COMBUSTION RESEARCH FACILITY

SAND2015-3098C

Image-Based Correlation of Engine Operating Parameters with Occurrence and Duration of Diesel Fuel Injector Dribble

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Abstract: Fuel dribble, defined here as fuel delivery to the combustion chamber outside the intended high-pressure spray event, can negatively affect both fuel efficiency and pollutant emissions. Previously, ensemble-averaged images of dribble have been used to show that dribble exists even for properly functioning fuel injectors and occurred in discrete events, immediately following injection, during expansion, and during exhaust blowdown. Ensemble-averaged dribble exhibit changes to some parametric variations, however the mechanism(s) controlling fuel dribble remain unknown. This study looks for statistical correlations in instantaneous images for the occurrence and duration of single-cycle resolved dribble events with parameter variations that cover fuel type, fuel rail pressure, combustion effects, injector body manufacturer (all mini-sac type), orifice size, and injection schedule – including a post-injection. Our results are consistent with X-ray measurements in which ingested gasses entered the needle sac during dribble. Several possibilities for the transient behavior of this ingested gas and its impact on the other observed dribble features are discussed. For the various timing of dribble events recorded here, we estimate bounds for the contribution of dribble to losses in single cycle fuel efficiency and increases in emissions. As final note on boundary conditions for spray modeling, we recommend that the needle sac volume is proscribed to be mostly gas at the start of needle motion.

Acknowledgements

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Injectors:

Cummins (XPI)Bosch (Lyle Pickett, spray B, ECN) Delphi

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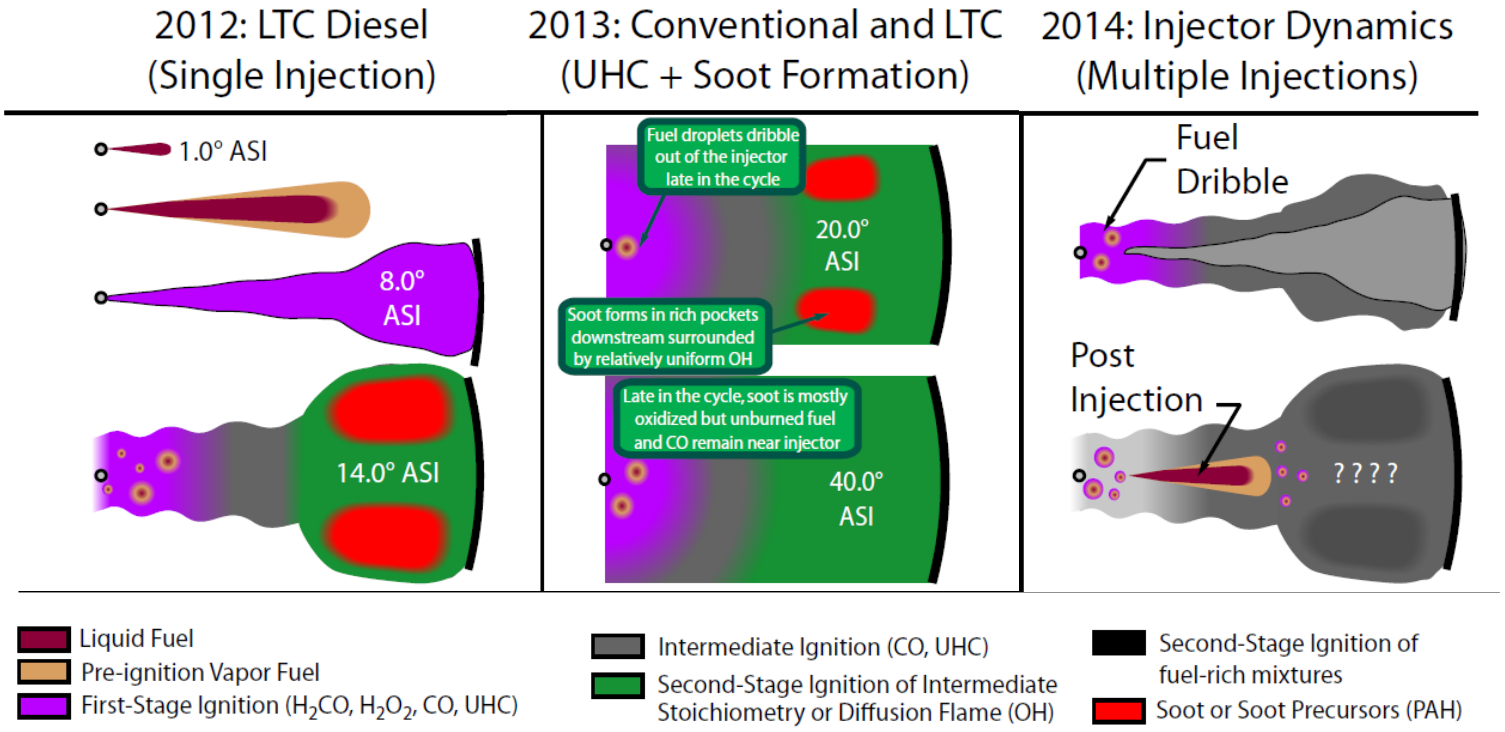
Building a conceptual understanding of dribble

Long-Term Objective

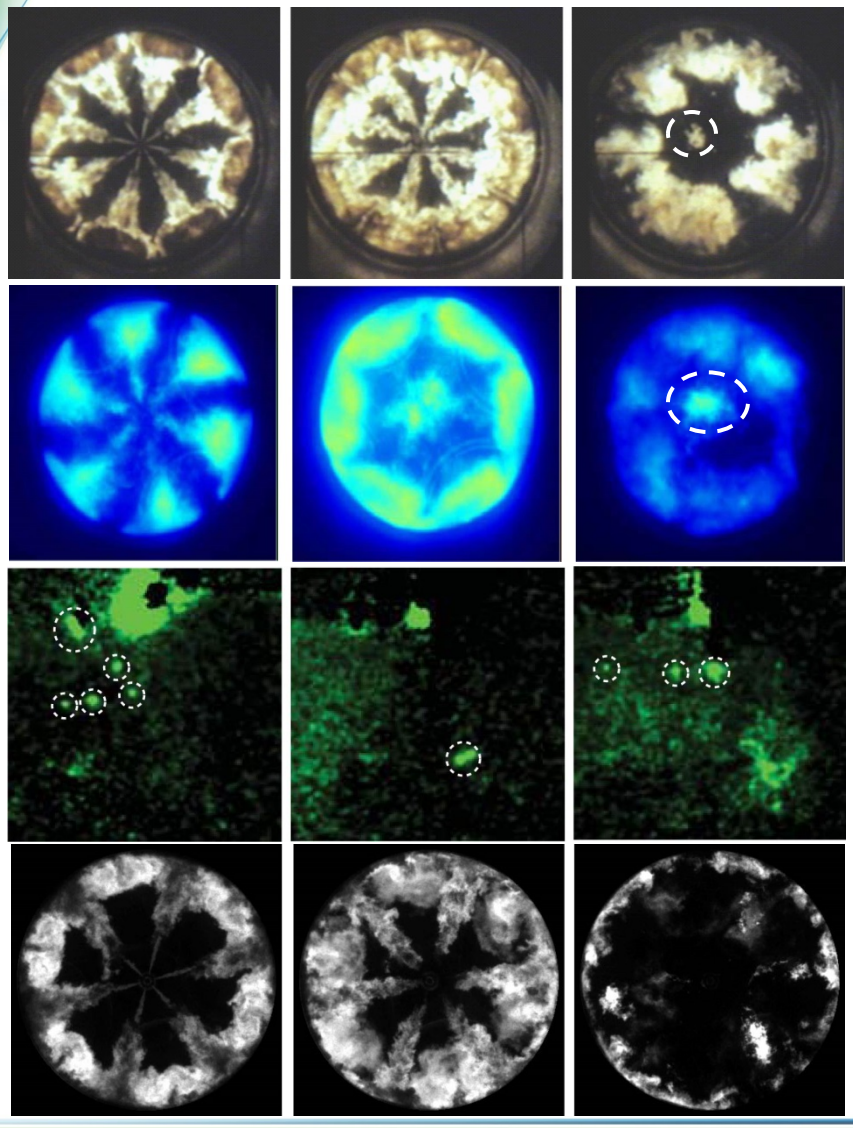
Develop the science base of in-cylinder spray, combustion, and pollutant-formation processes for both conventional diesel and LTC that industry needs to design and build cleaner, more efficient engines



Goals of this presentation

- Define dribble (and explain why we desire a definition)
- Describe some physical processes that affect dribble
- Examine how bad the problem is or could be

Previous studies indicate dribble events at a wide range of conditions



SAE 930971 (Dec, Sandia)
- Heavy-duty, diesel reference fuel
- Cam-driven, mini-sac injector
- Late soot at center

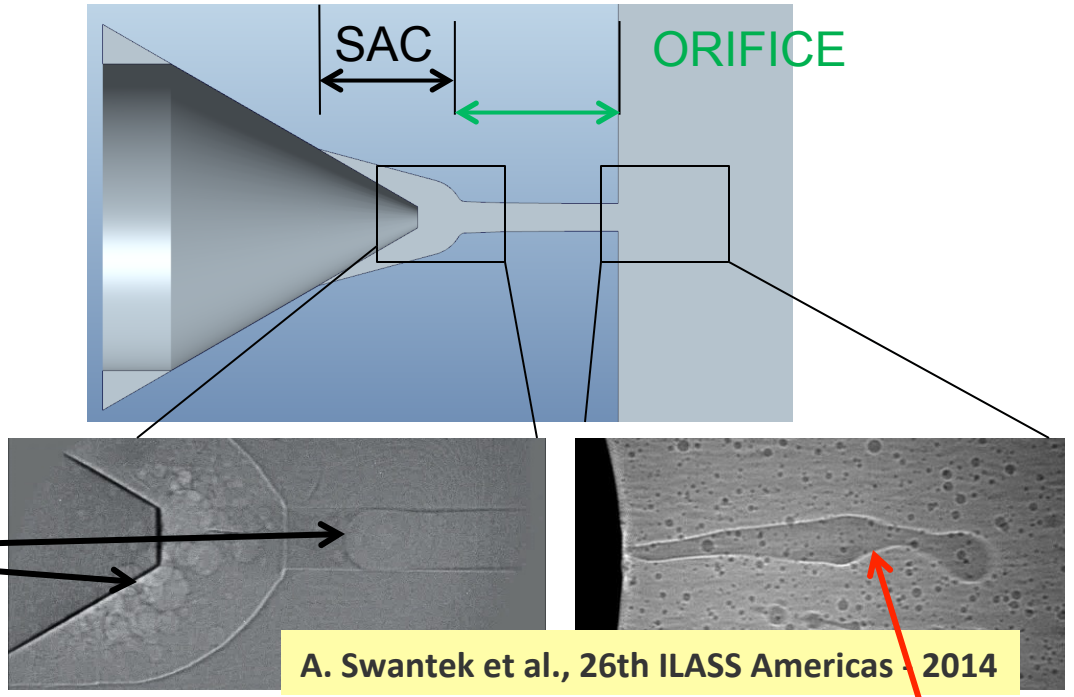
SAE 2005-01-3845 (Taschek et al., Aachen)
- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Conceptual model: Inj. sac vapor → soot

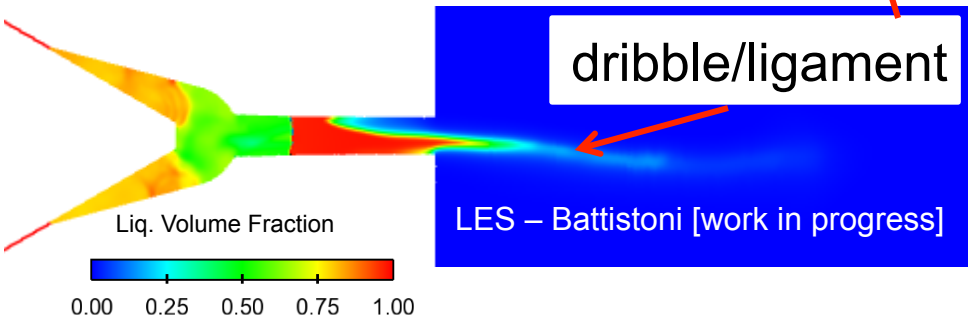
SAE 2009-01-1446 (Ekoto et al., Sandia)
- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Side-view PLIF, bright fuel droplets late

SAE 2001-01-2004 (Mueller et al., Sandia)
- Heavy-duty, diesel reference fuel
- HEUI, VCO injector
- No late soot at center (but sometimes yes)

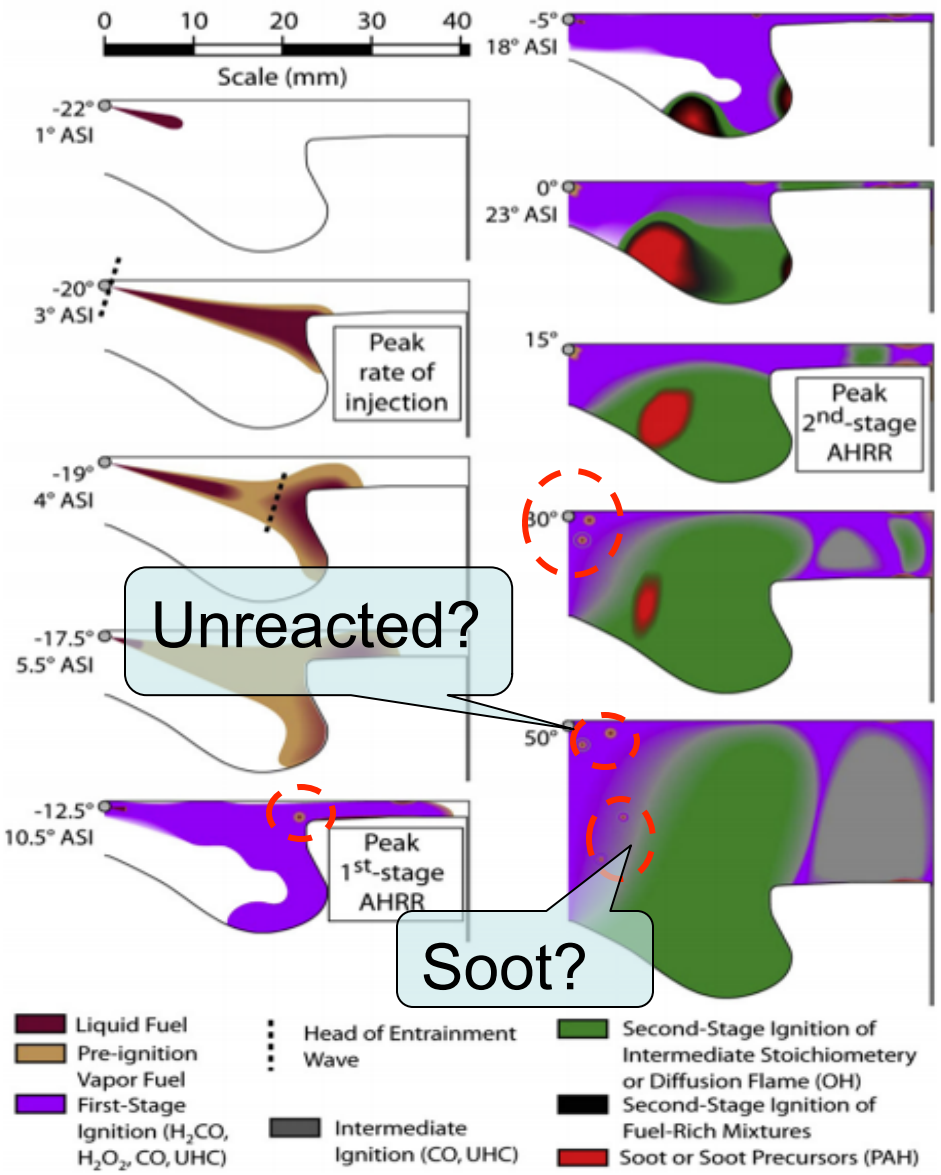
An incomplete list of candidate mechanisms affecting dribble

- Geometry
  - Uncontrolled Volume
  - Number of orifices
- Injector dynamics
  - Needle seal
  - Needle bounce
- Ingested Gasses
- Fuel Compressibility
- Dissolved Gasses
- Multi-component mixture speed of sound





Fate and transport of dribble



Heavy Duty

~12mg/injection per 1bar [IMEP]

Light Duty

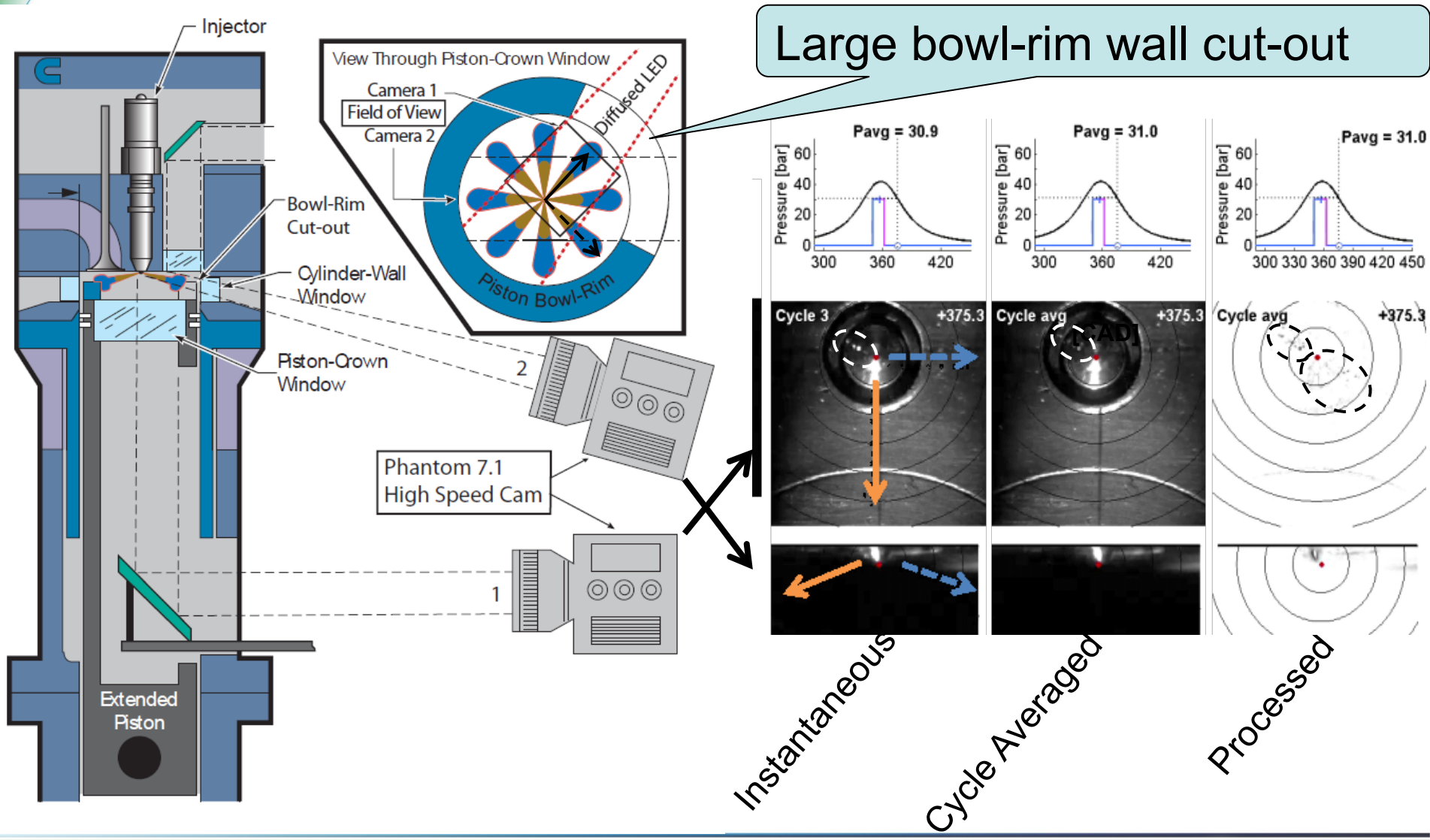
~2mg/injection per 1bar [IMEP]

Mini-sac volumes (holes + sac)

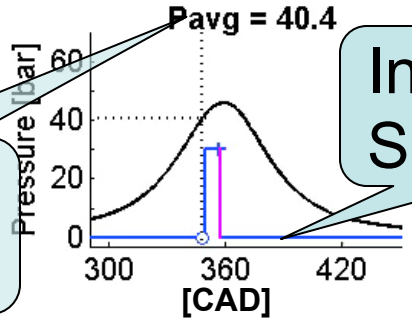
0.2-0.3mm^3 ~ 0.3mg/injection

Sandia Heavy Duty Optical Engine			
IMEP	1 bar	3 bar	5 bar
Injections /kg-fuel	4200	2100	1400
Dribble [g/kg-fuel]	1.49	0.73	0.49
Sandia Light Duty Optical Engine			
IMEP	6 bar	9 bar	12 bar
Injections /kg-fuel	7100	5000	3800
Dribble [g/kg-fuel]	2.48	1.75	1.35

Side-view dribble visualization at TDC requires bowl modifications

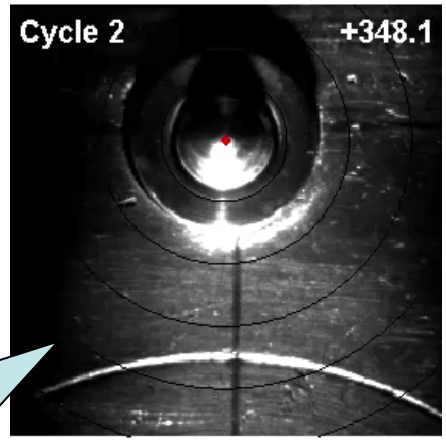


Important concepts

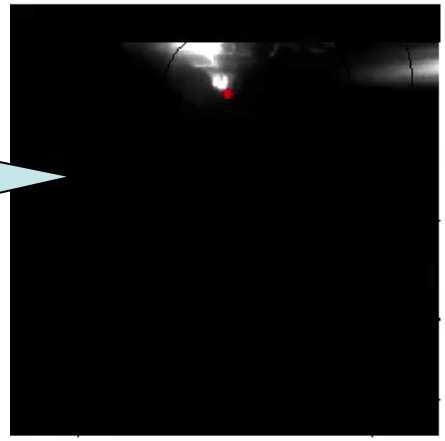


cylinder pressure

Injector SOI,DSE



Piston View 35mm



Liner View

Full Cycle

A definition of dribble includes:

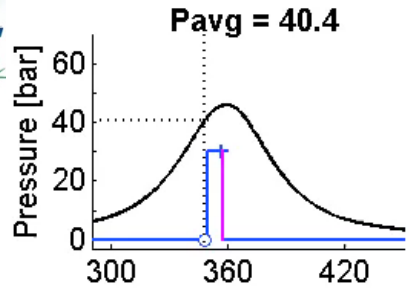
- **Liquid** and/or **vapor** fuel
- Dribble occurs in ***multiple events***
- Dribble is ***not due to malfunction***
- Dribble can contribute unburned hydrocarbons ***directly to the exhaust***

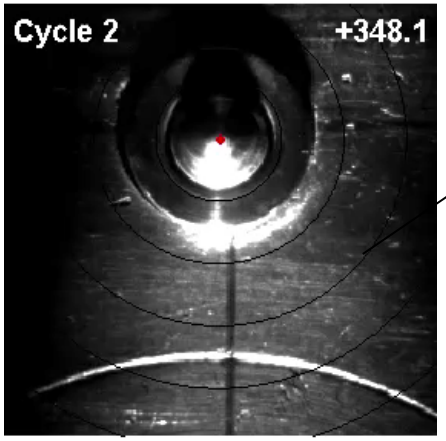
Fuel	Diesel #2, nC_7
Intake	0%, 18% O_2
DSE	1ms
T_{TDC}	930 K
ρ_{TDC}	16.6 kg/m^3
Intake T	156 C
Intake P	2.14 bar
CR SOI	350° (TDC 360)
Speed	1200 rpm
Engine r_C	9.93
View	~35 mm square
Framing	25000 fps
Filter	None

Boosted intake

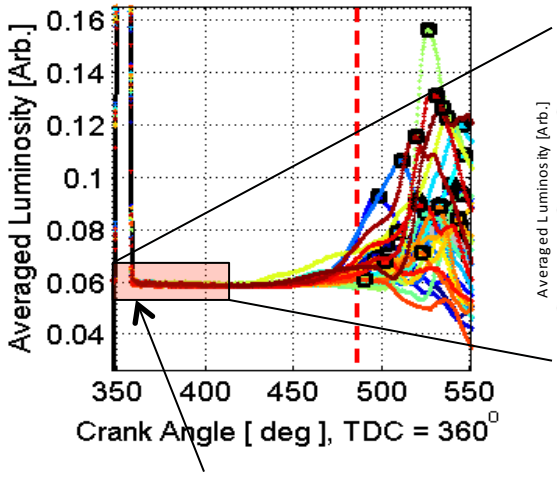
Low compression

Processing Dribble Movies

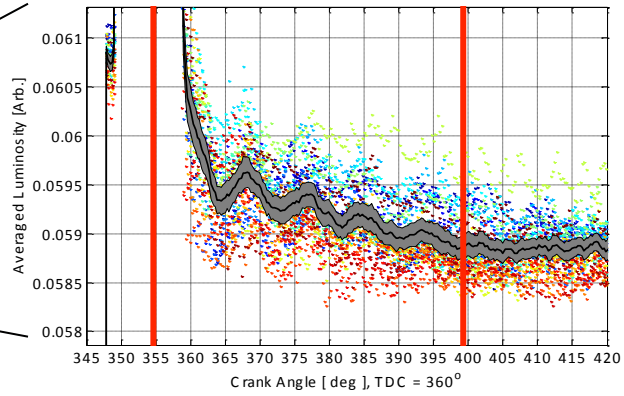




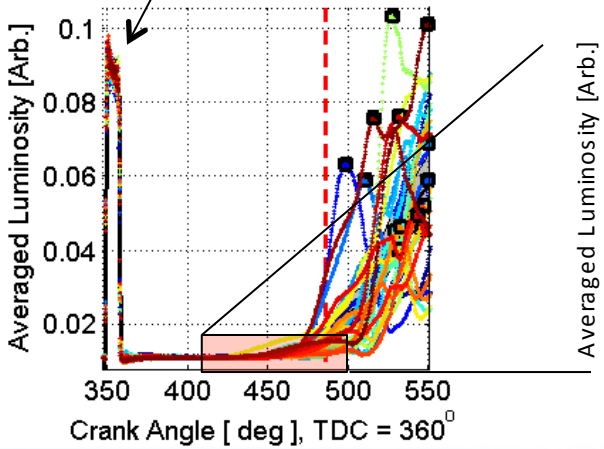
Dribble amount difficult to quantify from luminosity. But timing of different dribble events is possible.



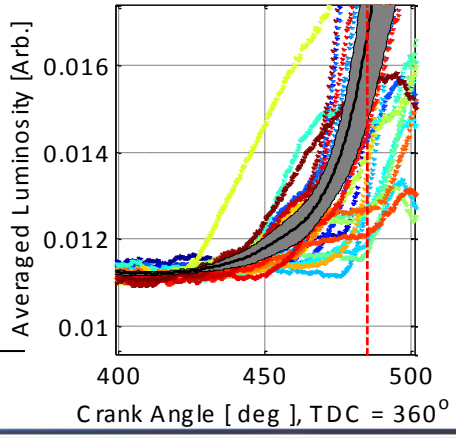
Immediate dribble



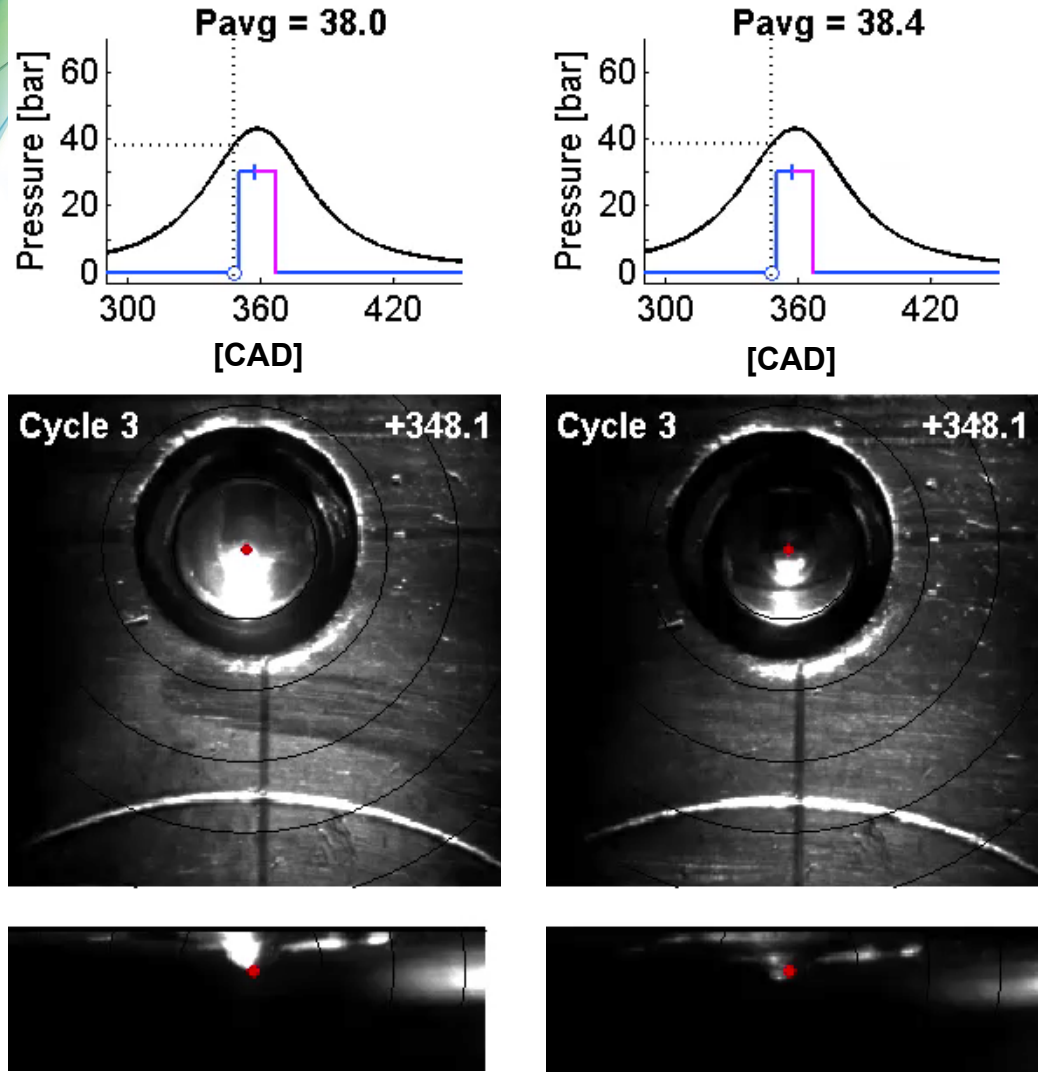
Injection



Late Dribble, condensation



Dribble is not a single event, but distribution among events is sensitive to fuel type



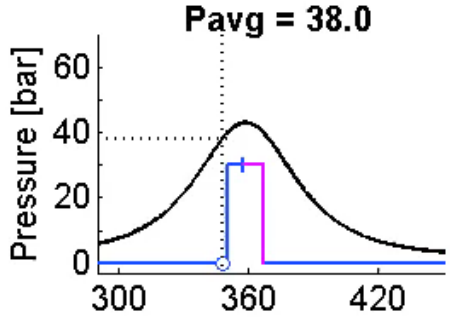
0.09mm XPI
D2 1000bar

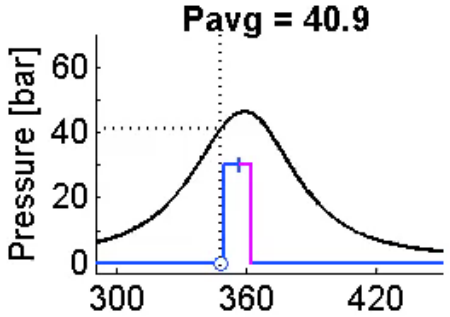
0.13mm XPI
nC_7 1000bar

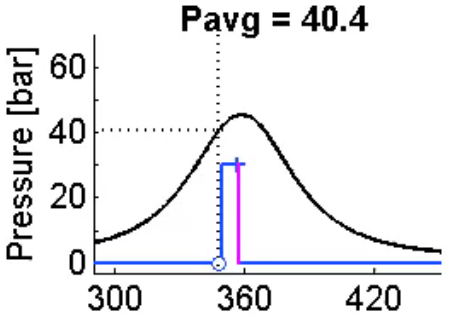
- **Immediate Dribble**
  - Liquid droplets
  - Hole-to-hole variation
- **Late Dribble**
  - Cylinder pressure actuation
  - Liquid or vapor which may condense back to liquid
  - Dribble exiting directly to exhaust (during blowdown)

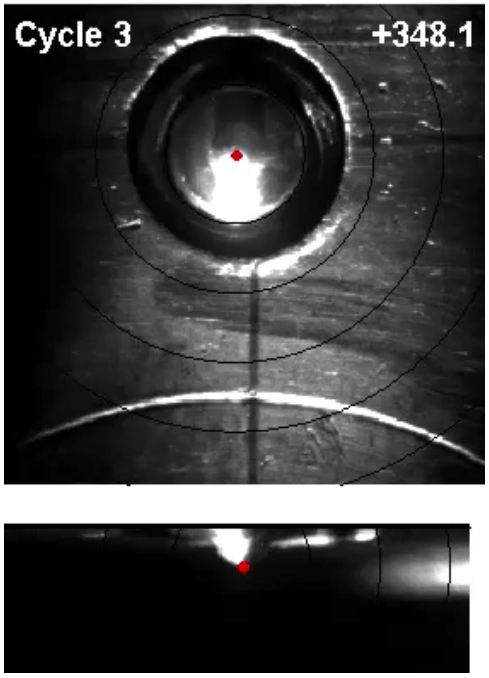
Intake	0% O_2
DSE	1ms
Intake T	156 C
Intake P	2.14 bar
CA SOI	350° (TDC 360)
Speed	1200 rpm
Engine r_C	9.93
View	~35 mm square
Framing	25000 fps
Filter	None

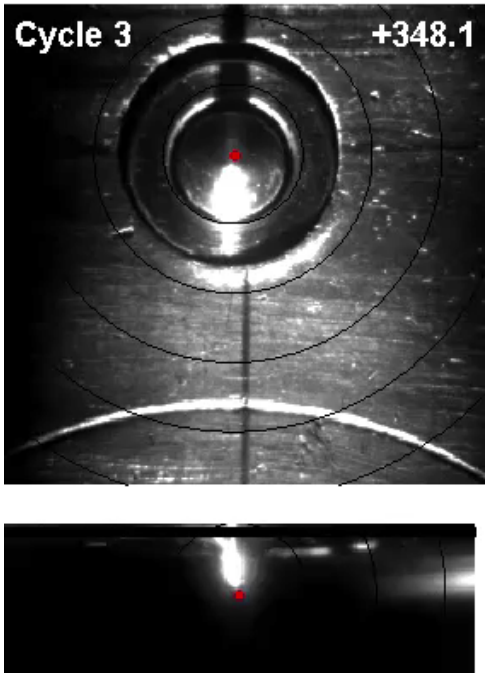
Dribble is not a malfunction, and exists for a range of orifice sizes and injector manufacturers

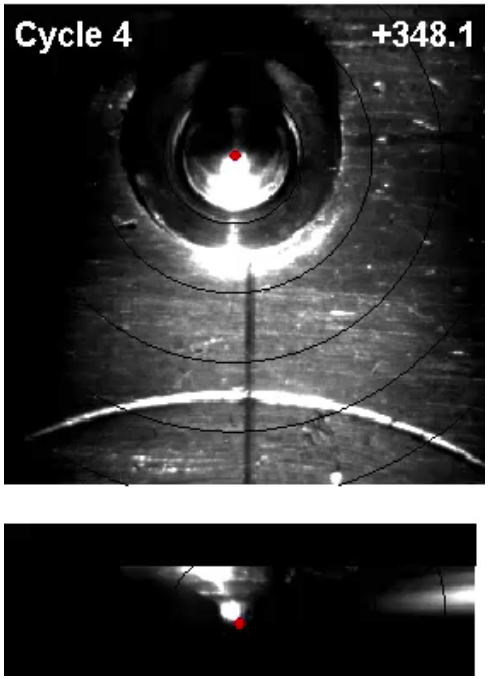










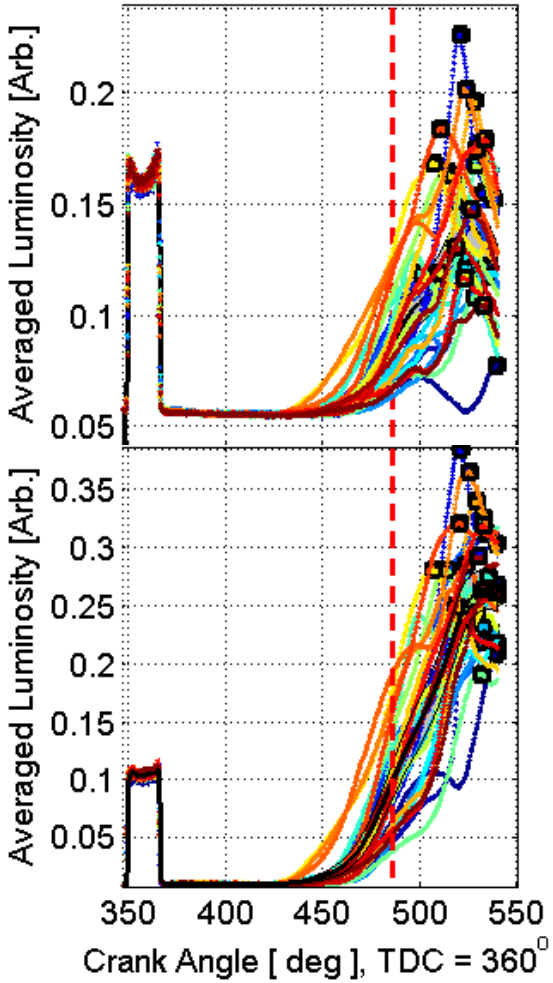


0.09mm XPI
D2, 1000bar

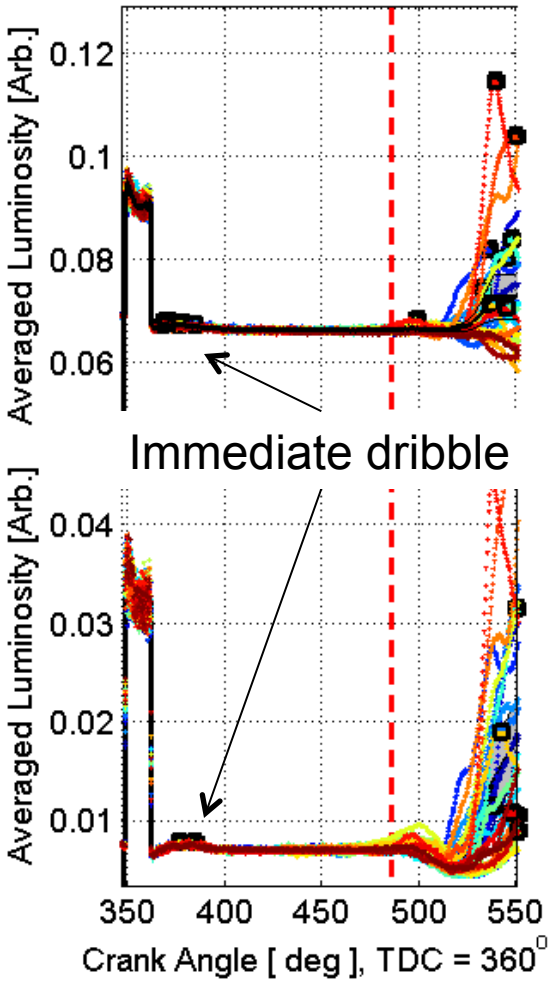
0.09mm Bosch
D2, 1000bar

0.13mm Delphi
D2, 1000bar

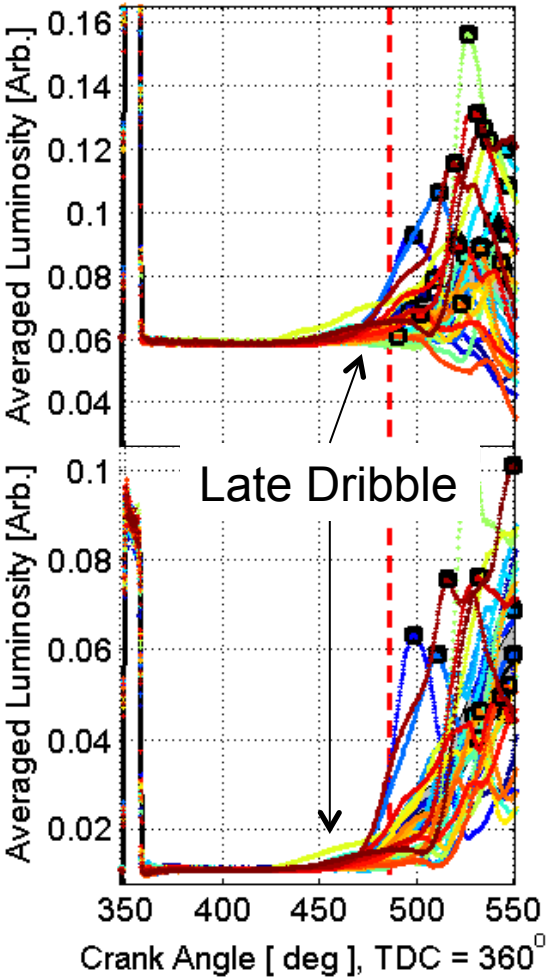
Instantaneous Dribble from motored injections at 0% O_2



0.09mm XPI
D2, 1000bar

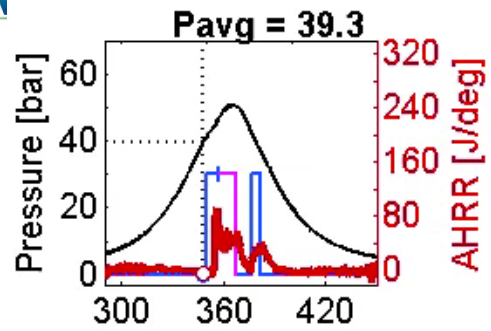


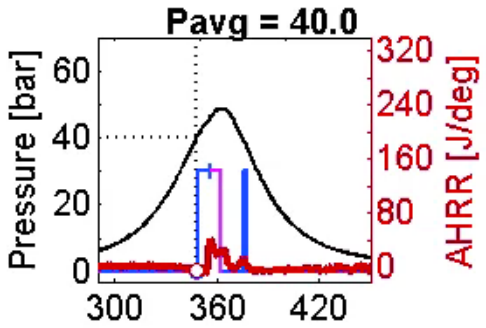
0.09mm Bosch
D2, 1000bar

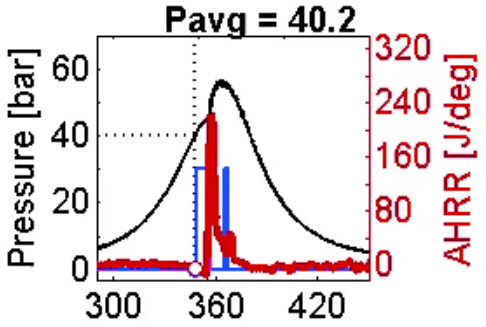


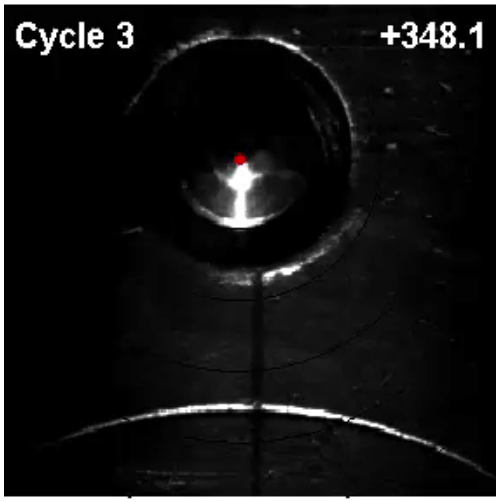
0.13mm Delphi
D2, 1000bar

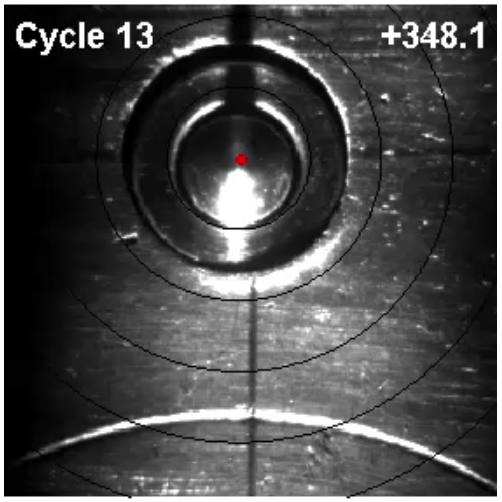
Dribble occurs after both main and post injection

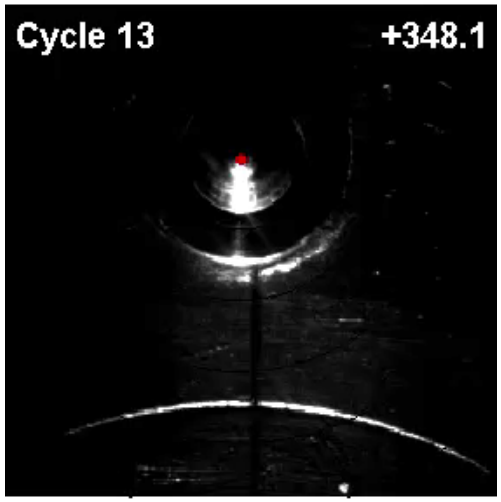


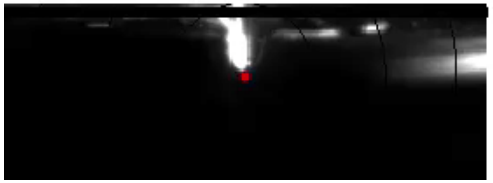


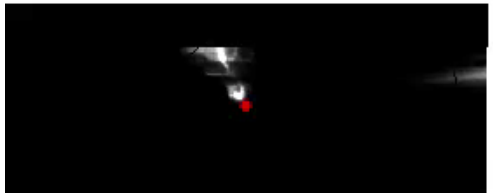












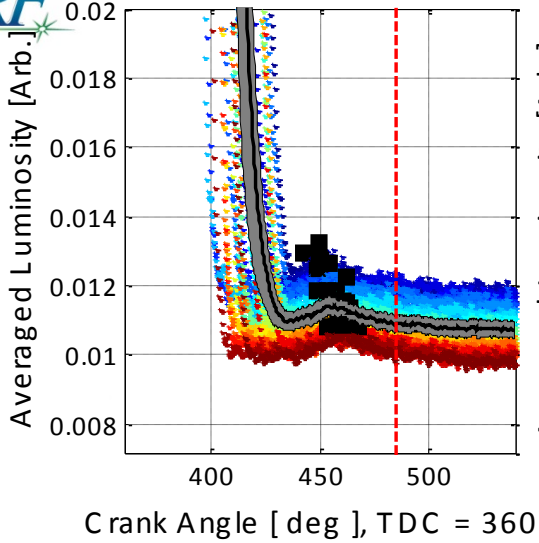
0.09mm XPI
nC_7, 1000bar

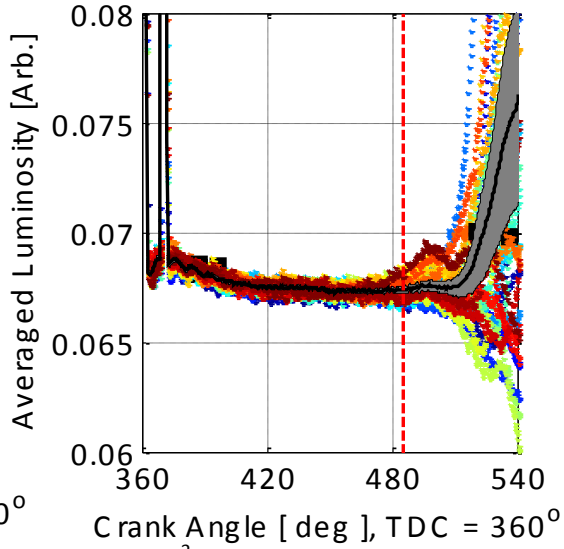
0.09mm Bosch
D2, 1000bar

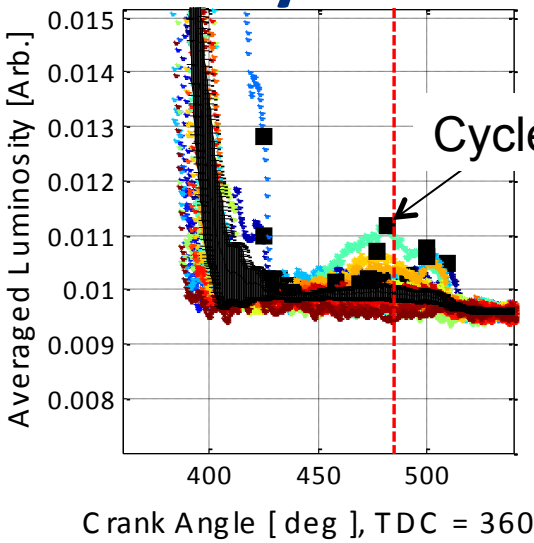
0.13mm Delphi
D2, 1000bar

Instantaneous Dribble from fired cycles

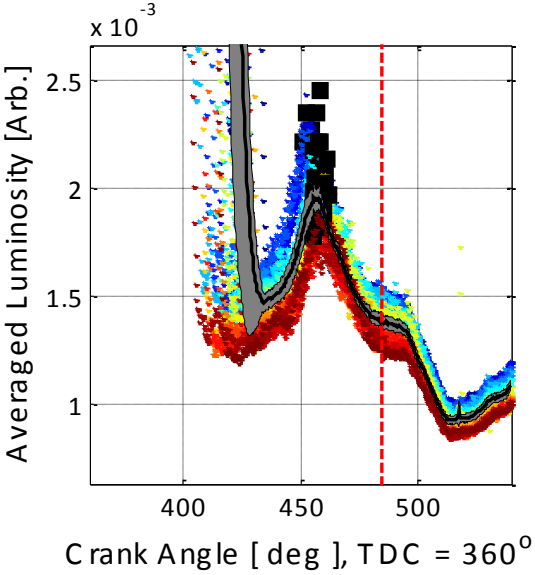
Bottom View

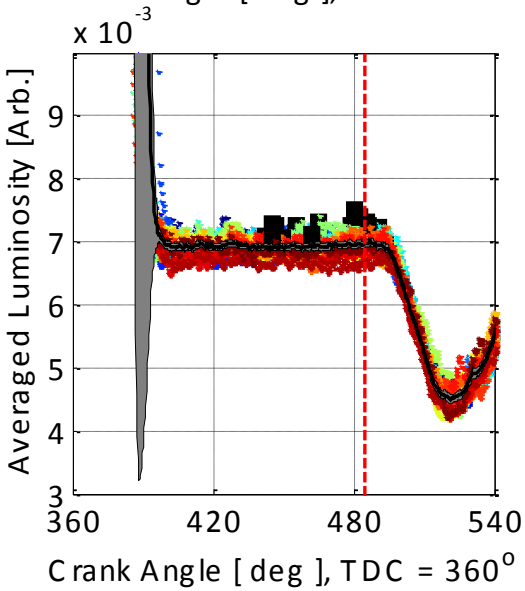


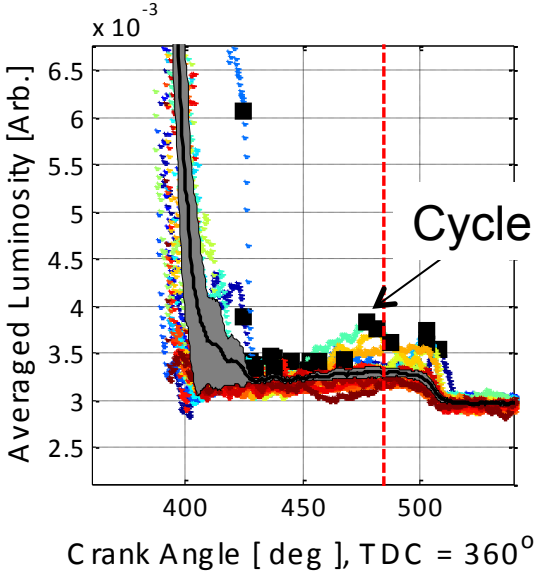




Side View





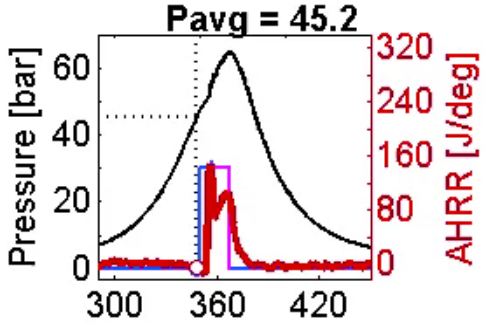


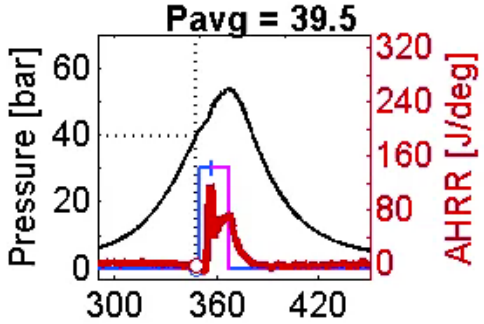
0.09mm XPI
nC_7, 1000bar

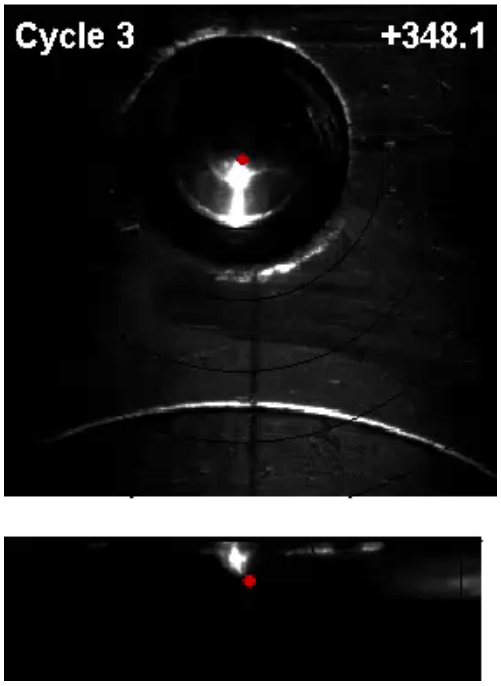
0.09mm Bosch
nC_7, 1000bar

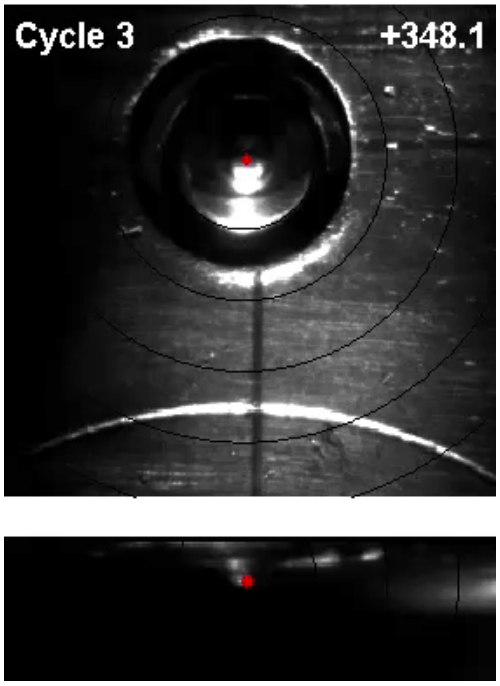
0.13mm Delphi
D2, 1000bar

Heat release has minimal effect on dribble, demonstrates UHC can go directly to exhaust









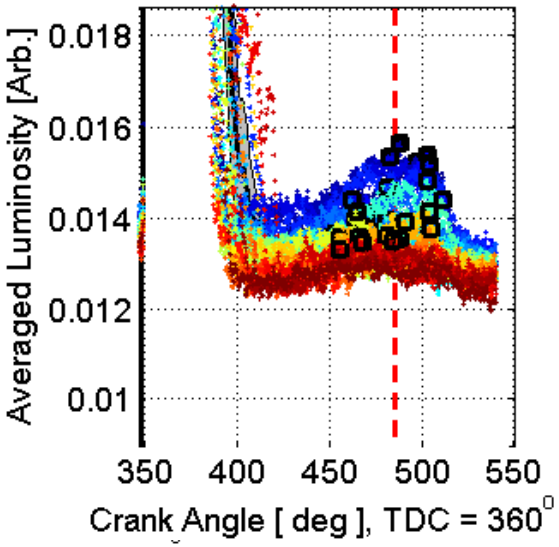
0.09mm XPI
D2 1000bar

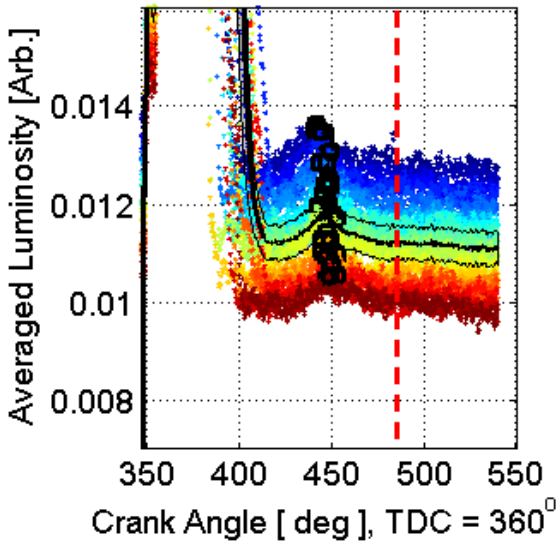
0.09mm XPI
nC_7 1000bar

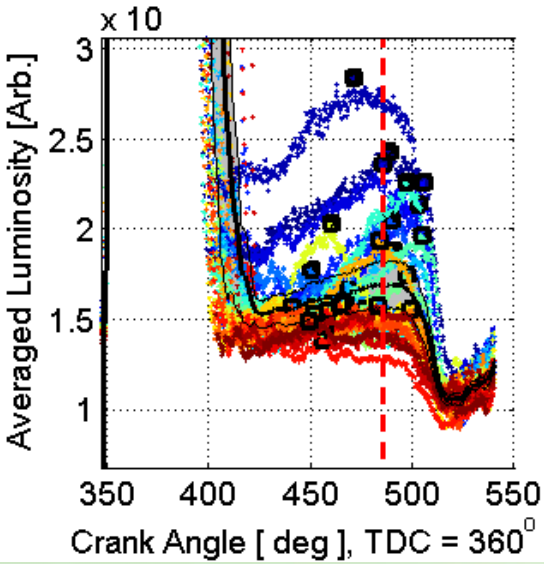
- Immediate Dribble
  - Liquid droplets (soot)
- Late Dribble
  - Pressure driven
  - Vapor or liquid (UHC)

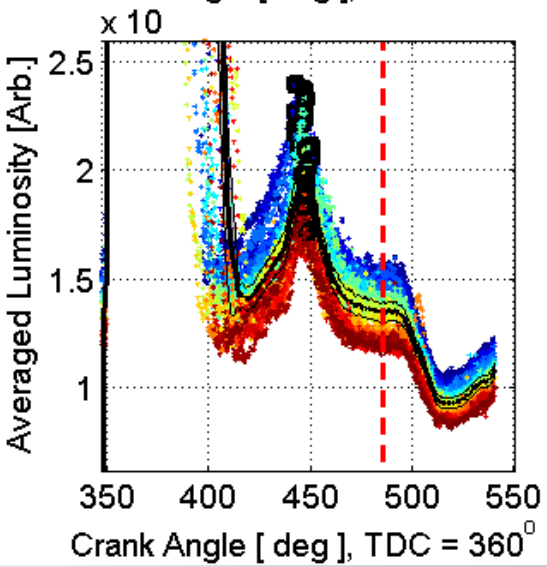
Intake	18% O_2
DSE	1ms
Intake T	156 ± 2C
Intake P	2.06 bar
CA SOI	350° (TDC 360)
Speed	1200 rpm
Engine r_C	9.93
View	~35 mm square
Framing	25000 fps
Filter	None

Diesel fuel dribble condensation shows greater stochasticity than n-heptane



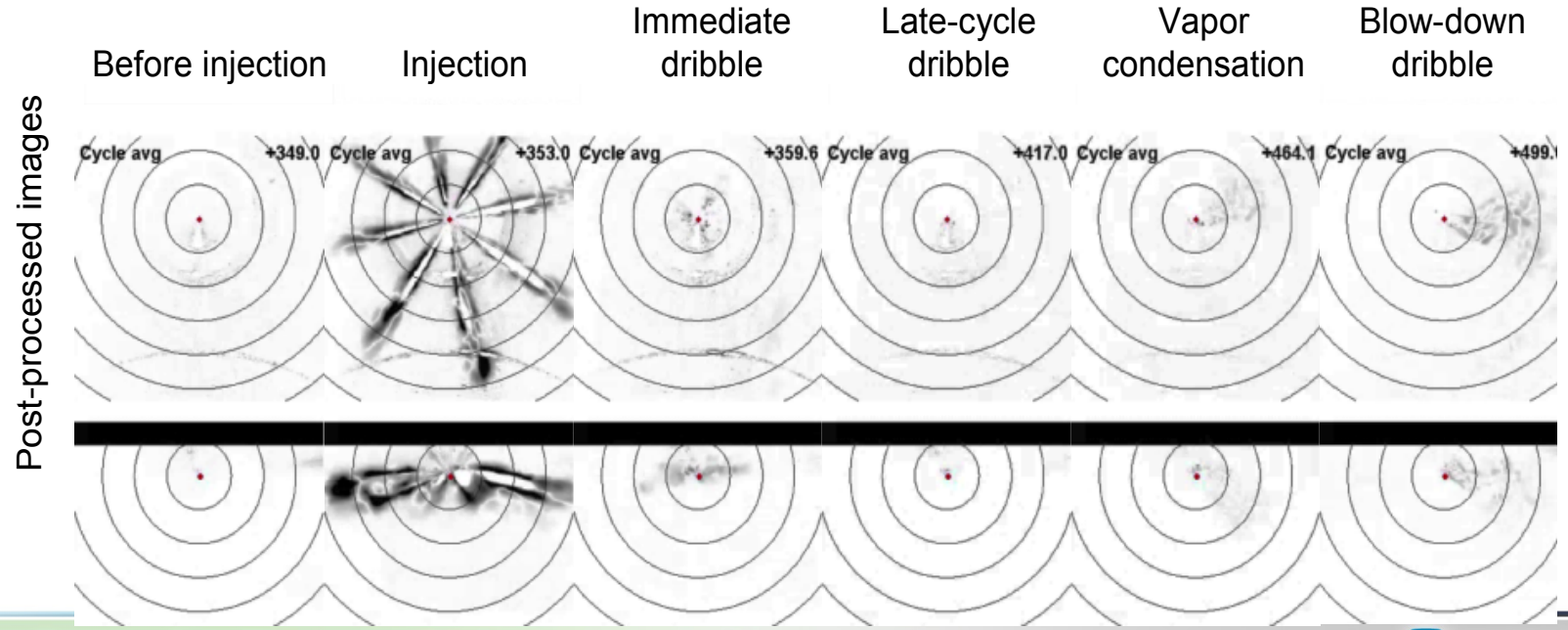




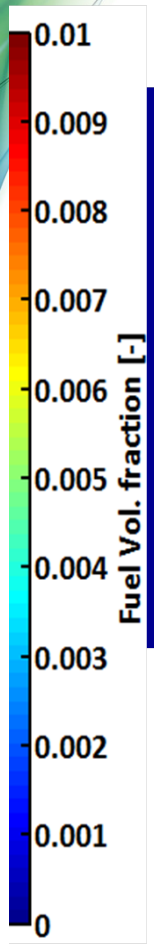


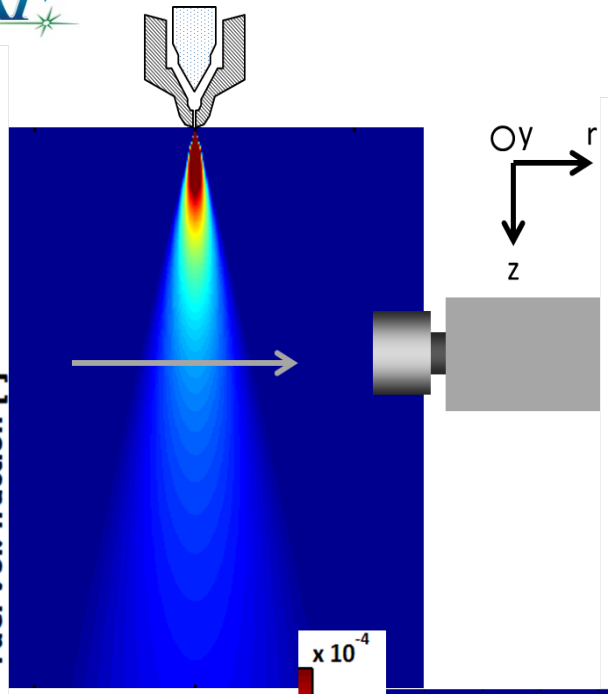
Summary

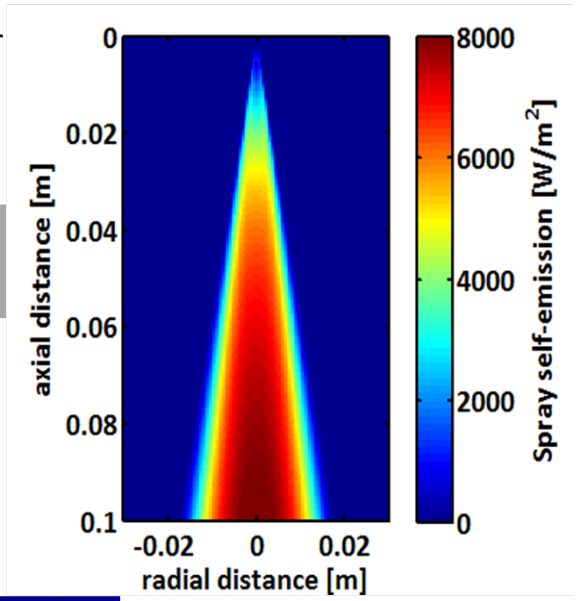
- Dribble, as defined here, is ***not due to malfunction***
  (the term 'leaking injector' is preferable in such cases)
- Dribble occurs in ***multiple events***
- Dribbled fuel may emerge as either ***liquid droplets or fuel vapors***
- Dribble contributes some unburned hydrocarbons ***directly to the exhaust***
- ***Stochastic behavior*** *of dribble between different types*

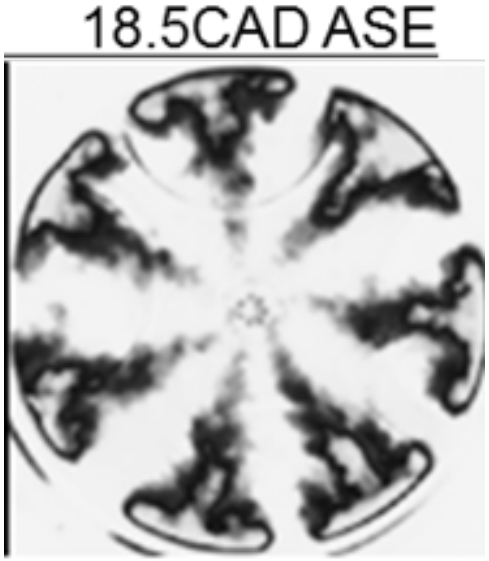


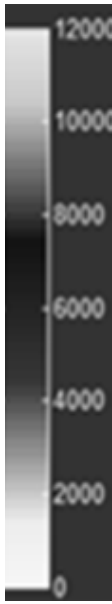
Future work – Quantifying Dribbled Fuel

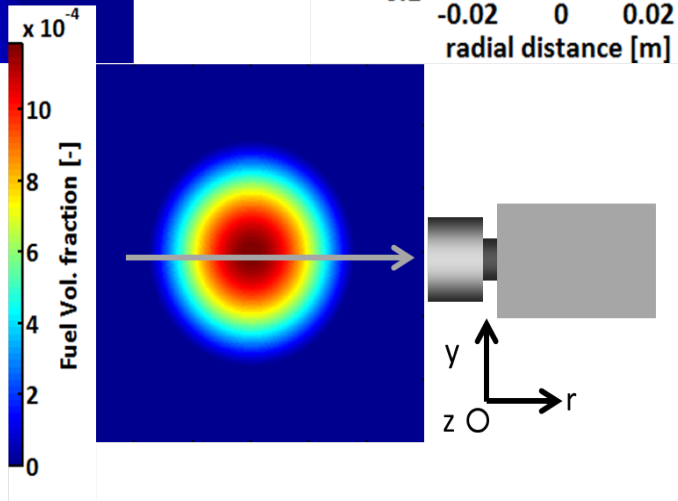












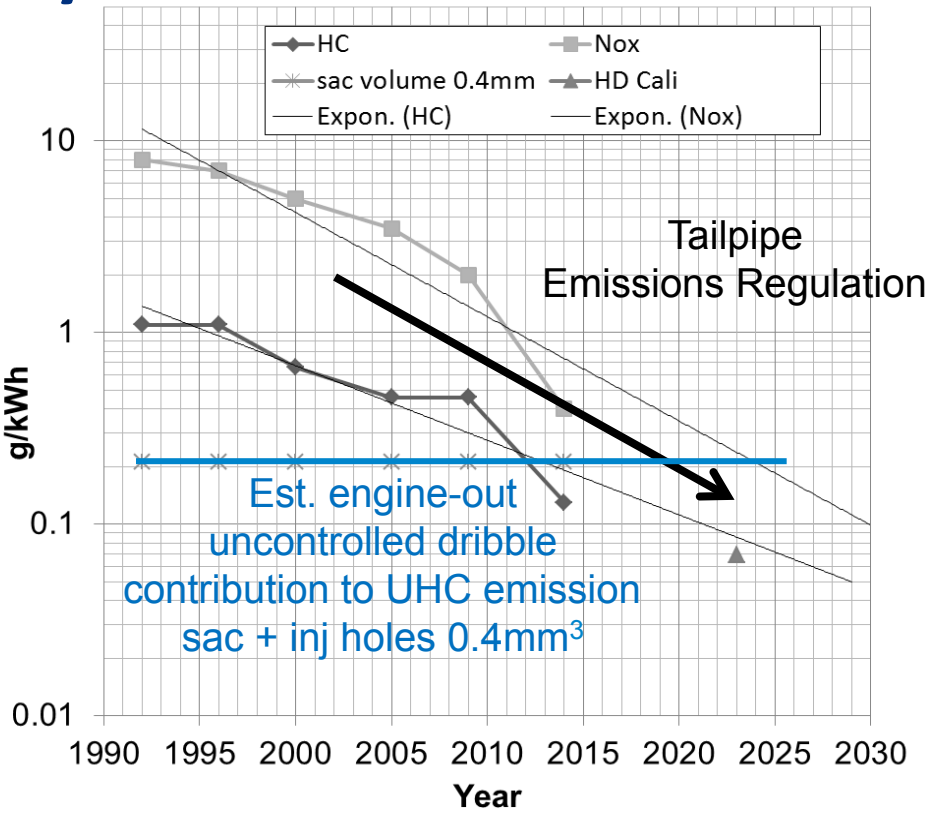
1-5 micron IR camera detection

Infrared Emission/Absorption from fuel at the injector tip (3.4 micron bandpass filter)

Impact on industry and the environment

$$m\downarrow dribble\ /inj = 0.2 \cdot m\downarrow fuel\_sac$$

Sandia Heavy Duty Optical Engine			
IMEP	1 bar	3 bar	5 bar
Injections/ kg-fuel	42000	21000	14000
Est. Dribble [g/kg-fuel]	2.8	1.4	0.94



- The emission factor g/kg_fuel allows us to estimate the total impact of dribble wrt HC emission and total fuel use.
- Los Angeles on-road diesel fuel usage of 2.9×10^9 L fuel/yr

  Fleet-average tailpipe emission of 2.1g/kg_fuel*

  Diesel fleet exhausts roughly 14,000 kg of fuel per day!

‡Greeves, G., Khan, I.M., Wang, C.H.T., Fenne, I.: Origins of Hydrocarbon Emissions from Diesel Engines. SAE Tech. Pap. (1977).

* Bishop, G.A., Stedman, D.H.: Remote Measurements of On-Road Emissions from Heavy-Duty Diesel Vehicles in California; Year 5 , 2012. 1–35 (2013).

Conclusions

- Significant impacts on dribble by further reductions in sac+orifice volumes is unlikely, and so **requires mechanistic understanding to further mitigate**.
- Because **dribble is a per-injection event**, contributions from dribble are expected to increase with decreasing load. (i.e. lowest for heavy-duty full-load and highest for light-duty, low-load)
  - Worst case presented: (2.48 g/kgf) * (1kgf/48MJ) * (3.6MJ/0.4kWh) = **0.465 g/kWhr**
    - As a baseline, Euro VI UHC emissions targets are **0.55g/kWhr**
    - but note: the problem gets relatively 'worse' with better fuel economy!
- **Fuel type** had the most significant (visual) impact on dribble, and other fuels should be investigated
  - Drastic difference in amount and character of dribble events
  - Opposite trends in dribble distribution between immediate and late with rail pressure
- Still, **other sources of UHC's exist**. Crevices and/or wall wetting may contribute as much or more depending on operating condition

Back-up Slides

Engine Operating Parameters

	SSE/DSE [CAD/ms] ‡	SSE/DSE2 [CAD/ms] ‡	P_{rail} [bar] ‡	Motored Speed [RPM] ‡	Cylinder Gas‡
Spray Start	-/1.0	-/-	1000	0	100% N2
TDC timing	347/1.0	*	*	1200	*
Early timing	327/1.0	*	*	*	*
Late timing	357/1.0	*	*	*	*
w/post	347/1.0	371/0.350†	*	*	*
High P TDC	*	-/-	1600††	*	*
Low P TDC	*	*	800	*	*
Fired TDC	*	*	1000	Skip Fired 10Hz	18% O_2
Fired TDC w/post	*	363/0.350	*	*	*
Spray End	-/1.0	-/-	*	0	100% N2

	Diesel Certification Fuel (2007)	n-Heptane
Density	841.7 kg/m^3	687.3 kg/m^3
Viscosity (STP)	2.35 cs	0.6285 cs
Cetane Number	45.7	56

Engine Variable	Operating Condition	Cameras	Phantom 7.1
Engine Speed	1200 ±10 RPM*	Frame Rate	25kHz (40µs)
Engine Load Range	1-6 bar gIMEP†	Exposure Time	25 µs
Intake O_2	0%, 18.0% ± 0.2	LED delay/duration	7 µs / 15 µs
Intake Pressure	206 ± 10 kPa	Lens	Nikon 55mm, 85mm
Intake Temperature	156 ± 2°C	f/#	1.8, 2.0 (respectively)
Intake Mass Flow	41.4 ±0.5g/s	Fuel Rail Pressure	800, 1000, 1600 ±20 bar
TDC Motored Density	16.6 ± 0.4 kg/m^3	BDC Pressure	164 ± 10 kPa
TDC Motored Temperature	936 K	BDC Temperature	78 ±4°C

Injector Operating Parameters

Fuel injector build(# tested)	Cummins XPI (3)	Bosch 'ECN Spray B' (1)	Delphi DFI-1.5 (1)
Number of holes & arrangement	8, equally-spaced	3	8, equally spaced
Pull-in / Hold Current [amps]	21 / 12	18 / 12	16.5 / 7
Nozzle Tip [orifice diameter, spray incl. angle]	0.090mm, 152° 0.131mm, 152° 0.200mm, 152° 0.200mm, 160°	0.090mm, 145°	0.200mm, 156°
Start of injection (SOI) delay from start of solenoid energizing (SSE) at 1000bar rail pressure*	0.400ms [2.9CAD] 0.400ms [2.9CAD] 0.480ms [3.4 CAD] 0.360ms [2.6 CAD]	0.320ms [2.3 CAD]	0.320ms [2.3 CAD]
Extra duration of injection (EDOI) for a duration of solenoid energizing (DSE) of 1ms at 1000bar rail pressure	1.400ms 0.700ms 0.000ms 0.400ms	0.840ms [6.0 CAD]	0.160ms[1.2 CAD]

*SOI and EOI determined from optical imaging, ±0.04ms