Novel Combustion Regimes for Higher Efficiency and Lower Emissions

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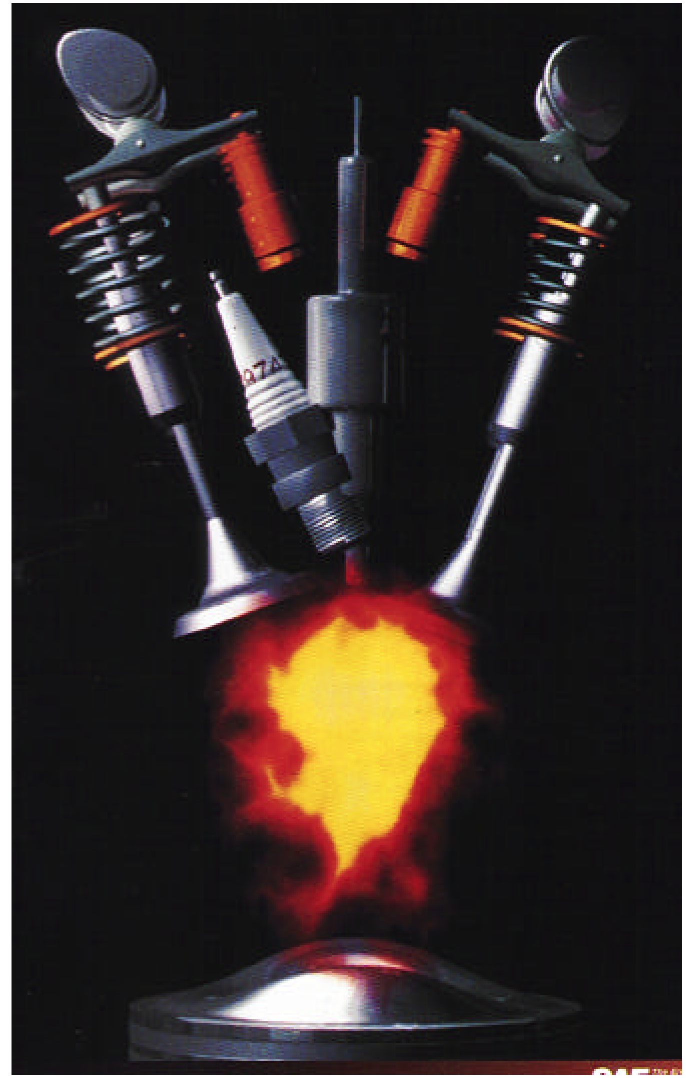
Internal Combustion Engines of National Importance

- Stoichiometric, homogeneous-charge SI engines dominate U.S. market
  - Engine-out NOx (nitrogen oxides) high, but exhaust cleanup well-developed
  - Potential for efficiency improvements dwindling
- Lean-burn engines (spark or diesel) offer efficiency improvements, however…
  - Lean exhaust treatment immature
  - Cool exhaust more difficult to treat
- Pending regulations require another order of magnitude reduction in NOx
- Low temperature combustion offers lower *engine-out* NOx and PM (soot), the principal pollutants in diesel engine exhaust

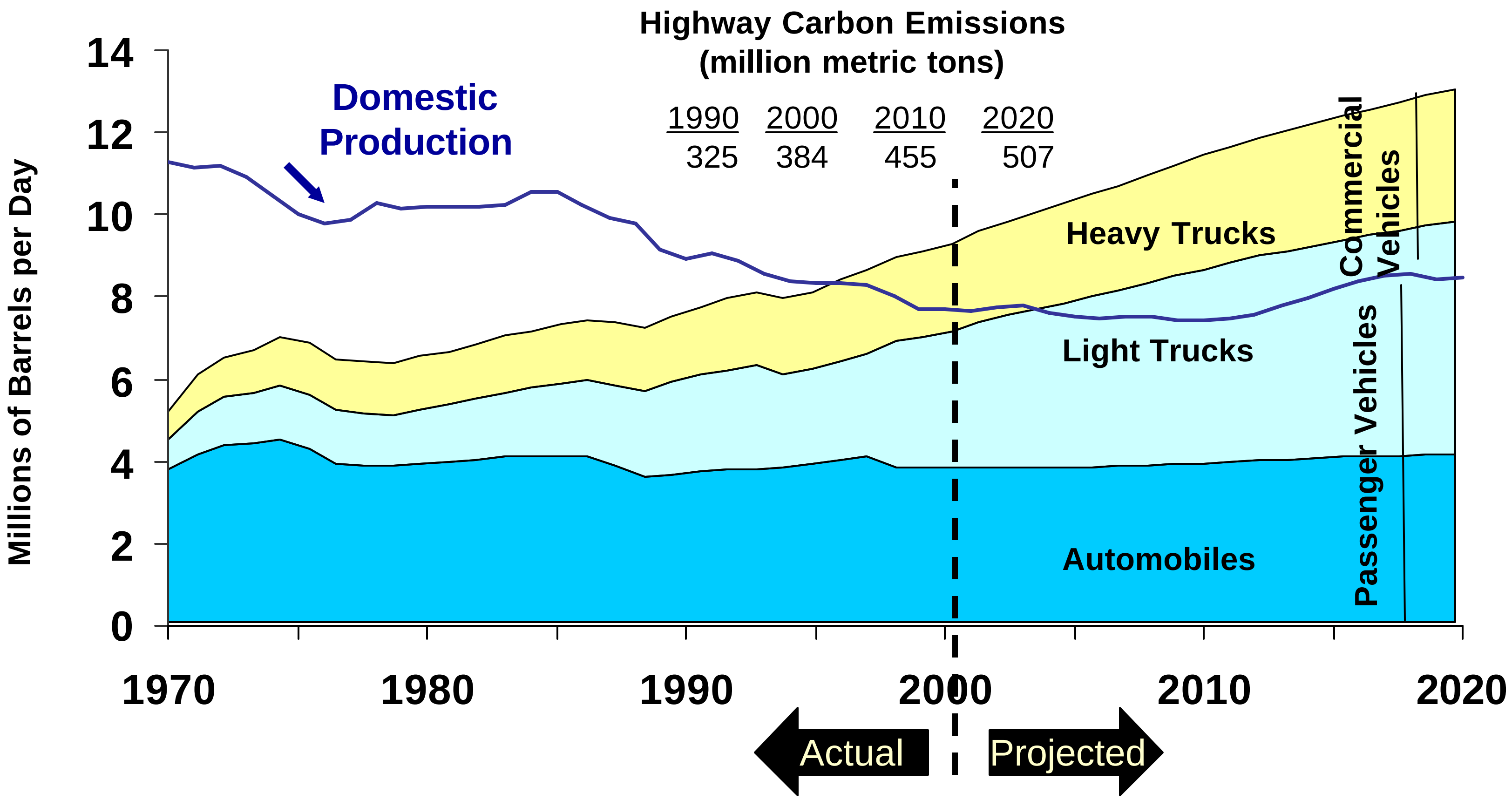


Internal Combustion Engines Can Play a Key Role in Solving Our Energy Problem

	1973	**1997**
U.S.	74 Quads	91 Quads
World	225 Quads	365 Quads

1 Quad of energy is equivalent to 340,000 tank cars of crude oil stretched from Miami to Seattle (3,300 miles).

EERE's Top Priority is to Reduce the Nation's Dependence on Foreign Oil



Source: Transportation Energy Data Book: Edition 21, DOE/ORNL-6966, September 2001, and EIA Annual Energy Outlook 2002, DOE/EIA-0383(2002), December 2001

The Challenge is to Seek Pathways to Higher Efficiency, While Meeting Emission and Cost Requirements

"The best way to understand techniques to increase efficiency is to understand how to decrease losses,"

"High cycle temperature is not synonymous with high efficiency…burning lean reduces peak cycle temperature but can increase indicated efficiency"

Dave Foster and Phil Myers, U. Wisconsin 1982

Higher engine efficiency also aids in reducing emissions.

Low Temperature Combustion (LTC) has Several Embodiments

- **Homogeneous Charge Compression Ignition (HCCI)**
  - **Requires control of kinetics**
  - **“Classical” HCCI research being conducted at Universities and Labs**
  - **Intriguing, but very high risk, minimal progress on controlling combustion initiation in last 25 years**
- **Exhaust-Diluted Diesel Combustion…retains most HCCI benefits, simultaneous low NOx and PM**
  - **Very high exhaust gas recirculation (EGR)**

    (Toyota’s Low Temperature Combustion)
  - **Late injection, longer ignition delay for increased pre-mix burn (Nissan’s Modulated Kinetics)**
  - **U.S. manufacturers quiet about their efforts**
  - **ORNL results corroborate potential of these approaches**

“Classical” HCCI Combustion has Great Potential and Great Technical Challenges

Potential of HCCI Engines

High efficiency
Very low NO_x
Low cost (no need for high pressure injection system, 1/3rd of engine cost)
Fuel flexibility

Technical challenges of HCCI

Difficult to control
Difficult to start
High peak heat release and peak pressure
High hydrocarbon and CO emissions

ORNL conjectures that it is possible to exploit the benefits, using controlled ignition to circumvent the challenges.

Explanation of Controlled Ignition Approach

Traditional HCCI ..largely in the hands of God (stochastic)

- **Somehow heat intake air to a "predetermined" temperature**
- **Fuel+air mixed and sent into cylinder, very lean.**
- **Compression stroke brings mixture to higher temperature. Most current concepts propose using VVA for intra-process adjustments**
- **If the initial heating and VVA corrections are correct, mixture goes "poof"**
- **If you're off by few deg K, either way, no "poof" or "ka-blooey," broken parts**

ORNL idea*..direct control to achieve HCCI-like combustion

- **Fuel + air mixed and sent to cylinder. Very lean**
- **Use high compression to bring mixture near point of classical HCCI.**
- **Insert energy from timed , large spark to "nudge" the mixture into HCCI.**
- **Three possibilities at this point**
  - **The compression heating due to local burning rapidly raises temp of remaining mixture to point of "poof" of 80-90% of mixture**
  - **Photons from arc initiate combustion at multiple sites, thus HCCI (is this plausible?)**
  - **Nothing happens**

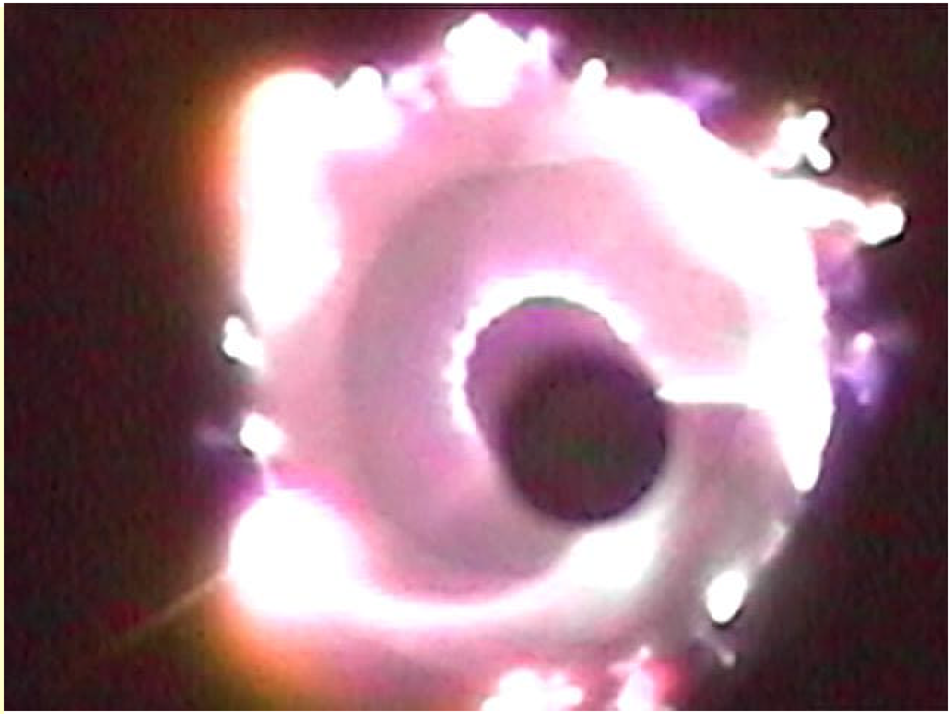
*ORNL proposed this to OAAT in July 2001

ORNL Invention, the Rotating Arc Spark Plug* (RASP), May Offer Better Chance to Initiate and Control HCCI-like Combustion

Higher probability of ignition
- **Large volume discharge (>100x common spark)**
- **Higher electron temperature in spark**

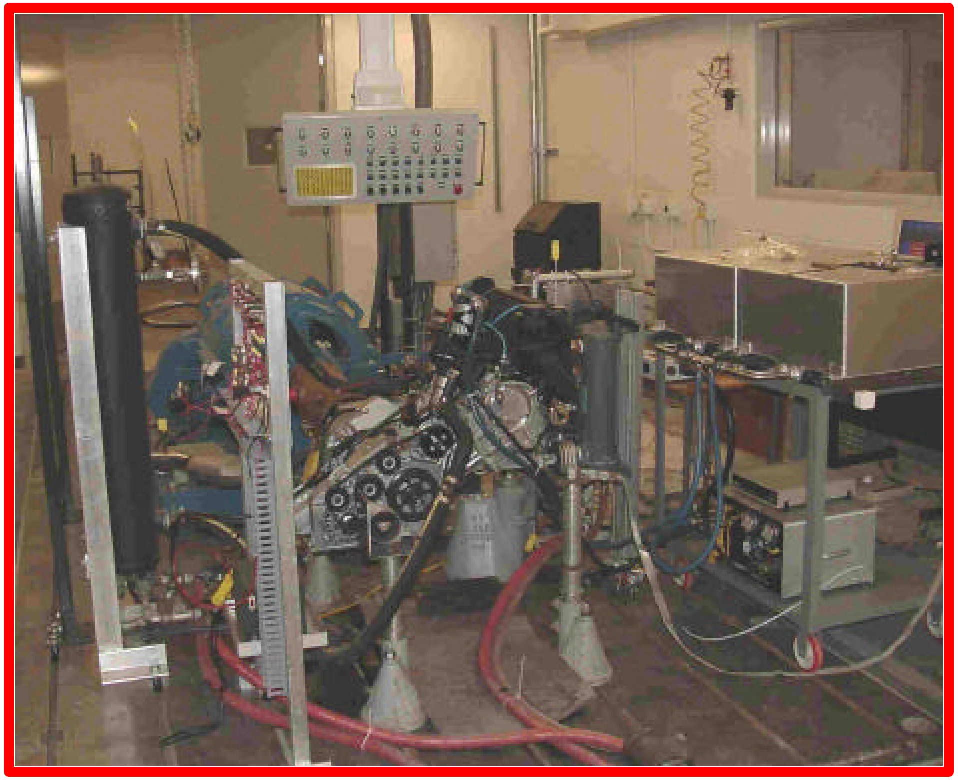
- **Has undergone initial trials in natural gas engine**
- **But not a critical path technology**

*Patent Pending



ORNL Explores and Finds Advanced Strategy for Diesel Emission Reduction

- **Extreme dilution of combustion process for lower combustion temperatures…89% less NOx**
- **Simultaneous 45% lower soot, paradigm shift (normally NOx and soot tradeoff)**
- **Must balance with power and efficiency**
- **Overall strategy would combine this with lean aftertreatment for near-zero emissions**

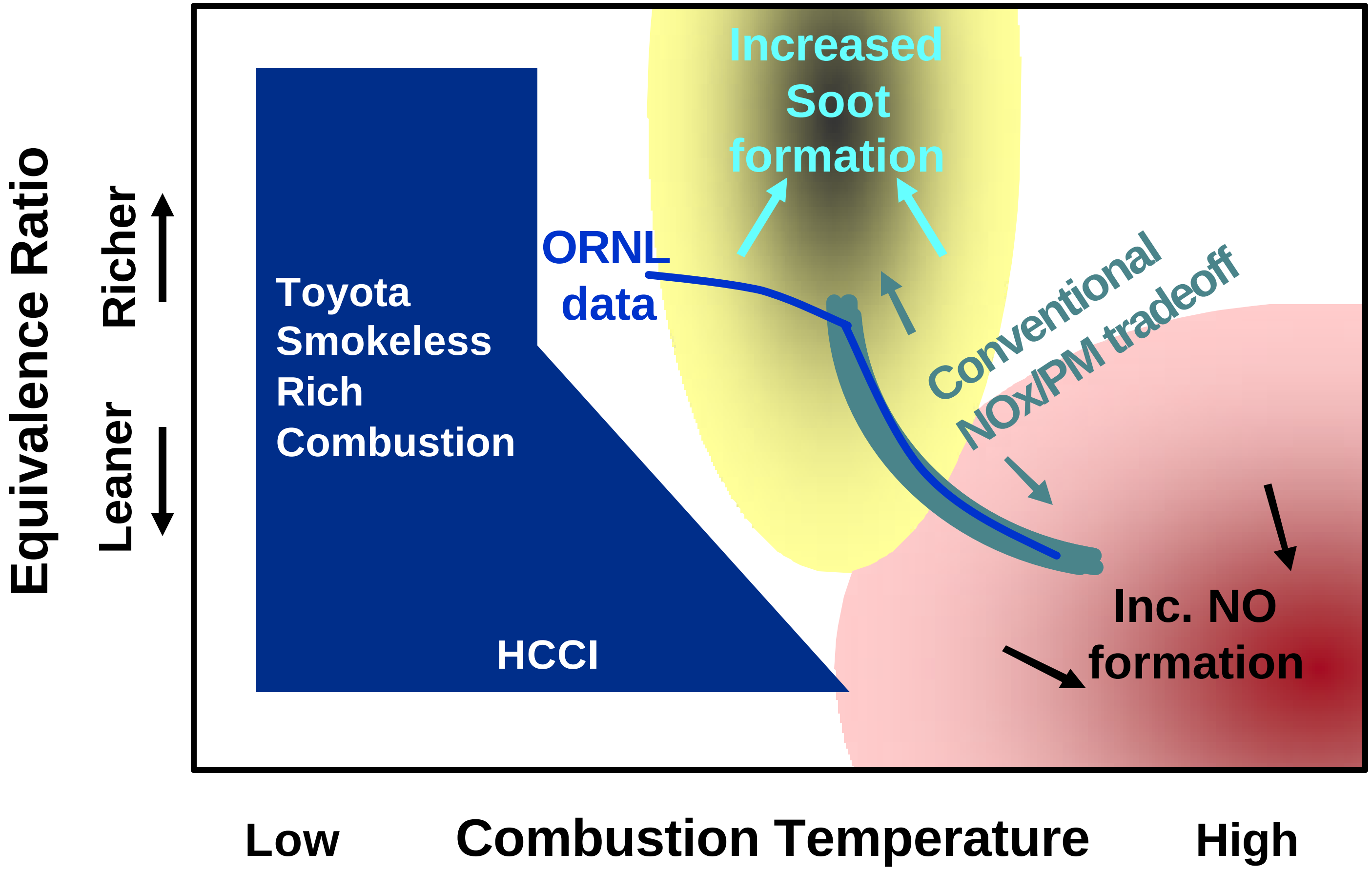


The research was performed at ORNL on a electronic-control, modified Mercedes Benz diesel engine. Sponsor- DOE

The "Traditional" Combustion Model States that PM Emissions Increase with High EGR

- **Any change in engine operating parameters to reduce NOx emissions results in an increase in PM emissions**
- **Conversely, higher combustion temperatures promote complete fuel oxidation and reduce PM emissions while increasing NOx emissions**
- **In recent years, exhaust gas recirculation (EGR) has been studied for use in diesel engines to reduce NOx emissions**
- **The exhaust gas dilutes the combustion process, lowering combustion temperature and NOx emissions**
- **As expected, however, higher EGR levels are normally accompanied by higher PM emissions**

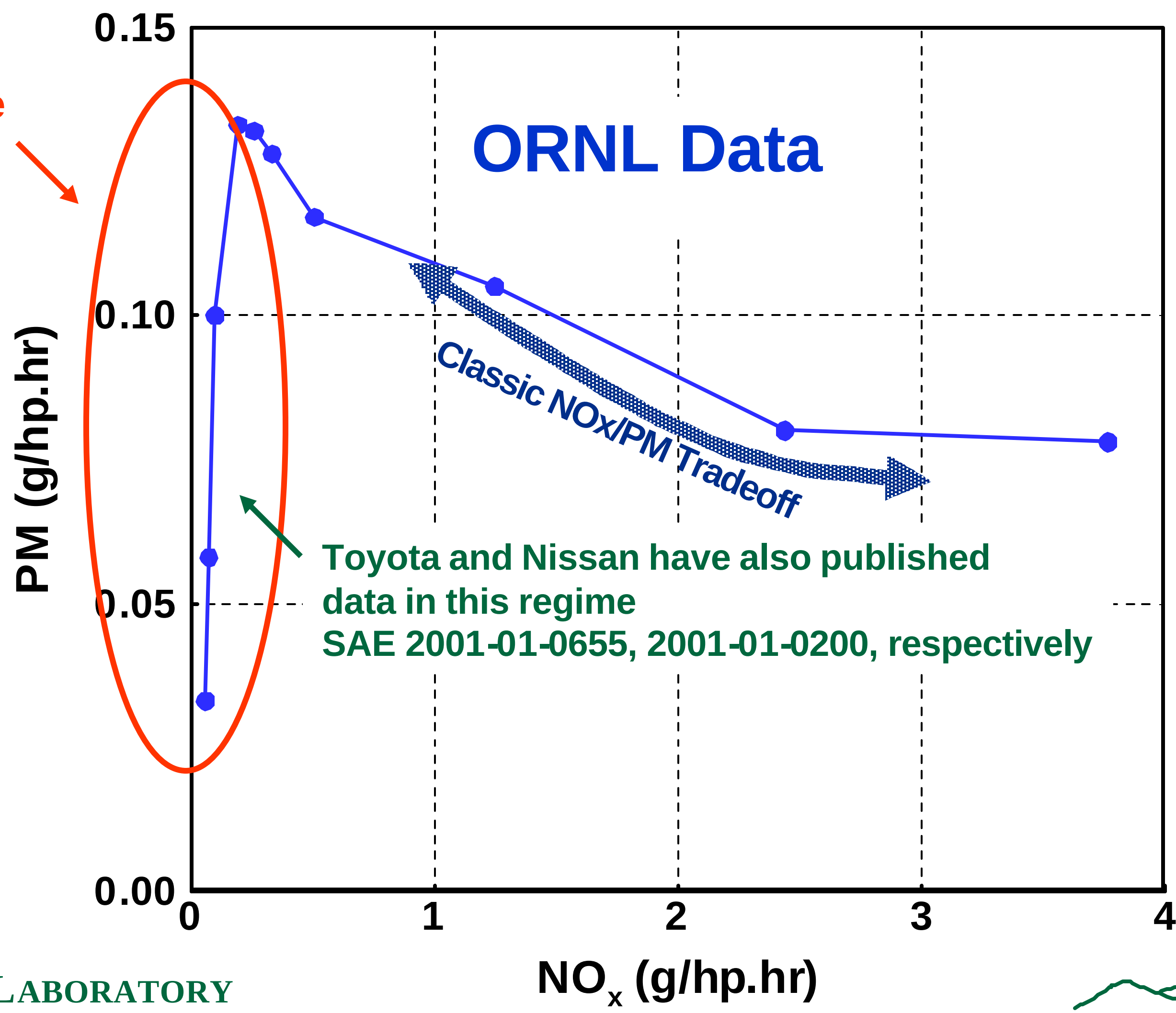
Novel Combustion Regimes Defy the "Classic NOx-PM Tradeoff"



Except for ORNL data (Wagner and Green, 2002), chart reproduced from SAE 2001-01-0655 (Akihama, et al, Toyota)

LTC Combustion Regime Reduces PM and NOx Emissions Simultaneously

PM drops in Low Temperature Combustion regime while maintaining low NOx emissions



Preliminary Results Reveal Significant NOx and PM Reduction with Little or No Impact on Fuel Efficiency

Results demonstrate a 89% reduction in NOx and a 45% reduction in PM

	EGR (%)	BSFC (g/hp.hr)	NOx (g/hp.hr)	PM (g/hp.hr)	HC (g/hp.hr)	Exh Temp (C)	Recovery Approach
Production	14	257.8	2.20	0.13	3.19	201.9	N/A
Approach One	47	253.1	0.24	0.07	6.28	224.2	Adv Timing
Approach Two	43	268.6	0.25	0.04	8.92	250.6	Increased Rail Press

Using current engine technology, lean aftertreatment devices will be required to reduce engine-out NOx and PM emissions by 90% to meet future federal emission standards.

Open Issues for Utilizing the High EGR Low Temperature Combustion Regime

- LTC combustion process is sensitive to air quality (i.e., humidity and temperature).
- Verification of LTC implementation at high engine speeds and loads. New control strategies likely needed.
- Employing this combustion regime in larger diesel engines (LTC more difficult to achieve in larger combustion chamber volumes).
- Detailed examination of the combustion products for an overall emissions strategy integrating advanced lean aftertreatment systems with LTC.
- Detecting when the engine is operating in the targeted combustion regime.
- Exploiting the potential efficiency gains from LTC.
- Examine fuel properties to enhance LTC regimes and determine LTC compatibility with non-petroleum fuels.

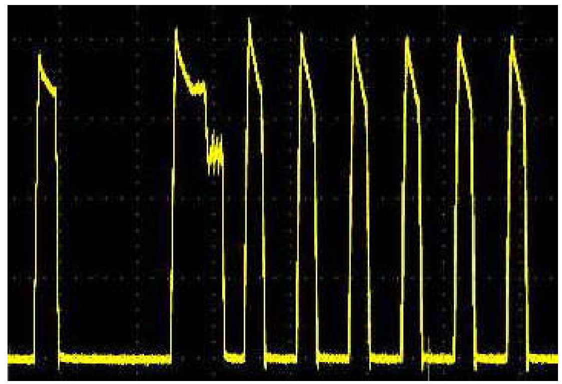
ORNL and Ford have Filed an Invention Disclosure for a "Virtual Sensor" Concept as a Diagnostic Tool for LTC Operation

- **Major claims:**
  - **Detailed information from the combustion process can be used to develop correlations between the "virtual sensor" combustion metric and PM emissions.**
  - **Diagnostic information can be used to determine cylinder-to-cylinder imbalances in EGR distribution or to provide active feedback for an EGR control strategy.**
  - **"Virtual sensor" could potentially be employed to detect when an engine is operating in these combustion regimes.**

Rapid Development Engine Control Systems at ORNL Enable R&D in this Field

Full-Pass Controller Developed with Ricardo, Inc. . . .

Up to Eight Injections Per Cylinder Event
(each with independent duration and timing control)



Full Control Over Turbo Wastegate, Intake Throttle, Fuel Rail Press., and EGR

Full-Pass Engine Control:

- Complete electronic control of important engine parameters
  - Fuel Injection
  - Intake throttle, EGR, Wastegate, etc.
- Unique capability within National Laboratories

- Benefits of "full pass" control
  - Allows proper integration of engine, fuel, and advanced aftertreatment
  - Exploration of new combustion regimes

Suggested Future Activities

- **Explore combustion fundamentals of low-NOx, low-PM combustion regimes:**
  - Seek pathways to exploit these types of combustion regimes for higher fuel efficiency
  - Further exploration of these regimes via other combustion parameters and/or at other engine loads
  - Fuel property effects, benefits
- **Hydrocarbon speciation:**
  - Discussions with industry revealed a strong interest in ORNL measuring the HC species emitted under these conditions
  - Improved understanding of the combustion process in this regime and its impact on aftertreatment components
- **PM characterization:**
  - Develop a better understanding the combustion process, as well as the benefit or harm to aftertreatment components
- **Measure EGR distribution:**
  - Examine the effect of EGR distribution on NOx, HC species, and PM

Summary

- Simultaneous reduction in PM and NOx observed with the LTC combustion regime.
- Significant reduction in PM and NOx without significant fuel efficiency penalties.
- Overall engine efficiency can probably be increased through novel combustion regimes if engines are designed with this objective.
- Novel combustion regimes offer a significant opportunity to lessen the efficiency demands and costs of aftertreatment devices.
- Closed-loop feedback control probably needed for simultaneous reduction of NOx and PM in the high EGR combustion regime.
- It appears likely that the use of novel combustion regimes will be a key feature of an overall emissions reduction control strategy.