# Enabling the Next Generation of High Efficiency Engines

*Opportunities and challenges of new technologies and an ever expanding parameter space*


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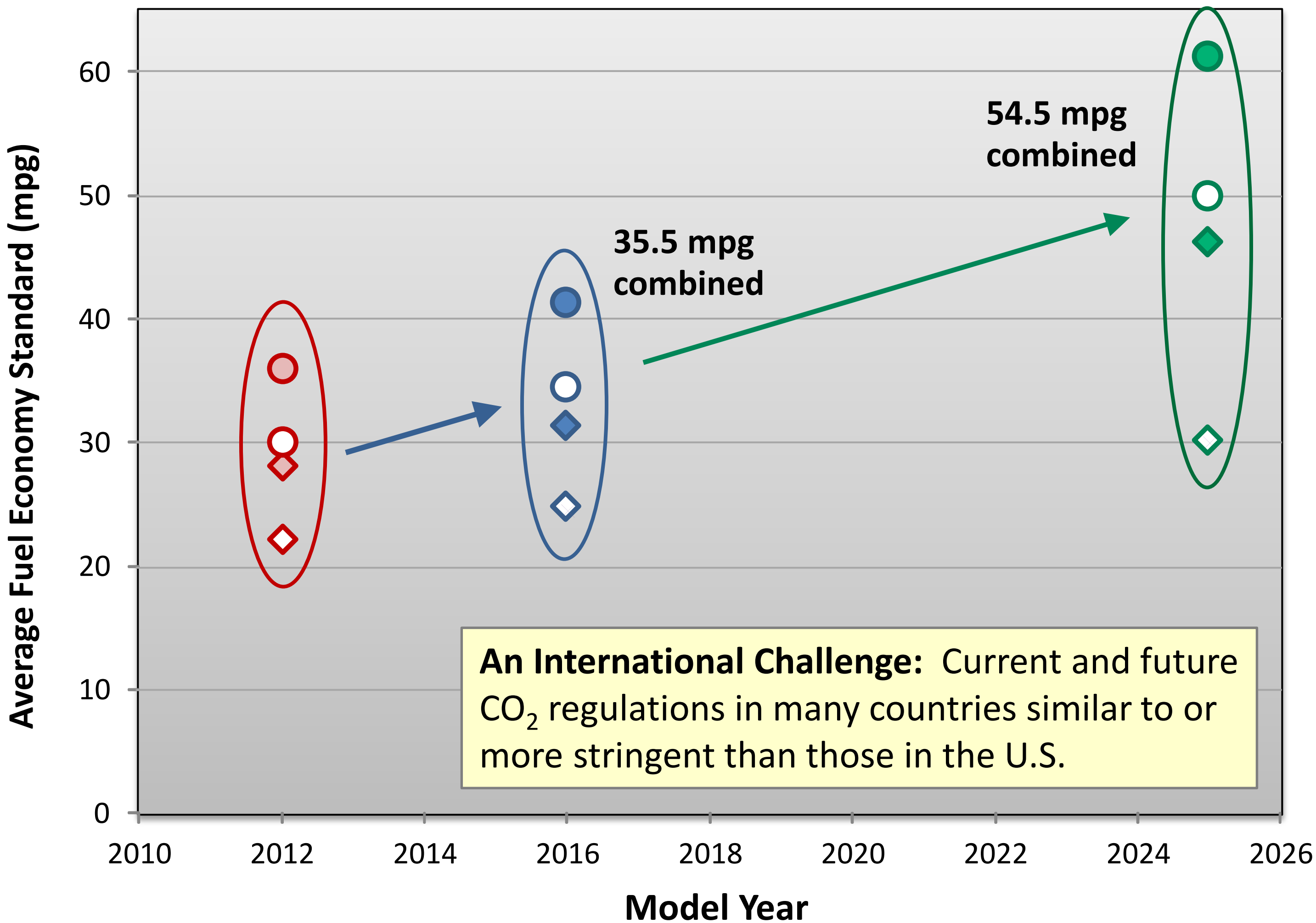
Directions in Engine-efficiency and Emissions Research conference

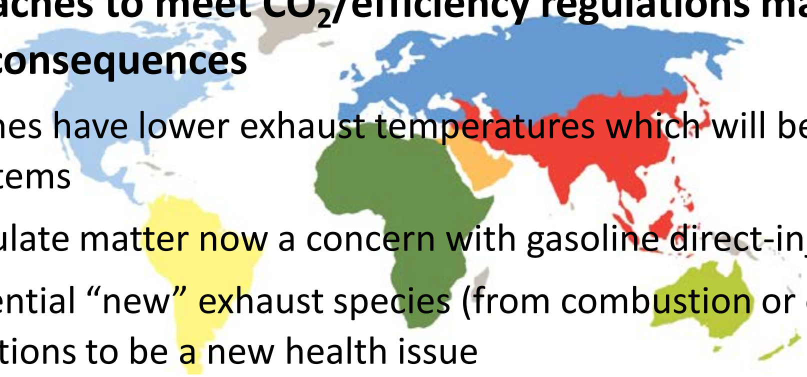
# Meeting new U.S. fuel economy standards and $CO_2$ regulations will require significant *production viable* advances in technology



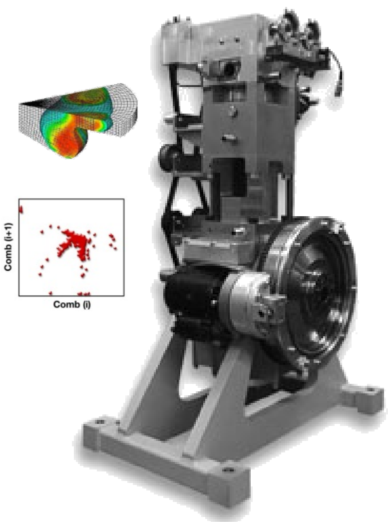

* Spread is due to range in standards for small/large passenger and light-duty truck

# Must also simultaneously meet evolving emissions standards

- **$CO_2$ and criteria emissions standards vary around the world but all becoming increasingly aggressive**
- **New technology approaches to meet $CO_2$/efficiency regulations may have unintended emissions consequences**
  - Higher efficiency engines have lower exhaust temperatures which will be a major challenge for aftertreatment systems
  - Gasoline-based particulate matter now a concern with gasoline direct-injection systems
  - Must be aware of potential "new" exhaust species (from combustion or emissions controls) in sufficient concentrations to be a new health issue
- **Requires systems approach to maximize efficiency with lowest possible emissions and minimum cost**



# Major challenge is the implementation of fundamental innovations *with* minimal loss in translation




### Fundamental combustion

*Metric: Indicated efficiency*

- Pressure work only
- Simulated boundaries

### Engine-system

*Metric: Brake (shaft) efficiency*

- Hardware limitations
- Parasitic losses
- Friction
- Engine-system controls
- Cylinder imbalances
- Aftertreatment integration

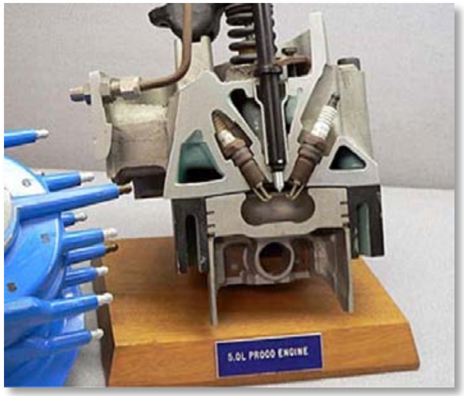
### Full vehicle

*Metric: Drive cycle efficiency*

- Drive system
- Fuel mix
- Drive cycle mismatch
- Vehicle system management

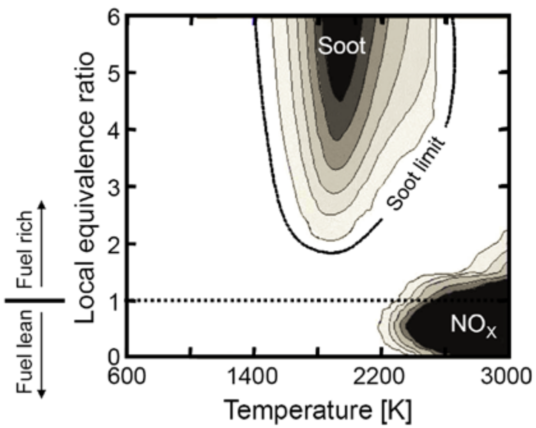
# Many high efficiency engine concepts historically limited by the state of technology

- **Direct Injection Spark Ignition**
  - Scussel, Simko, and Wade, "The Ford PROCO Engine Update“, SAE Technical Paper 780699, **1978**.
- **Low Temperature Combustion**
  - Najt and Foster, "Compression-Ignited Homogeneous Charge Combustion“, SAE Technical Paper 830264, **1983**.
  - Akihama, Takatori, and Inaga, “Mechanism of the smokeless rich diesel combustion by reducing temperature”, SAE Technical Paper 2001-01-0655, **2001**.
- **Dual-fuel Combustion**
  - Stanglmaier, Ryan, and Souder, “HCCI Operation of a Dual-Fuel Natural Gas Engine for Improved Fuel Efficiency and Ultra-Low NOx Emissions at Low to Moderate Engine Loads”, SAE Technical Paper 2001-01-1897, **2001**.
  - Singh, Kong, Reitz, Krishnan, Midkiff, “Modeling and Experiments of Dual-Fuel Engine Combustion and Emissions”, SAE Technical Paper 2004-01-0092, **2004**.



***Early SI Direct Injection***

*Ford 302 CI PROCO engine*




***Low Temperature Combustion***

ϕ-T *space shows regions of high soot and NOx production (Akihama et al., SAE 2001-01-0655)*

# Technology advances leading to a paradigm shift in engine management

- **Component development**
  - Robust and fast response turbomachinery
  - Flexible intake and/or exhaust valve systems
  - Variable compression ratio
  - Flexible fast-acting fuel injection systems
  - High pressure direct-injection fuel systems
  - Advanced ignition technologies

**Advances in component technologies allow for more complete control of engine boundary conditions and the combustion process**

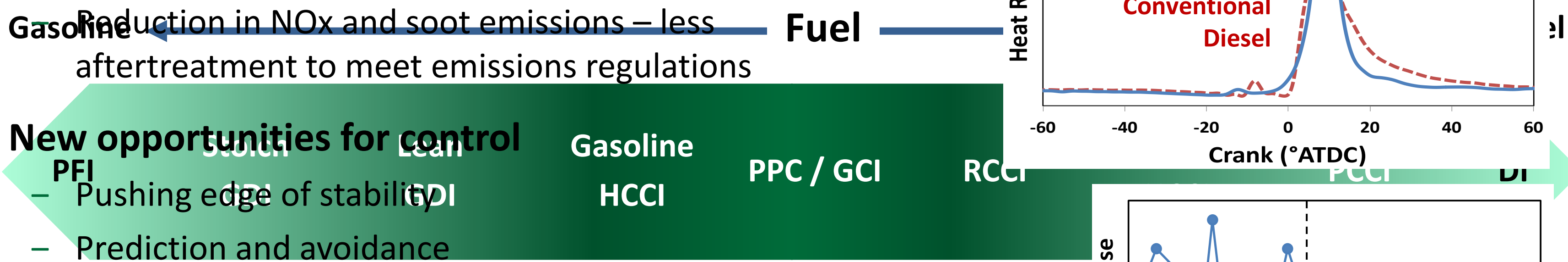
- **Sensor development**
  - High-speed pressure and temperature
  - Onboard emissions diagnostics
- **ECU development**
  - New, faster architectures
  - Combustion feedback
  - Ability to solve complex problems *on-the-fly*

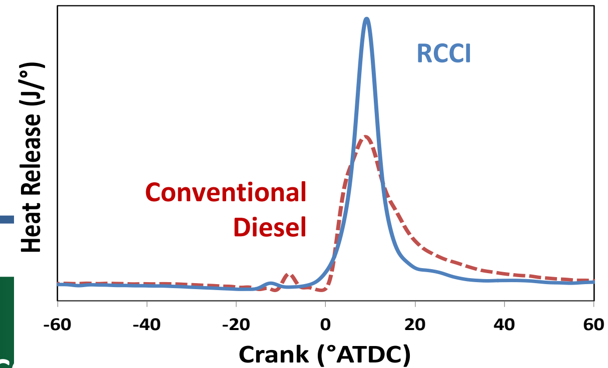
**Advances in sensors and on-board computing allow for more active control for pushing the boundaries of high efficiency operation**

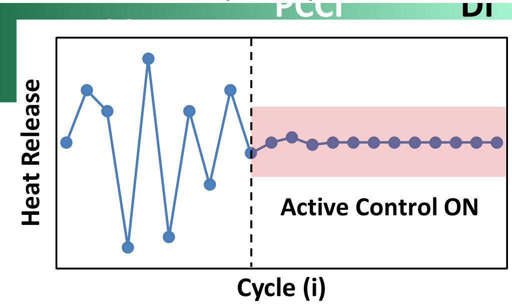
**TAKEAWAY: Unprecedented opportunities in combustion strategy and controls**

# Options no longer limited to conventional SI and CI combustion

- **More optimal combustion for highest efficiency**
  - More rapid energy release
  - Reduction in heat transfer losses
  - Reduction in NOx and soot emissions – less aftertreatment to meet emissions regulations
- **New opportunities for control**
  - Pushing edge of stability
  - Prediction and avoidance
  - Self-learning
- **Technology development on track for more widespread production use of advanced combustion**

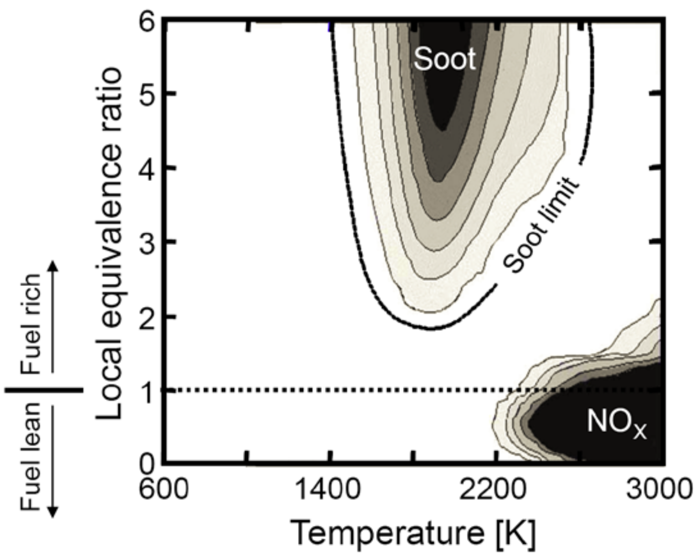


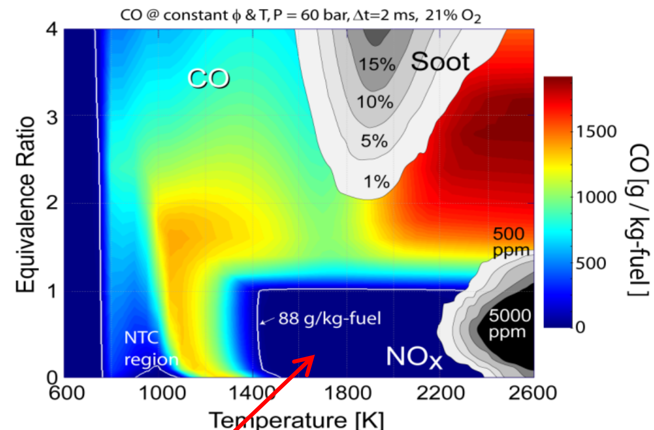



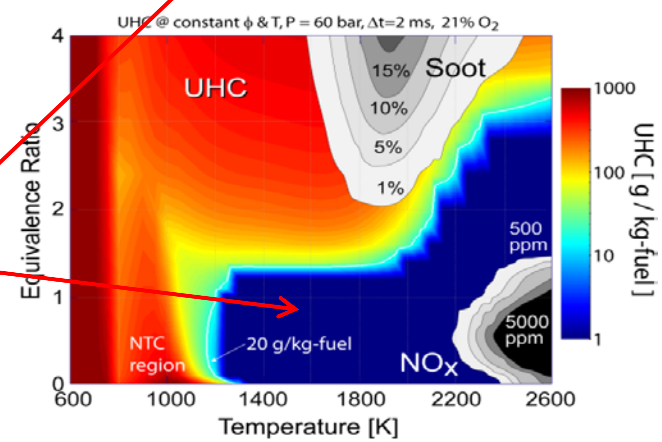
# Regardless of approach – end game objective is to maximize efficiency with lowest possible emissions

**Need to manage the combustion process to avoid soot and NOx formation …**




**…while at the same time avoid CO and UHC emissions**




**Charge must end up in this region after combustion is complete**

Slide adapted from DOE presentation, Gurpreet Singh *et al.*

# **Example:** Reactivity Controlled Compression Ignition (RCCI) combustion

- **In-cylinder fuel blending enables improved control of premixed combustion event**
  - Two fuels with different reactivity (e.g., gasoline and diesel) to form in-cylinder reactivity gradients
- **Benefits**
  - Diesel-like or higher brake thermal efficiency
  - Low NOx and particulate emissions (less aftertreatment requirements)
- **Multi-cylinder engine challenges**
  - Two fuel systems with precise control
  - High dilution (for some conditions)
  - Precise control of intake conditions
  - Combustion feedback control
  - ....

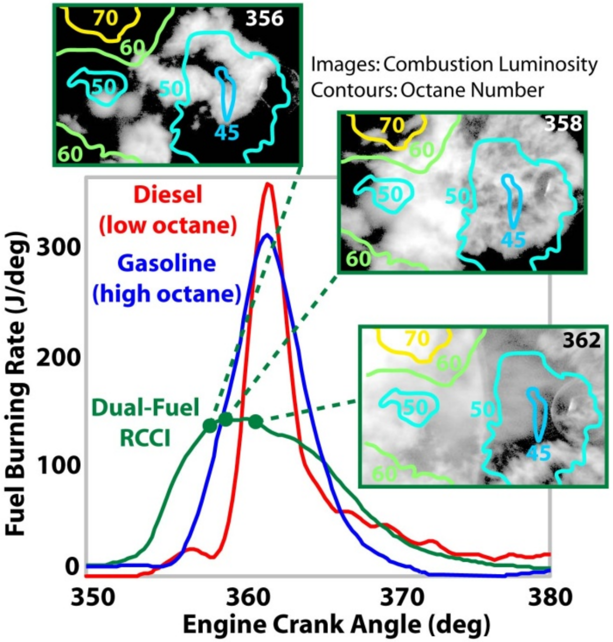


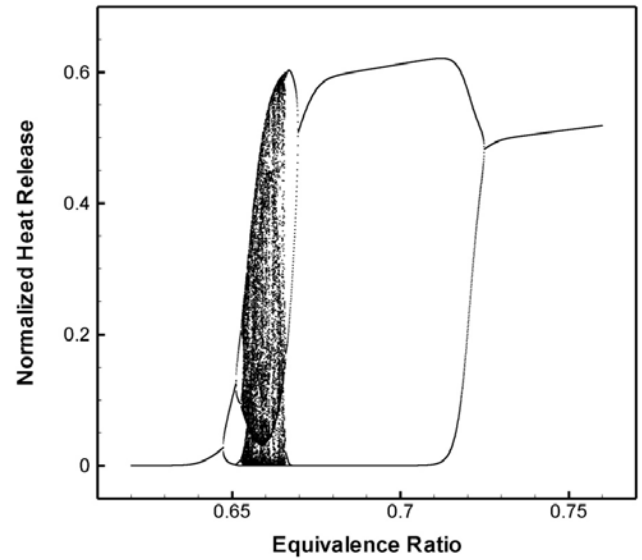

Figure Source: Sandia National Laboratories, “Optical Engine Research Rapidly Reveals How High-Efficiency RCCI Combustion Controls Burning Rates”, U.S. DRIVE Highlights of Technical Accomplishments 2011.

**For more information:**

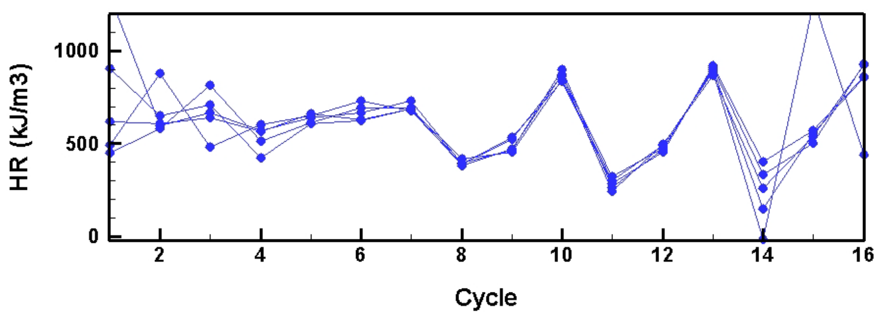
- Curran et al., ORNL, “Reactivity Controlled Compression Ignition (RCCI) Combustion on a Multi-Cylinder Light-Duty Diesel Engine”, accepted for publication *International Journal of Engine Research*, 2012.
- Curran et al., ORNL, “In-cylinder Fuel Blending of Gasoline/Diesel for Improved Efficiency and Lowest Possible Emissions on a Multi-Cylinder Engine”, Society of Automotive Engineers, Paper 2010-01-2206 .

# New control opportunities: Previous observations of structure in cyclic dispersion once thought of as academic curiosities

- **Lean Combustion Limit**
  - Kantor, "A dynamical instability of spark-ignited engines", *Science* 15 June **1984**: Vol. 224 no. 4654 pp. 1233-1235.
  - Daily, "Cycle-to-cycle variations: A chaotic process?", *Combustion Science and Technology,* **1988**, Vol. 57, pp 149-162.
  - Wagner, Drallmeier, and Daw, "Nonlinear Cycle Dynamics in Lean Spark Ignition Combustion", Twenty-Seventh International Symposium on Combustion, The Combustion Institute, **1998**.
- **HCCI Instabilities**
  - Wagner, Edwards, Daw, Green, and Bunting, "On the nature of cyclic dispersion in spark assisted HCCI combustion", SAE 2006-01-0418, **2006**.




*Simulation example of cycle-to-cycle variations for lean-burn SI combustion*

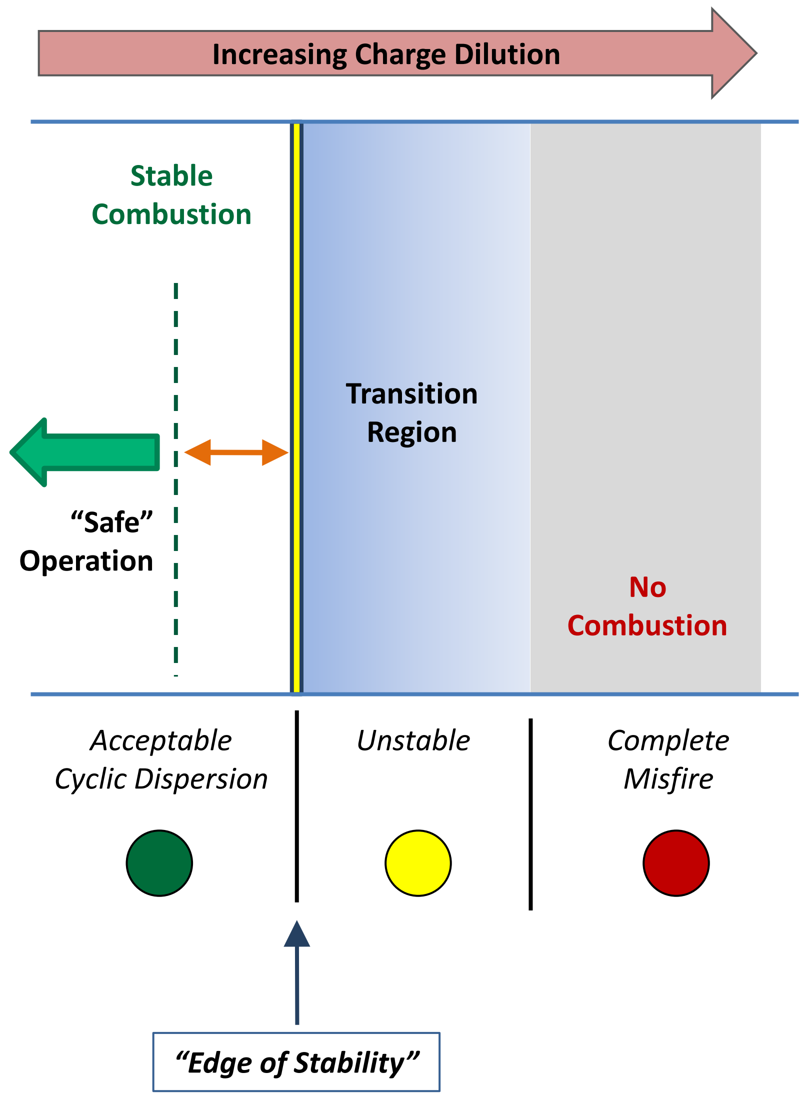



*Repeating patterns observed near the stability limit of spark assisted HCCI combustion*

# Opportunity is through the prediction and control for the forced stabilization of inherently unstable systems

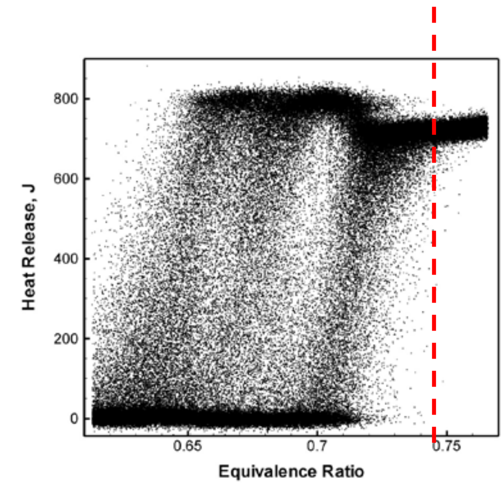
- **Stability potential roadblock to many advanced combustion implementations**
- **Current approach is distance from the edge of stability to avoid unintended excursions**
- **Driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes**
- **Further complicated by cylinder imbalances**

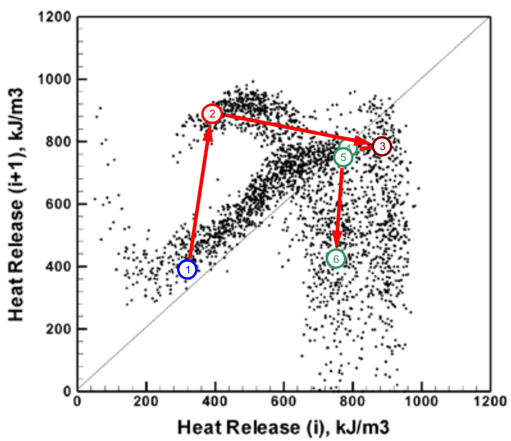
**TAKEAWAY: Dynamic instabilities are short-term predictable and conducive to control**



# Understanding of instability mechanisms coupled with advances in sensors and ECUs will enable unprecedented control opportunities

- **Operation near the "edge of stability"**
  - Avoid unintended excursions which may damage or destroy engine and aftertreatment systems
  - ➡ Example showing the **"edge of stability"** for lean burn SI combustion

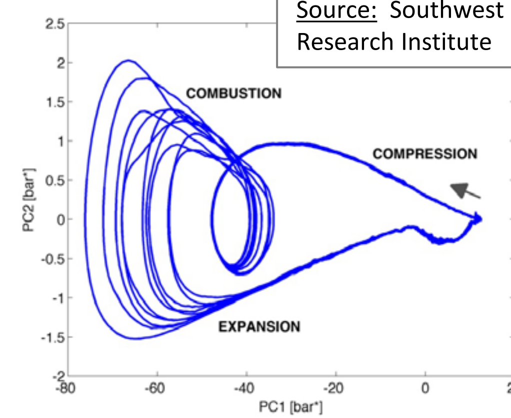



- **Transition and stabilization of LTC modes**
  - Multi-mode operation may require transition between combustion modes
  - Operation under inherently unstable conditions may provide benefits
  - ➡ Example of complex but **short-term predictable** patterns in spark assisted HCCI combustion

- **Avoiding abnormal combustion events**
  - Pre-ignition potential roadblock to extreme down-sizing
  - Advanced time-series methods used for prediction and avoidance
  - ➡ Example phase-space reconstruction which is one method that has potential for **prediction and avoidance** of abnormal combustion events

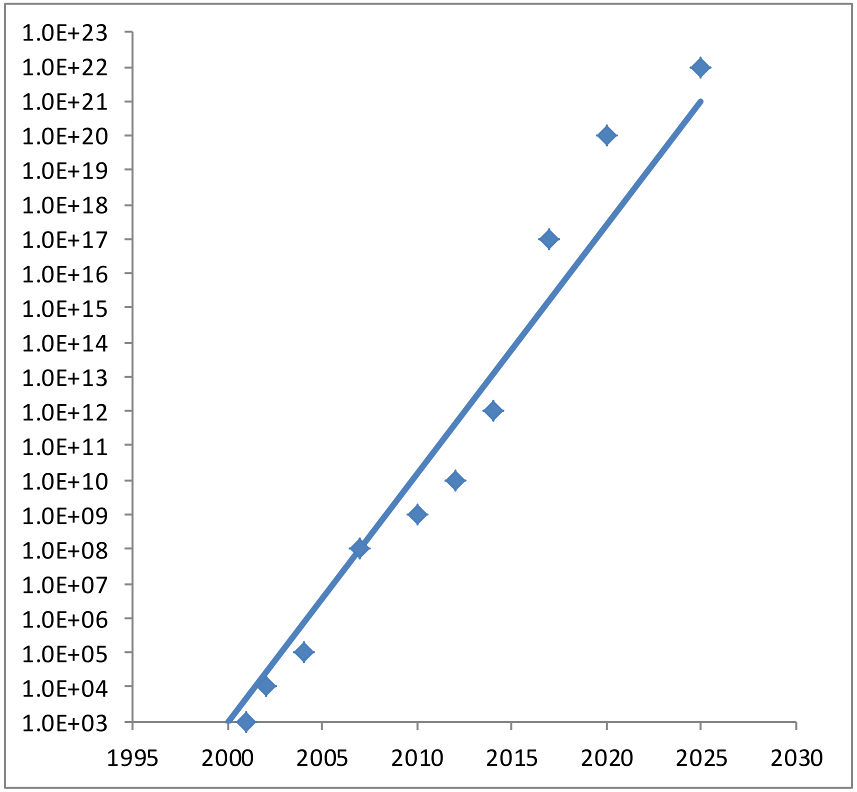
Source: Southwest Research Institute



# Parameter space is growing rapidly and expected to continue to grow

- **Challenge**
  - Conventional design methods may not be possible for optimal solution
  - Massive calibration space is difficult to manage
- **Opportunity**
  - Enable new high efficiency combustion strategies for real-world applications
  - Improved fuel flexibility – ability to make use of a more diverse fuel supply?

**TAKEAWAY: On path to fully own the engine for new levels of optimization**



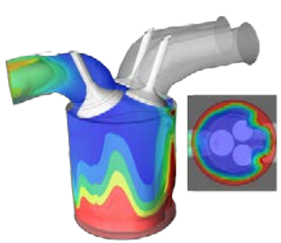

**Full Factorial Calibration Space (for 10 level variation in each parameter)**

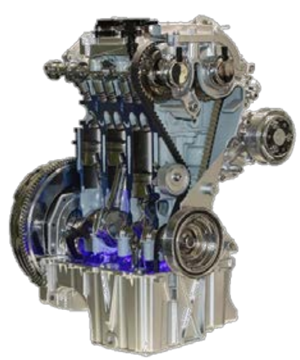
Source: Adapted from **Atkinson** et al., DEER 2011.

# Better simulation is critical to engine design and calibration optimization

- **Three levels of simulation with different purposes**
  - **Predictive combustion:** combustion optimization and methods development
  - **Full engine simulation:** engine system optimization and model-based controls
  - **Full vehicle simulation:** technology interactions, component optimization and supervisory controls
- **Each scale requires different level of fidelity**
  - High fidelity combustion on vehicle scales computationally impossible (at the moment)
- **Exponential increase in parameter space translates to exponential increase in simulation space and computational requirements**

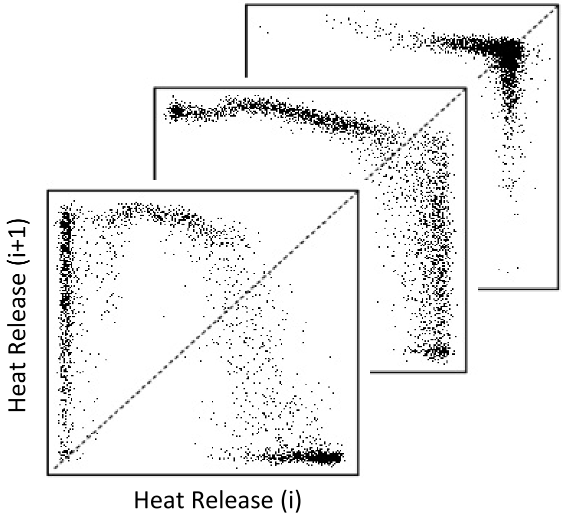
**TAKEAWAY: Need for faster simulation, faster optimization methods, and reduced models for on-board controls**





# Leadership High Performance Computing* (HPC) has potential to accelerate design and development at an unprecedented scale

- **ORNL applying unique combination of engine and catalysis expertise with world-class HPC expertise to address design and engineering challenges**
- **Example ORNL projects in progress with industry**
  - **Large Infrastructure computing for Multi-cycle Instability and Transient Simulations" (LIMITS)**
    - Addresses limits of fuel economy benefit of dilute combustion
    - Focus on stochastic and deterministic processes that drive cycle-to-cycle instabilities
    - Major challenge is scaling serial problem (cycle-to-cycle variations) to parallel architecture
  - **Injector design optimization**
    - Improve understanding and design optimization of fuel injector hole patterns for improved engine efficiency and reduced emissions



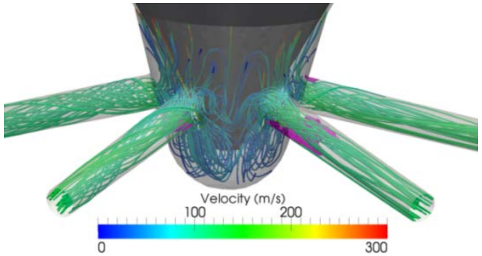
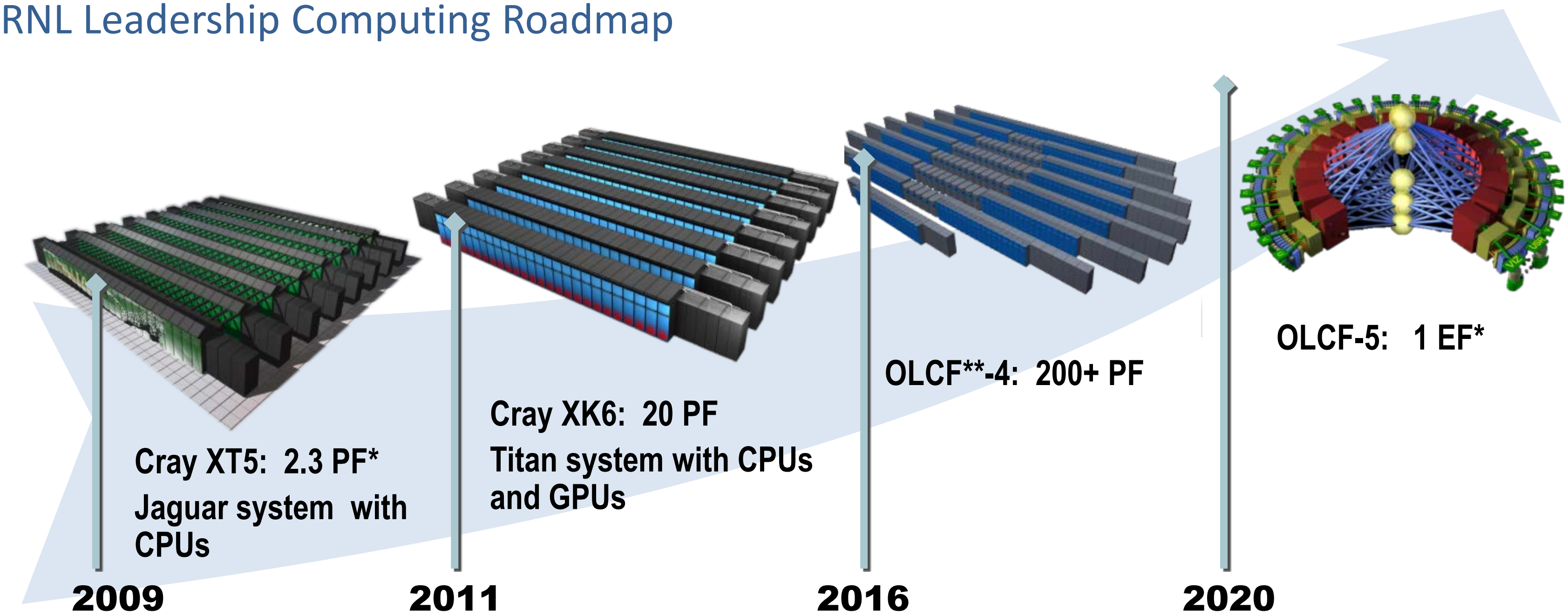




Figure reference: *Neroorkar, Mitcham, Plazas, Grover, Schmidt, "Simulations and Analysis of Fuel Flow in an Injector Including Transient Needle Effects", ILASS-Americas 24th Annual Conference on Liquid Atomization and Spray Systems, San Antonio, TX, May 2012.*

**Leadership HPC: DOE provides a portfolio of national high-performance computing facilities housing some of the world's most advanced supercomputers.*

# HPC speeds will increase 1000x over the next decade

## ORNL Leadership Computing Roadmap




- **Leadership technology of today provides foundation for desktop computers and small clusters of tomorrow**
- **Interesting factoids:**
  - Current laptop technology would have ranked in top 500 supercomputers of the late 1990s
  - System at bottom of current top 500 list equivalent to aggregate of all machines on 1999 list
  - An iPad 2 would have made the early lists of the top 500 machines in the world

**PF = Petaflop = 1 quadrillion floating point operations/second; EF = Exaflop = 1 quintillion floating point operations/second*

***OLCF = Oak Ridge Leadership Computing Facility*

# HPC challenges and opportunities going forward

- **Improved large scale modeling and simulation is critical to addressing evolving science and engineering problems to make the most of advances in engine and catalyst technologies**
- **Resources becoming more readily available**
  - HPC technology continues developing at fast pace
  - Multi-core systems now readily available and affordable
  - New hybrid architectures are combining traditional CPUs with GPUs to deliver new capabilities
- **Major challenge is many simulation codes not ready for large scale parallel and/or hybrid architectures**
- **Large scale simulation critical to understanding and developing reduced models for small clusters and eventually onboard computers**


*Jaguar, a Cray XK6 supercomputer housed at ORNL is a DOE flagship supercomputer and one of the fastest in the world for unclassified research*

# Takeaways

- **Engines are undergoing a paradigm shift in flexibility**
- **New control opportunities will push the boundaries of high efficiency operation**
- **New approaches to calibration will be necessary for optimization of the next generation of engines**
- **Predictive simulation is essential for optimal design and controls**
- **HPC is available and should be considered when developing new models and simulation codes**

# Acknowledgements

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