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Post Modern Diesel Engines on the Post-Injection Pathway

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Special thanks to: Mark Musculus and Paul Miles (Sandia)
Gupreet Singh (DOE Office of Vehicle Technologies)
Tim Lieuwen, Caroline Genzale, and Glenda Duncan (Georgia Tech)

Post-Modern Diesel Engines

- **Postmodernism**: "any number of trends or movements… in reaction to or rejection of the dogma, principles, or practices of established modernism"

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- **Thermodynamics (dogma) says…** higher compression ratio means higher thermal efficiency so high compression ratio engines are better

$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma - 1}}\left[\frac{\alpha\,\beta^{\gamma} - 1}{\alpha\,\gamma(\beta - 1) + \alpha - 1}\right]$$

Post-Modern Diesel Engines

- **Postmodernism**: "any number of trends or movements… in reaction to or rejection of the dogma, principles, or practices of established modernism"

- Compression ratio (CR) of production engines has been decreasing for the past ten years

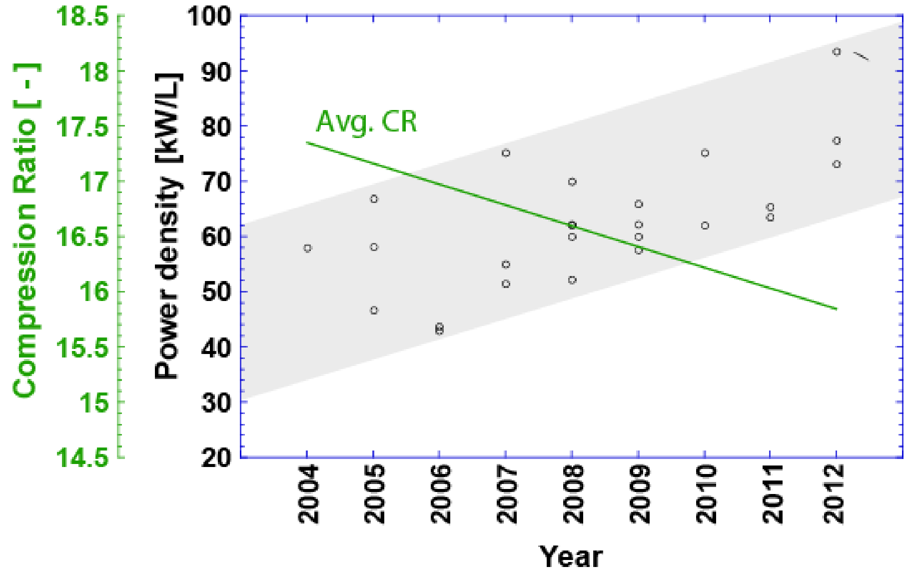


Image courtesy of Paul Miles

Post-Modern Diesel Engines

- **Postmodernism**: "any number of trends or movements… in reaction to or rejection of the dogma, principles, or practices of established modernism"

- Well, fine, then higher gamma (ratio of specific heats) can be used to increase efficiency even if compression ratio is decreasing

$$\eta_{th} = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{\alpha\,\beta^{\gamma} - 1}{\alpha\gamma(\beta - 1) + \alpha - 1}\right]$$

Post-Modern Diesel Engines

- **Postmodernism**: "any number of trends or movements… in reaction to or rejection of the dogma, principles, or practices of established modernism"

- Production diesel engines target EGR levels between 20-30%, significantly decreasing the ratio of specific heats

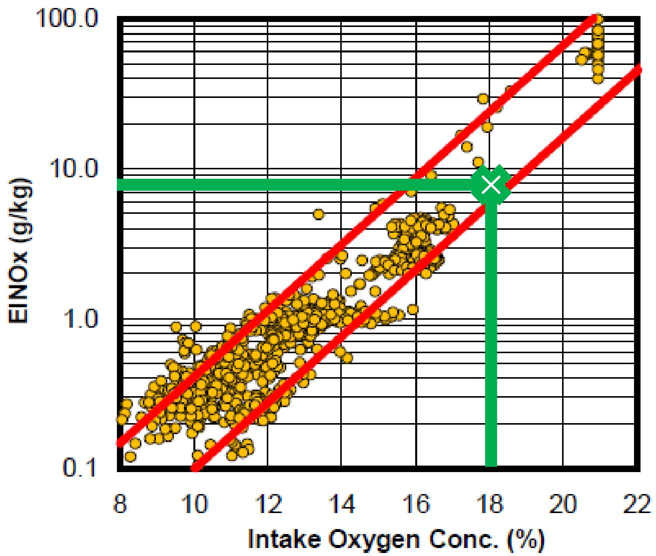
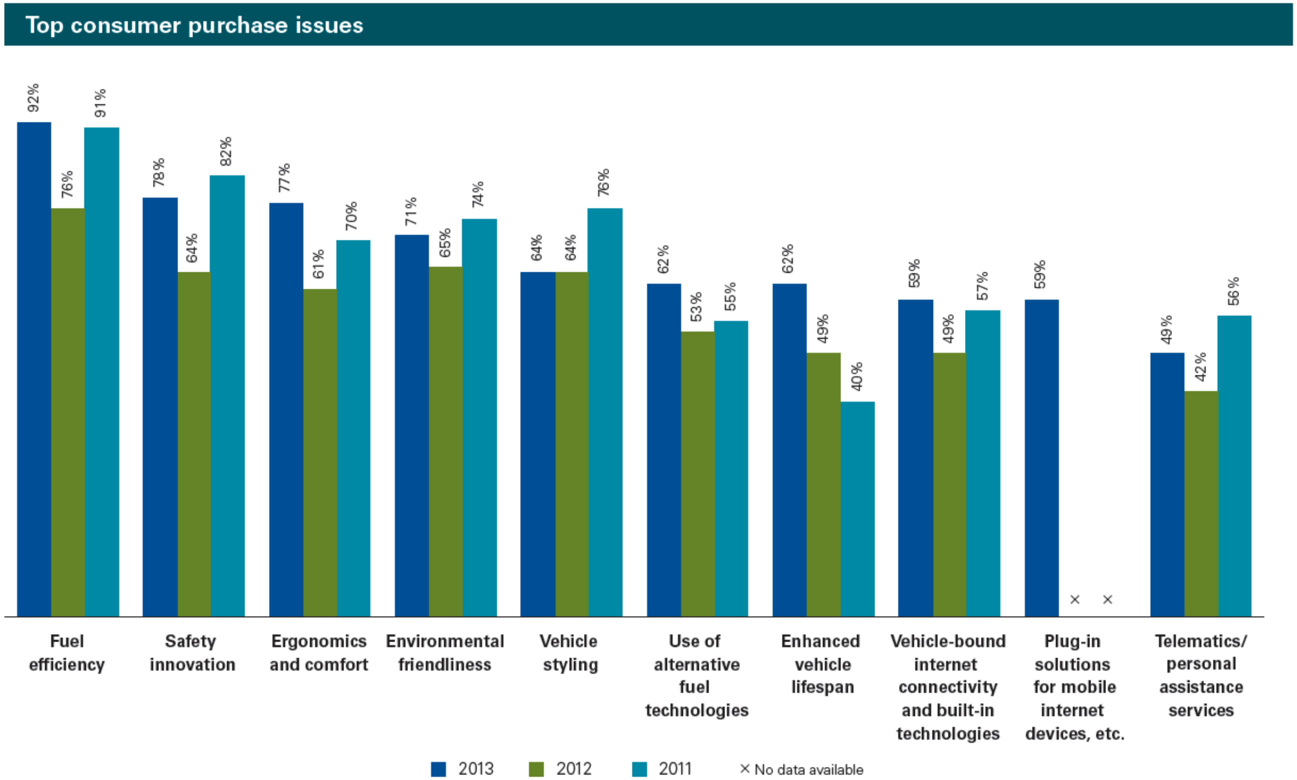


Figure courtesy of Russell Durrett, GM

The Passenger Vehicle Market (light-duty): Fuel efficiency is highest priority

- KPMG's Global Automotive Executive Summary (2013) identified fuel efficiency as the automotive consumer's greatest concern



Note: Percentage of respondents rating issues as 'extremely important' and 'very important'
Source: KPMG's Global Auto Executive Survey 2013

Auto Manufacturers Provide Consumers with a Variety of High-Efficiency Vehicle Options

Novel ICEs (gas & diesel)

mazda

SKYACTIV TECHNOLOGY

Hybrids

TOYOTA

Battery

NISSAN

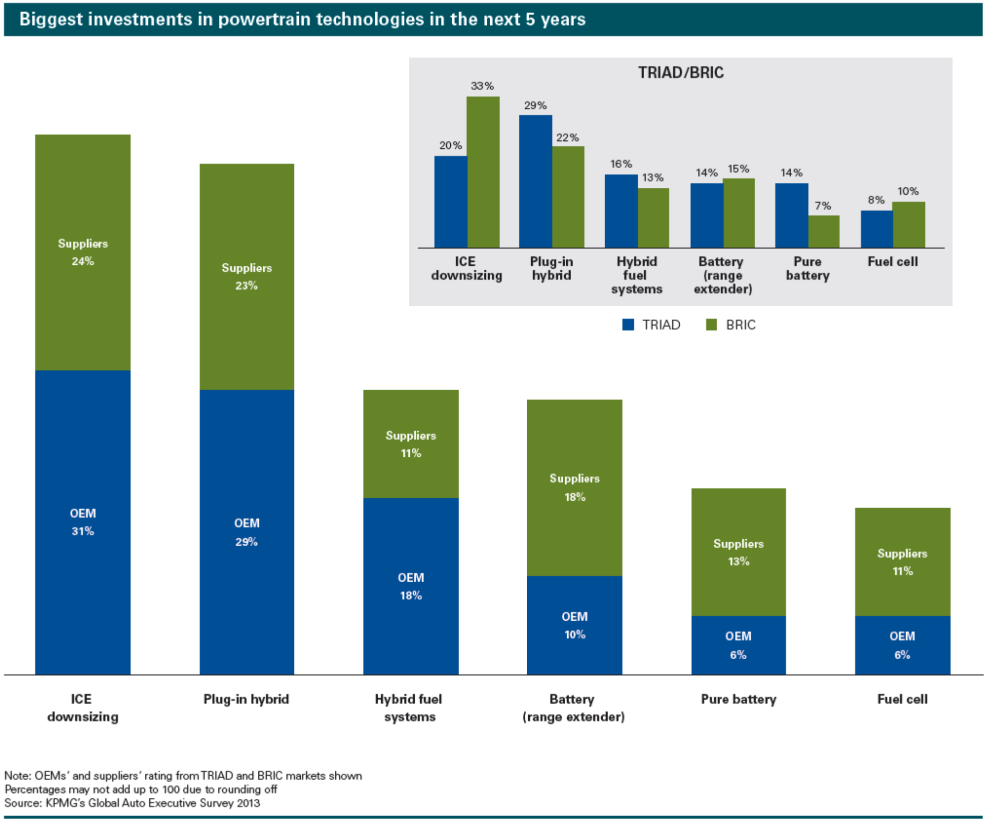
Plug-in Hybrid

Exciting battery

TESLA

ICEs will remain a competitive solution in light-duty and heavy-duty markets

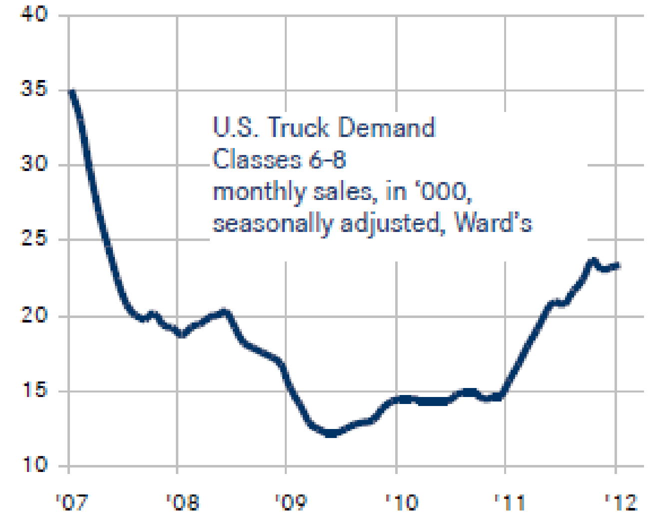
- OEMs and suppliers have identified internal combustion engine technology as a priority for achieving customer demands

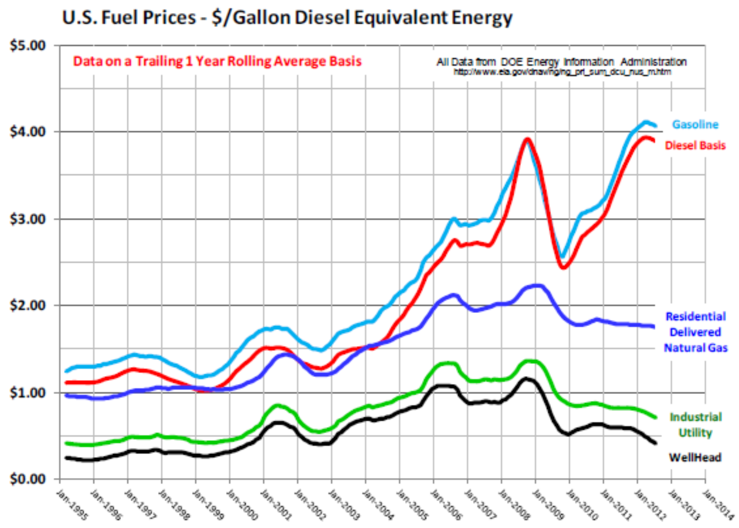


The Freight Vehicle Market (heavy-duty)

National Petroleum Council
"Advancing Technology for America's Transportation Future" 2012:

"**Diesel engines will remain the powertrain of choice for HD vehicles for decades to come because of their power and efficiency**. There are, however, opportunities to improve the technology. Significant fuel economy improvements in diesel powered trucks are possible. Indeed, the fuel economy (mpg) for new Class 7&8 HD vehicles, which consume more than 70% of the fuel in the trucking fleet, could be doubled."





Figures courtesy of Igor Gruden, Daimler Trucks (DEER 2012)
Micheal Ruth, Cummins (DEER 2012)

US Government is Supporting Heavy-Duty Diesel Advancement in Industry

- 21st Century Truck Partnership
  - Promote research focused on advanced heavy-duty vehicle technologies
  - 16 industrial partners
  - 4 federal agency partners (DOE, DOD, DOT, EPA)
  - 11 national laboratories, NASA Ames and NIST

- SuperTruck
  - 55% break thermal efficiency by April 2014
  - Industrial/university participation (Volvo, Daimler, Navistar, Cummins/Peterbilt)

Sandia's Engine Combustion Department Plays a Vital Role in Meeting these Demands

- Sandia is one of the last stops for engine combustion science before it becomes engineering

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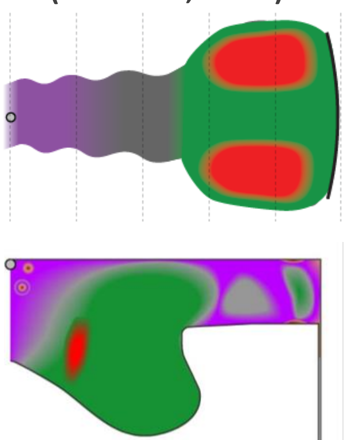
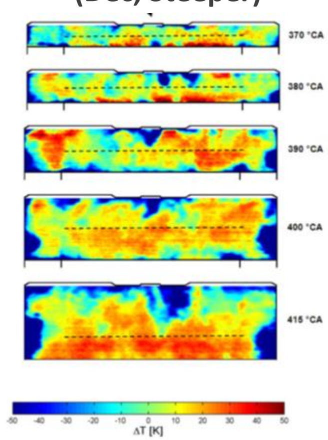
Advanced Combustion

Low-temperature combustion (Musculus, Miles)



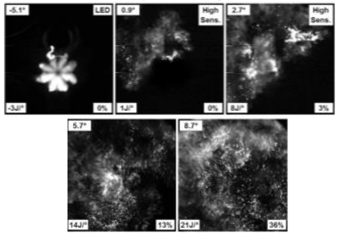
Musculus et al., PECS, 2013

HCCI/SCCI (Dec, Steeper)



Dronniou and Dec, SAE 2012-01-1111

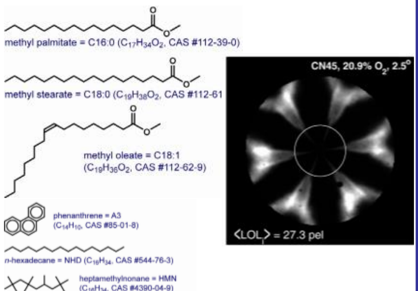
SI Direct Injection (Sjoberg)



Sjöberg and Reuss, SAE 2012-01-1643

Novel Fuels

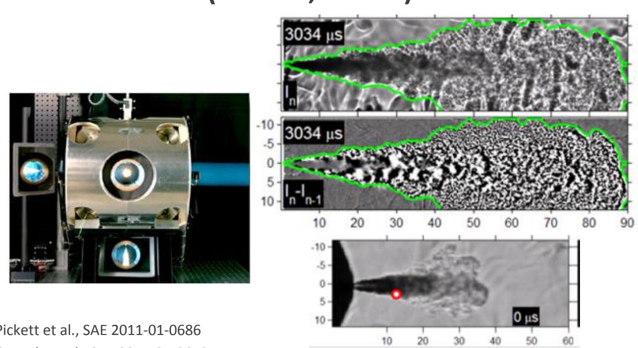
Diesel Fuels (Mueller)



Mueller et al., SAE 2009-01-1792

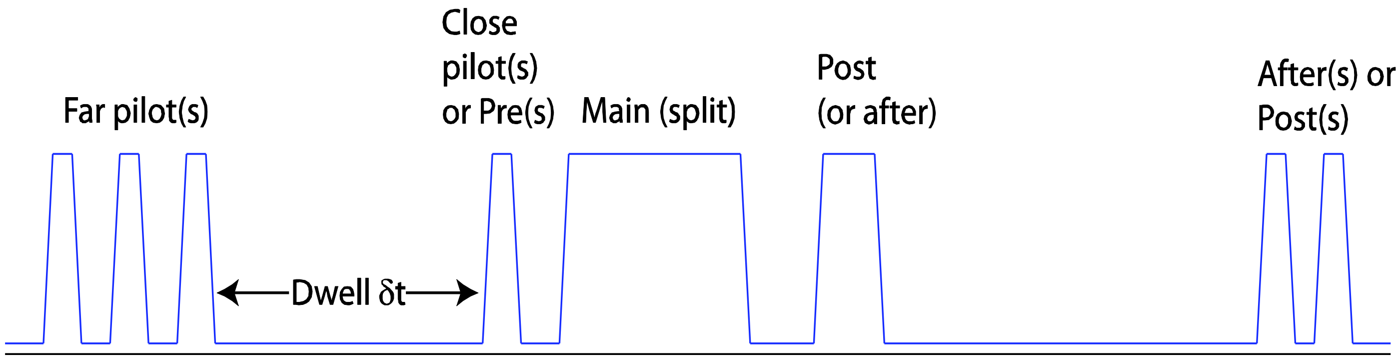
Fundamental Sprays

Diesel and Gasoline Sprays (Pickett, Skeen)

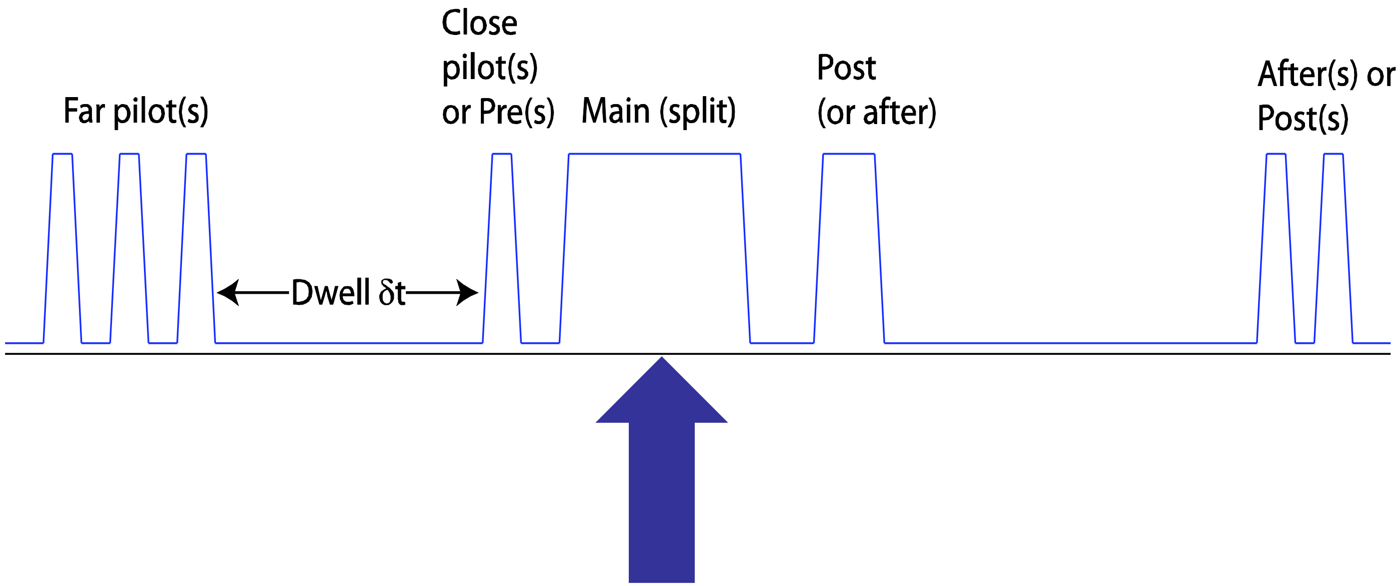


Pickett et al., SAE 2011-01-0686
Genzale et al., SAE 2011-01-0659

Multiple Injection Strategies can Reduce Emissions and Engine Noise

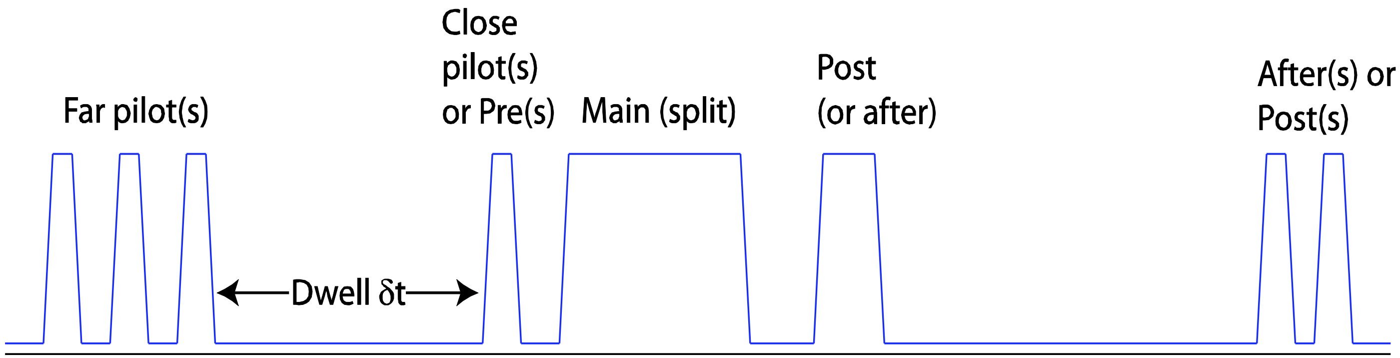


Multiple Injection Strategies can Reduce Emissions and Engine Noise

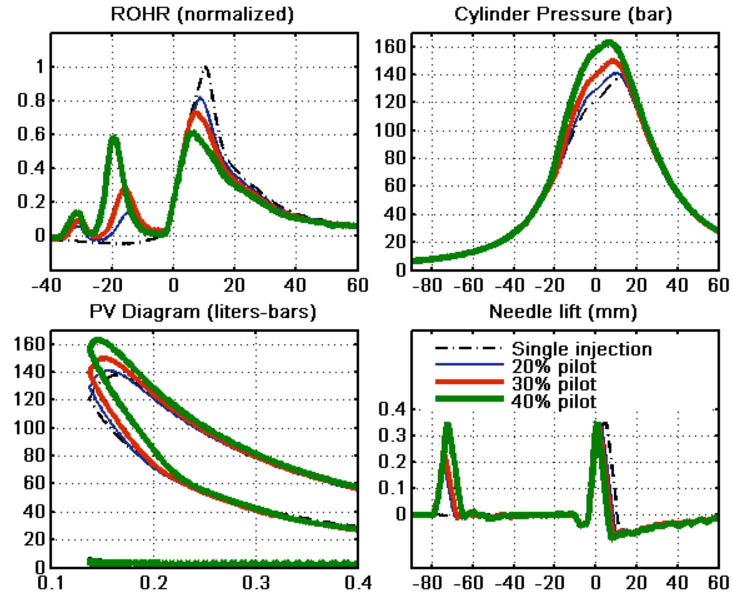


Main injection is responsible for the majority of the fuel delivery each cycle

Multiple Injection Strategies can Reduce Emissions and Engine Noise

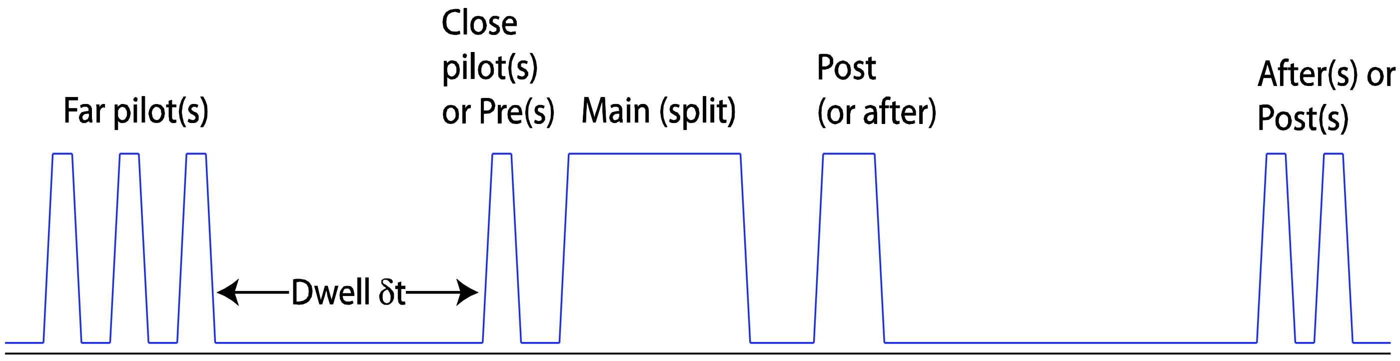


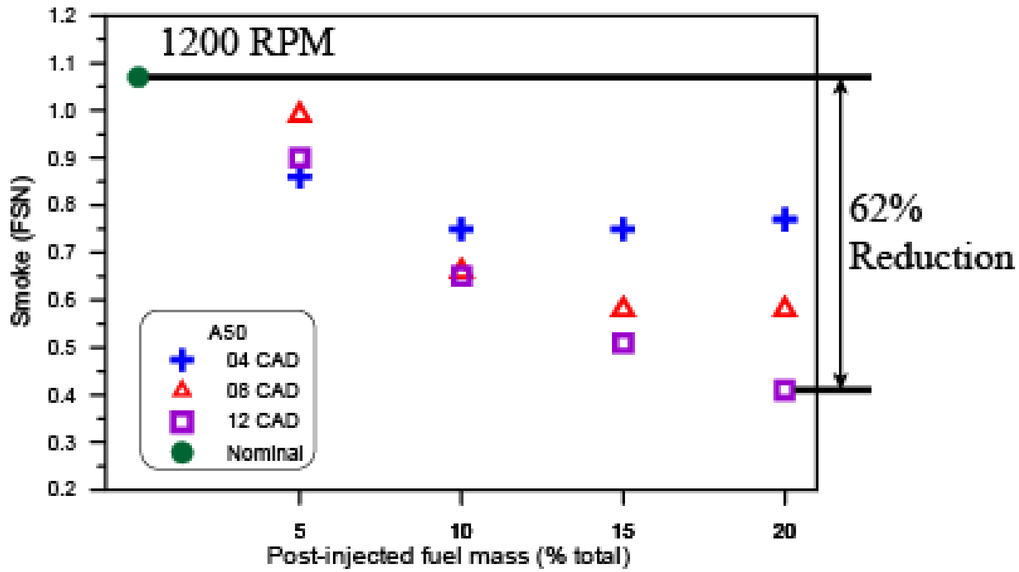
Pilot injections are used to decrease the ignition delay of the mixture, which **stages combustion** and **reduces combustion noise**



Dronniou et al., SAE 2005-01-3726

Multiple Injection Strategies can Reduce Emissions and Engine Noise

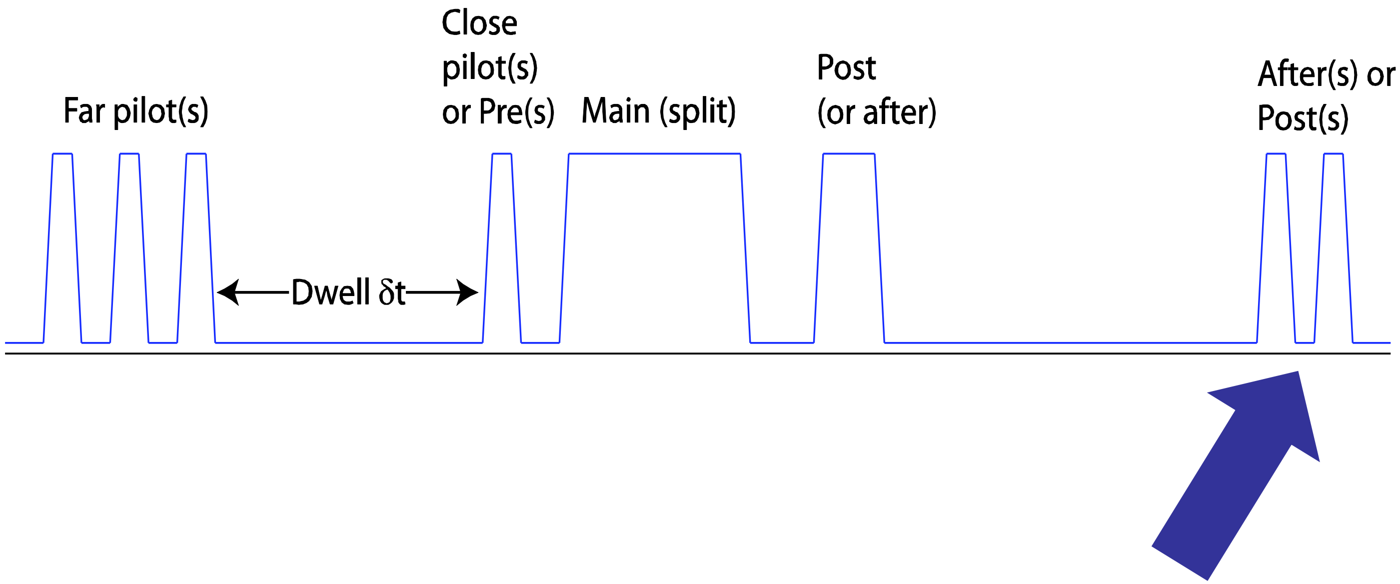




Post injections are used to **reduce engine-out emissions**, including soot and unburned hydrocarbons

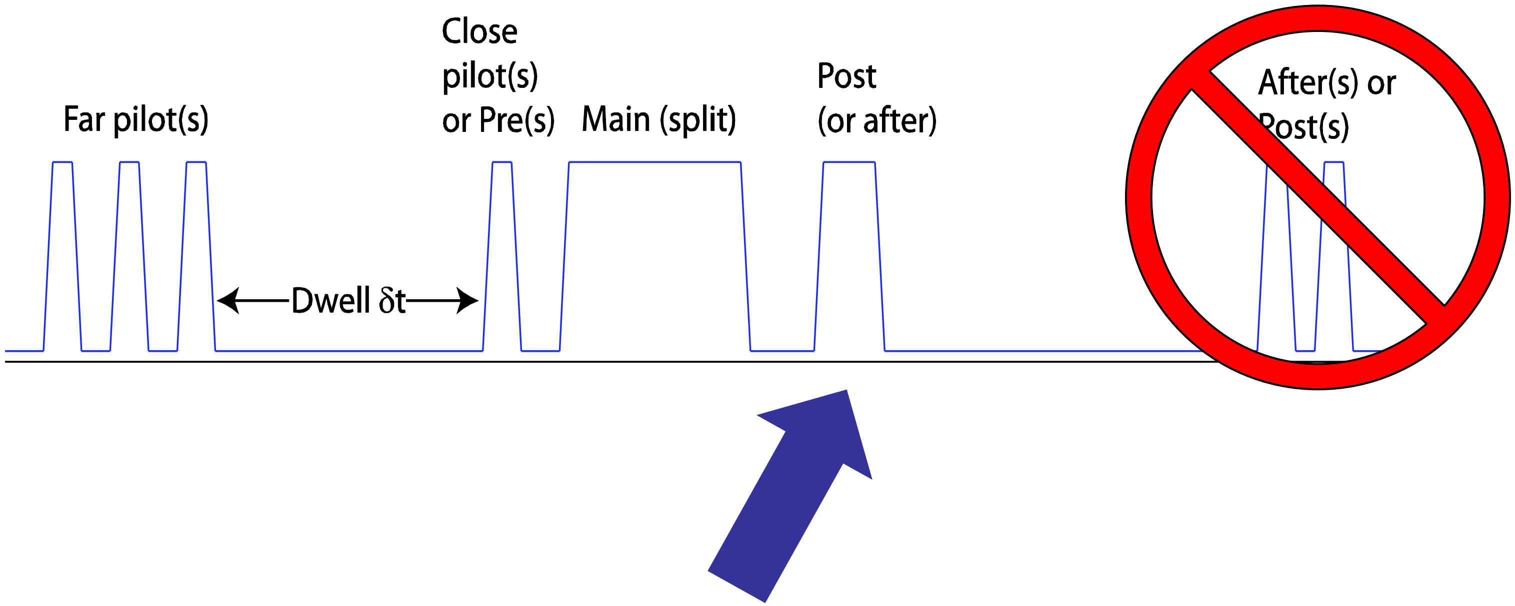
Payri et al., SAE 2002-01-0502

Multiple Injection Strategies can Reduce Emissions and Engine Noise



After injections are used to **enhance aftertreatment performance**, as aftertreatment systems often need additional fuel to sustain high temperatures for efficient performance

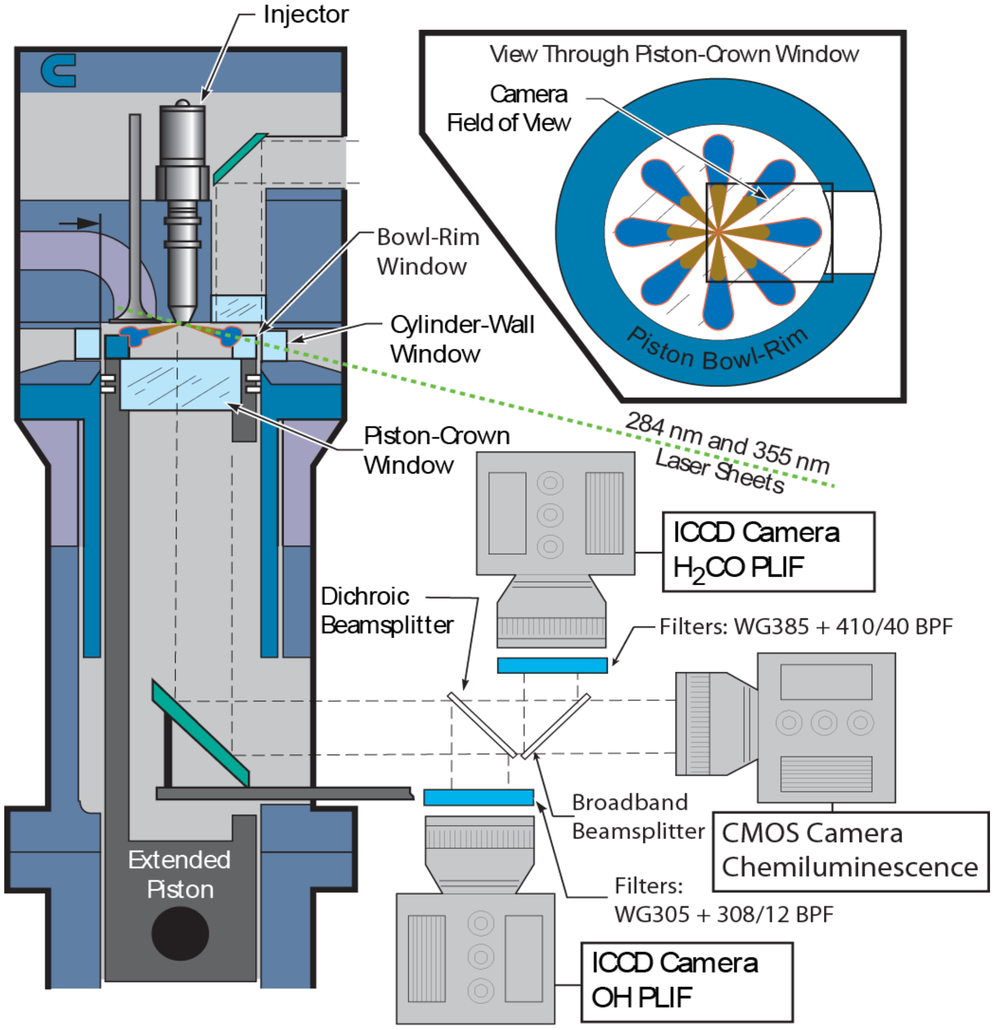
Multiple Injection Strategies can Reduce Emissions and Engine Noise



The goal of our work is to provide industry with a better understanding of how post injections reduce engine out emissions so that aftertreatment can be downsized or eliminated

Experimental Methodology: LIF, LII, High-speed Visualization, Exhaust Measurements

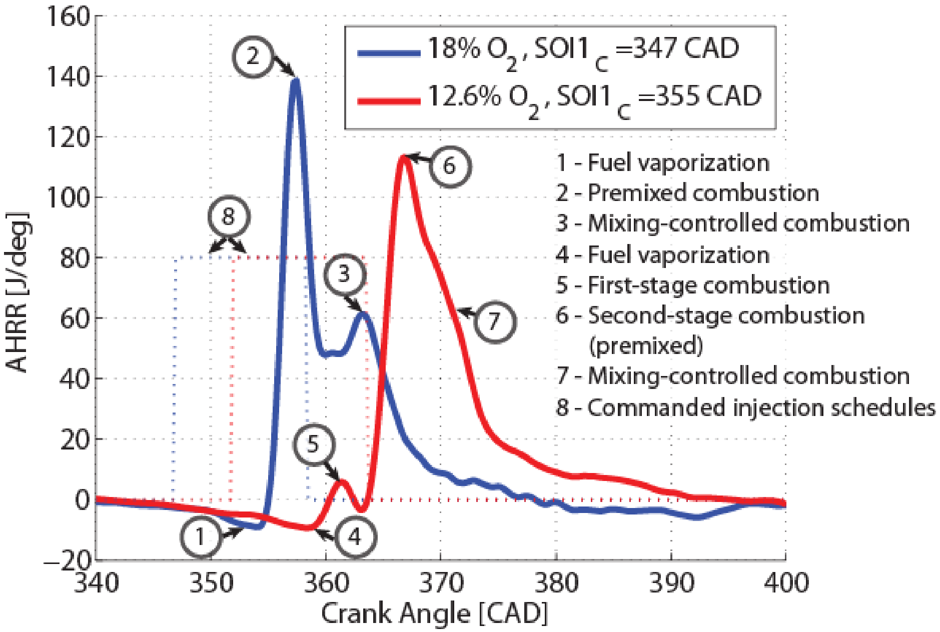
- Engine-out emissions measurements (soot, UHC, etc.)
- High-speed visualization
- Laser-induced fluorescence of H_2CO, OH
- Laser-induced incandescence of soot (LII)



Example #1: Post Injections Can Reduce UHC at Low-Temperature Combustion Conditions

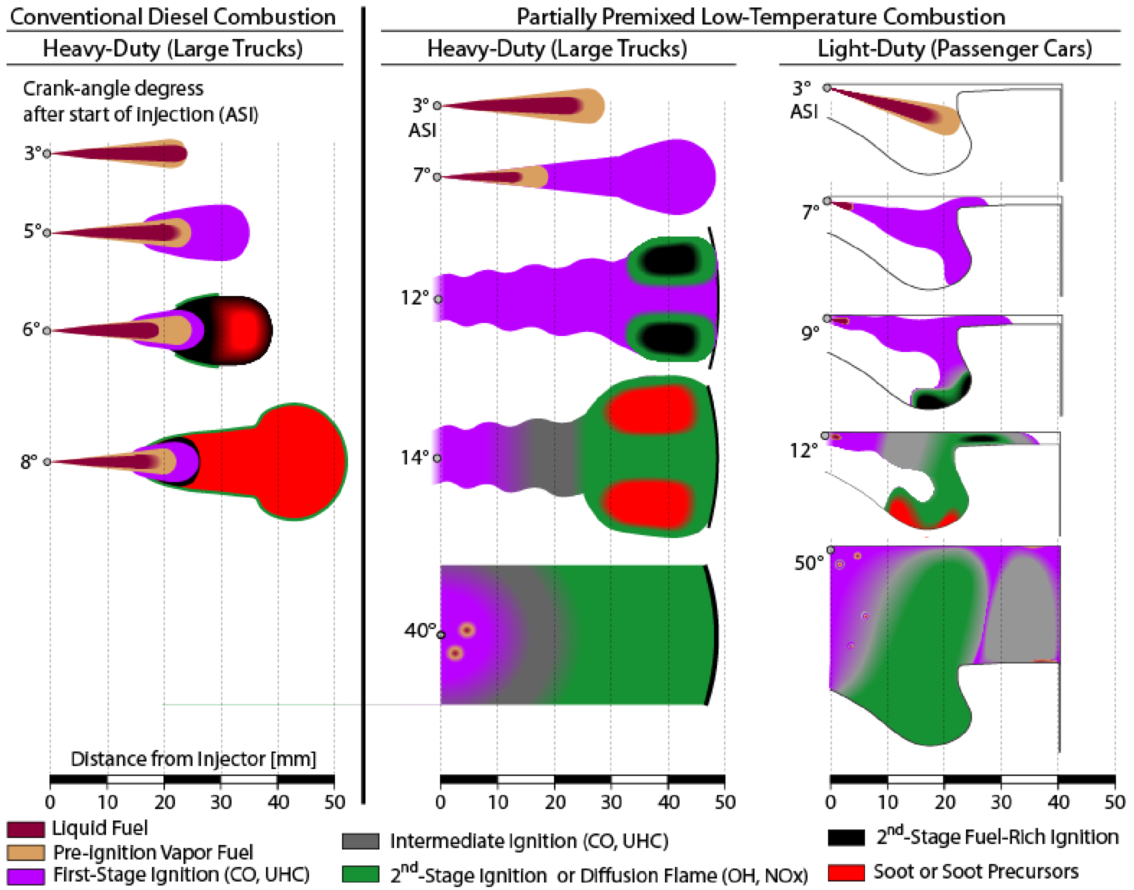
LTC: Lowering emissions with EGR dilution and enhanced premixing

- High dilution with EGR
  - Reduces combustion temperature
  - Reduced temperature suppresses NO_x formation
- Enhanced premixing
  - Late injection creates a mixture with a long ignition delay, allowing more time for premixing
  - Premixing reduces rich zones where soot is formed, significantly reducing soot formation



Low Temperature Combustion: Conceptual Model

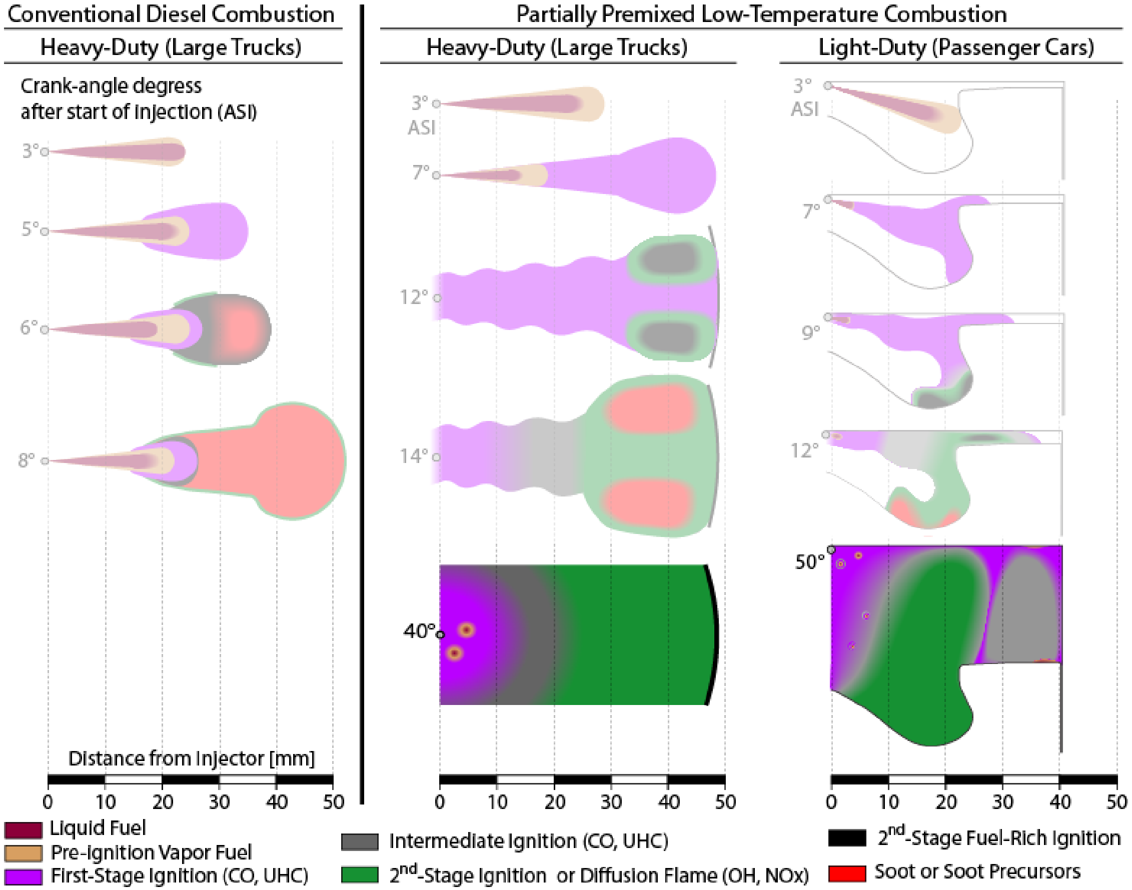
- LTC operation has very different spatio-temporal development of the combustion process than conventional diesel operation



PECS 2013, Musculus *et al.*

LTC Drawbacks: Increase in UHC emissions originating in overly-lean regions

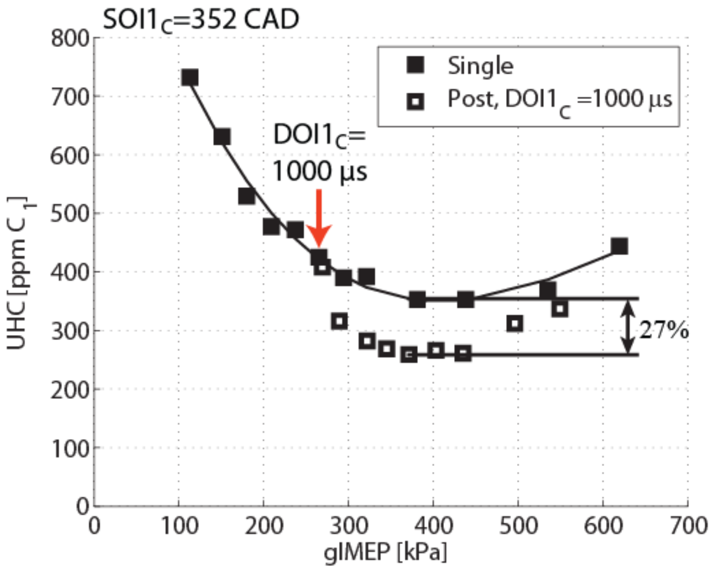
- High dilution and long ignition delays lead to overly-lean mixtures that never reach 2nd stage ignition at low load conditions



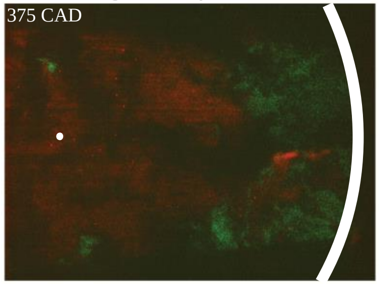
Musculus *et al.*, PECS 2013

Multiple Injections: New data suggests post injections work over a wide range of conditions

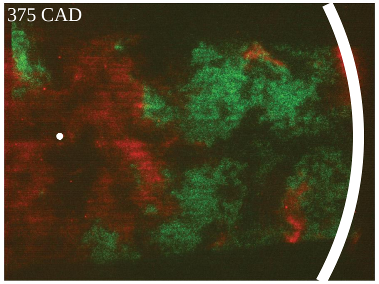
- Results from the current study indicate that post injections can reduce engine-out UHC by up to ~30% at the same load
- Post injection efficacy is most dependent on post-injection duration and post-injection ignition delay
- Post injections reduce UHC by enriching overly-lean regions near the injector, "kicking" them into second-stage ignition



Single Injection

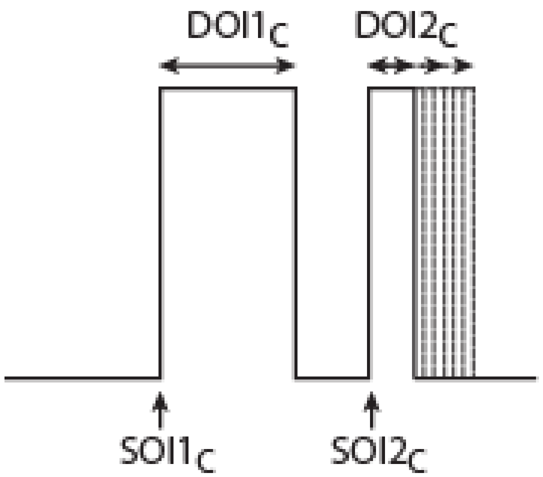


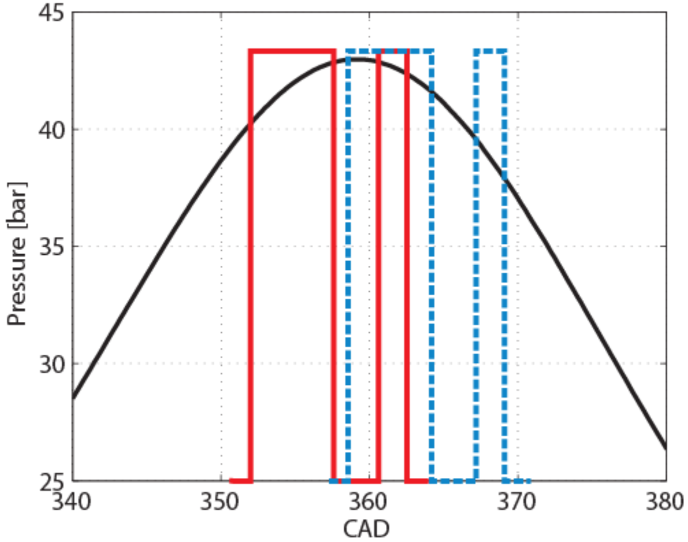
Main+Post Injection



Goals: Understanding mechanism of UHC reduction with post injections

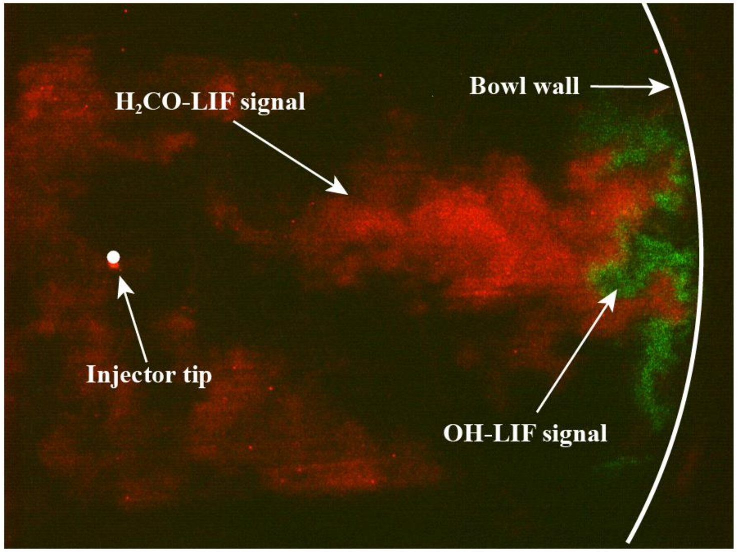
- Understand the sensitivity of post-injection efficacy to fluid-mechanic and chemical considerations
  - Post-injection duration/penetration (fluid mechanic)
  - Post-injection ignition delay (chemical)

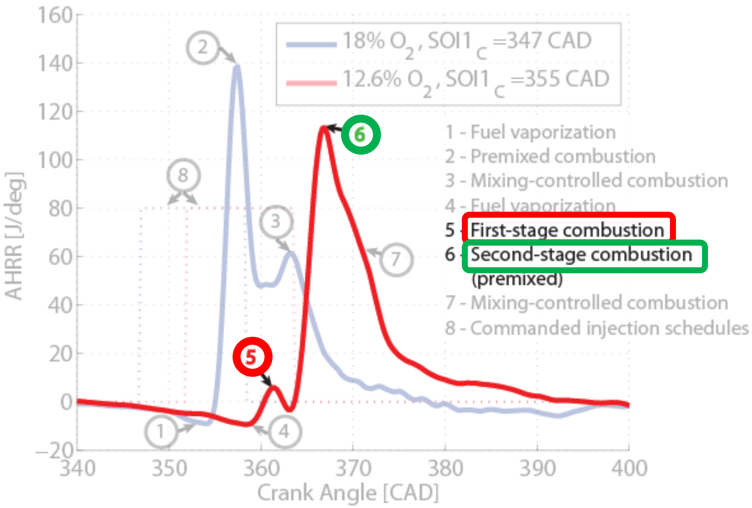




Experimental Methodology: LIF

- Laser-induced fluorescence of H_2CO – 1st stage combustion
  - Excitation at 355 nm at 80 mJ/pulse
  - Emission collected with HQf Gen-III intensified CCD, 50 ns gate
  - Long-wave-pass at λ>310 nm and λ>310 nm, BP at λ=408 nm
- Laser-induced fluorescence of OH – 2nd stage combustion
  - Excitation at 284 nm at 80 mJ/pulse
  - Emission collected with Super-blue Gen-II intensified CCD, 410 ns gate
  - Bandpass at λ=310 nm and color-glass λ=305 nm to reject laser at 284 nm



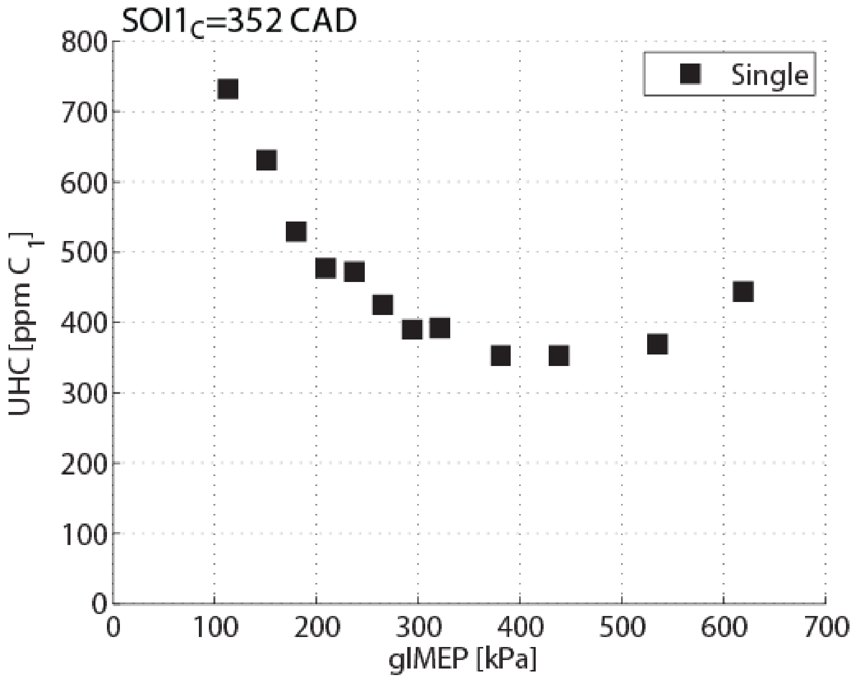


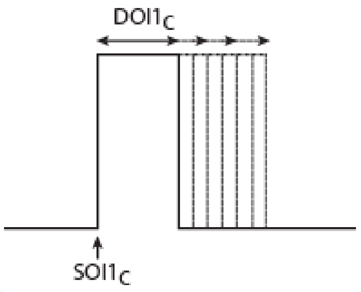
Single Injections: Engine-out UHC emissions results

- Single-injection schedules were run at a range of $DOI1_C$
  - $SOI1_C$=352 CAD, $DOI1_C$=600-2400 µs

- High UHC at short $DOI1_C$ due to occasional partial burns

- High UHC at long $DOI1_C$ due to “rich-source” UHC





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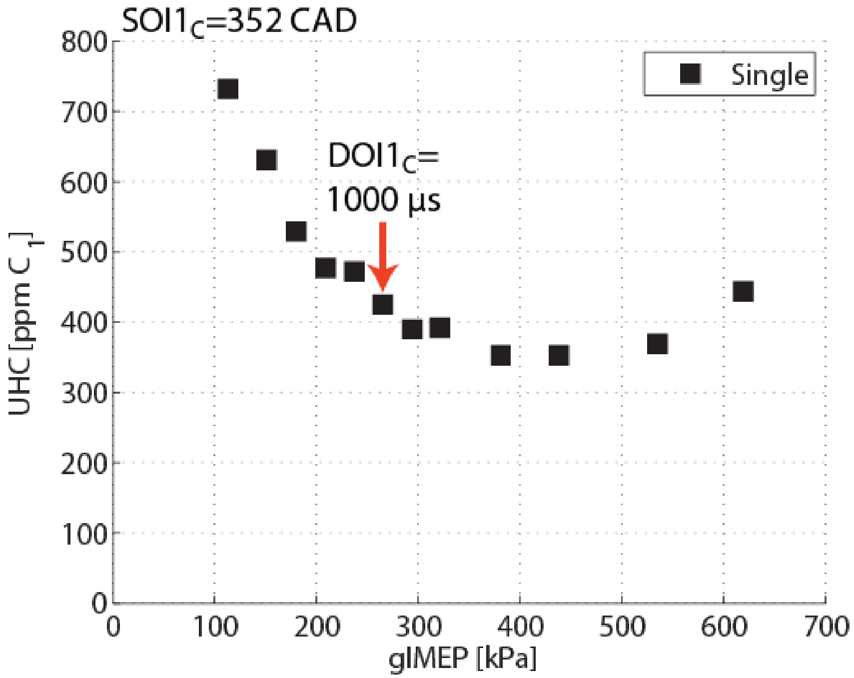
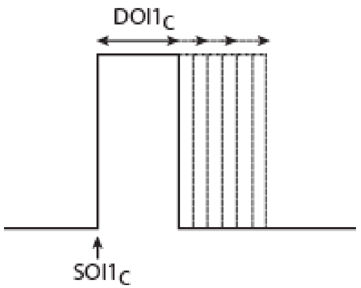
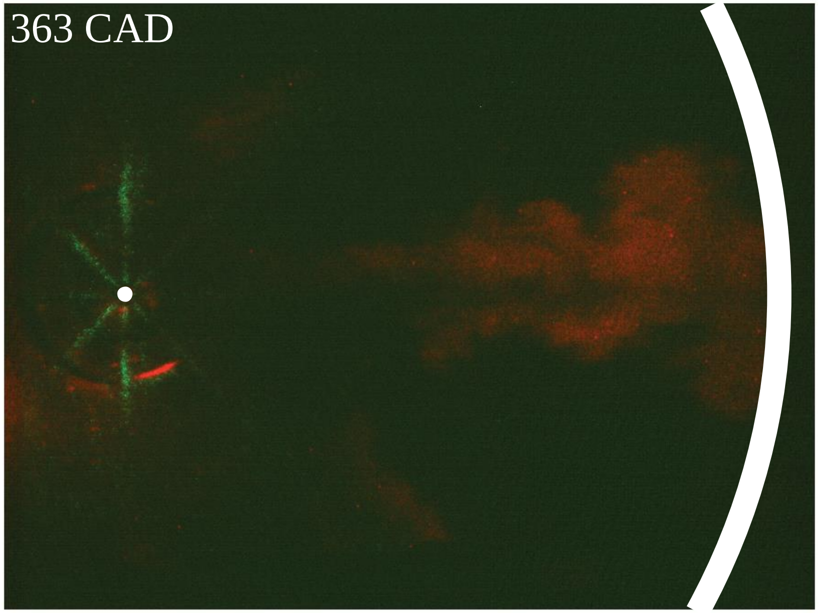
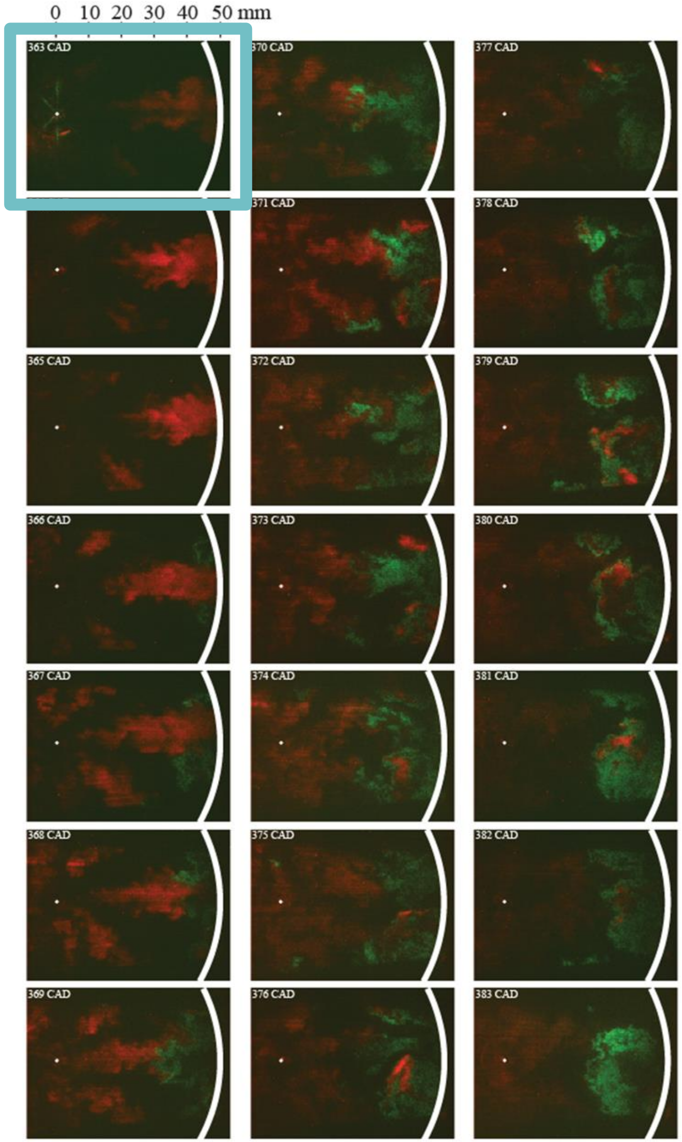




Single Injections: First-stage combustion in the jet starts before EOI

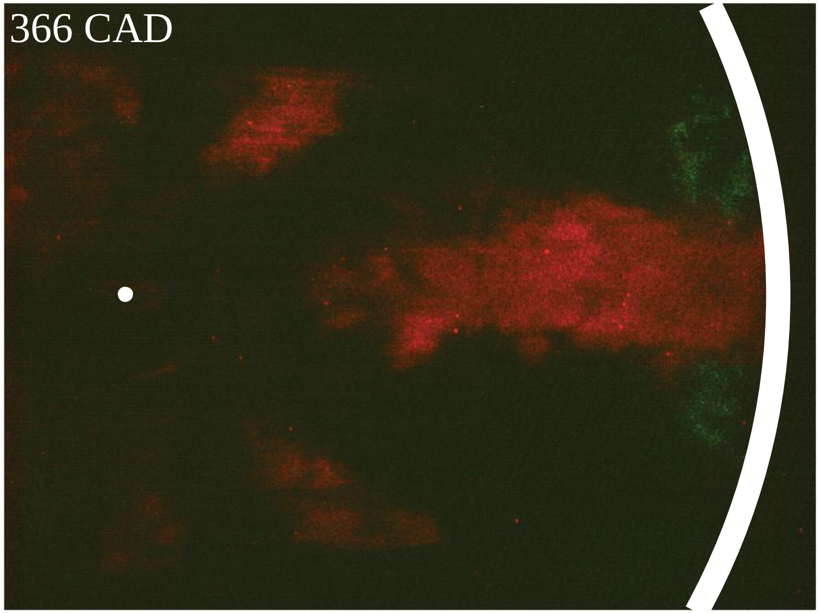
- First-stage combustion is evident in the jet during and after the injection

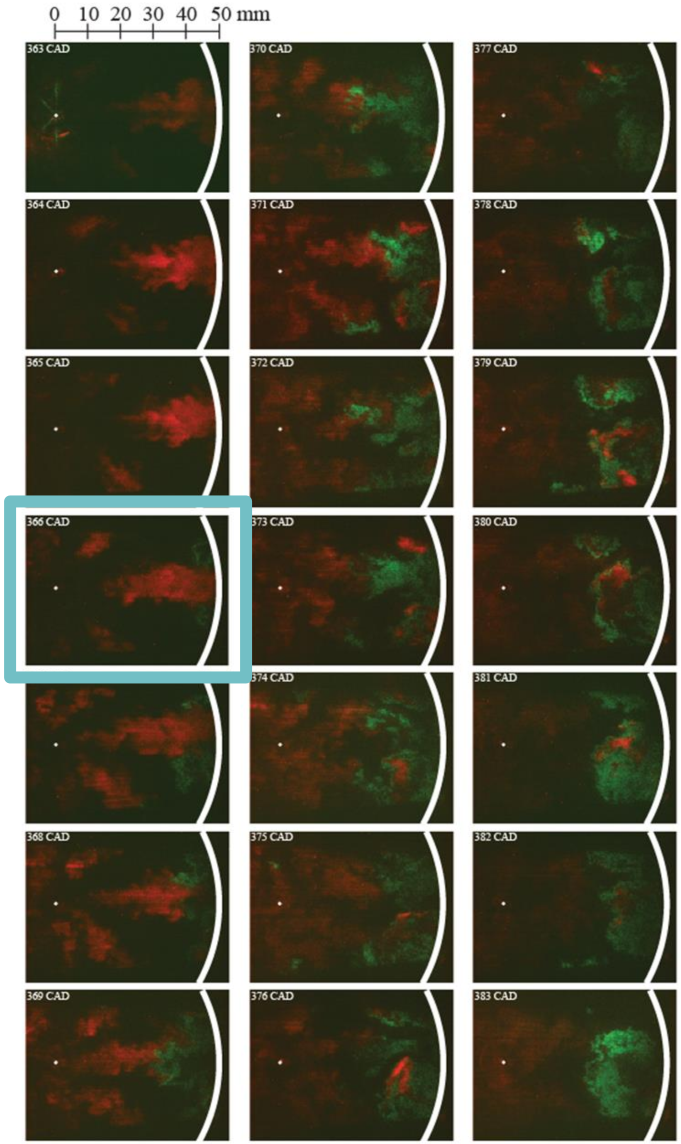




Single Injections: Second-stage combustion begins at the bowl wall

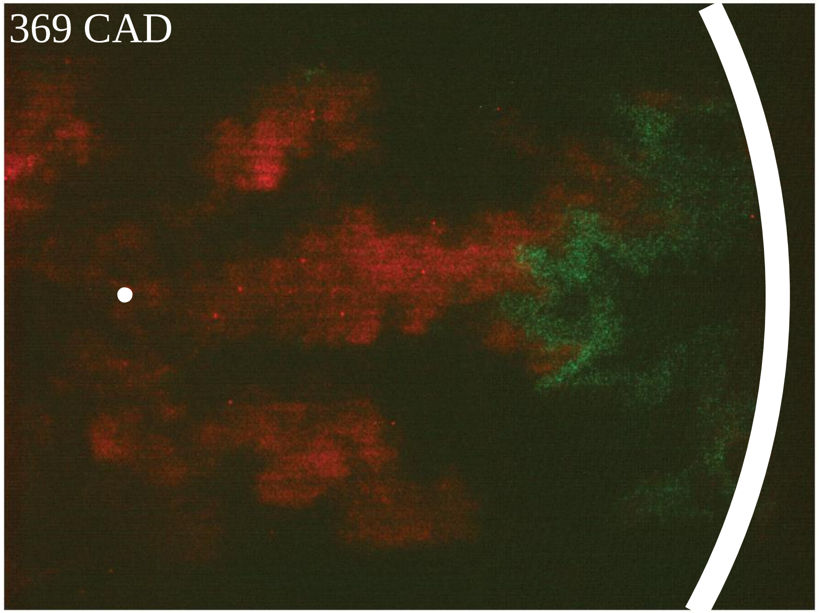
- Second-stage combustion begins in the recirculation zones on either side of the jet, along the bowl wall

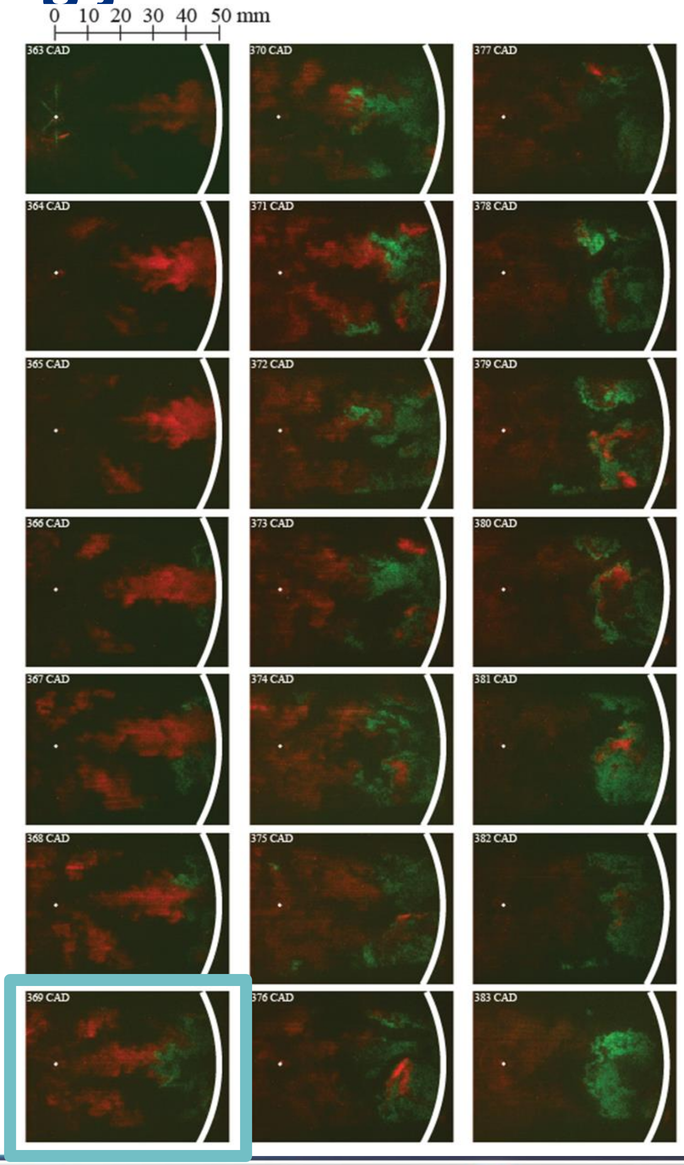




Single Injections: Second-stage ignition "races back" along jet axis

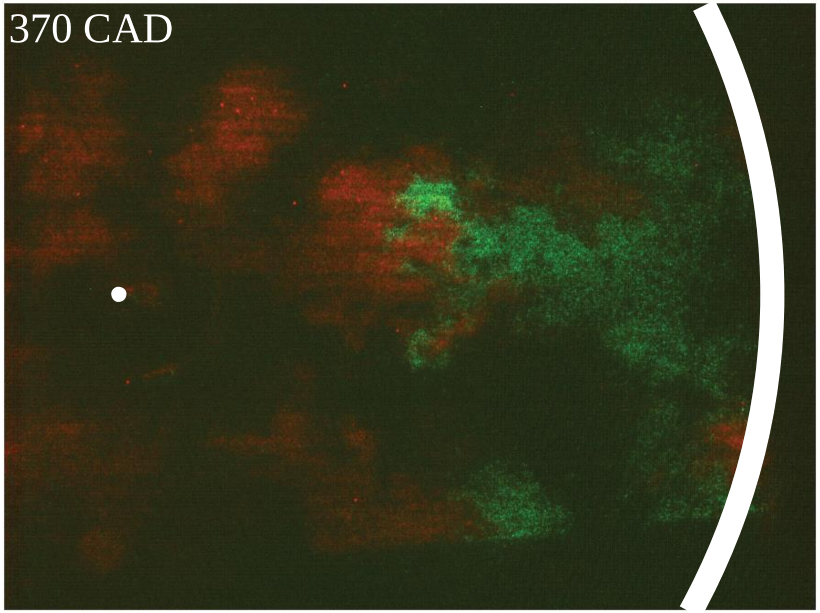
- Second-stage reaction reaches the jet centerline, still in the region of the bowl wall

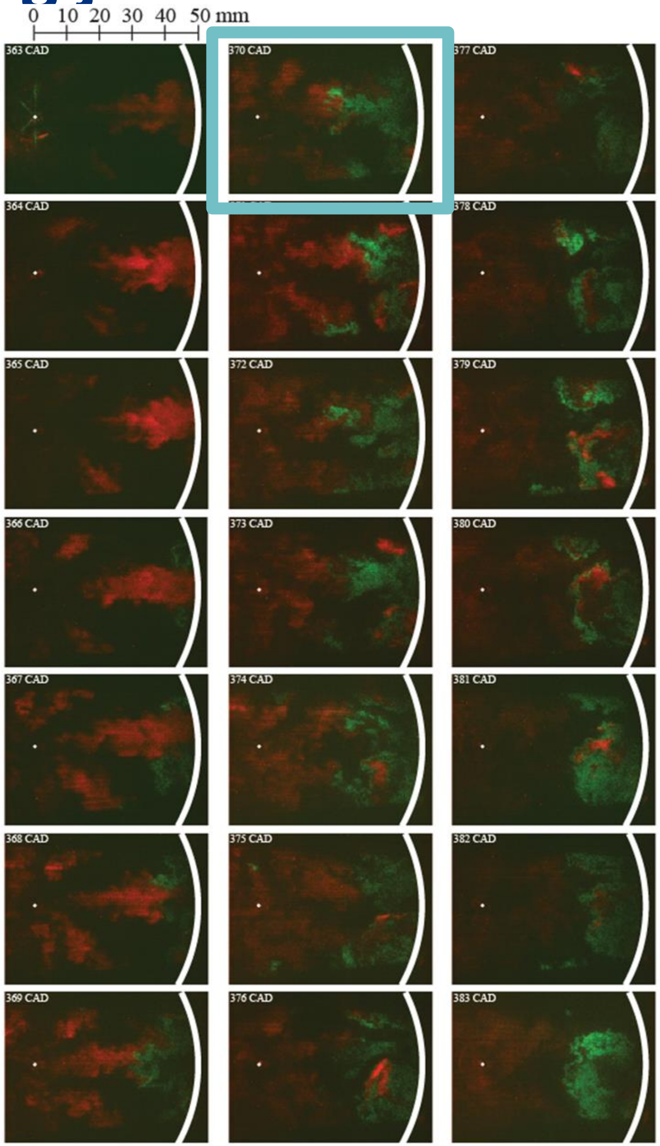




Single Injections: Second-stage ignition "races back" along jet axis

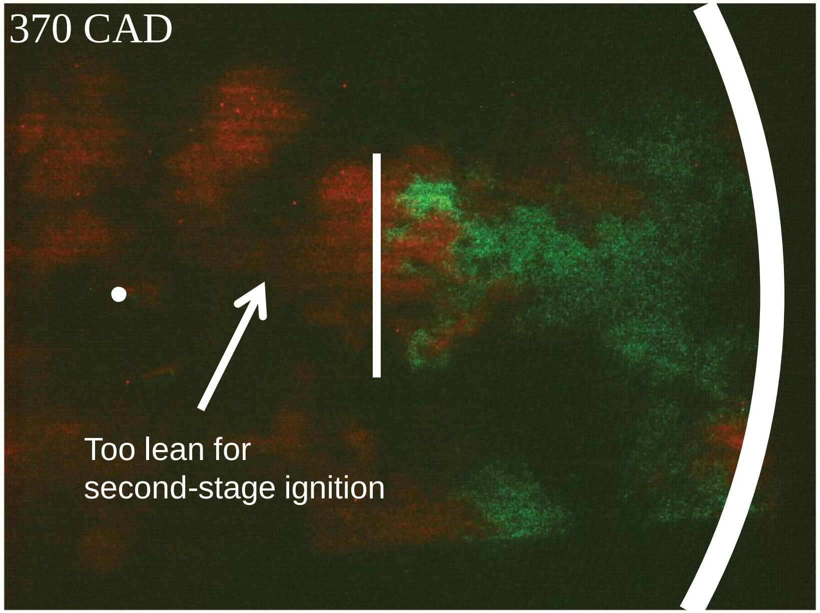
- Second-stage reaction "races back" along jet axis, reaching approximately half the radial distance back to the injector

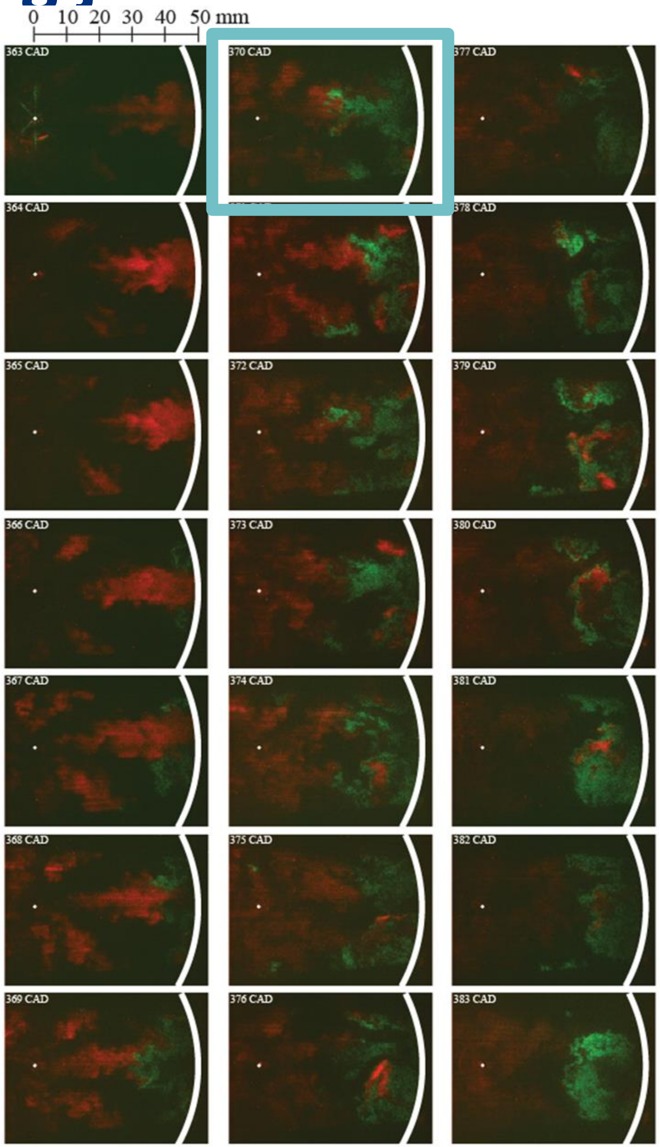




Single Injections: Second-stage ignition "races back" along jet axis

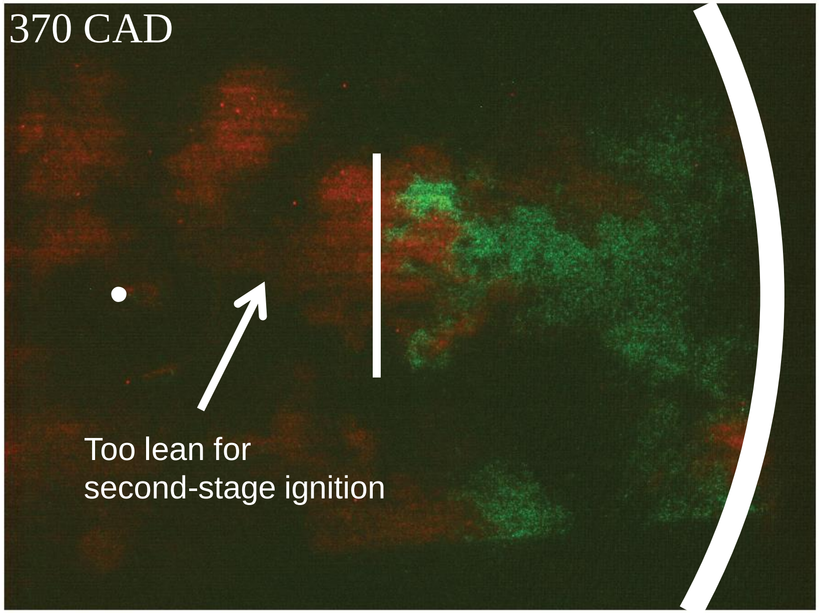
- Second-stage ignition can only "race back" so far due to overly-lean mixture near the injector

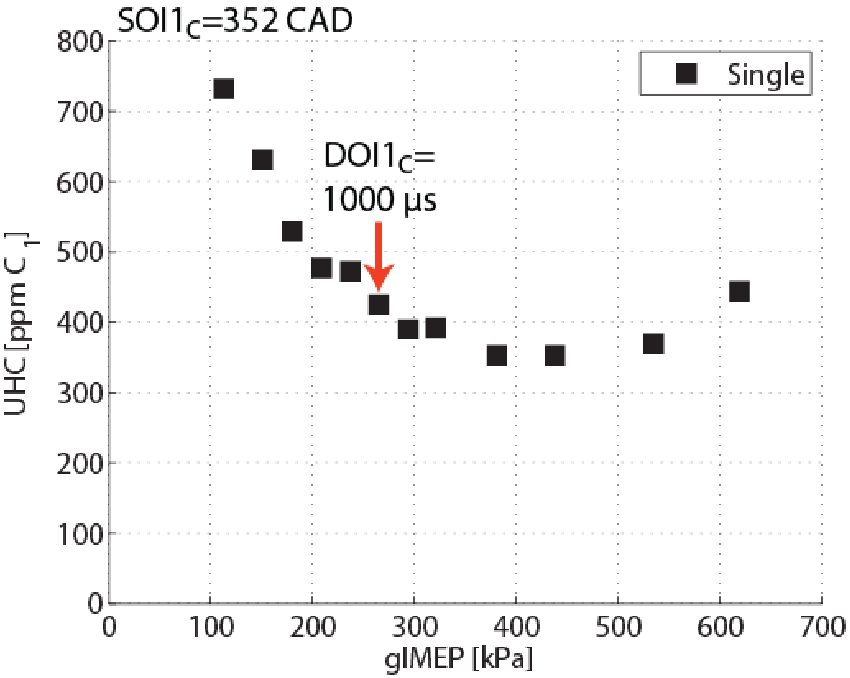




Main + Post Injections: Post injections could enrich overly-lean mixtures

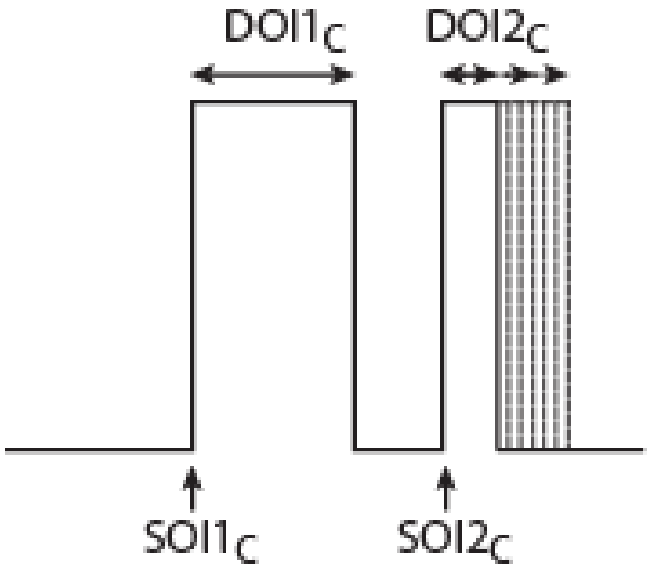
- Post injections are added to the main injection to try to enrich overly-lean mixtures near the injector

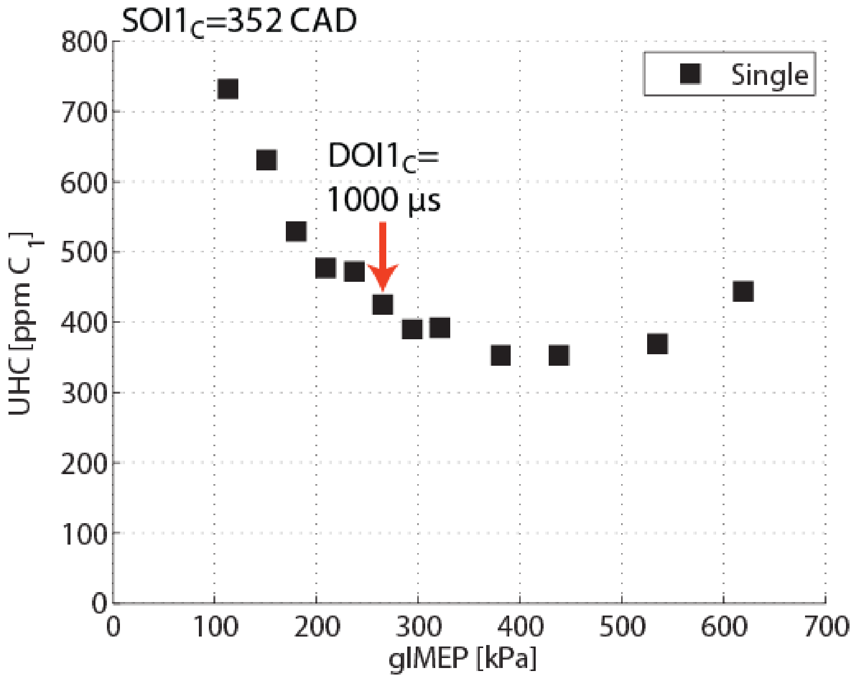




Main + Post Injections: Sensitivity to Fluid Mechanic Effects ($DOI2_C$)

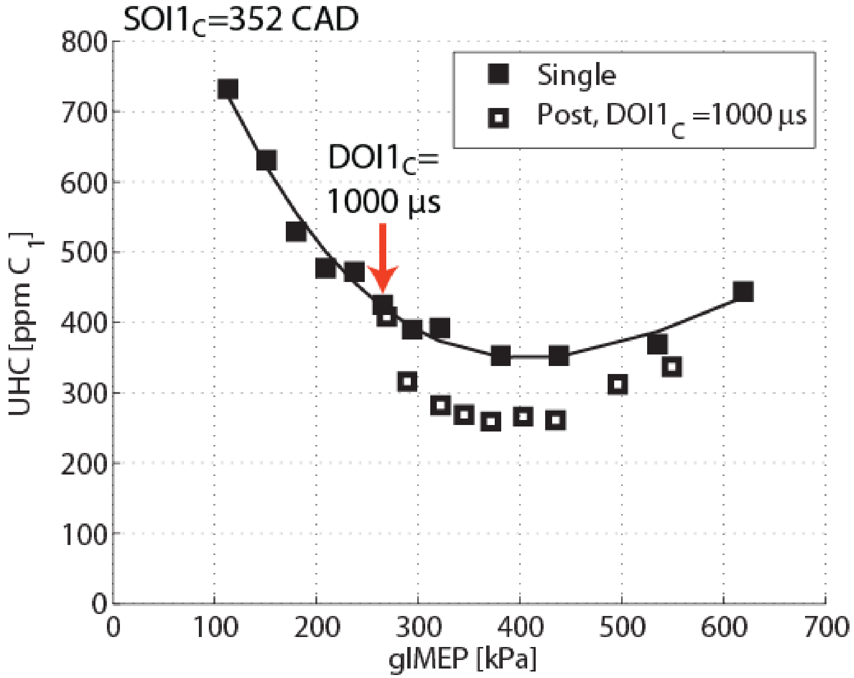
- During these tests, main-injection duration ($DOI1_C$) is held constant and the duration of the post injection is varied with constant dwell ($SOI2_C$)

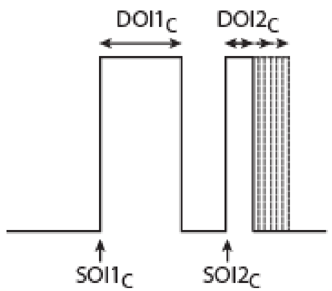




Main + Post Injections: Sensitivity to Fluid Mechanic Effects ($DOI2_C$)

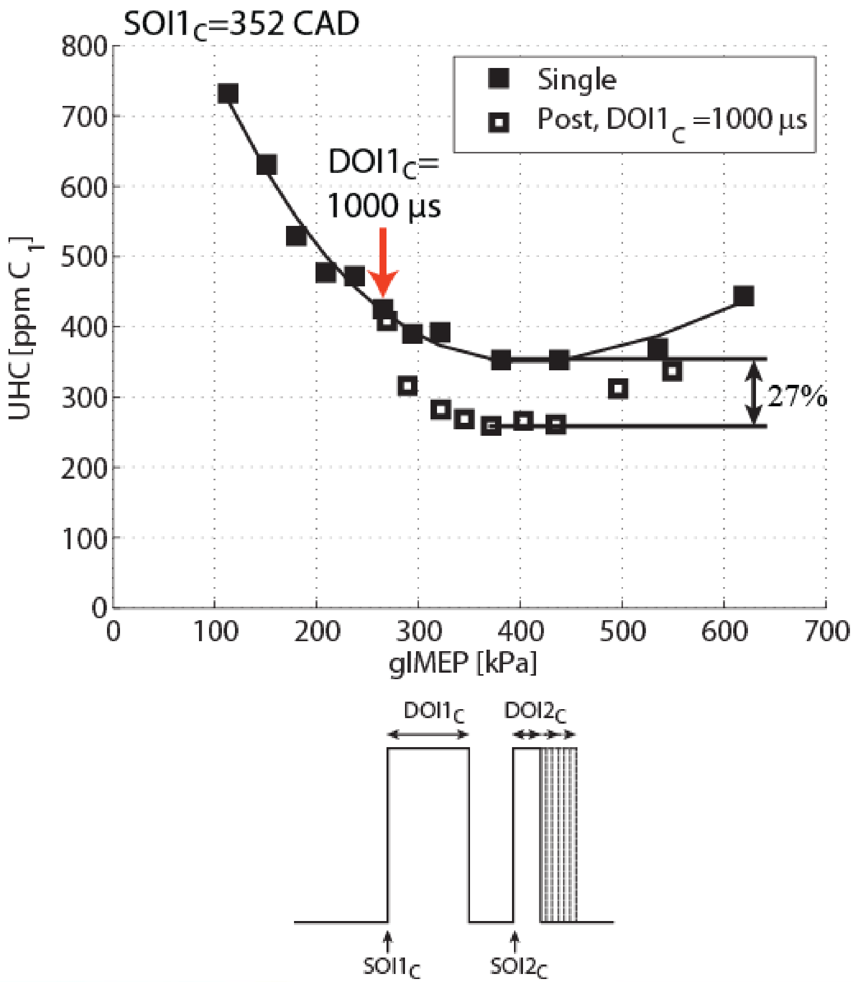
- Addition of a post injection lowers engine-out UHC emissions at a range of $DOI2_C$
- Minimum UHC measured at $DOI2_C$=400 µs
- Longer post injections do little to reduce UHC – seem to asymptote to single-injection trend





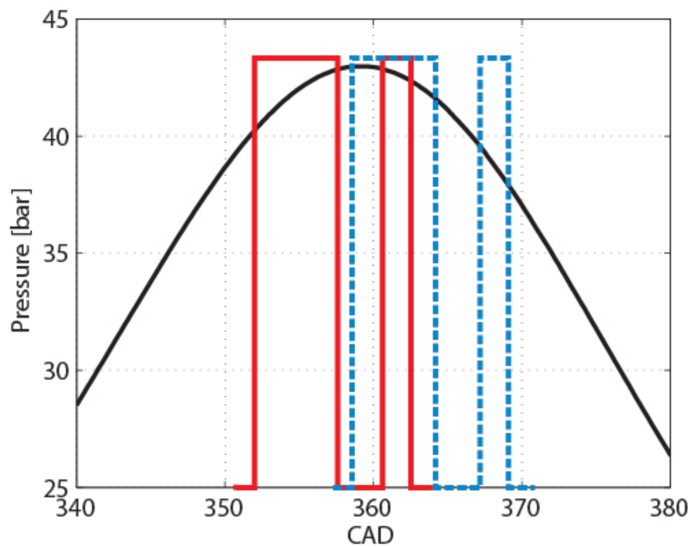
Main + Post Injections: Post injections can reduce UHC emissions by up to 27%

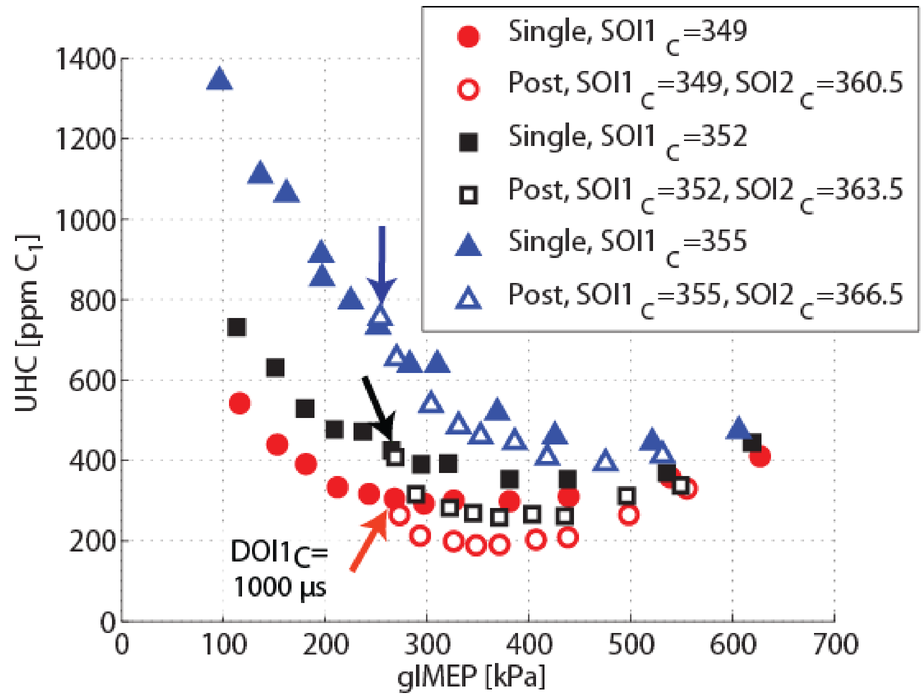
- Addition of a post injection lowers engine-out UHC emissions at a range of $DOI2_C$
- Minimum UHC measured at $DOI2_C$=400 μs
  - Maximum reduction of 27% at constant load
- Longer post injections do little to reduce UHC – seem to asymptote to single-injection trend



Main + Post Injections: Sensitivity to Chemical Effects ($SOI1_C$)

- Trend in post-injection efficacy is similar over three $SOI1_C$
  - Short post injections do little to reduce UHC emissions
  - Minimum engine-out UHC occurs with post-injection durations close to 400 µs

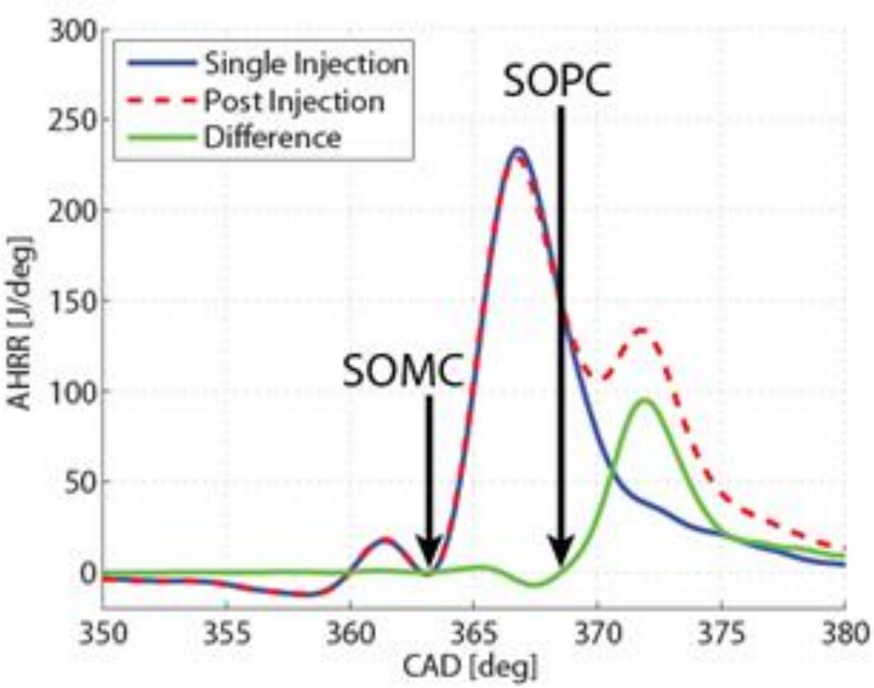




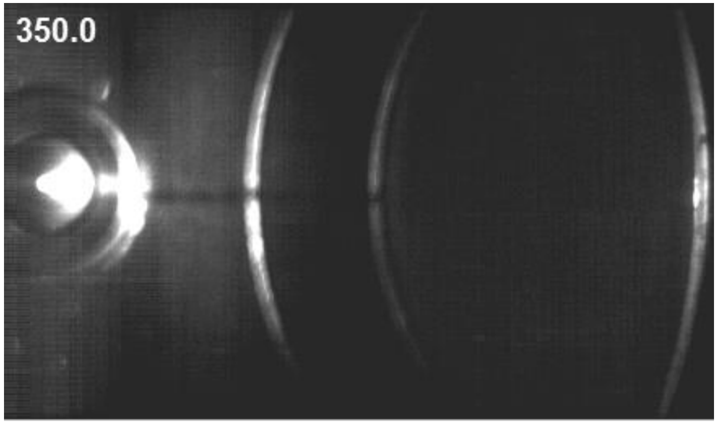
Calculation of Ignition Delay

- Ignition delay = SOC [°CA] – SOI [°CA]

Start of combustion (SOC)

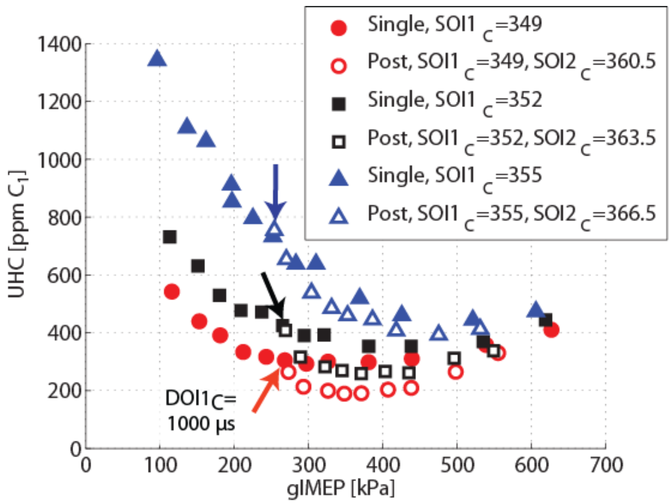


Start of injection (SOI)



Main + Post Injections: Changes to $SOI1_C$ alter post-injection ignition delay

- Significant changes in ignition delay of the post-injection mixture at these three timings
  - $SO1_C$=349 CAD, ID_{post}=3.4 °CA
  - $SO1_C$=352 CAD, ID_{post}=3.6 °CA
  - $SO1_C$=355 CAD, ID_{post}=5.5 °CA
  - Main-injection mixture ignition delay is not significantly different
- Difference in post-injection ignition delay translates to mixing time available for post-injection fuel and overly-lean mixture near the injector

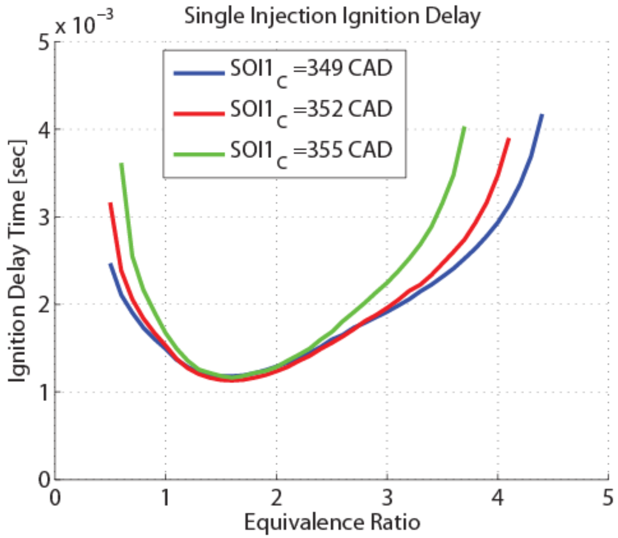


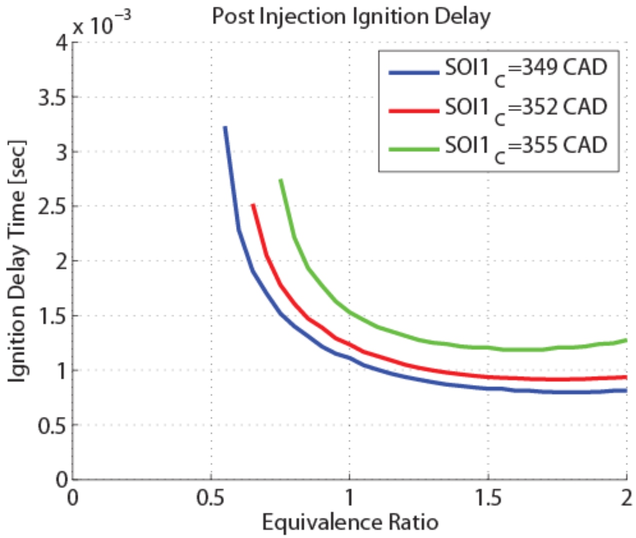
$SOI1_C$ [CAD]	$DOI1_C$ [µsec]	$SOI2_C$ [CAD]	$DOI2_C$ [µsec]	ID_{main} [ºCA]	ID_{post} [ºCA]
352	Varies			9.1	
352	1000	363.5	Varies	9.1	3.8
352	1000	363.25	Varies	9.1	3.4
352	1000	365	Varies	9.2	3.6
355	Varies			9.6	
355	1000	366.5	Varies	9.6	5.5
349	Varies			9.1	
349	1000	360.5	Varies	9.1	3.4

Main + Post Injections: Changes to $SOI1_C$ alter post-injection ignition delay

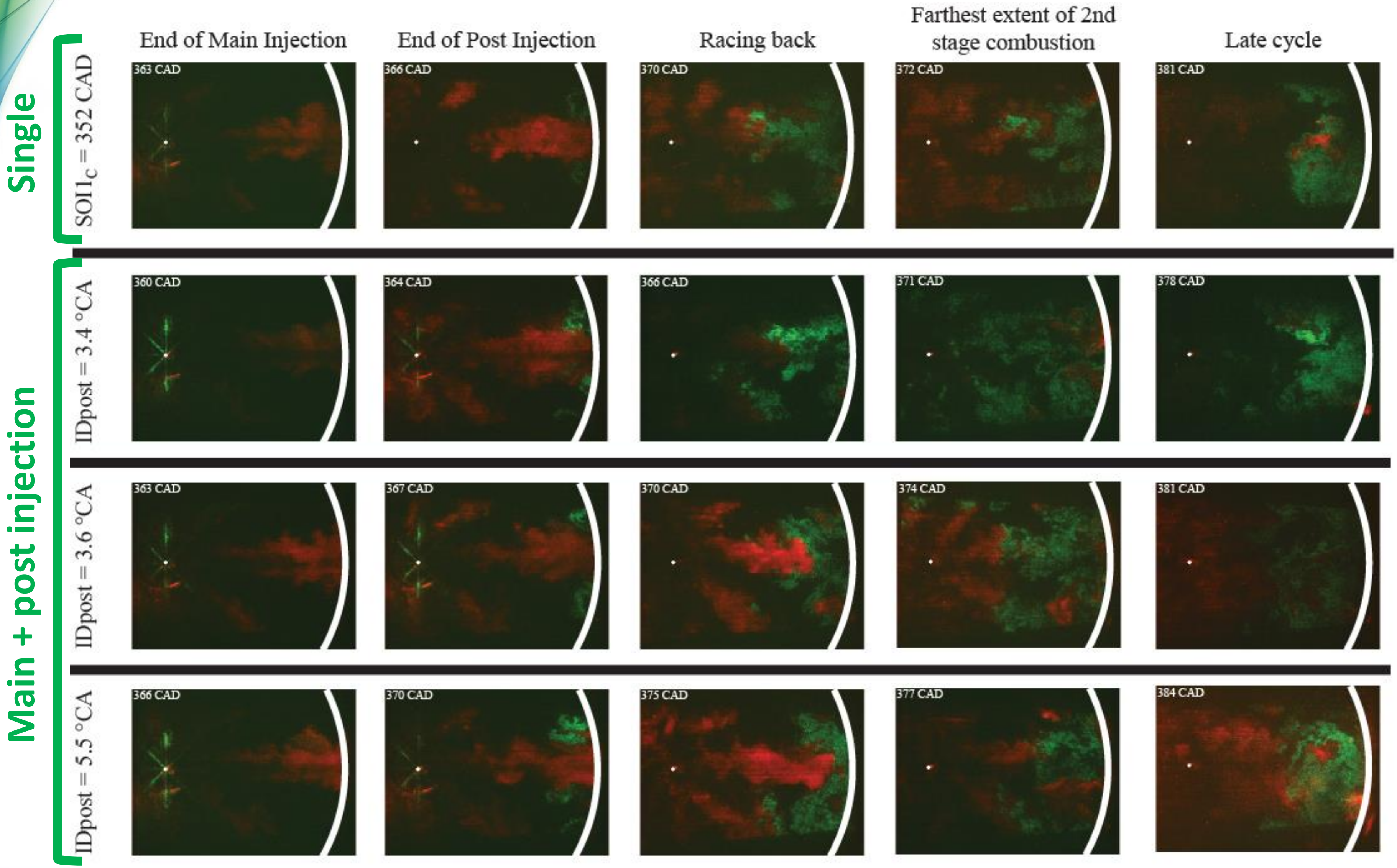
- Chemkin calculations using a homogeneous closed reactor under varying pressure (measured from the engine) calculates very similar ignition delay times for the main injection

- Trend in post-injection ignition delay times is captured in Chemkin calculations, but further work is required to better model post-injection combustion

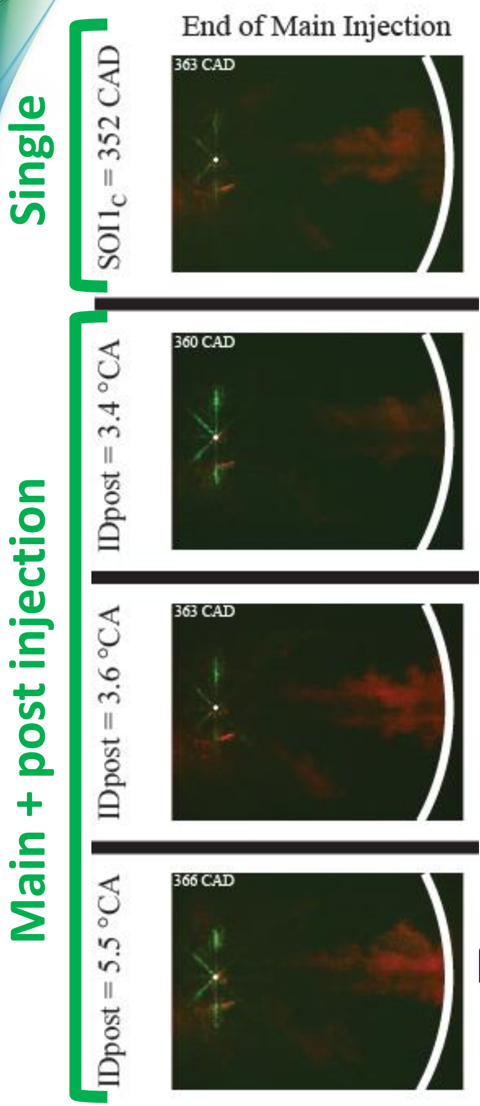




Main + Post Injections: Effect of post-injection ignition delay on UHC

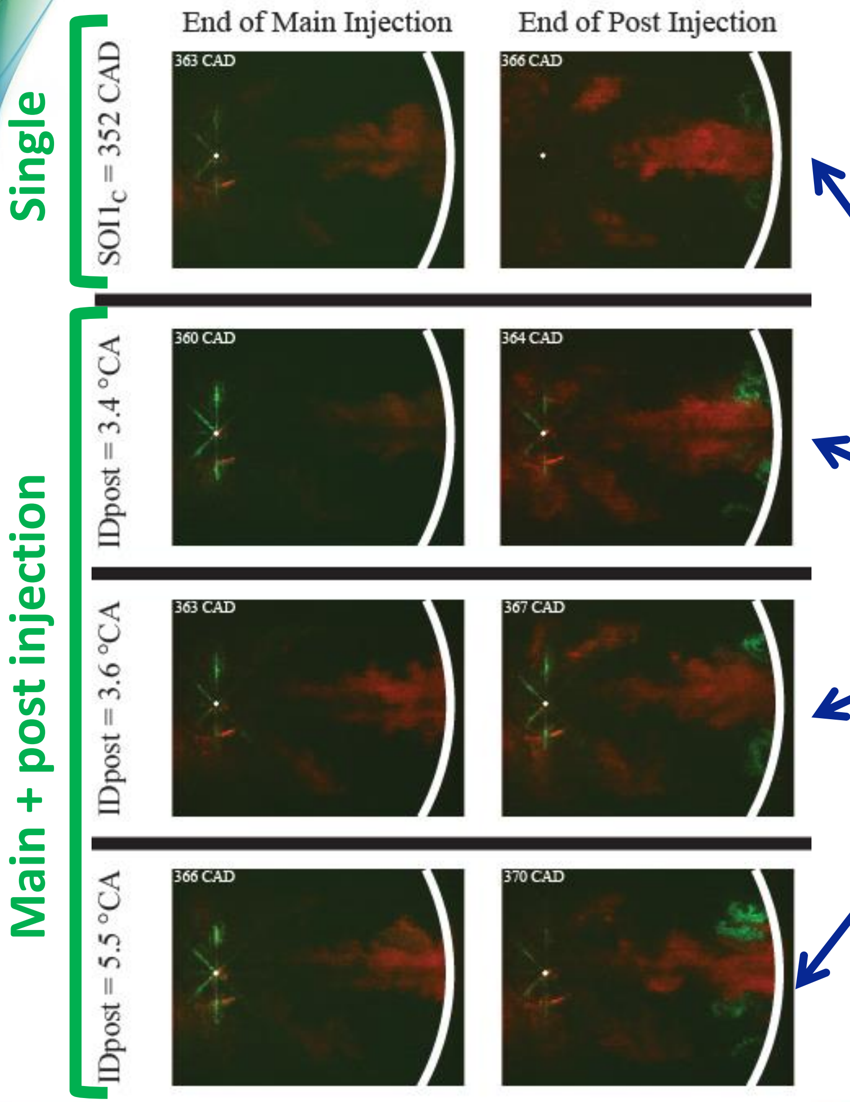


Main + Post Injections: Main injection combustion processes are not sensitive to $SOI1_C$



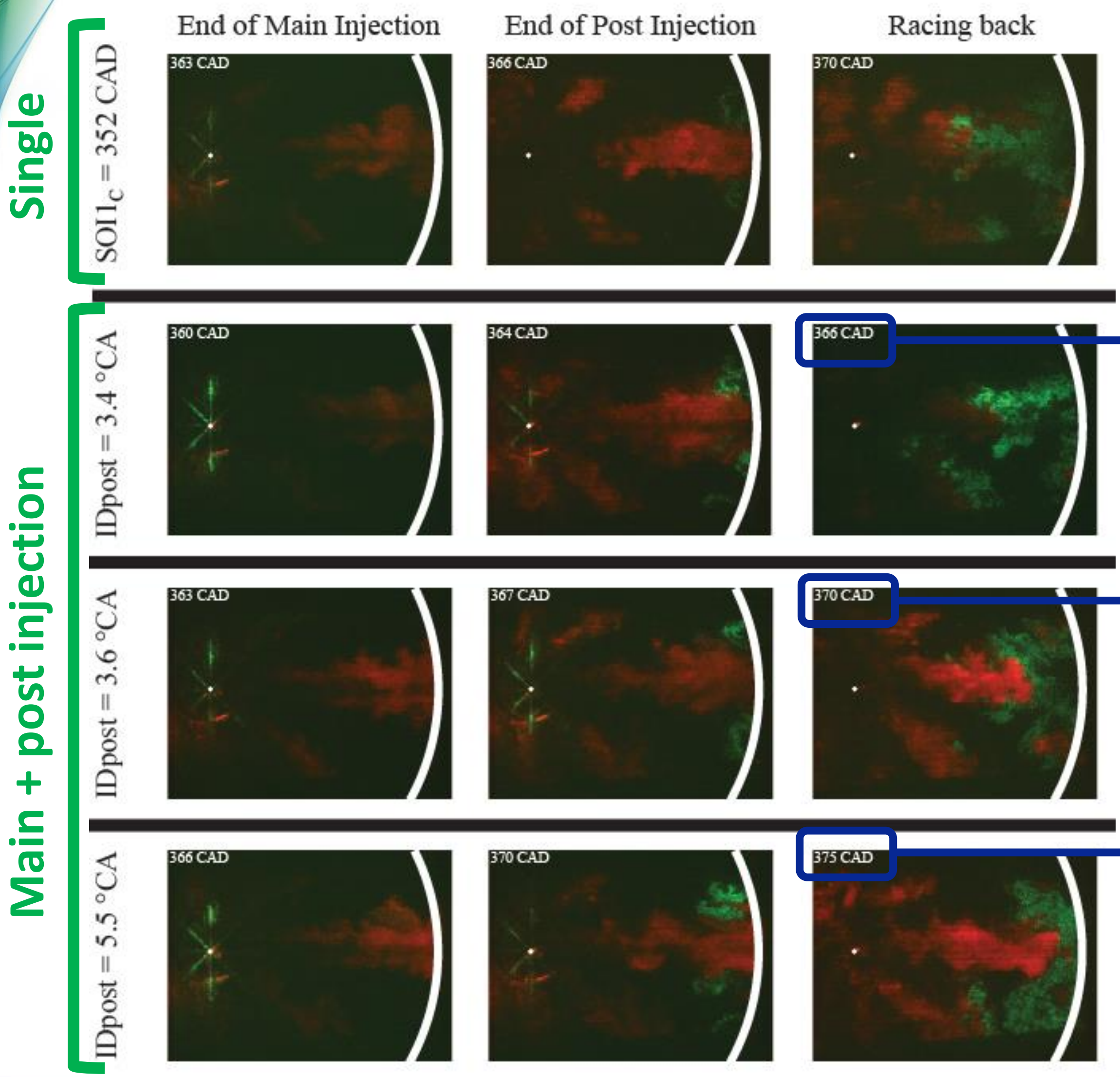
First-stage ignition of the main injection looks similar at all timings

Main + Post Injections: Main injection combustion processes are not sensitive to $SOI1_C$



Second-stage ignition of the main injection looks similar at all timings

Main + Post Injections: Racing back earlier with short post-injection ignition delay

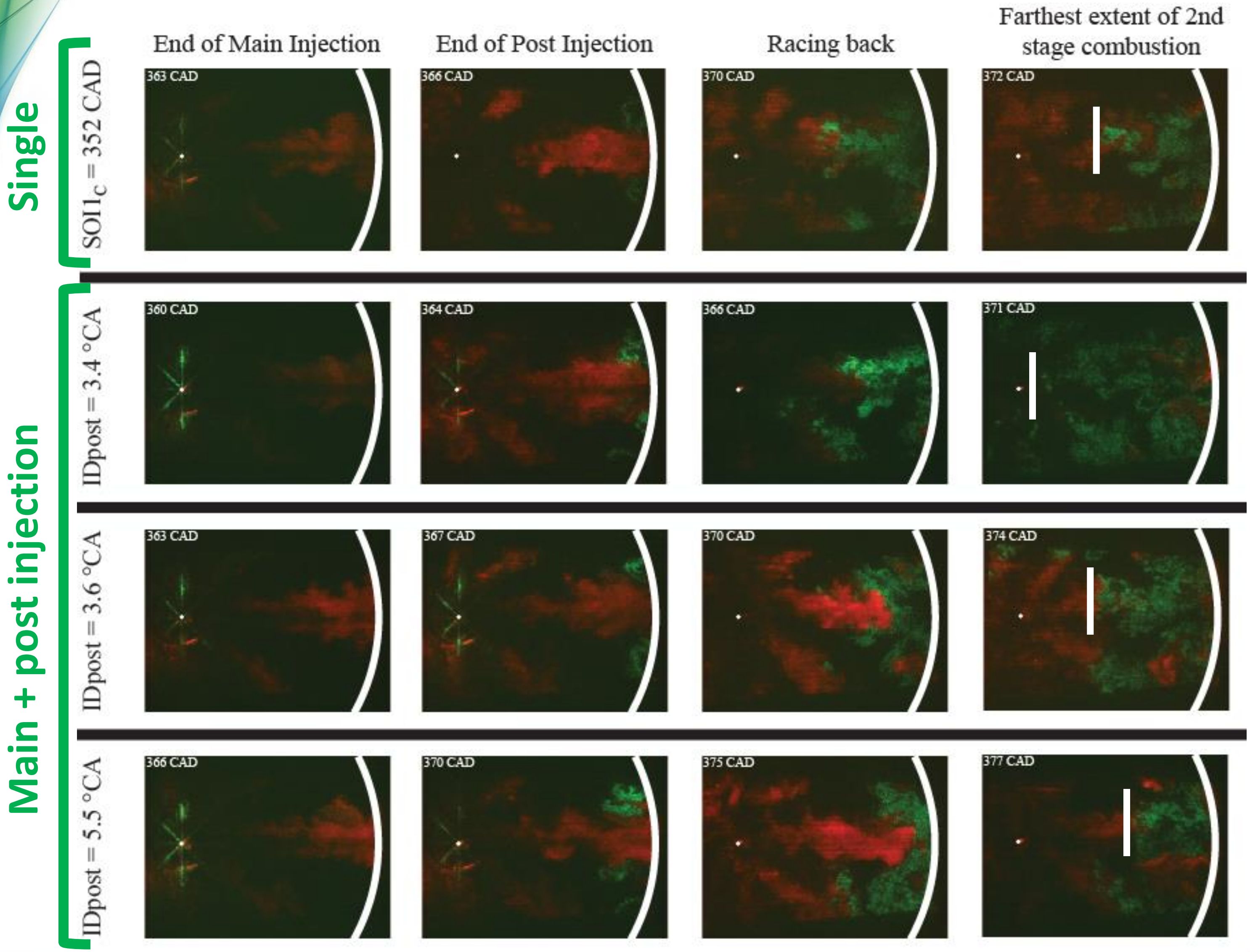


AEI_{post}=2 °CA
ID_{post}=3.4 °CA

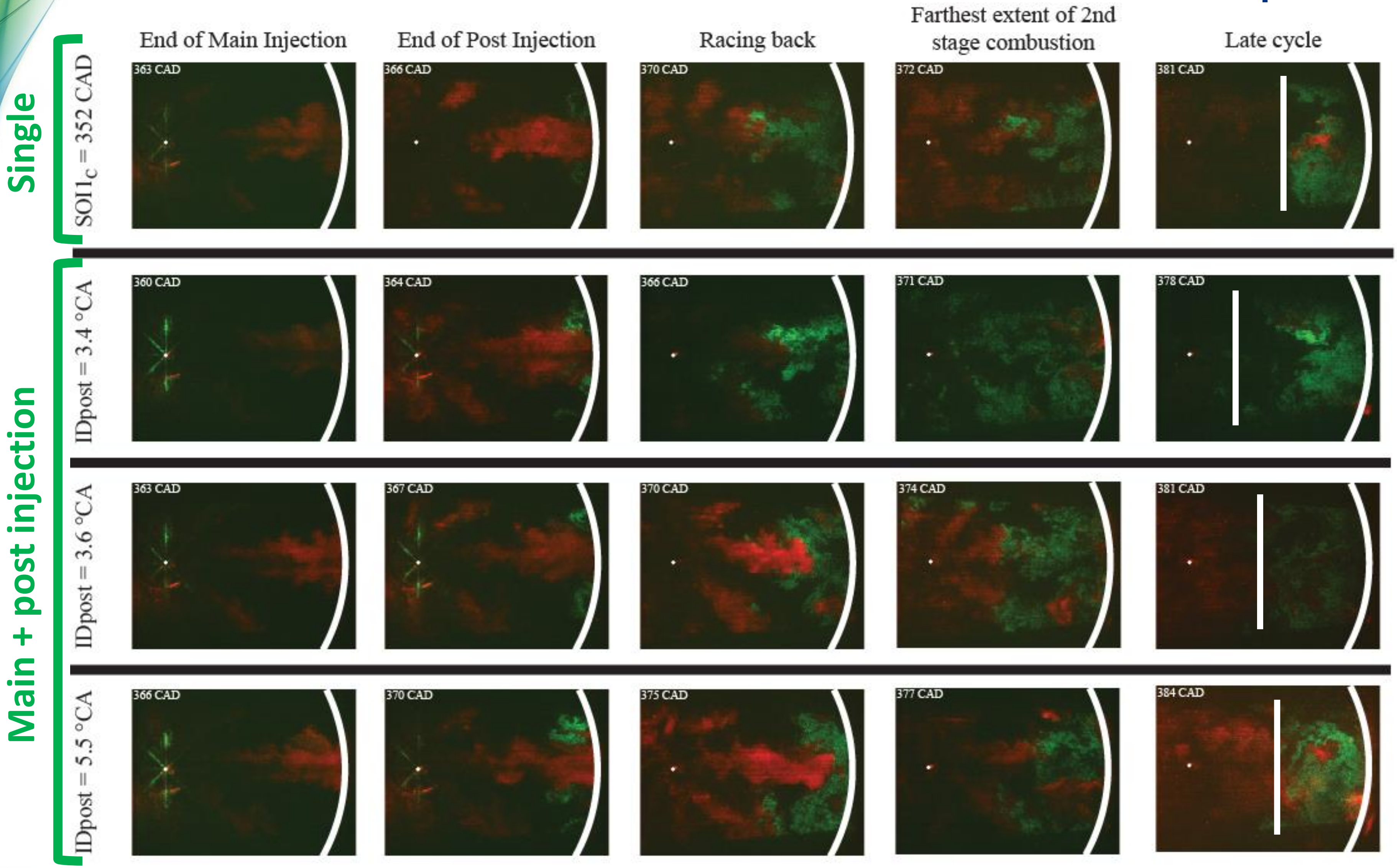
AEI_{post}=3 °CA
ID_{post}=3.6 °CA

AEI_{post}=5 °CA
ID_{post}=5.5 °CA

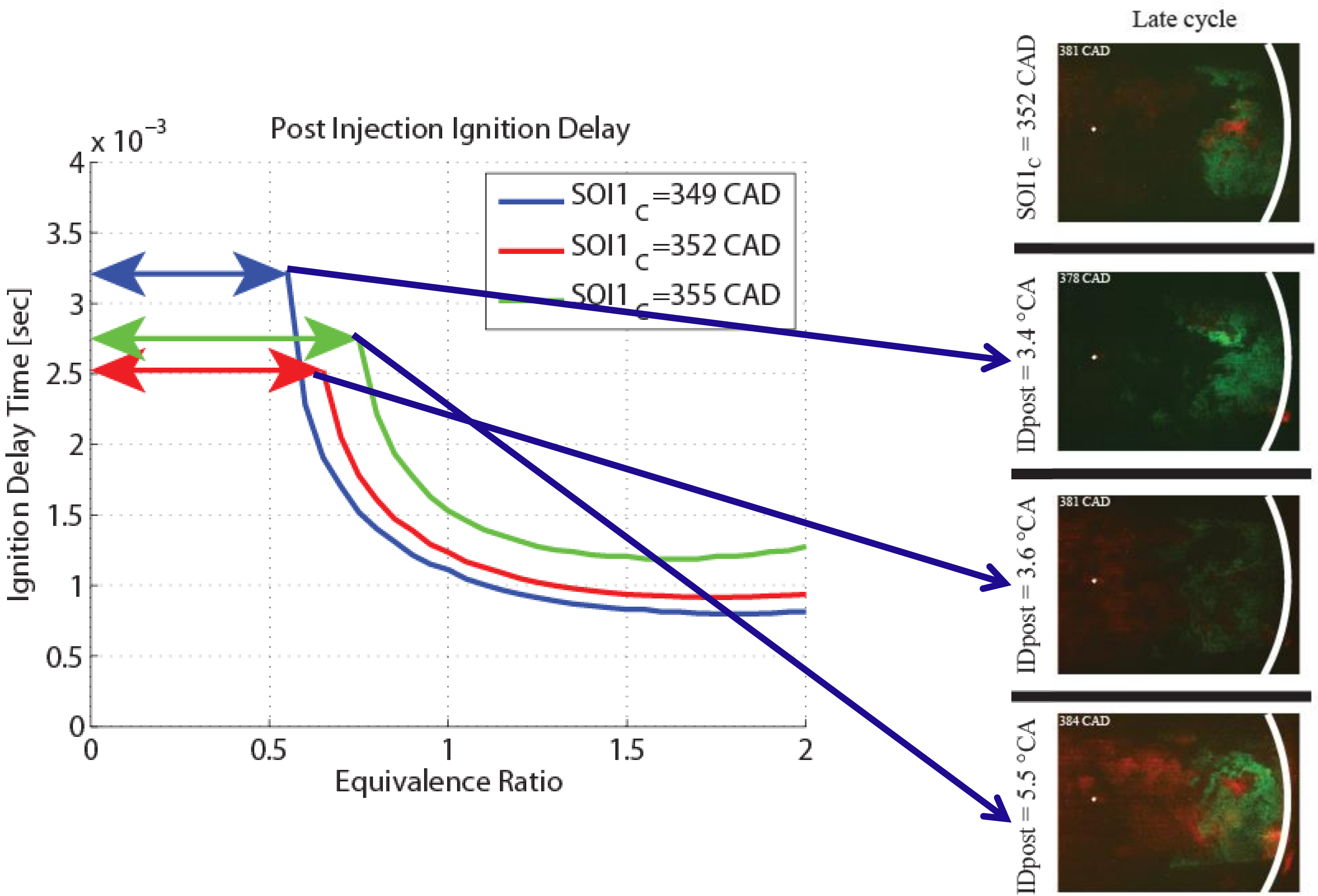
Main + Post Injections: Racing back farther with short post-injection ignition delay



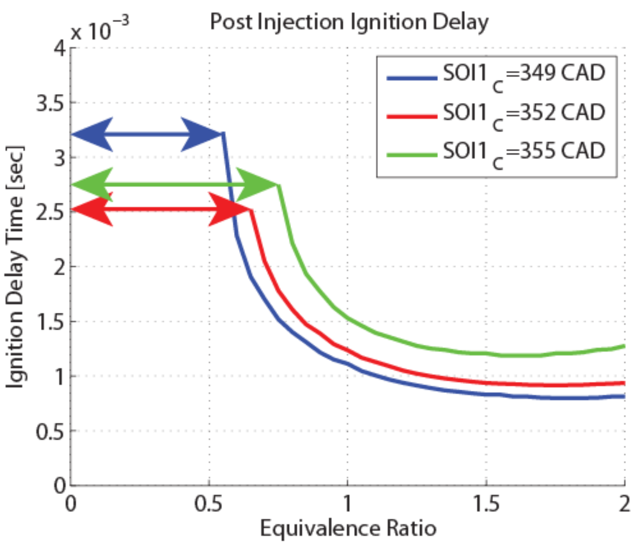
Main + Post Injections: Greater extent of second-stage combustion with short ID_{post}

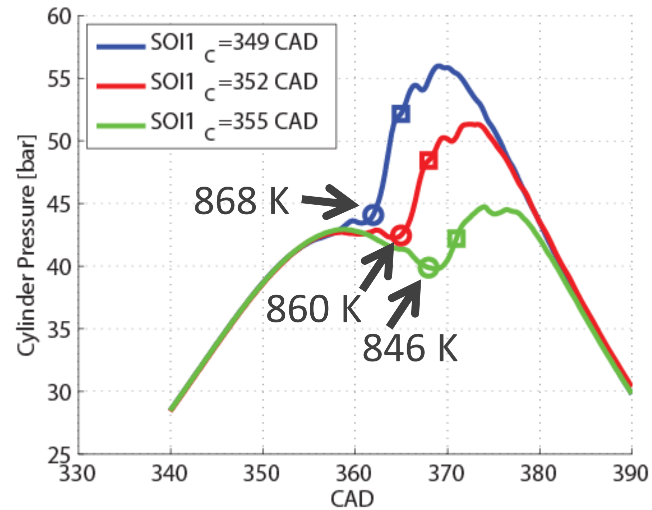


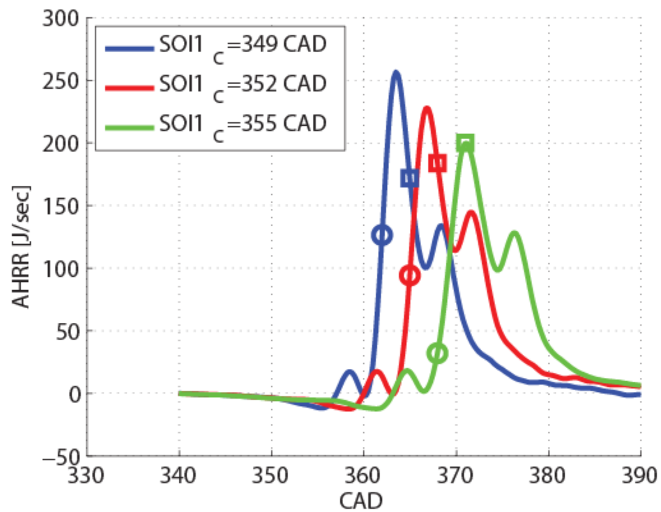
Chemkin modeling indicates larger equivalence ratio range that does not ignite at late timings

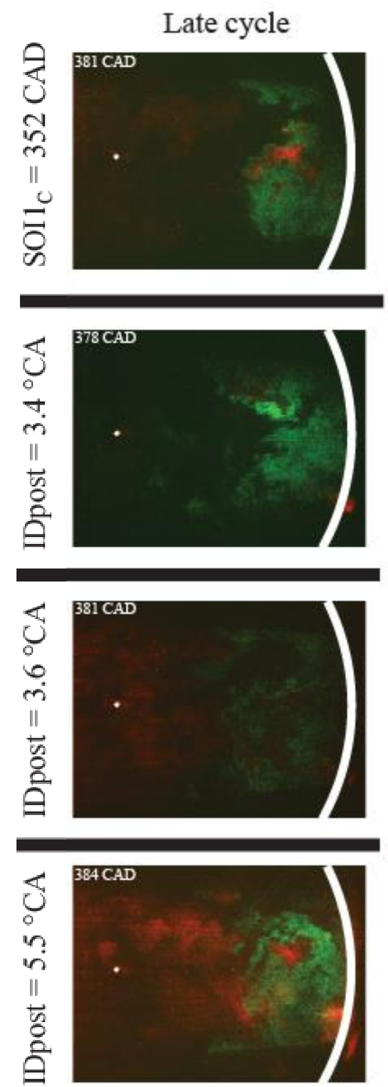


Chemkin modeling indicates larger equivalence ratio range that does not ignite at late timings



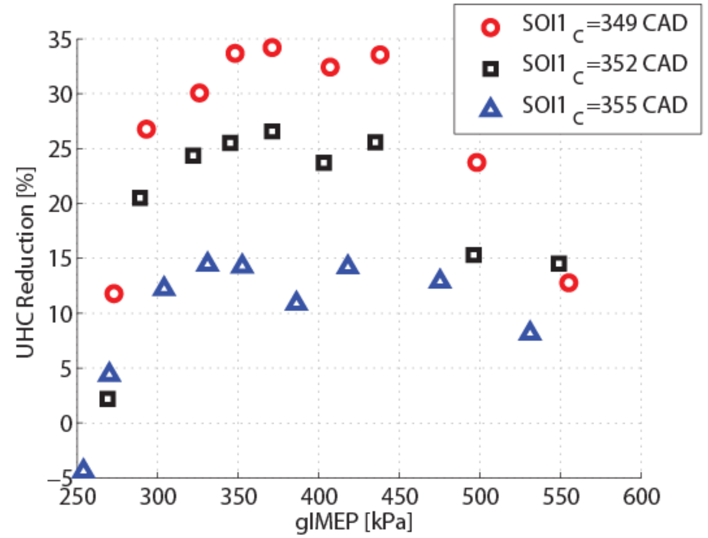


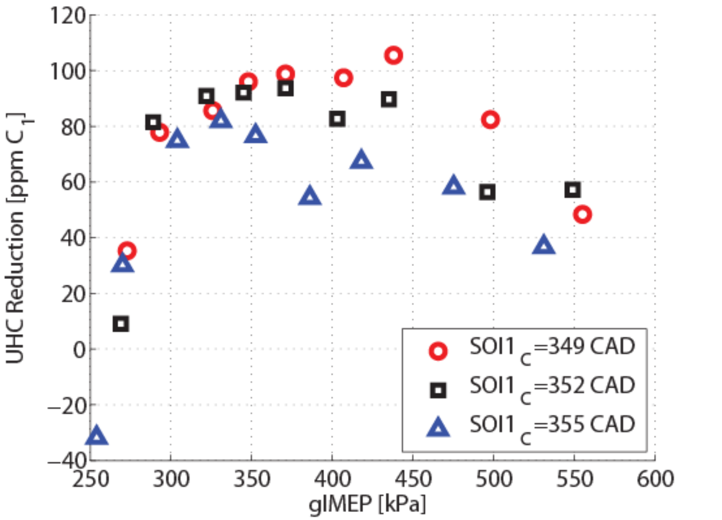




Conclusions: Post injections with short ignition delays are most effective at UHC reduction

- Post injections are **effective at reducing UHC** emissions at LTC conditions
- Post-injection efficacy is **sensitive to post-injection duration and post-injection ignition delay**
- **Shortest post-injection ignition delays** produce the greatest UHC emissions reduction
- Post injections reduce UHC by **enriching overly-lean mixtures** near the injector, allowing second-stage ignition to "race back" further





Example #2: Post Injections Can Reduce Soot at Conventional Diesel Operating Conditions

Post Injections – A Promising In-Cylinder Soot-Reduction Method

DAIMLER

"Daimler Trucks ushers in a new era: the launch of the Mercedes-Benz OM 470x, under the name "Blue Efficiency Power", heralds the arrival of a completely redesigned range of heavy-duty engines that sets a new benchmark in so many ways. … ***A post-injection ensures the almost complete combustion of the particulates***." (Daimler, Mannheim, Mar 18, 2011)

SCANIA

"As the first heavy vehicle manufacturer, Scania introduced Euro V engines utilizing exhaust gas recirculation (EGR) and no exhaust gas aftertreatment. … A pilot injection is used to reduce noise, and ***a post-injection to reduce soot and NOx emissions***." (http://www.dieselnet.com/news/2007/09scania.php)

CATERPILLAR®

"Caterpillar has demonstrated Tier 3 compliance on an ACERT mid-range industrial Cat 3126 engine, with HC+NOx below 2.8 g/bhp-hr and PM below 0.08 g/bhp-hr (the Tier 2 PM standard is 0.15 g/bhp-hr). … ***Multiple injections allow the use of a late "post-injection" event for PM control***, which can allow further injection timing retard for NOx control." (http://www.dieselnet.com/news/2001/11epa.php)

RENAULT

"Laguna will be premiering the Renault-Nissan Alliance's new 2.0 dCi engine, a 1995 cc unit featuring up-to-the-minute diesel engine technologies. … ***The post-squirts sustain the main injection combustion, to burn off soot and thus bring down pollutant emissions before the exhaust gases have even left the combustion chamber***." (http://www.renault.co.ir/html/%23Agu-Newsletter/Engine-en.php)

Post-Injection Soot Reduction Mechanisms: Mixing vs. Thermal vs. Duration

Enhanced Mixing

- The post injection enhances mixing of fuel and air to suppress soot formation and/or soot and air to enhance soot oxidation
- Fluid mechanic effect

Increased Temperature

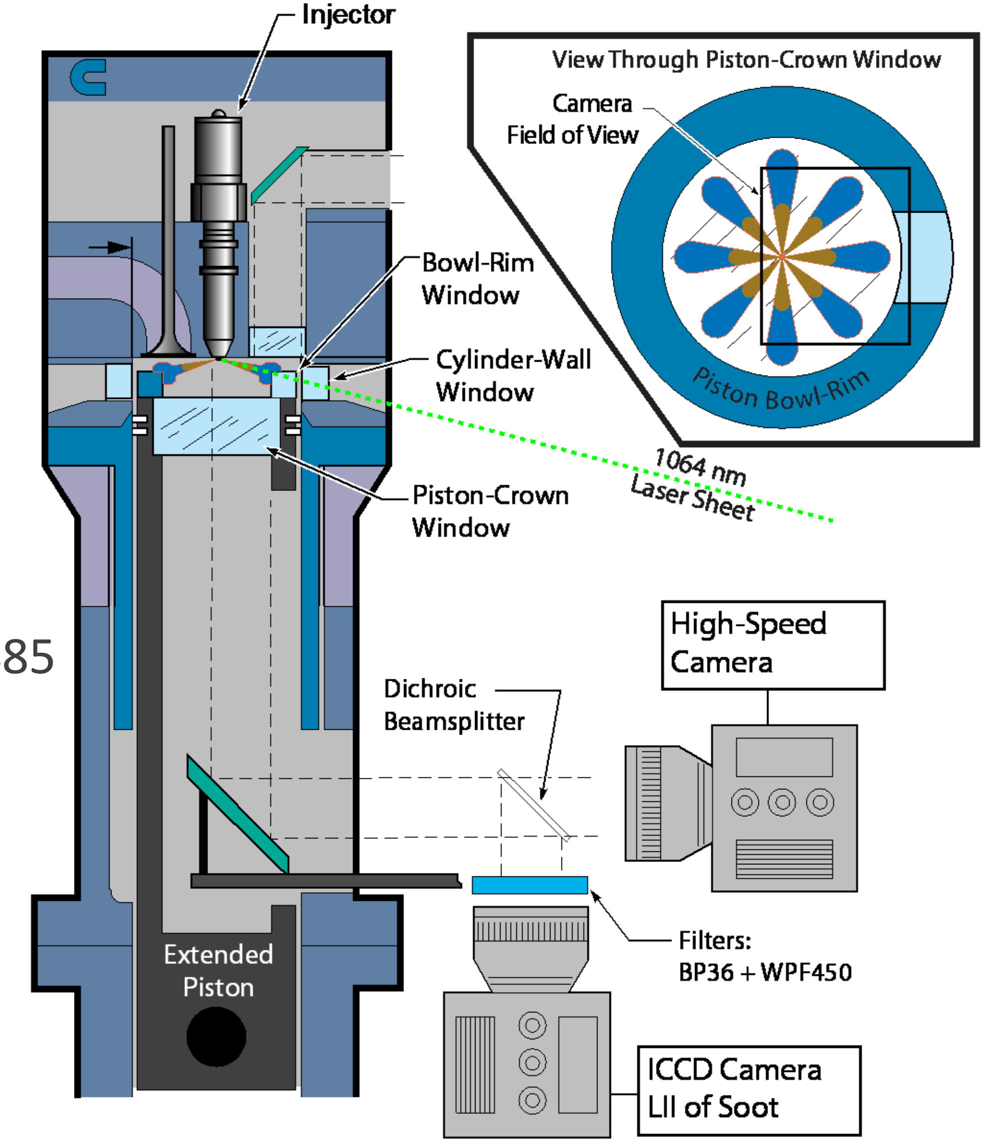
- Additional heat release from the post-injection fuel raises chamber temperatures
- Increased temperature enhances soot oxidation

Injection Duration Effects

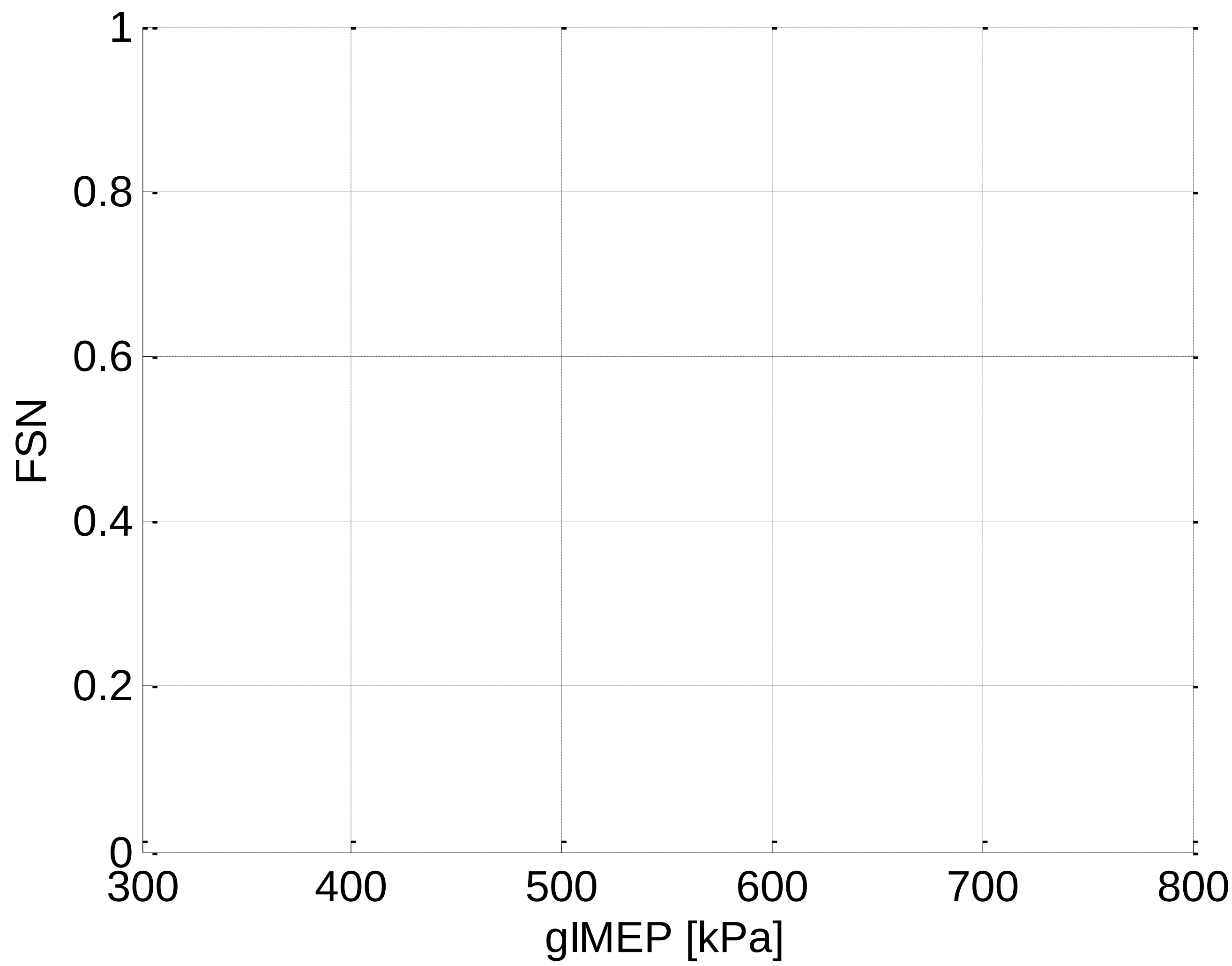
- Net soot increases non-linearly with injection duration
- Shorter main + post yields less soot than longer main injection
- Minimal enhanced oxidation, just less soot exhausted at a given load

Experimental Methodology: LII, High-speed Visualization, Exhaust Soot Measurements

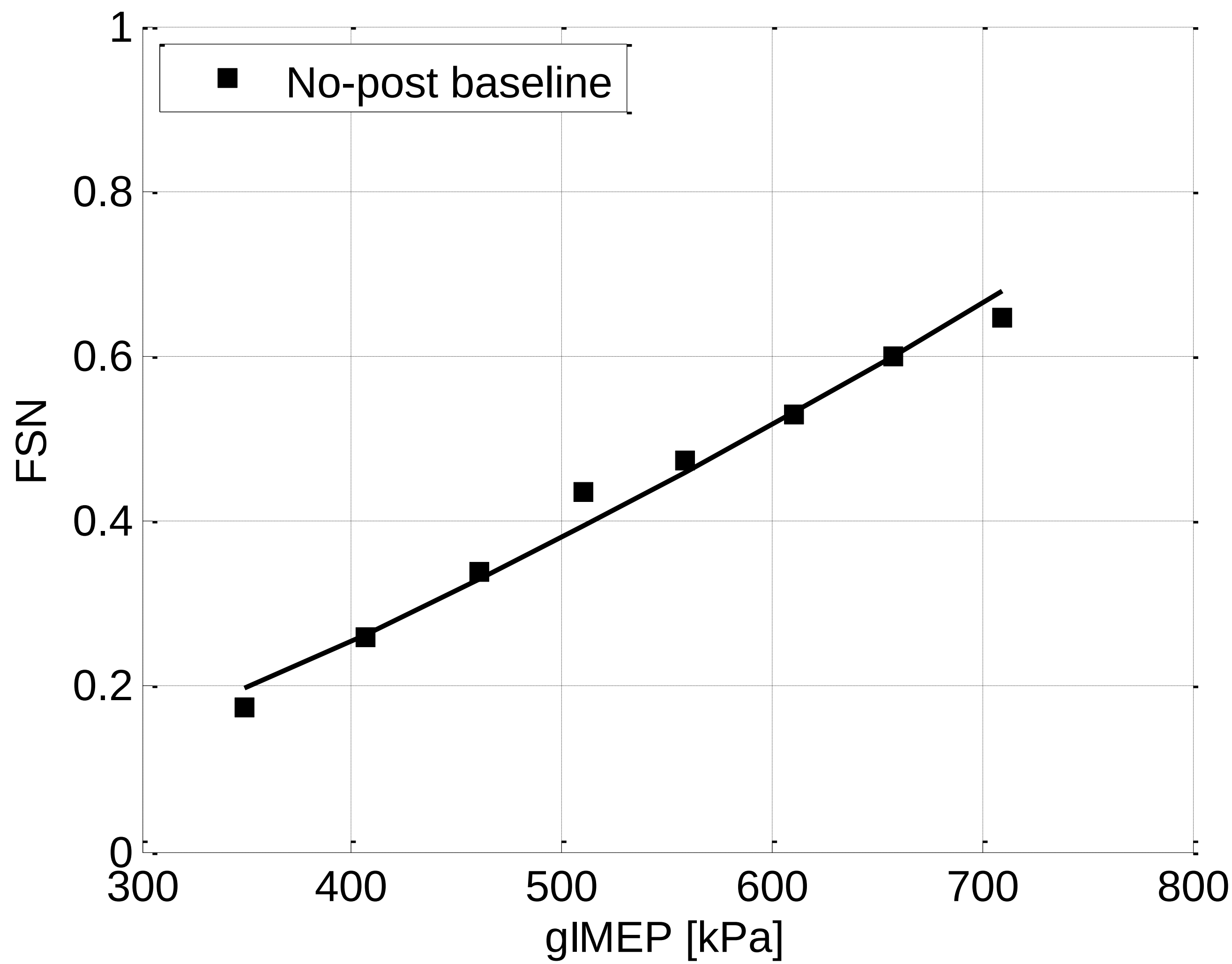
- High-speed visualization
  - Measure soot luminescence at λ>485 nm, *dt*=½ CAD
- Laser-induced incandescence
  - Excitation at λ=1064 nm, 130 mJ/pulse
  - Measure incandescence at λ<485 nm with PI-Max, t_{exp}=15 ns
- Soot measurements
  - AVL 415S smoke meter



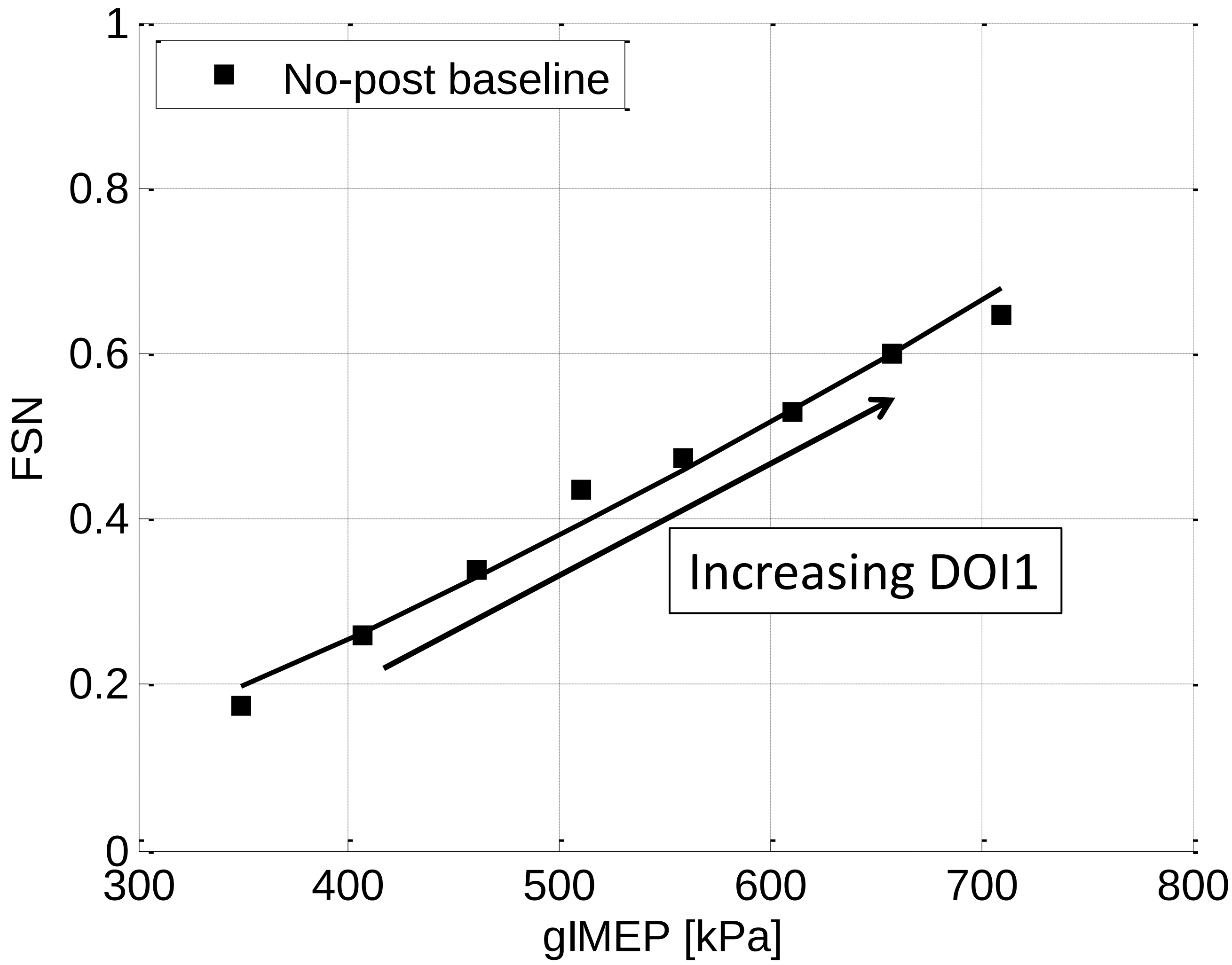
18% O_2 (19-29% EGR): Exhaust Soot Minimized as Close-Coupled Post Duration Increases



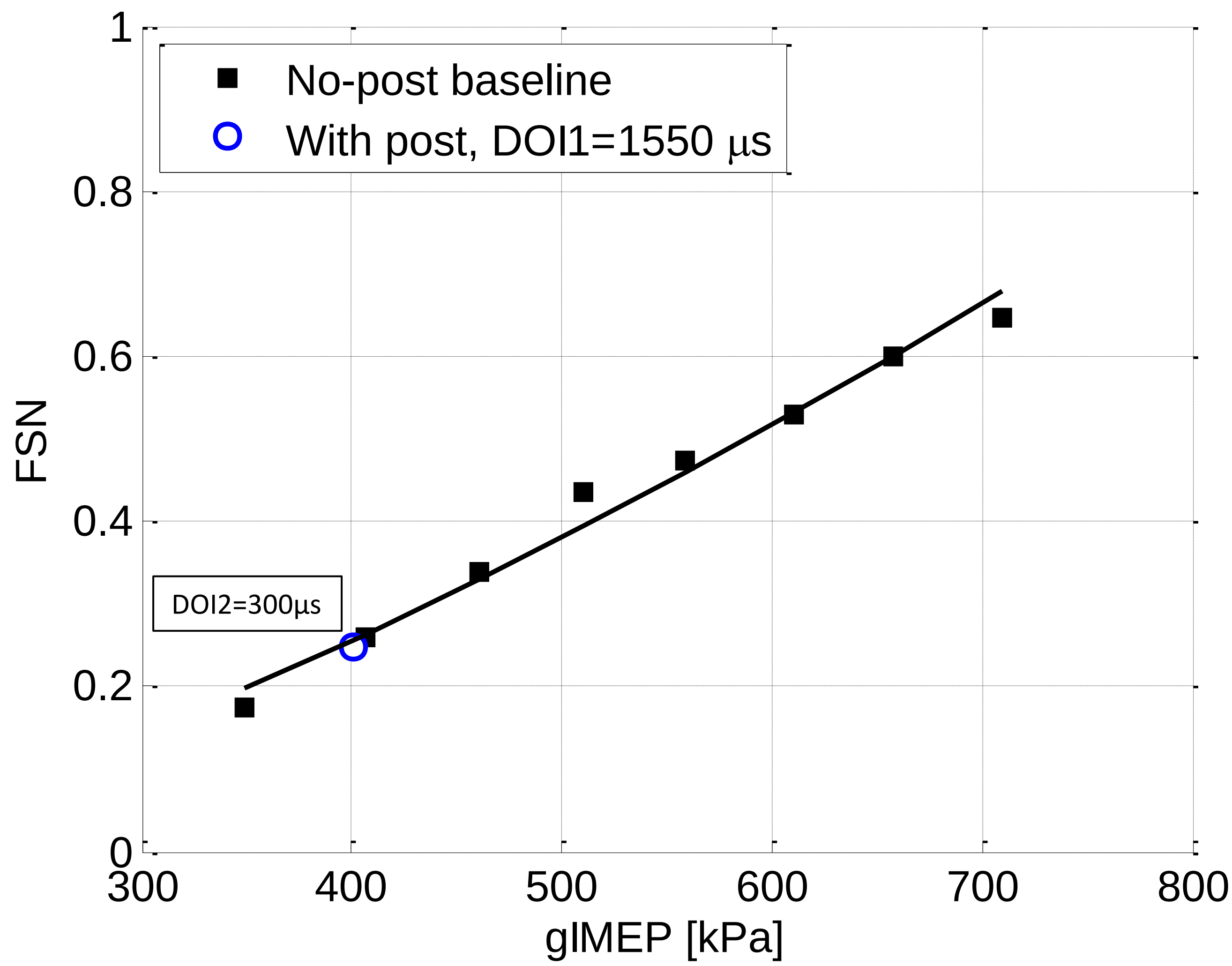
18% O_2 (19-29% EGR): Exhaust Soot Minimized as Close-Coupled Post Duration Increases



18% O_2 (19-29% EGR): Exhaust Soot Minimized as Close-Coupled Post Duration Increases



18% O_2 19-29% EGR): Exhaust Soot Minimized as Close-Coupled Post Duration Increases



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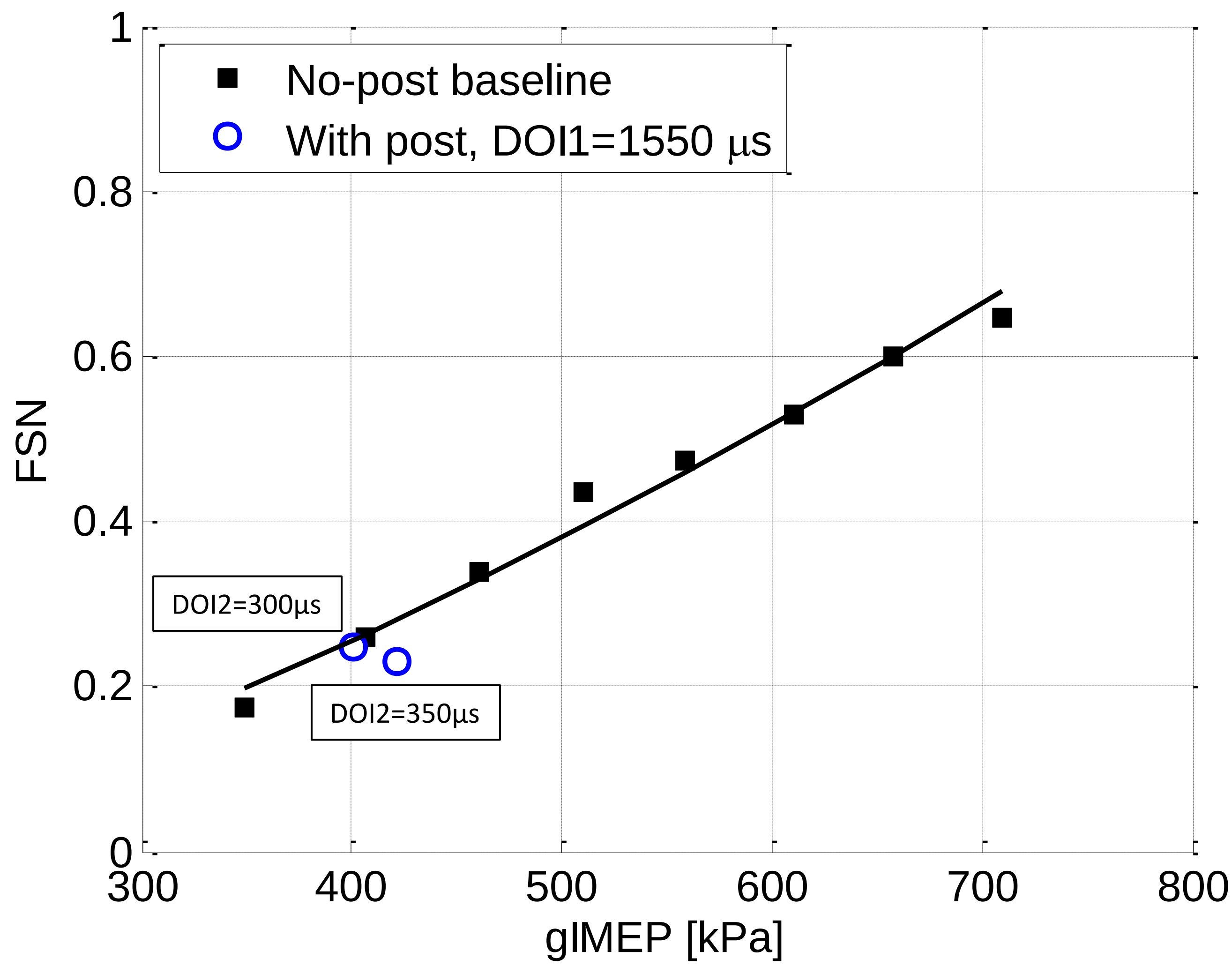

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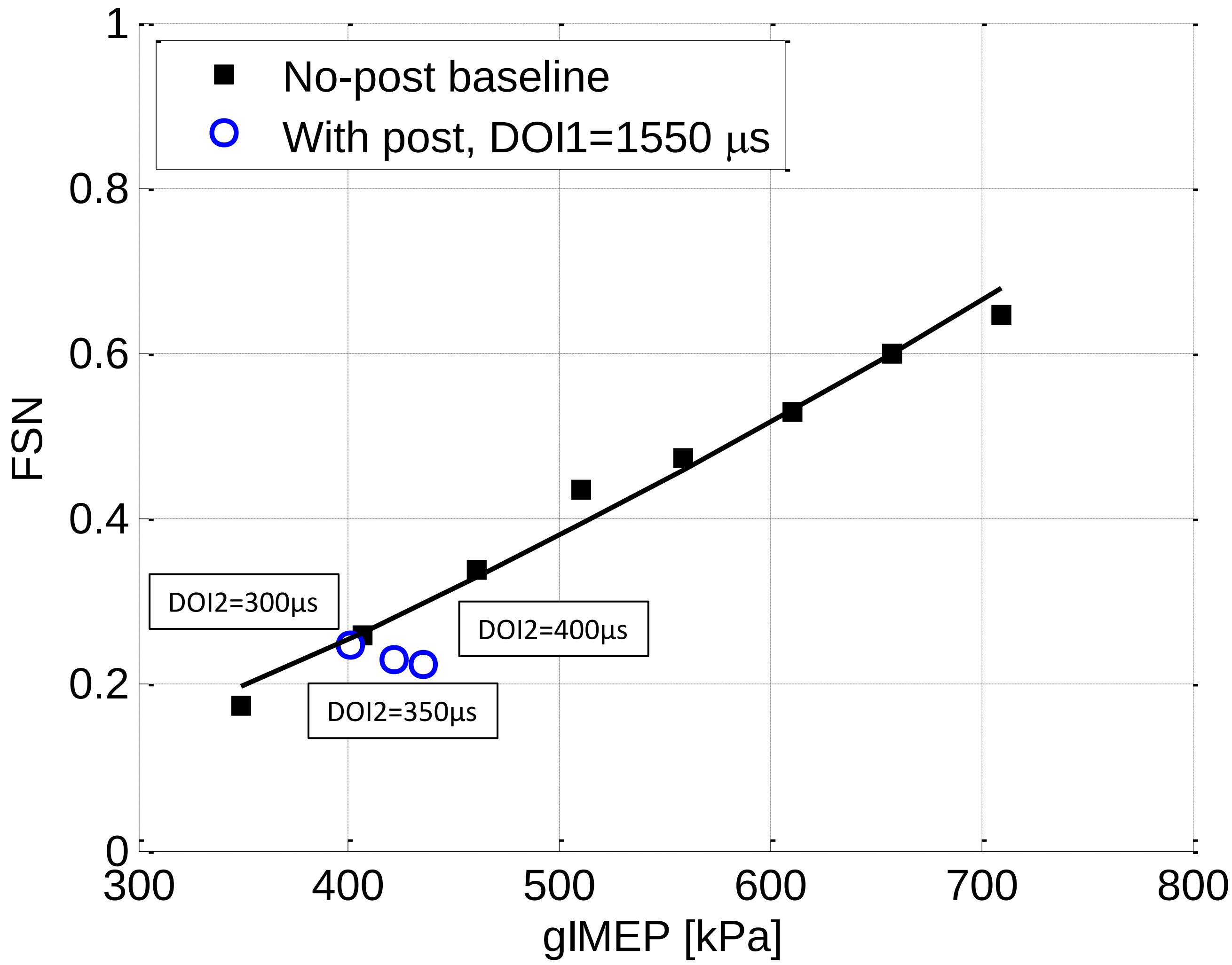

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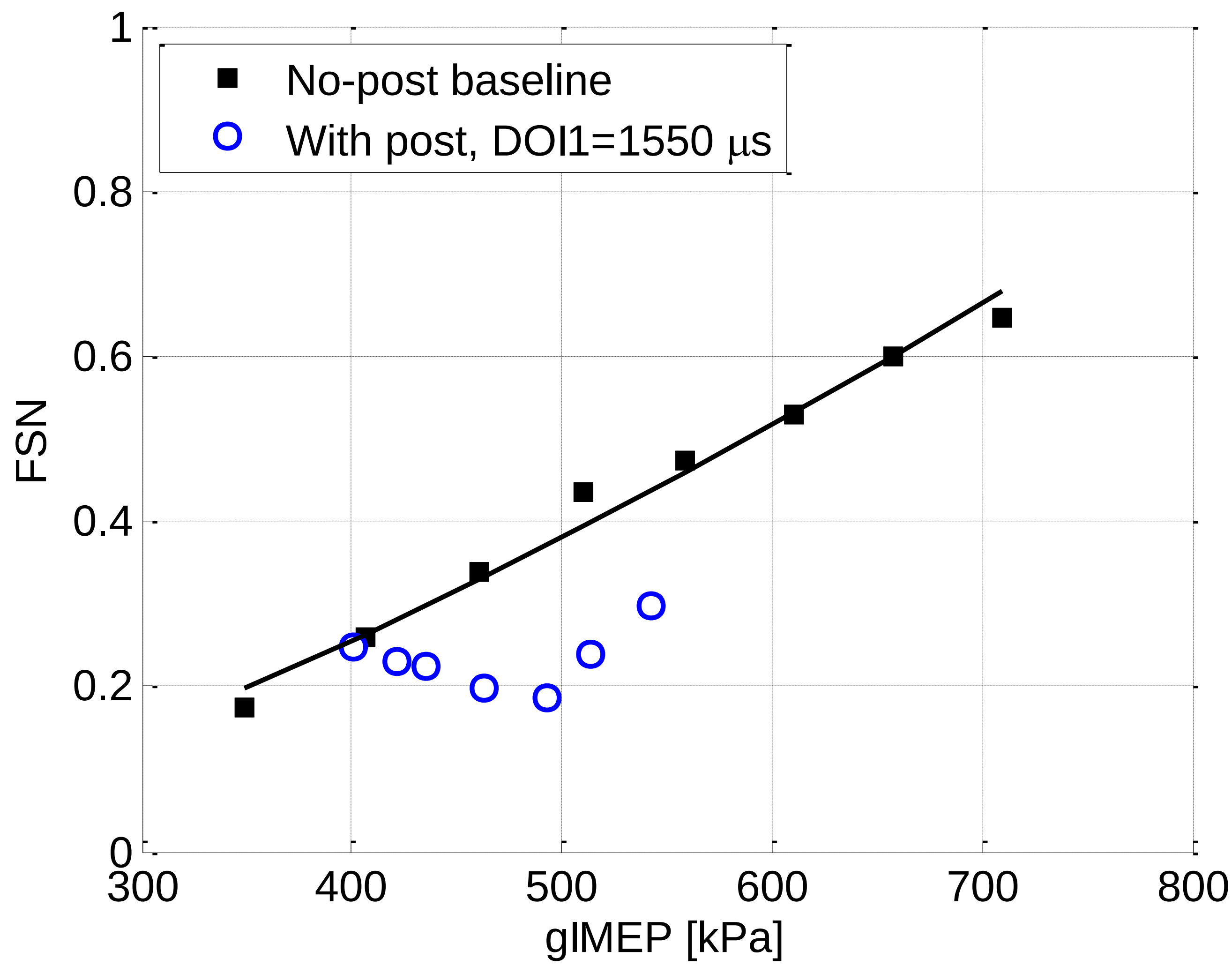
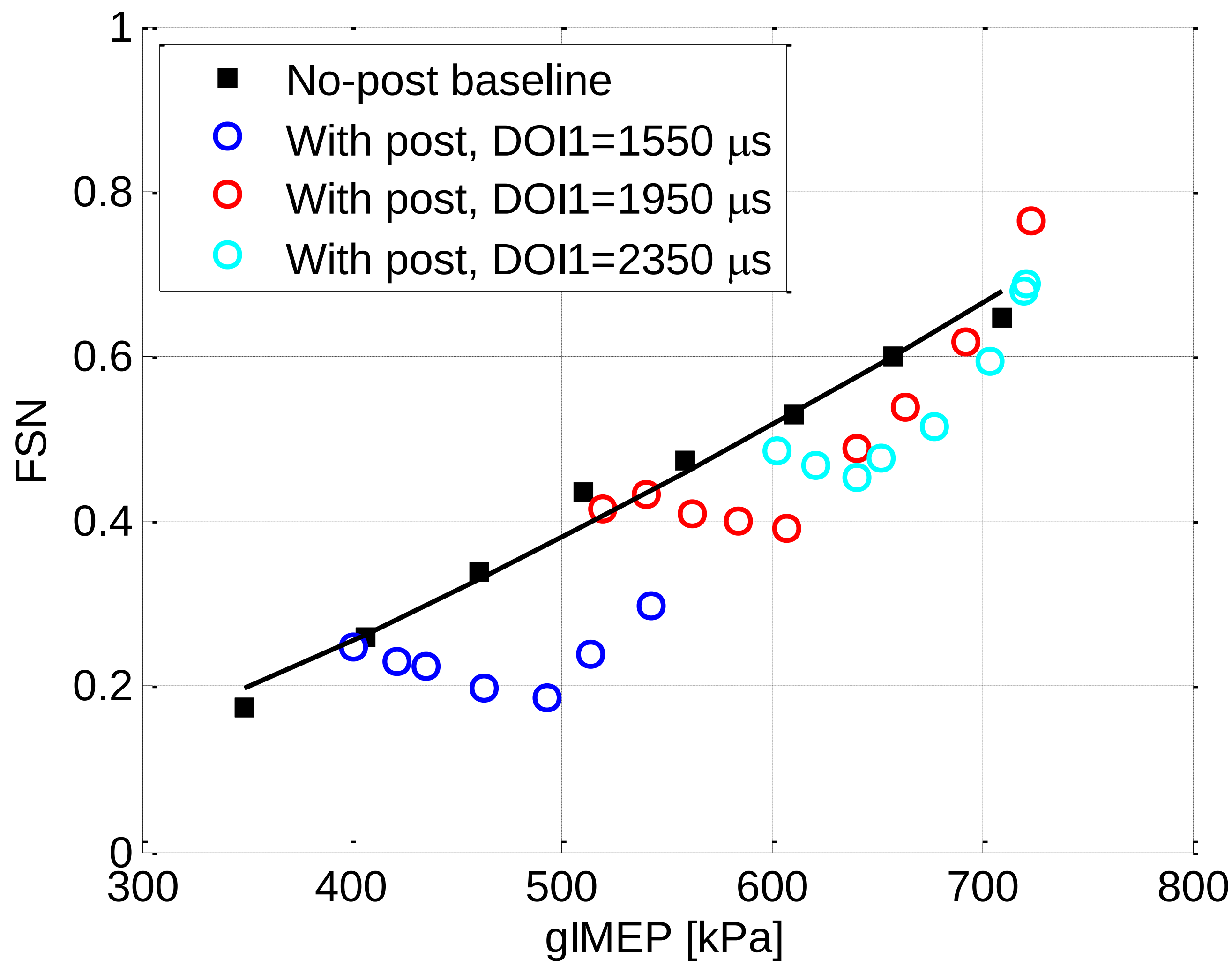


$18\% O_2$ (19-29% EGR): Exhaust Soot Minimized as Close-Coupled Post Duration Increases



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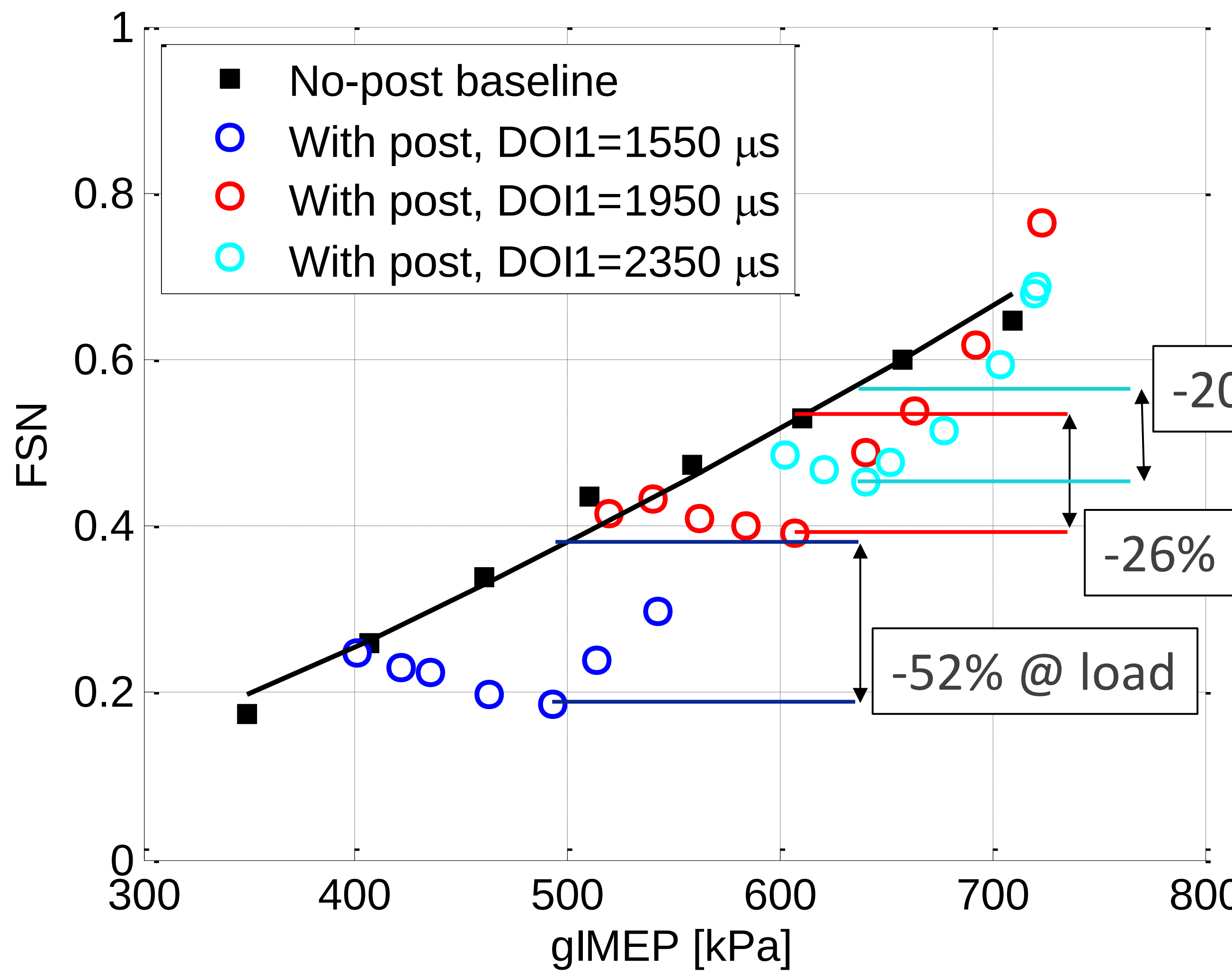

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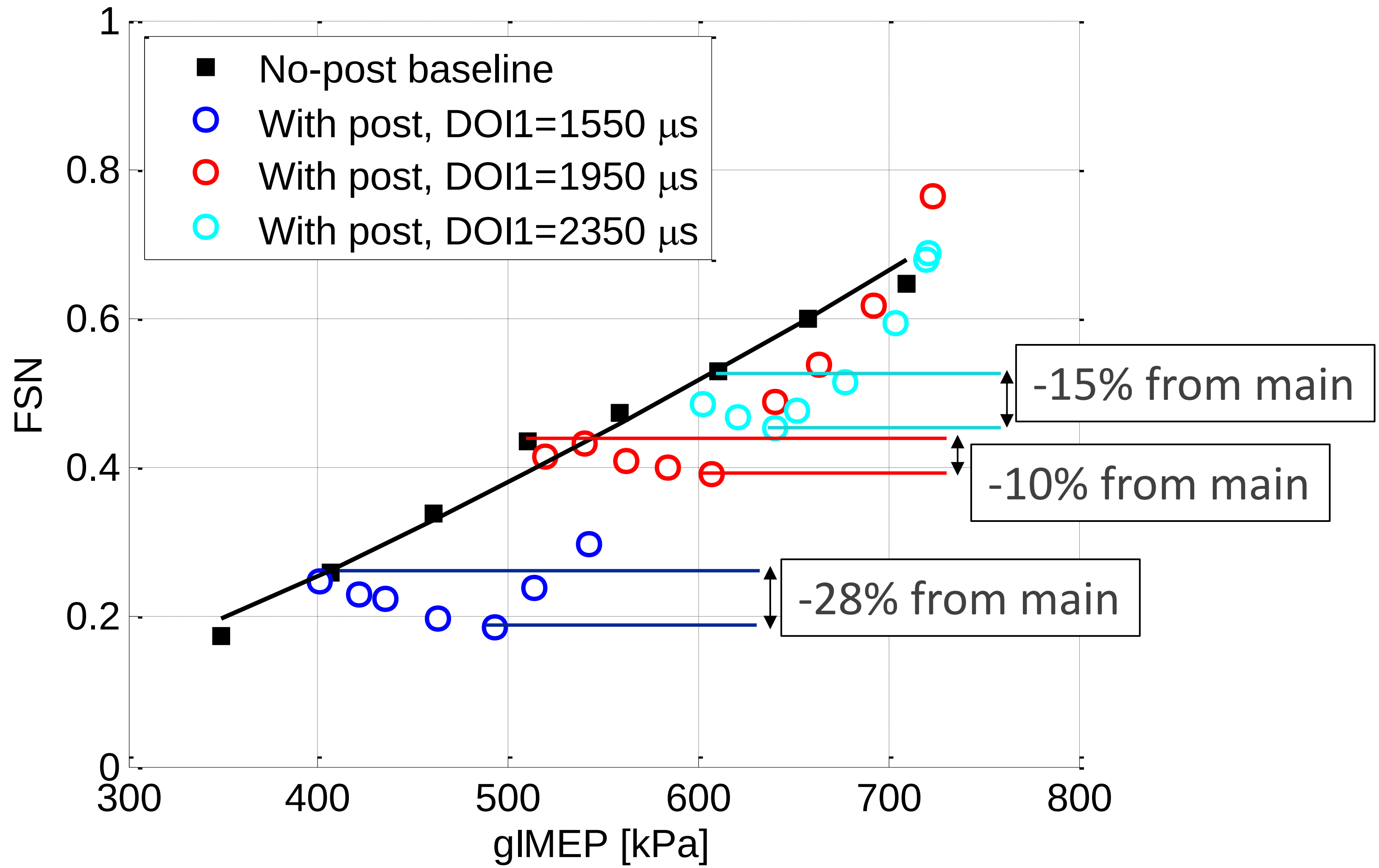


Post Injections Reduce Soot by Interacting with the Main-Injection Mixture

Post jet displaces main-injection mixture

- Soot from the main injection forms at the bowl wall
- Post jet penetrates through main-injection mixture
- Displacement could help mixture access additional oxygen

Post jet entrains main-injection mixture

Post jet burns near main-injection mixture

Post Injections Reduce Soot by Interacting with the Main-Injection Mixture

Post jet displaces main-injection mixture

Post jet entrains main-injection mixture

- Soot from the main injection forms at the bowl wall
- Main-injection mixture is entrained into tail of post jet, enhancing large-scale mixing and bringing main-injection soot into the reacting region of the post jet

Post jet burns near main-injection mixture

Post Injections Reduce Soot by Interacting with the Main-Injection Mixture

Post jet displaces main-injection mixture

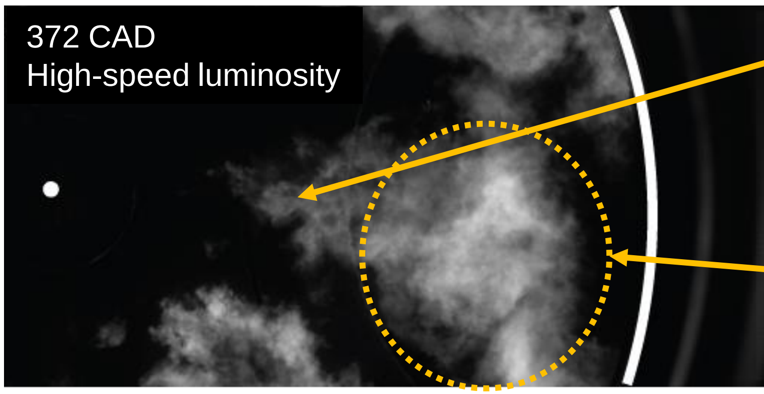
Post jet entrains main-injection mixture

Post jet burns near main-injection mixture

- Soot from the main injection forms at the bowl wall
- Post jet penetrates through main-injection mixture
- Reacting of post jet can locally increase temperature, enhancing soot oxidation

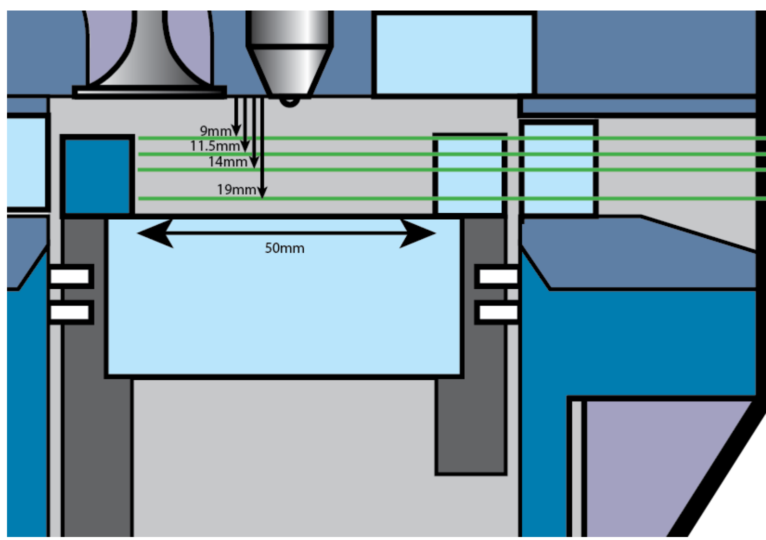
Multi-planar soot-LII provides view into three-dimensional shape of soot-cloud interactions

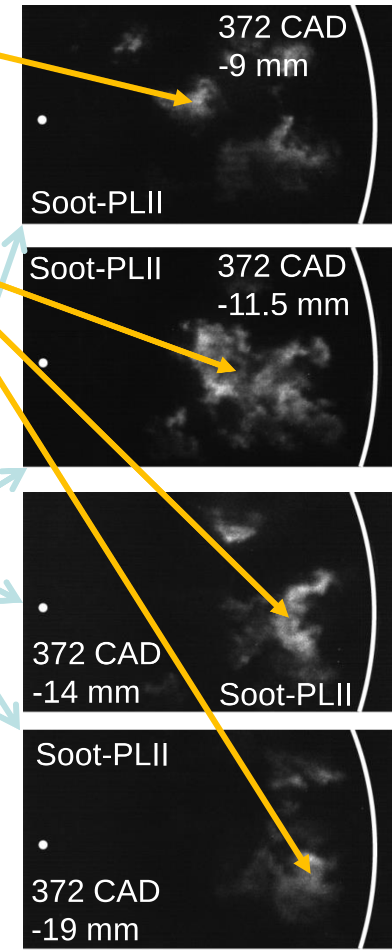
- Horizontal laser sheet aligned at four different distances from firedeck
- Soot-PLII at each elevation helps discriminate main and post soot



Post-injection soot

Main-injection soot



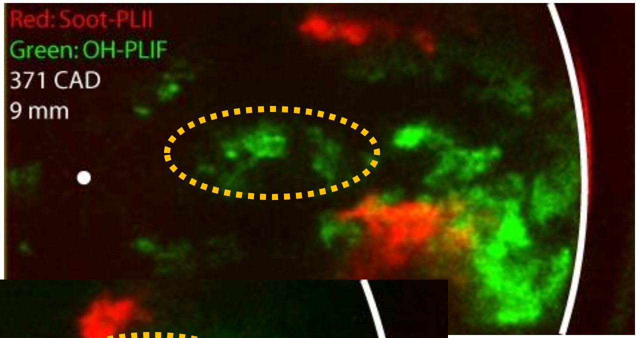


Multi-plane soot-PLII is helpful, but discerning main- from post-soot is often difficult.

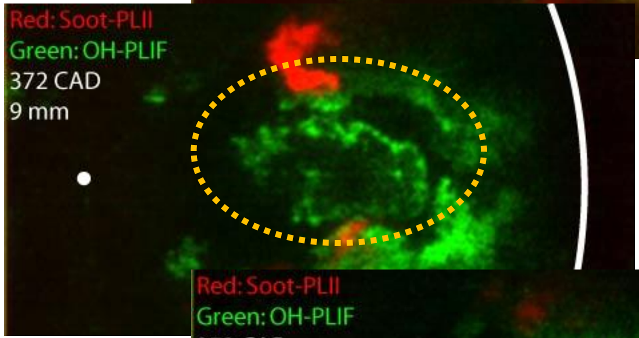
We need a separate indication of jet boundaries.

Adding OH-PLIF to soot-PLII shows post-injection displacing and mixing with main-injection products

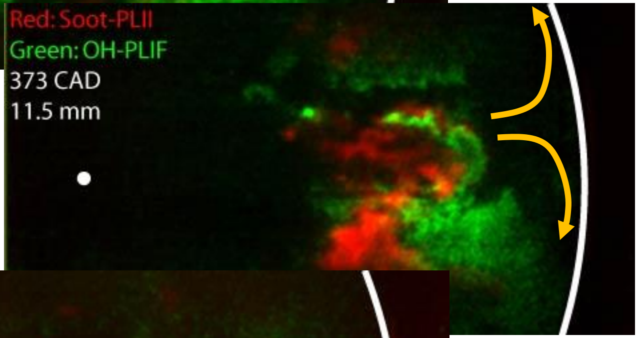
Post injection is first evident in OH-PLIF (green) at its ignition event



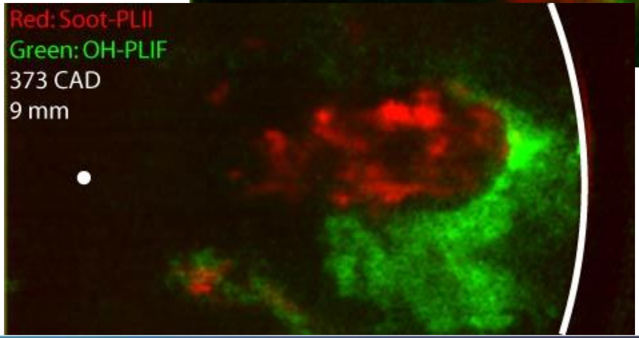
As post injection penetrates, it often displaces main-injection products, with OH-free zone (black) outside post-jet



Soot later forms throughout post-jet cross section as main-injection products are further displaced, but not always...



Some cycles show uniform OH with the post-jet combining with main products; no distinct boundary: cycle-to-cycle variations could be important



Where do we go from here?

- Post injections for soot reduction – conventional operation
  - Late-cycle soot processes for single- and multiple-injection operation
  - More direct measurement of soot reduction mechanisms
  - Effect of operational parameters on post-injection efficacy (load, speed, boost, etc.)

- Post injections for UHC reduction – LTC operation
  - Chemical (Chemkin) modeling for better understanding of ignition and mixing processes
  - Injection rate shaping for lean-region avoidance

Goal: Develop a conceptual model for multiple injections (pilot + main + post) to provide engine manufacturers with a design-level understanding of multiple-injection schedules

Acknowledgements

- Mark Musculus, Paul Miles, Lyle Pickett, Dennis Siebers, Dave Cicone, Keith Penney, Chris Carlen, Gary Hubbard, Dipankar Sahoo, Jasmine King-Bush (Sandia National Labs)
- Philip Dingle (Delphi)
- Gurpreet Singh (Department of Energy)

A Few Words About Post-Docs…

- Typical reasons for doing a post-doc:
  - Additional publications
  - New experiences (new techniques, new facilities, etc.)
  - Networking
- Bonus reason for doing a post-doc: "dry-run" for your career while being on "science vacation"
- Unsolicited advice from a crotchety old graduate: change fields

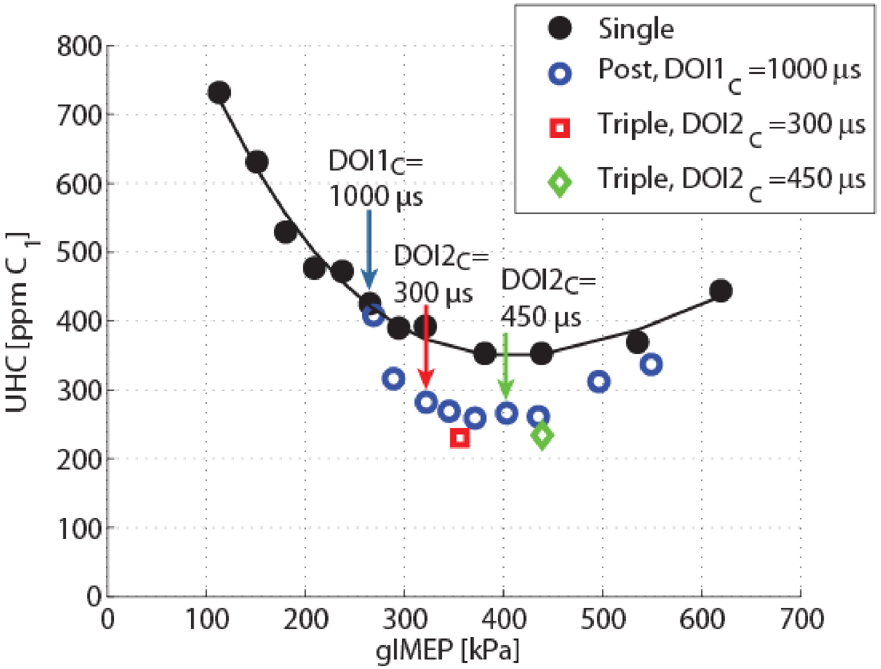
Questions?

UHC Backups

Triple Injections: If two injections work, could three do better?

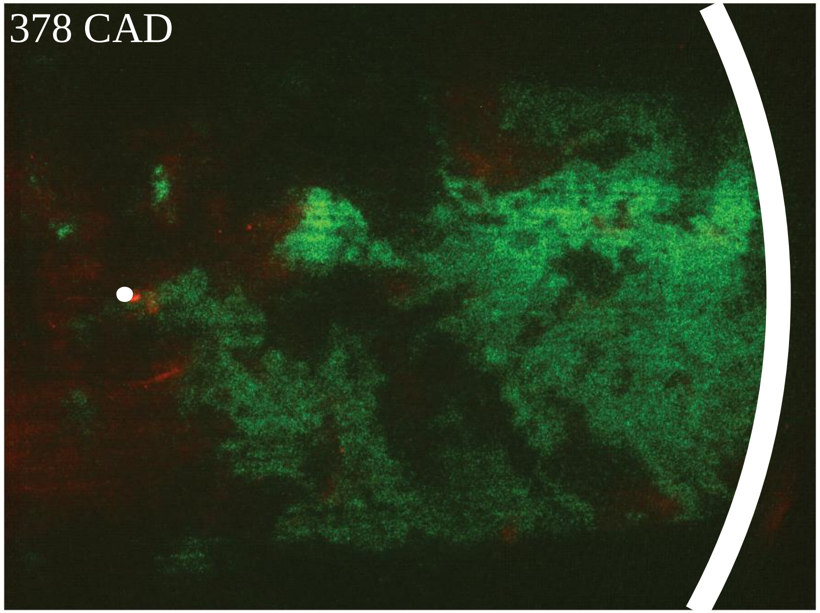
- Emissions and optical data suggest that further reduction in UHC is possible by eliminating lean-source UHC near the injector

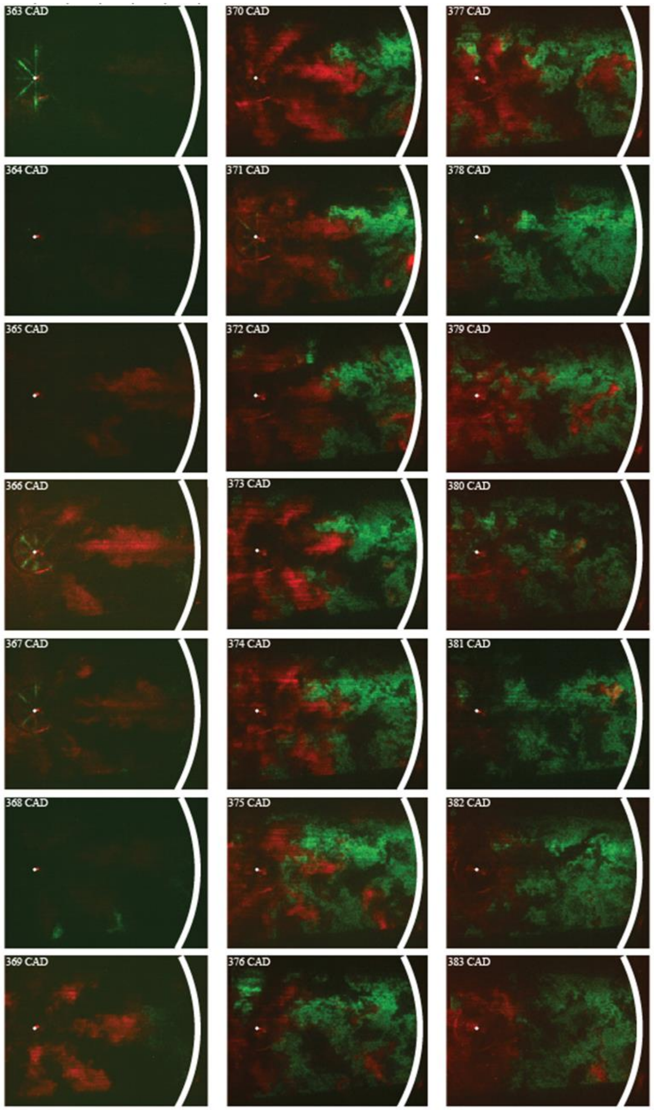
- A short, close-coupled third injection does improve UHC emissions, but not by the same extent as a post injection



Triple Injections: Third injection works to enrich some of remaining lean-sources UHC

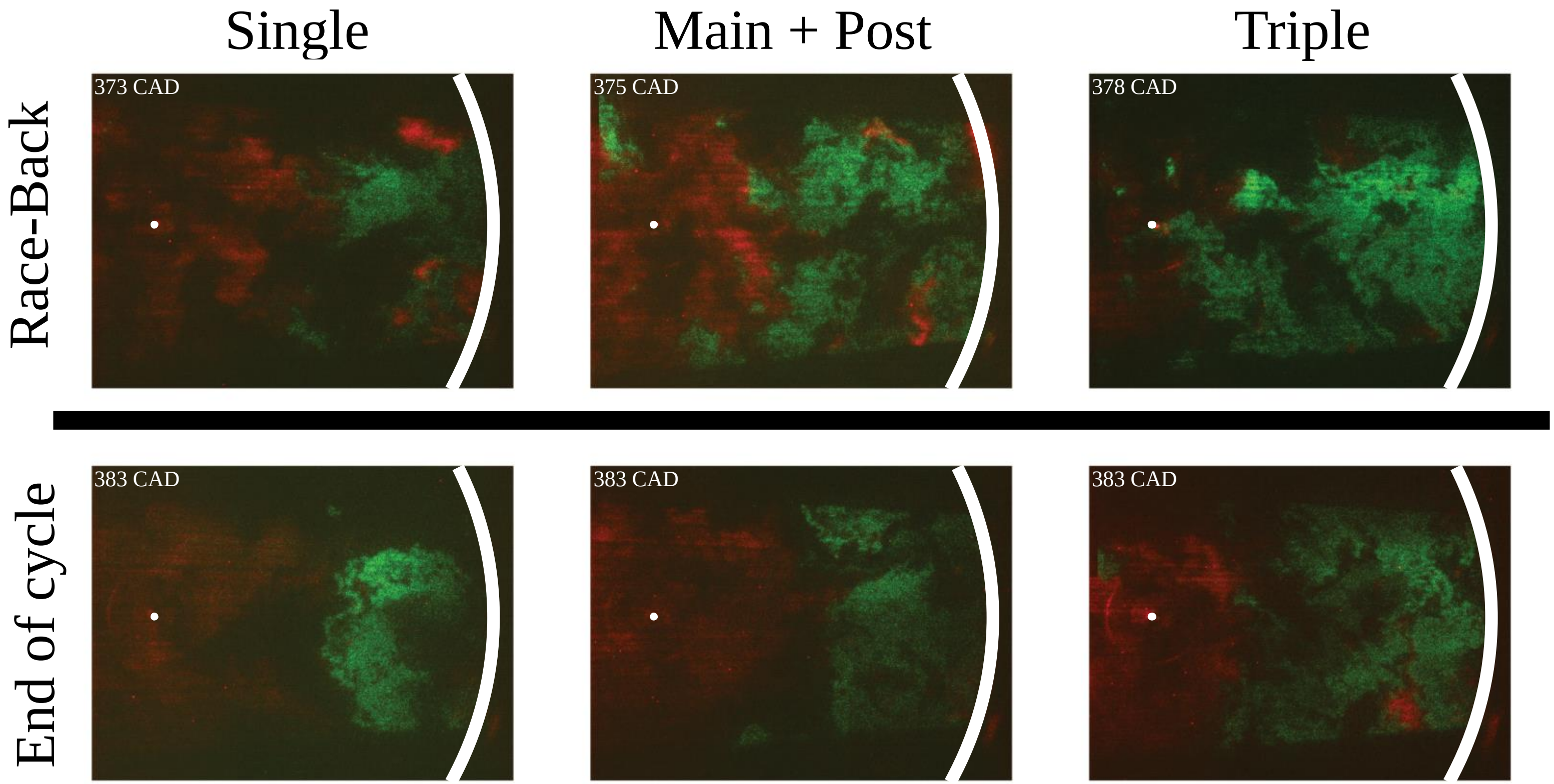
- Mechanism of UHC reduction is similar with a third injection – enrichment of overly-lean mixture near injector





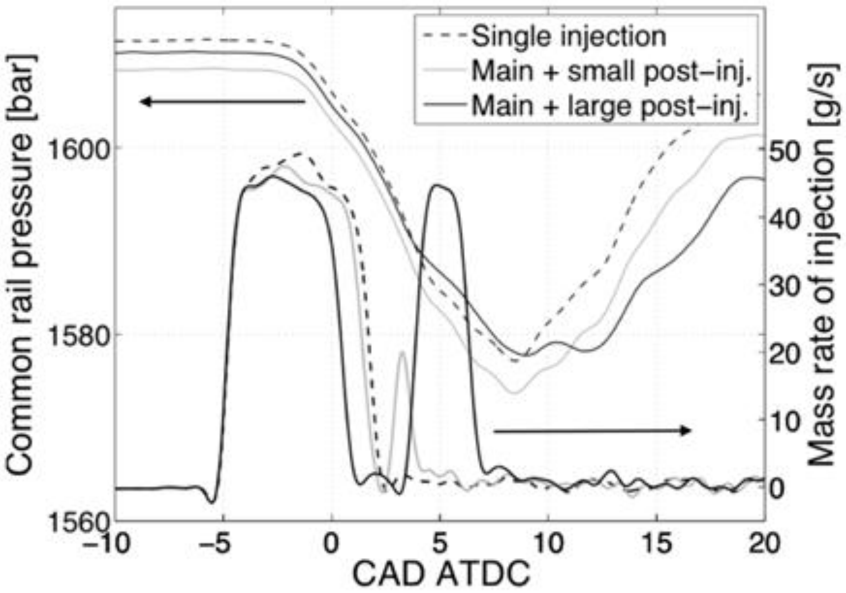
Triple Injections: Third injection works to enrich some of remaining lean-sources UHC

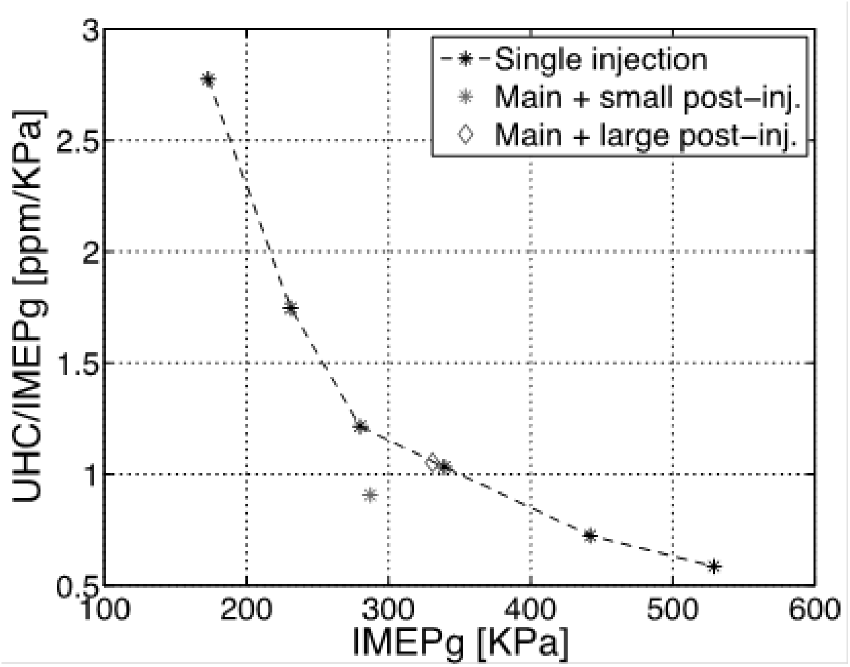
- Second-stage combustion reached further back to injector and remained in that region longer



Can multiple injections help reduce UHC emissions?

- Could the addition of more fuel into the mixture help ignite the regions that are too lean to burn after the main injection?

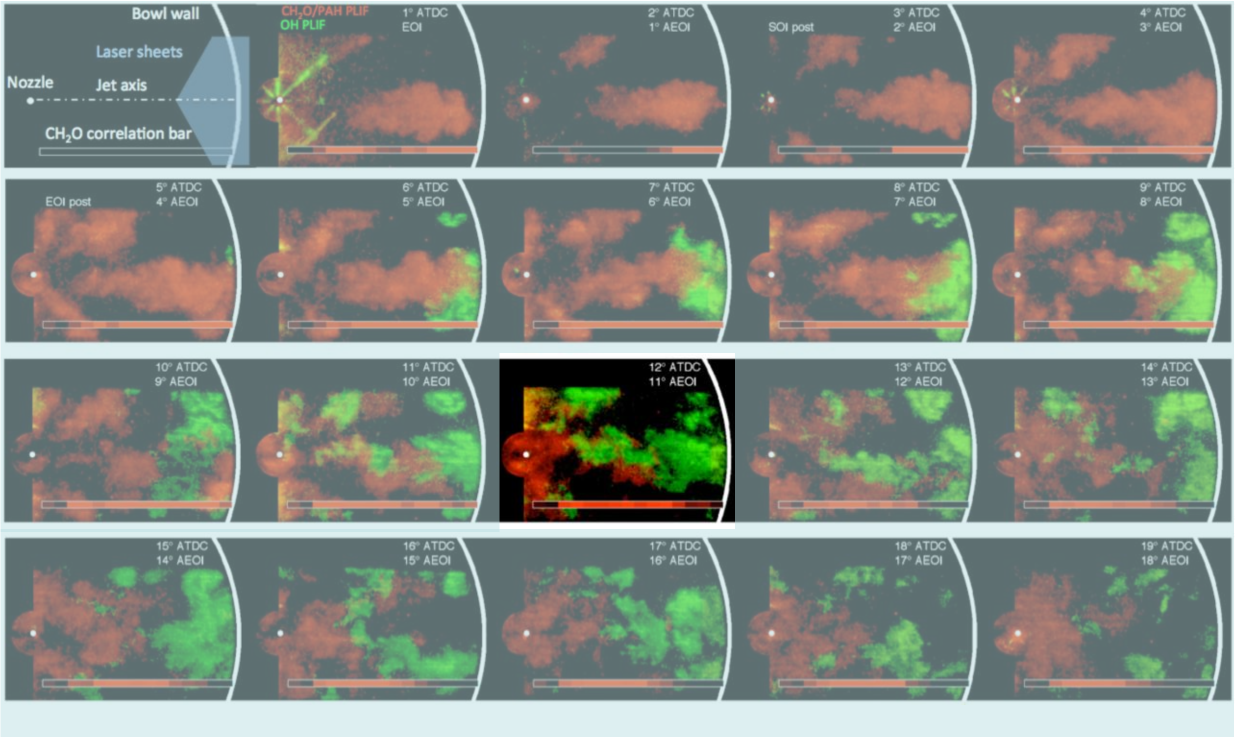


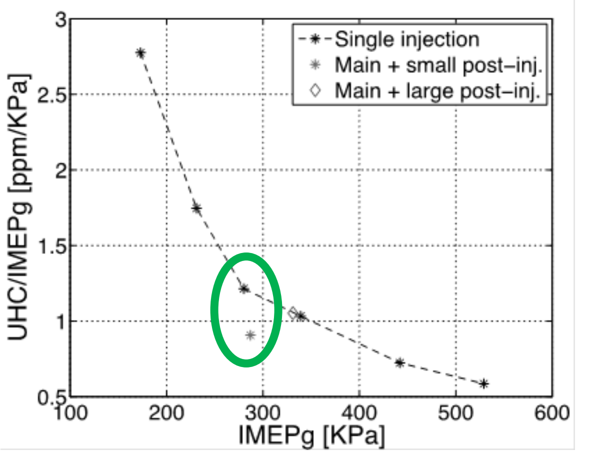


Chartier *et al.*, SAE 2011-01-1383

Multiple injections: Previous studies indicate UHC reduction with post

- Multiple injections have been suggested as a way to reduce UHC emissions by eliminating the “overly-lean” regions through additional fuel injections

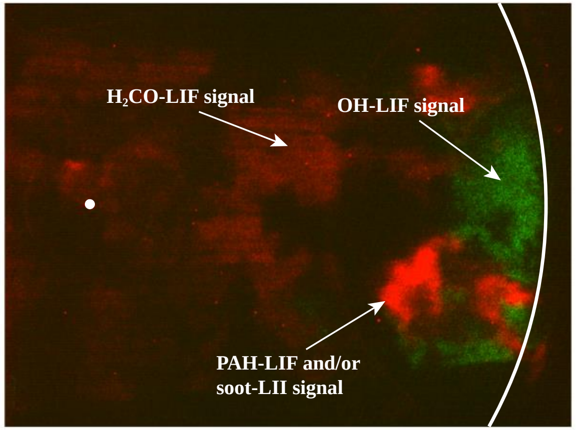


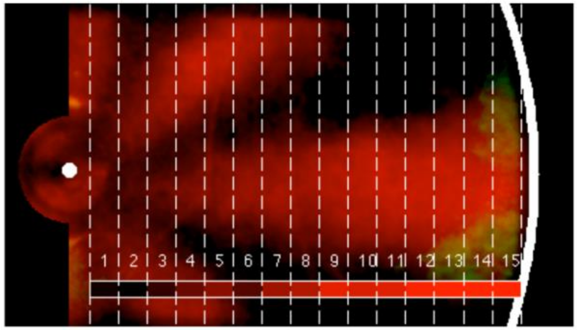


Chartier *et al.*, SAE 2011-01-1383

Experimental Methodology: Issues with LIF Imaging (PAH-LIF and LII)

- Laser-induced fluorescence of H_2CO can also result in signal from LIF of PAH and LII of soot
- Previous studies used a spectrometer to determine which signals originated from H_2CO
- H_2CO-LIF signals have a very different signature in the images, and PAH-LIF/soot-LII signal can be differentiated this way



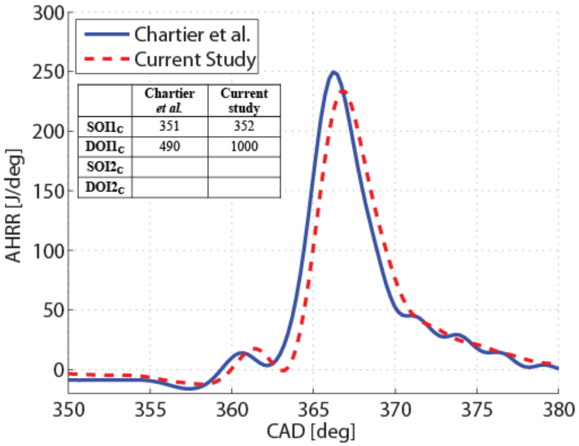


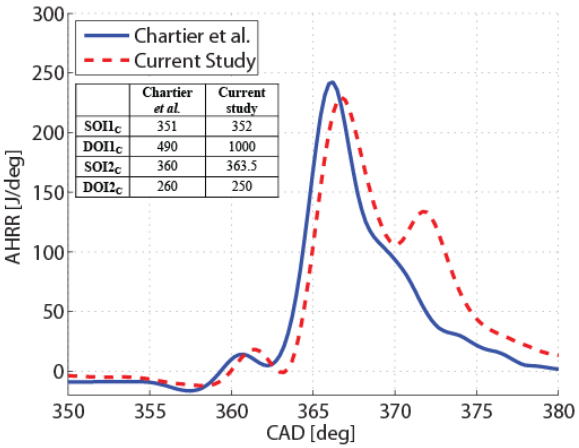
Chartier *et al.*, SAE 2011-01-1383

Comparison to Chartier et al.

- This study was a follow-on to Chartier *et al*.

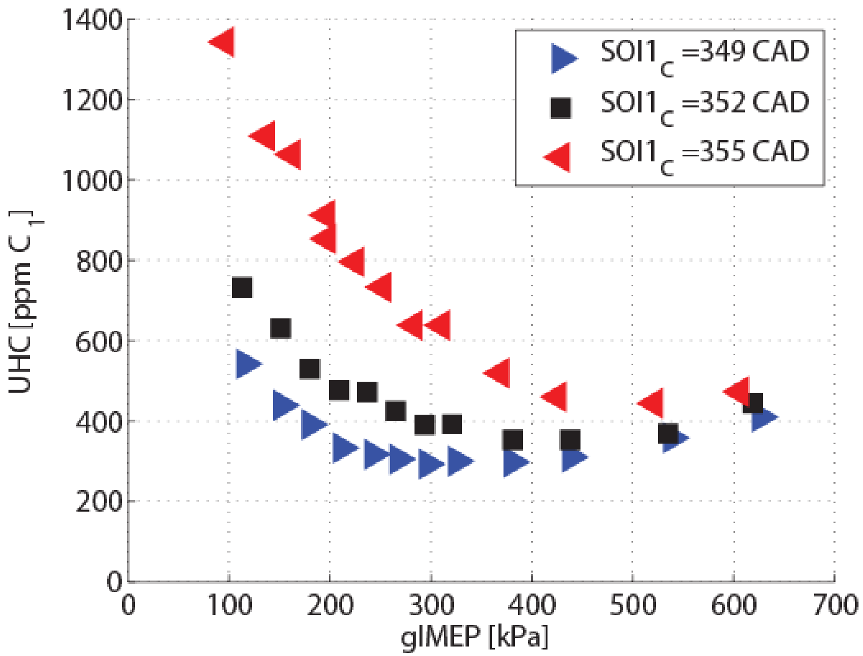
	Current Study	Chartier et al.
Intake O_2	12.6%	12.7%
Fuel	n-heptane	32.3% cetane 67.7% heptamethylnonane
Cetane number	56	42.5
TDC Motored Density	18 kg/m^3	22.1 kg/m^3
TDC Motored Temperature	837 K	837 K
TDC Motored Pressure	43.2 bar	54.9 bar
Start of main combustion	360.1 – 366.6 CAD	362.2 CAD
Ignition delay to main combustion	9.1-9.6 CAD	7.2 CAD
Injector	Delphi DFI 1.5	Cummins XPI

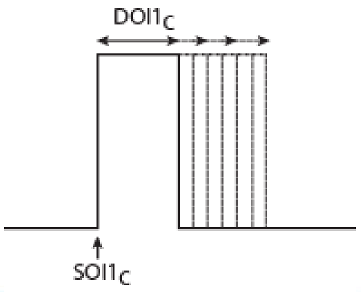




Single Injections: Ignition delay stays constant across $SOI1_C$

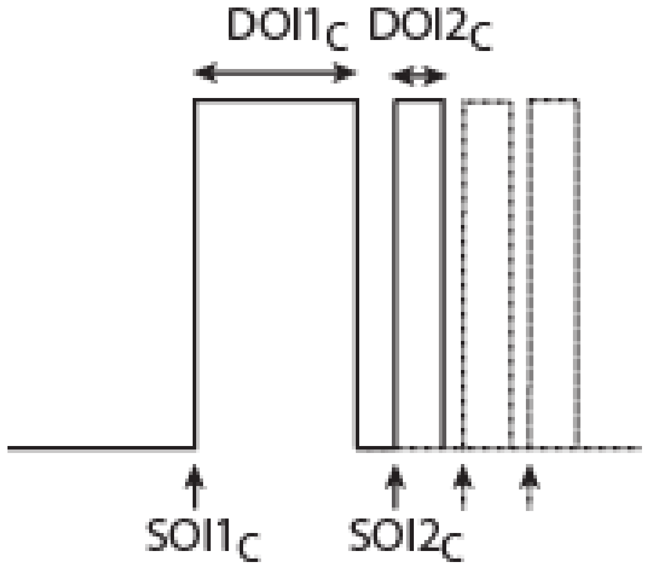
- Ignition delay of fuel-air mixture at three $SOI1_C$ timings is very similar
  - $SOI1_C$=349 CAD, ID=9.1 °CA
  - $SOI1_C$=352 CAD, ID=9.1 °CA
  - $SOI1_C$=355 CAD, ID=9.6 °CA
- This indicates the mixing times are similar for these three conditions

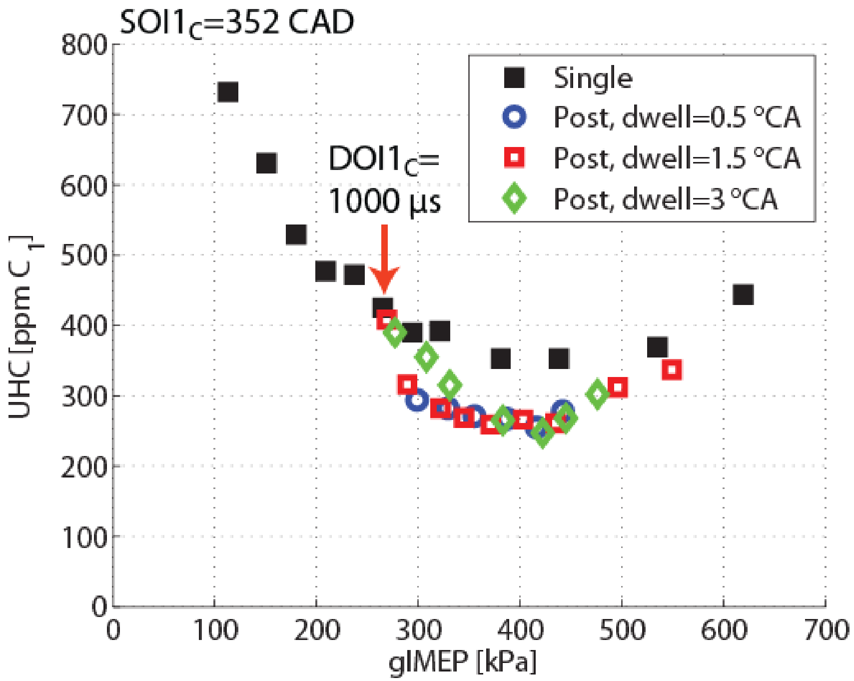




Main + Post Injections: Sensitivity to $SOI2_C$/dwell at constant $SOI1_C$, $DOI1_C$

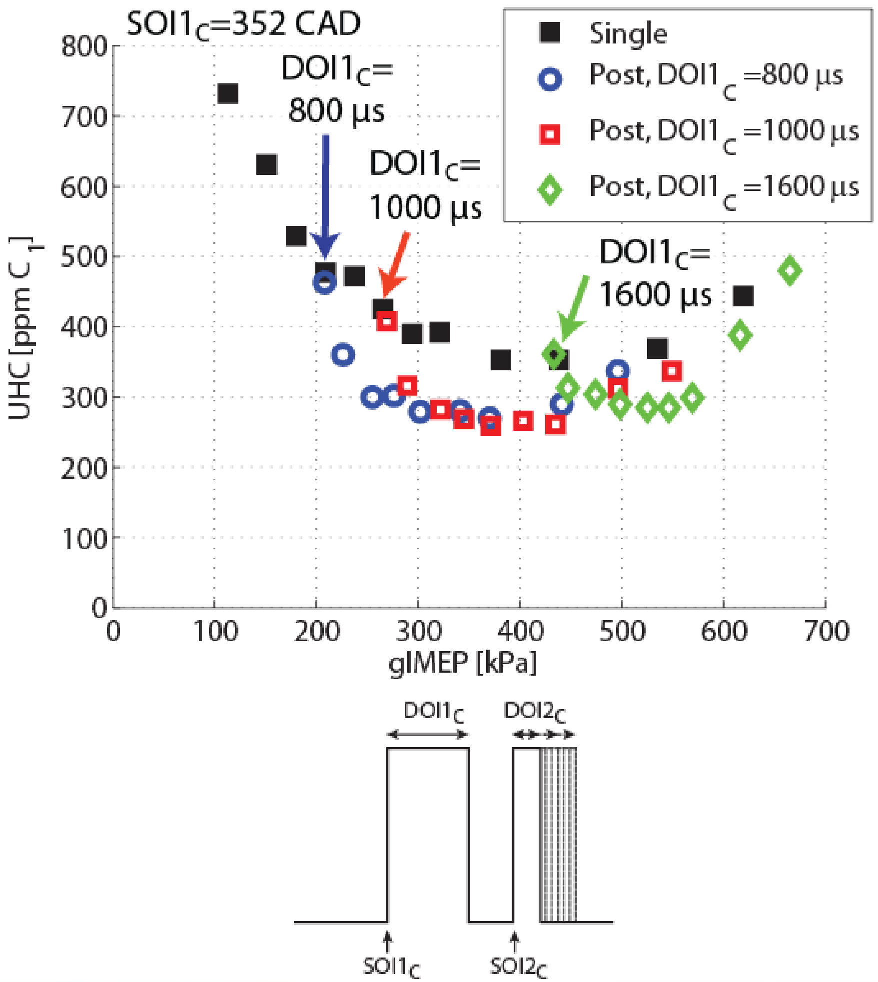
- Post-injection efficacy is relatively insensitive to dwell between the end of the main injection and start of the post injection





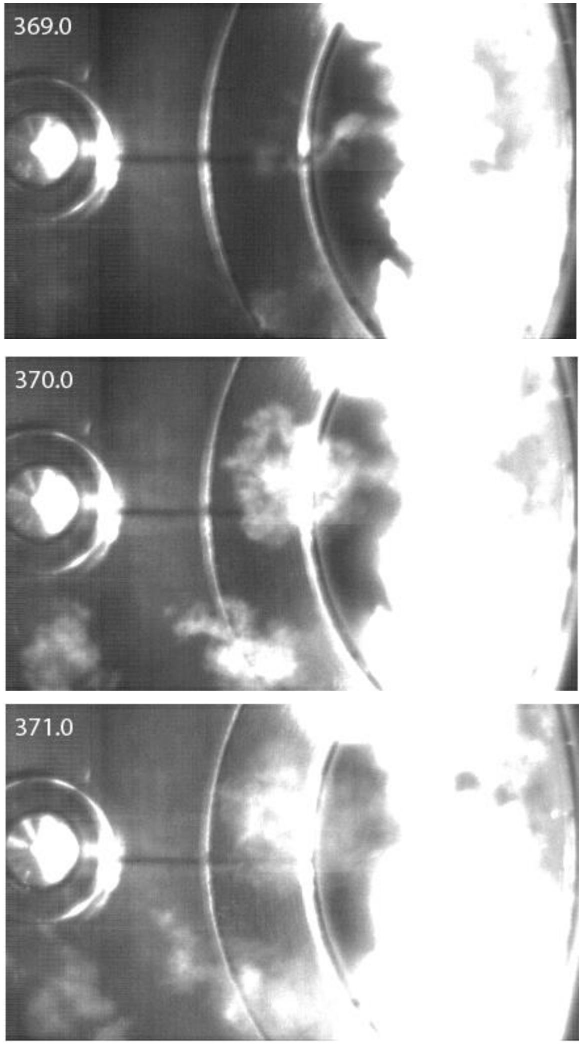
Main + Post Injections: Sensitivity to $DOI1_C$ with constant dwell

- Similar trends were observed at three $DOI1_C$
  - 800, 1000, 1600 µs
- Minimum engine-out UHC observed at $DOI2_C$=400 µs in each case
  - Indicates that optimal post-jet penetration, injection rate/profile, and fuel mass is not a function of main-injection duration



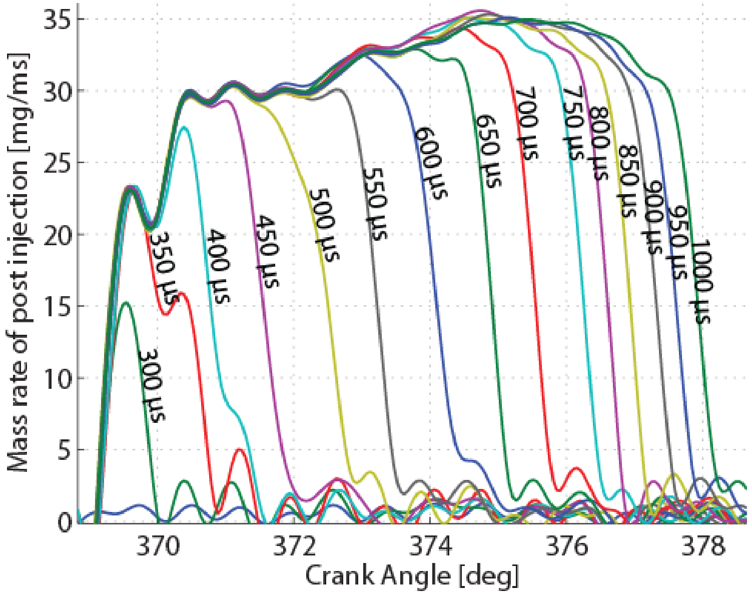
Main + Post Injections: $DOI2_C$ = 400 µs post injection minimizes UHC at many conditions

- 400 µs post jet penetrates at the end of the injection
  - Shorter post injections do not penetrate to wall before reacting
  - Longer post injections penetrate to wall, continuing to roll up on either side, like a main injection
- Mid-range post-injection duration may be a "sweet-spot" of penetration for this bowl diameter
  - Different DOI2C may be most effective with different bore size, bowl geometry



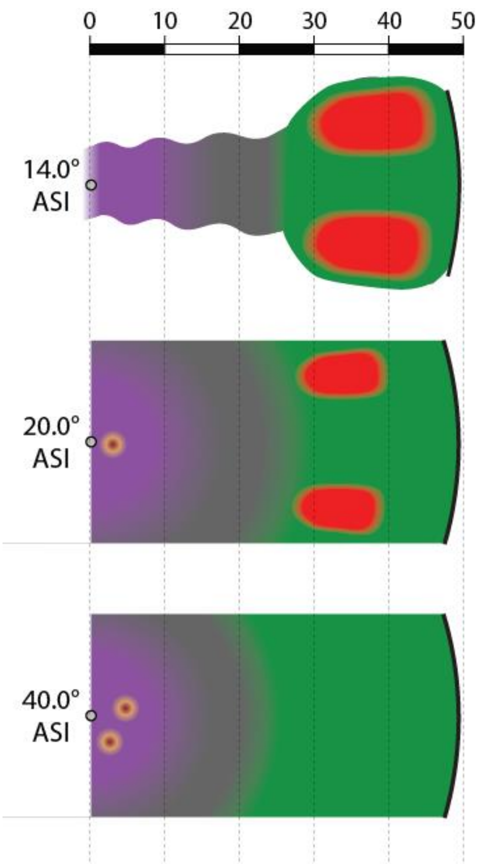
Main + Post Injections: $DOI2_C$ = 400 µs post injection minimizes UHC at many conditions

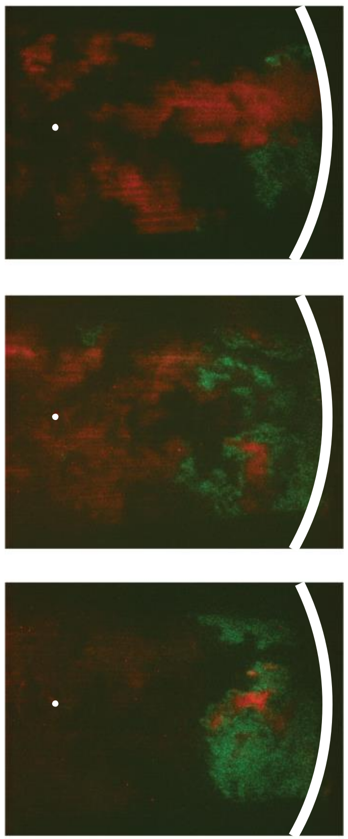
- 400 µs post jet rate shape may optimize end-of-injection mixing
- Injections with durations between 200 and 800 µs not only change length, but also change shape
- Ramp up/down rates of the 400 µs post injection may be different enough to optimize mixing

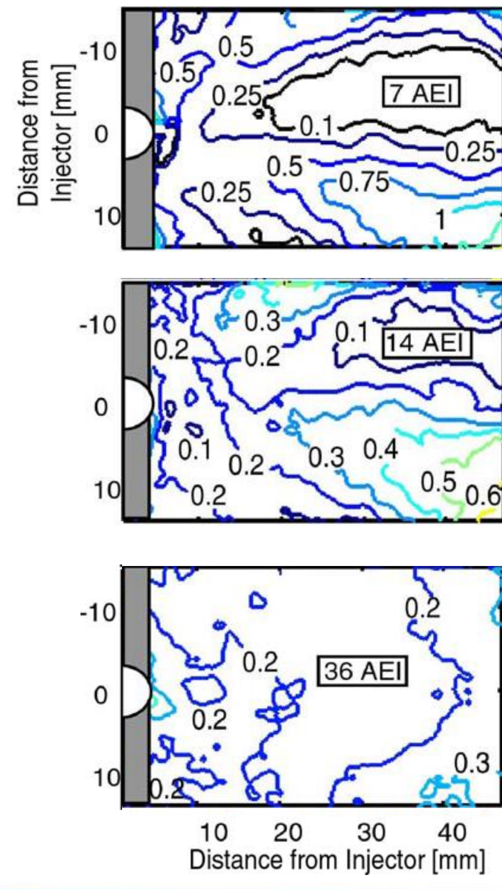


LTC Drawbacks: Increase in UHC emissions originating in overly-lean regions

- High dilution and long ignition delays lead to overly-lean mixtures that never reach 2nd stage ignition at low load conditions







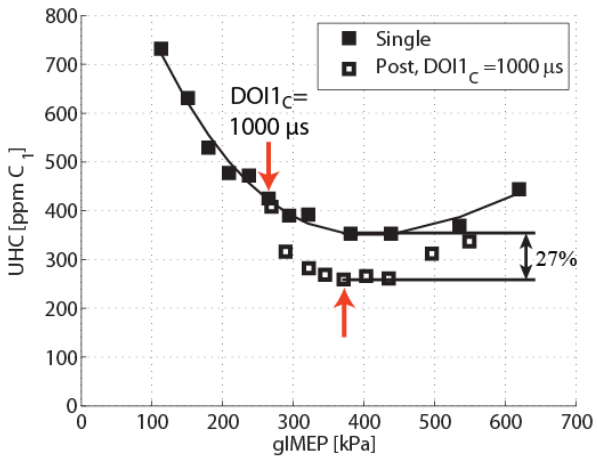
Musculus *et al.*, PECS 2013

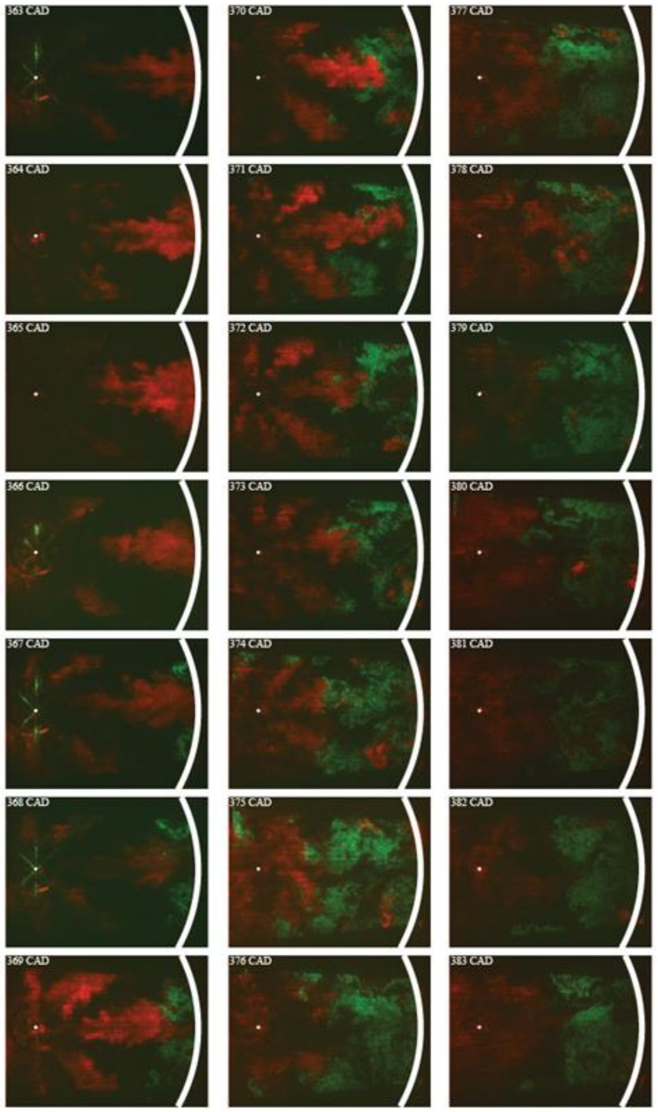
Musculus *et al.*, SAE 2007-01-0907

Main + Post Injections: Post injections reduce UHC by enriching over-lean region near injector

- Extent of second-stage ignition "racing back" to the injector is greater with a post injection

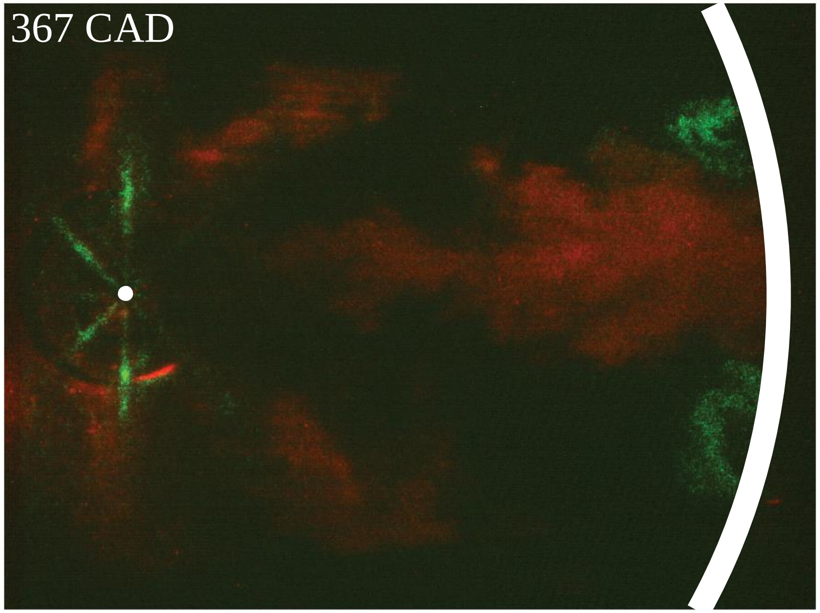
- This is an indication that more fuel near the injector is being burnt to completion – less UHC emissions

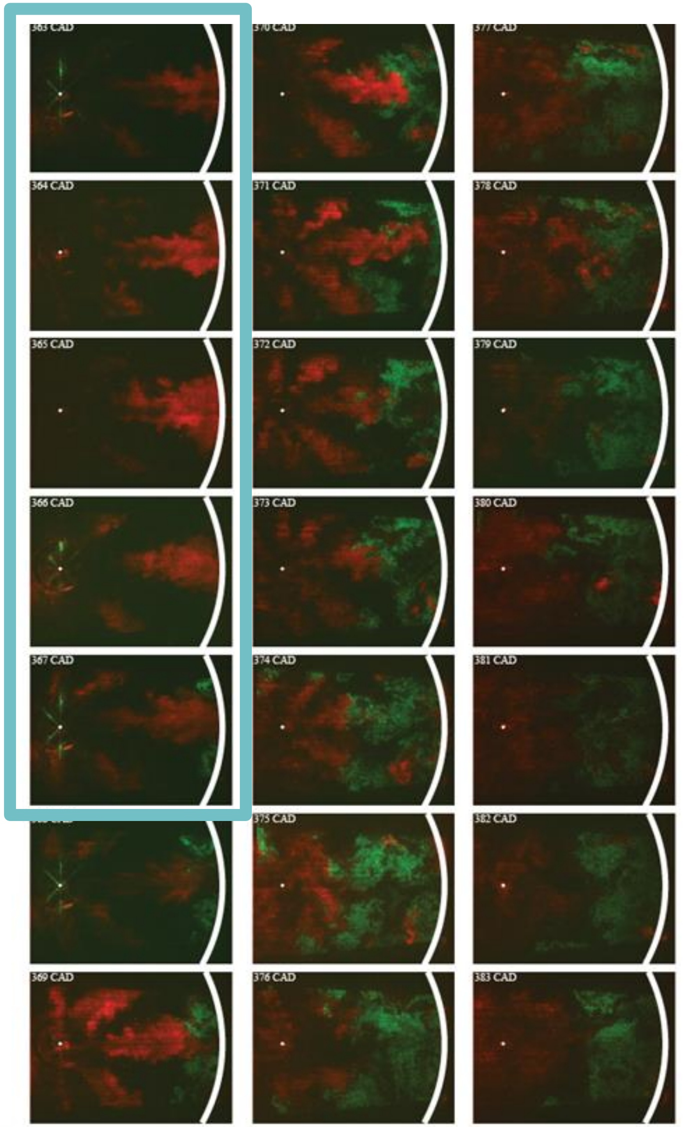




Main + Post Injections: Second-stage ignition of main injection is similar to single injection

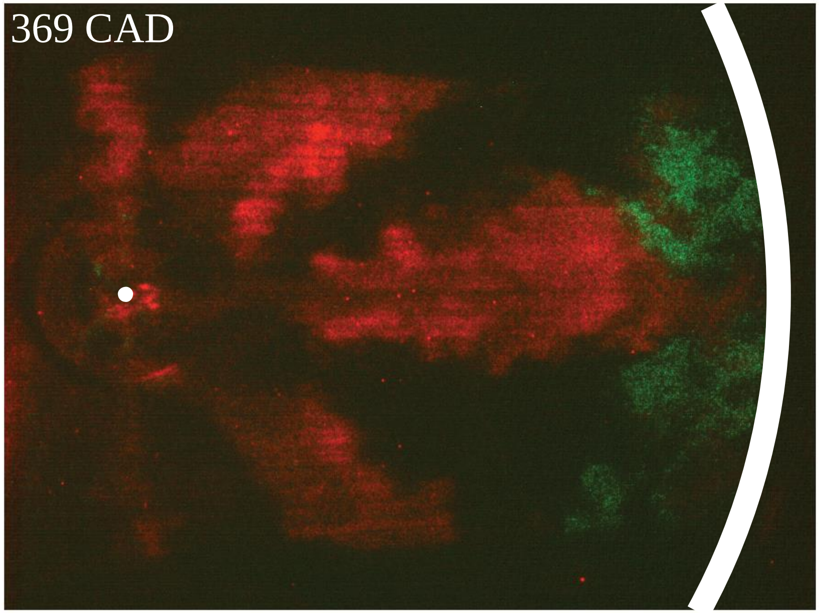
- Initial structure and second-stage ignition of the main injection is similar to that of the single-injection case

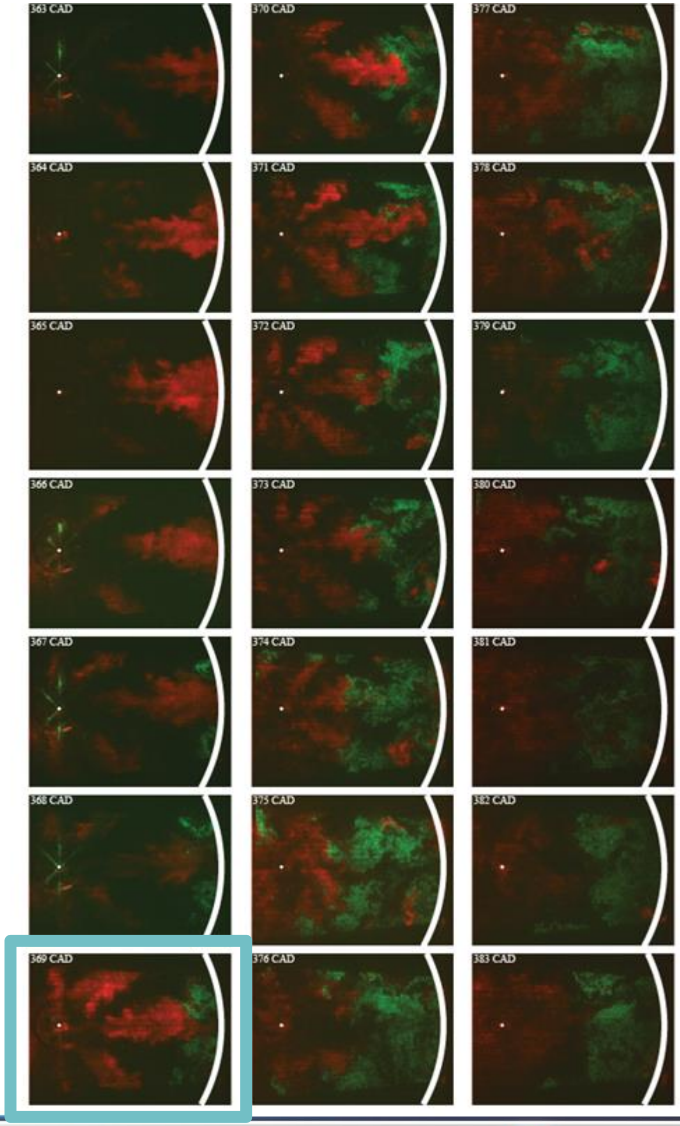




Main + Post Injections: First-stage ignition of post injection in the jet

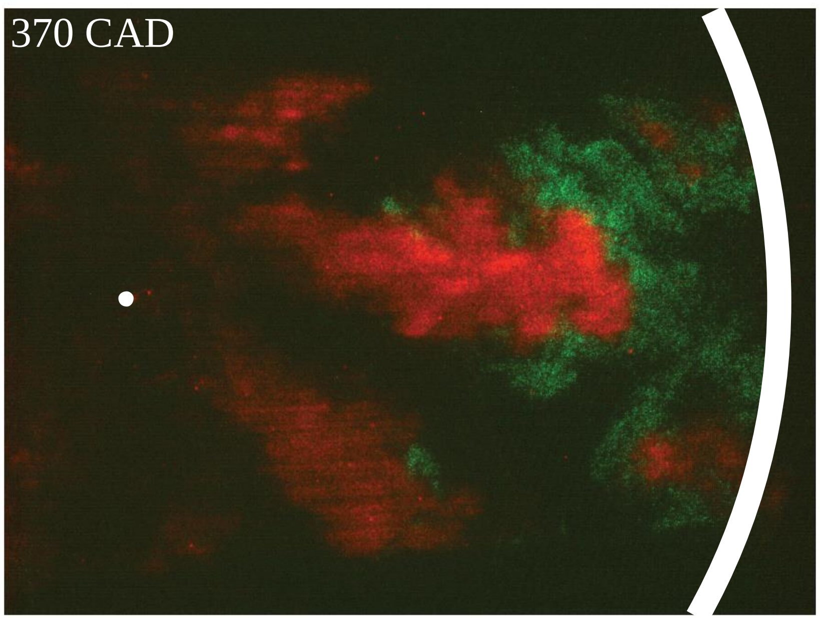
- After the end of the post injection, enhanced first-stage combustion in the jet
  - Higher H_2CO signal and jet structure

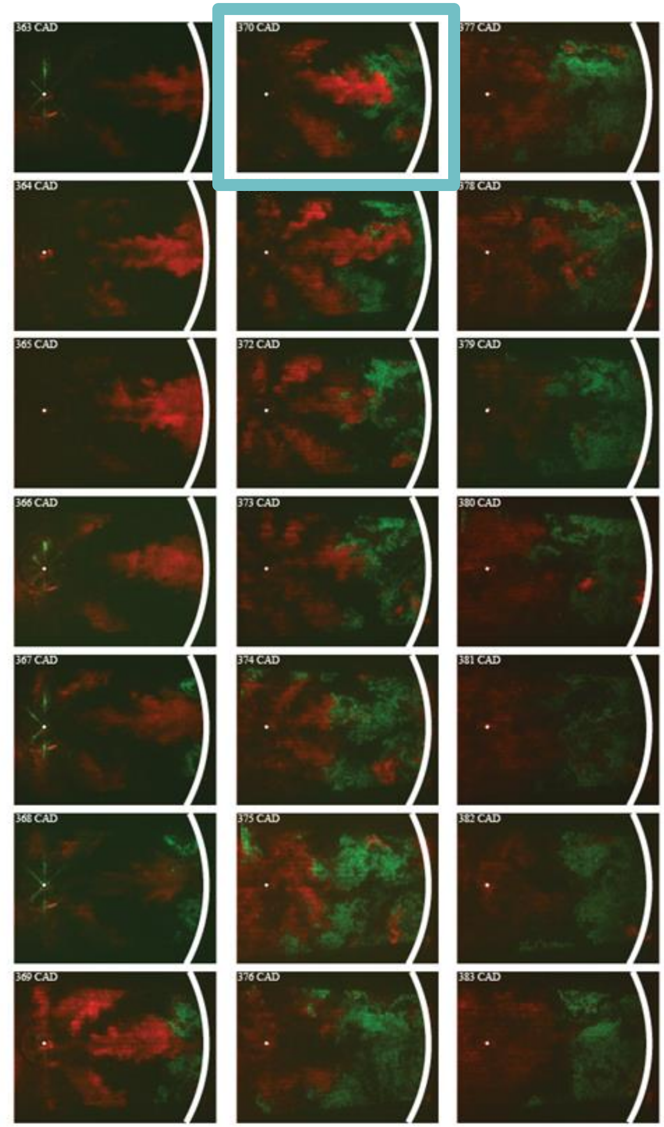




Main + Post Injections: Second-stage ignition races back along jet centerline

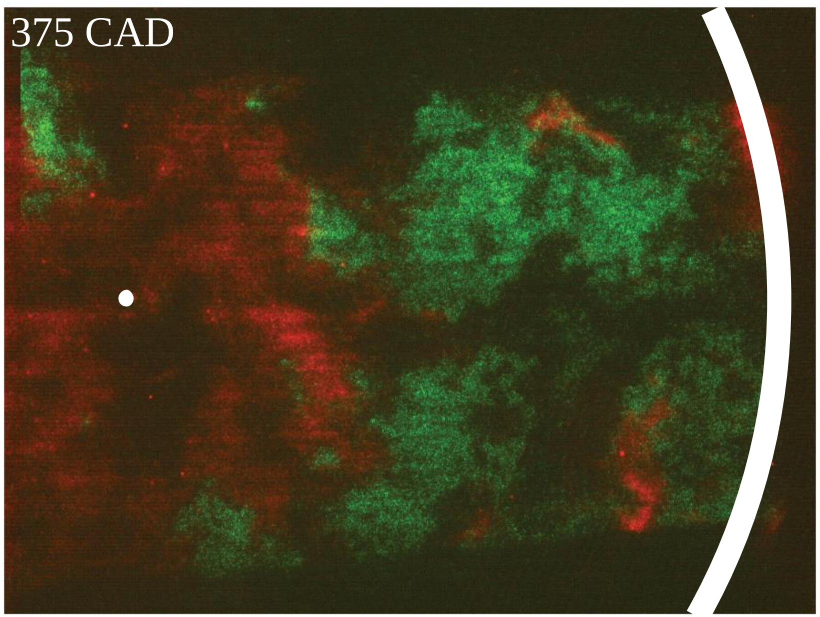
- Second-stage combustion “races back” along jet centerline as in the single-injection case

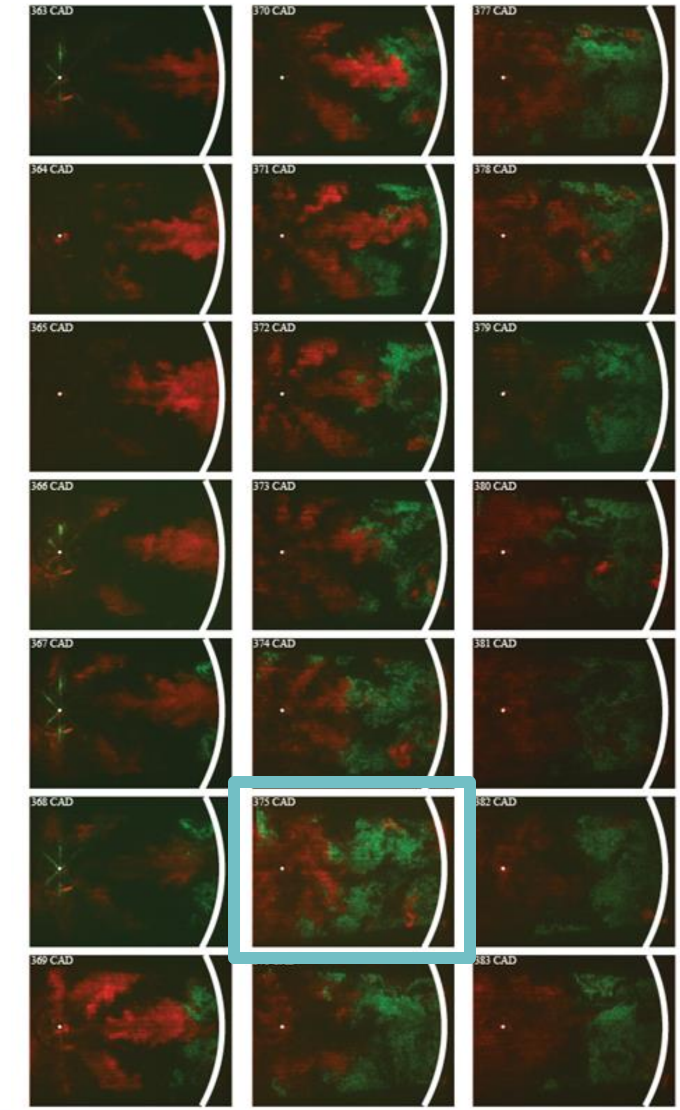




Main + Post Injections: Second-stage ignition reaches further towards injector with post

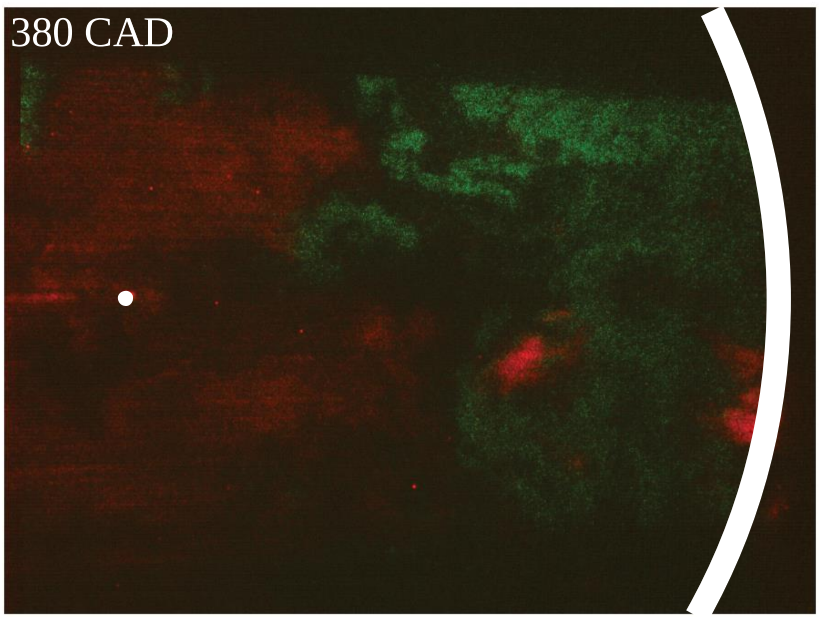
- Second-stage combustion reaches further towards the injector with a post injection

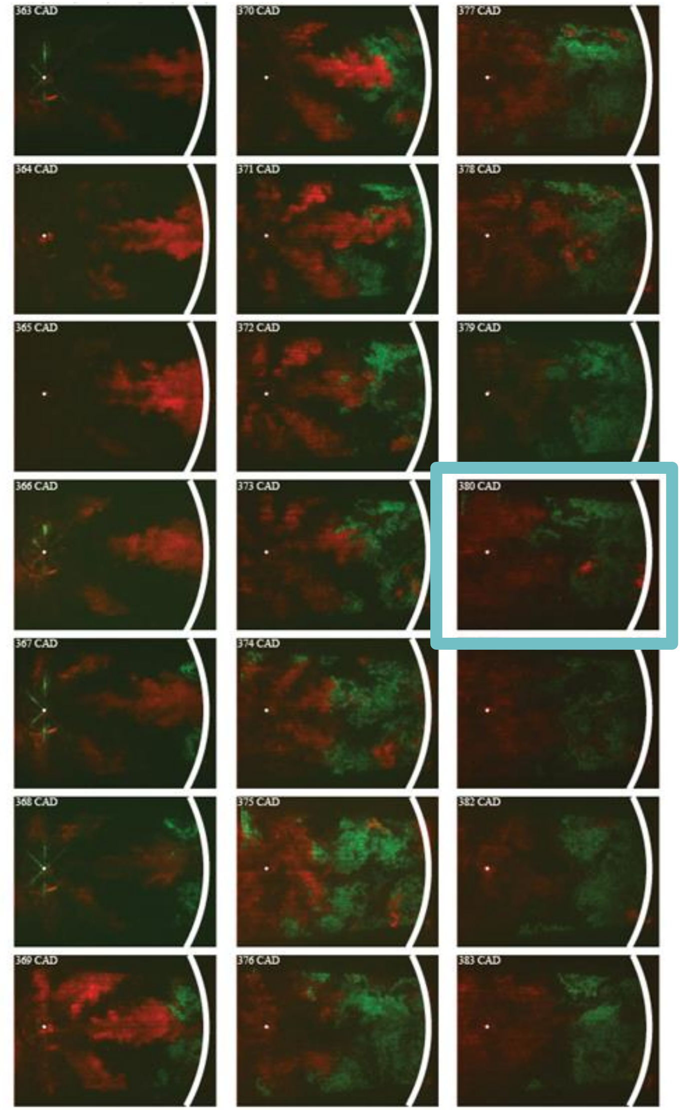




Main + Post Injections: Greater extent of second-stage combustion late in cycle with post

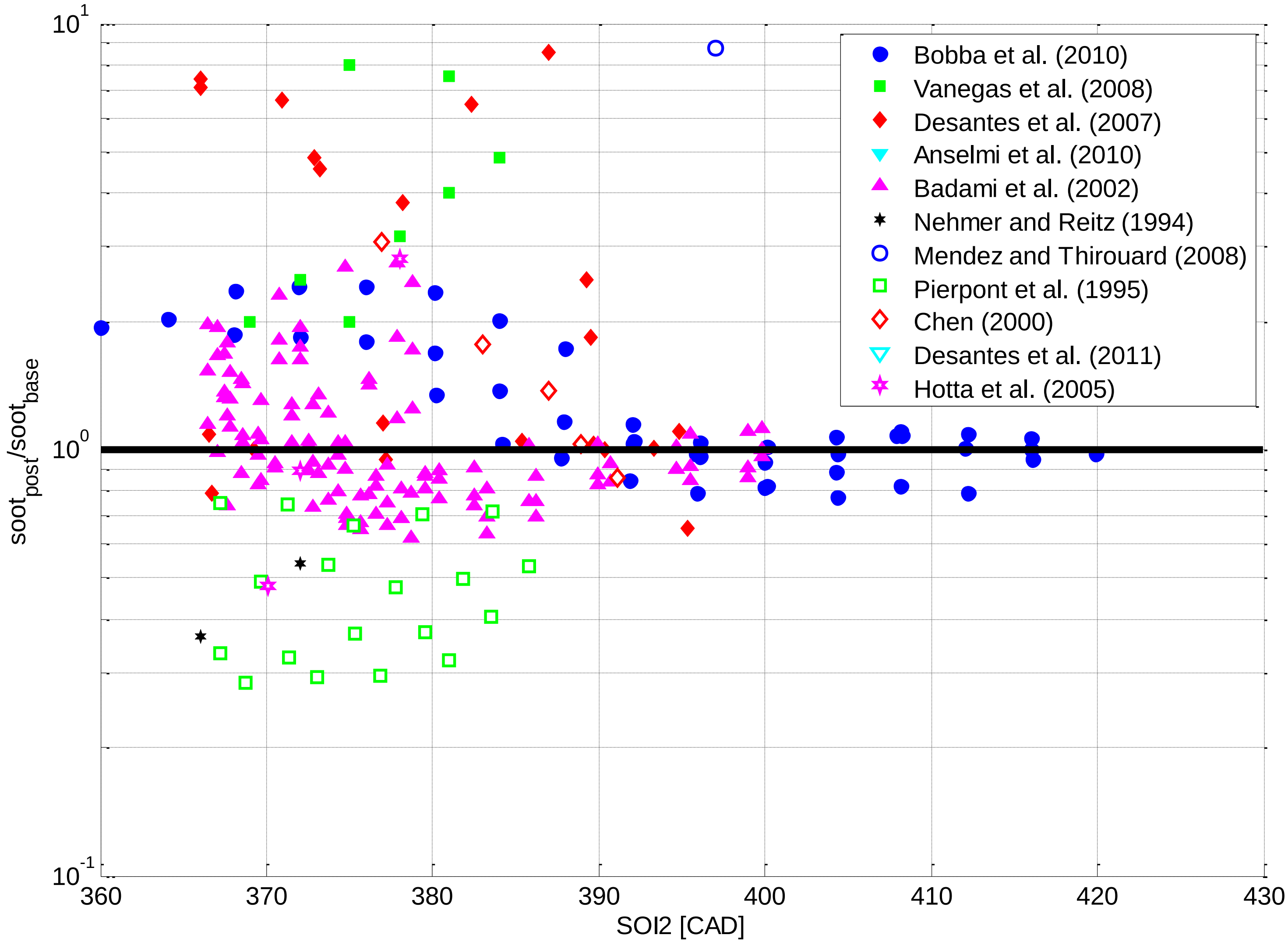
- Later in the cycle, second-stage combustion extends over a greater portion of the bowl





Soot Backups

How do Post Injections Work: Previous Studies Provide a Wide Array of Results



Text Matrix Sweeps in EGR from 12.6% - 21% Oxygen

- Sweep in EGR considers the effect of O_2 content
  - 12.6%, 15%, **18%**, and 21% O_2
  - 41-53%, 34-45%, **19-29%**, and 0% EGR
- 18% O_2 is used as the baseline to meet 2010 NO_x regulations with Urea-SCR aftertreatment
  - 0.2 g/bhp-hr = 1.4 g/kg $EINO_x$ at 42% thermal efficiency
  - 80-85% SCR effectiveness allows 7-9 g/kg EINOx engine-out

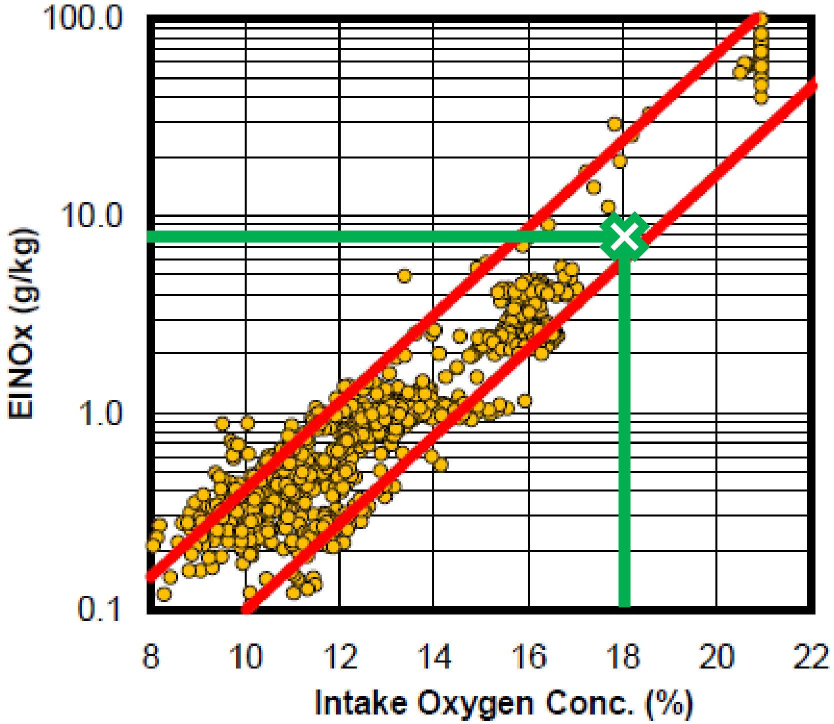


Figure courtesy of Russell Durrett, GM

Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency

NOx

Soot

Efficiency

Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency

NOx

Soot

Efficiency

EGR

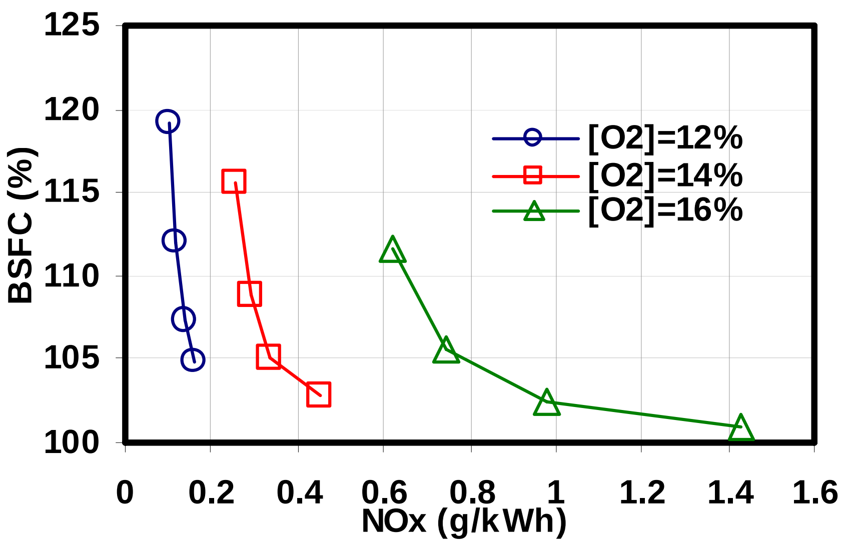
Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency

NOx

Soot

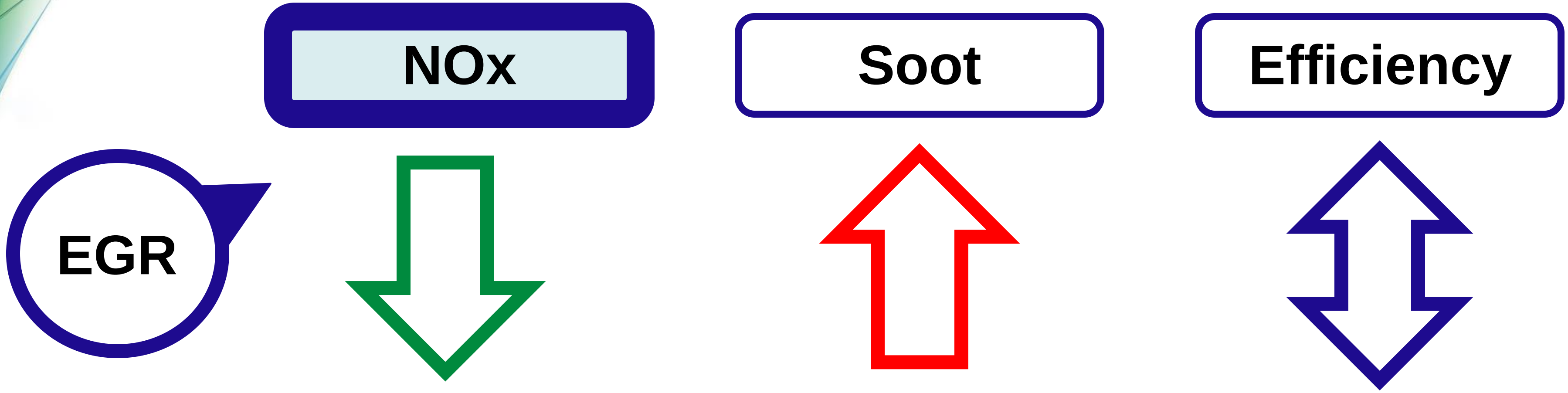
Efficiency

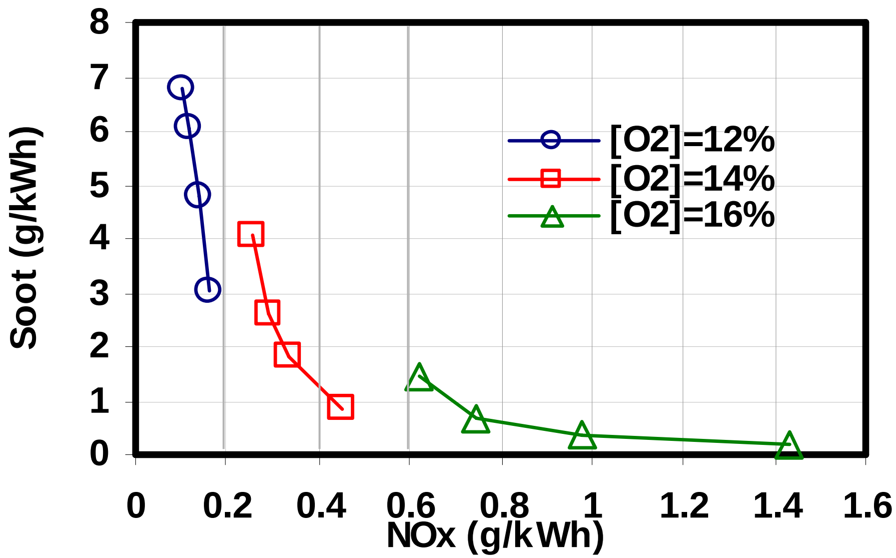
EGR



Dronniou et al., SAE2005-01-3726

Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency





Dronniou et al., SAE2005-01-3726

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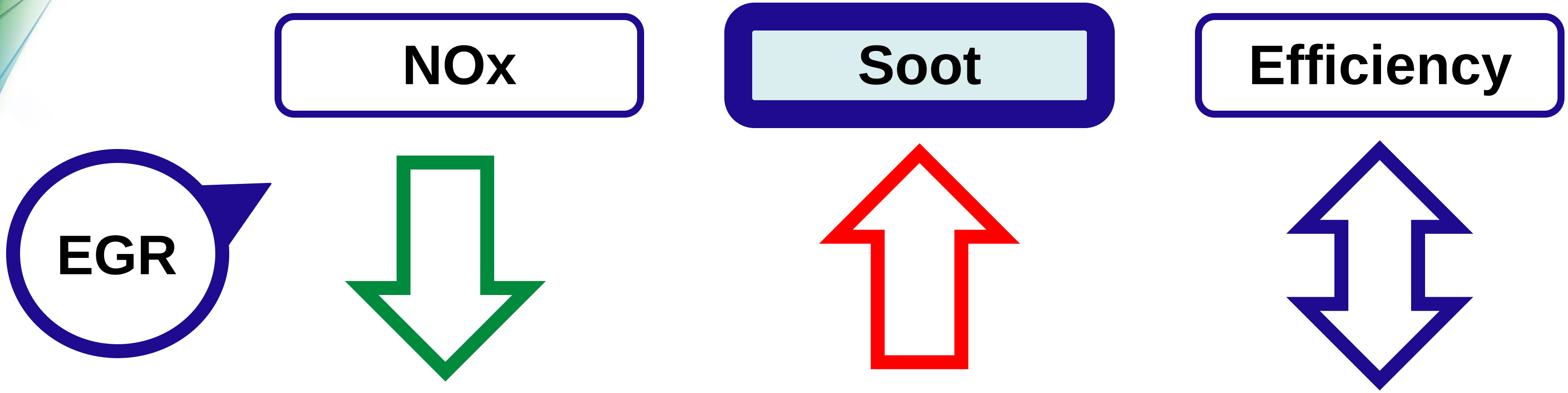

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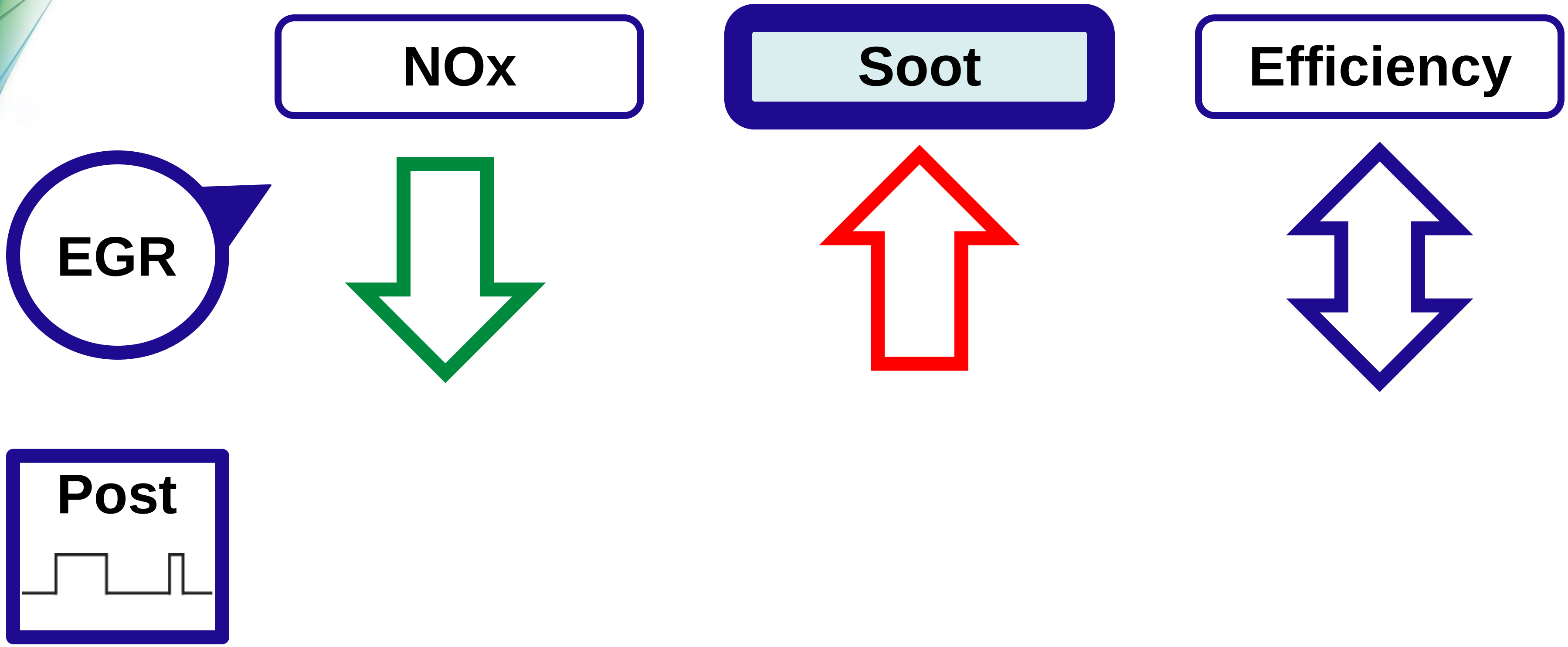

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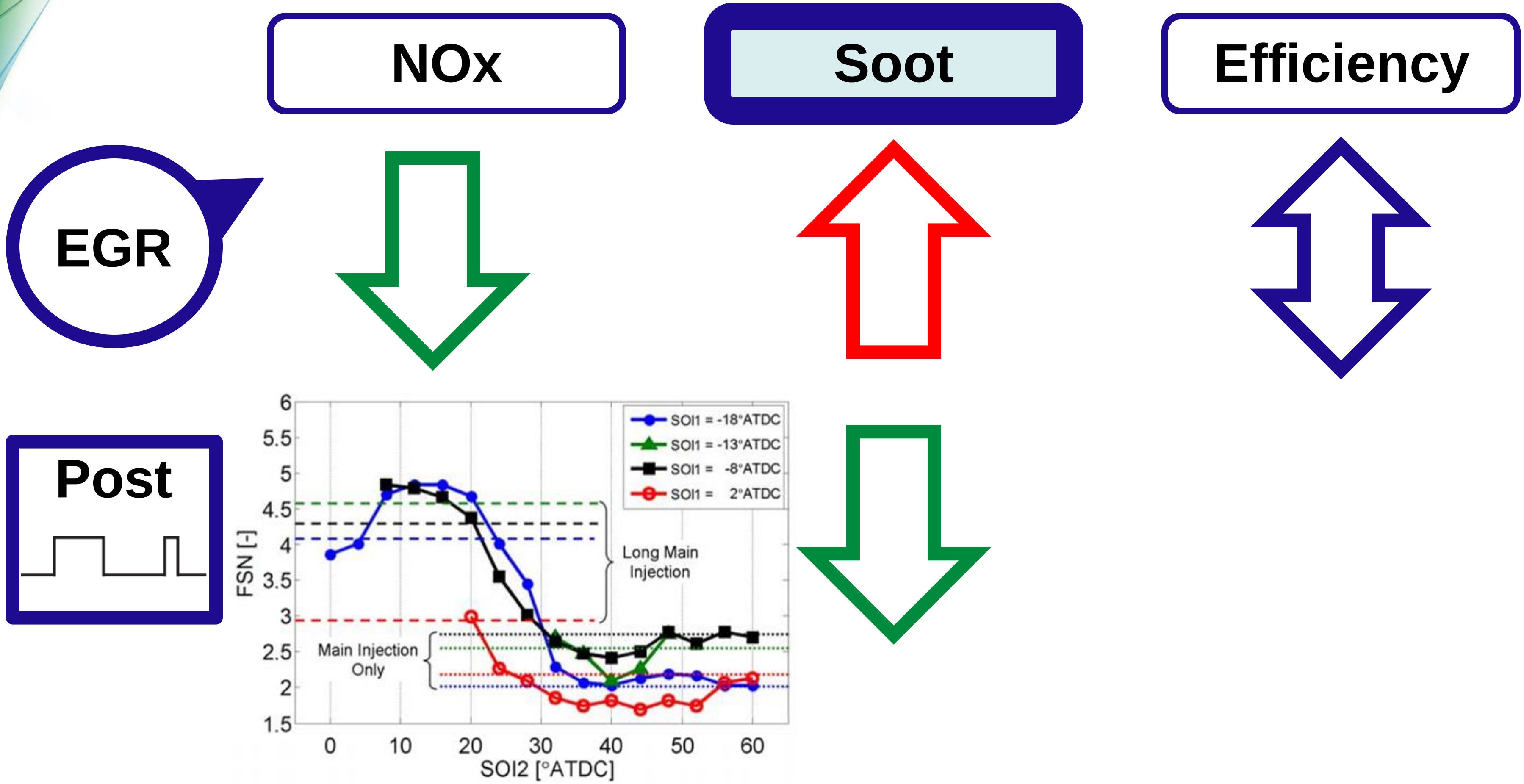
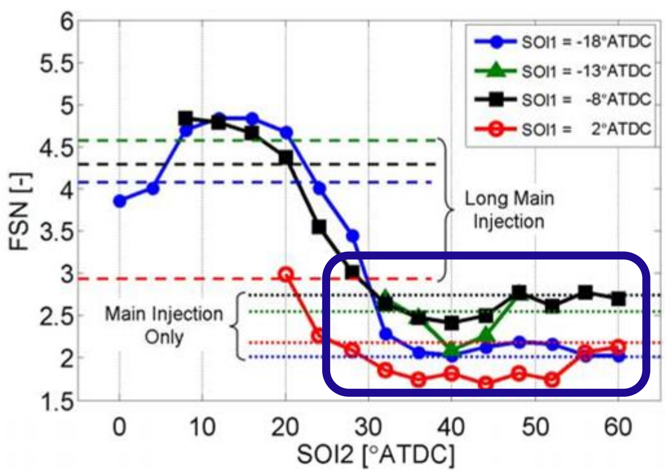


Bobba et al., SAE2010-01-0612

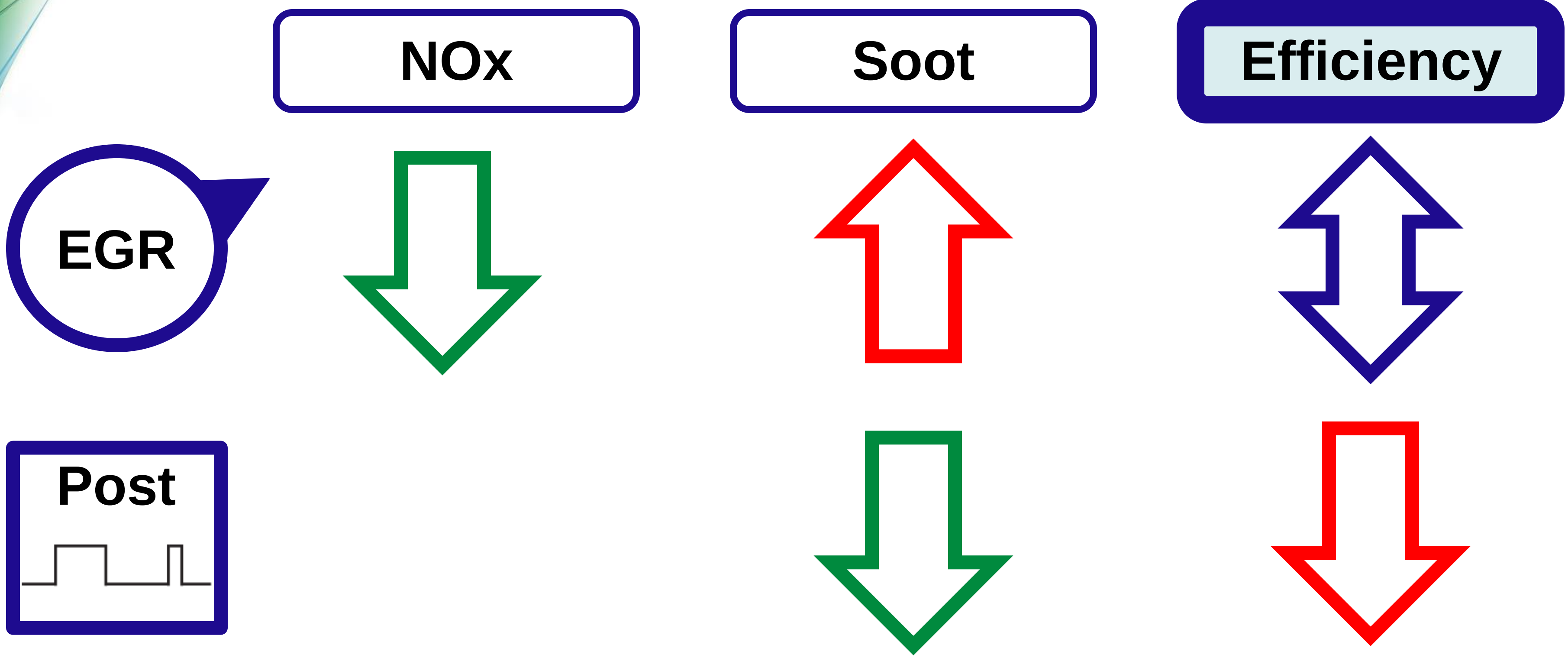
Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency

	NOx	Soot	Efficiency
EGR	↓	↑	↕
Post		↓	↓

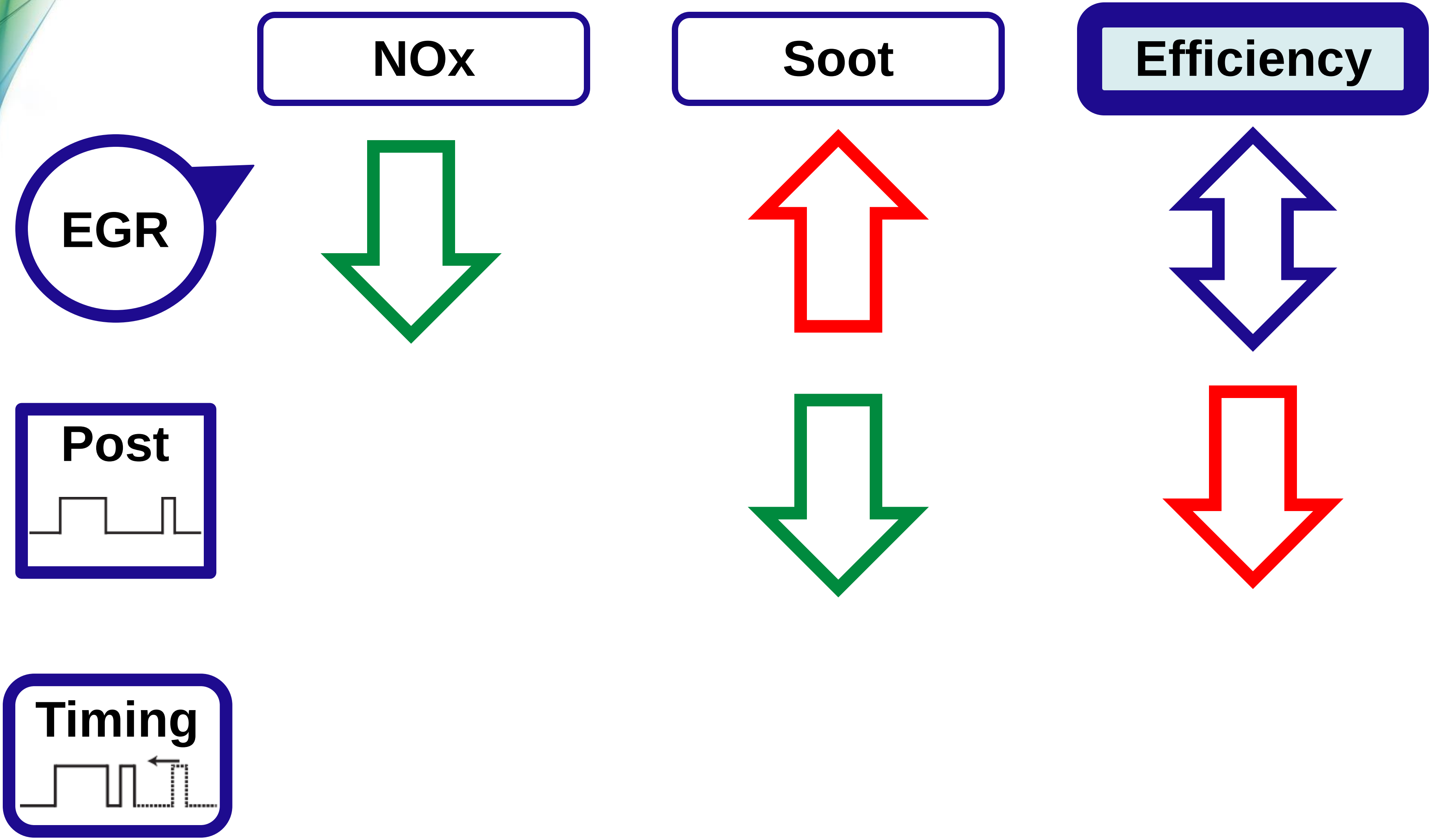


Bobba et al., SAE2010-01-0612

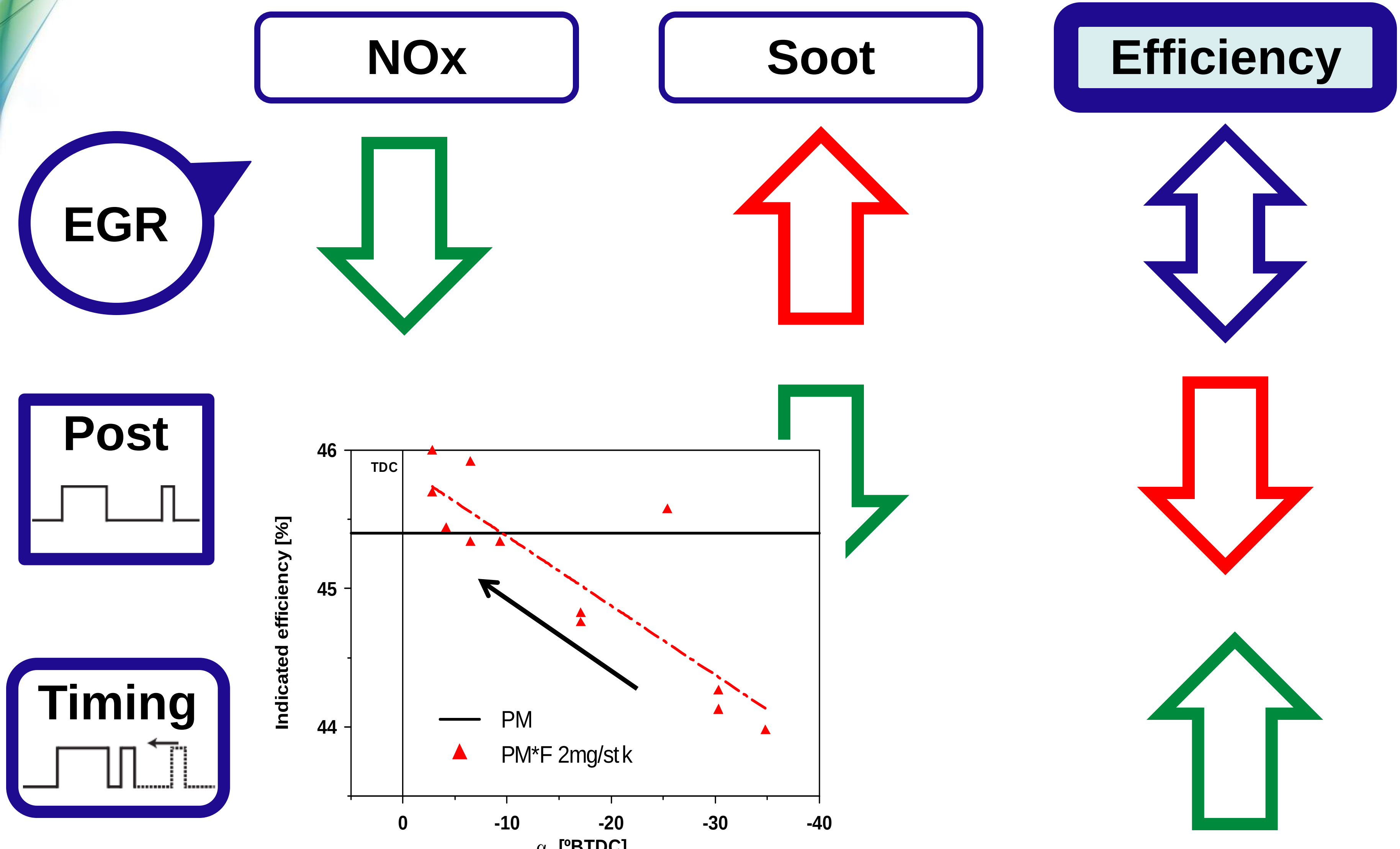
Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency



Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency

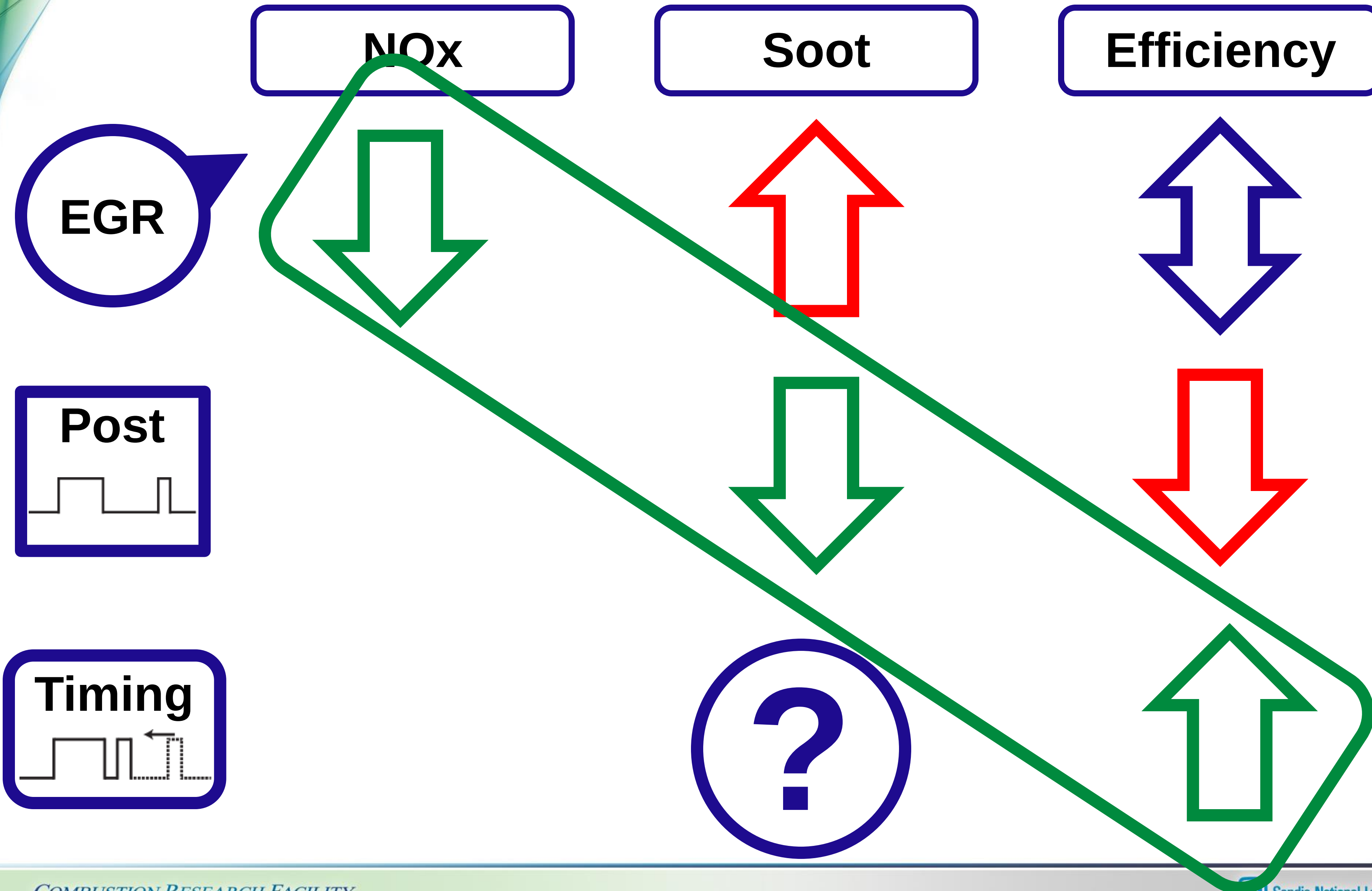


Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency



Desantes et al., SAE2007-01-0915

Close-Coupled Post Injections Lead to Lower Soot while Maintaining Efficiency



Where do Close-Coupled Post Injections Work? – EGR and DOI Dependencies

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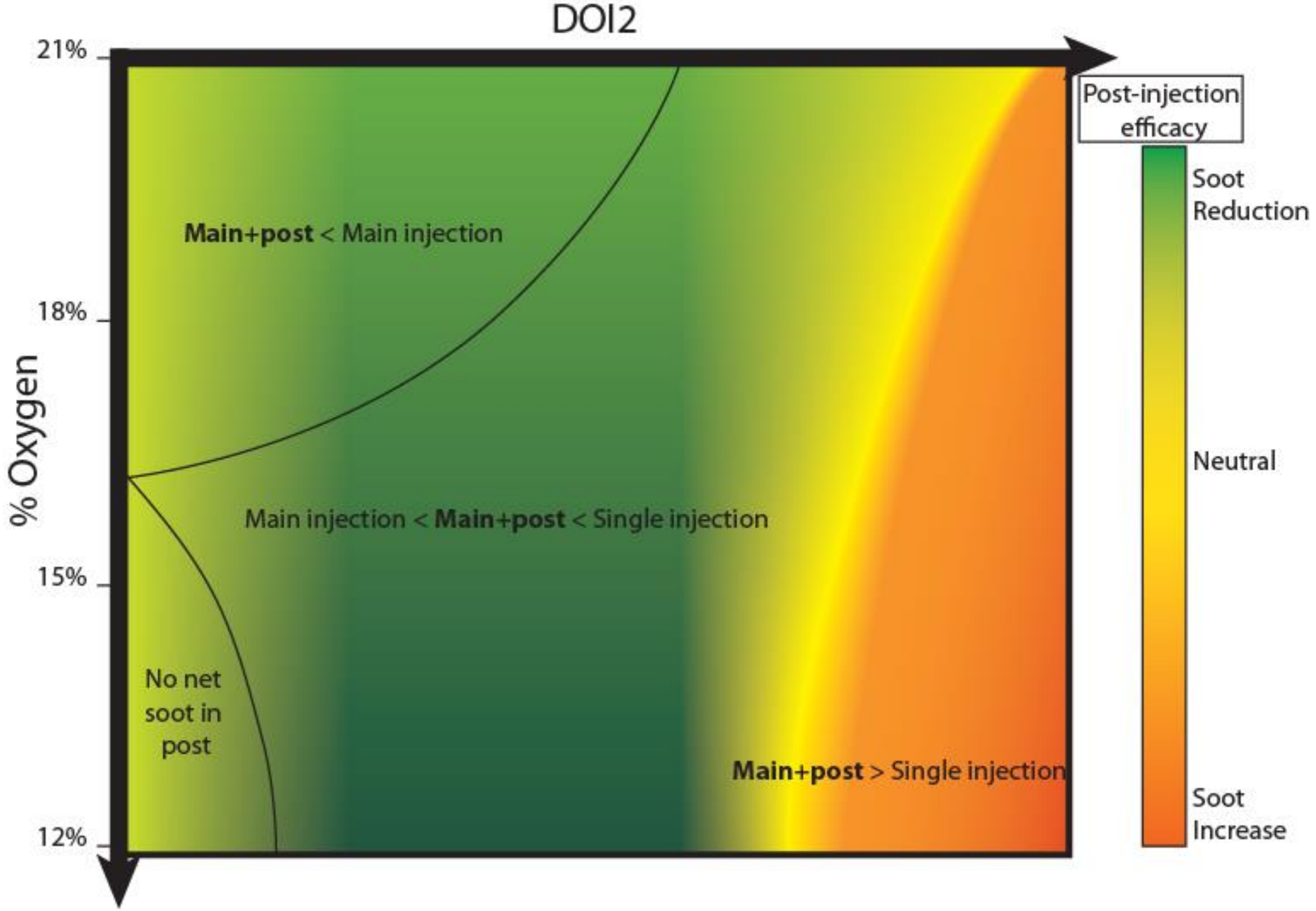
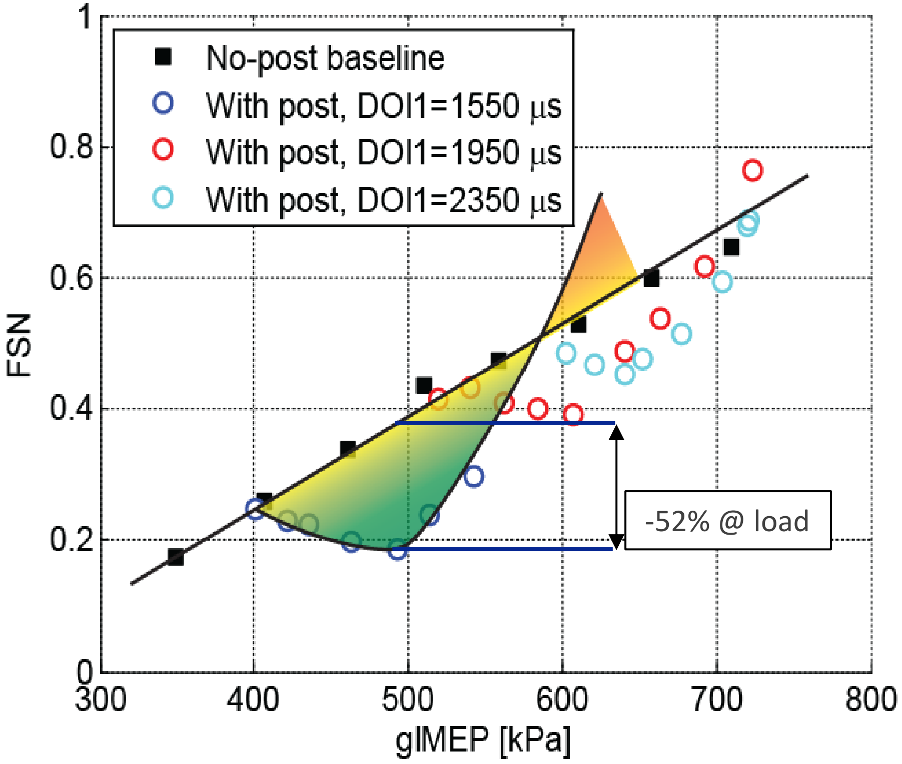
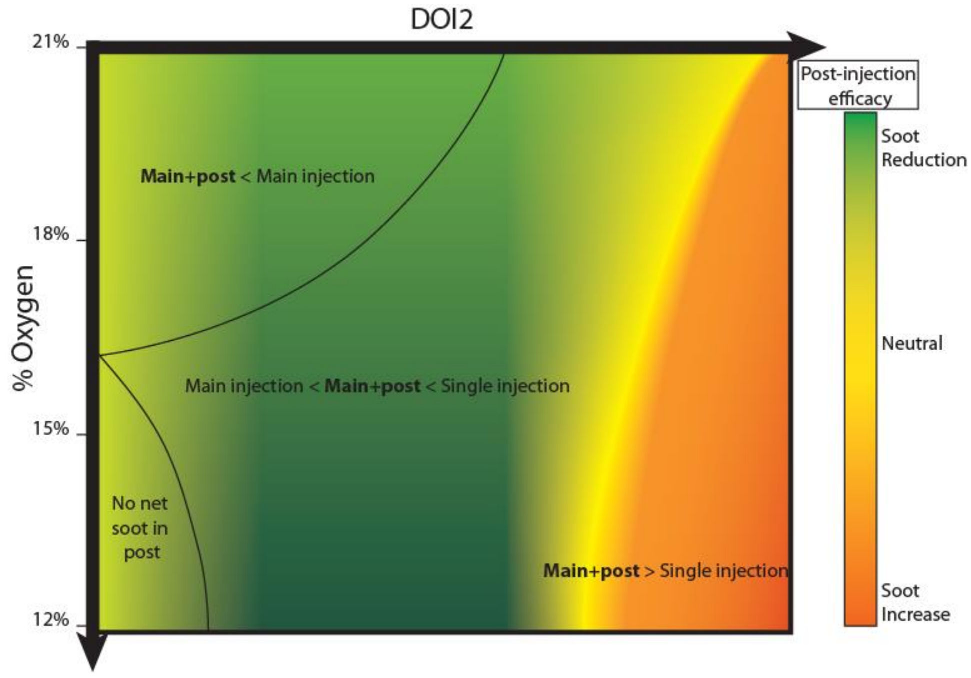


18% O_2 (19-29% EGR): Exhaust Soot Minimized as Close-Coupled Post Duration Increases





Experimental Methodology: LII, High-speed Visualization, Exhaust Soot Measurements

- High-speed visualization
  - Measure soot luminescence at λ>485 nm, *dt*=½ CAD
- Laser-induced incandescence
  - Excitation at λ=1064 nm, 130 mJ/pulse
  - Measure incandescence at λ<485 nm with PI-Max, t_{exp}=15 ns
- Soot measurements
  - AVL 415S smoke meter

Benefits:

- High resolution in time

Limitations:

- Line-of-sight integrated data

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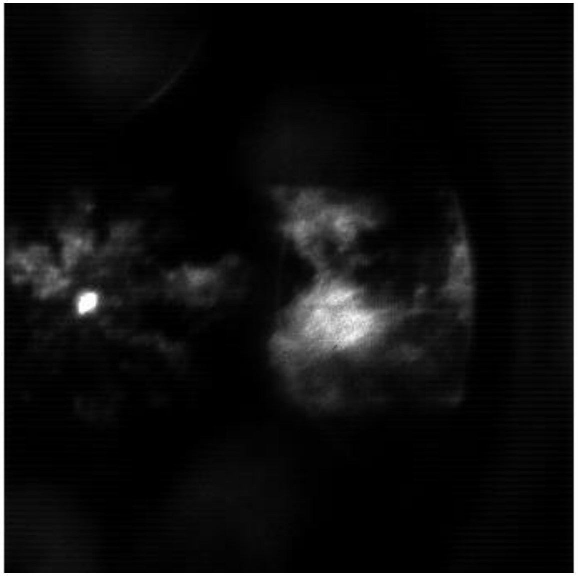


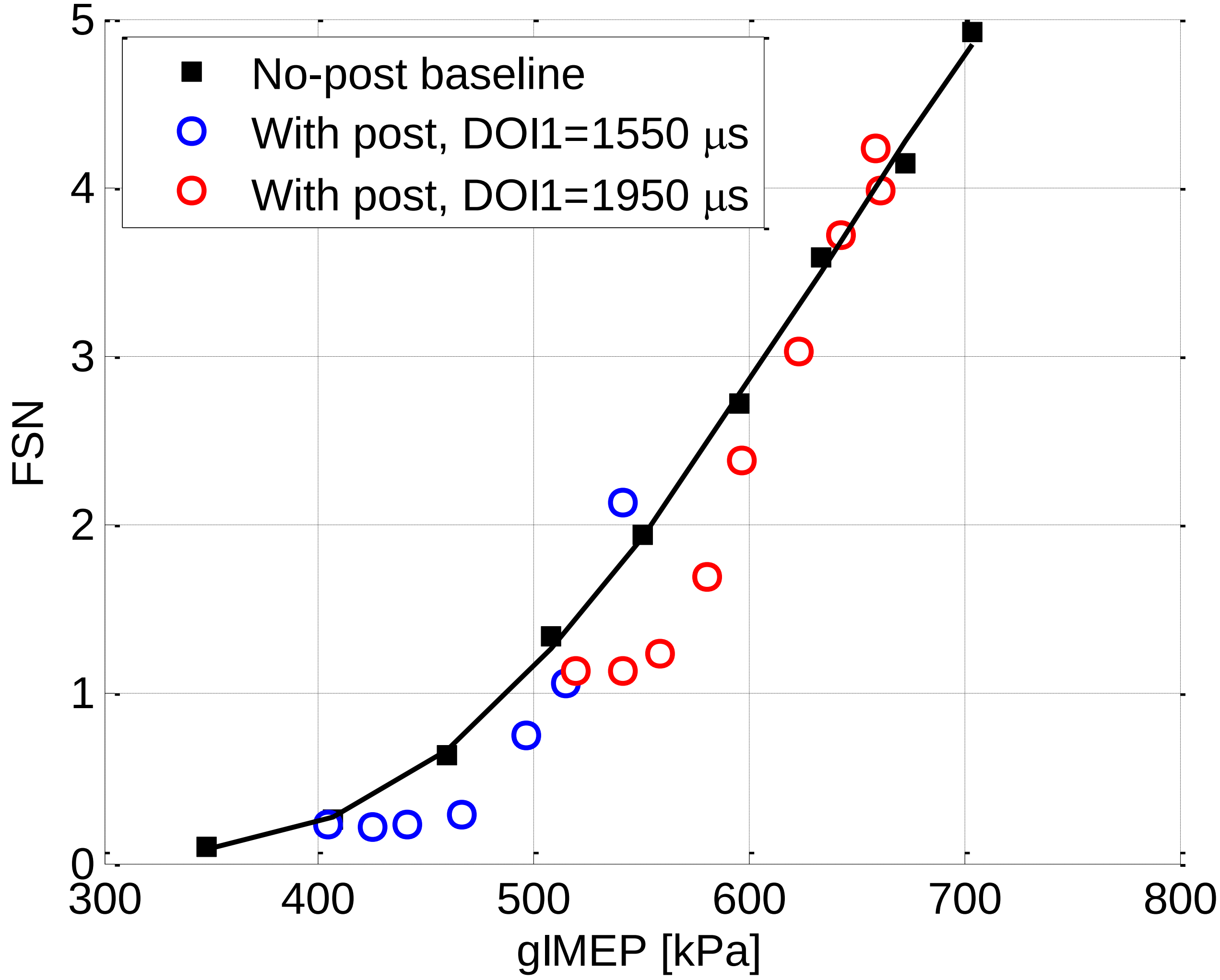
Benefits:

- Planar imaging for direct visualization of interactions

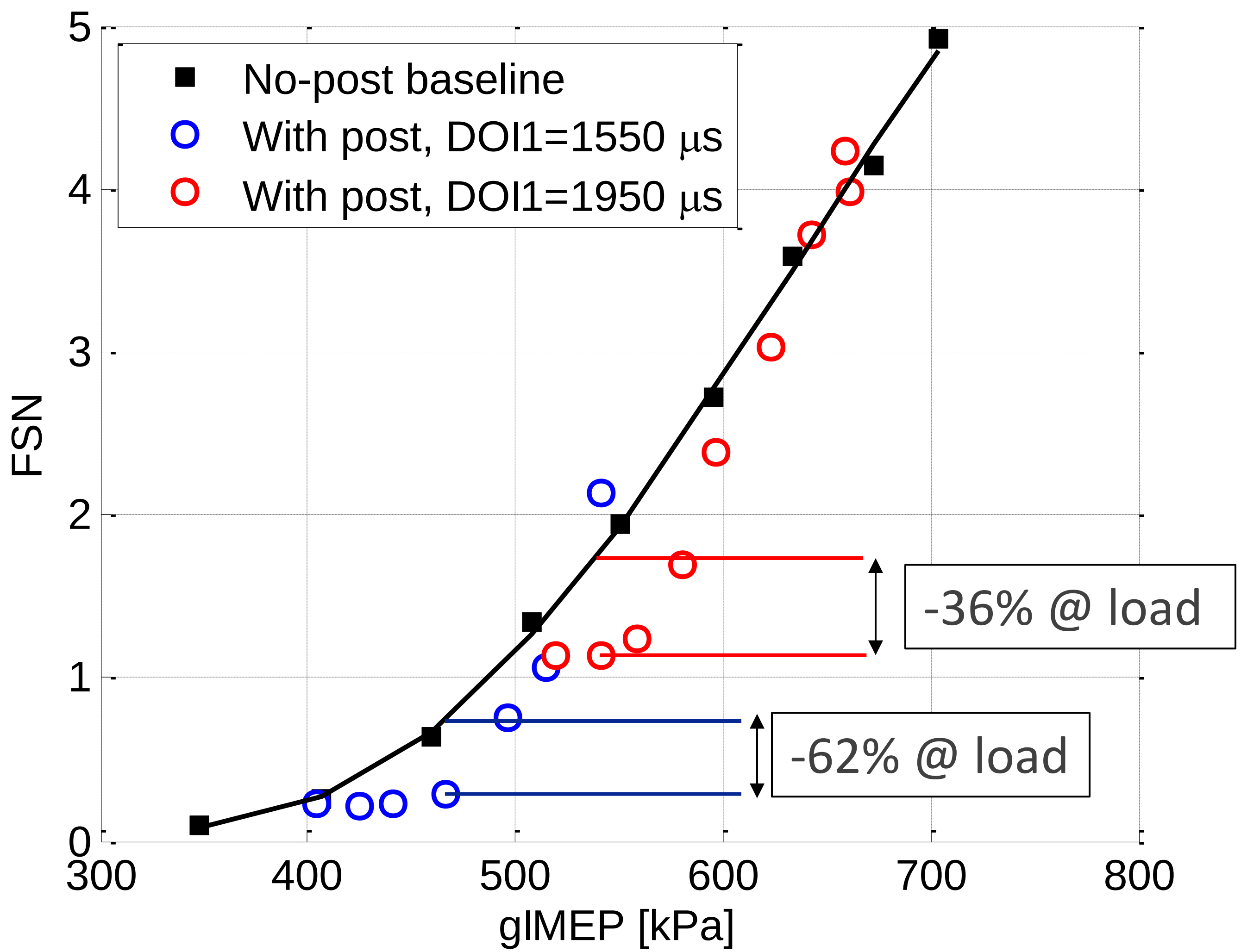
Limitations:

- Single-shot images
- Limited probe volume (sheet width, position)

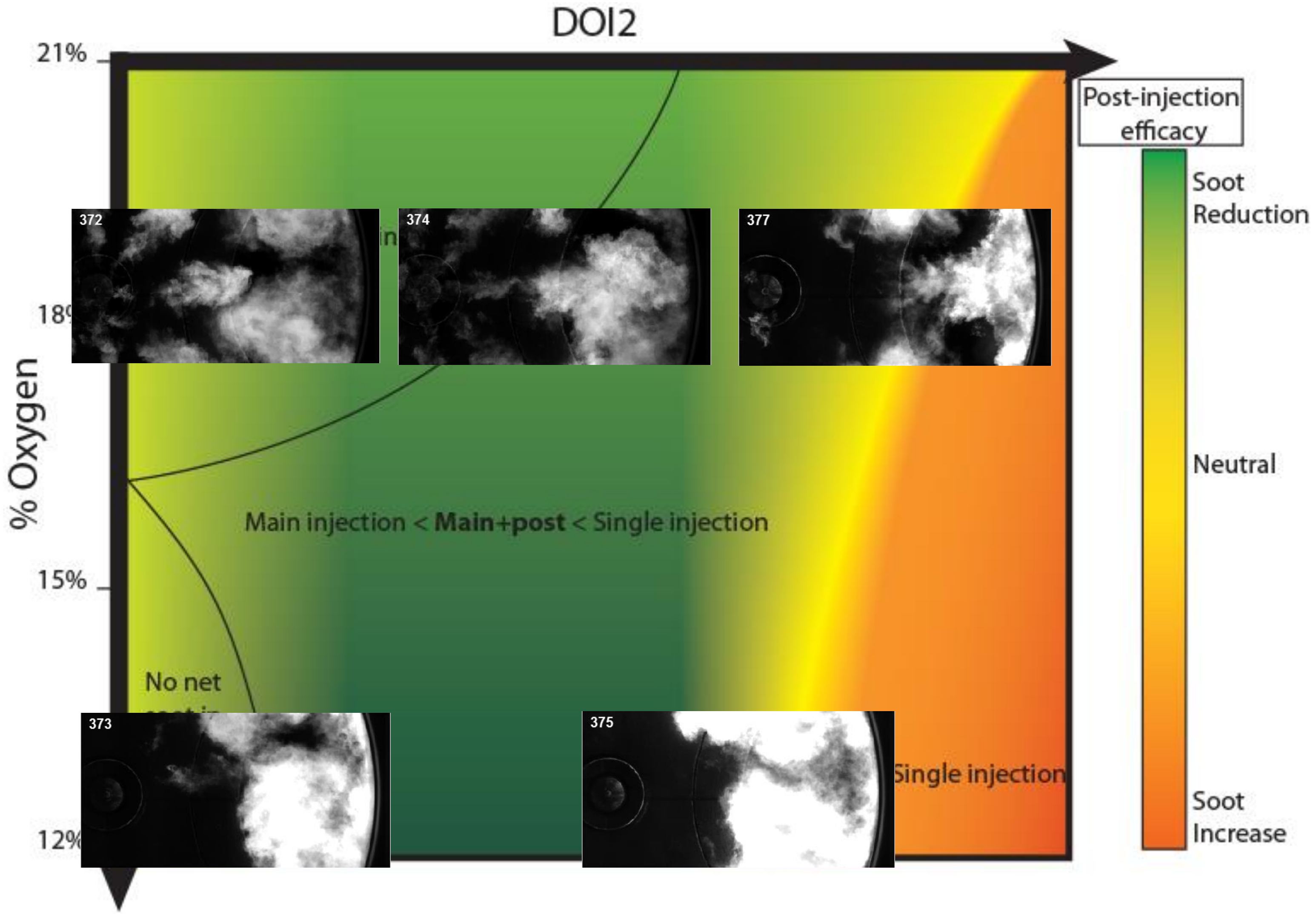
12.6% O_2 (41-53% EGR): Post-Injections are Less Effective Relative to Constant Main



12.6% O_2 (41-53% EGR): Post-Injections are More Effective at Constant Load



Where do Close-Coupled Post Injections Work? – EGR and DOI Dependencies



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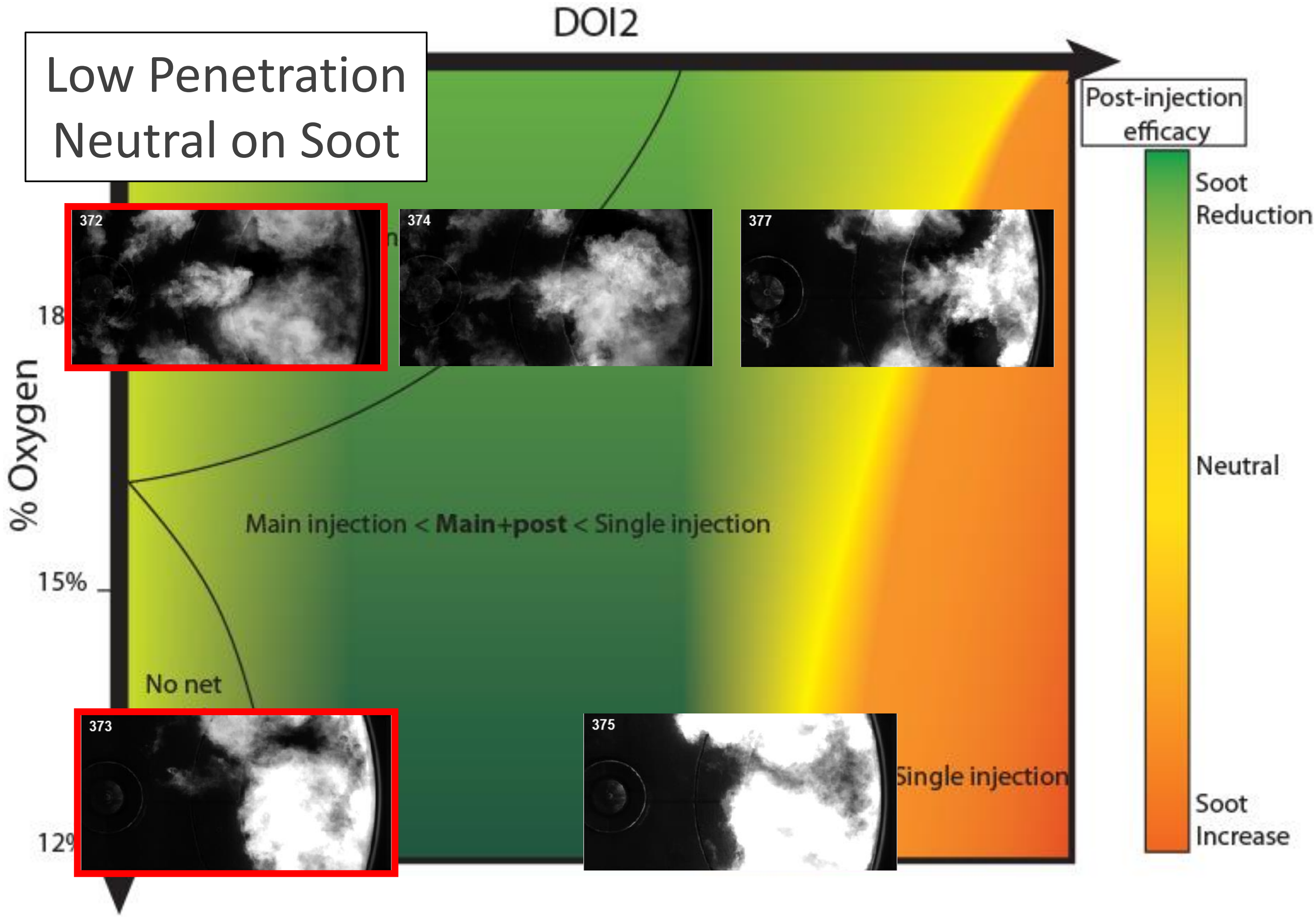

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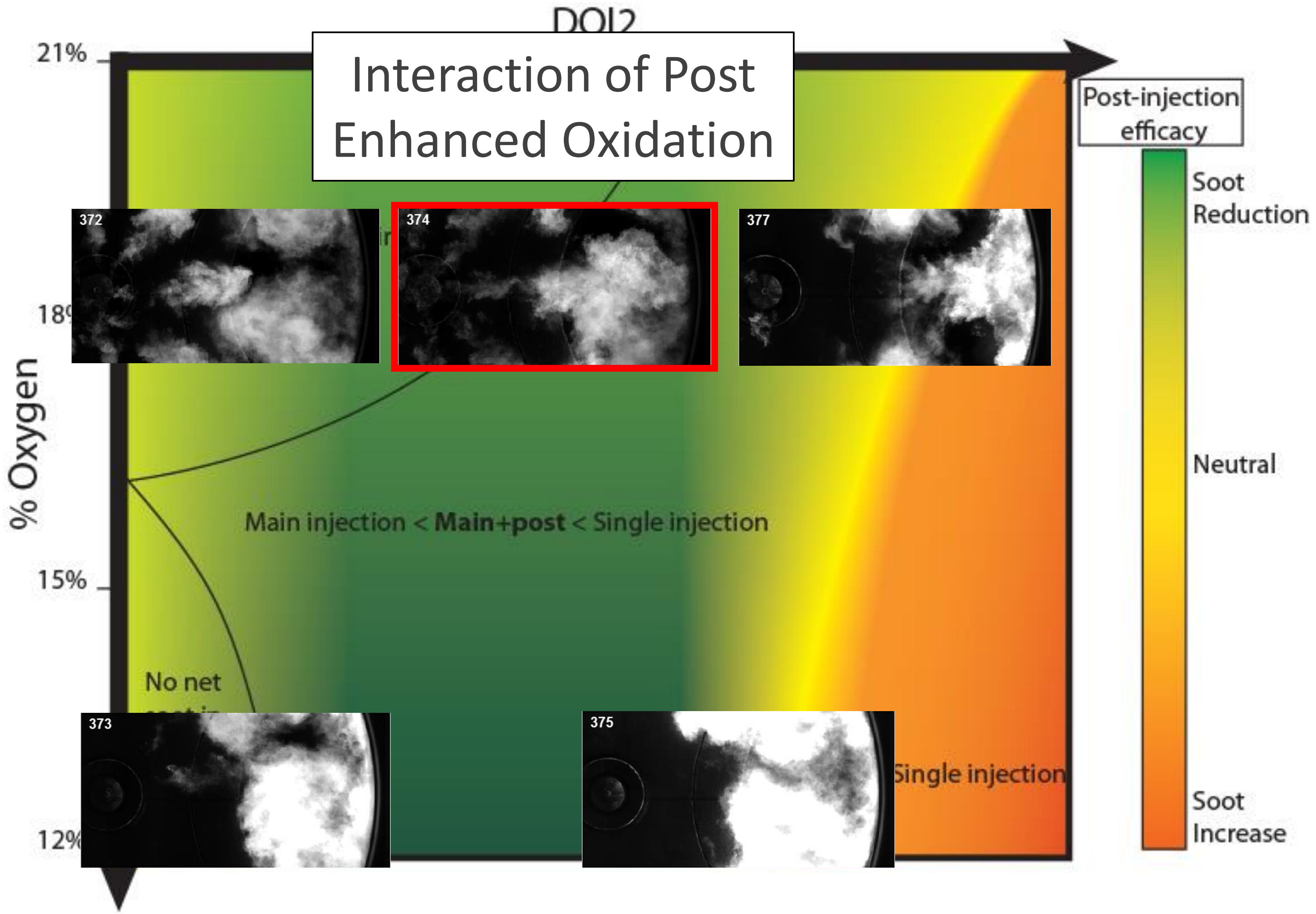

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