# Hyundai Multi-Mode GCI Engine

**Annual Merit Review – 2021**

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**Hyundai-Kia America Technical Center Inc.**

**June 24, 2021**

Project ID: ft100
Award #: DE-EE0008478

HYUNDAI
Multi-Mode GCI

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

# OVERVIEW

## Timeline

- Start date: 1/2/2019
- End date: 12/30/2021
- 70% Complete

## Budget

- Total Funding for 3 years
- $2.17M Federal-Share
- $2.78M Cost-Share (56%)
- $4.95M Total Project Budget
- Funding Year 2: $817,802
- Anticipated Year 3 funds: $407,481

## Project Partners

- US Dept of Energy-VTO
- Michigan Tech University
- Phillips 66
- Project Lead: Hyundai

## Barriers

- Co-optimizing GCI combustion system with novel gasoline blendstock fuel specification to maximize efficiency potential
- Gasoline CI limits. Improved fuel properties and chemistry models are needed to develop combustion system
- Advanced Combustion System hardware are needed to cover multi-mode operation range
- Multi-mode engine operation requires mode switching strategy thus advanced controller will require strategy with up to 3 modes

# RELEVANCE

- To meet 2025 VTO goals, an advanced multi-mode (SI+GCI) combustion system is being co-optimized with gasoline fuel for LD vehicle application

- **Challenges** to apply GCI technology to LD passenger car engine.
  - Low-load stability, High load burn rate

- **Extensive CFD** modeling:
  - Development of real fuel chemistry and fuel properties models are needed
  - Improve GCI fundamental understanding to address challenges above
  - Fuel and combustion mode co-optimization

- **Key Engine Hardware** needed:
  - High ROI gasoline DI injector and 1000bar + gasoline pump
  - High efficiency VIC turbo technology
  - Dual CVVD&CVVT valvetrain
  - **Advanced engine controller** needed:
    - multi-mode operation and mode switching.
    - Cylinder pressure feedback control with CPS
    - Prediction of in-cylinder conditions (temp, residuals)

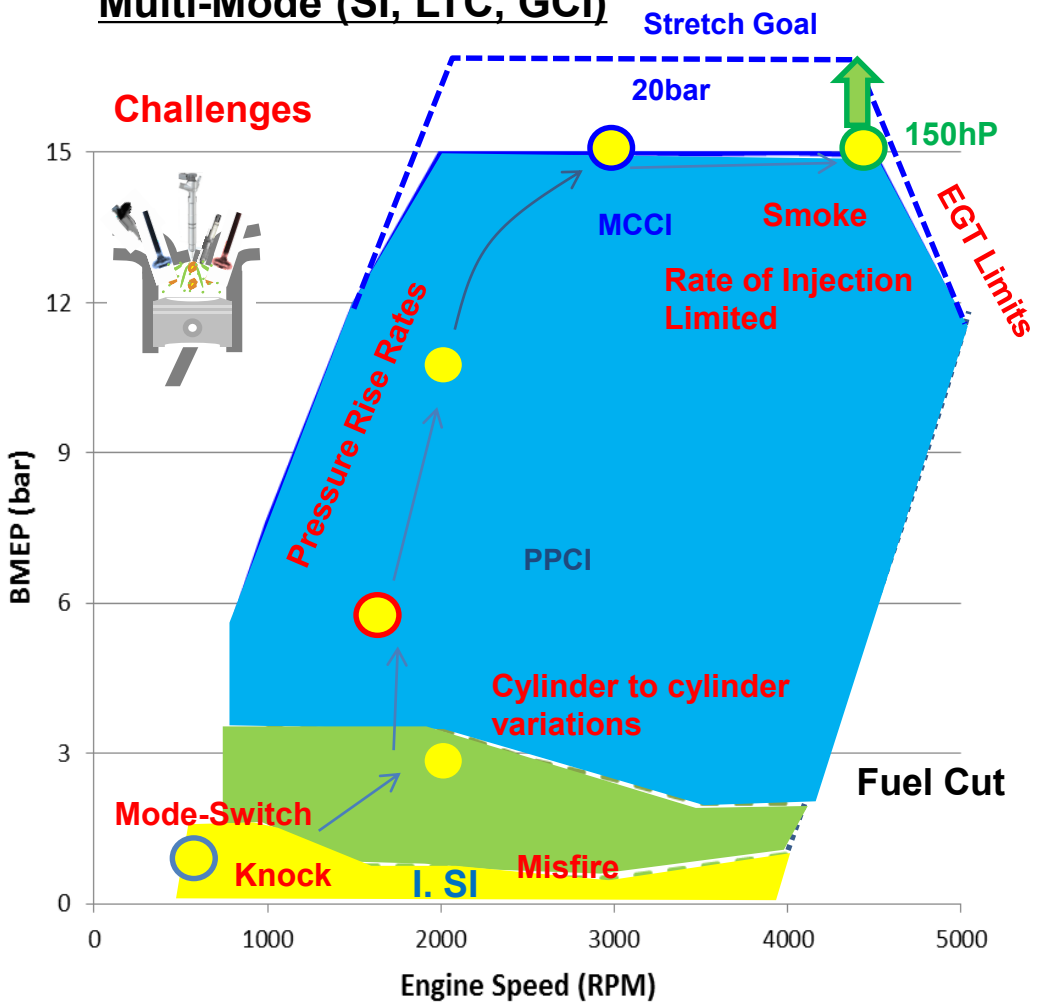
# MILESTONES

| Month/Year | Description of Milestone | Status | R/Y/G |
|---|---|---|---|
| June 2020 | M1.3 Fuels formulation selection and justification of down-selected fuel for GCI testing. | Completed | |
| June 2021 | M2.2. four fuels modeled in simulation and recommendations made for optimal fuel formulation | Completed | |
| June 2021 | M2.3 Multi-mode engine controls setup on engine in dyno and full functionality validated. | Completed | |
| Aug 2021 | M2.4: Multi-mode engine & fuel formulation strategy, demonstrated BSFC and emission and performance targets have been met | In-Process | |
| Sept 2021 | M2.5/M3.5 Go/No Go: 15% fuel economy improvement over baseline from MCTE dyno test over 1D FTP75 | In-Process | |
| Nov 2021 | Final representative 3D CFD Model delivery | In-Process | |

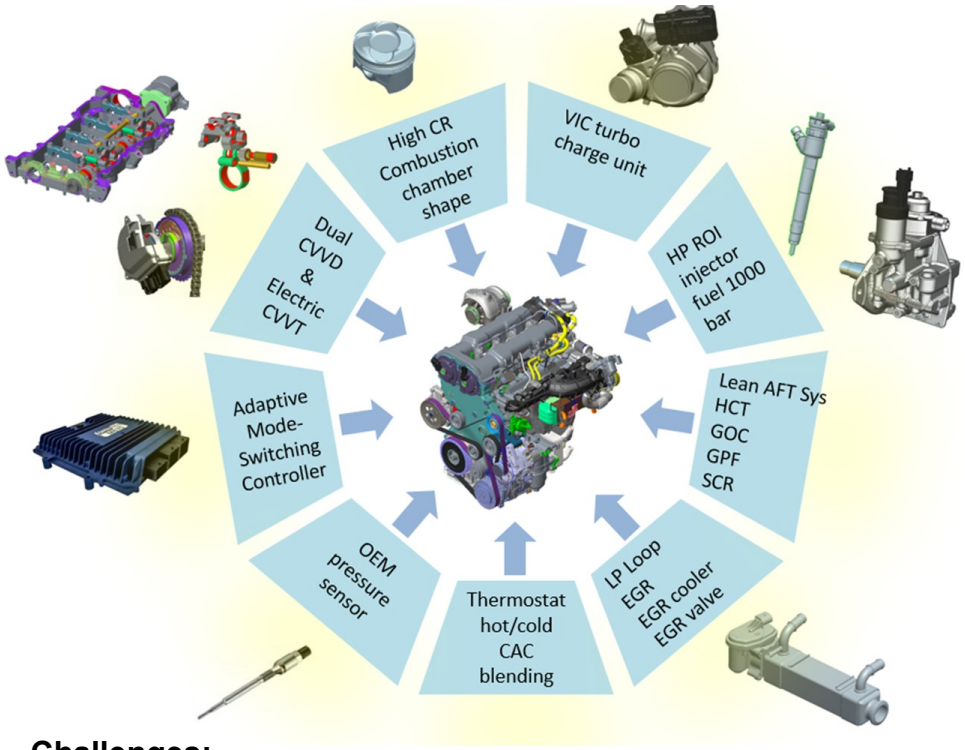
- **FTP75 simulation was conducted on data from baseline engine.**
- **GCI_01 engine was commissioned and tested. Exploration of low load GCI mode**
- **GCI_02 engine was designed and built. Controls commissioning in-process**

# TECHNICAL APPROACH

## Multi-Mode (SI, LTC, GCI)




## Enabling Hardware




**Challenges:**

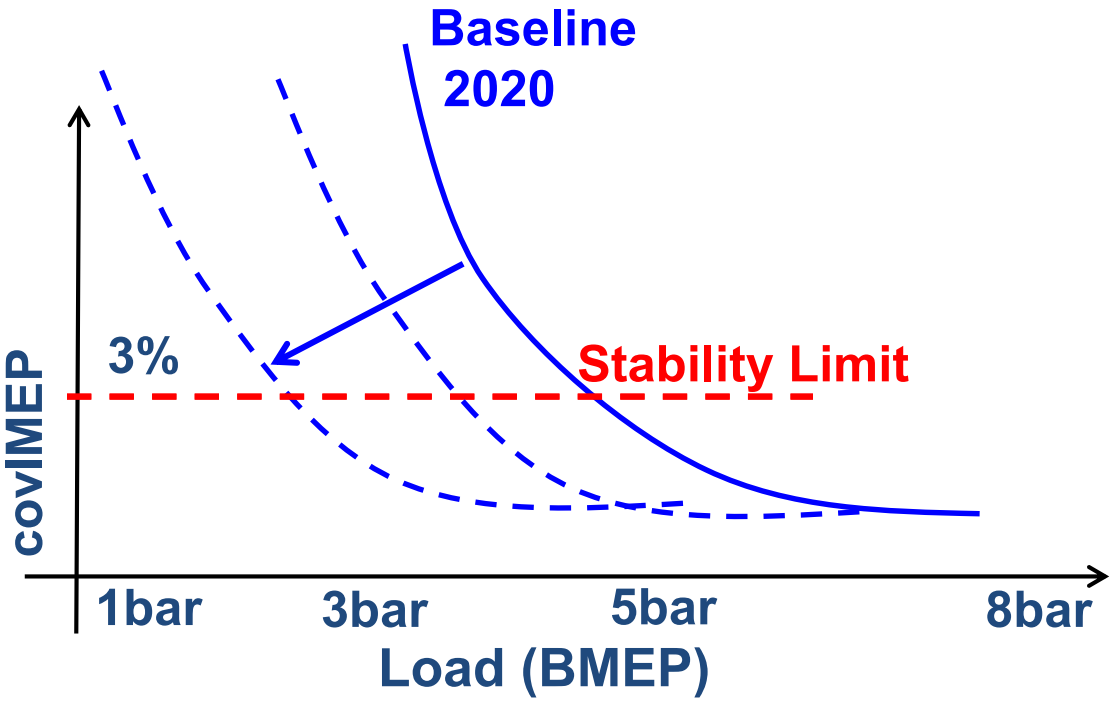
- Low Load GCI - stability
- High Load GCI – Burn rate too slow
- Mode switching –Advanced controls development
- Lean NOx-aftertreatment
- Engine cost and complexity

**Project Goal: 15% fuel economy improvement over SI engine baseline on a simulated FTP 75 cycle. Engine must also achieve 150hP and have a useable torque curve.**

# GCI MODE: LOW LOAD LIMIT EXTENSION

Challenges of Low Load GCI operation:
Ultra lean conditions λ>3, cylinder-to-cylinder variations in stack-up, flow field, trapped mass, heat transfer, injector variations, EGR distribution

## GCI Mode Low Load Extension



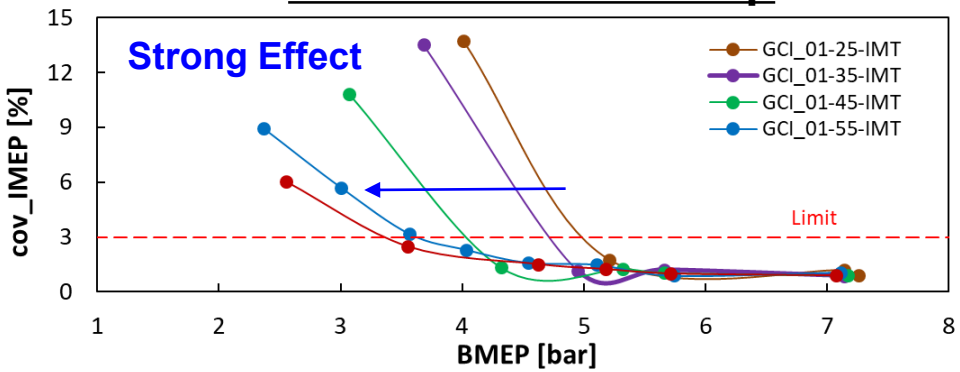

**Extending GCI low load limit**

1. Intake Heating
2. Boosting
3. Spark Assist
4. Fuel Pressure
5. CA50 control
6. IMEP balancing
7. Fuel Reactivity
8. EGR Effects
9. Engine Coolant temp
10. NVO Residuals – GCI_02

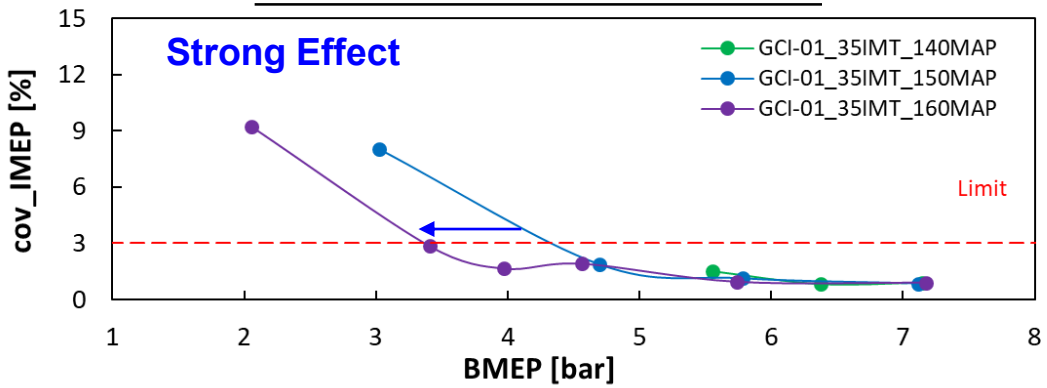
**Research Plan is designed to address major challenges in low load GCI operating range extension.**

# LOW LOAD LIMIT EXTENSION – GCI MODE

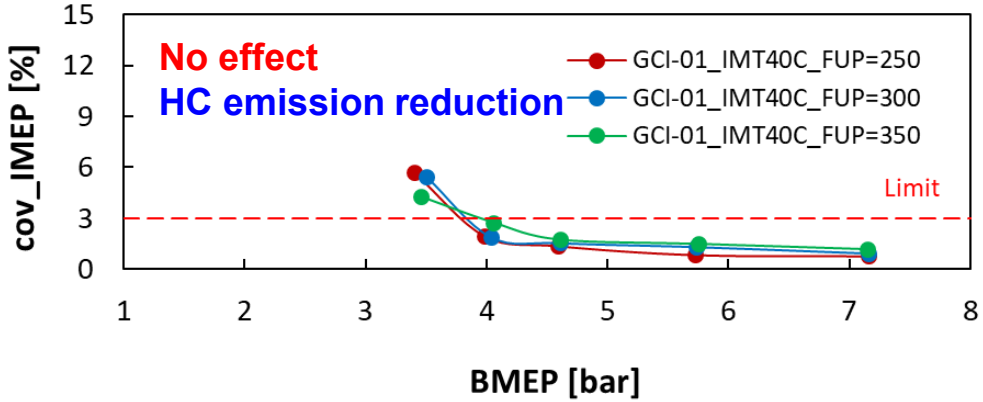
## Intake Manifold Temp



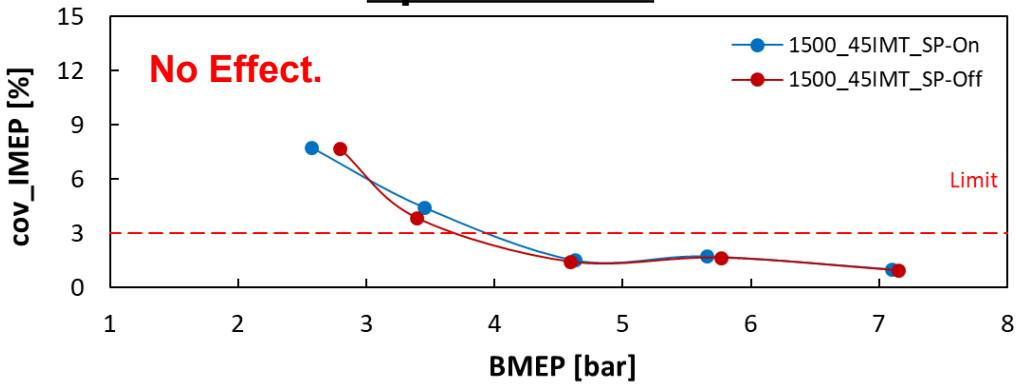

## Intake Manifold Pressure




## Fuel Pressure




## Spark Assist




- Increased Intake manifold temp & pressure extends lean limit.
- Fuel pressure does not extend limit here, but reduces HC emissions
- Spark assist had no effect

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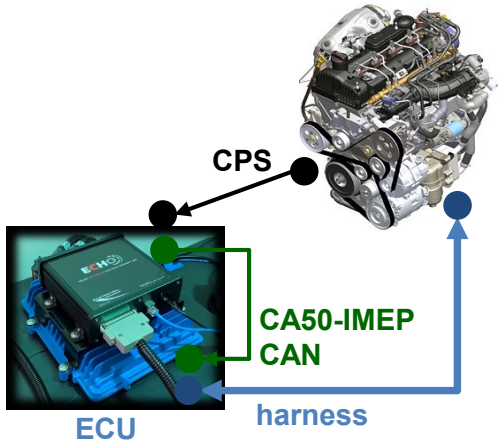
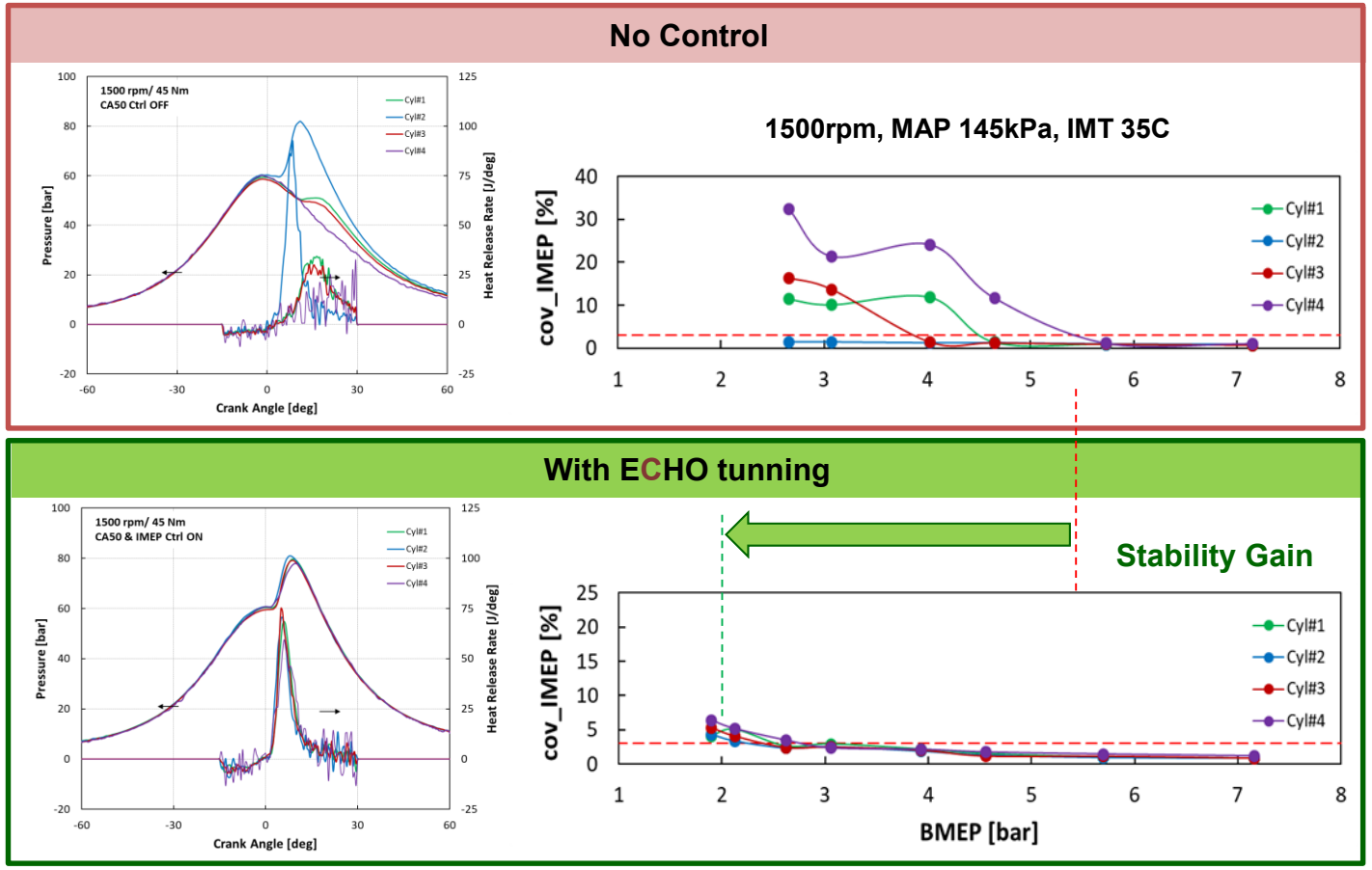
# CYLINDER PRESSURE FEEDBACK CONTROL – GCI MODE

Problem: Under part-load dilute conditions, cyl-cyl variations cause GCI to misfire.

Cause: Uneven air/EGR distribution, thermal, stack-up, etc.

**ECU with Engine Controller HS Oversight (ECHO) provides real time Cylinder Pressure Sensor Feedback and Tuning**

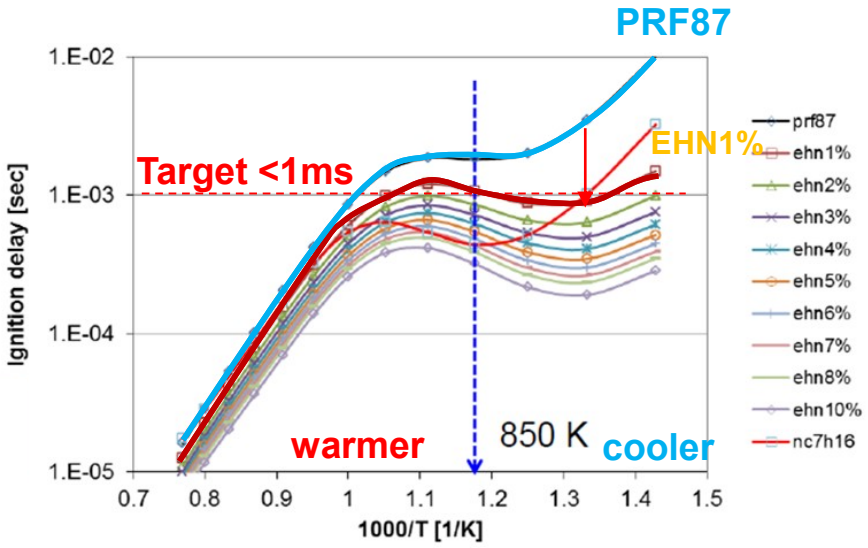


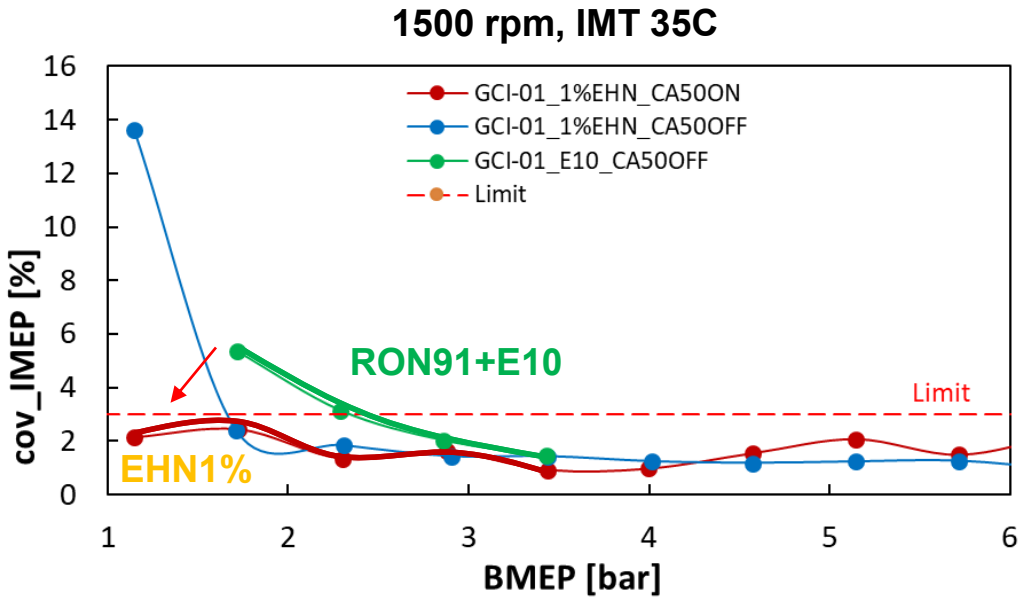

**Cylinder pressure feedback control is a key enabler low load GCI operating range extension – w/ dilution**

# ADDITIVE EFECTS ON REACTIVITY – GCI MODE

- Fuel Reactivity: Increasing fuel reactivity can extend low load limit by decreasing the ignition delay (target 1ms)
- Ignition Delay data for EHN* added to gasoline shows strong effect.
- EHN1% was added to RON91 gasoline to obtain an ignition delay of 1ms




- Test Results: EHN 1% & RON91 E10 Gasoline
- Low load stability limit significantly improves with both CA50 and EHN1% additive to RON 91 E10.

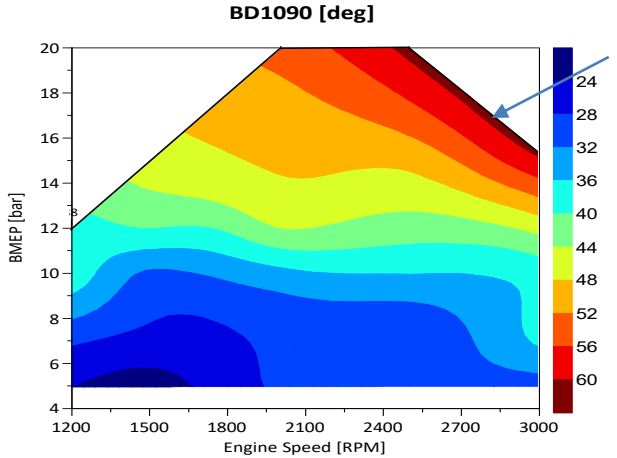


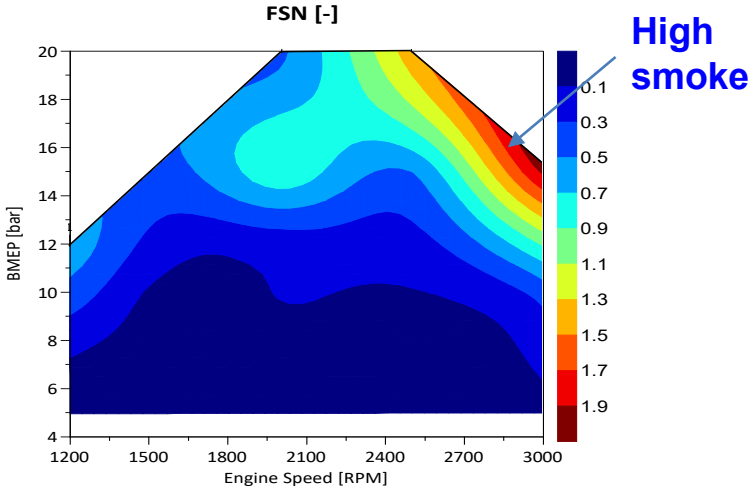

**EHN1% added to RON91 E10 gasoline had strong effect on GCI mode low load combustion stability**

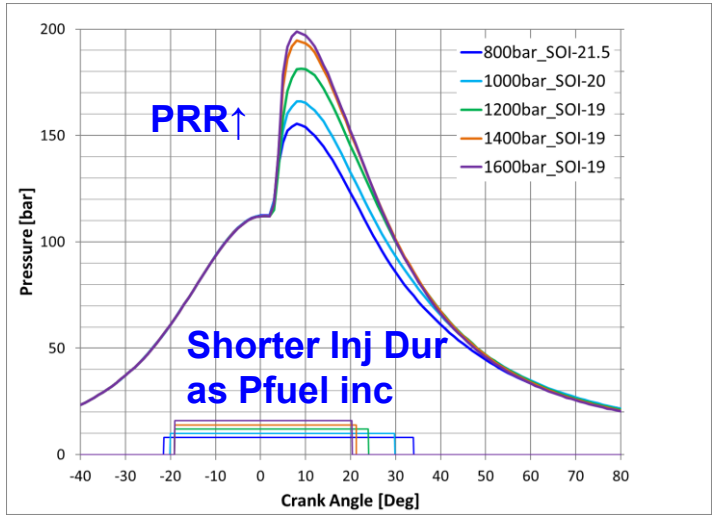
# HIGH LOAD GCI – FUEL PRESSURE BENEFITS

**Challenges:**

- ❑ **At high speed high load: (GCI mode E10) combustion duration increases with engine speed / load**
- ❑ **Leads to high EGT and smoke**

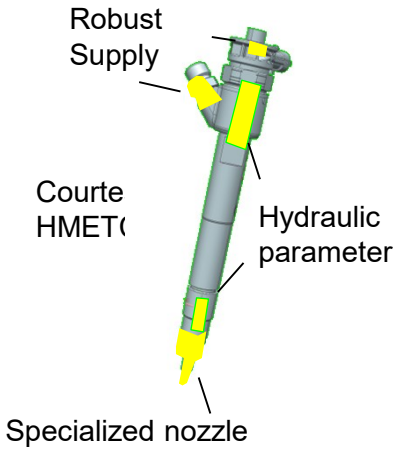


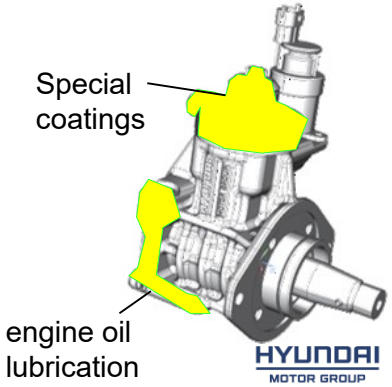

- ❑ **Solution: improve rate of injection with High ROI DI fuel injector and pump developed by HMETC.**

**Hyundai GCI Injector**




**HMETC HEFP Gen2**

**Roller Bearing High Pressure Pump**
- HMETC patent-

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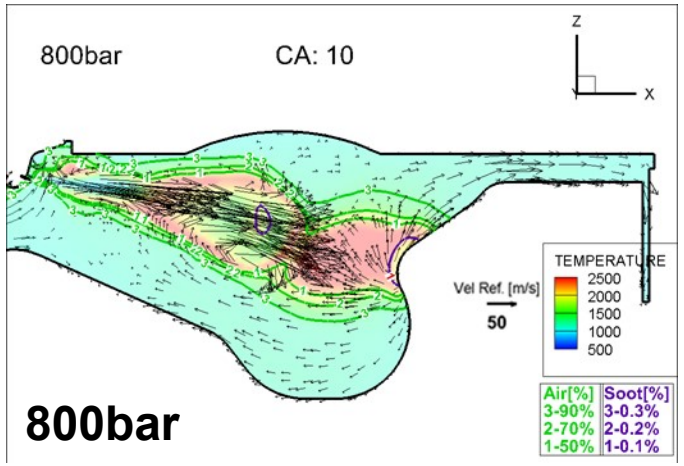
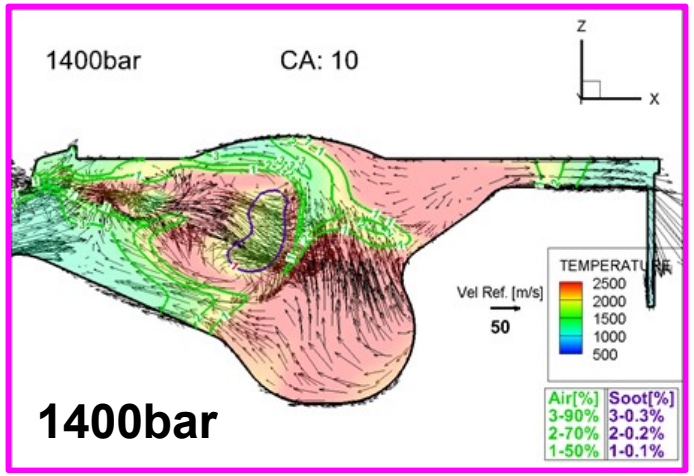
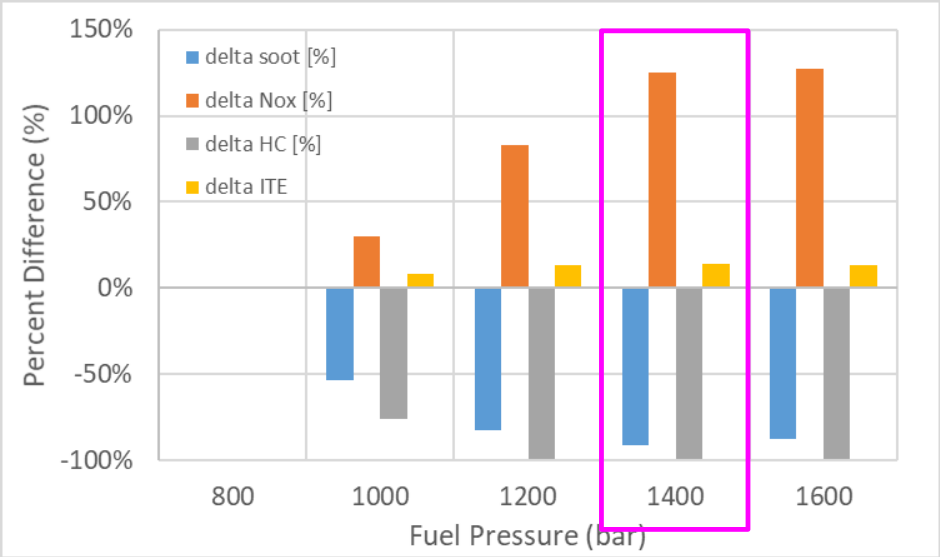
# GCI COMBUSTION SYSTEM OPTIMIZATION-E10




**4500rpm 18.1bar BMEP**




**Increasing Fuel P:**

- **Increase rate of injection and speeds up diffusion burn**
- **Decreases Soot, HC, but inc NOx**
- **Improves Thermal efficiency 14.4% @ 1400bar vs baseline**

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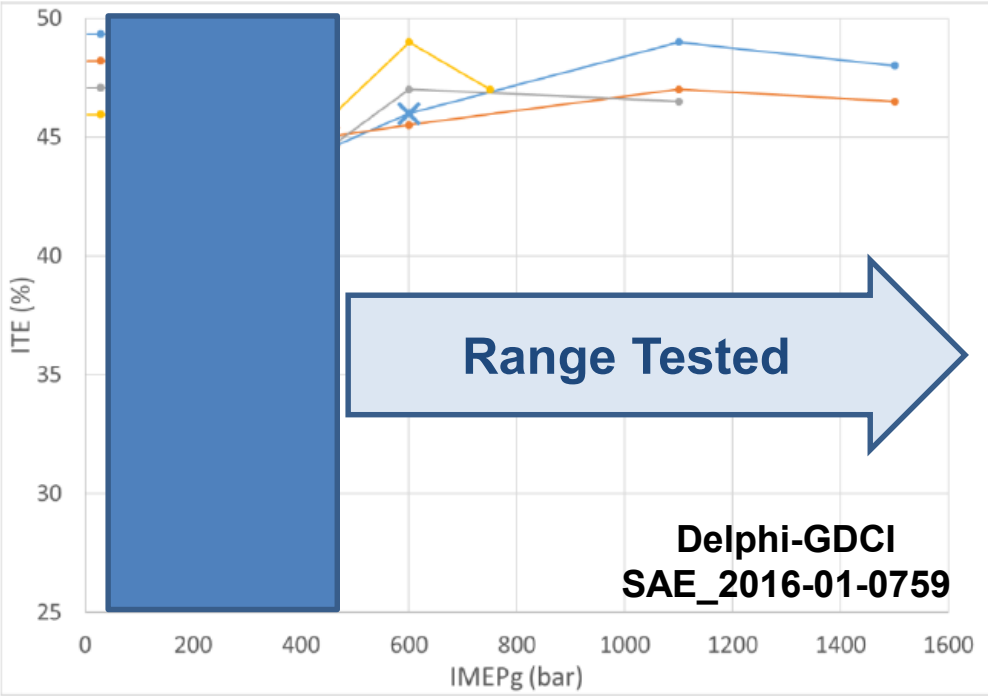
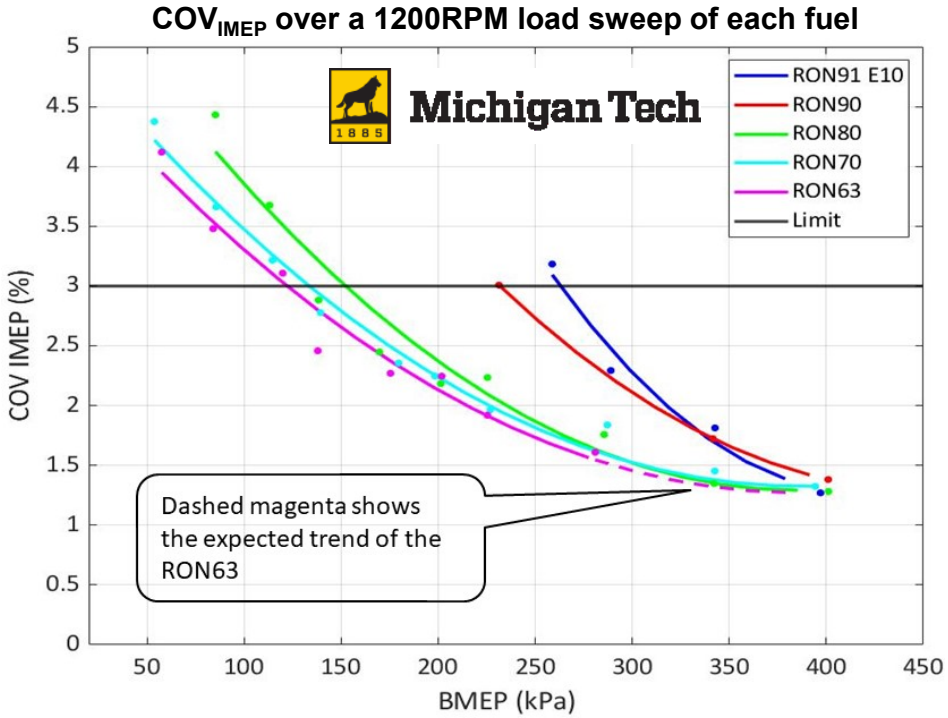
# FUEL MATRIX EFFECTS ON REACTIVITY – LOW LOAD GCI

- Fuel Reactivity: Delphi GDCI program and ANL previously looked at varying effect of RON60 through RON91E10




**M2.2: Low load GCI is very sensitive to octane # of fuel, with lowest RON63 extending the limit the best.**

- Test at MTU confirmed similar behavior at low loads in GCI mode
- RON 63, 70, 80, 90, & RON91+E10
- Bio-Blends (RON63+EtOH, RON63+i-butanol)




- **The ability of fuel reactivity to extend operation is demonstrated by the load sweeps performed**
- **Phillips 66 RON 63, 70, and 80 fuels show similar abilities to operate at low loads**

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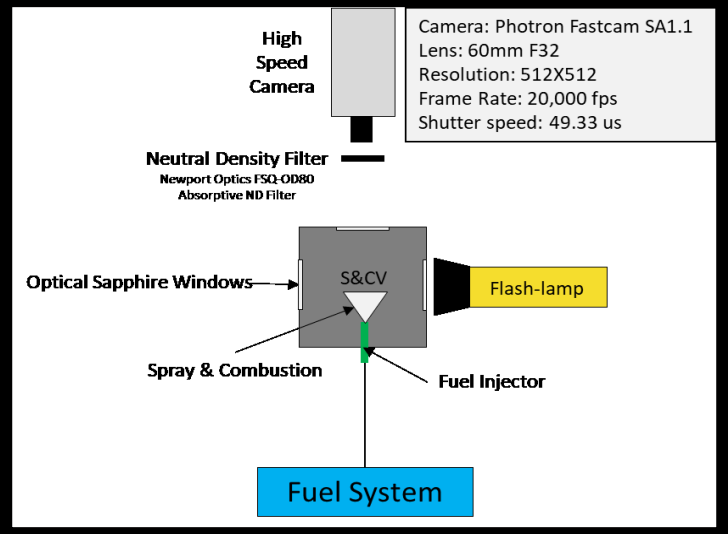
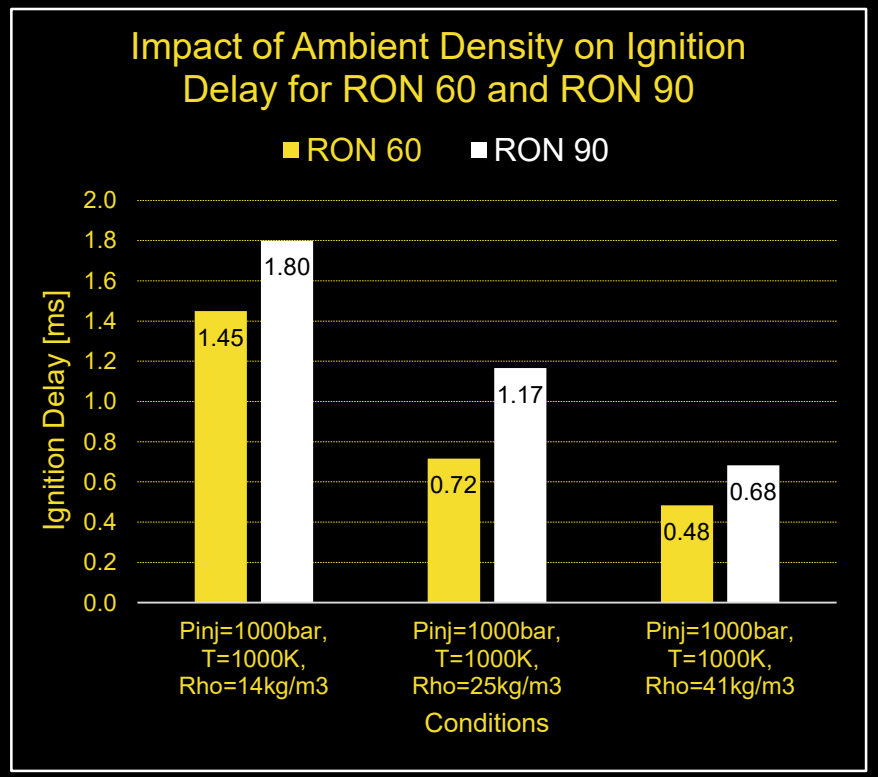
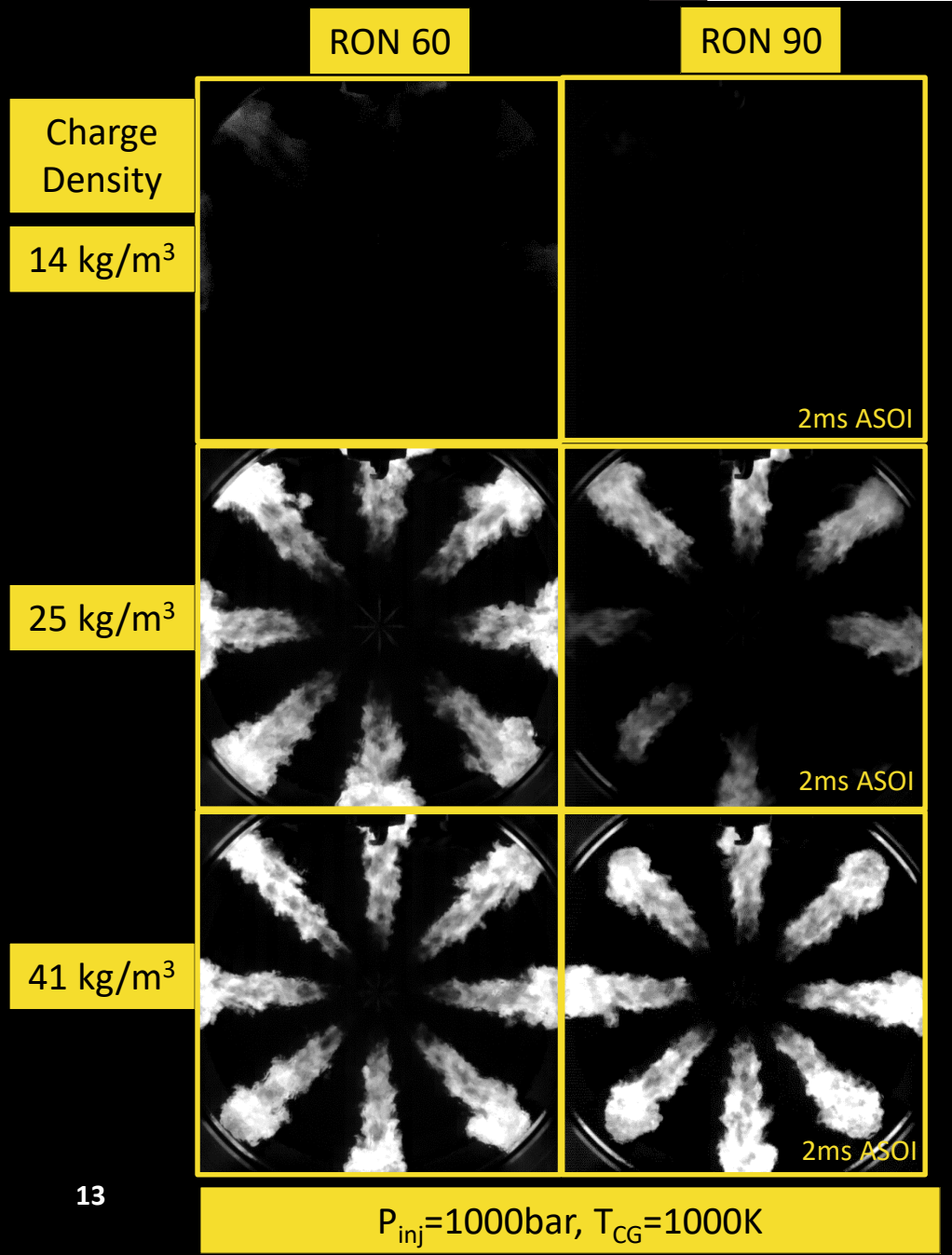
# Michigan Tech - Spray and Combustion Vessel

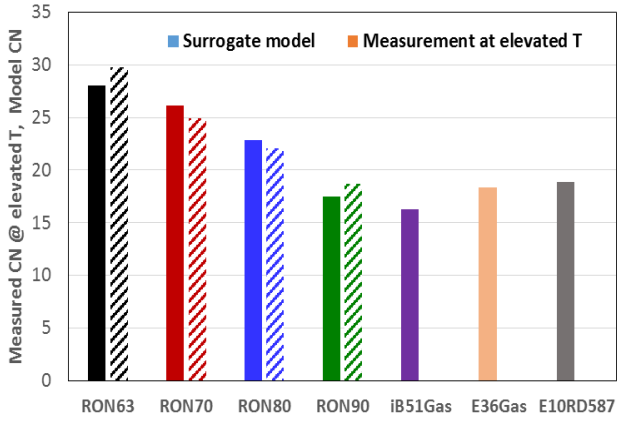


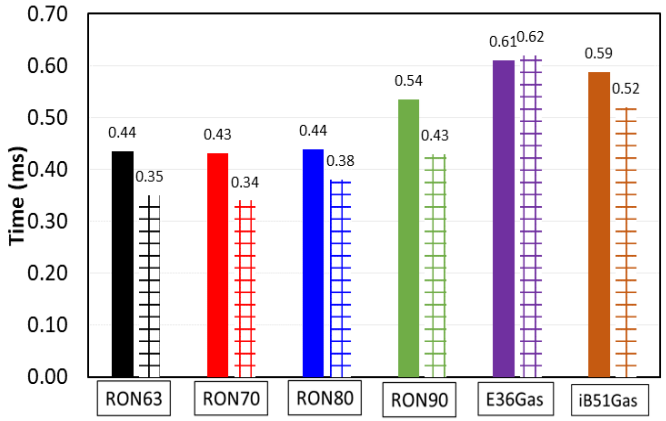



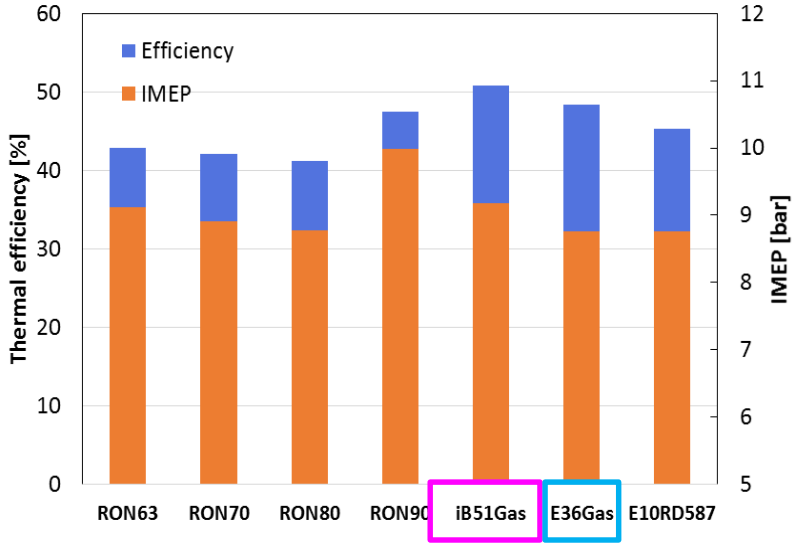
# CO-OPTIMIZATION OF FUEL AND GCI MODE

## CN comparison




## Ignition delay comparison



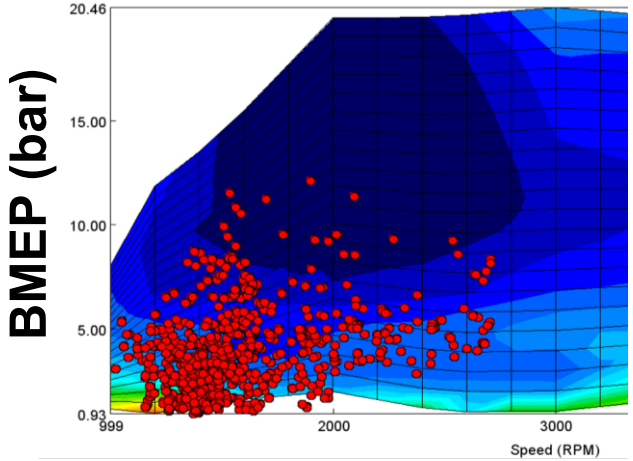

| Fuel | LHV [MJ/kg] | CN | Eff_th [%] | IMEP [bar] | UHC [g/kg-f] | CO [g/kg-f] | NOx [g/kg-f] |
|---|---|---|---|---|---|---|---|
| RON63 | 44.4 | 28.0 | 42.9 | 8.1 | 0.2 | 0.3 | 25.2 |
| RON70 | 44.2 | 26.1 | 42.1 | 8.9 | 0.6 | 0.8 | 40.4 |
| RON80 | 44.5 | 22.9 | 41.1 | 8.0 | 0.2 | 0.6 | 26.3 |
| RON90 | 43.9 | 17.5 | 44.4 | 9.3 | 7.8 | 23.5 | 12.3 |
| iB51Gas | 37.7 | 16.3 | 50.3 | 9.1 | 2.5 | 10.6 | 5.1 |
| E36Gas | 37.9 | 18.3 | 48.3 | 8.8 | 20.6 | 50.1 | 1.1 |
| E10RD587 | 42.4 | 18.9 | 45.3 | 8.8 | 3.4 | 9.8 | 6.2 |

**Preliminary simulation results at 1500rpm**

**Ind. Thermal efficiency of 50.3% reached with iso-butanol 51% fuel blend**

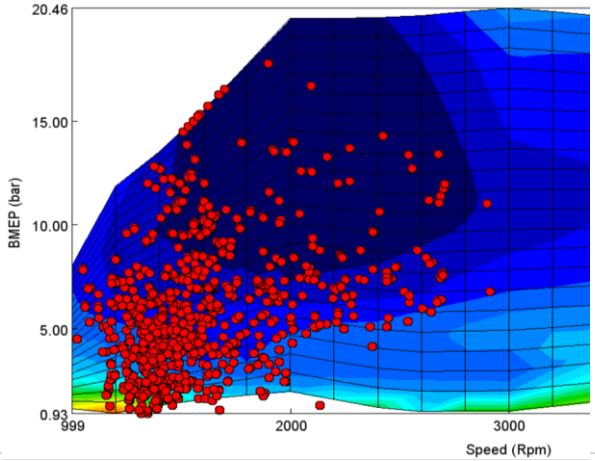
# APPLICATIONS CONSIDERATIONS

**1D FTP75 2.2L GCI Multi-Mode 6AT**



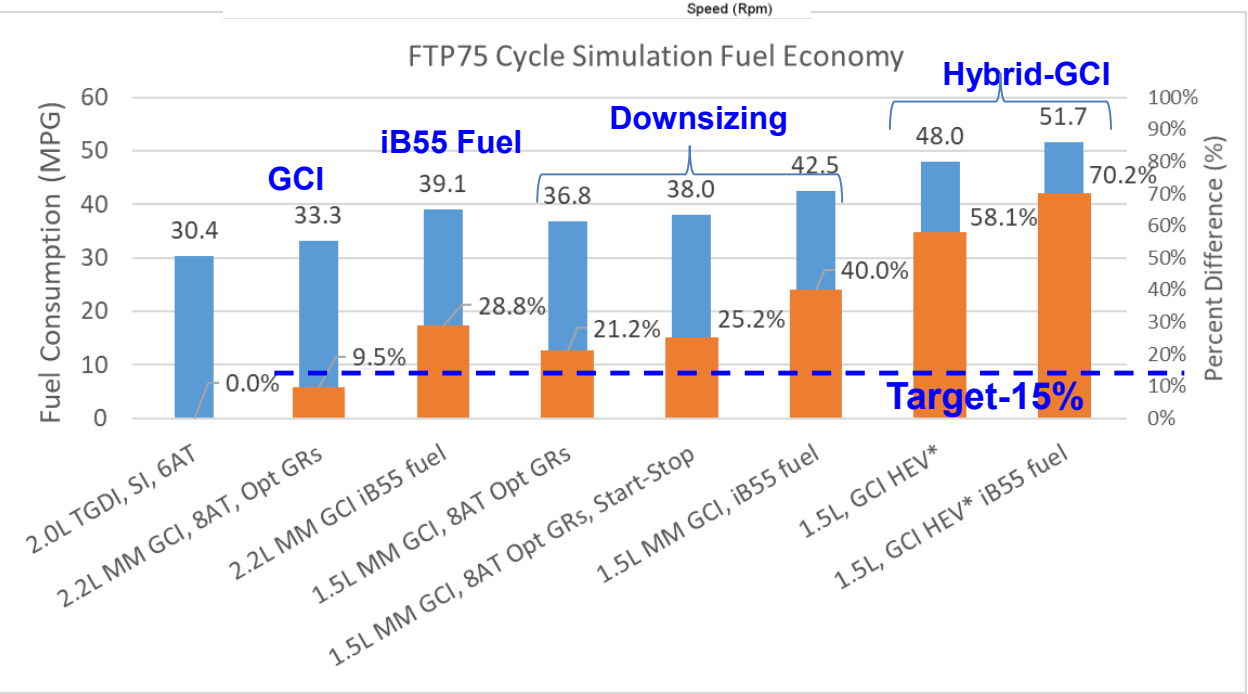

**Downsizing, 8AT, Gear Ratio, Start-stop**

**1D FTP75 1.5L GCI 8AT Optimized Gear, Start-Stop**




**Better utilization of high efficiency island for GCI**

**Target Vehicle:**
Hyundai Tucson ULEV 70
114,735 units/year total




**M2.5: Multimode GCI has potential for BSFC improvement of 25% with an 8AT, downsizing , start-stop, 29% with iso-butanol and GCI and 58% with Hybrid GCI and iB55 fuel**

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# RESPONSES TO PREVIOUS YEARS COMMENTS

| Comment | Response | Status |
|---|---|---|
| Review previous works (GCI mode) parame tric sensitivity & conduct own engine testing | Reviewed and conducted extensive engine testing of both SI and GCI modes | |
| After-treatment not addressed | AT assumptions are within scope. Review LNT vs SCR in this presentation. | |
| Lubrication not addressed | Out of scope | |
| No plans for vehicle demo | Out of scope | |
| VVA should be used | In plan for end of 2021 | |
| Novel fuels has delayed year 2 | Conducted extensive fuels testing in 2021. More te sts being planned. High load | |
| Work with injector company | HMETC engaged - internal injector specialists | |
| Work with Experts - National Labs | ANL has been invited as advisors to the project (Autonomie LCA and fuels reactivity) | |
| Any plans to address knock SI mode | Testing of SI mode is underway, will investigate multiple DI injection strategy | |

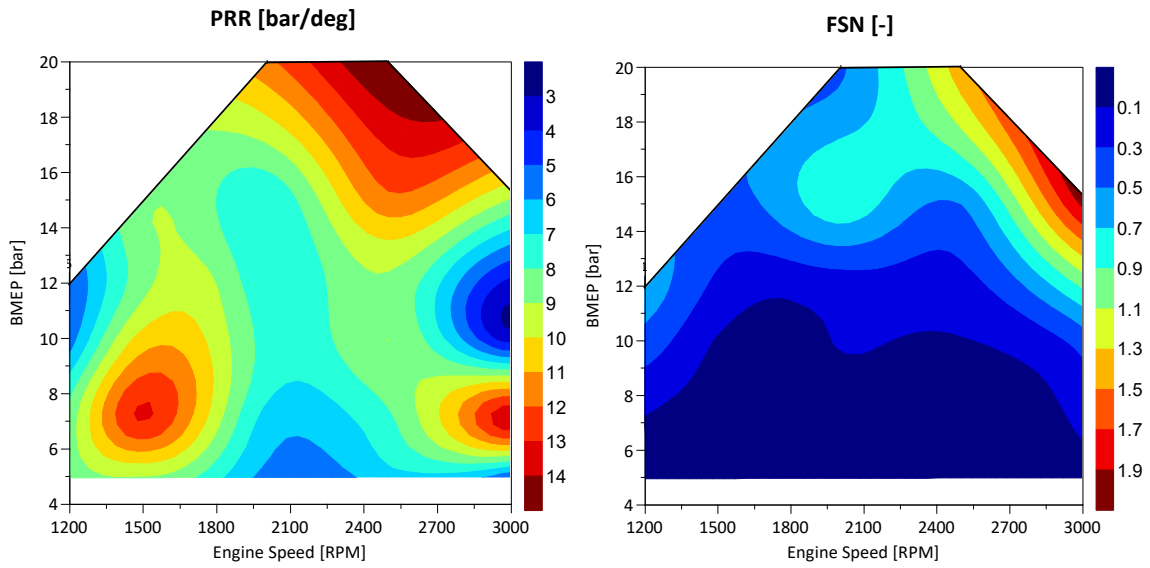
# COLLABORATION AND COORDINATION WITH OTHERS

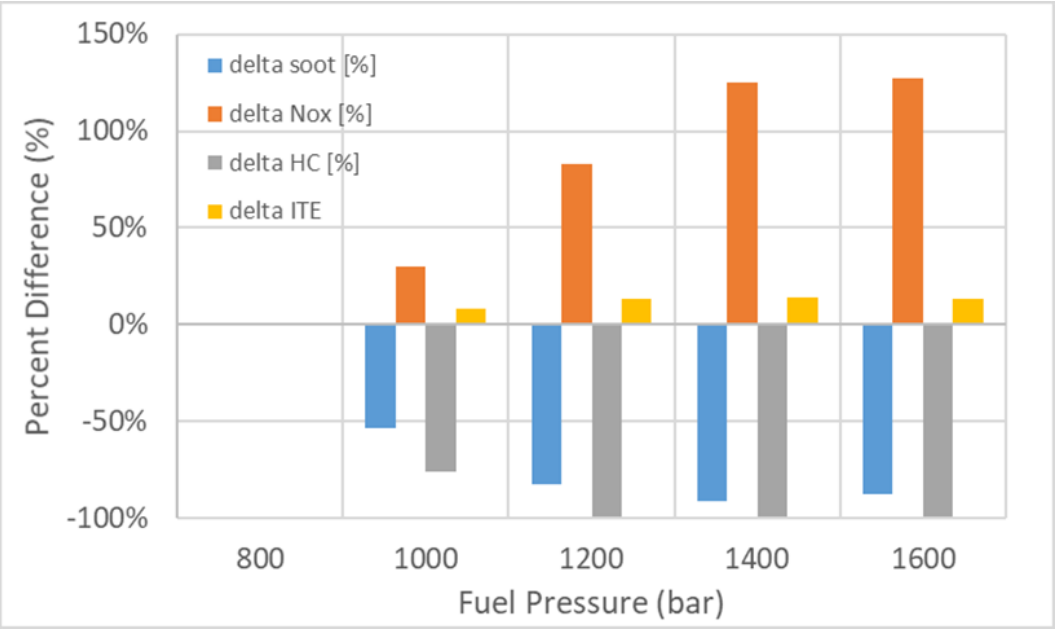
| Organization | Role |
|---|---|
| Hyundai America Technical Center Inc. | Lead org, base engine, 1D simulation, engin e testing, combustion, controls & calibration E10 fuel testing |
| Michigan Technological University | 3D CFD Model build<br>SCRE and S&CV chamber testing<br>Advanced Control estimators<br>Fuels & GCI study |
| Phillips 66 | Fuel formulation development & research fue l supply |
| Garrett-Motion | Turbocharger supply |
| HMETC | DI Injector characterization & supply<br>Validation |
| WM International Engineering | Multi-mode base controller development<br>Cylinder pressure feedback system |
| Argonne National Lab | Autonomie Model LCA GHG analysis<br>Fuel Formulation down selection support |

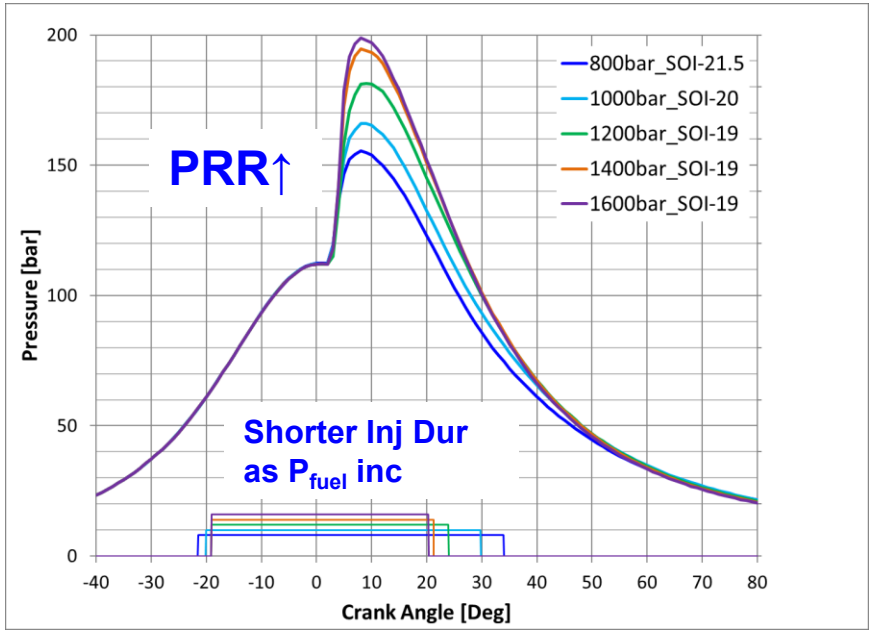
# REMAINING TECHNICAL CHALLENGES & BARRIERS

- **Barriers:**
- **Managing Pressure Rise Rates < 10bar/deg at high loads Increased fuel pressure will shorten burn duration and limit smoke emissions.**
- **However, this will higher NOx emissions as shown below**

- **Challenges:**
- **Increase EGR to mitigate NOx and manage smoke to stay within SULEV30 if possible.**
- **SA-LTC mode operation and range extension**
- **Development of in-cylinder condition estimators**

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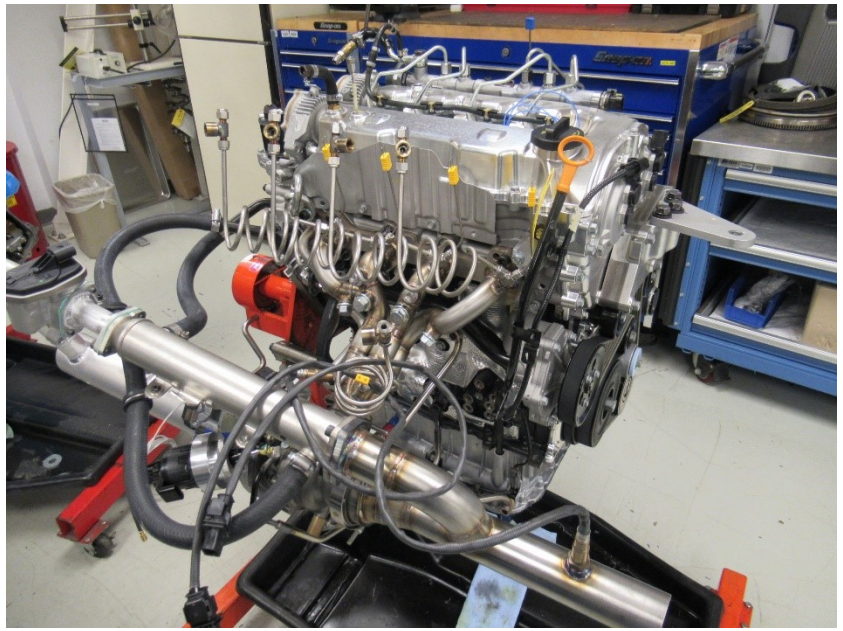
# PROPOSED FUTURE RESEARCH

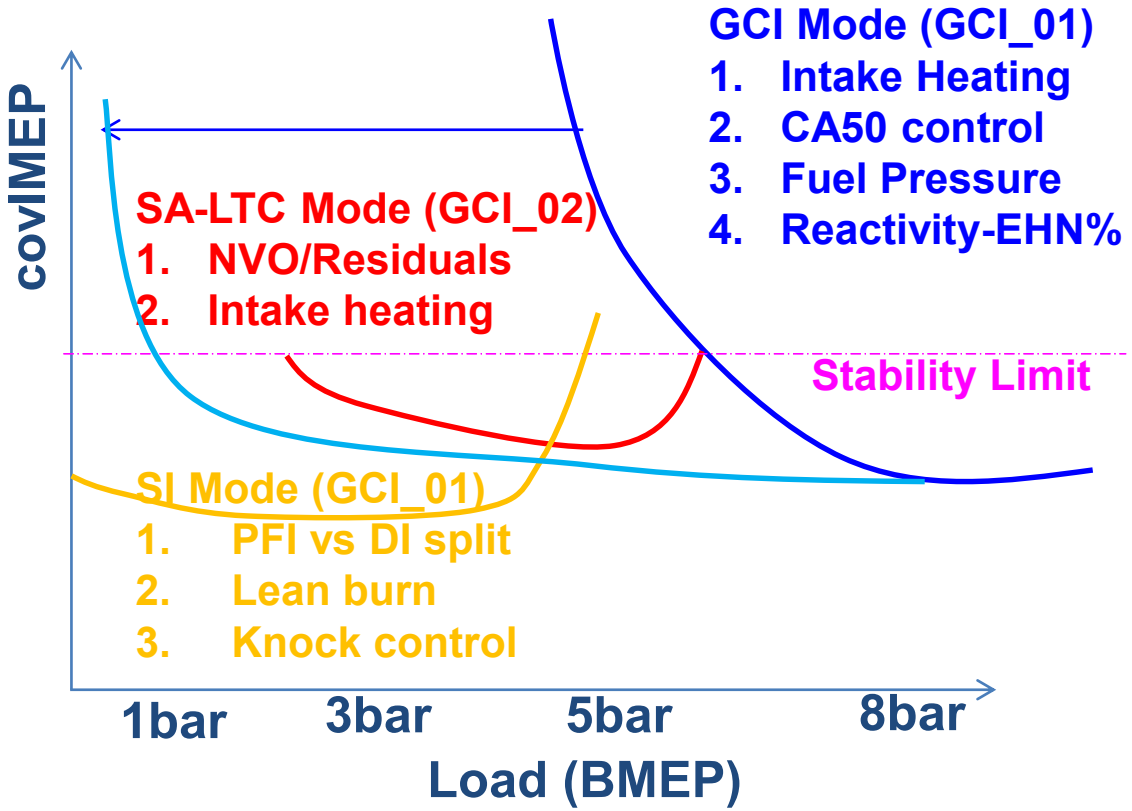
Objective: Low load fuel economy and emissions improvement



| Test Planning | Timing |
|---|---|
| GCI_01_B1 Engine 1st Fire | Sept 2020 |
| SI to GCI Mode Switch | Dec 2020 |
| GCI Low Load Extension Tactics | March 2021 |
| SA-LTC Exploration without CVVD | Aug 2020 |
| GCI and Low RON Fuel | April 2021 |
| GCI_02_B1 CVVD Engine 1st Fire | June 2021 |
| SA-LTC Mode exploration | July 2021 |
| SI to SA-LTC to GCI Mode Exploration | Aug 2021 |

**Fuel economy at part load can improve by employing SA-LTC which is similar to HCCI combustion**

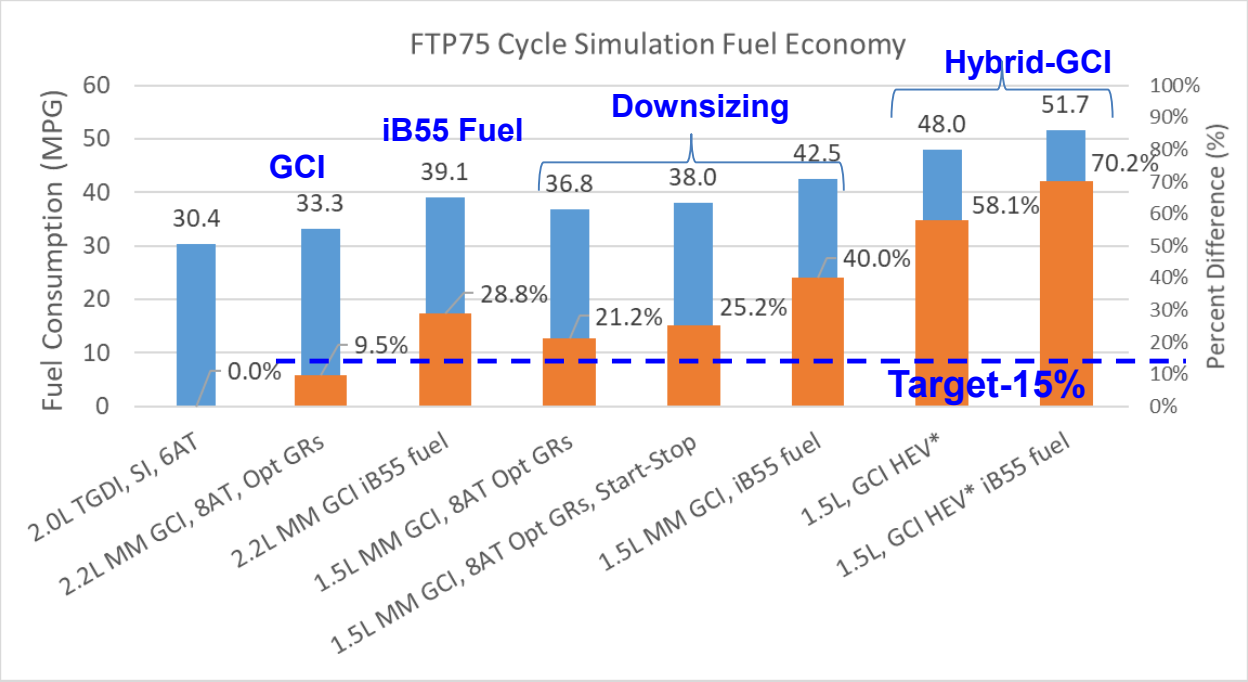
1. **Dual CVVD build will enable investigating ability to trap mass and benefits of hot residuals on stability**
2. **Investigate other parameters**




**Research Plan adequately designed to address major challenges in operating range extension.**

# SUMMARY

- M1.3 Fuels formulation selection & down-selection for GCI completed. Advanced CI Merit fnc in-process
- M2.2 CFD and Fuels: four fuels modeled and recommendation made. iB55
- M2.3: Multi-Mode Controls
  - GCI_01 Multimode engine controls setup on engine in dyno,
  - GCI_02 in-process
- M2.4: Multi-Mode Engine testing, GCI_01 testing on low-load complete. GCI_02 planned next
- M2.5 Go/No Go: High confidence hardware will meet program targets 150hP@4500rpm & 15% in simulated FTP75 fuel economy over baseline.
  - 25% ΔBTE if we employ 8AT and downsizing as well as start-stop.
  - 40% ΔBTE if we use iso-butanol 55% fuel mixed with RON60.
  - 51% ΔBTE if we combined iB55 GCI with Hybrid system (80kW motor, 8Ah batter)

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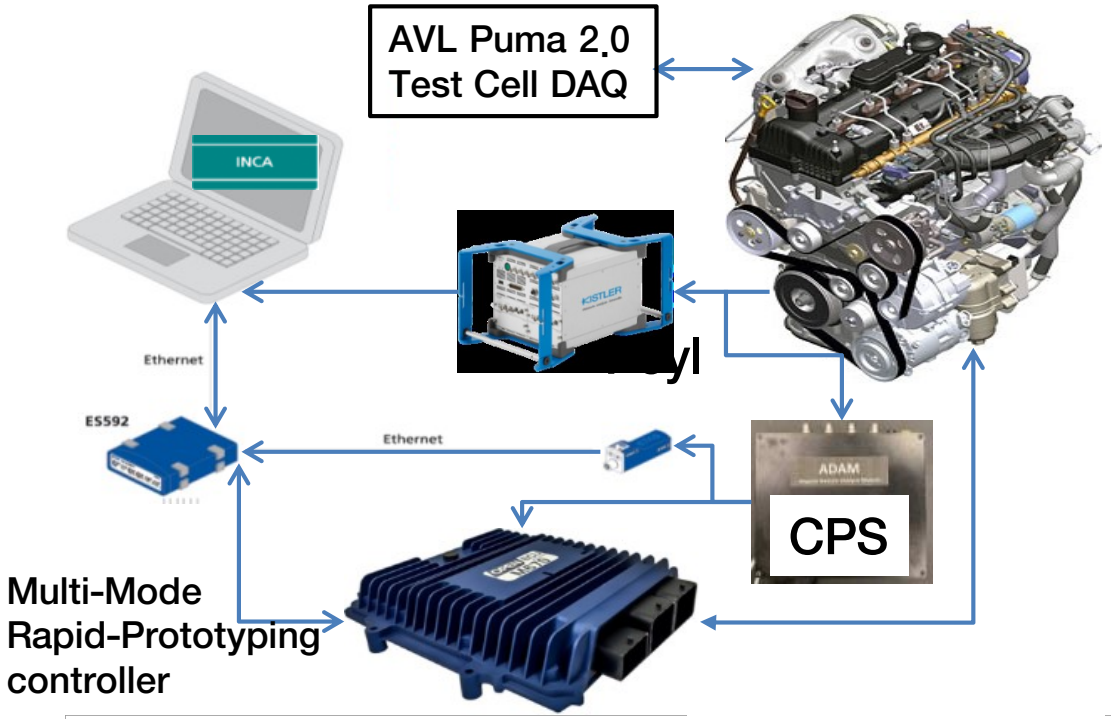
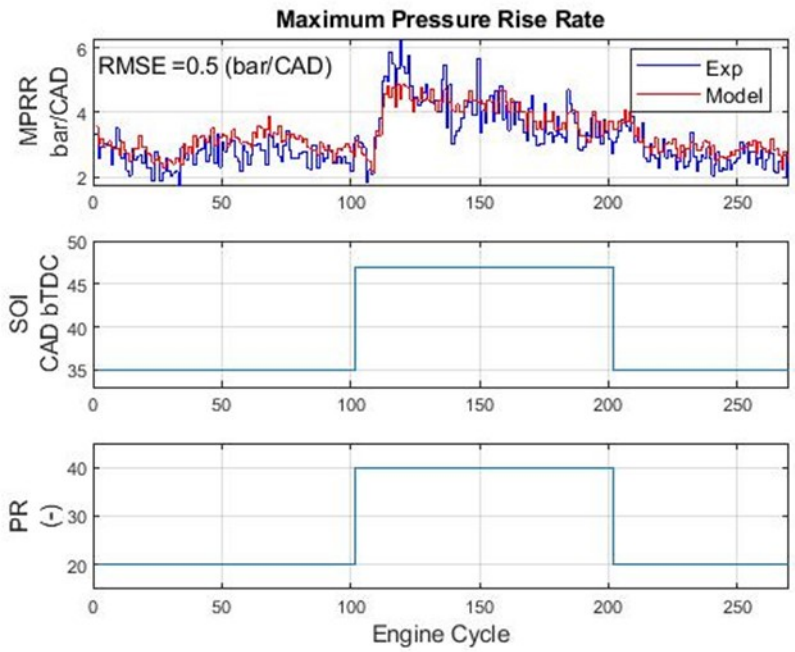
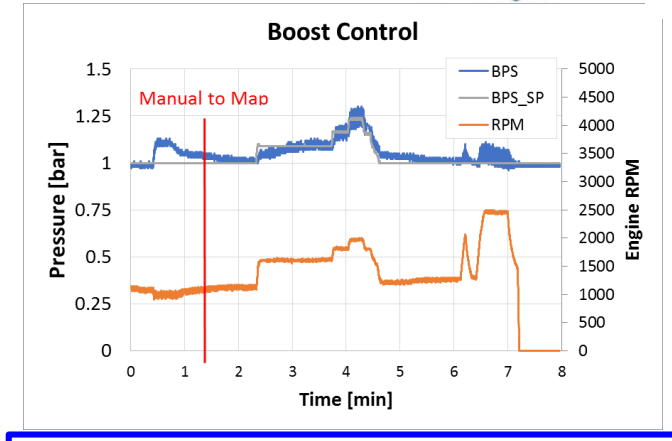
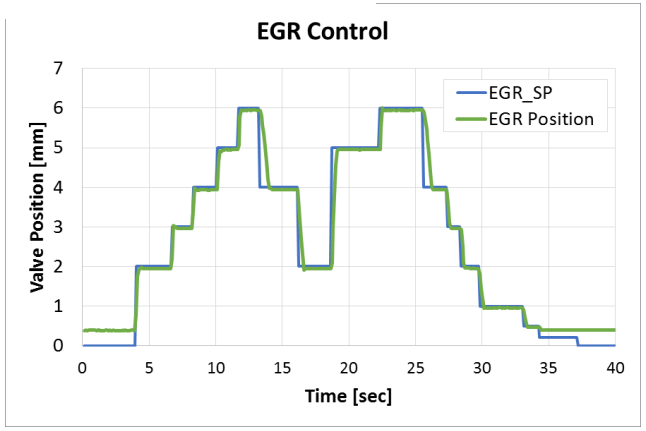
# Technical Back-Up Slides

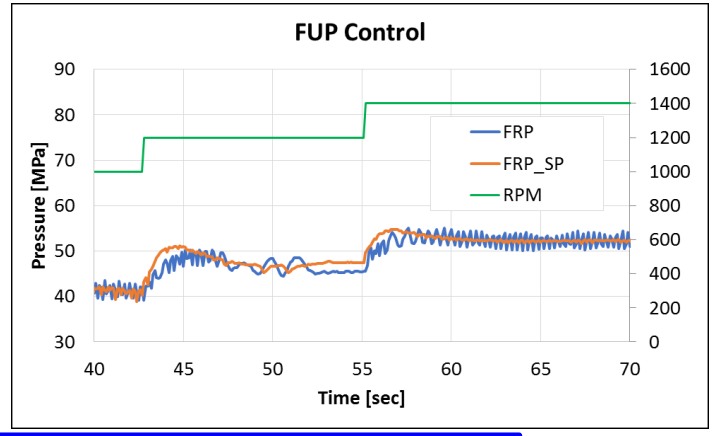
# ADVANCED ENGINE CONTROLS



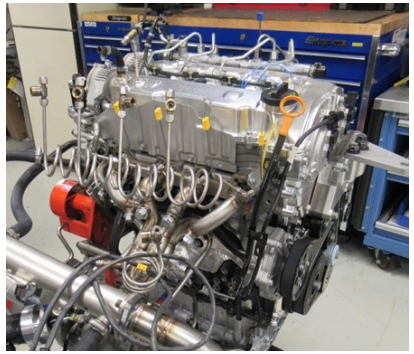



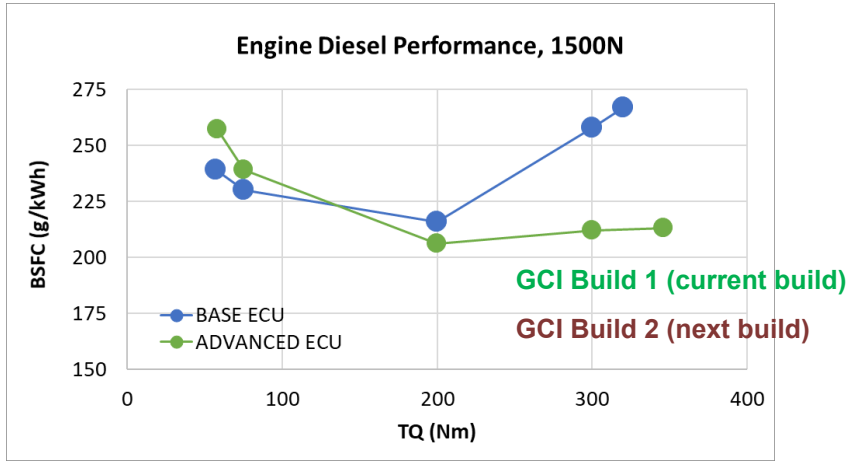

M2.1: 1st Generation Multi-Mode Rapid-Prototyping controller has been developed & commissioned

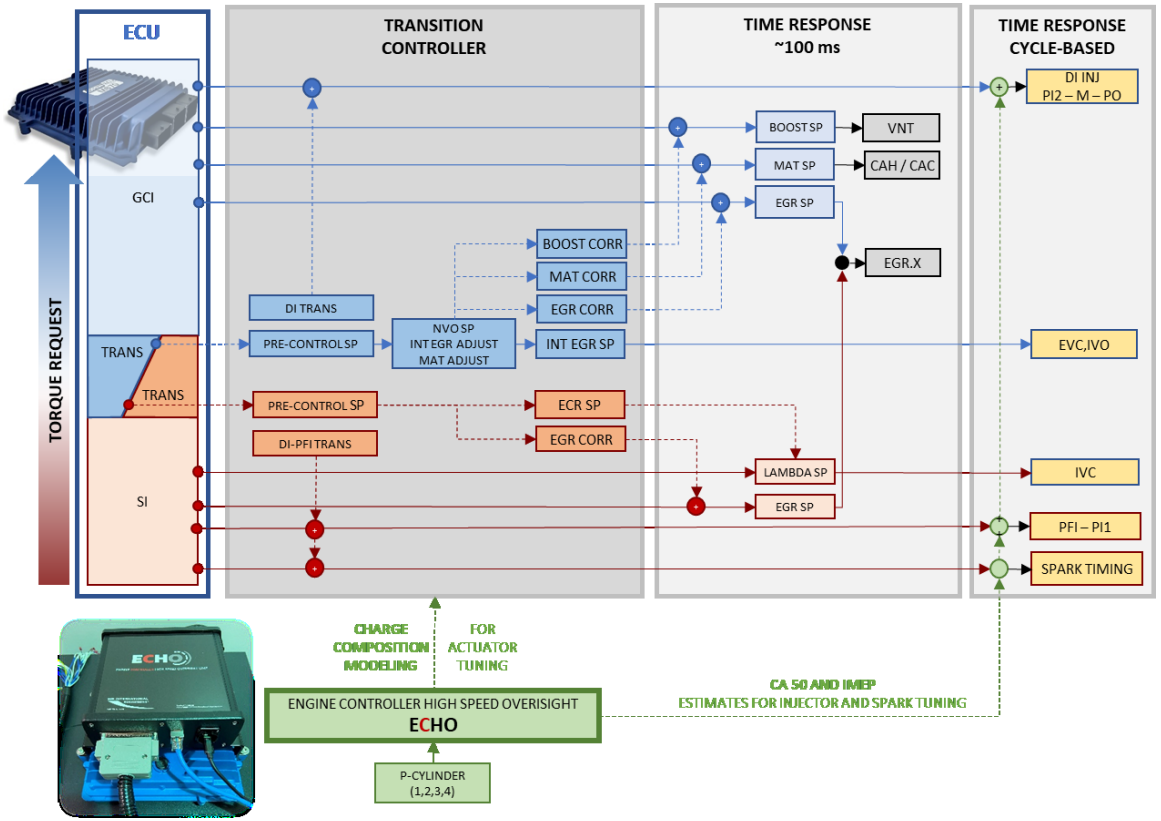
# ENGINE CONTROLLER AND MODE SWITCH OVERVIEW

**BASE 2.2L Diesel ENGINE**
**and production controller**



**ADVANCED 2.2L ENGINE**
**with WMI ECU and ECHO**
**and MODEL BASED CONTROLS**

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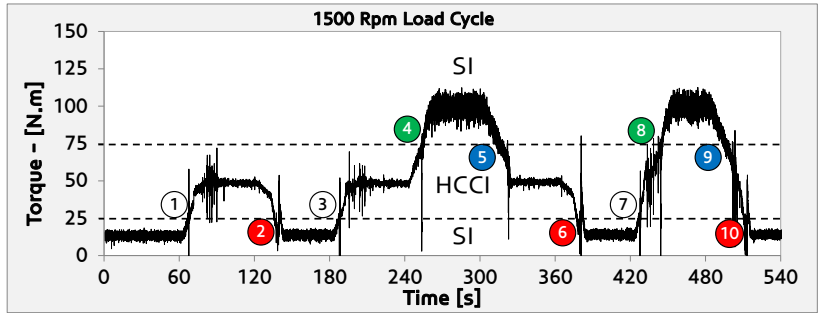
# MODE-SWITCHING – ADVANCED CONTROLS

Challenge:

- ❑ SI to GCI mode switch is challenging
  Boundary conditions required for each mode different. Ex. AFR and boost, intake temp and fuel pressure

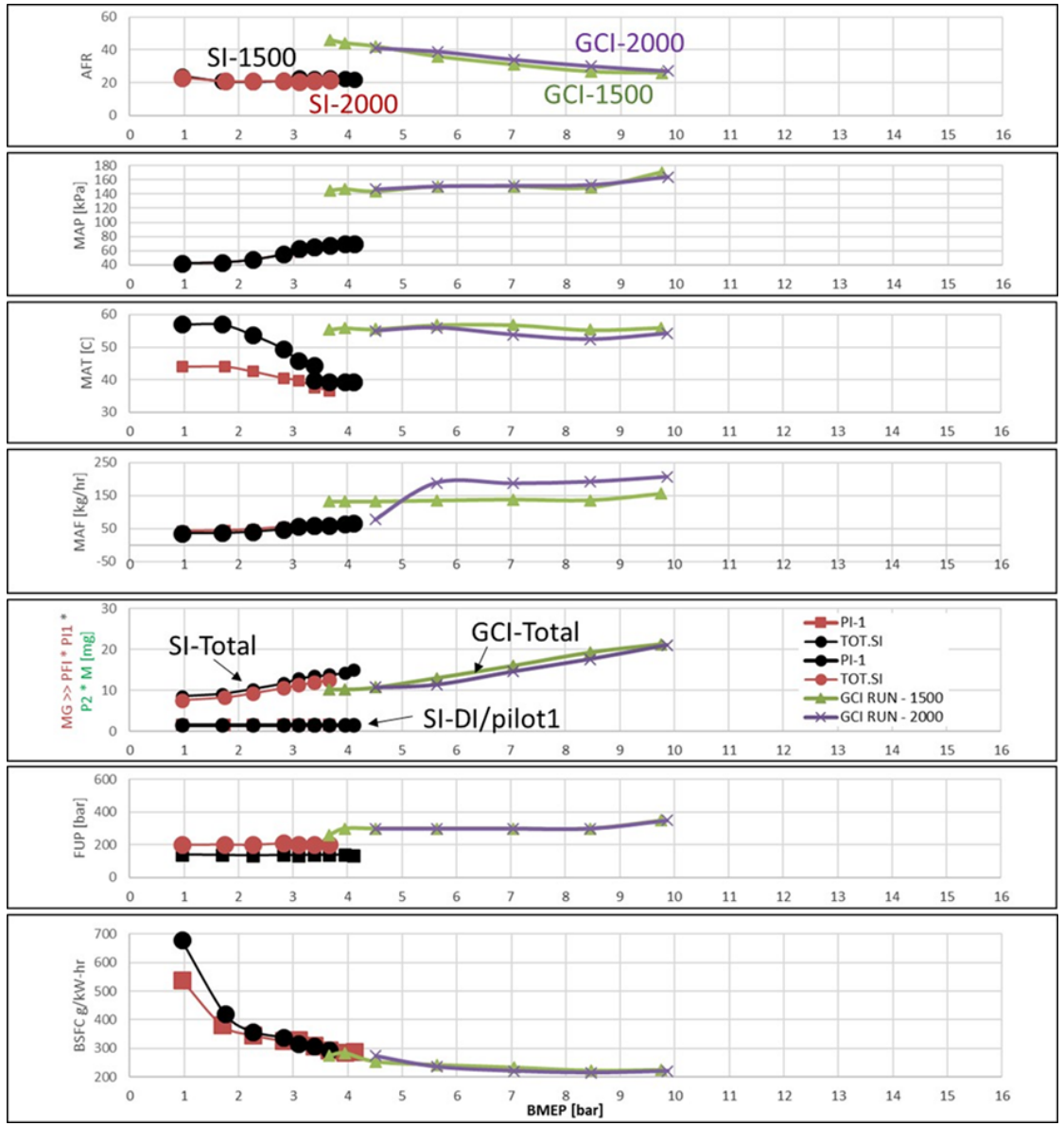
- ❑ Mode switch results in misfire and torque drops.




Approach:

- ❑ Development of in-cylinder condition estimators: EGR, temps, check to see if in-cylinder reactivity is sufficient for GCI

To avoid torque drops during mode-switch => Advanced Mode Switch Algorithm development needed

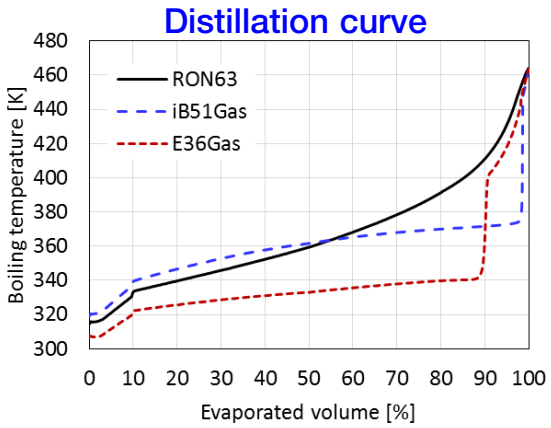


# GCI MERIT FUNCTION

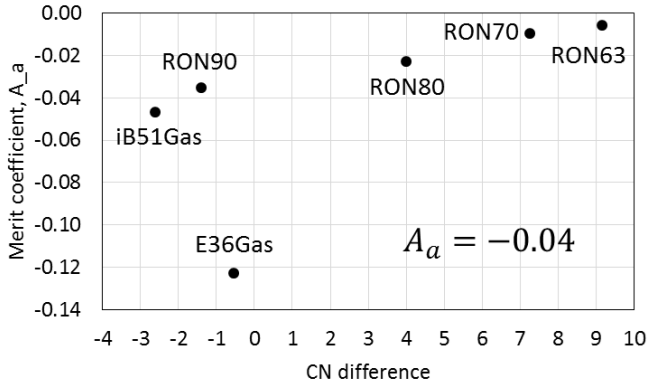
$$Merit = 100 \times \frac{\eta - \eta_{ref}}{\eta_{ref}} = \frac{\Delta\eta_b}{\eta_b} = \sum_i \frac{1}{\eta_b}\frac{\partial \eta_b}{\partial p_i}(p_i - p_{i,ref})$$

$$= A_a(CN_{mix} - A_b) \quad + B_a(T_{80} - B_b) \quad + C_a\left(\frac{HoV_{fuel}}{AFR+1} - \frac{415}{15.0}\right)$$

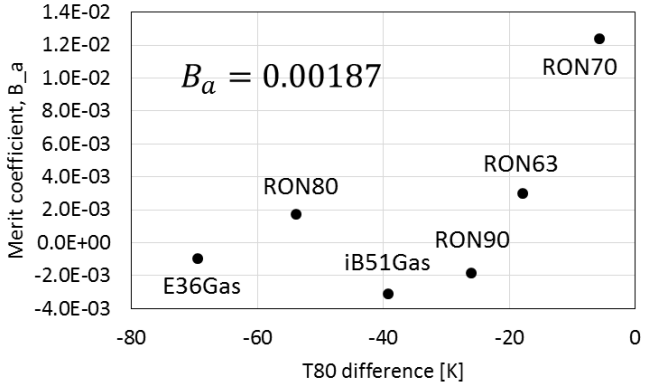
Fuel reactivity effect | Distillation temperature effect | Evaporation cooling effect



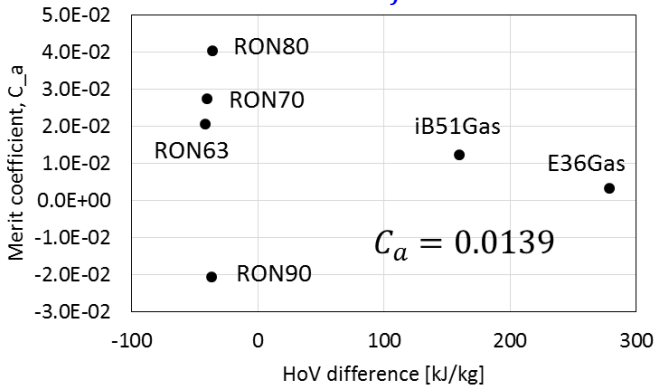

$$A_a = \frac{1}{\eta_b}\frac{\partial \eta_b}{\partial CN_{mix}}$$




$$B_a = \frac{1}{\eta_b}\frac{\partial \eta_b}{\partial T_{80}}$$




$$C_a = \frac{1}{\eta_b}\frac{\partial \eta_b}{\partial HoV_{fuel}}(AFR + 1)$$

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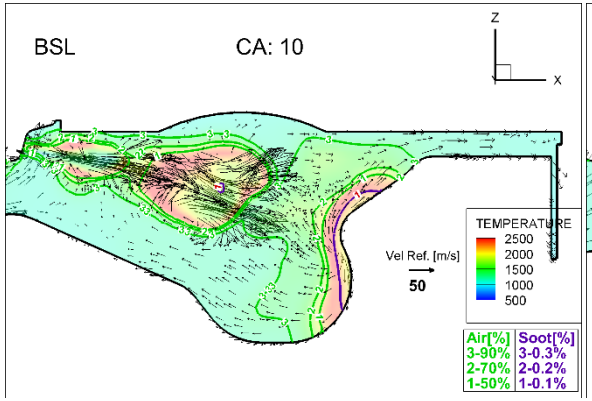
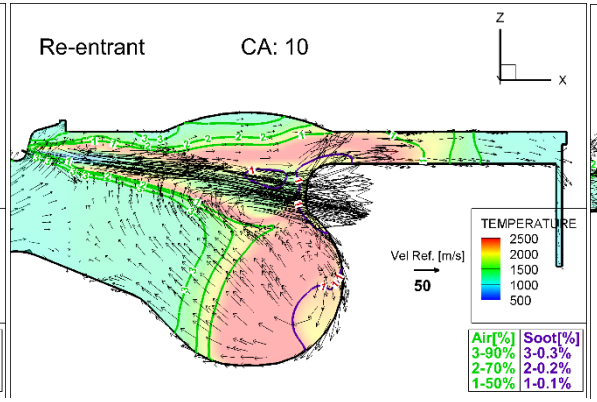
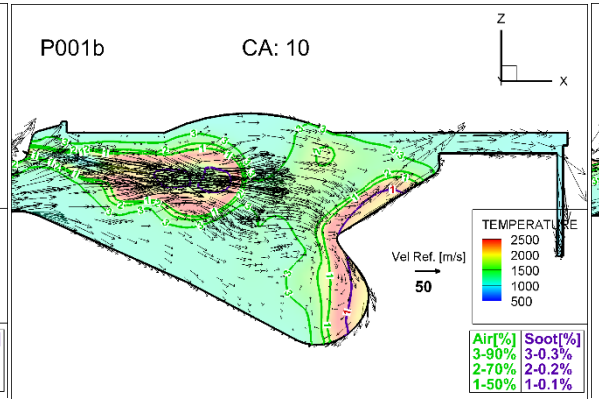
GCI Merit function is in process of being formulated.

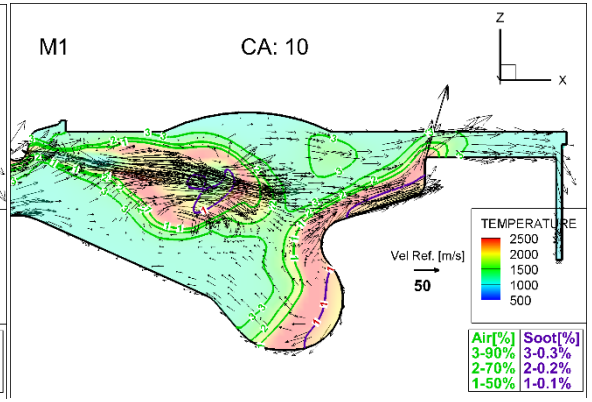
- Three fuel properties are considered; Cetane number (CN), Boiling temperature at 80% volume evaporated (T80), and heat of vaporization (HoV).
- The reference fuel is E10RD587 which has an octane number of 87.
- Merit coefficients were obtained by the average of normalized sensitivity of all the cases for each fuel property.
- E35Gas is an outlier in CN sensitivity.
- RON70 is the least volatile fuel and E36Gas is the most volatile fuel.
- RON90 is an outlier in HoV sensitivity.

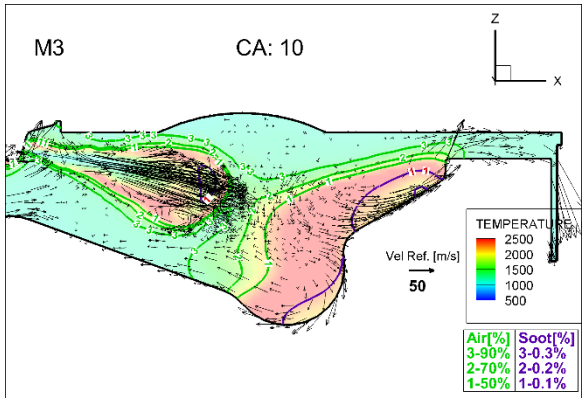
# PISTON OPTIMIZATION- GCI HIGH LOAD




| Piston | Speed [rpm] | IMEP [bar] | Pmax [bar] | PRR_max [bar/deg] | ITE | Δ Soot [%] in g/kwh | Δ NOx [%] in g/kwh | Δ HC [%] in g/kwh | Δ ITE |
|---|---|---|---|---|---|---|---|---|---|
| BSL | 4500 | 20.4 | 166 | 18 | 41.5% | BSL | | | |
| Re-entrant | 4500 | 20.1 | 165 | 16 | 40.9% | -13% | -24% | -59% | -1.5% |
| P001b | 4500 | 20.6 | 169 | 18 | 41.8% | -23% | 8% | -71% | 0.8% |
| M1 | 4500 | 20.6 | 169 | 17 | 41.8% | -25% | 4% | -69% | 0.7% |
| M3 | 4500 | 20.6 | 168 | 17 | 41.9% | -18% | 9% | -57% | 0.9% |

**3D CFD Modeling for 4500rpm/18bar, E10 Fuel, 1000bar FUP**

- **4 piston bowl concepts evaluated & compared to BSL**

M1.5: 3D CFD Optimized GCI showed ~70% HC reduction and ~ 20% soot reduction with similar ITE

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