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FUEL DESIGN FOR LTC APPLICATIONS: QUANTIFYING FUEL PERFORMANCE IN GCI ENGINES

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Advanced Combustion Engine R&D / Fuel and Lubricant Technologies
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Program Manager: Kevin Stork

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OVERVIEW

Timeline

- Project started FY 2015
- Project ends FY 2017
- 50 % complete

Barriers

- Lack of fuel quality specifications for petroleum and non-petroleum based fuels
- Inadequate data and predictive tools for fuel property effects on combustion and engine efficiency optimization

Budget

- Total project funding
  - DOE share: $1,000 k
  - CETC in-kind: $273 k
- FY 2016 DOE / VTP funding
  - $325 k

Partners

- ANL – Lead, Goldsborough (PI)
- Chevron Energy Technology Company (CETC) – provides fuels, blending and characterization, technical expertise

OBJECTIVES AND RELEVANCE TO DOE

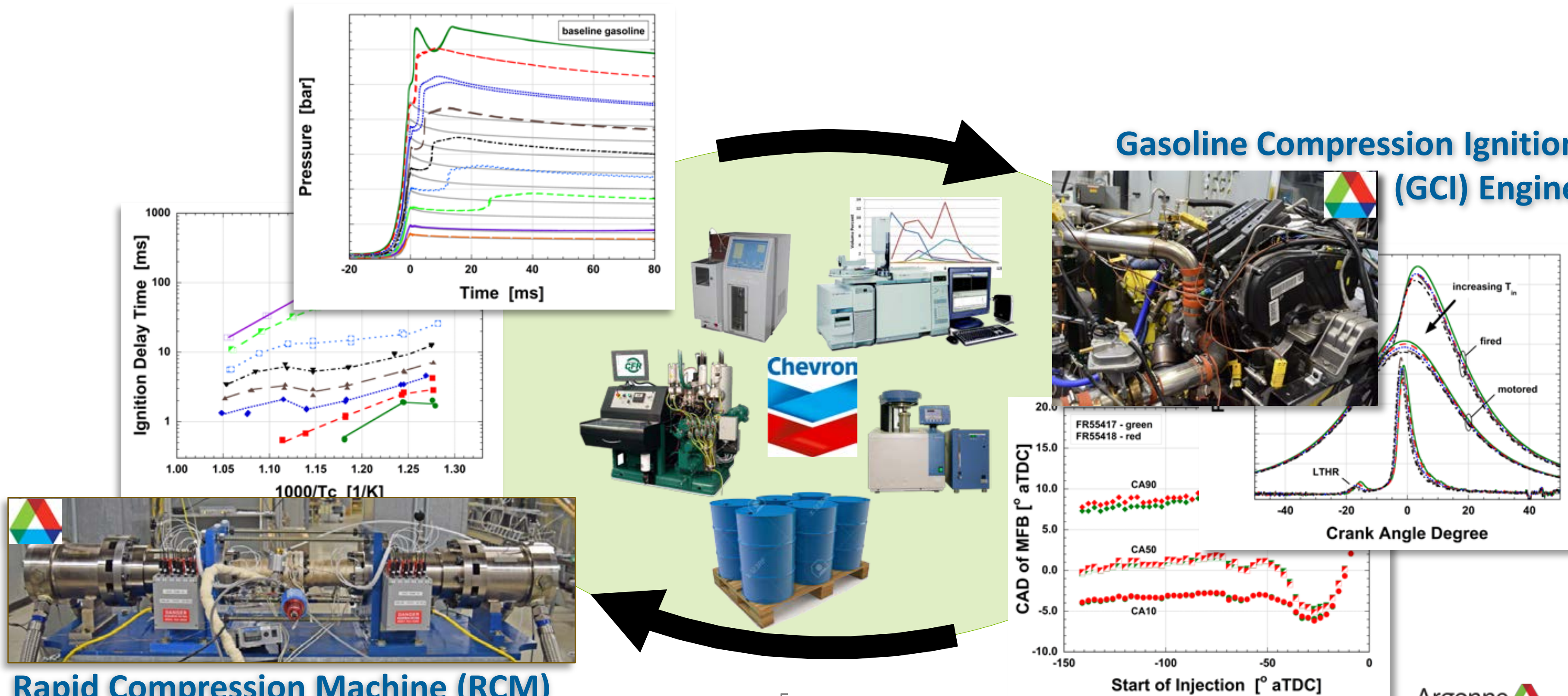
- Formulate and validate new few quality metrics (FQM) that can overcome limitations of conventional and modern fuel rating indices (RON, OI) towards predicting the performance of, and operating parameters required for, petroleum and non-petroleum based fuels across a variety of LTC operating modes, e.g., homogeneous charge compression ignition (HCCI), partially premixed combustion (PPC).
- New fuel quality metrics could be utilized to overcome technical barriers that currently inhibit the specification of fuels for, and design/deployment of LTC-capable engines in the ground vehicle fleet, thereby enabling required gains in engine efficiency and pollutant reductions.

PROJECT APPROACH

PROJECT APPROACH

Rapid Compression Machine / GCI Engine Experiments

- Utilize ANL's RCM to acquire fundamental autoignition data at relevant conditions; understand effects of fuel composition on LTC trends (e.g., τ, LTHR); formulate correlation based on data. Employ GCI engine with variety of fuels; generate testing protocol; validate FQM correlation.



Gasoline Compression Ignition (GCI) Engine

Rapid Compression Machine (RCM)

PROJECT MILESTONES

FY2015/2016

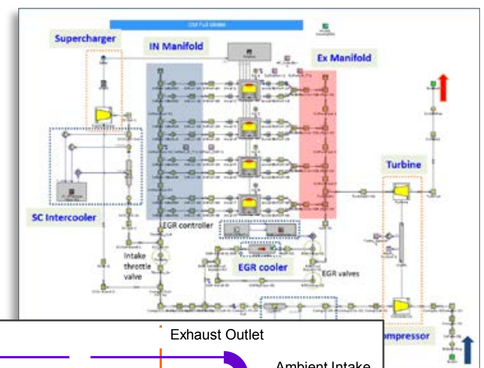
Phase	Milestone	Status
I – Baseline Gasoline (FY2015)	Physico-chemical characterization of baseline gasoline (RON/MON, D86 distillation, DHA, heat of combustion, etc.)	✓
	RCM tests with fuel – parametric sweeps covering temperature, pressure; identify trends of τ, LTHR, ITHR	✓
	GCI engine tests with fuel – parametric sweeps covering speed / load; identify trends with boost, injection(s) timing, EGR, swirl	✓
	Correlation development for RCM and GCI engine – formulate operating points for FQM validation at T/P conditions; demonstrate agreement between experimental platforms	✓
II – Blended Gasolines (10% v./v.) (FY2016)	Physico-chemical characterization of 10% v/v blended gasolines (RON/MON, D86 distillation, DHA, heat of combustion, etc.)	ongoing
	Extend FQM correlation to account for ϕ-sensitvity, EGR-tolerance, covering range of conditions	ongoing
	RCM tests with blended fuels to facilitate extension of FQM	ongoing
	GCI engine tests with blended fuels at FQM validation test points; identify deficiencies / needs	ongoing

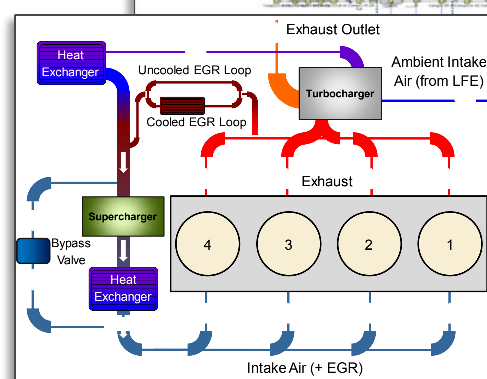
TECHNICAL ACCOMPLISHMENTS / PROGRESS

TECHNICAL ACCOMPLISHMENTS / PROGRESS

- Modifications to twin-piston RCM
  - Implemented high-speed DAQ card (1 MHz, 16-bit) to improve heat release analysis during high-temperature heat release;
  - Redesigned heating system / control for mixture feedline from supply tank;
  - Refined post-processing script to identify / quantify LTHR, ITHR;
  - Incorporated high-precision, automated feed valve for reaction chamber ;
  - Previously limited to ~16 shots/day; up to 40 shots/day now possible, excellent repeatability.

- Modifications to multi-cylinder GCI engine
  - GT Power model developed for baseline operating condition to assess IVC in-cylinder conditions;
  - Redesigned supercharger pulley to achieve wider range of boosted intake pressures (P_{in} = 1.0–1.4 bar at idle) for stable operation with high to low reactivity fuels;
  - Created post-processing script to identify / quantify LTHR, ITHR, compare with RCM data.





TECHNICAL ACCOMPLISHMENTS / PROGRESS

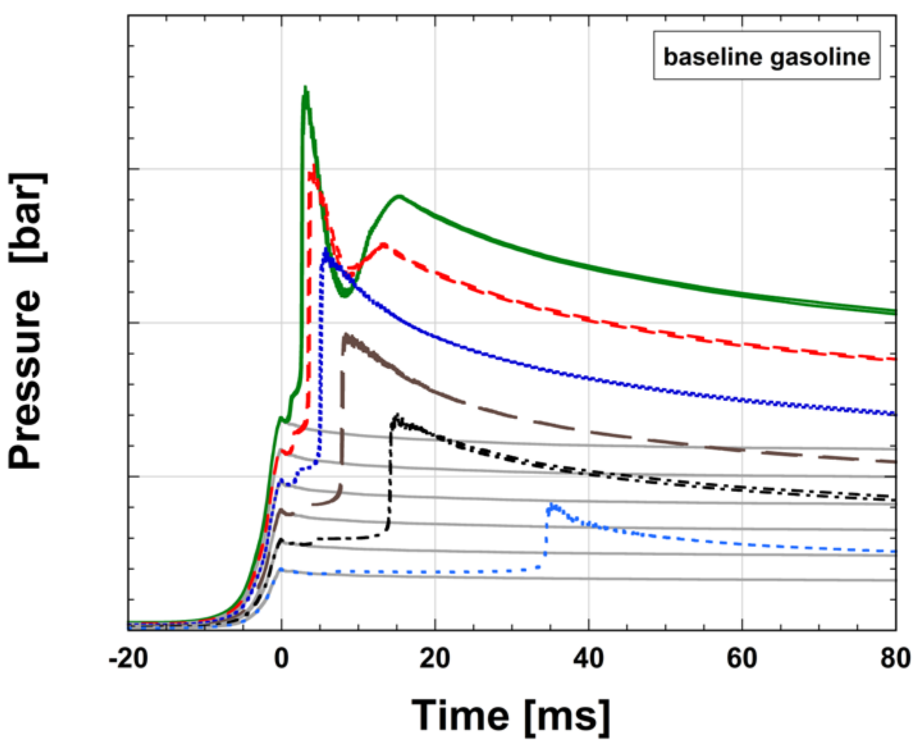
Fuel blending and physico-chemical characterization

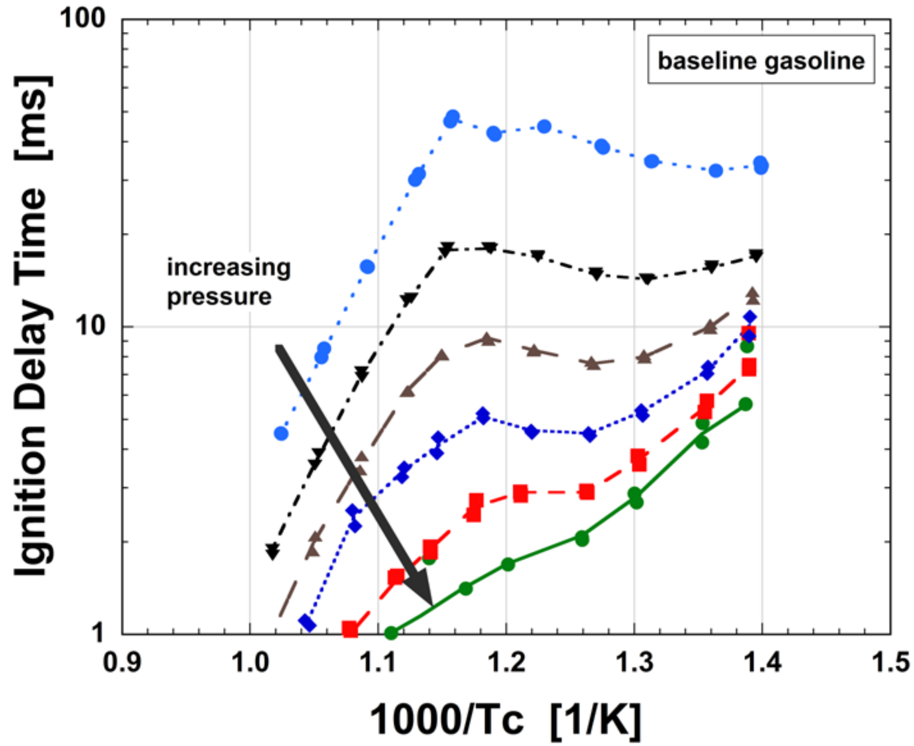
- Fuel blending
  - Baseline gasoline, and blends doped with single-component surrogates representing variety of structural classes (e.g., alkanes, aromatics, alcohols)
    - 10% vol./vol. fuels covering RON ≈ 80–92, S ≈ 1.5–8
    - 20% vol./vol. fuels covering RON ≈ 73–97, S ≈ 0–11
- Physical characterization
  - ASTM tests for RON/MON, specific gravity, H:C ratio, average MW, net heat of combustion, D86 distillation, detailed hydrocarbon analysis (DHA)

TECHNICAL ACCOMPLISHMENTS / PROGRESS

RCM measurements of baseline fuel

- Identified / quantified reactivity trends covering low to intermediate temperatures and range of engine-relevant pressures, using nominal fuel loading (ϕ) and dilution (%O_2)
- Achieved excellent repeatability over entire NTC regime

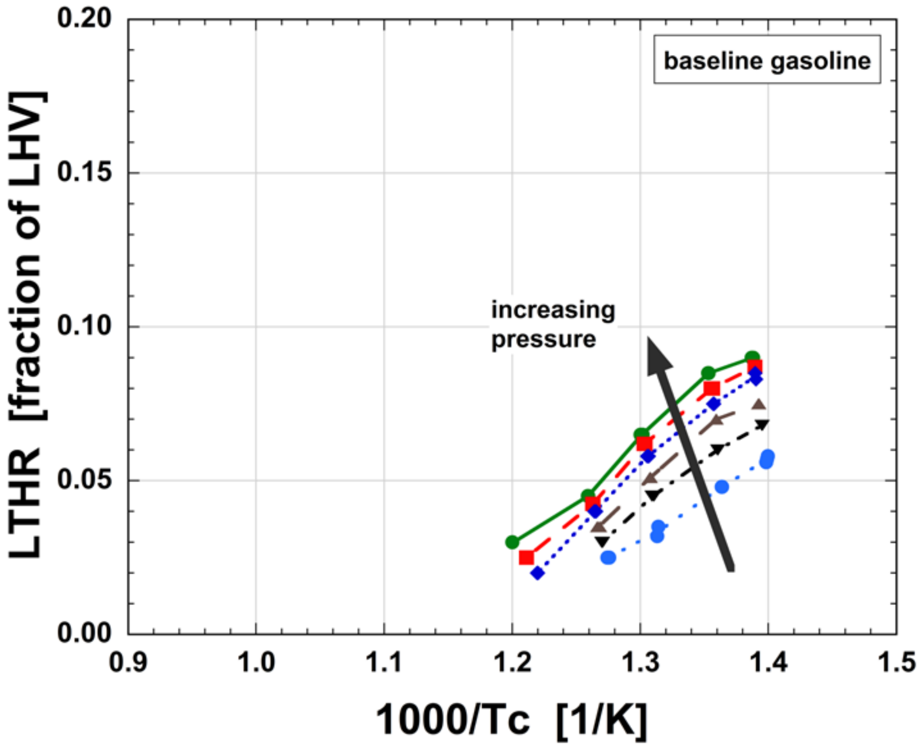


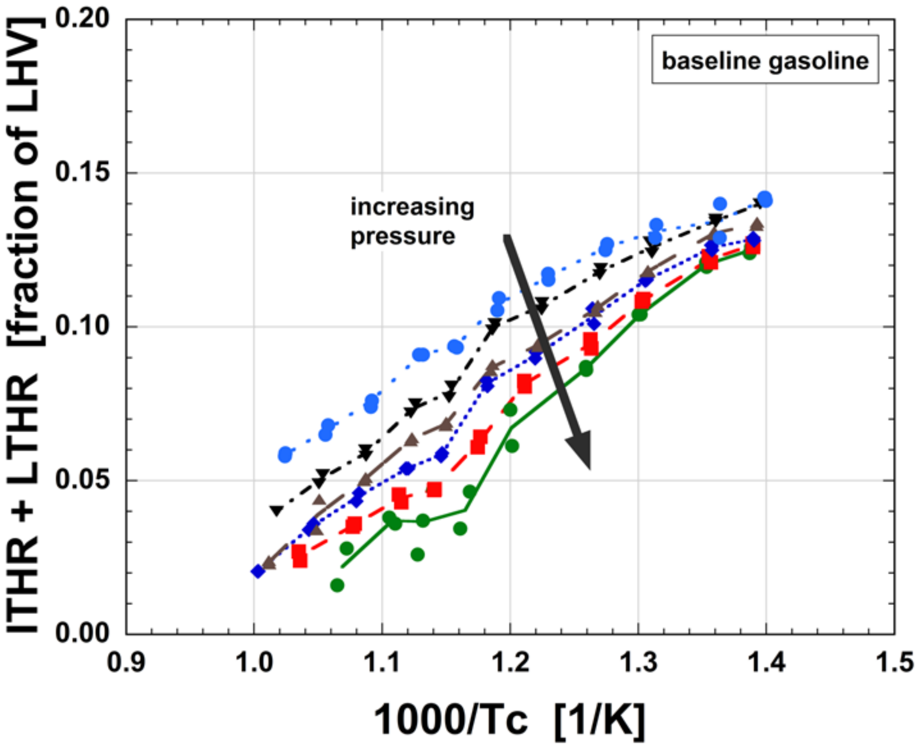


TECHNICAL ACCOMPLISHMENTS / PROGRESS

RCM measurements of baseline fuel

- Quantified trends of low- and intermediate-temperature heat release (LTHR, ITHR) over range of temperature, pressure
  - LTHR found to be greater at lower temperature, higher pressure
  - ITHR found to be greater at lower temperature, lower pressure

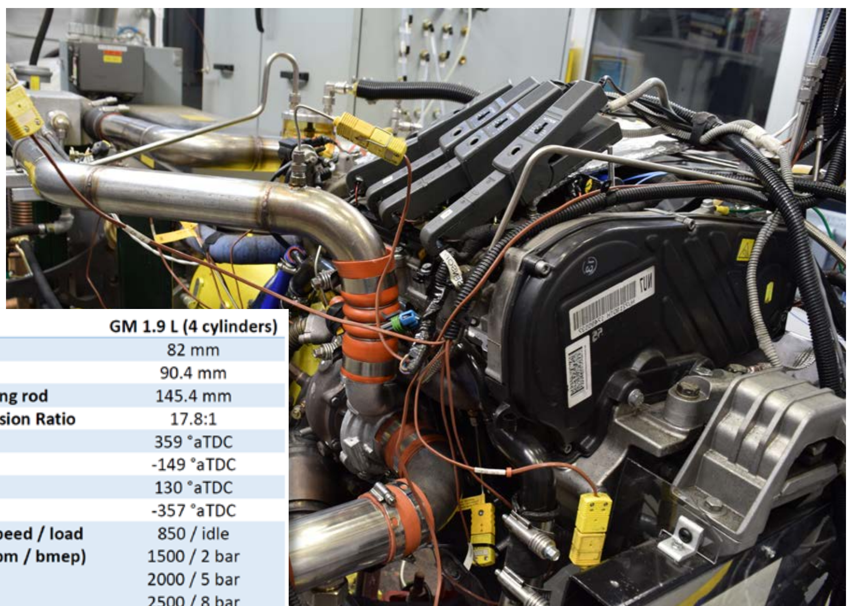




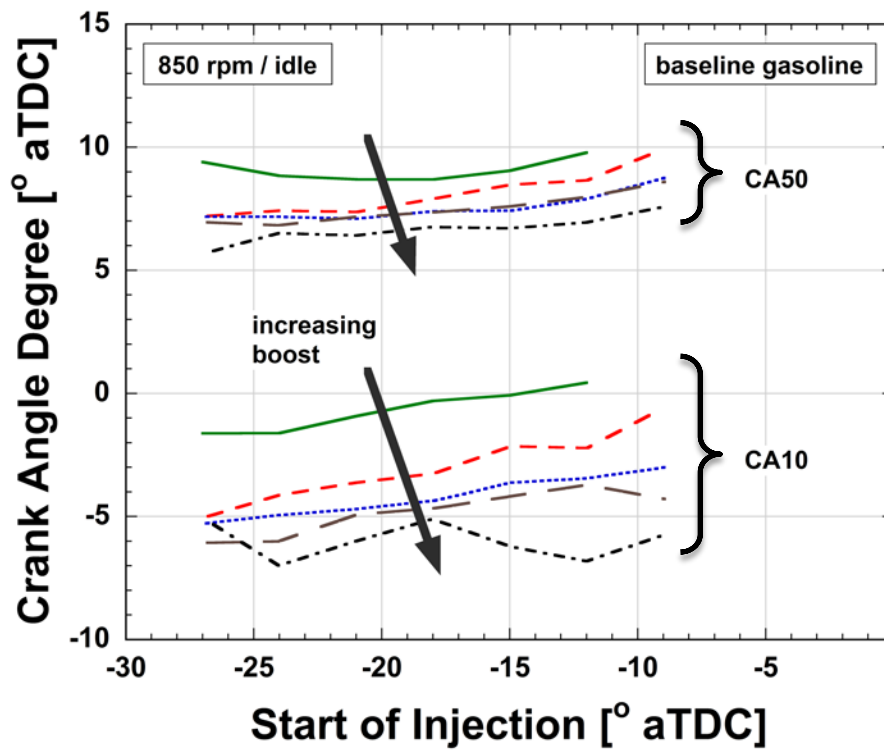
TECHNICAL ACCOMPLISHMENTS / PROGRESS

GCI engine measurements of baseline fuel

- Parametric sweeps covering 5 speed / load points
  - Quantified reactivity and emissions trends with boost, start of injection (SOI), number of injections, EGR rate, swirl, injection pressure
  - Identified challenges / limits for FQM validation; consistent, stable operation with wide variety of fuels requires careful definition of target conditions



Engine	GM 1.9 L (4 cylinders)
Bore	82 mm
Stroke	90.4 mm
Connecting rod	145.4 mm
Compression Ratio	17.8:1
IVO	359 °aTDC
IVC	-149 °aTDC
EVO	130 °aTDC
EVC	-357 °aTDC
Engine speed / load (rpm / bmep)	850 / idle 1500 / 2 bar 2000 / 5 bar 2500 / 8 bar 2750 / 12 bar
Intake Pressure (abs.)	1.0 to 1.2 bar
Intake temperature	46-49 °C
Injectors	Bosch
Number of holes	7
Nozzle diameter	0.141 mm
Spray angle	120°
Injection Pressure	400 to 600 bar



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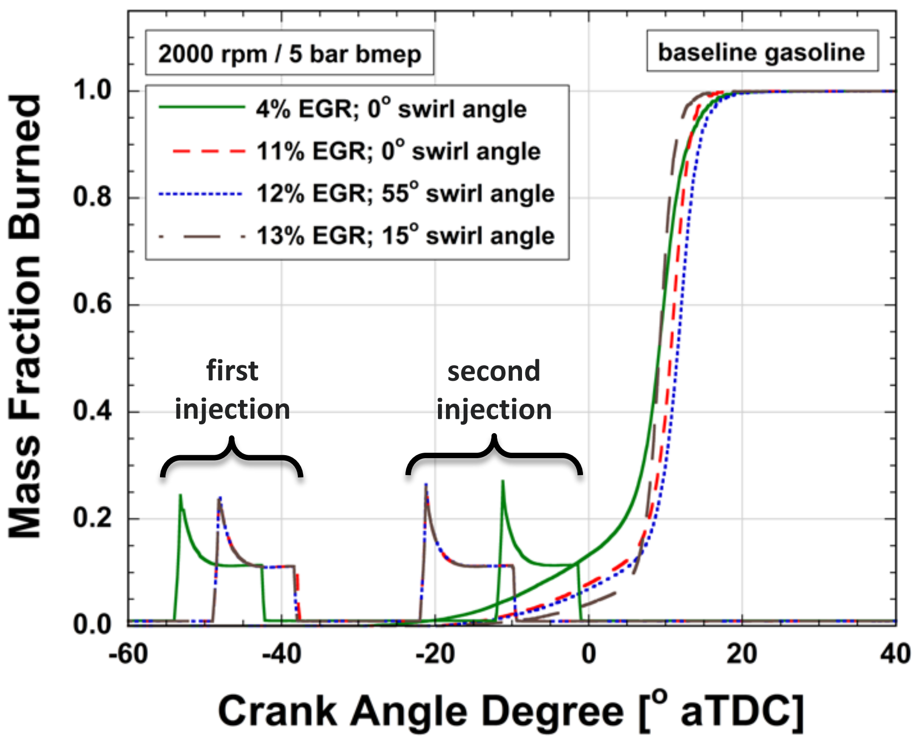

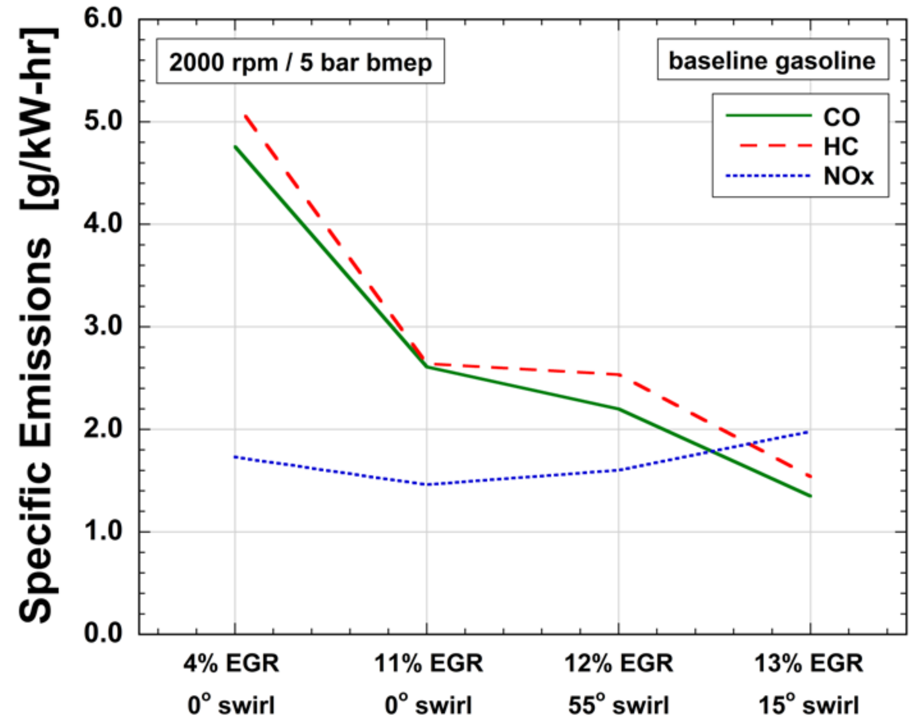

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TECHNICAL ACCOMPLISHMENTS / PROGRESS

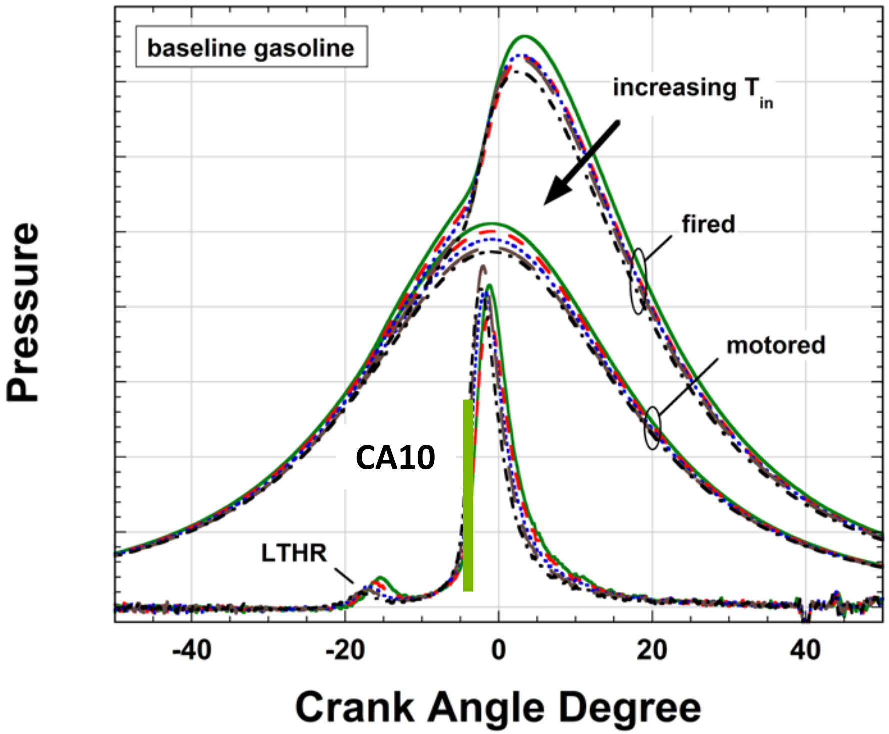
Correlation between GCI engine and RCM

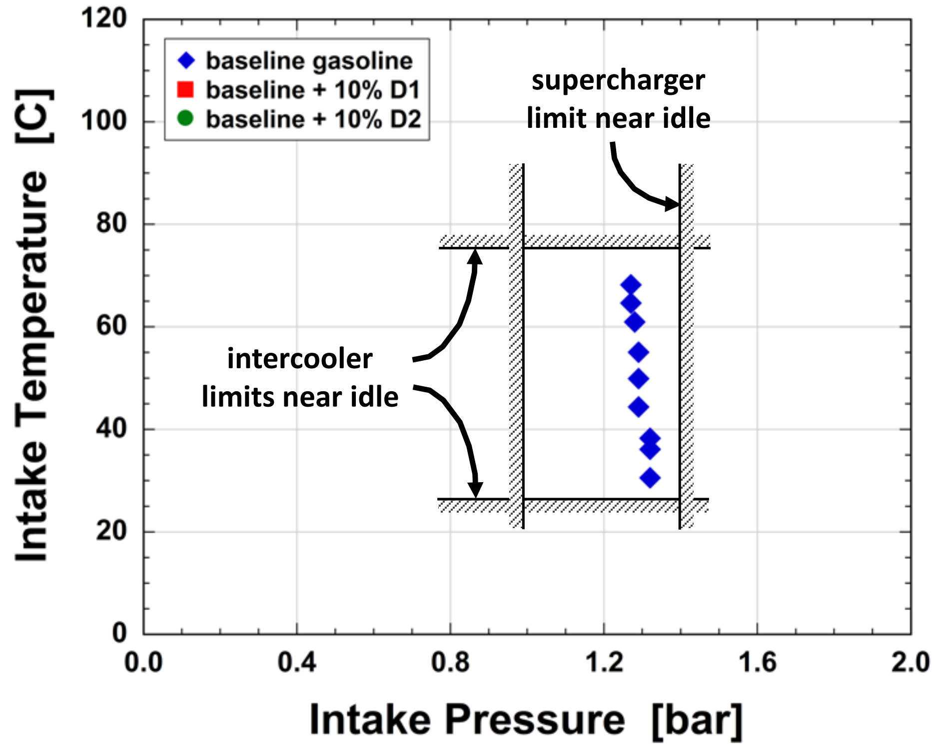
- Formulated test points (engine / RCM) for FQM validation
  - Engine operating conditions selected to:
    - Isolate temperature and pressure influences on fuel reactivity
      - Low-speed, low-load, very early SOI (quasi-HCCI)
    - Isolate ϕ–sensitivity, EGR-tolerance of fuel reactivity
      - Mid-speed, mid-load, late/multiple SOIs (PPC)
  - RCM conditions selected to:
    - Replicate quasi-HCCI operating condition (T, P, ϕ, EGR) for direct comparison against GCI engine measurements – demonstrating agreement between static reaction chamber, and variable-volume engine environments
    - Quantify reactivity trends over wide range of conditions which could be seen across a variety of LTC concepts to ensure broad applicability of FQM

TECHNICAL ACCOMPLISHMENTS / PROGRESS

Correlation between GCI engine and RCM

- Low-speed, low-load, very early SOI (quasi-HCCI) operation
  - 1000 rpm, near-minimum fueling, SOI = -141 aTDC
  - Constant phasing sweeps: vary T_{in} = 30–75 C, adjusting P_{in} to hold CA10 fixed
  - Identify compressed conditions (T_c, P_c) during T_{in}–P_{in} sweep for comparison against RCM data





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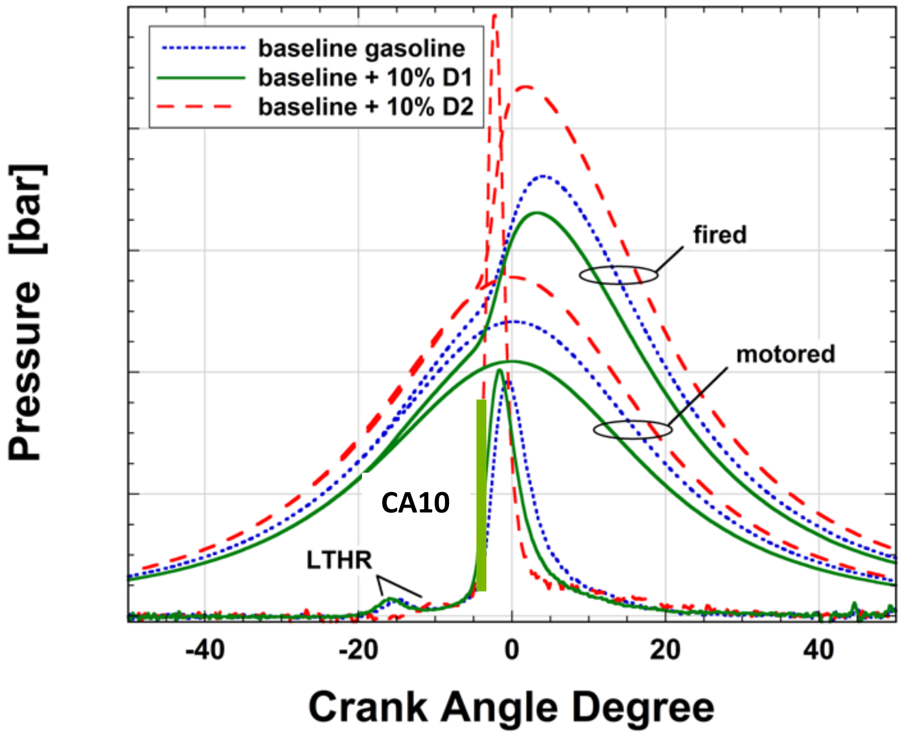

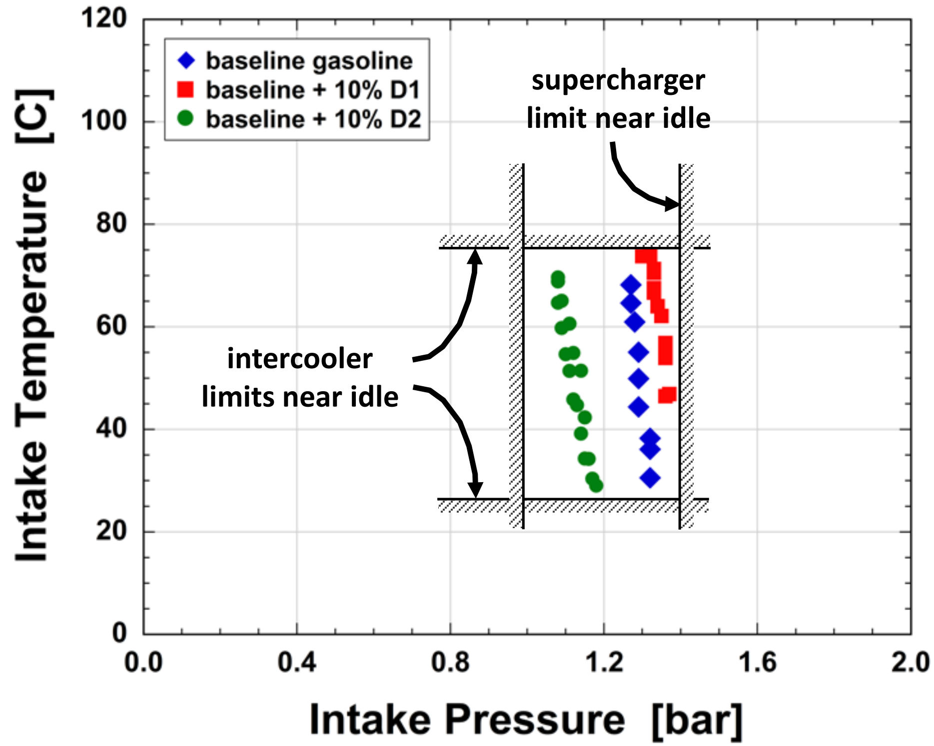

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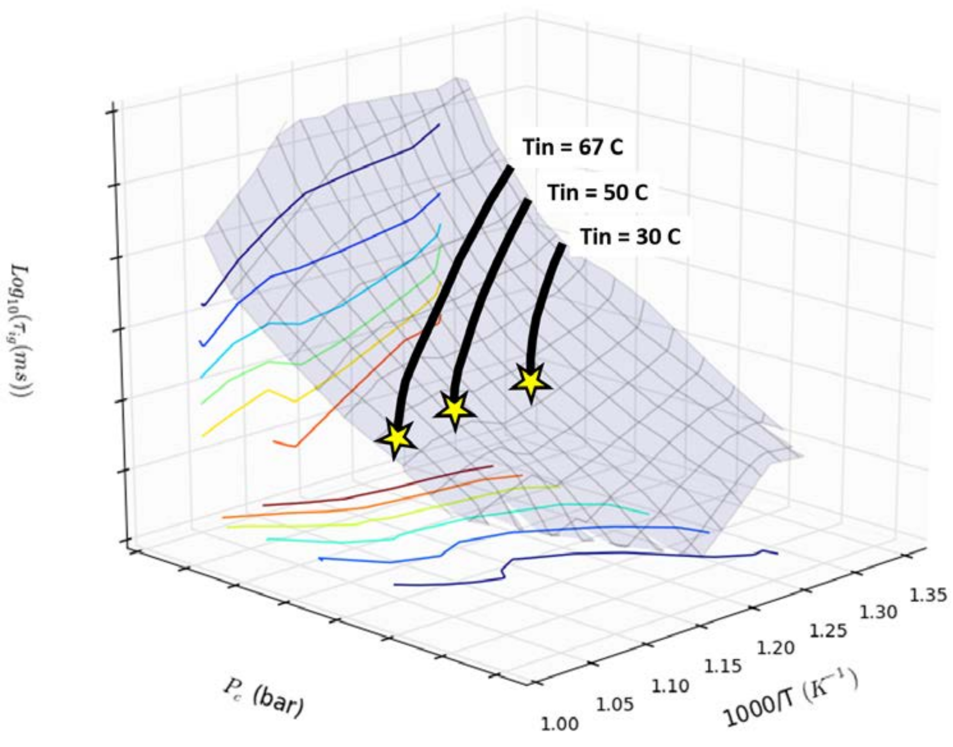
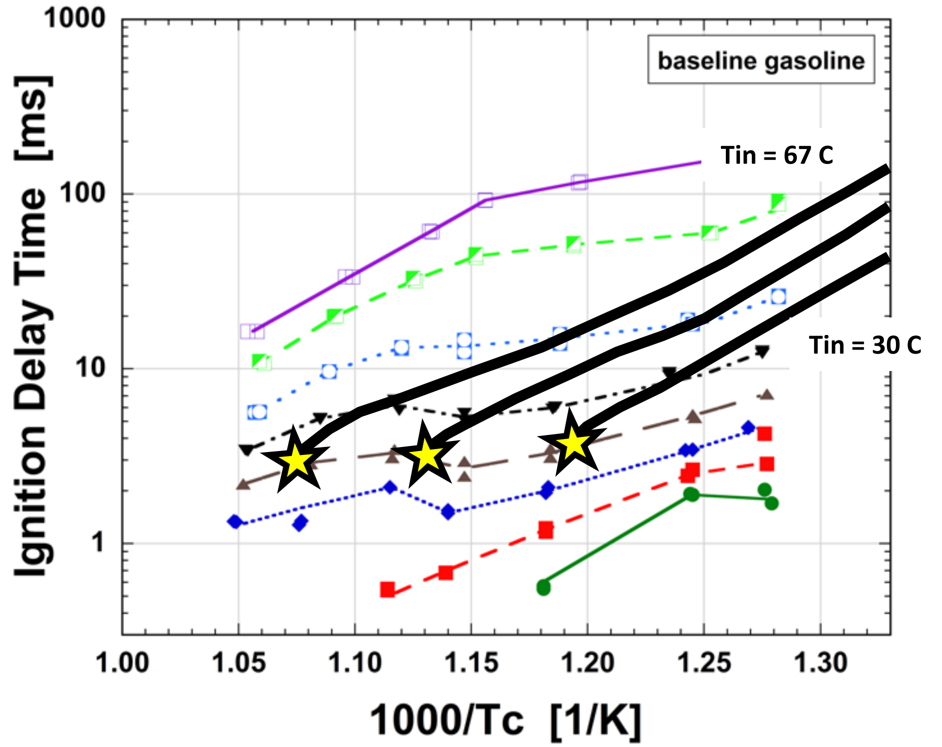
TECHNICAL ACCOMPLISHMENTS / PROGRESS

Correlation between GCI engine and RCM

- RCM tests using identical fuel loading, covering T_c /P_c representative of conditions experienced by in-cylinder charge during compression
  - Overlaid T/P trajectories for three engine cases indicates good correspondence, relevant chemistry captured in RCM experiments

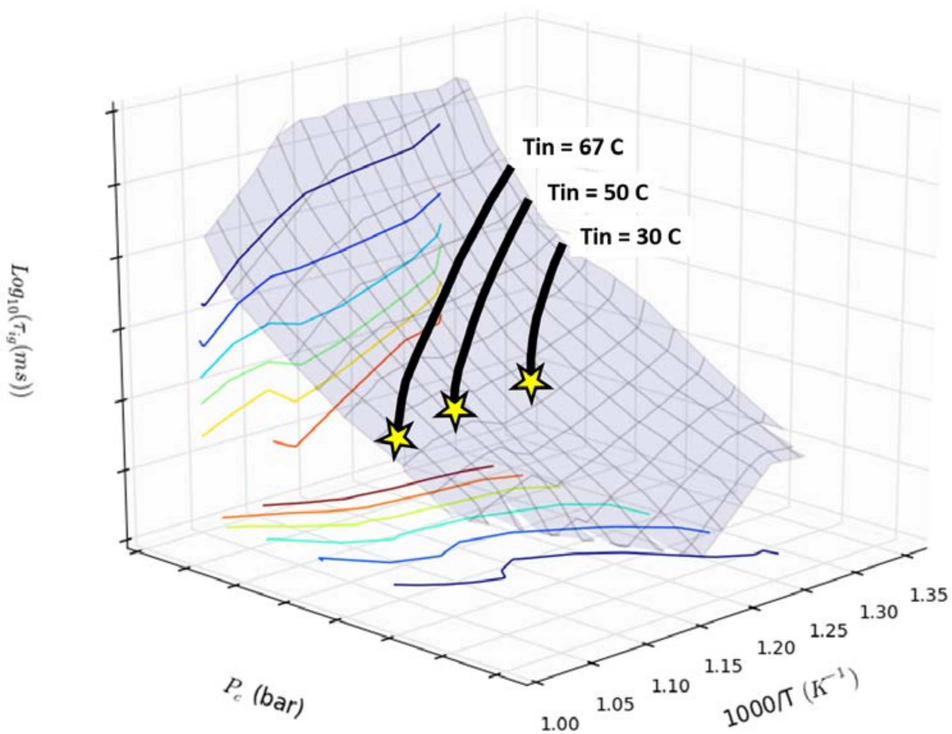


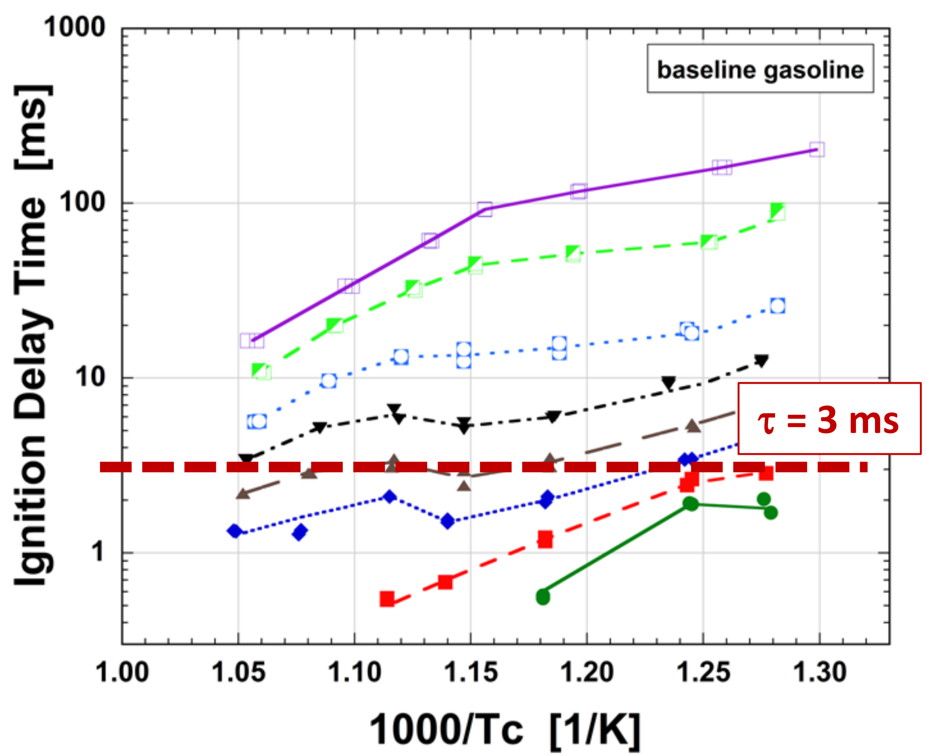


TECHNICAL ACCOMPLISHMENTS / PROGRESS

Correlation between GCI engine and RCM

- RCM tests using identical fuel loading, covering T_c /P_c representative of conditions experienced by in-cylinder charge during compression
  - Constant combustion phasing in engine (CA10) corresponds to RCM data at trajectory of constant ignition delay ($\tau \approx 3$ ms)





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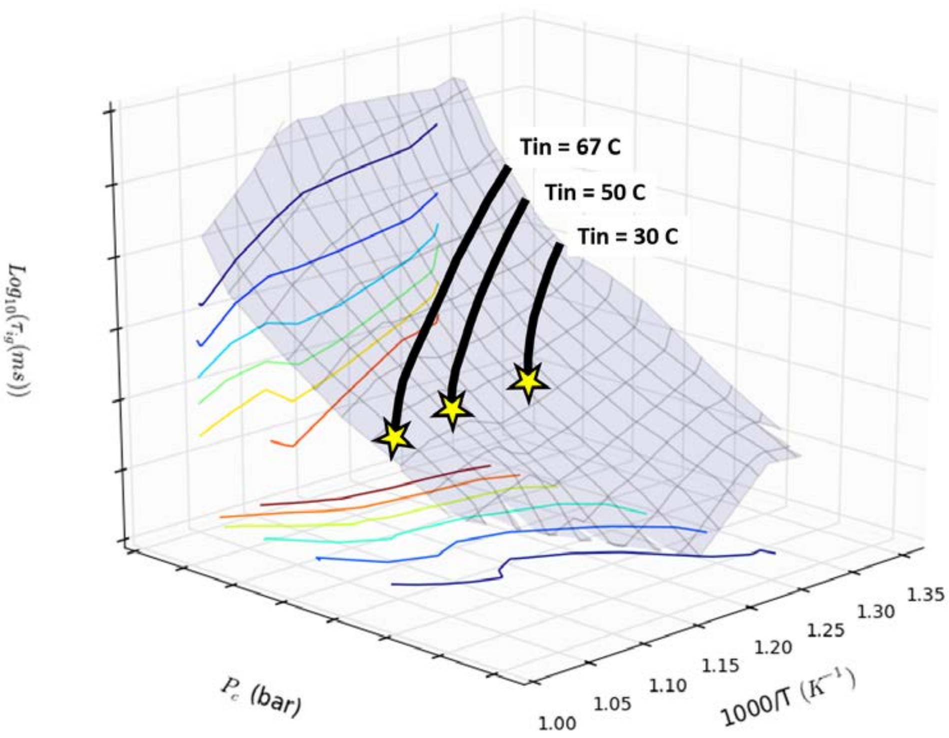
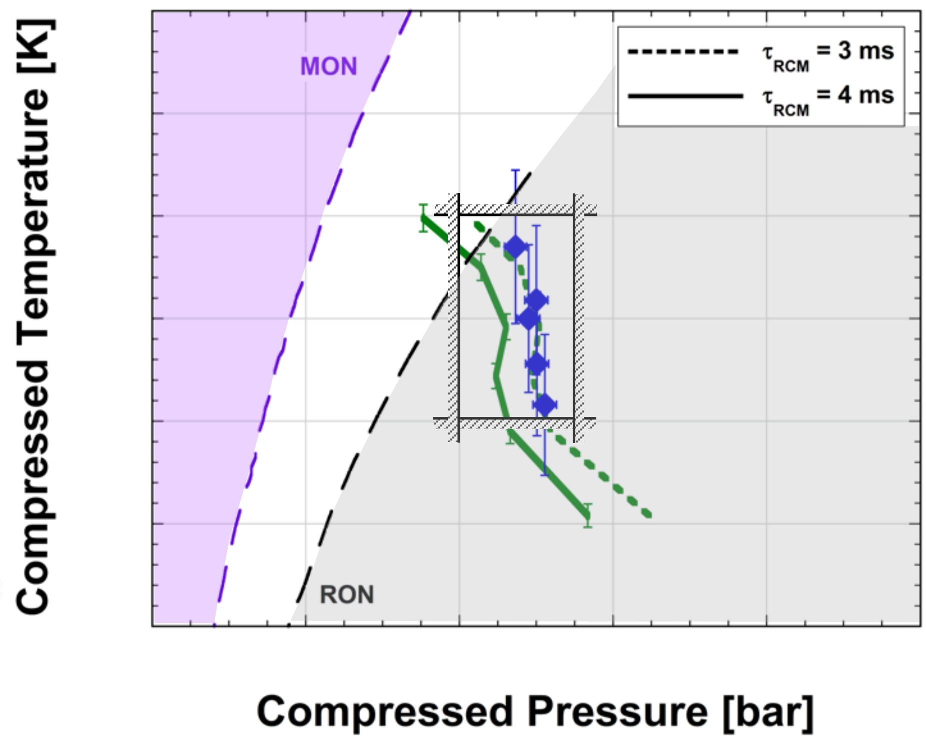
TECHNICAL ACCOMPLISHMENTS / PROGRESS

Correlation between GCI engine and RCM

- RCM tests using identical fuel loading, covering T_c /P_c representative of conditions experienced by in-cylinder charge during compression
  - Comparison between conditions in engine required for constant CA10, and those in RCM required for iso-τ highlighted in (T_c–P_c) representation





RESPONSE TO REVIEWER COMMENTS

- Project was not reviewed last year.

COLLABORATION / COORDINATION

- Chevron continuing to blend / characterize fuels
  – Remaining Phase II fuels to be delivered in FY2016, Q3/Q4
    - Fuel storage facility at ANL has limited space, but small quantities delivered to RCM facility for testing
    - Physico-chemical characterization enables planning of RCM and GCI engine tests
  – Phase III fuels delivered by FY2017, Q2
- RCM / GCI engine comparisons
  – Iteration of FQM testing protocol within RCM, and operating conditions to be used in GCI engine for validation is ongoing
  – Refinement of analysis tools, e.g., extension of GT Power model over wider range of conditions, will reduce uncertainties in comparison between RCM and GCI engine data

REMAINING CHALLENGES / BARRIERS

- Demonstrated correlation between RCM experiments, and trends observed in GCI engine under quasi-HCCI operation, but
  - mechanical constraints of multi-cylinder engine, e.g., super-/turbo-charger, compression ratio, valve timing, noise, limit the operating range for comparison between fuels. Testing protocol iteratively designed / refined to quantitatively rank fuels under various operating regimes. Extension of operating range for engine may be possible, but would require hardware modifications, e.g., piston compression ratio.
- Development of test point for stratified condition (ϕ, EGR effects)
  - Careful definition / iteration required to ensure apple-to-apple comparison where fuel effects are quantitatively isolated
- Influence of heat of vaporization (HOV) still challenging to quantify, but will be considered in FY2017

PROPOSED FUTURE WORK

- Nominal FQM test conditions selected for RCM, and tests underway with Phase I blended fuels.
  - FQM test series designed to identify / quantify fuel response to ϕ-gradients and EGR-tolerance experienced during engine operation.
- GCI engine validation test points will be defined to quantitatively rank fuels under stratified conditions, e.g., late SOI, and EGR-diluted operation.
  - Validation tests with Phase II, 10% blended fuels during FY2016, Q4
- Extension of tests to Phase III 20% v./v. blended fuels
  - Modifications to FQM and validation test points may be necessary depending on unexpected changes in reactivity trends;
  - Modifications to supercharger (e.g., smaller pulley), addition of heater in intake manifold, etc. could extend T_c /P_c, operating window for validation tests.

SUMMARY

- Fuel Quality Metric under development to overcome limitations of conventional and modern fuel rating indices (RON, OI)
  - FQM will enable specification fuels for, and design of LTC-enabled engines, highlighting parameters that are controllable, e.g., boost, stratification, EGR
- FY2015/16 accomplishments and progress include:
  - Fuels with range of reactivity and molecular structure blended with physico-chemical properties characterized
  - RCM utilized to fundamentally understand autoignition trends (τ, LTHR) of fuels in matrix, and formulate FQM protocol
  - GCI engine experiments used to quantify fuel influences over range of operating conditions (speed/load), validate FQM
  - Engine validation point designed to isolate T/P influences at LTC conditions; validation test point(s) to isolate ϕ–sensitivity, EGR–tolerance will be established by end of FY2016
  - Excellent correlation demonstrated between RCM and GCI engine data under quasi-HCCI conditions for baseline gasoline
    - Further testing underway with Phase II fuels

THANK YOU

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TECHNICAL BACK-UP

GCI engine measurements of 10% blended fuels

- Design of Experiments covering range of speed/load
  - Variations in fuel injection pressure, start of injection, air-fuel ratio (λ), intake manifold pressure, and fuel type
- Analysis highlights dominant parameters
  - Effects on combustion phasing (CA10, CA50), IMEP, COV, noise, BFSC, and NOx, HC and CO emissions

Engine	GM 1.9 L (4 cylinders)
Bore	82 mm
Stroke	90.4 mm
Connecting rod	145.4 mm
Compression Ratio	17.8:1
IVO	359 °aTDC
IVC	-149 °aTDC
EVO	130 °aTDC
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Engine speed	1000 rpm 2000 rpm
Intake Pressure (abs.)	1.0 to 1.4 bar
Intake temperature	46-49 °C
Injectors	Bosch
Number of holes	7
Nozzle diameter	0.141 mm
Spray angle	120°
Injection Pressure	400 to 600 bar

	Engine Speed	1000 rpm		2000 rpm*		Unit
	Level	Low	High	Low	High	
DOE 1	Boost	0.2		0.45, **0.3**		bar
	Injection pressure **(P)**	400	600	400	600	bar
	Start of injection **(S)**	15	141	70/20	70/40	deg. BTDC
	Lambda **(L)**	3.6	4.5	2.7, **2.5**	3.7, **3.5**	
	Fuel **(F)**	F1	F2	F1	F2	
DOE 2	Lambda	4.2		3.1, **3.0**		
	Injection pressure **(P)**	400	600	400	600	bar
	Start of injection **(S)**	15	141	70/20	70/40	deg. BTDC
	Boost **(B)**	0.15	0.3	0.35, **0.2**	0.55, **0.4**	bar
	Fuel **(F)**	F1	F2	F1	F2