Opportunities for Improved Efficiency in Spark Ignited Engines

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Presentation for the Knoxville-Oak Ridge Section of the American Institute of Chemical Engineers (AIChE)

Acknowledgement

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ORNL is managed by UT-Battelle
for the US Department of Energy

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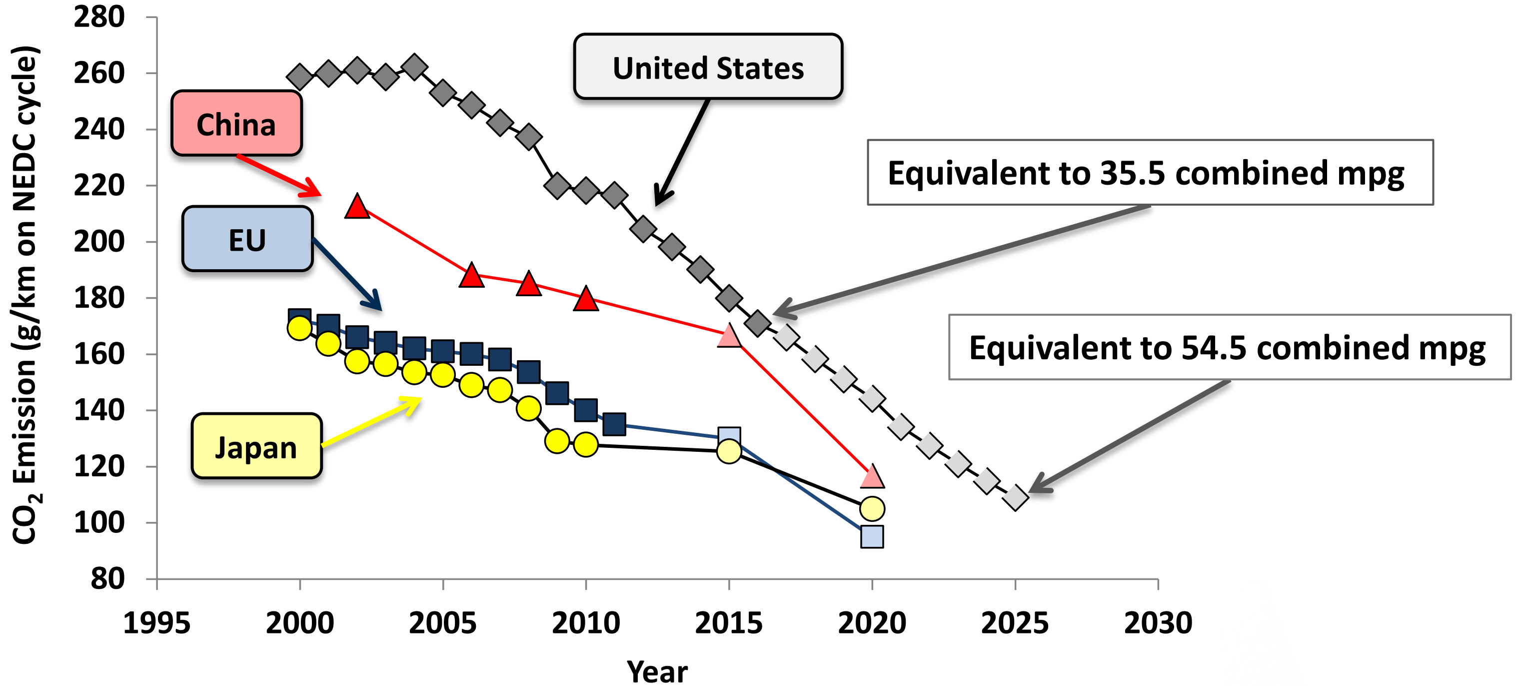
Legislated Targets for CO_2 Emissions and Fuel Economy are in a Period of Rapid Transition in the U.S. and Around the World



Data from the International Council on Clean Transportation http://www.theicct.org/info-tools/global-passenger-vehicle-standards

- OEMs are taking an all-inclusive approach to reduce CO_2 emissions:
  - Reducing vehicle weight
  - Vehicle electrification
  - Intelligent engine controls
  - Higher efficiency engines

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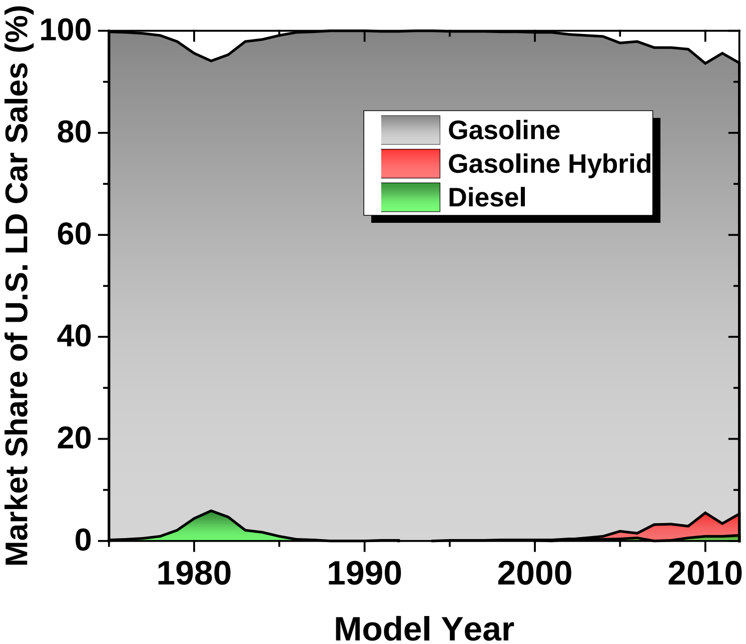
Isn't the Internal Combustion Engine an Outdated Technology? Why Focus on Spark-Ignited Engines?

Internal Combustion Engines Continue to Dominate Transportation

"The performance, low cost, and fuel flexibility of ICEs makes it likely that they will continue to dominate the vehicle fleet for at least the next several decades. ICE improvements can also be applied to both hybrid electric vehicles (HEVs) and vehicles that use alternative hydrocarbon fuels." DOE QTR 2011[1]

Gasoline Engines Dominate the Light Duty Market in the U.S.



U.S. Goal of having 1 Million Electric Vehicles on the Road by 2015

- Electric vehicles are an important technology
- Technological improvements in gasoline engines cannot be neglected
  - Fuel savings from 1 million electric vehicles: 0.5 bgpy
  - U.S. gasoline consumption: 130 bgpy

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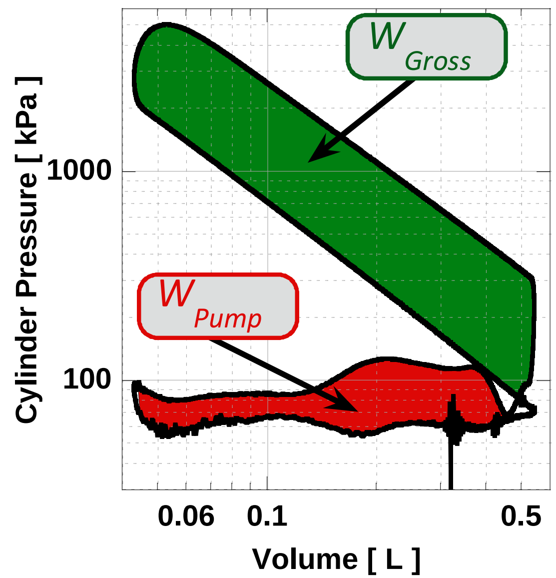
Braking Down the Thermodynamic Engine Lingo: From Gross Work to Brake Work

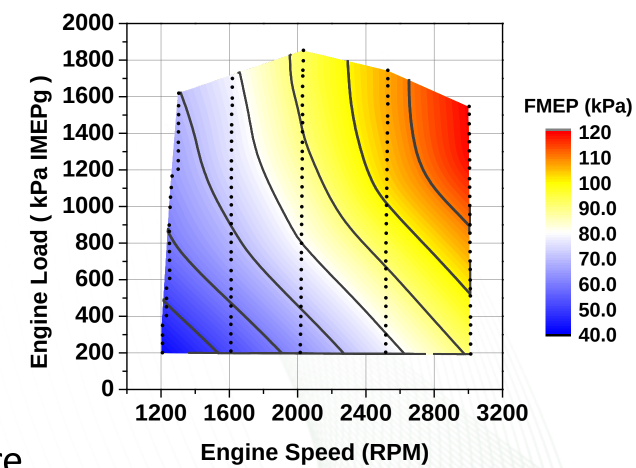
$$W_{Brake} = \underbrace{W_{Gross} - W_{Pump}}_{W_{Net}} - W_{Friction}$$



- W_{Gross} is typically the only opportunity to create positive work from the engine
  - Includes compression and expansion, portion of cycle described by the Ideal Otto cycle
  - W_{Gross} includes heat transfer

$$\eta_{thermal} = 1 - \left(\frac{1}{r_c^{(\gamma-1)}}\right)$$

- W_{Pump} is the thermodynamic expense of moving air into and out of the cylinder
  - Pumping work typically increases as load decreases in SI engines due to throttling
- $W_{Friction}$ is the thermodynamic expense of getting the work out of the engine
  - Typically includes parasitics (alternator, fuel pump, belts, etc.)
  - $W_{Friction}$ increases with engine speed and peak cylinder pressure



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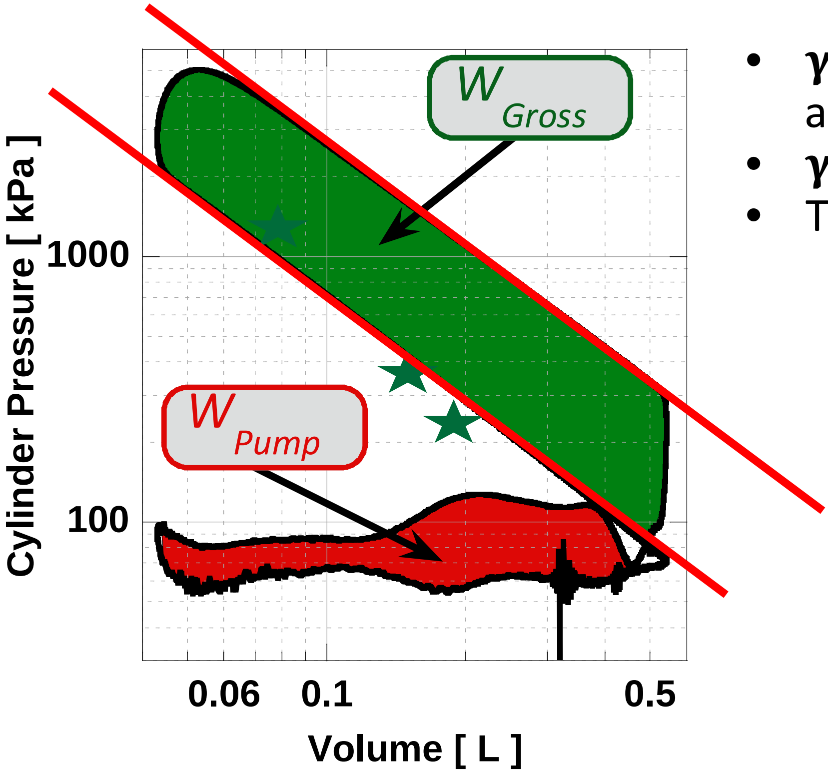
Understanding How to Obtain High Efficiency: Insights from the Ideal Otto Cycle

Ideal Gross Otto Cycle Efficiency $$\eta_{thermal} = 1 - \left(\frac{1}{r_c^{(\gamma-1)}}\right)$$

- Efficiency is a function of the mechanical system (compression ratio, r_c)
- Efficiency is a function of the working gas properties $\gamma = \frac{c_p}{c_v}$



- γ is the slope of compression and expansion on a log-log PV diagram
- γ directly affects the area under the curve
- The area under the curve is the Work

Note: While ideal Otto Cycle Efficiency is useful for providing insight, real engines are not governed by Carnot efficiency because the working fluid composition is renewed every cycle, and the composition changes throughout the cycle.

UNDERSTANDING HOW TO OBTAIN HIGH EFFICIENCY: INSIGHTS FROM THE IDEAL OTTO CYCLE

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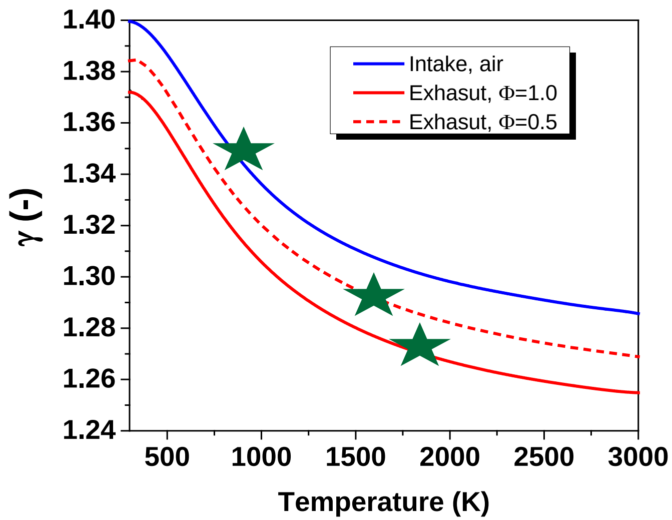
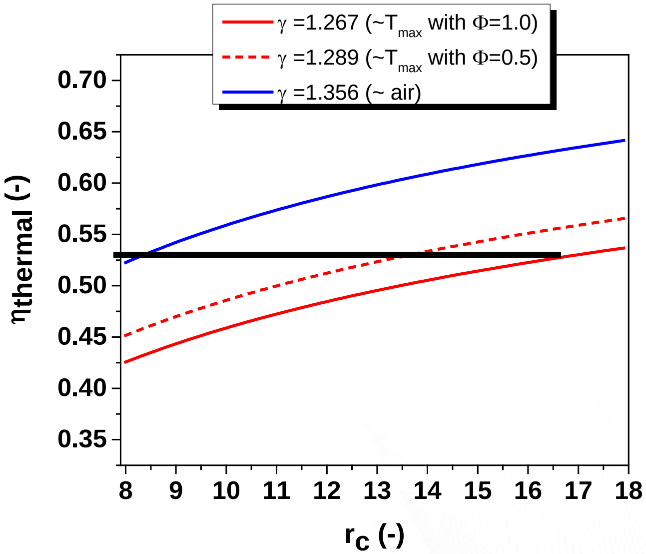




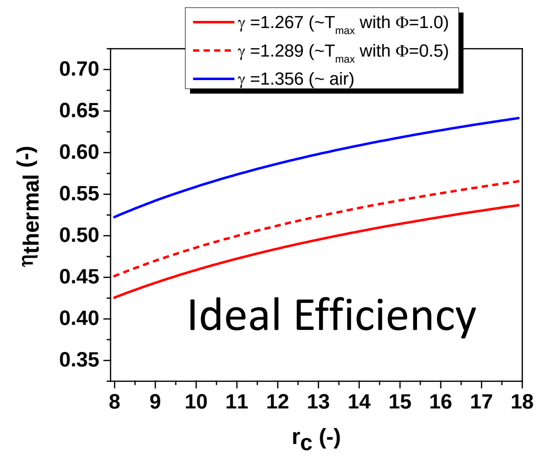
Low Temperature is Beneficial

High Compression Ratio is Beneficial

Note: While ideal Otto Cycle Efficiency is useful for providing insight, real engines are not governed by Carnot efficiency because the working fluid composition is renewed every cycle, and the composition changes throughout the cycle.

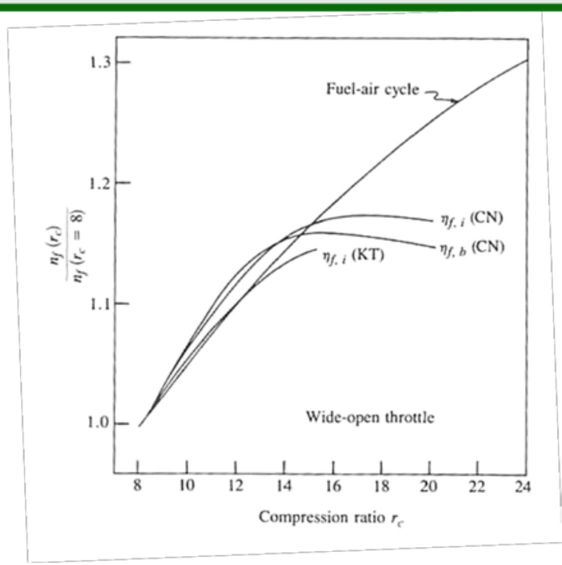
Ideal vs. Real World Benefits of Compression Ratio

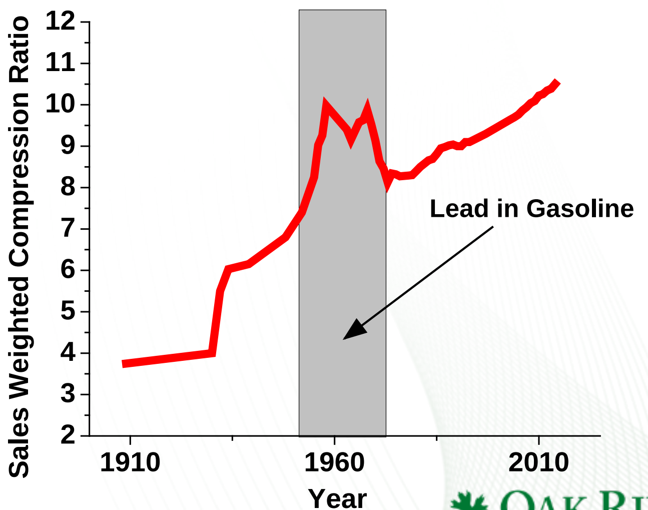
- Ideal Otto cycle efficiency increases with compression at a rate of diminishing returns
- Practical tradeoffs with high compression ratio
  - T_{max} increases: heat transfer increases
  - P_{max} increases: friction increases



Compression for highest brake efficiency is between 13:1 and 15:1

Vehicle compression ratio is significantly below that for max efficiency





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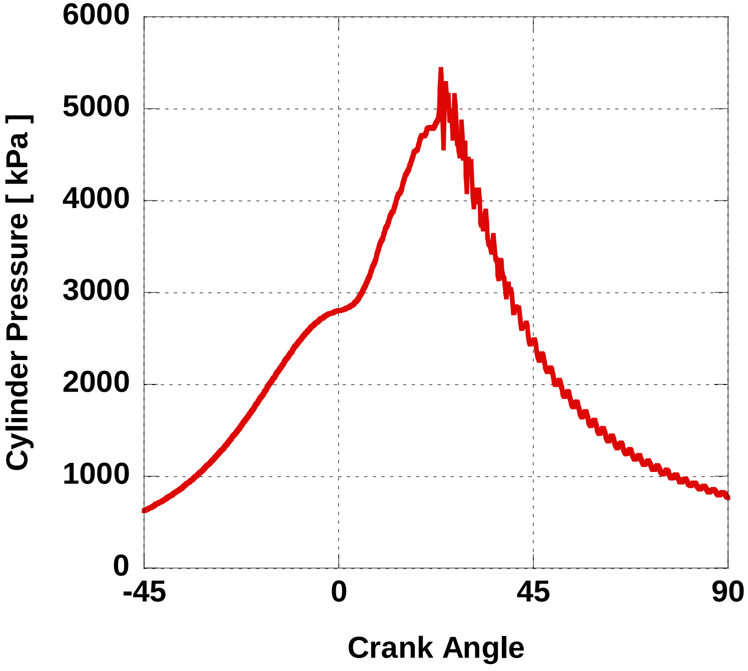
High Efficiency Pathway 1. High Octane Fuels

Compression Ratio and Efficiency are Limited by End Gas Knock

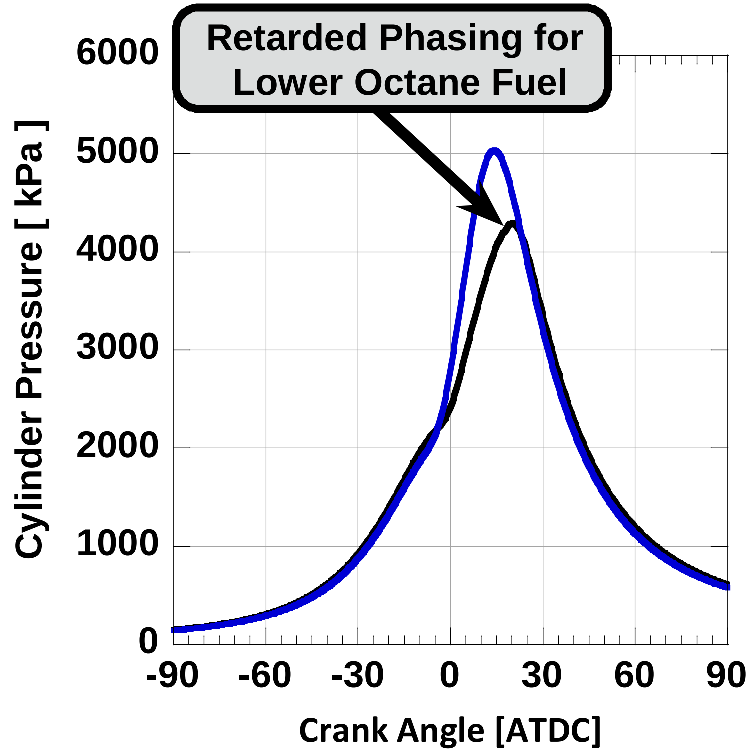
- Knock is the phenomenon of end gas autoignition
  - Causes a ringing or pinging sound in the engine
  - Severe knock can cause engine damage
- Propensity to knock increases as compression ratio increases
  - Caused by hotter cylinder temperatures
  - Limit on compression ratio and efficiency

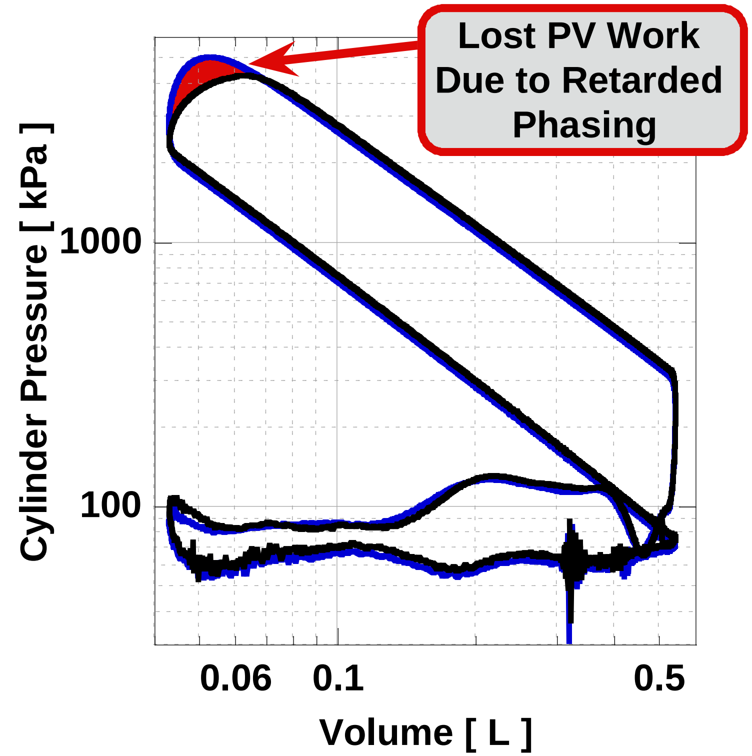


- All modern automotive SI engines are knock-limited at high engine load
  - Electronic sensors and controls typically mitigate knock prior to driver awareness
  - Knock mitigation comes at the expense of efficiency
- Octane number of the fuel is a measure of its resistance to knock
  - Higher octane fuel can enable higher efficiency engines if they are designed for it
  - Simply swapping to a higher octane fuel in the same engine doesn't necessarily increase efficiency

Increasing Octane Number at a Given Compression Ratio Results in Better Combustion Phasing, Higher Efficiency

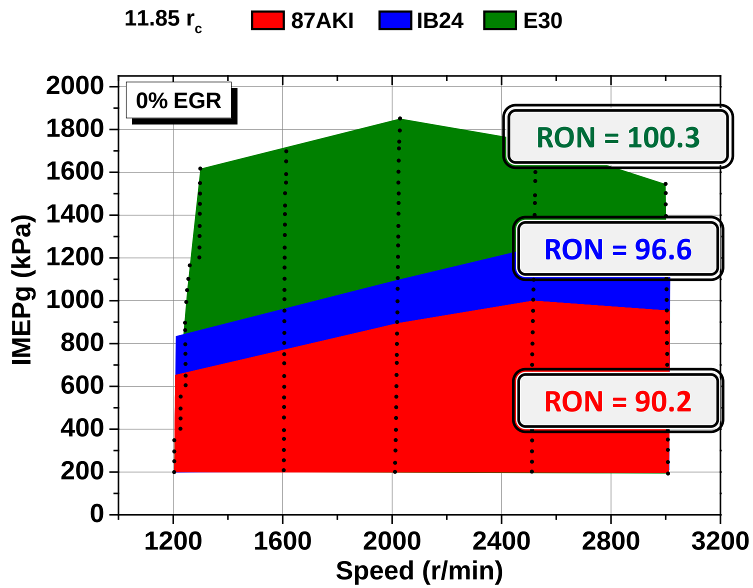
- At the optimal combustion phasing, the expansion stroke is fully utilized
- Retarding combustion phasing is an effective method to mitigate knock
  - The expansion stroke is under-utilized with retarded combustion phasing





High Octane Fuels Combined with Turbochargers can Enable Higher Specific Output Engines for Dowisizing and Downspeeding

- Higher specific power output can be achieved with high octane fuels
  - Efficient turbochargers and engines capable of very high cylinder pressure are enablers
- High specific power output is an enabler to downsizing and downspeeding
  - Downsizing: using a smaller displacement engine to provide the required performance
  - Downspeeding: operating the engine at a lower engine speed to provide the required power
- Downsizing and downspeeding primarily improve efficiency through two mechanisms
  1. Reduced friction: Decreases with smaller displacement and lower speed
  2. Reduced pumping work: Higher load, less throttling required



$$W_{Brake} = W_{Gross} - W_{Pump} - W_{Friction}$$

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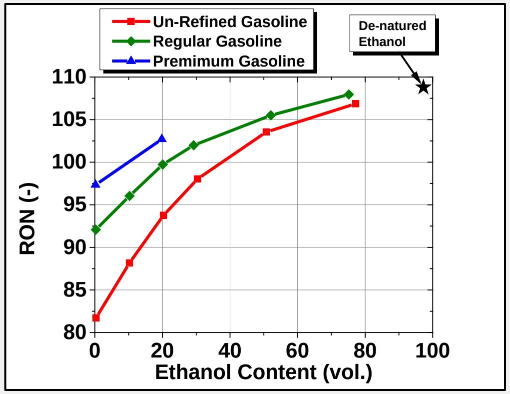
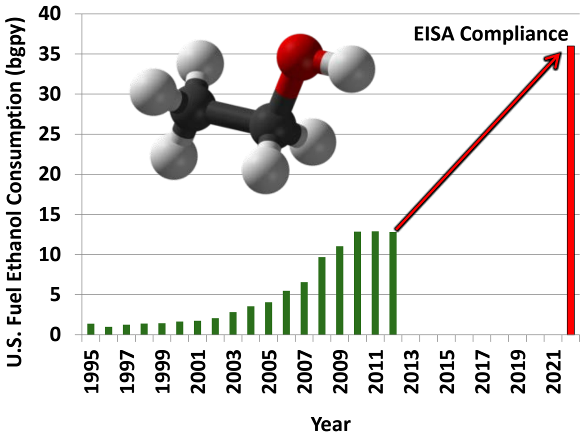
High Octane Fuel is Potentially Synergistic with Low Carbon Fuels and the Renewable Fuel Standard (RFS)

- Ethanol is a very high octane fuel component!
- Rapid increase in octane number as ethanol is blended
  - Anderson has shown octane blending is more linear on a molar basis (*Energy & Fuels, 24(12):6576-6585, 2010; SAE 2012-01-1274, 2012*)
  - Rule of thumb: 2/3 of the potential octane number benefits are realized with first 1/3 ethanol blending by volume
  - Additional anti-knock benefits due to high latent heat of vaporization
- Legislation targets 36 billion gpy of renewable fuels by 2022
  - Currently consuming 13 billion gpy ethanol
  - Gasoline pool is nearly saturated at E10 on a national level
  - This "E10 blend wall" is a barrier moving forward, there is a need to use ethanol differently moving forward

High octane "Renewable Super Premium" fuel containing 20-30 % ethanol could provide synergism between efficient vehicles and renewable fuels!



Redrawn from Stein et al., Int. J. Fuels Lubr, 5(2) 2012, SAE2012-01-1277



ORNL Engaged Stakeholders for a High Octane Renewable Super Premium Fuel by Organizing 2013 and 2014 Symposia

- Symposium brought together stakeholders and technical experts
  - Speakers from regulatory agencies, OEMs, energy companies, convenience stores, and academia
- Widespread agreement that high octane, high ethanol content can lead to higher efficiency
  - Ethanol benefits of latent heat of vaporization go beyond octane number
  - Efficiency benefit can make up for the reduced energy density of ethanol blends
  - Optimized vehicle would most likely not be compatible with lower octane market fuel
- Primary conclusion is that switching to a new fuel on a national scale is non-trivial
  - EPA regulatory authority not straight-forward: reliant on GHG emissions, numerous hurdles
  - OEMs conflicted: concerns over misfueling, fuel availability, and fuel pricing
  - Oil industry opposed to new fuel: lifecycle GHG emissions unclear, RFS should be revised or repealed because of lack of cellulosic ethanol, premium grade gasoline already available
- Retailers do not have deep pockets for potential > $10 billion cost of equipment upgrades
- Despite significant obstacles, introduction of new “renewable super premium” offers a real opportunity for increasing efficiency of vehicles on a national scale

Complete symposium overview available at: http://info.ornl.gov/sites/publications/Files/Pub41330.pdf

High Octane Fuel Potential

- Knock is a barrier to achieving higher efficiency in SI engines
- High octane number fuel will help mitigate knock
  - Enable higher compression ratio for better thermal efficiency

    and/or
  - Enable downsizing/downspeeding for better system efficiency

  → Product-specific choice
- Synergism exists through ethanol between increased use of renewables and highly efficient engines
- Other refinery routes to high octane fuels exist, but unclear if they produce a lower lifecycle carbon footprint
- Technologically using a high octane fuel for high efficiency is straight-forward
- Changing fuel in the marketplace is a very difficult thing to do
  - Many stakeholder (OEM's, energy companies, fuel distribution, consumers)
  - Chicken-and-egg scenario – neither engines nor fuel are likely to be fully backward compatible

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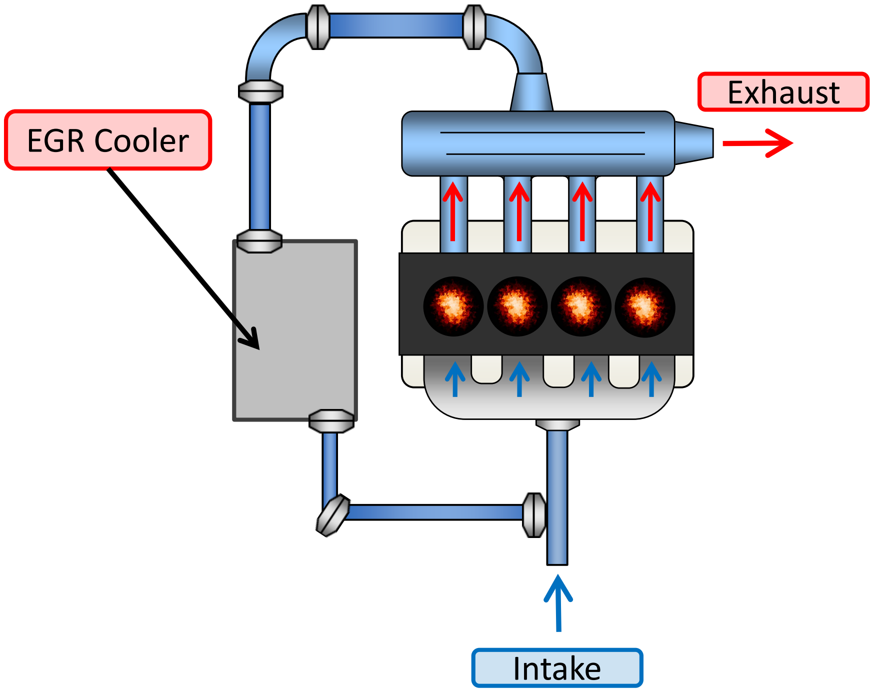
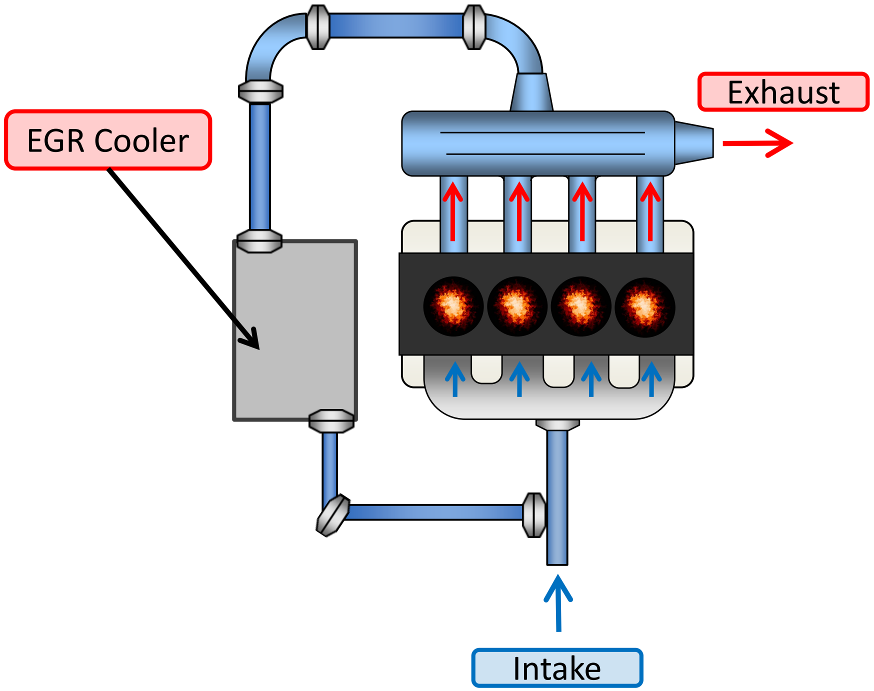
High Efficiency Pathway 2. EGR Dilution

Exhaust Gas Recirculation Involves Diluting the Intake Charge with Cooled Exhaust Gas



Why in the world would anyone want to do this???

Exhaust Gas Recirculation Involves Diluting the Intake Charge with Cooled Exhaust Gas



$$W_{Brake} = W_{Gross} - W_{Pump} - W_{Friction}$$

$$\eta_{thermal} = 1 - \left(\frac{1}{r_c^{(\gamma-1)}}\right)$$

γ: Increases due to composition ✓

γ: Increases due to lower temperature ✓

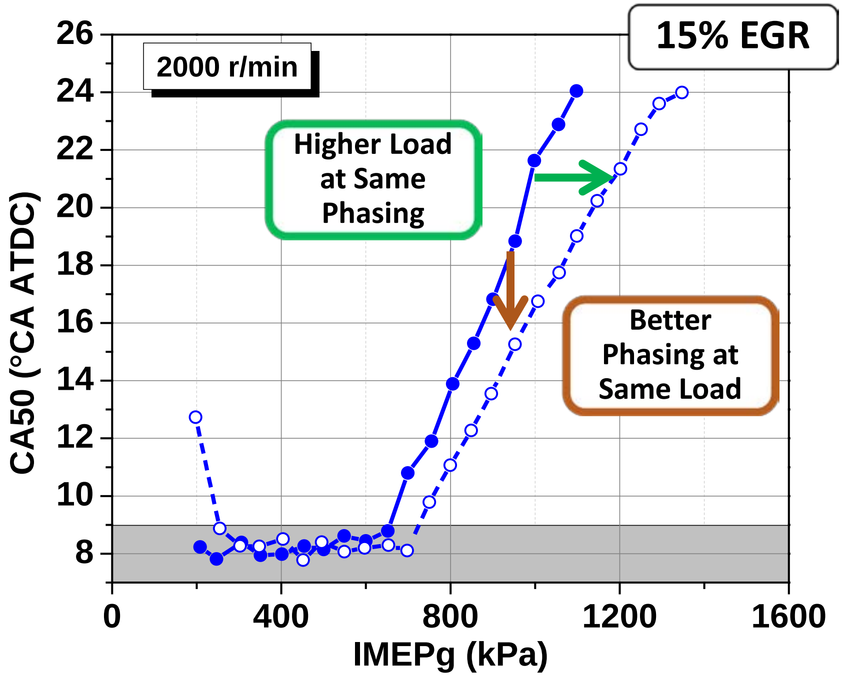
r_c: Can be increased due to reduced propensity to knock ✓

W_{Pump} is reduced due to higher intake manifold pressure ✓

$W_{Friction}$ is higher due to an increase in peak cylinder pressure ✗

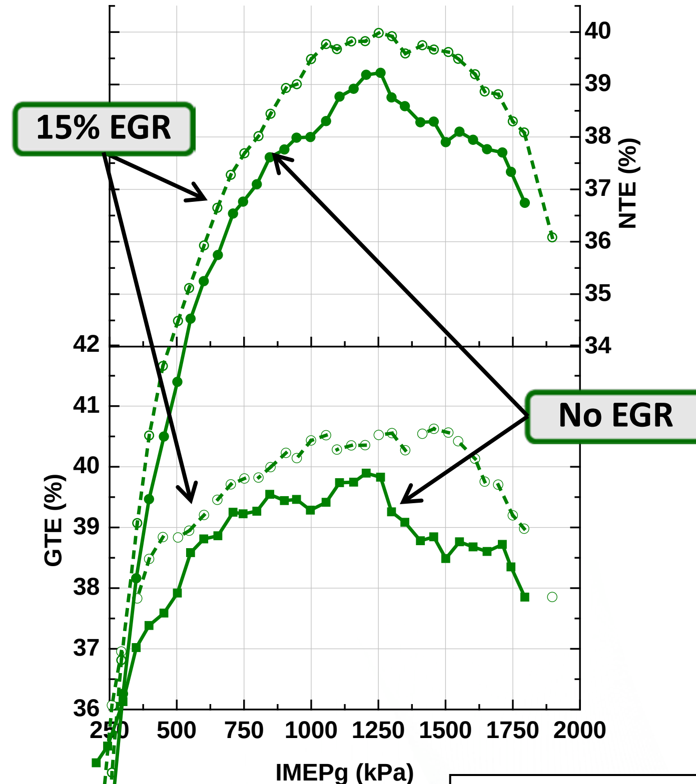
EGR Dilution Decreases Knock Propensity, May Enable Compression Ratio Increase for Further Efficiency Gains

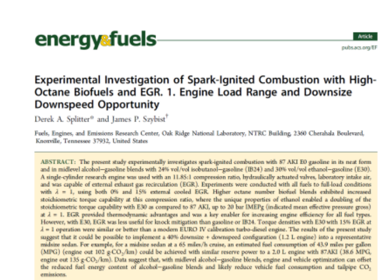
- EGR reduces knock propensity because increased dilution decreases the cylinder temperature during combustion
  - Rule of thumb: Each % EGR is equivalent to 0.5 octane number for commercial gasoline (Alger et al., SAE 2012-01-1149)
- At a constant compression ratio, this enables…
  - More advanced combustion phasing before knock is encountered
  - Increased peak load for downsizing and downspeeding (if not limited by volumetric efficiency)
- Alternately, EGR may also enable higher compression ratio for higher efficiency
  - Same phasing retard with load, but at a higher efficiency



15% EGR DILUTION CAN INCREASE EFFICIENCY BY 1-2 PERCENTAGE POINTS

- Gross thermal efficiency (GTE) increase is due to improved γ, more advanced combustion phasing, and reduced heat transfer
- Net thermal efficiency (NTE) improvement is due to higher GTE and reduced pumping
- Thermal efficiency increase of 1-2 percentage points reduces fuel consumption by up to 5%
- Efficiency benefits can be realized beyond 15% EGR
- Combustion stability and drivability concerns effectively limit the use of EGR
  - The quantity of EGR that is used in a particular calibration
  - Whether external EGR is used at all





energy&fuels Article pubs.acs.org/EF

Experimental Investigation of Spark-Ignited Combustion with High-Octane Biofuels and EGR. 1. Engine Load Range and Downsize Downspeed Opportunity

Derek A. Splitter* and James P. Szybist†

Fuels, Engines, and Emissions Research Center, Oak Ridge National Laboratory, NTRC Building, 2360 Cherahala Boulevard, Knoxville, Tennessee 37932, United States

ABSTRACT: The present study experimentally investigates spark-ignited combustion with 87 AKI E0 gasoline in its neat form and in midlevel alcohol–gasoline blends with 24% vol/vol isobutanol–gasoline (IB24) and 30% vol/vol ethanol–gasoline (E30). A single-cylinder research engine was used with an 11.85:1 compression ratio, hydraulically actuated valves, laboratory intake air, and was capable of external exhaust gas recirculation (EGR). Experiments were conducted with all fuels to full-load conditions with $\lambda = 1$, using both 0% and 15% external cooled EGR. Higher octane number biofuel blends exhibited increased stoichiometric torque capability at this compression ratio, where the unique properties of ethanol enabled a doubling of the stoichiometric torque capability with E30 as compared to 87 AKI, up to 20 bar IMEPg (indicated mean effective pressure gross) at $\lambda = 1$. EGR provided thermodynamic advantages and was a key enabler for increasing engine efficiency for all fuel types. However, with E30, EGR was less useful for knock mitigation than gasoline or IB24. Torque densities with E30 with 15% EGR at $\lambda = 1$ operation were similar or better than a modern EURO IV calibration turbo-diesel engine. The results of the present study suggest that it could be possible to implement a 40% downsize + downspeed configuration (1.2 L engine) into a representative midsize sedan. For example, for a midsize sedan at a 65 miles/h cruise, an estimated fuel consumption of 43.9 miles per gallon (MPG) (engine out 102 g-CO_2/km) could be achieved with similar reserve power to a 2.0 L engine with 87AKI (38.6 MPG, engine out 135 g-CO_2/km). Data suggest that, with midlevel alcohol–gasoline blends, engine and vehicle optimization can offset the reduced fuel energy content of alcohol–gasoline blends and likely reduce vehicle fuel consumption and tailpipe CO_2 emissions.

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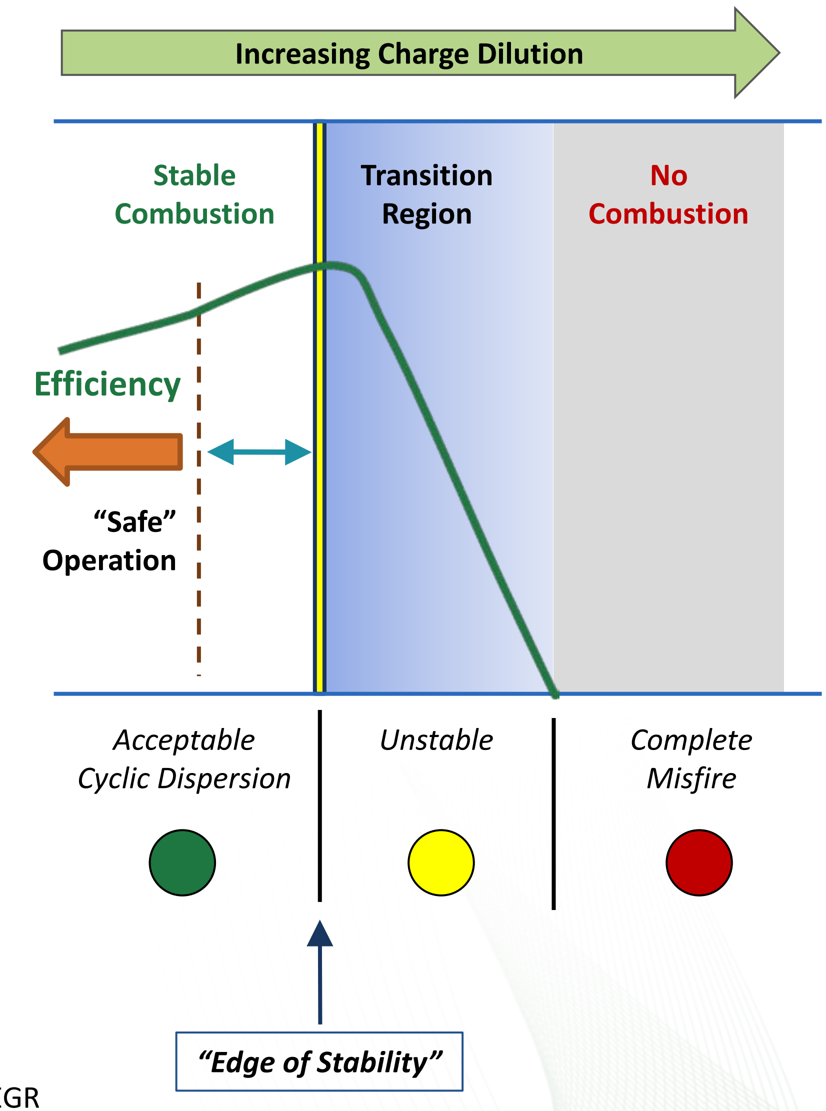
High Levels of EGR Dilution Lead to Cycle-to-Cycle Instabilities Caused by a Combination of Stochastic and Deterministic Processes

*ORNL work in this area led by Brian Kaul

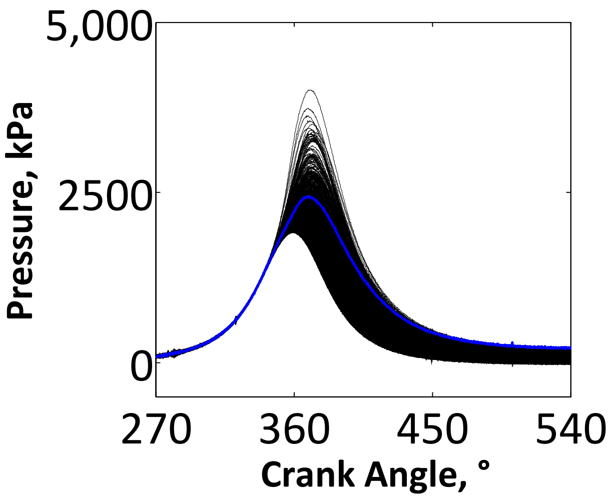
- Stochastic: in-cylinder variations
- Deterministic: cycle-to-cycle coupling
- Practical implementations operate well away from the edge of stability to avoid unintended excursions
- Advanced controls could enable operation at the "edge of stability"
  - Requires a detailed understanding of instability mechanisms

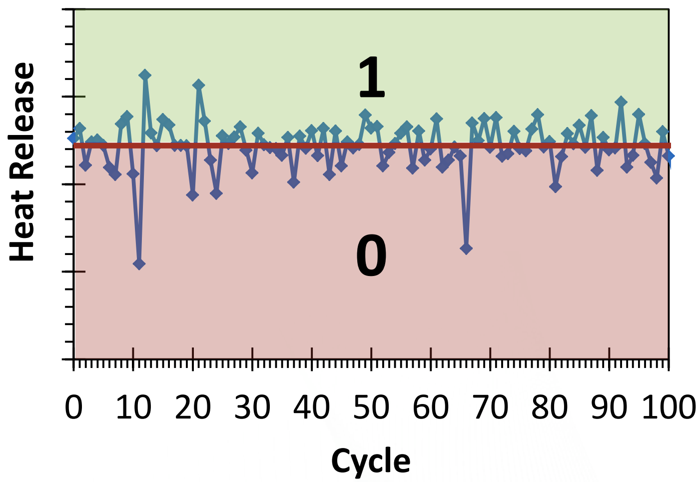


[1] Kaul BC, Finney CE, Wagner RM, Edwards ML. "Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion," SAE Int. J. Engines. 2014; 7(2), doi:10.4271/2014-01-1236.

SYMBOL-SEQUENCE STATISTICS ANALYSIS FINDS ORDER IN CHAOS

- Symbolization of chaotic time series data
  - Discretize data and identify patterns of recurring sequences
  - Enables automated identification of recurring, non-random trajectories
  - Robust even for low-quality or noisy input data





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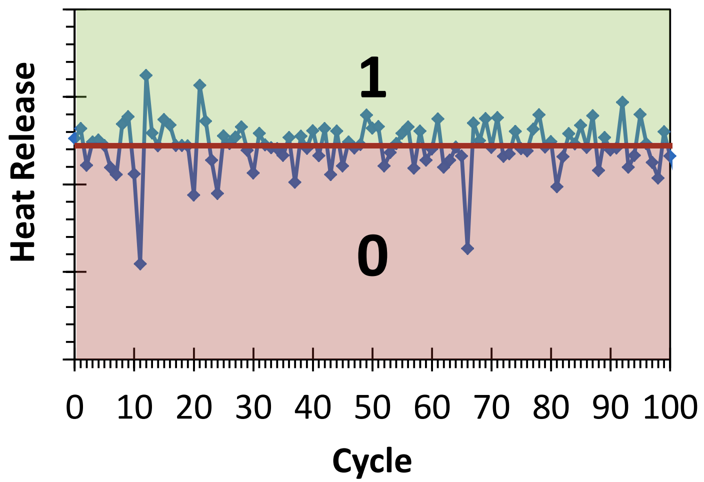
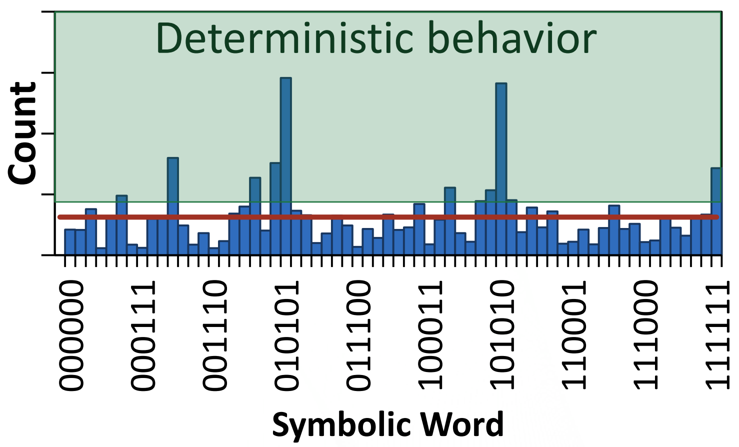
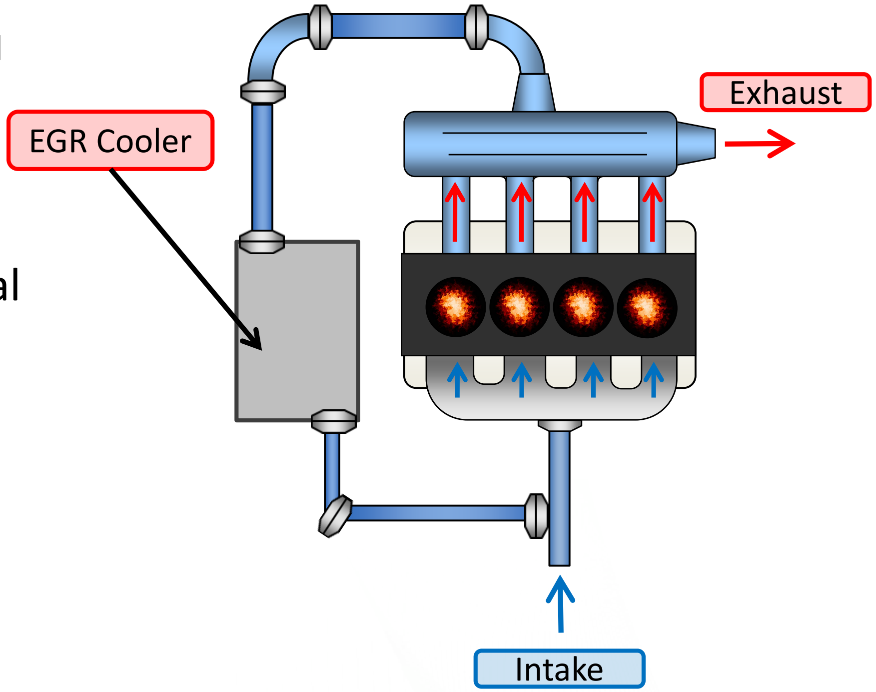




Highly Dilute Combustion Potential

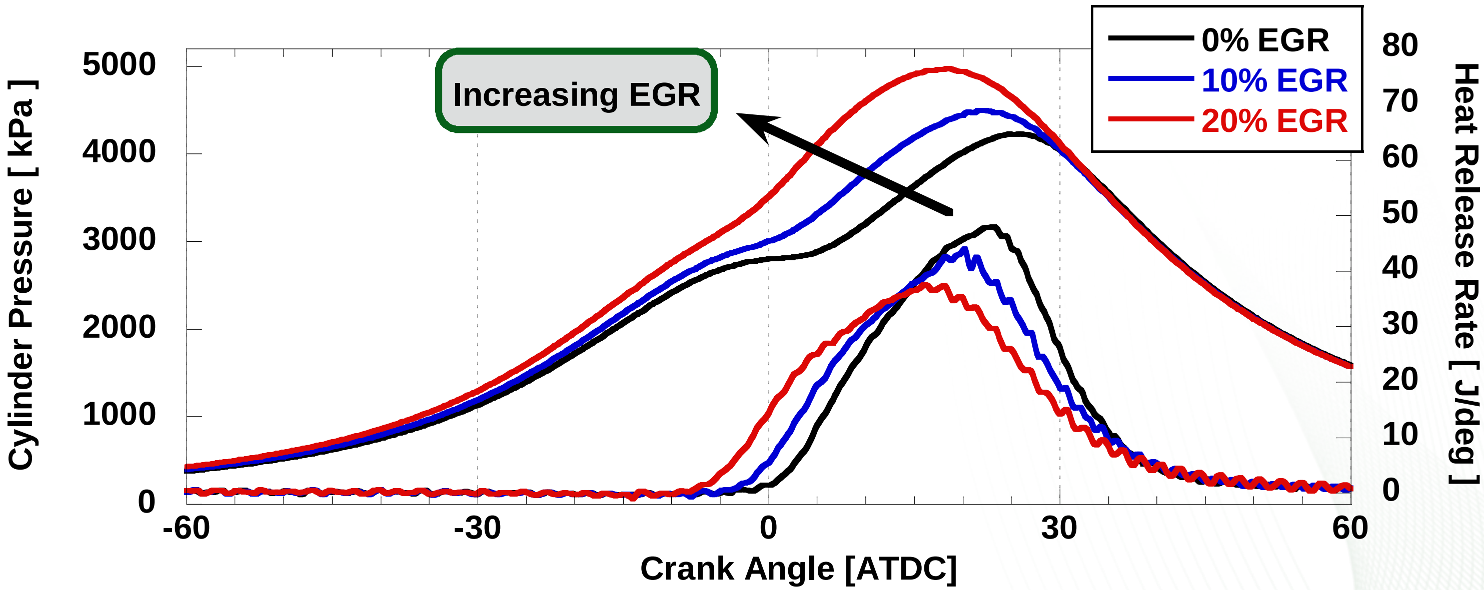
- Engine efficiency is increased through well-understood thermodynamic routes
  - Higher γ compression ratio, reduced heat transfer and pumping
  - Enabled by reduced propensity to knock
- In contrast to high octane fuel route, implementation challenges are purely technical
  - No political or infrastructure barriers
- Cycle-to-cycle instabilities are a barrier to implementation of high dilution EGR systems
  - Managing instabilities is an area of active ORNL research



High Efficiency Pathway 3. Fuel Reforming to Support High Levels of EGR Dilution

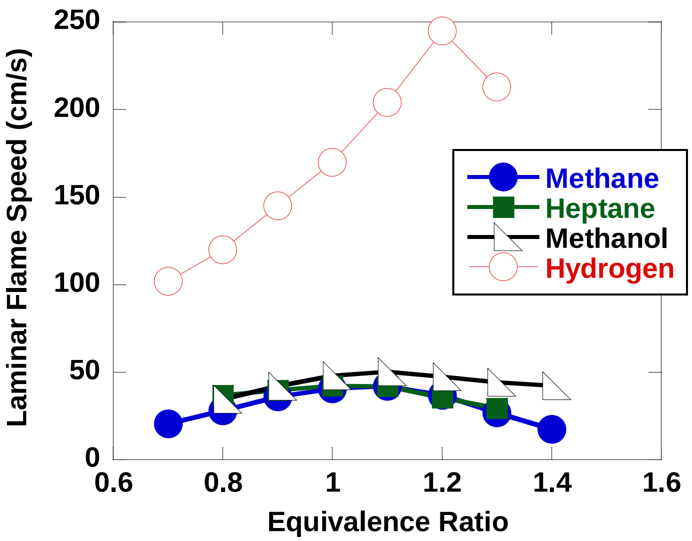
Dilution Limit with EGR is due to Decreased Ignitibility and Slower Flame Speed

- Dilution with EGR decreases rate of combustion (lower temperature and decreased mole fraction of reactants)
- Alternate forms of combustion attain more globally dilute mixtures for higher efficiency
  - Mixing controlled combustion (i.e., diesel): Diffusion flame at near-stoichiometry, globally dilute
  - Kinetically controlled combustion: Sequential auto-ignition, globally and locally too dilute to support flame propagation
- Further efficiency increases can be realized with SI combustion if combustion instability can be overcome



Hydrogen has a Very High Flame Speed, has been Shown to Stabilize Highly Dilute Combustion

- Flame speed of hydrocarbons and alcohols vary within a relatively narrow range (± 20%)
- Flame speed of H_2 is 3-5 times higher than of hydrocarbons and alcohols (excluding acetylene)



Data from *Combustion, Third Edition*, Glassman, 1996
S_L with air at 25 deg C

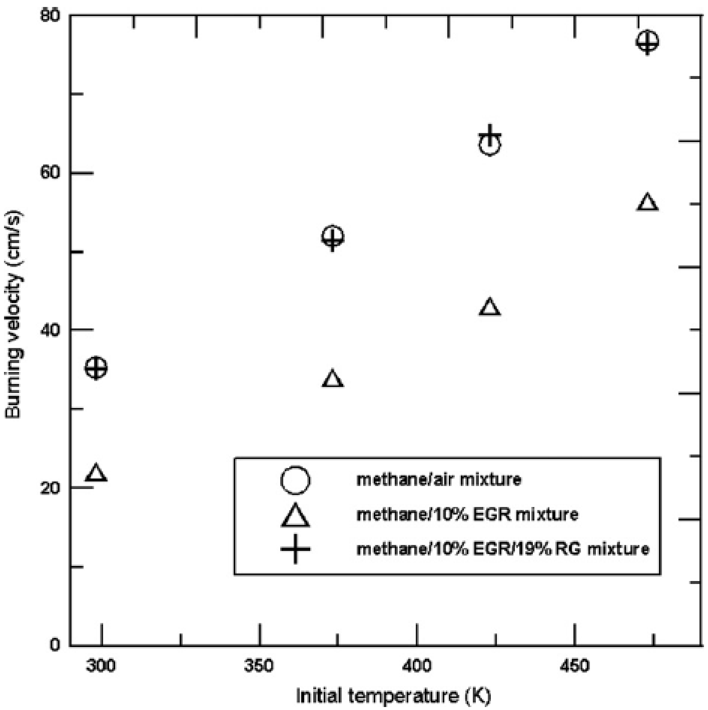


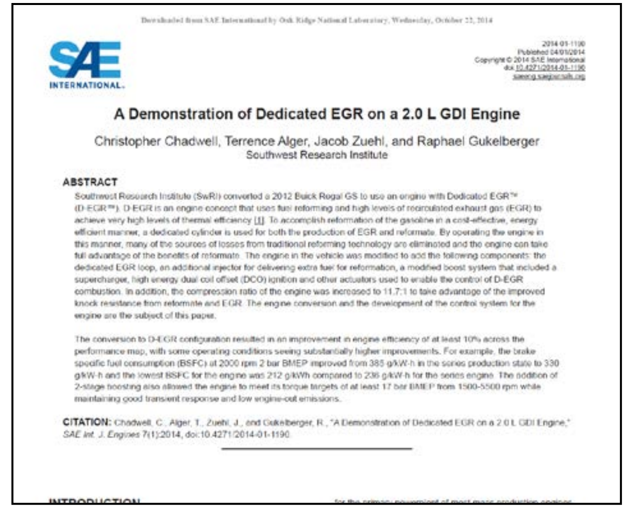
Figure from Han et al., *Fuel*, **86**, pp. 585-596, 2007.

- Previous studies have shown that reformer gas containing hydrogen can recover flame speed decrease from dilution
  - In this case, H_2 accounted for 15% of the total fuel energy

Until the H_2 economy is developed, how can H_2 be generated on-board in a thermodynamically inexpensive manner?

Research at SWRI at the Vehicle Scale is Generating Reformate with H_2 through Fuel-Rich Combustion to Extend the Dilution Limit

- H_2 generated with fuel-rich combustion is recirculated with the EGR to the intake manifold
- Fuel consumption decreases an average of 7-13% compared to the baseline map with similar performance
- ORNL approach to using the reformate is very similar to SWRI approach
- ORNL approach to generating reformate is unique



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saeeng.saejournals.org

A Demonstration of Dedicated EGR on a 2.0 L GDI Engine

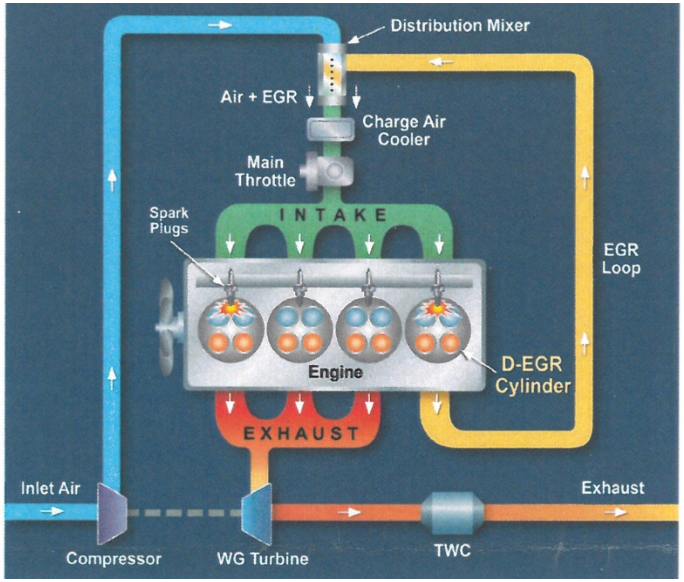
Christopher Chadwell, Terrence Alger, Jacob Zuehl, and Raphael Gukelberger
Southwest Research Institute

ABSTRACT

Southwest Research Institute (SwRI) converted a 2012 Buick Regal GS to use an engine with Dedicated EGR™ (D-EGR™). D-EGR is an engine concept that uses fuel reforming and high levels of recirculated exhaust gas (EGR) to achieve very high levels of thermal efficiency [1]. To accomplish reformation of the gasoline in a cost-effective, energy efficient manner, a dedicated cylinder is used for both the production of EGR and reformate. By operating the engine in this manner, many of the sources of losses from traditional reforming technology are eliminated and the engine can take full advantage of the benefits of reformate. The engine in the vehicle was modified to add the following components: the dedicated EGR loop, an additional injector for delivering extra fuel for reformation, a modified boost system that included a supercharger, high energy dual coil offset (DCO) ignition and other actuators used to enable the control of D-EGR combustion. In addition, the compression ratio of the engine was increased to 11.7:1 to take advantage of the improved knock resistance from reformate and EGR. The engine conversion and the development of the control system for the engine are the subject of this paper.

The conversion to D-EGR configuration resulted in an improvement in engine efficiency of at least 10% across the performance map, with some operating conditions seeing substantially higher improvements. For example, the brake specific fuel consumption (BSFC) at 2000 rpm 2 bar BMEP improved from 385 g/kW-h in the series production state to 330 g/kW-h and the lowest BSFC for the engine was 212 g/kWh compared to 236 g/kW-h for the series engine. The addition of 2-stage boosting also allowed the engine to meet its torque targets of at least 17 bar BMEP from 1500-5500 rpm while maintaining good transient response and low engine-out emissions.

CITATION: Chadwell, C., Alger, T., Zuehl, J., and Gukelberger, R., "A Demonstration of Dedicated EGR on a 2.0 L GDI Engine," *SAE Int. J. Engines* 7(1):2014, doi:10.4271/2014-01-1190.



Research at ORNL Aims to use Reform Fuel through Thermochemical Recuperation for More Thermodynamically-Favorable Method

Motivation for Thermochemical Recuperation

- TCR is an attractive path to exhaust heat recovery that maintains a single work conversion device
- TCR through reforming theoretically increases lower heating value and exergy of fuel through endothermic reactions, driven by exhaust heat

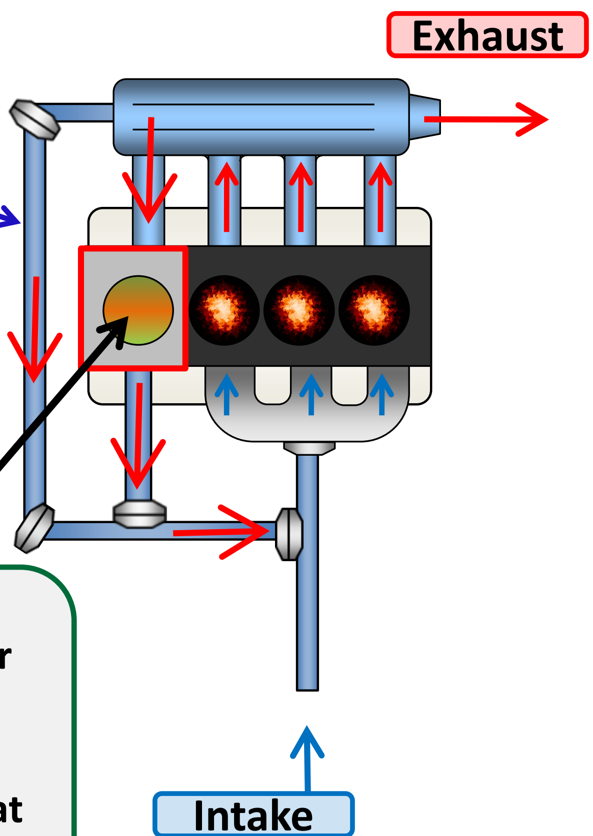
	Reforming Reaction	LHV Increase	Exergy Increase
Octane	$C_8H_{18} + 8H_2O \rightarrow 8CO + 17\ H_2$	25%	14%
Ethanol	$C_2H_5OH + H_2O \rightarrow 2\ CO + 4H_2$	24%	9%
Methanol	$CH_3OH \rightarrow CO + 2H_2$	20%	3%

*For information on why LHV increase is higher than exergy, See Szybist et al., *Energy & Fuels*, 2012 **26**; 2798-2810.

Pursuing Reformate-Assisted SI Combustion through Two Parallel Strategies

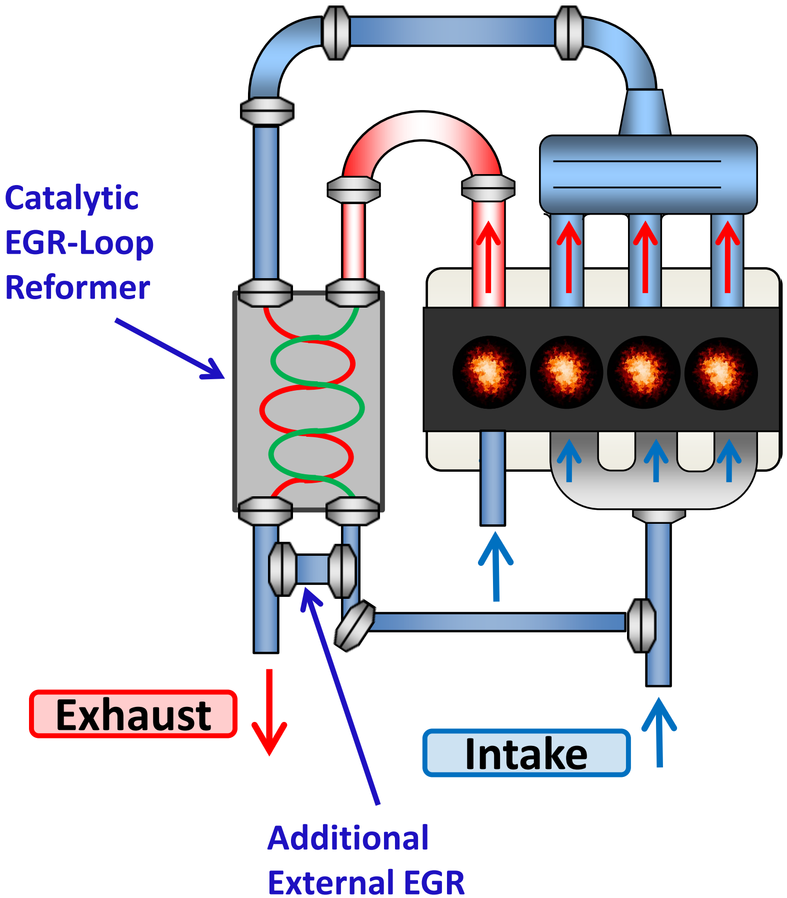
Flexible Hydraulic Valve Actuation for Cylinder 4 Enables Both Strategies to be Investigated on the same Experimental Engine Platform

In-Cylinder Reforming



Study on in-cylinder reforming chemistry published at 2014 SAE

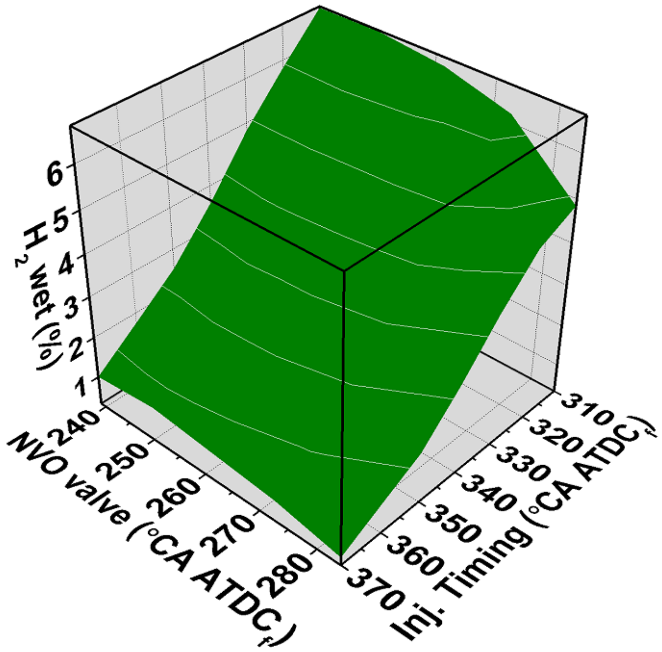
EGR-Loop Reforming



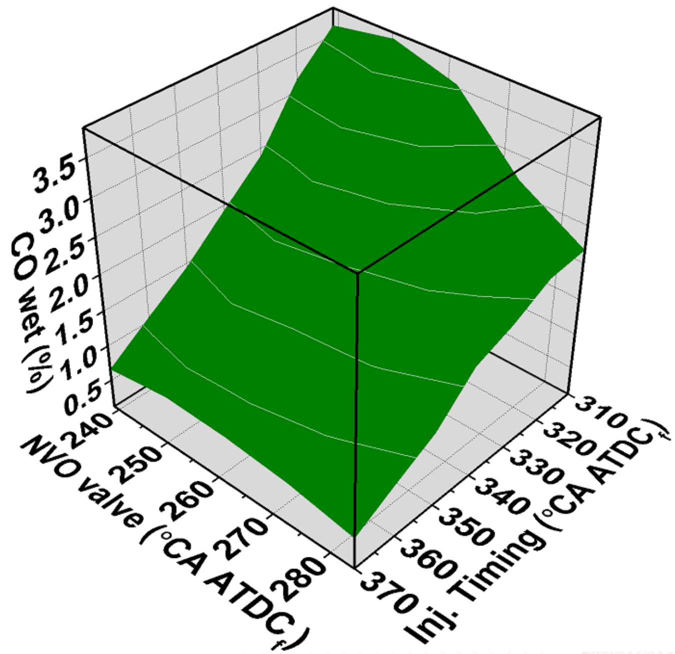
Significant Amounts of H_2 and CO Generated in Single-Cylinder Experiments that Isolated In-Cylinder Reforming

- Developing an understanding of reforming as a function of engine conditions
  - Fuel injection timing is the dominant factor in the amount of H_2 and CO produced
  - Other factors, such as NVO duration, appear to be less sensitive
- Initial results generated in a highly controlled single-cylinder engine experiment
- Shifting efforts to a more realistic multi-cylinder engine experiment

Hydrogen

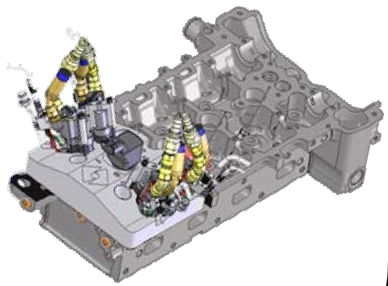


Carbon Monoxide

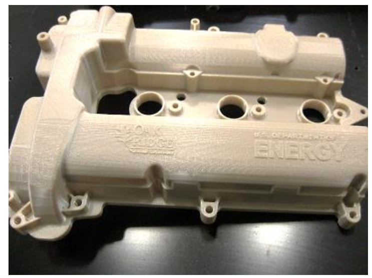


Effort to Build a Flexible Multi-cylinder Engine Platform at ORNL Capable of TCR Operating Strategy

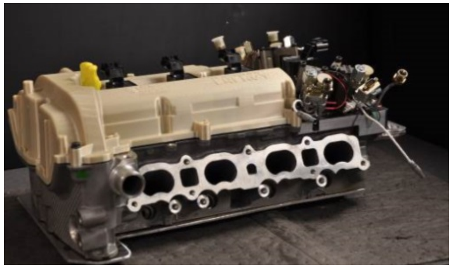
Cylinder head design for 3 cam-based cylinders and 1 HVA cylinder

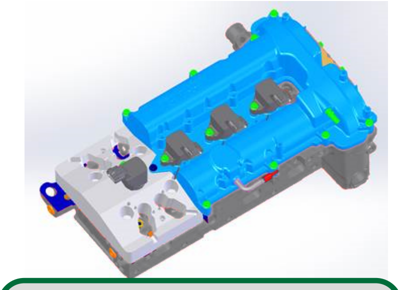


Custom valve cover fabricated with 3D printing at ORNL's MDF

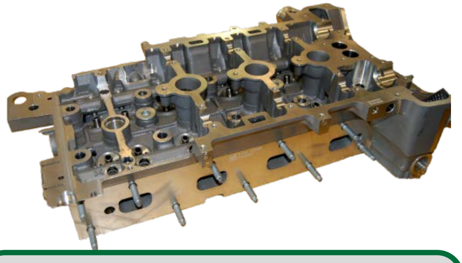


Major hardware modifications complete



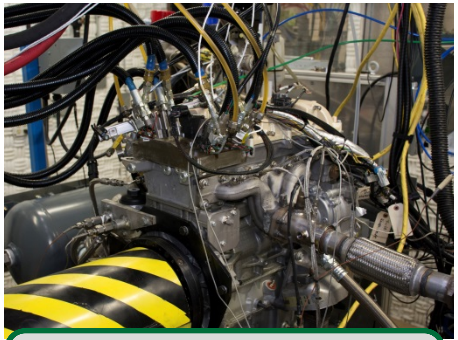


Design of custom valve cover complete



Machining of cylinder head and HVA transfer plate

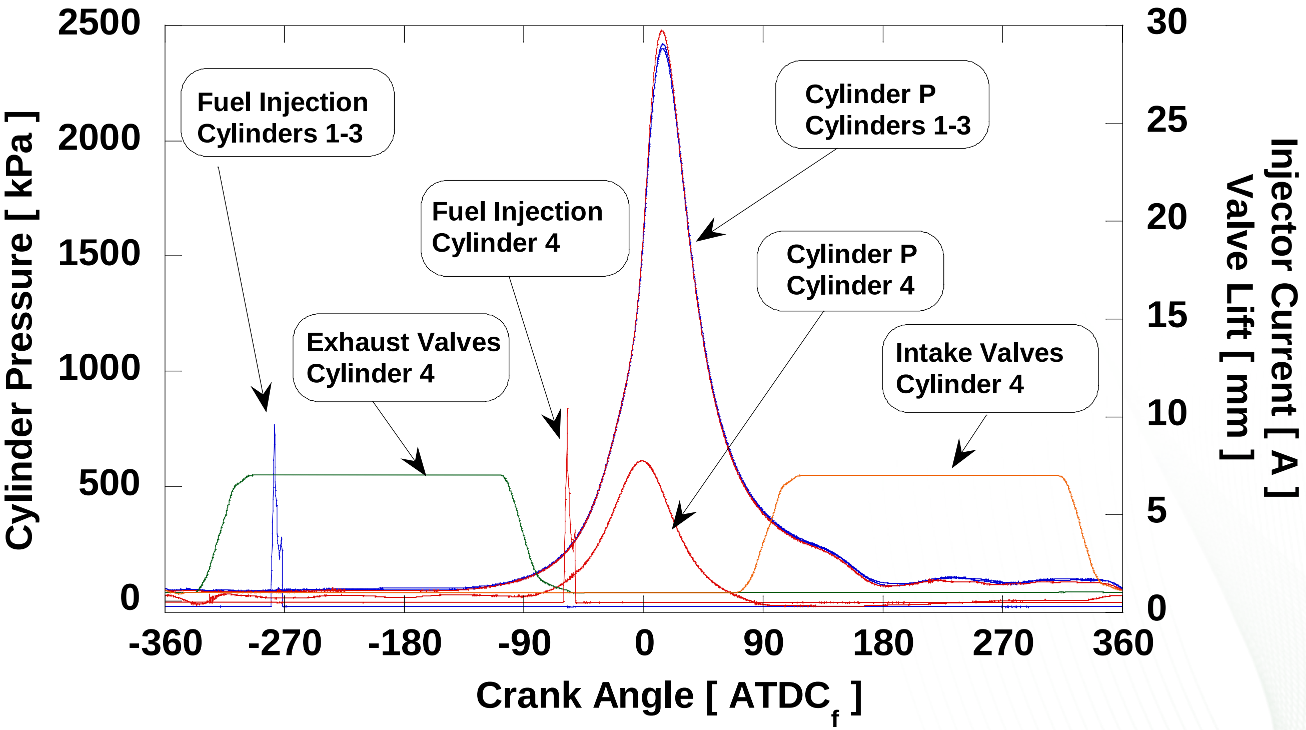
High pressure fuel cart completed and tested



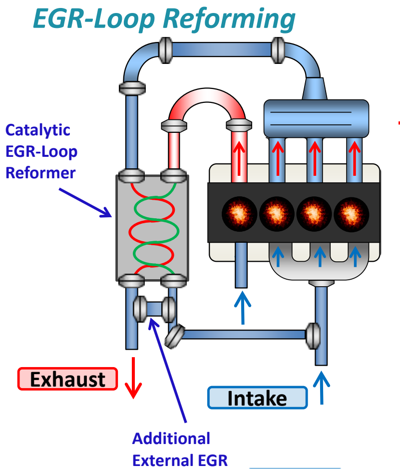
Engine assembly and installation complete

In-Cylinder Reforming Strategy Operable, Reforming and Efficiency Results will be Generated during the Coming Year

- Successful execution of valve strategy for in-cylinder reforming
  - Cylinder 4 breathing in from the exhaust manifold and exhausting into the intake system
- Control over in-cylinder temperature and pressure conditions can be controlled by the effective compression ratio of cylinder 4

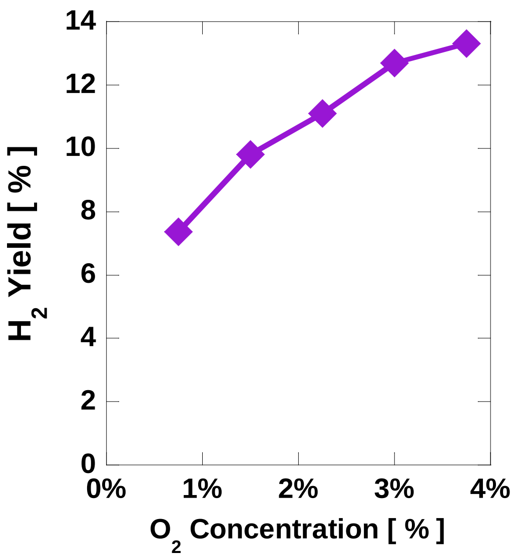


EGR-Loop Reforming:
A Challenging and Constrained Environment

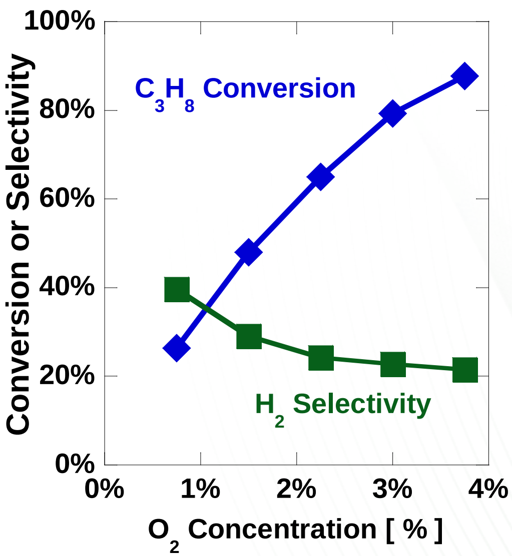


- Available conditions onboard an engine are challenging compared to industrial steam reforming
  - Temperature typically limited to exhaust (550-650° C), cooler with EGR
  - Steam/carbon ratio is limited by steam in exhaust
- Adding O_2 boosts H_2 yield and C_3H_8 conversion by increasing T
  - Decreases H_2 selectivity (starting to oxidize to H_2O)
- **Thermodynamically undesirable because fuel energy is consumed in catalyst**

H_2 Yield

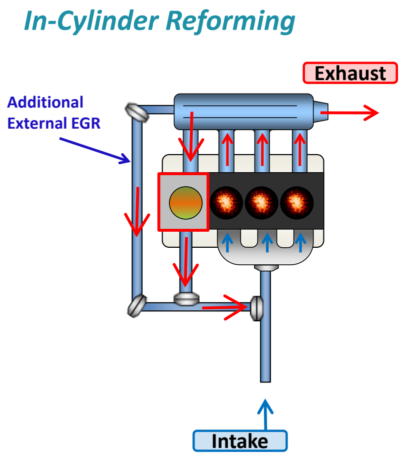


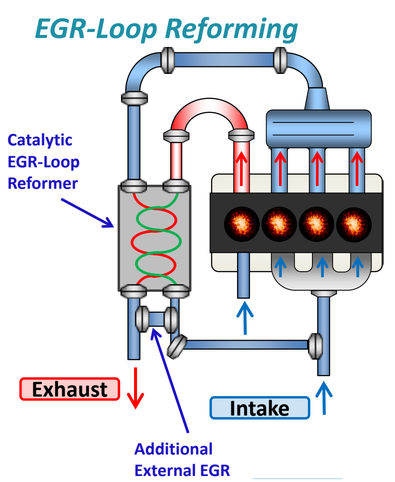
C_3H_8 Conversion & H_2 Selectivity



Potential of Reforming to Support Dilute Combustion

- H_2 has can increase flame speed and enable more dilute combustion for higher efficiency
- ORNL is investigating two methods of onboard fuel reforming with a low thermodynamic expense, or even thermochemical recuperation
    1. In-cylinder reforming
    2. Catalytic EGR-loop reforming
- Both techniques are technologically challenging and have a significant amount of development
- Barriers to implementation are purely technical and cost-related, similar to EGR dilution
    - No political or infrastructure barriers as with high octane fuel





CONCLUSIONS

- Internal combustion engines will remain relevant for years to come
  - U.S. light duty market is dominated by spark ignited engines
- Efforts to increase engine efficiency at ORNL are both firmly grounded in thermodynamics and applicable to real-world problems
- Three paths to increase efficiency in spark-ignited engines were discussed
  1. High octane fuels
  2. EGR dilution
  3. Reforming to support higher levels of dilution
- Each path has a unique set of challenges that need further exploration and development
- These are real opportunities to improve the efficiency of spark-ignited engines!

QUESTIONS?