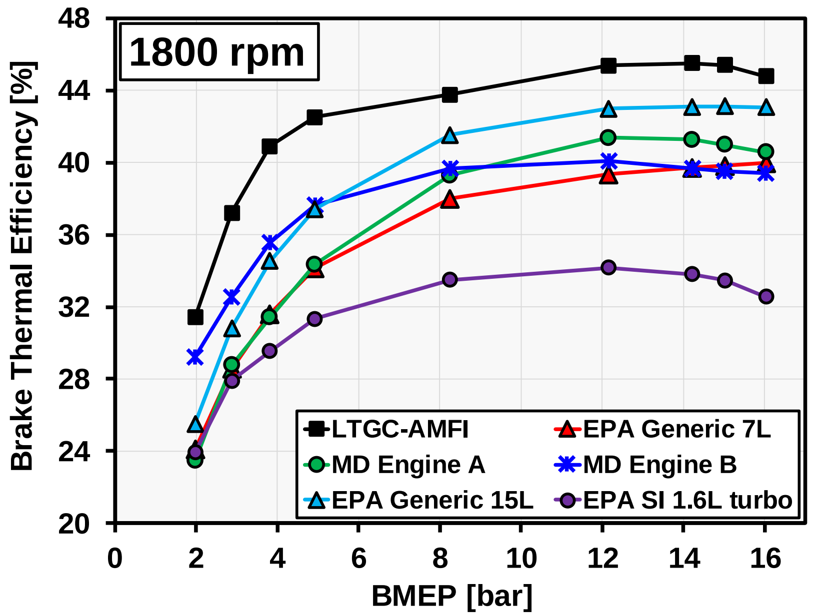


* https://www.epa.gov/regulations-emissions-vehicles-and-engines/greenhouse-gas-emissions-model-gem-medium-and-heavy-duty

Effect of Engine Load on BTE

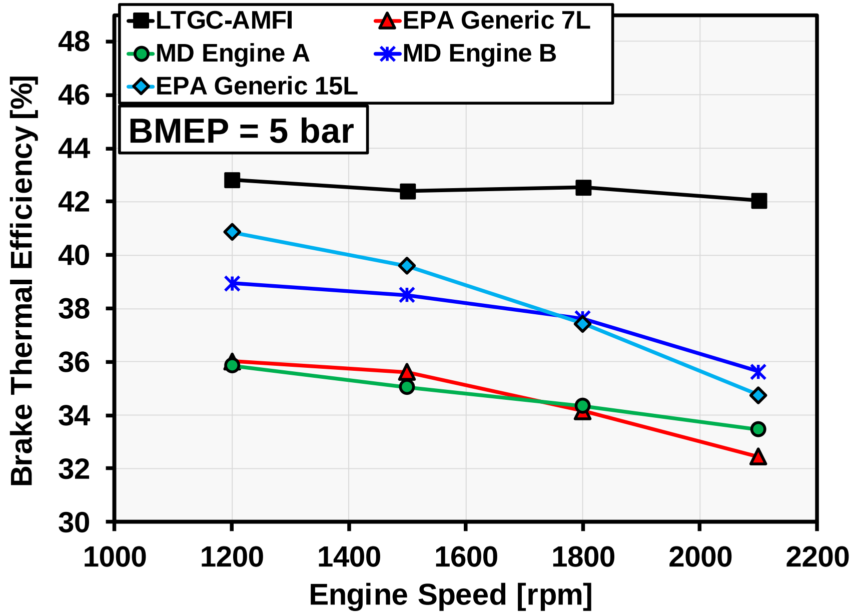
- LTGC-AMFI load sweeps at 1200 and 1800 rpm have similar trends and BTEs
  - BTE increases rapidly with load up to about 5 bar BMEP, then
    ⇒ increases more gradually up to 12 – 14 bar BMEP
    ⇒ slight drop in BTE at highest loads
  - Max. BTE is ~45.5% at 1800 vs. ~44.7% at 1200 rpm
- Overall trend for LTGC is similar to the EPA Generic 7 L diesel, but
  - **BTE of LTGC is about 6%-units higher than Diesel at both speeds**
    ⇒ For example, at BMEP = 8.2 bar shows LTGC~ 44% vs. Diesel ~ 38%
- Compare against two production diesel engines, MD-Engine A & B
  - Similar to or a little more efficient than the EPA Generic 7 L
  - **BTE of LTGC is substantially higher than the production MD diesels**
- Compared to EPA Generic 15 L HD Diesel:
  - **LTGC is ~2%-units higher at 1800 rpm & at 1200 rpm for BMEP ≤ 5 bar**
  - At 1200 rpm and high loads 15 L diesel is only ~1%-unit better than LTGC
- BTE of LTGC is 12 – 16%-units higher than best turbo-charge LD engine
  ⇒ Demonstrates large BTE advantage of LTGC vs. using gasoline in an SI engine, as sold for trucks up to Class 6 due to lower fuel prices & lower-cost aftertreatment

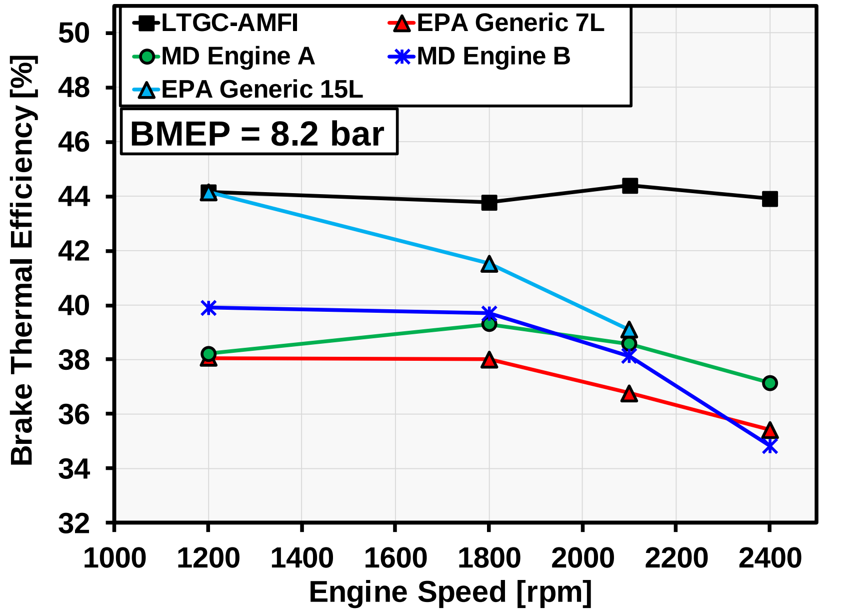




Effect of Engine Speed on BTE

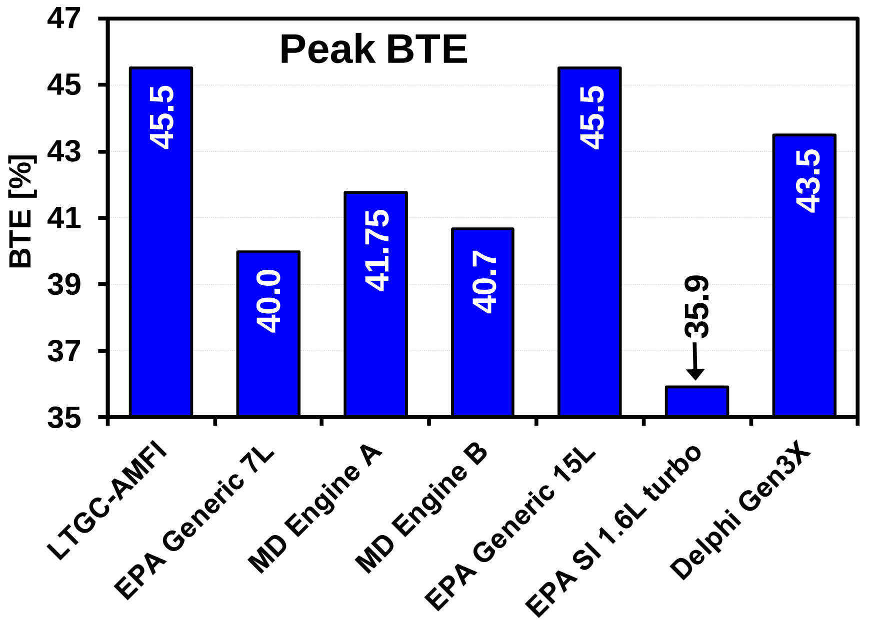
- **Trends in BTE w/ speed are similar at both BMEP = 5.0 & 8.2 bar**
  ⇒ BTEs are about 2%-units higher at BMEP = 8.2 bar
- BTE of LTGC is nearly constant with speed
- BTE of EPA Generic 7L diesel drops significantly over the speed sweep
- The BTEs of production MD diesels A & B drop with speed similar to Generic 7 L
  - At BMEP = 5 bar: BTE of MD-diesel B is 3%-units higher than Generic 7 L, but still 4.5%-units less than LTGC
  - At BMEP = 8.2 bar: Both MD-diesels A & B have moderately higher BTE's than Generic 7
- **Generic 15 L** ⇒ BTE less than LTGC, except 1200 rpm, 8.2 bar point and falls rapidly with speed at both loads, BMEP = 5.0 and 8.2 bar
- **BTE of LTGC remains nearly constant with speed, increasing the advantage of LTGC over both the 7 and 15 L diesels at higher speeds.**

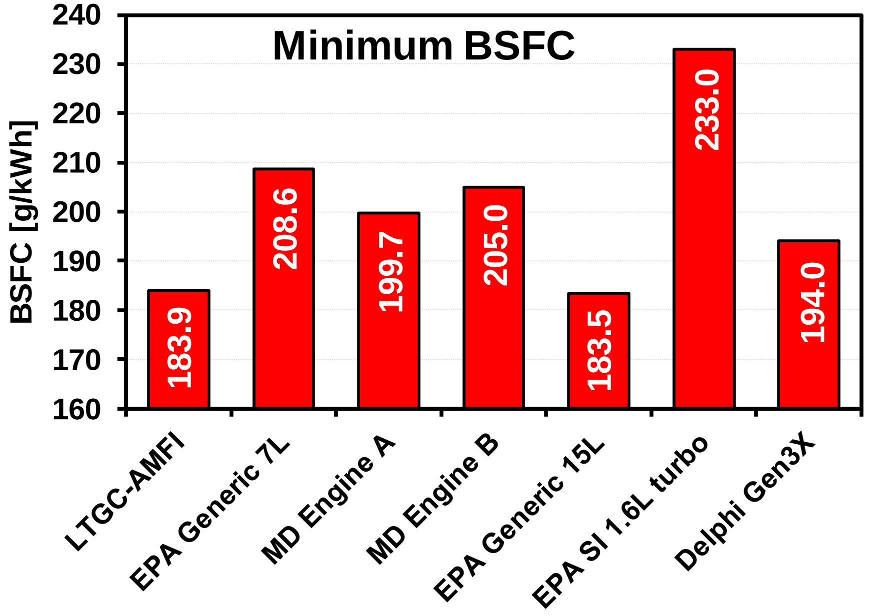




Peak BTE and BSFC Comparison

- **The peak BTE = 45.5% of the MD LTGC engine** is well above the peak BTEs of the three MD diesel engines (EPA Generic 7 L, MD-Engine A and MD-Engine B)
- **Comparing BSFC: LTGC-AMFI can reduce fuel consumption by 8 – 12% compared to MD diesel engines.**
- Improvements over the operating map are likely to be even greater because LTGC's BTE is proportionally higher than that of the 7 L diesel at higher speeds and at lower loads.
- The high peak BTE and **low minimum BSFC = 183.9 g/kWh** of LTGC match those of the EPA Generic 15 L HD-diesel
  ⇒ despite its displacement being 2.5 times smaller
- If the 5%-unit difference in BTE between the 15L and 7L diesel engines holds for LTGC, it suggests that a 15L HD-LTGC engine could reach 50% BTE
  ⇒ Especially since our LTGC engine was only slightly optimized
- Poor BTE and BSFC of the best LD SI engine strongly suggests
  ⇒ SI-gasoline engines for MD will substantially increase BSFC
- BTE and BSFC of LTGC are a little better than Delphi-Gen3X LTC LD engine ⇒ good values for Gen3X help verify potential of LTGC.

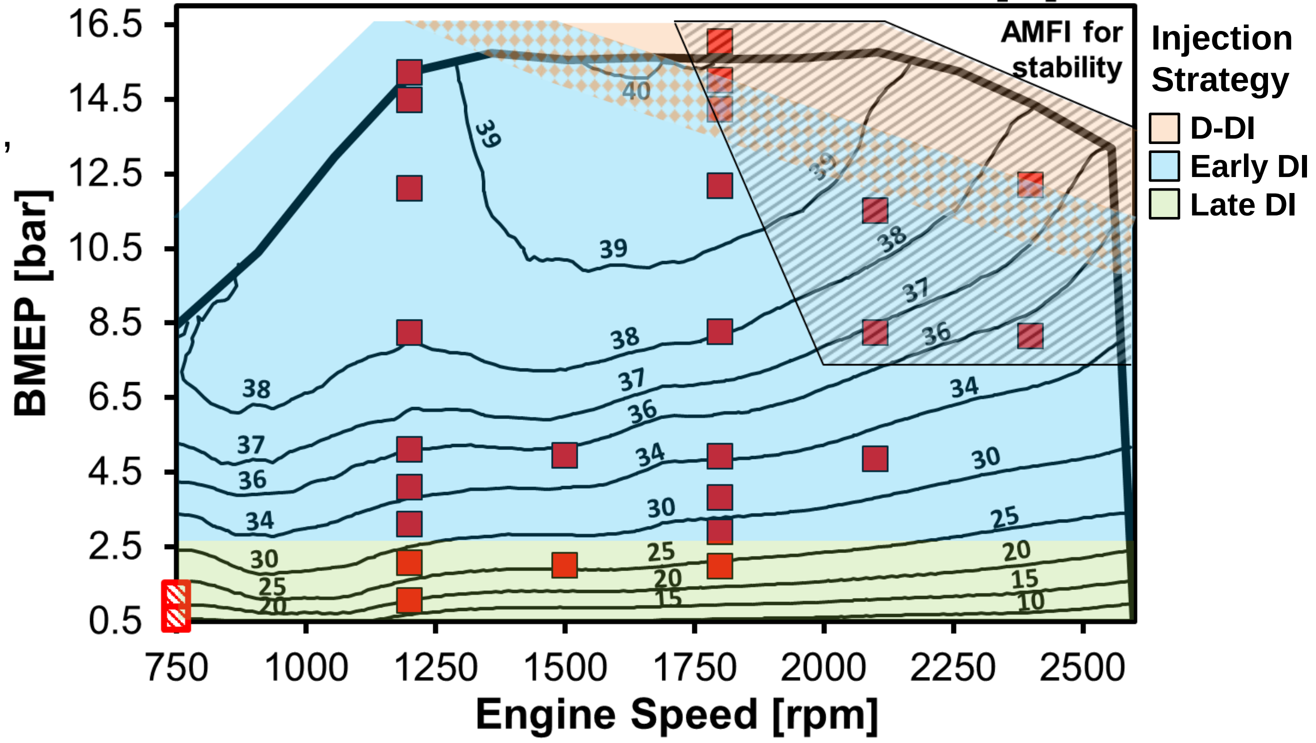




LTGC-AMFI Fuel-Injection Strategies

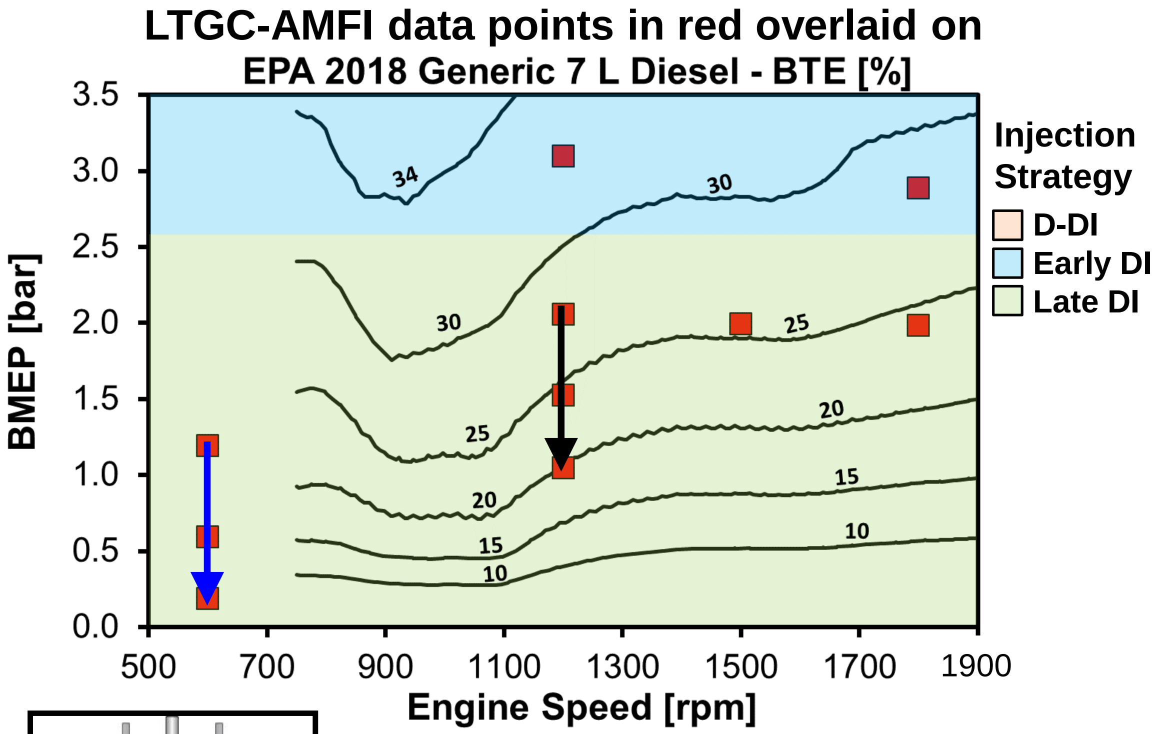
- Achieving good LTGC-AMFI performance over the load-speed map requires proper selection of LTGC operating strategies for each region.
- Three different strategies have been applied to acquire the current data.
  1) **Early-DI PFS:** Single Early-DI (60°CA **aTDC-intake**) produces mild non-uniformities in fuel distribution (partial fuel stratification, PFS) ⇒ Used over central part of operating map
  2) **Late-DI Stratification:** Single DI in latter part of compression stroke (~290 – 335°CA aTDC-intake). Fuel concentrated in central combustion chamber for good CE and low EHN consumption.
  3) **Double-DI (D-DI) PFS:** Early-DI for 70-90% of fuel, late-DI for remainder (~290 – 325 °CA). PFS reduces HRR allowing more advanced CA50 for better stability and/or lower noise.
- Adding a small amount of EHN can improve stability at high loads and high speeds even though it is not required to achieve autoignition. ⇒ Use for speeds > 1800 rpm for both Early-DI and D-DI PFS.
- Operation down to idle is discussed in next slide

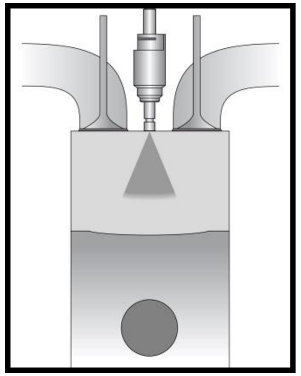
LTGC-AMFI data points in red overlaid on EPA 2018 Generic 7 L Diesel - BTE [%]

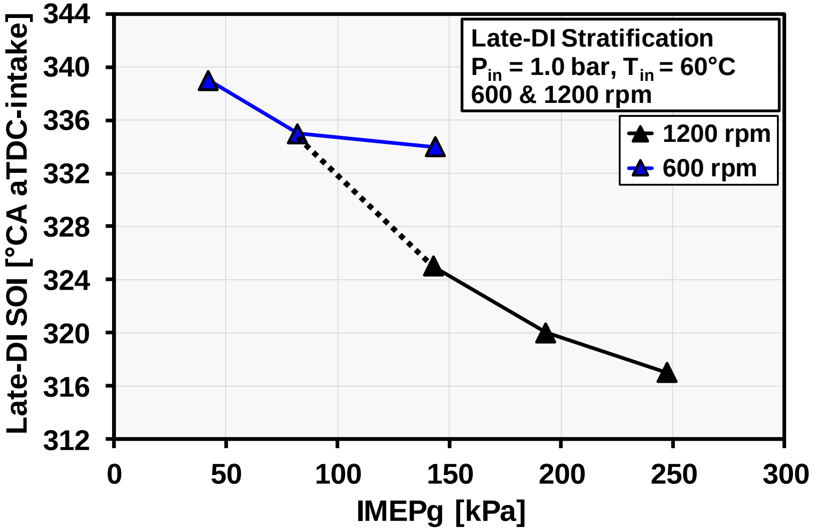


LTGC-AMFI Strategy for Low Loads

- Low-load operation is particularly challenging for almost all LTC techniques
  - If charge is too well-mixed, combustion temperatures are low, resulting in poor combustion efficiency (CE)
  - Charge stratification can increase the local ϕ & improve CE, but achieving autoig. often difficult due to insufficient heat
- LTGC-AMFI provides a good solution ⇒ the additive increases the fuel's ϕ-sensitivity, so stratification to increase CE also enhances the autoignition
  - Allows low loads with little or no intake heating
  - Greatly reduces the EHN required at low loads, minimizing NOx emissions and EHN consumption
- Use **late-DI fueling** in late compression stroke to stratify charge, concentrating fuel in the central part of chamber
- As load is decreased, further retard Late-DI SOI to increase stratification for good CE and autoignition
- LTGC-AMFI with late-DI stratification provides very good low-load performance down to idle (IMEPg = 42 – 82 kPa)
  - Good CE, very low NOx and PM, and very low EHN

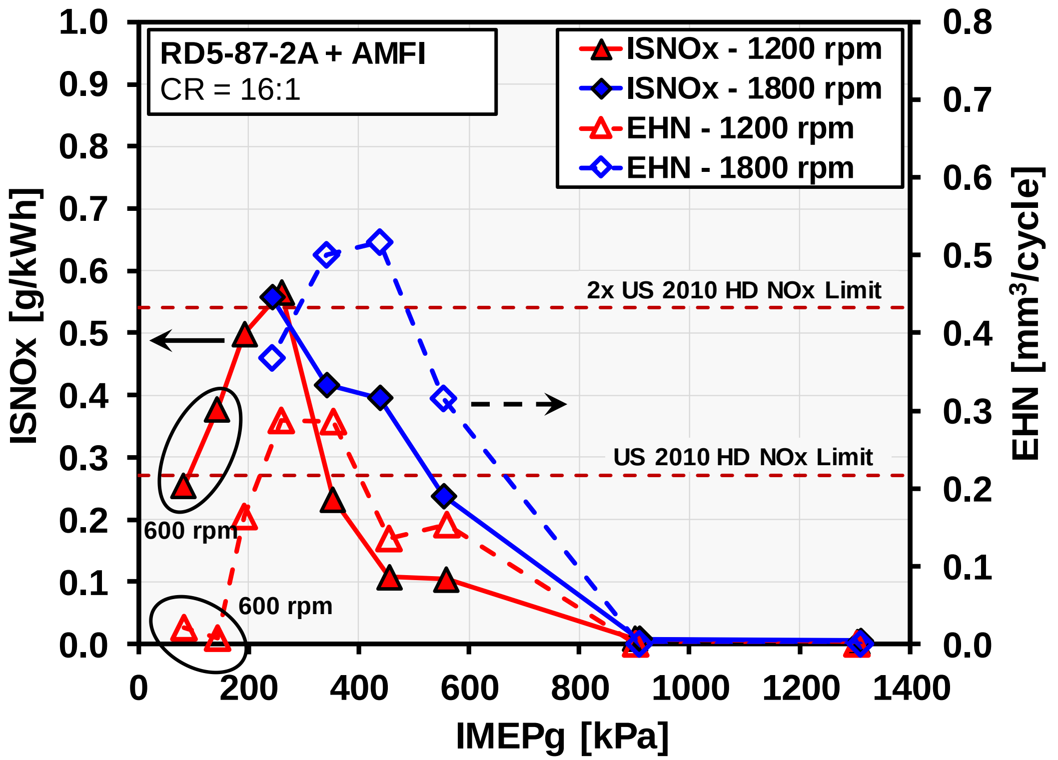






Changes in NOx and EHN with Load

- **NOx is very low for all LTGC data points shown on the load-speed maps**
  ⇒ PM near or below the detection limit of AVL smoke meter
- **Highest ISNOx is only ~2x the US 2010 HD limit, in range of lean-NOx catalysts**
  ⇒ Occurs around IMEPg = 2.5 bar for both 1200 & 1800 rpm
  - EHN is required to achieve autoignition at these lower loads.
  - Stratification required to get good CE increases thermal NOx
- At lower loads, less EHN required because ↗stratification enhances reactivity due to ↗ϕ-sensitivity with EHN
  - ↘EHN results in ↘NOx (~1/3 of the N in EHN goes to NOx)
  - Lower fueling rate ↘Thermal NOx
  - **NOx emissions decrease at lower loads**
- **At high-load boosted conditions, IMEPg ≥ 9 bar, NOx is extremely low**
  - Charge is fairly well mixed ⇒ low peak temps ↘Thermal NOx
  - Only small amounts of EHN used for stability and control
    ⇒ With boost, EHN not required for autoignition



- **Peak NOx values can almost certainly be decreased with better optimization** of mixture stratification ⇒ Currently no optimization except for injection timing of a single injection

Responses to Previous Year Reviewers' Comments

- Comment: Two reviewers wanted to see the LTGC-AMFI approach extended to operation over the full load and speed range

  Response: As reported here, we have worked hard this past year to achieve this. Multiple strategies have been developed to operate LTGC-AMFI over almost the full operating range of an MD engine, with good performance and very high efficiencies. Future efforts will extend operation to higher loads and speeds, and improve stratification methods for low loads.

- Comment: Multiple reviewers commented on LTGC-AMFI being similar to RCCI and wanted to understand what was different about this approach from other LTC approaches. This is key question, so a detailed answer is provided:

  Response: Although there are naturally commonalities between LTC approaches, LTGC-AMFI is unique in that the **reactivity of all the fuel is adjusted** as the engine traverses the operating map, and the **fuel is always gasoline-like**. This is fundamentally different from RCCI where the reactivity of each fuel is unchanged and only the ratio of the amounts of each fuel is varied, and more importantly, the mixture distribution between the two fuels varies as the ratio varies. This can cause problems at low and high loads.

  At low loads, the RCCI engine must operate almost as a diesel, because the gasoline distribution will be too dilute for good combustion efficiency with the typical gasoline fueling systems used for RCCI. With the LTGC-AMFI system, all the fuel is stratified as we explain on slide 13, giving good combustion efficiency. Moreover, with RCCI, the diesel fuel will not be well-mixed, compared to gasoline, due to it's lower volatility and the diesel-like fuel injectors, resulting in much higher soot and NOx at low loads compared to LTGC-AMFI.

  For high-loads, gasoline becomes overly reactive, and EGR must be used to reduce reactivity. For high-load LTGC-AMFI, only very tiny amounts of ignition improver are added to provide control, thus only slightly changing the overall reactivity of the fuel and the amount of EGR required. However, for RCCI, small amounts of diesel are added for control, and their reactivity is very high, so they react rapidly driving the entire charge in autoignition even though they are only injected into a small fraction of the volume. Thus, much more EGR is required for RCCI, and the maximum load can become oxygen limited at a significantly lower value when regular gasoline is used as the low-reactivity fuel. Therefore, premium gasoline and/or alcohol fuels have often been used.

  Finally, with RCCI two fuels are required, and both tanks must be regularly refilled. However, for LTGC-AMFI a small (1-2 gallon) additive reservoir will last ~8000 miles, so refilling is only required at service intervals, and the customer only refills with gasoline on a regular basis.

- Comment: Modeling interactions are good, and the reviewer would like to see more modeling results.

  Response: We also find the modeling to be very fruitful and have expanded this effort with a new collaboration for CFD at Clemson University that will focus on improving the Late-DI stratification used at low loads. This new project is coming up to speed rapidly, and results are expected within the next few months. CFD of D-DI-PFS is continuing at SUNY-Stony Brook, but due to a succession of PhD students, significant new results have been delayed.

- Comment: Two reviewers expressed a desire for more optical-engine results

  Response: Optical engine data can be very valuable, but it is critical that they focus on relevant problems. Thus, viable operating strategies must be first determined in the metal engine. We had planned optical imaging of fuel distributions this year, but were requested to support a new effort on surrogates.

Collaborations

- Project is conducted in close cooperation with U.S. Industry through the **Advanced Engine Combustion (AEC) Working Group**, under a memorandum of understanding (MOU).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.
- **Cummins:** Engine hardware support
- **General Motors:** Support for GDI injectors. Special presentation and discussions
- **Hyundai-Kia America Tech Center, Inc. (HATCI):** Working to establish a collaboration to support their LTC engine project and to apply AMFI and fuel stratification techniques for improved performance
- **LLNL:** RD5-87 surrogate development, testing kinetic-mechanisms, adding EHN chemistry to LLNL mechanism
- **ANL:** Collaborate on analysis of LTGC-AMFI data over operating map
- **SUNY-Stony Brook:** CFD-LES modeling of LTGC using D-DI-PFS
- **Clemson University:** CFD modeling of stratification for improved low-load operation
- **Univ of Connecticut:** Collaborated on development of skeletal mechanism for CFD
- Collaborations with DOE Co-Optima and PACE programs – Separately funded

Remaining Challenges and Barriers

- AMFI system can control combustion timing over a wide range of conditions
  $\Rightarrow$ Control is inherently very rapid, but development of a practical system with fast response is required
- Research is needed on late-DI fueling strategies for low-load operation to improve the stratified fuel distribution for improved combustion efficiency while minimizing NOx
- Research is also needed on D-DI PFS strategies to further improve combustion stability at high loads
- Improved modeling of fuel-injection, CFD for stratified operation, with validation against measured in-cylinder fuel distributions and combustion performance data
- Optical imaging studies to better understand and optimize fuel-mixture stratification and to validate CFD for both: 1) Late-DI fueling for low loads, and 2) D-DI-PFS for improved stability at high loads
- Improved control of additive dosing for conditions requiring very small amounts of additive
- Improved understanding of fuel effects, additive (EHN) chemistry, and how EHN interacts with various fuel components to enhance autoignition.
- Determine the performance of LTGC-AMFI, fuel stratification, and other techniques on multi-cylinder engines

Proposed Future Research

Any proposed future work is subject to change based on funding levels.

- **Extend operating range of LTGC-AMFI to higher loads and speeds**
  - Apply D-DI-PFS and very small additive dosing strategies to improve stability
- **Develop a new high-speed micro-valve to better control additive dosing**
  - Needed to improve stability at high-loads, high-speeds and at very low loads ⇒ Initial design is underway
- **Improve AMFI system to provide faster response times** and conduct transient tests
  - Design of components for new setup with reduced dead volume is nearly complete
- **Investigations to further improve low-load performance** using AMFI system with late-DI fueling
  - Apply additional techniques such as increased P-injection and multiple late-DI injections for improved stratification
- **Optical engine measurements of fuel distributions** to improve stratification techniques and to validate CFD modeling. Apply to late-DI stratification for low loads and to DDI-PFS for high loads
- **Continue LES-CFD modeling to improve stratification techniques** for both late-DI and D-DI-PFS ⇒ In collaboration with Clemson University and SUNY-Stony Brook
- **Finish adding EHN chemistry to LLNL detailed mechanism**, validate, & apply to LTGC-AMFI studies ⇒ Investigate potential of adding EHN to skeletal mechanism for CFD
- **Continue efforts establish a collaboration with Hyundai-Kia America** to apply LTGC-AMFI control and advanced stratifications techniques to multi-cylinder engine

Summary

Relevance

- New MD/HD engines are needed that provide significantly higher brake thermal efficiencies (BTEs)
  - LTGC with AMFI offers BTEs above those of diesel engines with very low NOx and PM
    ⇒ Could significantly lower operating cost with higher BTE, lower fuel prices for gasoline, and less DEF (perhaps no DEF)
  - SNL-LTGC project focuses on fundamental understanding to overcome barriers to practical LTGC engines
    ⇒ Substantial progress made on developing techniques to overcome most key barriers
- Applied these techniques for LTGC operation over the load/speed map of MD diesels with high efficiencies & low emissions

Approach

- SNL-LTGC uses kinetically controlled CI of a dilute charge combined with well-controlled low-to-moderate stratification
- Extend this LTGC method with AMFI for 1) CA50 control, 2) eliminate charge heating, 3) better performance with stratification
- Use single-cyl. LTGC engine based on 5.9 L MD diesel with a CR=16:1 LTGC piston for high BTE and improved operation
- Supplement experiments with CHEMKIN and CFD modeling, the latter through collaborations with two universities

Accomplishments

- Demonstrated good LTGC performance over essentially the entire operating map of typical MD diesel engines
  - Accomplished by using LTGC-AMFI with various stratification techniques and operating strategies
- Achieved substantially higher BTEs than MD diesel ⇒ peak BTE = 45.5% & BTEs are 14 – 30% above diesel over the map
- Showed that the best BTE and BSFC of LTGC-AMFI match EPA's15 L diesel engine, despite LTGC's much smaller size
- Showed that LTGC maintains near-peak BTEs over a wider range of speeds and loads than comparable diesel engines
- Demonstrated very good low-load performance down to idle (IMEPg = 42 – 82 kPa) using a Late-DI fueling strategy with AMFI
- Demonstrated improved high-load stability with D-DI-PFS fueling, & improved high-speed stability with small amounts of EHN
- Achieved this performance with very low NOx and soot emissions
  - NOx was well below US-2010 standards except for a narrow range around 2.5 bar IMEPg ⇒ could be decreased with optimized stratification
  - Soot was very low, near or below the detection limit of the smoke meter

Collaborations: Multiple collaborations are listed on Collaborations slide.

Future Research: Extend LTGC operation to higher loads & speeds, further improve low-load performance, optical measurements of fuel distributions to improve stratification, continue CFD modeling. More details given on Proposed Future Research slide

Acknowledgement

- This work was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA.

  Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

Technical Backup Slides