ASME
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Internal Combustion Engine Fall Conference

Evolution of Light-duty Gasoline Compression Ignition (LD-GCI) for High Efficiency and Near-zero Emissions

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ASME Future of the Internal Combustion Engine Webinar Series
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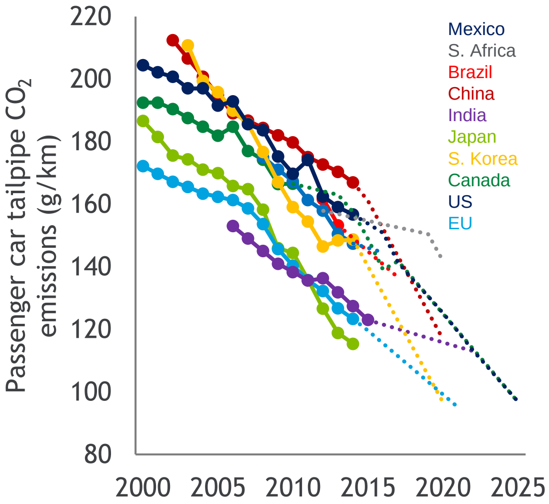
Contents

- ICE Challenges and Opportunities
- Engine Concept & Subsystems
- Simulation Results
- Engine Test Results
- Summary & Conclusions

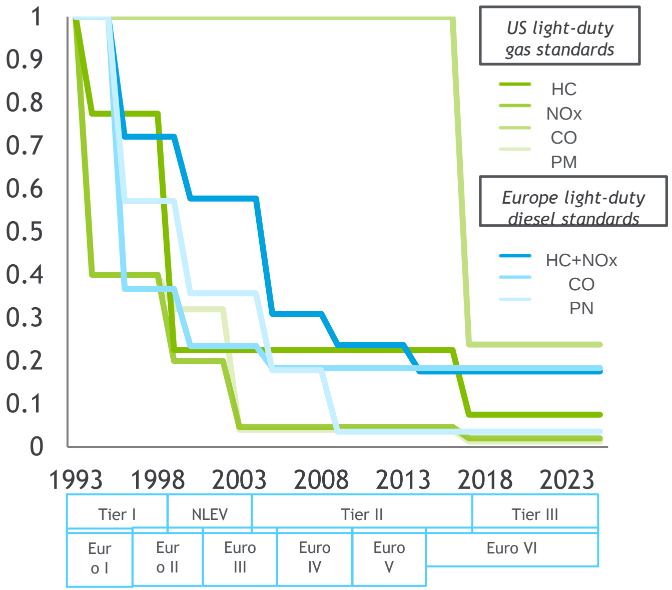
Light-Duty Vehicle Challenges Worldwide – CO_2, Criteria Pollutants, and Fines

- Regulations for GHG & criteria emis are main drivers to develop future & alt. powertrain technology
- Threats include BEVs, diesel demonization, ICE bans & reduced ICE investments

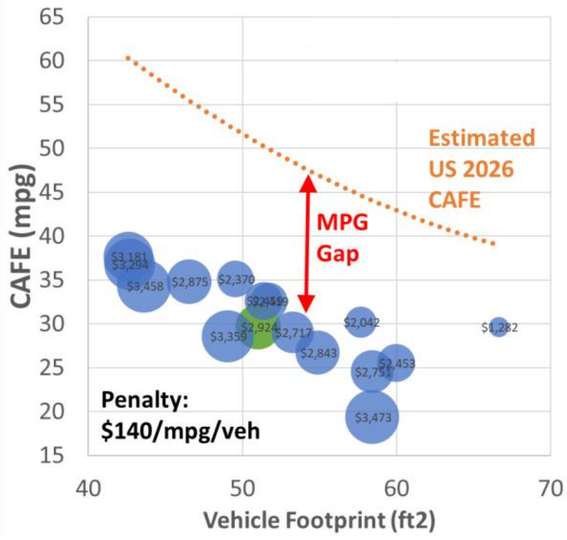
Tank-to-Wheel CO_2 Emissions*



Tailpipe Criteria Emissions



Est'd CAFE Penalties (2026)



*Source: adapted from 2017 Global update: Light-duty vehicle greenhouse gas and fuel economy standards (ICCT)

Light-Duty Vehicle Challenges Worldwide – CO_2, Criteria Pollutants, and Fines

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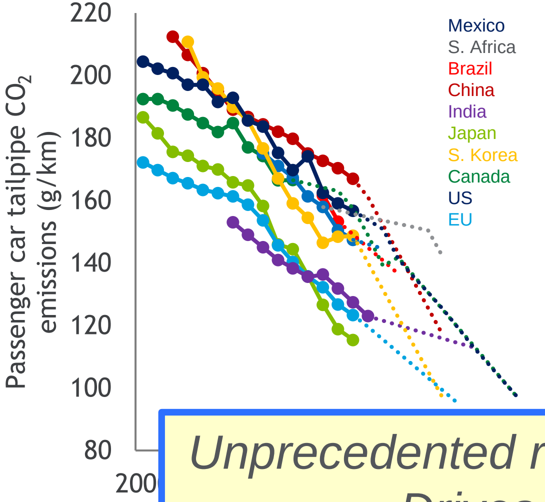

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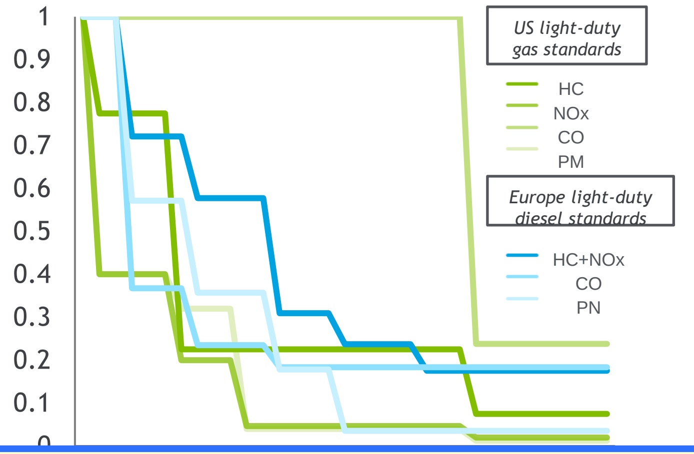

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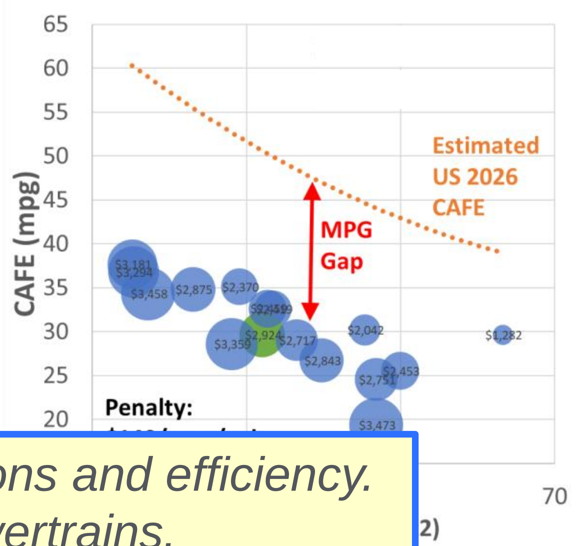

Unprecedented regulatory pressure on ICE emissions and efficiency. Drives the need for greatly improved powertrains.

*Source: adapted from 2017 Global update: Light-duty vehicle greenhouse gas and fuel economy standards (ICCT)

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Future Internal Combustion Engines

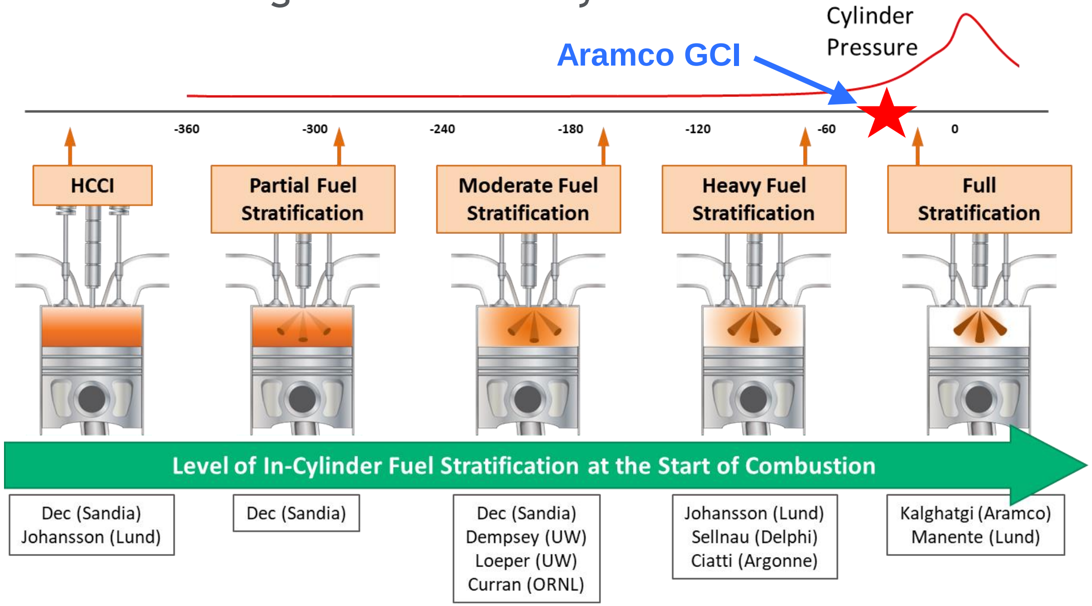
- >45% Brake Thermal Efficiency
- Near-zero Criteria Emissions (NOx, PM, HC, CO)
- Hybridized for low CO_2 Emissions on the Drive Cycle
- Compatible with Future Synthetic Low-carbon Fuels

Program Technical Goals- Light-Duty GCI

- 48% BTE (equivalent $BSFC_{E00}$ 174 g/kWh)
  - 40% BTE over wide speed-load range
- +90% fuel economy (MPG) relative to SI-turbo baseline (large SUV & pickups)
  - Reduced fuel consumption & CO_2 emissions by 35%
- Near-zero criteria emissions
  - US 2025 Tier3-B30 & Euro7 RDE compliance
- “Robustness” comparable to modern diesel engines (comb. & controls)
- Diesel-like torque and power
- Cost & complexity reduced relative to Euro7 diesel

Spectrum of GCI Strategies

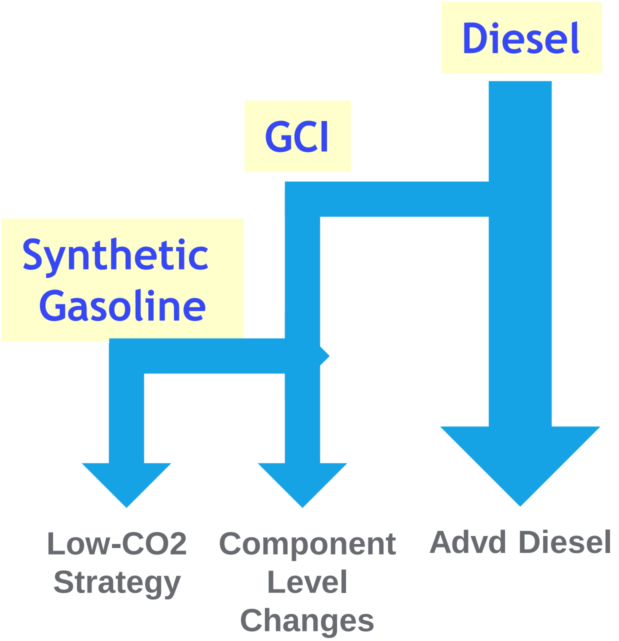
- Various GCI modes or strategies have been investigated in recent years
- Characterized by the level of fuel-air stratification prior to SOC
- Controlled by the injection process (timing, split, pres.)
- Aramco GCI is generally more stratified
  - Late injection (not premixed)
  - Shorter injection dwell
- Benefits
  - Most robust
  - Less sensitive to ext. factors
  - Higher efficiency



Splitter, D., et al., SAE 2015 GCI Symposium

"Fuel Agnostic" Powertrain

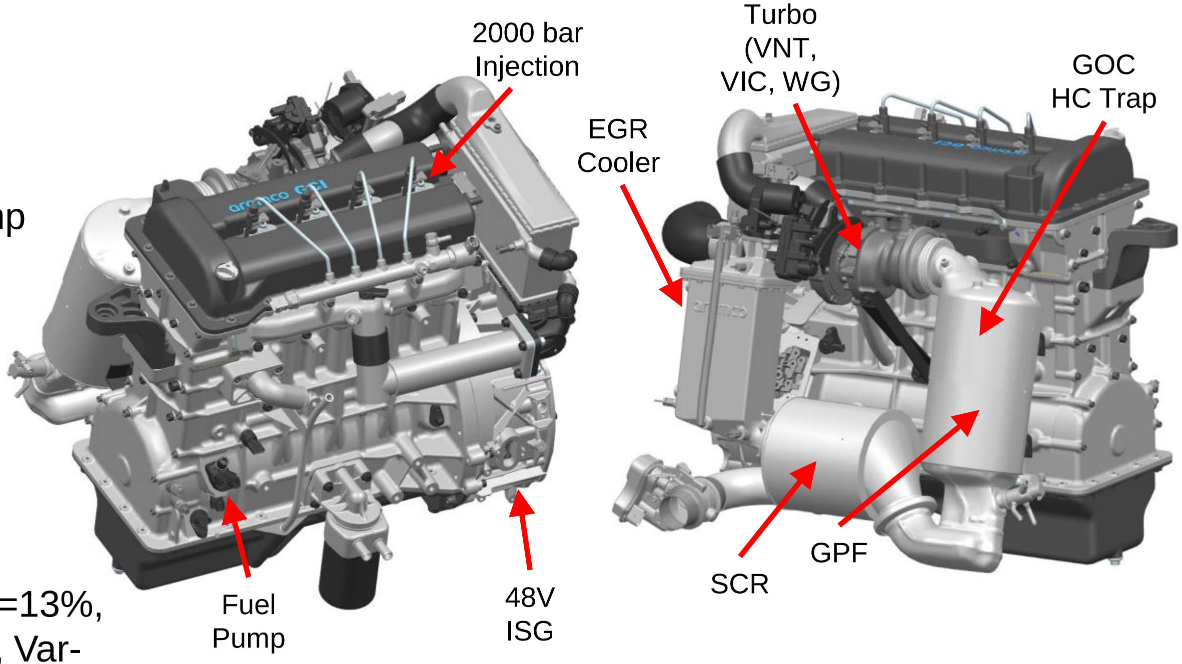
- Concept: a powertrain platform that is compatible with various fuels
- Platform: Existing diesel – diesel conversion
- Fuels: diesel, gasoline, synthetic fuels, CH_4, H_2
- Benefits:
  - Sales adaptable to fuel trends
  - Lower total cost of ownership (TCO) for fleets
  - Longer-term, low-CO_2 strategy using synthetic gasoline



Low-cost, low-risk commercialization pathway for GCI

Light-duty GCI Engine Concept (2.6L L4)

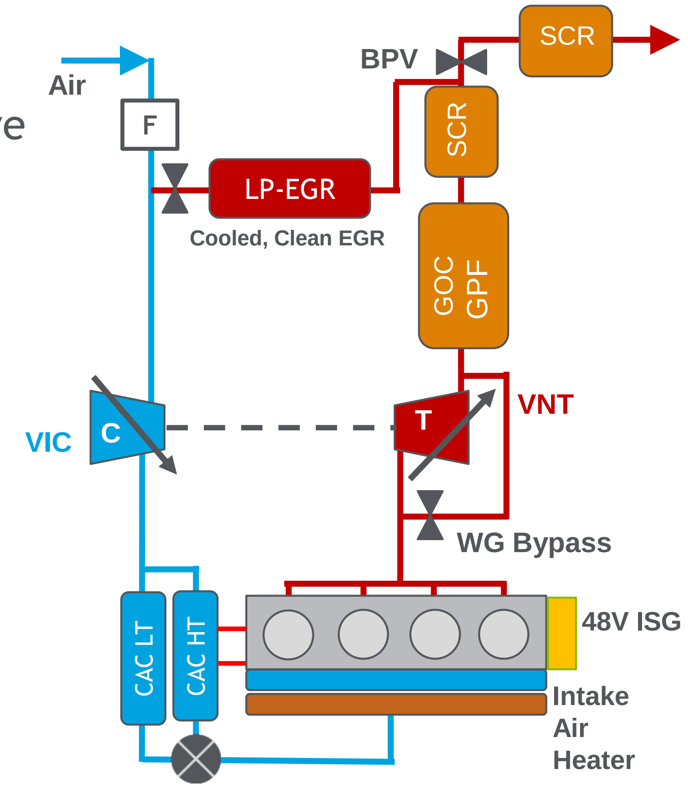
- PPCI-Diffusion Comb System (low NOx & smoke at all loads)
- High-Pres Fuel System (2000 bar)
- Adv Turbo with VNT, Var. Inlet Comp (VIC), & Waste Gate Bypass
- 2-Step Exhaust Rebreathing
- Fast Cold Start System
- Adv Aftertreatment w/LP-EGR
- 48V P1/P2 Mild Hybrid for braking energy recovery
- Base Engine CR=17, S/B=1.5, CO=13%, Th. Barrier Coatings, PCP=230bar, Var-Displ Oil Pump, Wet-belt Cam Drive



Addressing all fundamental loss mechanisms (comb, HT, friction, pumping)

Engine Architecture

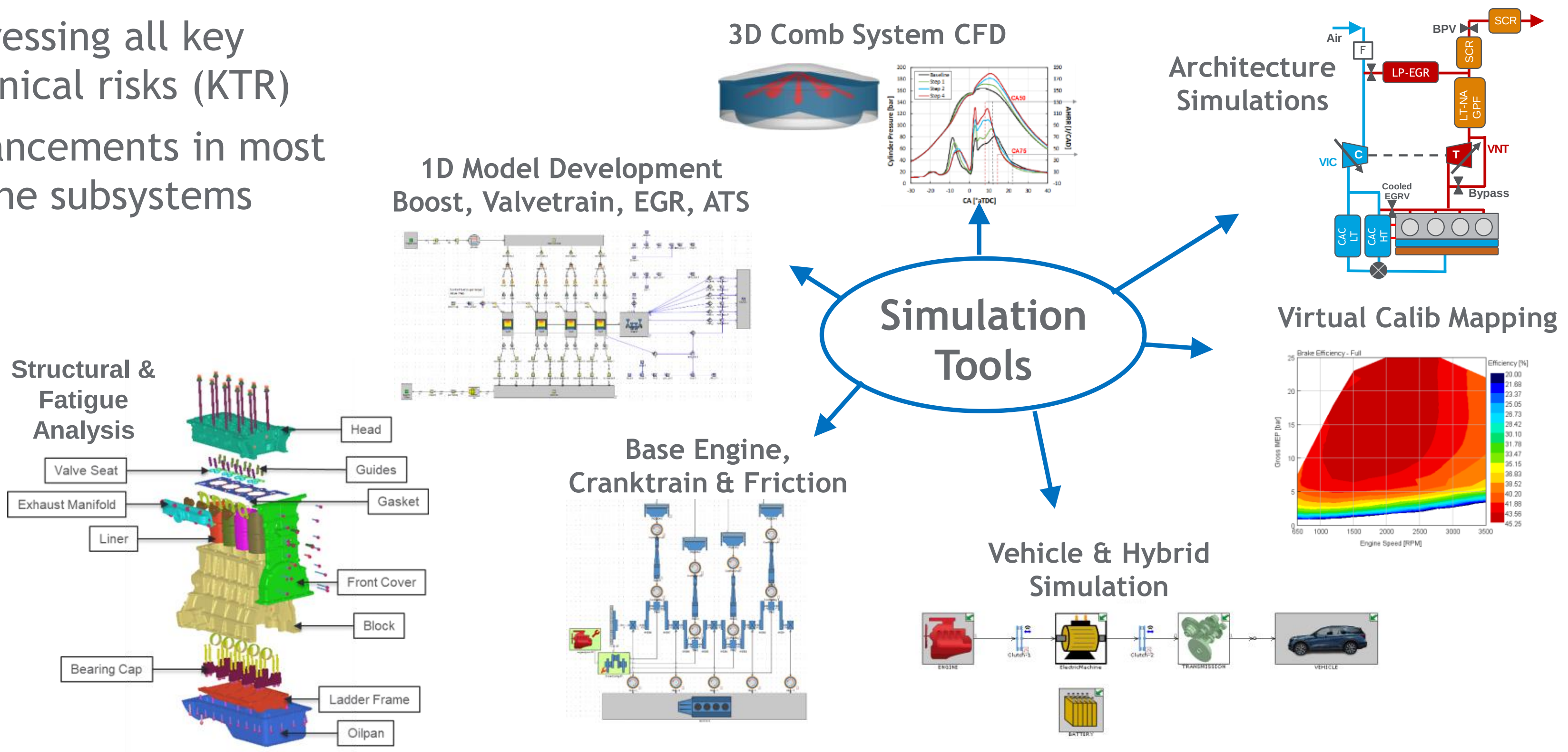
- Single-stage Turbo (VNT, VIC, WG)
- Fast IAT Control – Dual Charge Coolers w/ Blend Valve
- Fast Elect. Intake Air Heater (IAH)(Cold Start only)
- LP-EGR Only (clean feed stream post ATS)
- Lean Aftertreatment System
- 48V P2 Integrated Starter Generator (MHEV)
    - Braking Energy Recovery
    - Transient Torque Assist
    - Cold Start load



Relatively simple powertrain that uses existing production components

Extensive Use of 1D & 3D Simulation Tools

- Addressing all key technical risks (KTR)
- Advancements in most engine subsystems

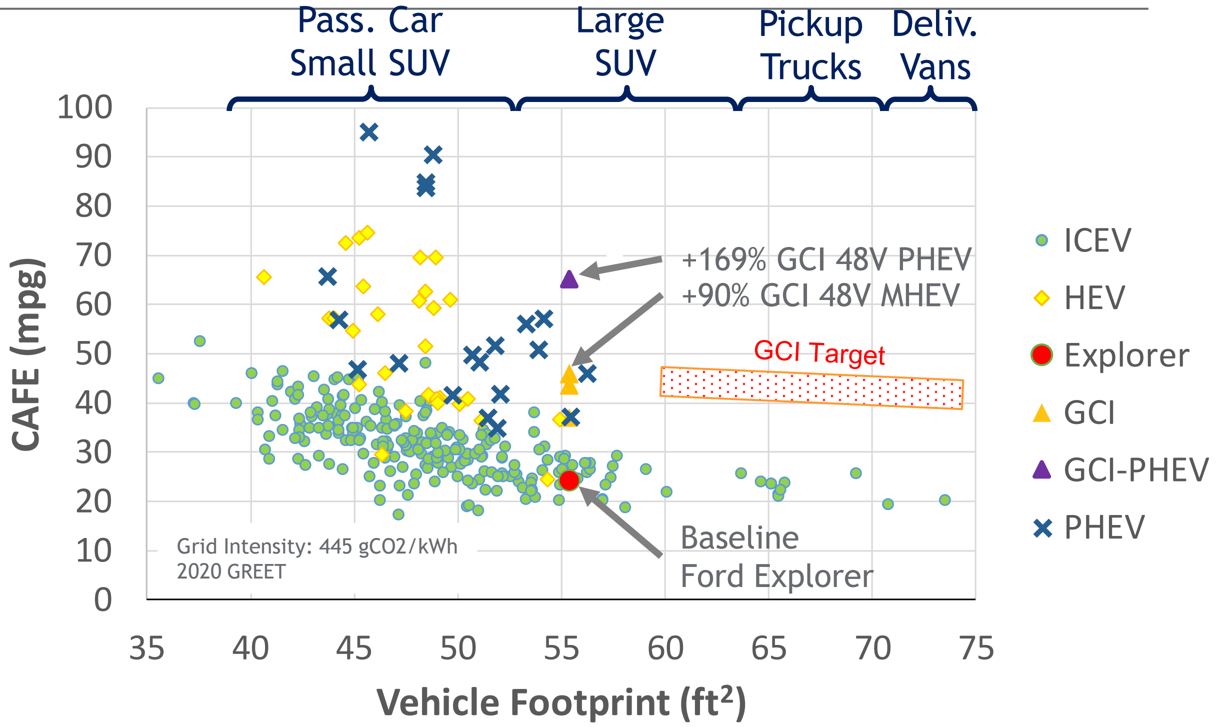


Classification: Public Information

CAFE– US EPA 2018 Database with Advd GCI Vehicle

- Simulated 2.6L Adv GCI engine in a large SUV 4500lb test wgt.
- +90% MPG with 48V MHEV
- +169% MPG with 48V PHEV
- Fuel economy for large SUV & LT in US fleet is poor

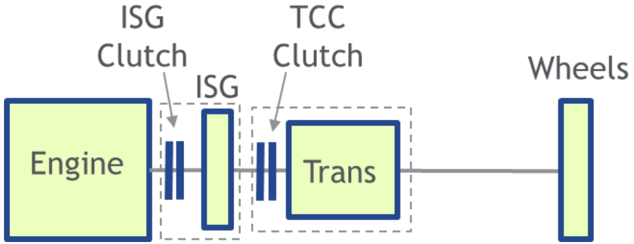
- Targeted Market Segments (previously pass. car)
  - Large SUV, Light trucks, Delivery vehicles

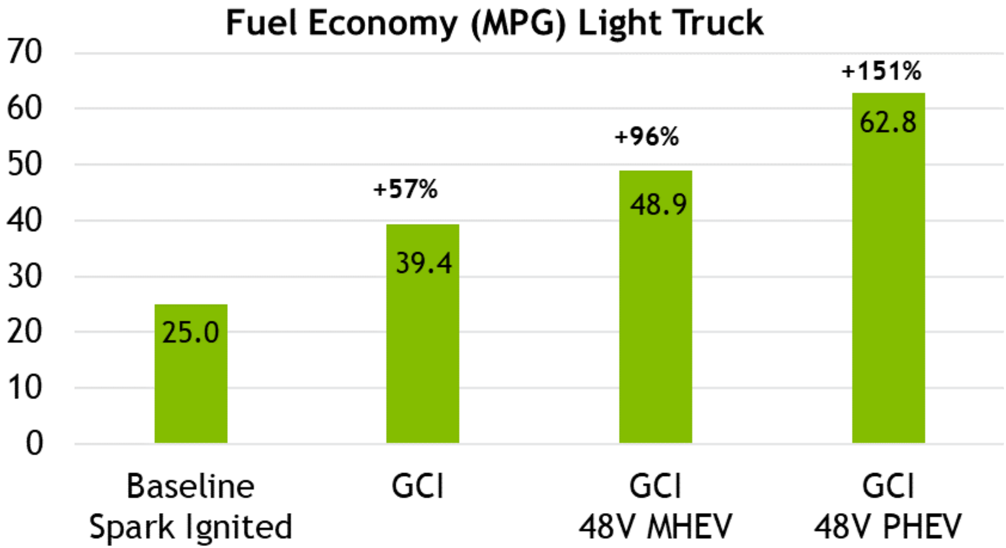


GCI technology with 48V MHEV greatly improves CAFE for large SUV & trucks.

Simulated Fuel Economy: 1500 Pickup

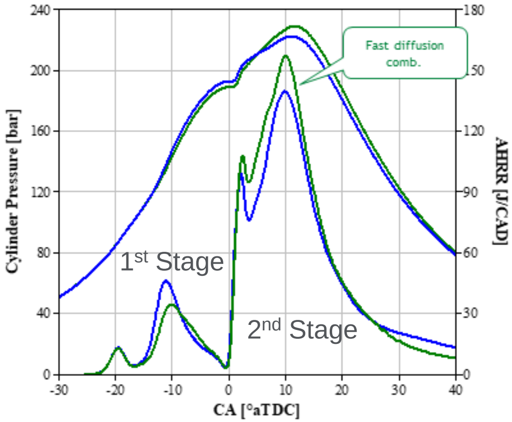
- Engine: Adv GCI 3.9L L6 - 48V P2 MHEV
- Drive Cycle: US FTP City/Hwy Combined
- Baseline: 5.7L SI V8

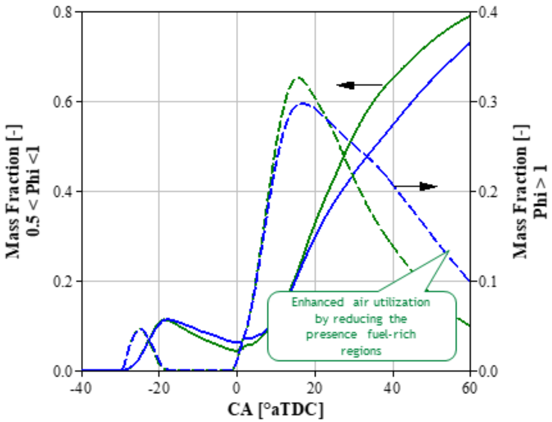




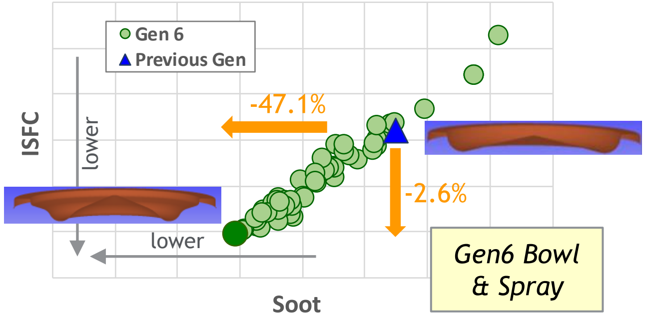
PPCI-Diffusion Combustion Process

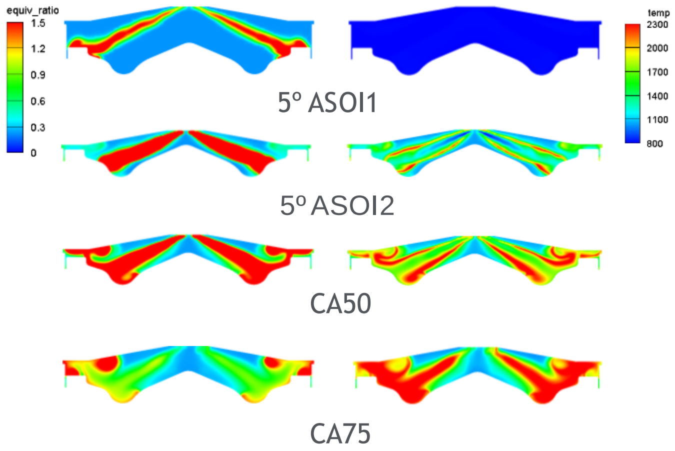
- 2-stage PPCI-Diff combustion process
- HR tailorable for optimum effic., emis., noise
- Combines high inj. pres. & rate with high Pcyl
- Fast diffusion comb., favorable comb. phasing, and reduced rich parcels late in comb. process
- CFD simul. to opt. inject., spray, and bowl (Gen6)





Gen6 Optimization: 70 Bowl-Spray Design Candidates





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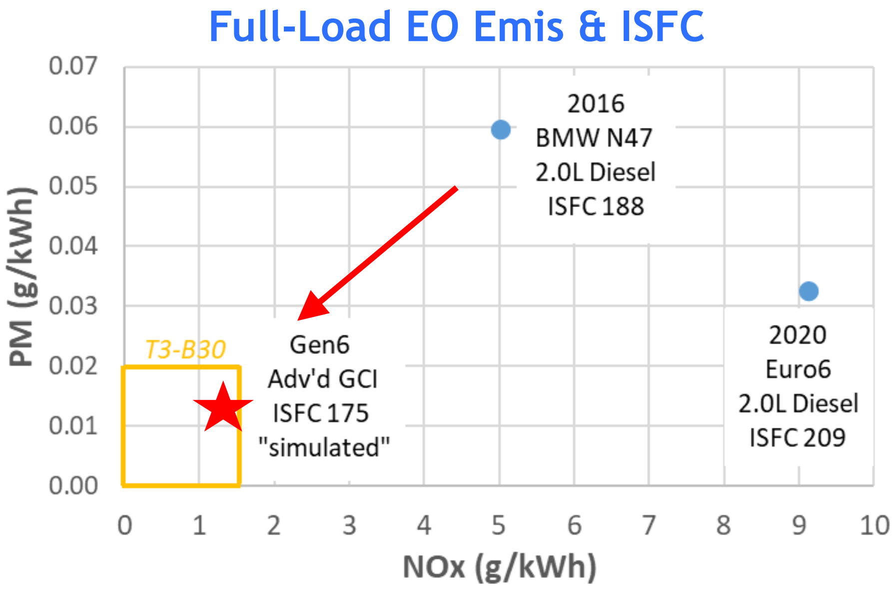
Competitive Assessment – Full Load

- Advanced GCI with Gen6 Bowl & Sprays
  - Simulation results
- Relative to production N47 diesel
  - 70% lower NOx
  - 70% lower PM
  - 7% lower ISFC



GCI comb. combined with Adv'd FIE promises very low full-load NOx, PM, & ISFC

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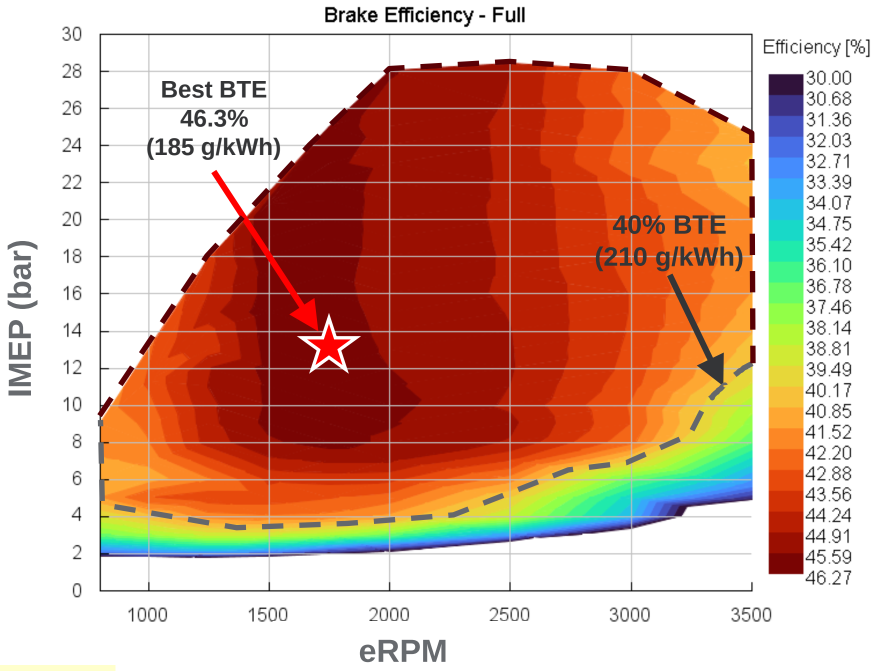
Simulated BTE Map – 2.6L GCI L4

- Simulated BTE map indicates potentials of GCI technology
- Large region BTE>40%
  - Best BTE ~46.3% (on drive cycle)
  - Min. BSFC ~185 g/kWh
- Max Output (simulated)
  - Power: 151 kW (167.5 kW with ISG)
  - Spec. Pwr: 58 kW/l
  - Torque: 522 Nm (>650 Nm with ISG)
  - Spec. Trq: 200 Nm/l
  - BMEP: 25.2 bar



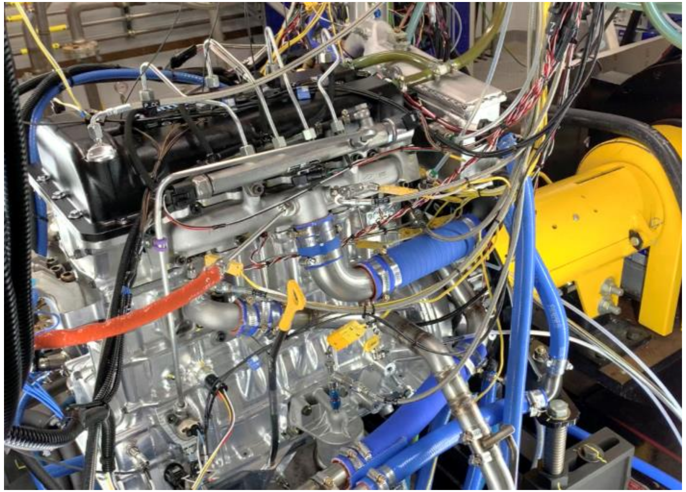
Engine testing & calibration mapping in process

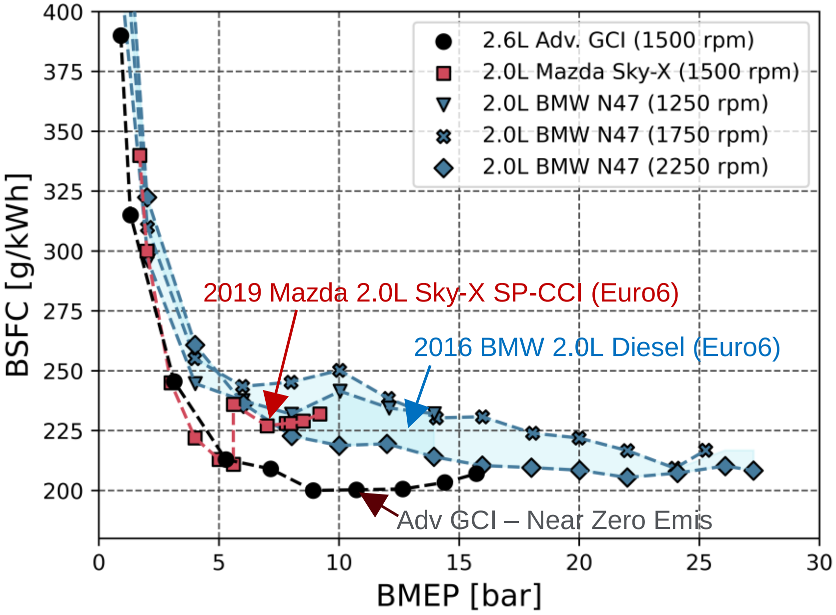
Fuel Consumption- Engine Tests

2.6L GCI L4 on Dyno

- New engine & controls including full aftertreatment
- Gen4 bowl & injector – no TBC (older designs)
- Prelim. calibrations - not considered optimized
- Relative to N47, BSFC was reduced 10-20%

Fuel:	E10 Cert Gasoline
Lube Oil:	0W-30 full synth.
Oil/Water Temp:	90 deg C





M. Sellnau 22Jul22

Classification: Public Information

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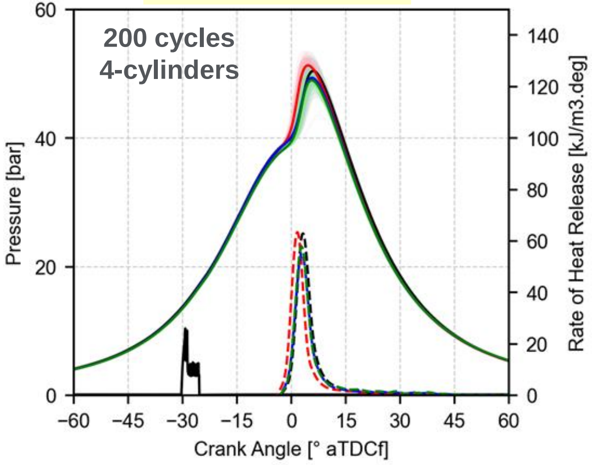
Low-Load Robustness (Rebreathing)

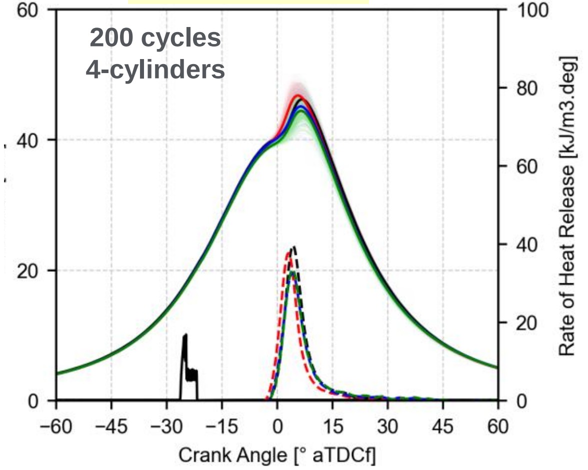
- Exhaust RB & increased IAT strongly promote auto-ignition
- Single-injection with Pinj 155bar
- Stable, quiet, clean comb. with minimal cyl. spread
- High Texh provides high conversion effic. for HC, CO, NOx

IMEP (bar)	1.5	1	0.5
CA50 (atdc)	3.2	4.8	5
STD CA50 (CAD)	0.6	0.8	0.7
T_GOCmid (C)	244	218	132

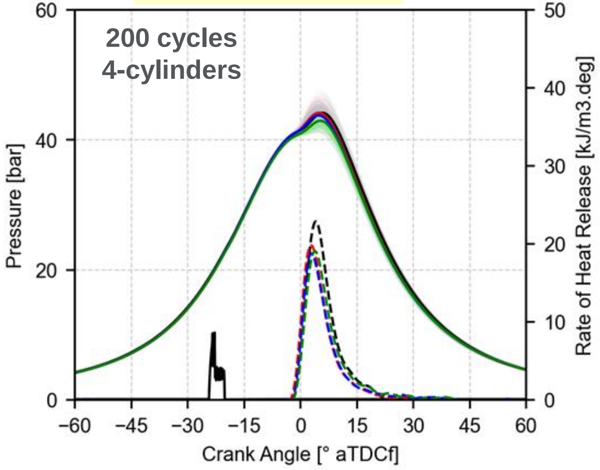
800rpm- 1.5bar



800rpm- 1bar



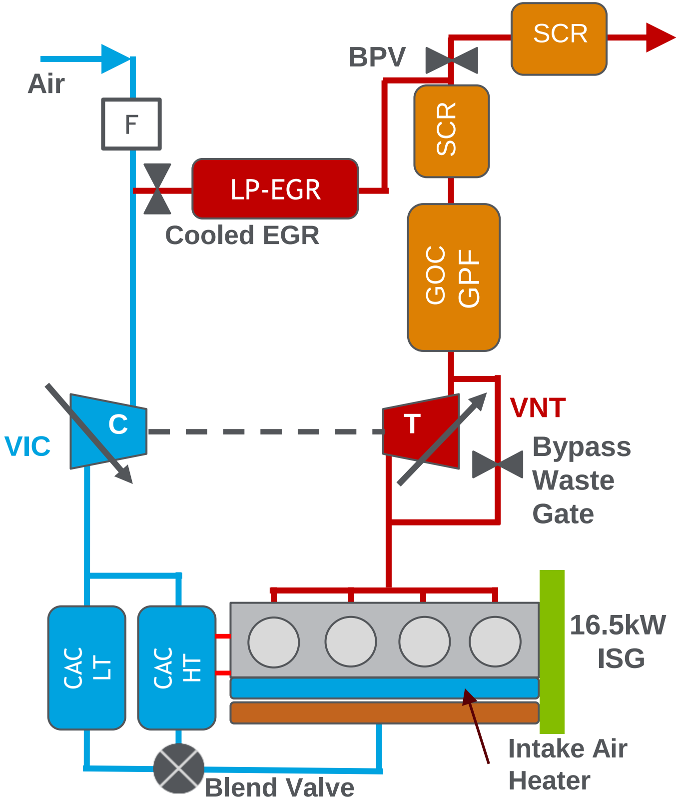
800rpm- 0.5bar



Cold Start Strategy for Fast Catalyst Light-off

SAE 2020-01-1301

- Fast catalyst light-off is required to meet future emissions regulations
- Strategy includes 4 key elements to produce high Texh (>500 C) and high exhaust heat flux (>10 kW)
  1. Increased Load to 6bar IMEP using Integrated Starter Generator (ISG)
  2. Increased Back Pressure to 3 bara using BPV
  3. Intake air heating (IAH) 2.5kW
  4. Turbine bypass for heat conservation (WG open & VNT closed)



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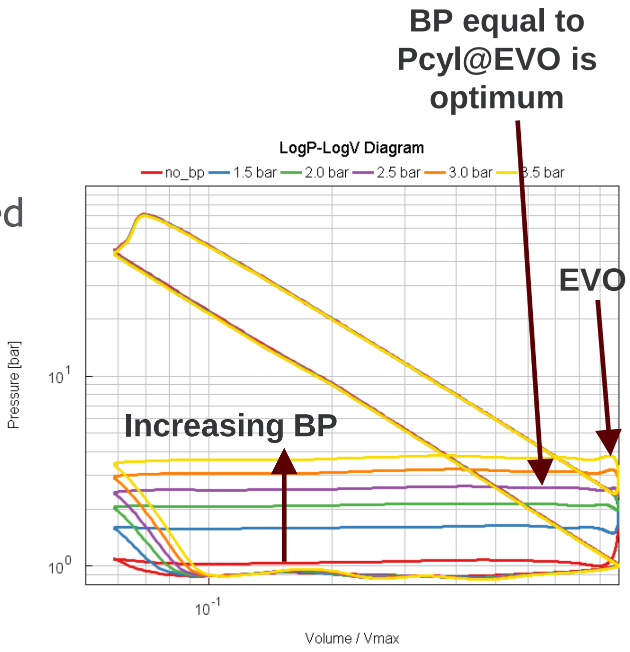
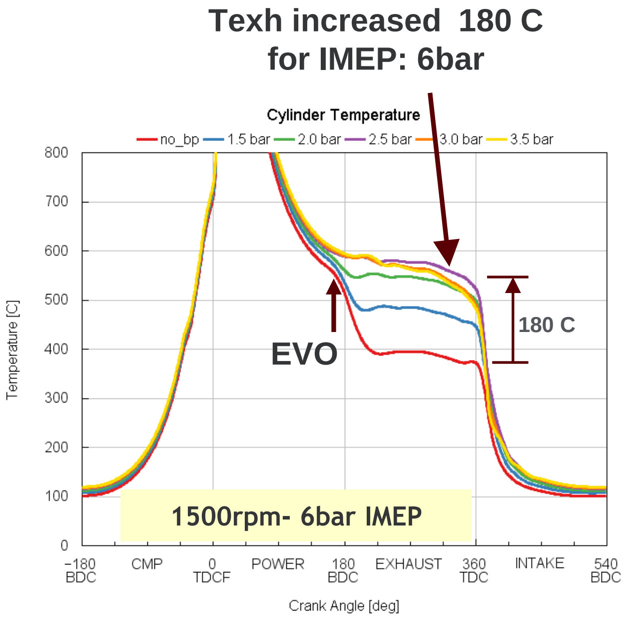
Strong Heating Effect from Increased Back Pressure (BP)

- The production BP valve is used to increase BP on flare up.
- High BP prevents blowdown of hot exh. gases (180 C effect)
- High BP also increases hot residuals (RSG) to promote auto-ignition (AI)



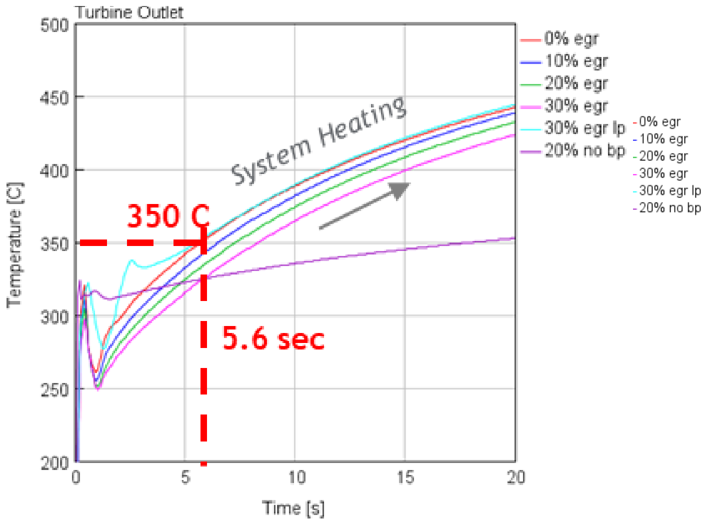


Transient Simulation of Fast Catalyst Light-off

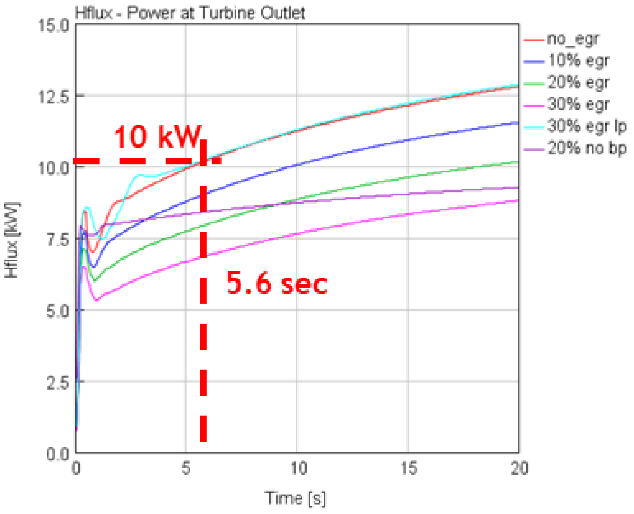
- At 1500rpm- 6bar IMEP, simulation predicts catalyst light-off <6 sec
- Catalyst inlet 350 deg C with 10kW exhaust heat flux
- Similar experimental results observed on dyno engine – in process

Catalyst Light-Off Temperatures
- CO 200 deg C
- HC 350 deg C

Exh Temp at Catalyst Inlet

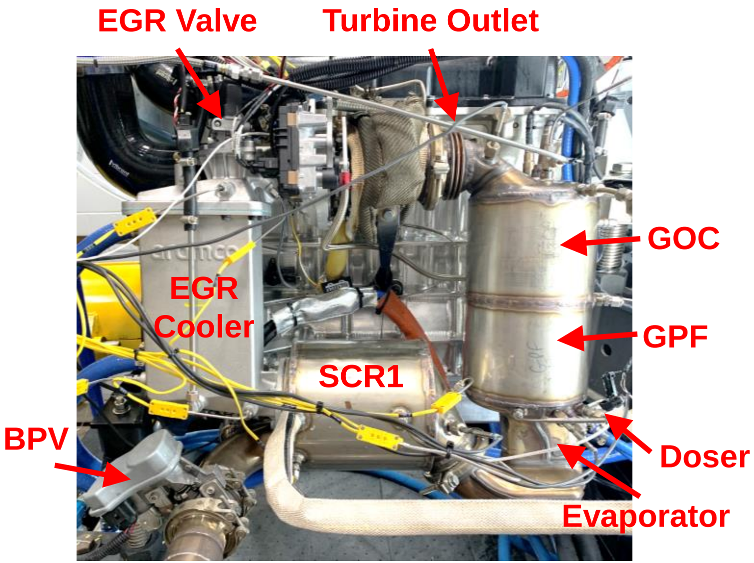


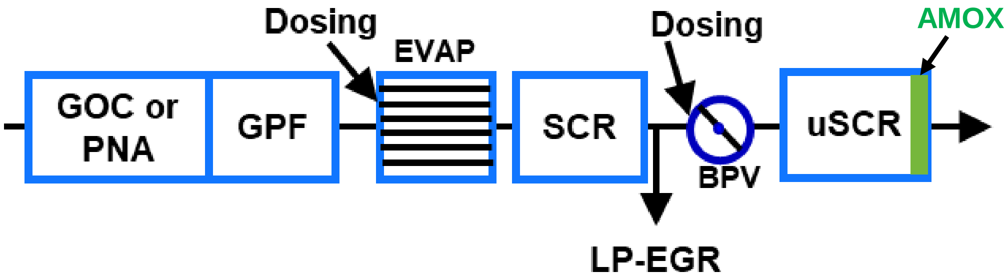
Heat Flux (kW) at Catalyst Inlet



Aftertreatment System

- Compact, close-coupled syst. for fast catalyst light-off
- Low-temp GOC with HC trap & high NO_2 formulation
- Custom GPF - Passive Regen using NO_2
  - Near 100% trapping effic.
- Dual SCR: Close-coupled SCR & underfloor SCR
  - High conv. Effic. over wide temp range
- Targeting 50% of US Tier3- Bin30 regulation





	US Federal T3- B30	TP Targets	EO Targets	Conv Eff. 100% of Std	Conv Eff. 50% of Std
	g/m	g/kWh	g/kWh	%	%
NOx	0.015	0.045	1.5	97.00	98.50
NMHC	0.015	0.045	1	95.50	97.75
CO	1	3.14	60	94.76	97.38
PM	0.003	0.009	0.02	55.00	77.50

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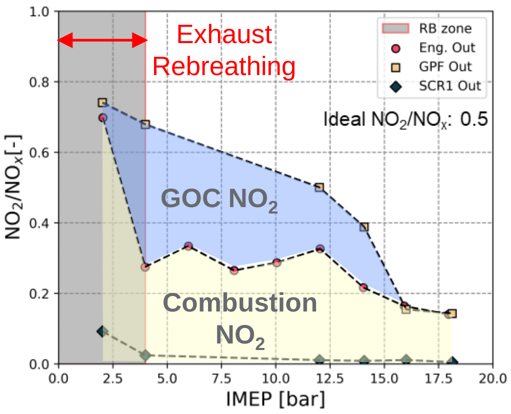
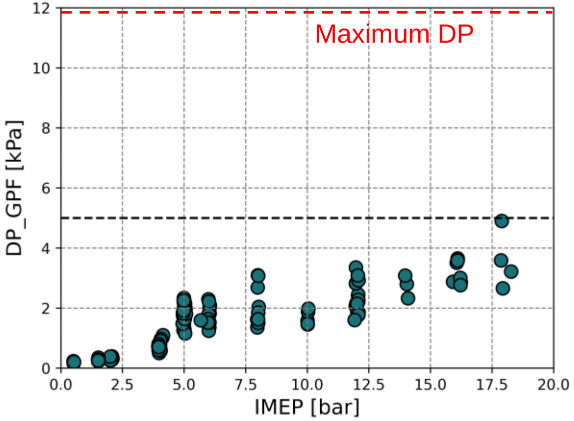
Passive Regeneration of GPF

- NO_2 is a known oxidant for carbon in temp. range 250 to 400 C
- GOC wash coat designed to produce significant NO_2.
- Test data shows ample NO_2
  - from GOC
  - from comb. process
- Enabled "passive only" GPF regeneration for all tests to date
- For SCR, NO_2 greatly improves low-temp conv. effic.
- [N2O] consistently low for all tests

NO_2 Production in System



GPF DeltaP (kPa)

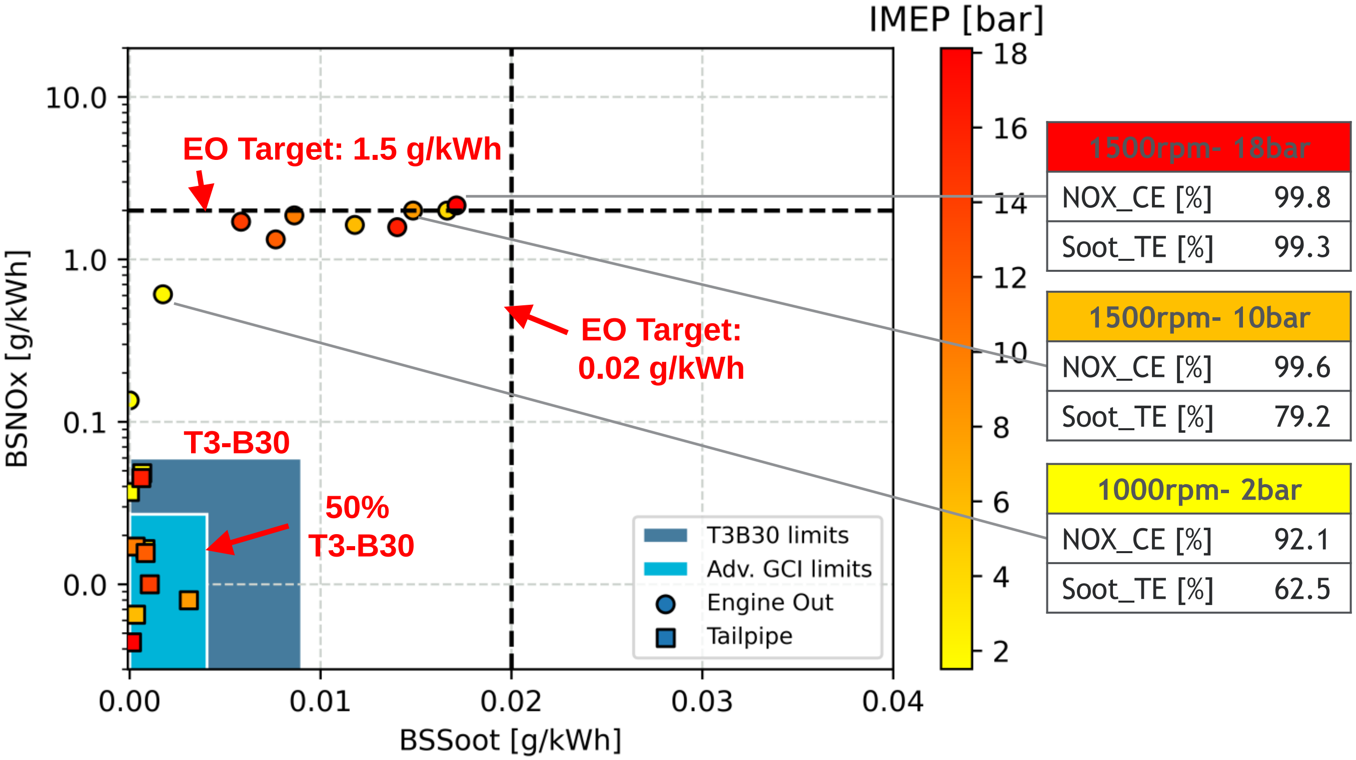


Testing is continuing over the op. map to confirm robust GPF regeneration

Classification: Public Information

Aftertreatment Performance – NOx and PM

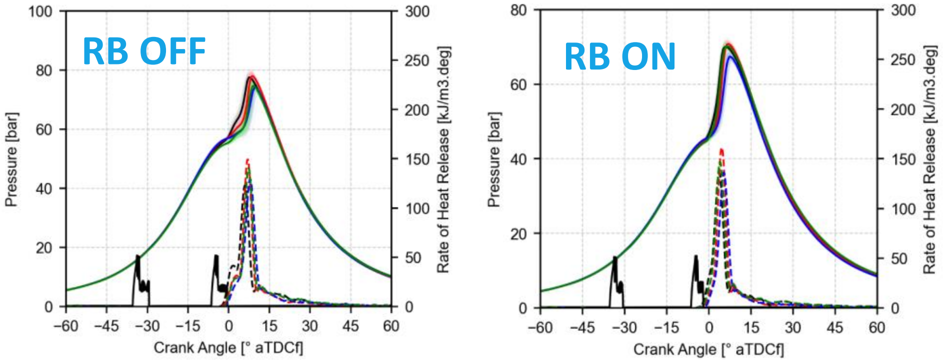
- NOx meeting T3-B30 target with most data below 50% of target.
- All soot data was below 50% of T3-B30 target
    - Soot emissions are not a constraint in calib process



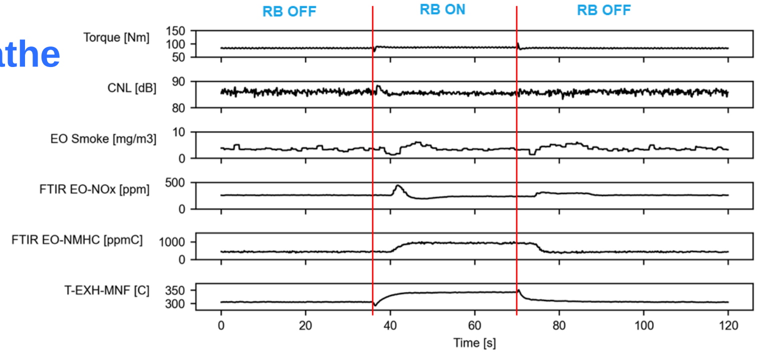
Exhaust Rebreathing (1200rpm- 4.7bar IMEP)

- Demonstrates the low-load benefits of exhaust RB for efficiency, Texh, and TP emissions
- RB ON: BTE 39.2%
- Near-zero Tailpipe NOx, CO, NMHC, PM
- Fast, seamless RB mode switching

		RB-OFF	RB-ON
BSFC_E0	g/kW.h	222.6	214.1
P-INT_MNF	kPa-g	29	7
COV-IMEP	%	1.3	1
STD-CA50	CAD	0.4	0.2
T-GOCmid	°C	290	346
T-SRCmid	°C	285	331
EO-Nox	g/kW.h	1.3	1.2
EO-NMHC	g/kW.h	1.7	2.5
EO-ISCO	g/kW.h	17	8
EO-Smoke	FSN	0.21	0.28
TP-NOx	ppm	1.6	1.8
TP-NMHC	ppmC	15.3	4
TP-CO	ppm	0.7	0.2
TP-Smoke	FSN	0.00	0.02



Rebreathe Mode Switch



Summary – Light-Duty Gasoline Compression Ignition

- The ICE engine continues to evolve with higher efficiency, near-zero emissions, and low life-cycle CO_2 emissions.
- PPCI-diffusion combustion produced quiet & stable torque with low EO NOx & soot.
- BSFC was 10-20% lower than the BMW 2.0L N47 diesel over the load range. Simulation data indicate potential for peak BTE of 46% for the current engine design.
- For low loads, 2-step exhaust Rebreathing provided robust combustion with high Texh. for active catalysis.
- The aftertreatment system delivered near-zero tailpipe NOx, soot, HC, & CO for all tests to date. NO_2 produced in comb. & GOC enabled passive GPF regeneration and improved SCR effic. at low temps.
- GCI, when combined with 48V MHEV and synthetic gasoline, has potential for very low life-cycle CO_2 emissions for a range of vehicle applications.

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Thank You

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VIRTUAL EVENT