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CONCENTRATION AND SIZE DISTRIBUTION OF NANOPARTICLE EMISSIONS DURING LOW TEMPERATURE COMBUSTION USING FUELS FOR ADVANCED COMBUSTION ENGINES

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EXTENDED SUMMARY

Due to tightening emissions legislations, both within the US and Europe, including concerns regarding greenhouse gases, next-generation combustion strategies for internal combustion (IC) diesel engines that simultaneously reduce exhaust emissions while improving thermal efficiency have drawn increasing attention during recent years. In-cylinder combustion temperature plays a critical role in the formation of pollutants as well as in thermal efficiency of the propulsion system. One way to minimize both soot and NO_x emissions is to limit the in-cylinder temperature during the combustion process by means of high levels of dilution via exhaust gas recirculation (EGR) combined with flexible fuel injection strategies. However, fuel chemistry plays a significant role in the ignition delay; hence, influencing the overall combustion characteristics and the resulting emissions. The Advanced Vehicles, Fuels, and Lubricants (AVFL) committee of the Coordinating Research Council (CRC) specified and formulated a matrix of nine test fuels for advanced combustion engines (FACE) based on the variation of three properties, namely, cetane number (CN), aromatic content, and 90 percent distillation temperature (T90).

The primary objective of this work was to study the effects of various FACE diesel fuels on the nanoparticle formation during low temperature combustion processes. An experimental study was performed at West Virginia University's Engine and Emission Research Laboratory (EERL) to determine the FACE property effects on the low temperature combustion (LTC) process in a turbo-charged GM 1.9L light-duty compression ignition engine under steady-state operating conditions (2100rpm/3.5bar BMEP). A comprehensive test matrix was developed including intake oxygen (O_2), as a surrogate for EGR fractions, and rail-pressure parameter variations during single injection timing settings. Furthermore, the influence of varying injection timing and fuel fraction during split injection strategy onto nanoparticles was investigated as well.

Diluted exhaust gas emissions extracted from the full-flow CVS tunnel were measured continuously using a Horiba MEXA-7200D gaseous emissions analyzer and included total hydrocarbons (THC), carbon monoxide (CO) as well as carbon dioxide (CO_2) and oxides of nitrogen (NO_x). NO_x and O_2 concentrations were measured in the raw exhaust and intake manifold using zirconia-oxide type sensors (Horiba MEXA-720 NO_x), respectively.

Furthermore, the AVL Micro Soot Sensor (MSS-483), consisting of a measuring unit and an exhaust conditioning unit, was used to measure the soot concentration in the raw exhaust.

Nanoparticle concentration and size distributions were determined using the Exhaust Emissions Particle Sizer (EEPS™) spectrometer from TSI Inc. (model 3090) as well as the Differential Mobility Spectrometer (DMS) from Cambustion (model DMS500). Continuous exhaust gas samples were extracted from the CVS tunnel (dilution ratio DR ≈ 10) and routed through a double stage dilution system using ejector type dilutors (AirVac, TD H-110). The first stage was maintained at 140°C (DR ≈ 6) in order to suppress condensation of organic materials onto carbonaceous particles as well as particle nucleation phenomena, while the second stage utilized dilution air at ambient temperatures (~25°C, DR ≈ 11) in order to further reduce the partial pressures of any volatile compounds and reduce the sample temperature to the required instrument inlet conditions.

Results showed that particle number concentration increased with a simultaneous increase in particle

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diameter for both single and split injection strategies in case of FACE diesel fuels with increasing CN for the low NO_x, low soot and highest BTE tests. Advancing the start of injection timing led to a decrease in total particle number concentration, but a simultaneous increase in nanoparticle (< 50nm) emissions was observed for low CN fuels.

Table 1 lists the FACE diesel fuel target values together with actual values resulting from ASTM International standard analyses.

Table 1 FACE Diesel Fuel Properties

Fuel	**Cetane Number [-]**		**Aromatic Content [Mass %]**		**90% Distill. Temperature [°C]**		**Specific Gravity [-]**	**H/C Ratio [-]**	**Net Heat of Combustion [MJ/kg]**
	Tgt.	*Act.*	Tgt.	*Act.*	Tgt.	*Act.*	*Actual*	*Actual*	*Actual*
FACE 1	30	*29.93*	20	*26.1*	270	*269*	*0.8084*	*1.956*	*42.803*
FACE 2	30	*28.00*	20	*23.1*	340	*336*	*0.8037*	*1.988*	*43.155*
FACE 3	30	*32.02*	45	*50.0*	270	*270*	*0.8401*	*1.749*	*42.147*
FACE 4	30	*28.44*	45	*40.7*	340	*337*	*0.8355*	*1.819*	*42.495*
FACE 5	55	*54.20*	20	*22.2*	270	*276*	*0.8086*	*1.967*	*42.897*
FACE 6	55	*53.30*	20	*21.1*	340	*341*	*0.8411*	*1.871*	*42.797*
FACE 7	55	*44.30*	45	*46.2*	270	*267*	*0.8375*	*1.773*	*42.359*
FACE 8	55	*50.00*	45	*43.5*	340	*342*	*0.8682*	*1.704*	*42.196*
FACE 9	42.5	*44.95*	32.5	*37.0*	305	*321*	*0.8465*	*1.788*	*42.465*
ULSD	-	*44.00*	-	*34.7*	-	*306*	*0.8496*	*1.796*	*42.857*

Note: Tgt. = Target Value; Act. = Actual Value

The particle size distribution for the optimal split injection tests for low NO_x condition is depicted on a double-logarithmic scale in Figure 1. The particle diameter D_p in nanometers is plotted versus the normalized particle concentration, which is integrated over each size bin (instrument channel), in number of particles per volume (cm^3). In general, there was an increase in particle number concentration with simultaneous increase in particle diameter as the fuel CN increases for the low NO_x tests, as indicated by an arrow in Figure 1. The shorter ignition delay for higher CN fuels leads to a greater inhomogeneity of the cylinder charge and therefore, increased particle emissions due to higher fuel fractions allocated to the diffusion burning, as compared to lower CN fuels.

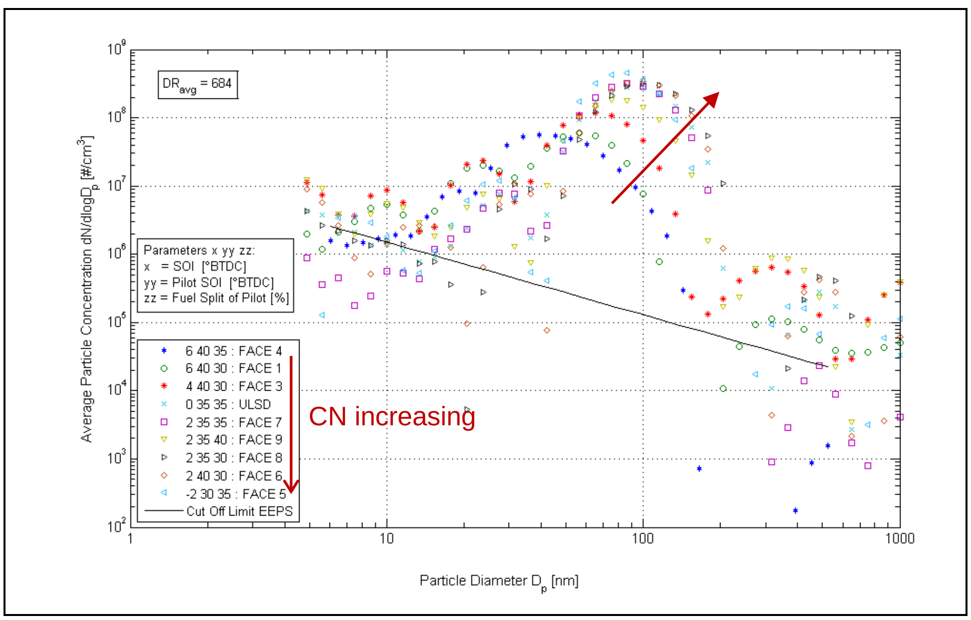

Figure 1 Particle Size Distribution for Optimal Split Injection Tests for Low NO_x – Filled Markers for EEPS™, Hollow Marker for DMS-500

In Figure 2, selected test runs for the low cetane group are shown. There was a trend towards a more pronounced bimodal distribution observed when comparing FACE 4 (high T90 / high aromatics) with FACE 1 (low T90 / low aromatics) and FACE 3 (low T90 / high aromatics), which could be explained by the difference in distillation temperature (T90) between FACE 4, FACE 1 and FACE 3.

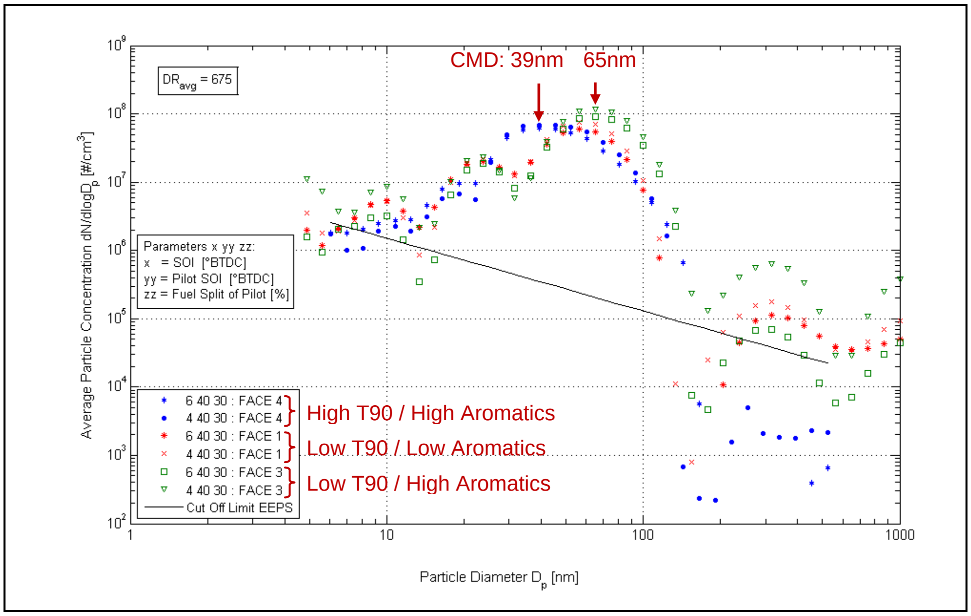

Figure 2 Particle Size Distribution for Low Cetane Fuels – Filled Markers for EEPS^{TM}, Hollow Marker for DMS-500

In general, advancing start of injection (SOI) timing provides more time for homogenization; hence, leading to a decrease in particle concentration. This is shown in Figure 3 for a low and high CN fuel, namely FACE 4 and 8, respectively. Even though this trend is observed for both, high and low CN fuels, it is somewhat restricted to accumulation mode particles, since a simultaneous increase in nanoparticle emissions was observed for low CN fuels, shown here for FACE 4 (see arrows). Due to higher variability in the data, this trend in enhanced nanoparticles could not be confirmed for FACE 8.

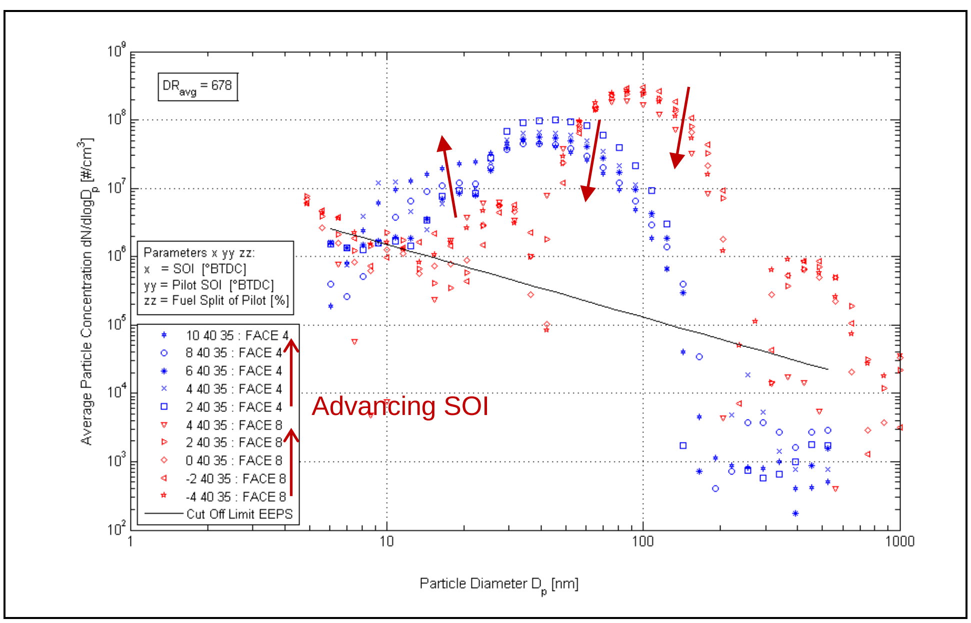

Figure 3 Particle Size Distribution for Low and High CN and Varying SOI Timing

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Background and Motivation

- The Advanced Vehicles, Fuels, and Lubricants (AVFL) committee of the Coordinating Research Council (CRC) specified and formulated a matrix of 9 test fuels for advanced combustion engines (FACE) based on the variation of three properties: [1,2]
  1. Cetane number (CN)
  2. Aromatic content
  3. 90 percent distillation temperature (T_{90})
- Published studies discussing FACE diesel fuel property effects on combustion and exhaust emissions (gaseous & soot) [3,4,5]
- PM composition, concentration and size distribution studies focused on advanced combustion modes [6,7]
  - ➢ Higher SOF compared to conventional diesel
  - ➢ Lower count mode diameter (CMD) than conventional diesel
  - ➢ Almost same total number concentration (TNC)
- Study of the variation of 4 engine parameters (VGT, EGR, Pilot SOI, RP) on PM concentration and size distribution using a low and high CN fuel [8]

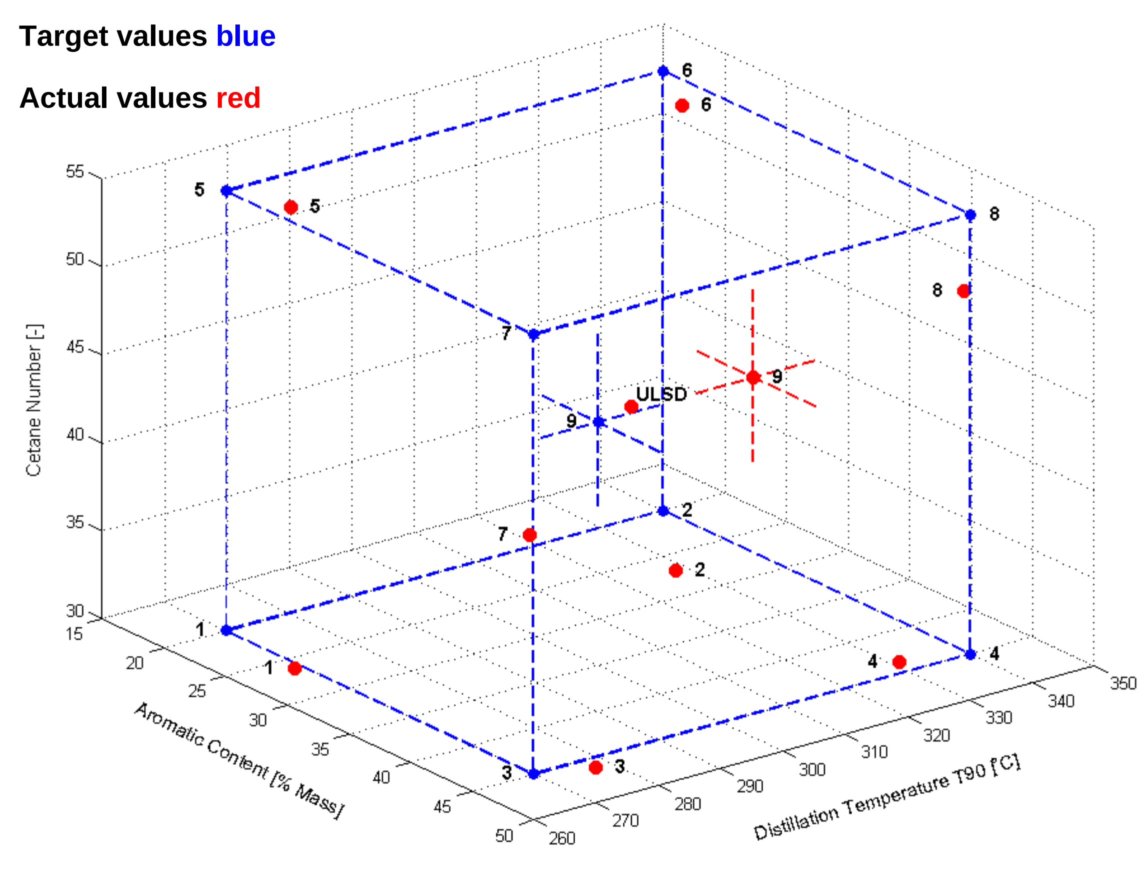
➢ No particle concentration and size distribution data in published literature as a function of FACE diesel fuel property effects

Objectives

- Primary objective:
  - To study the effects of various FACE diesel fuels on the nanoparticle formation during LTC modes

- Specific objectives:
  - To assess the influence of the three main properties of FACE diesel fuel, CN, T_{90}, and aromatic content on particle concentration and size distributions during LTC operation
  - To investigate single and split injection strategies

Methodology - Fuel Properties



- FACE 2 was substituted by an ultra low sulfur (ULSD) 2007 certification fuel as a "check fuel"

Target Fuel Properties:

Cetane Number	30 and 55
90% Distillation Temperature	270 and 340ºC
Aromatic Content	20 and 45% (mass)

Actual Fuel Properties:

Fuel	Cetane Number [-]	Aromatic Content [Mass %]	90% Distillation Temp. [ºC]
FACE 1	29.93	26.1	269
FACE 2	28.00	23.1	336
FACE 3	32.02	50.0	270
FACE 4	28.44	40.7	337
FACE 5	54.20	22.2	276
FACE 6	53.30	21.1	341
FACE 7	44.30	46.2	267
FACE 8	50.00	43.5	342
FACE 9	44.95	37.0	321
ULSD	44.00	34.7	306

Methodology - Injection Strategies/Test Selection

- Engine operating conditions for injection strategies:

Single Injection Strategy:

Engine Speed	2100rpm
BMEP	3.5bar
CA50	7°ATDC
Fuel Temperature	32°C*
Coolant Temperature	84°C*

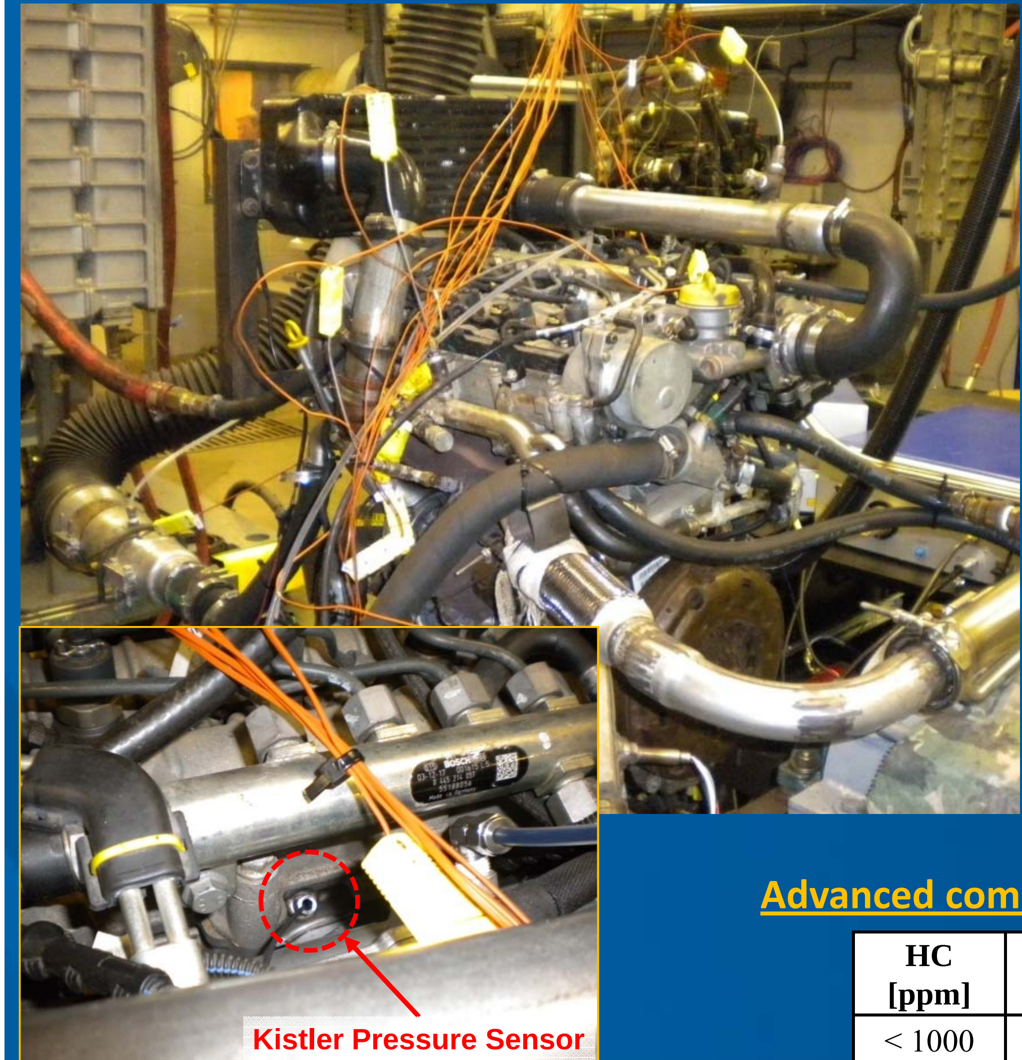
** Note: average value*

Split Injection Strategy:

Engine Speed	2100rpm
BMEP	3.5bar
Intake Oxygen Concentration	16%
Rail Pressure	1600bar
Fuel Temperature	31°C*
Coolant Temperature	86°C*

- Optimal Split and Single Injection Tests:
  - ➢ For first comparison, isolated the 10 tests with highest BTE, then selected:
    - – test with highest BTE -> "Highest BTE"
    - – test with lowest soot emissions -> "Low Soot"
    - – test with lowest NO_x emissions -> "Low NO_x"
- Low, Medium and High Cetane Fuel Comparison:
  - ➢ Blocked out predominant effect of CN
  - ➢ Investigated effects of T_{90} and aromatic content

Experimental Setup - Engine



Test Engine Specifications:

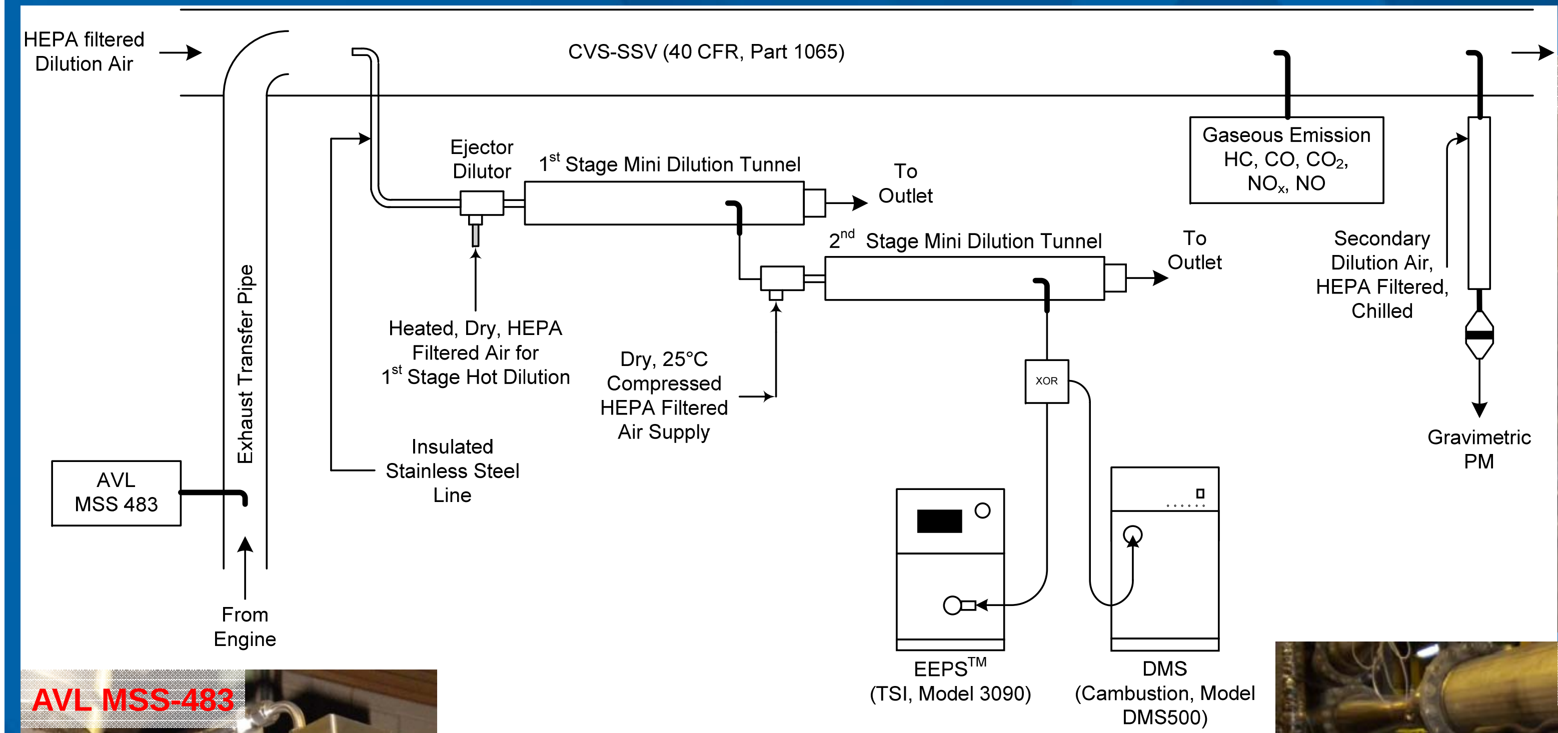
Type	CDTi Diesel Engine
Manufacturer	General Motors
Model	Z19DTH
Valve Configuration	4 Valves per Cylinder
Year	2005
Configuration	In-Line 4 Cylinder
Displacement	1.9L
Bore	82mm
Stroke	90.4mm
Compression Ratio	17.5:1
Turbocharger	Garret VGT (Intercooler)
Injection System	Common Rail
EGR	Cooled, External
Rated Power	110kW @ 4000rpm

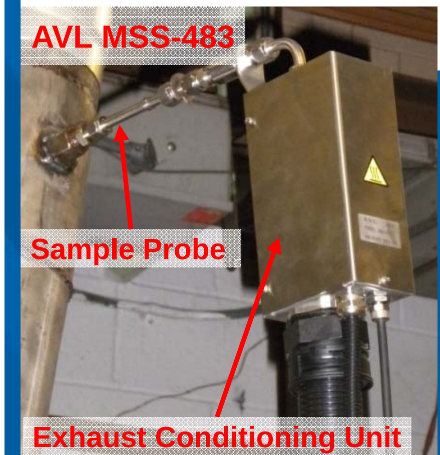
- Drivven Automotive Control ECU
- Intake and raw exhaust O_2 measurement (MEXA-720 ZrO_2-sensor) => EGR fraction
- Kistler in-cylinder pressure transducer

Advanced combustion criteria for GM Z19DTH engine:

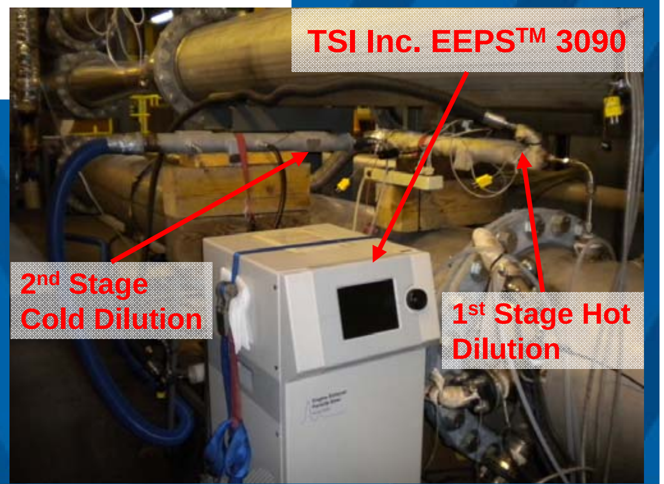
HC [ppm]	NO_x [ppm]	CO [ppm]	Soot [mg/m^3]	BTE [%]
< 1000	< 50	< 3000	< 10	> 30

Experimental Setup - PM Instrumentation

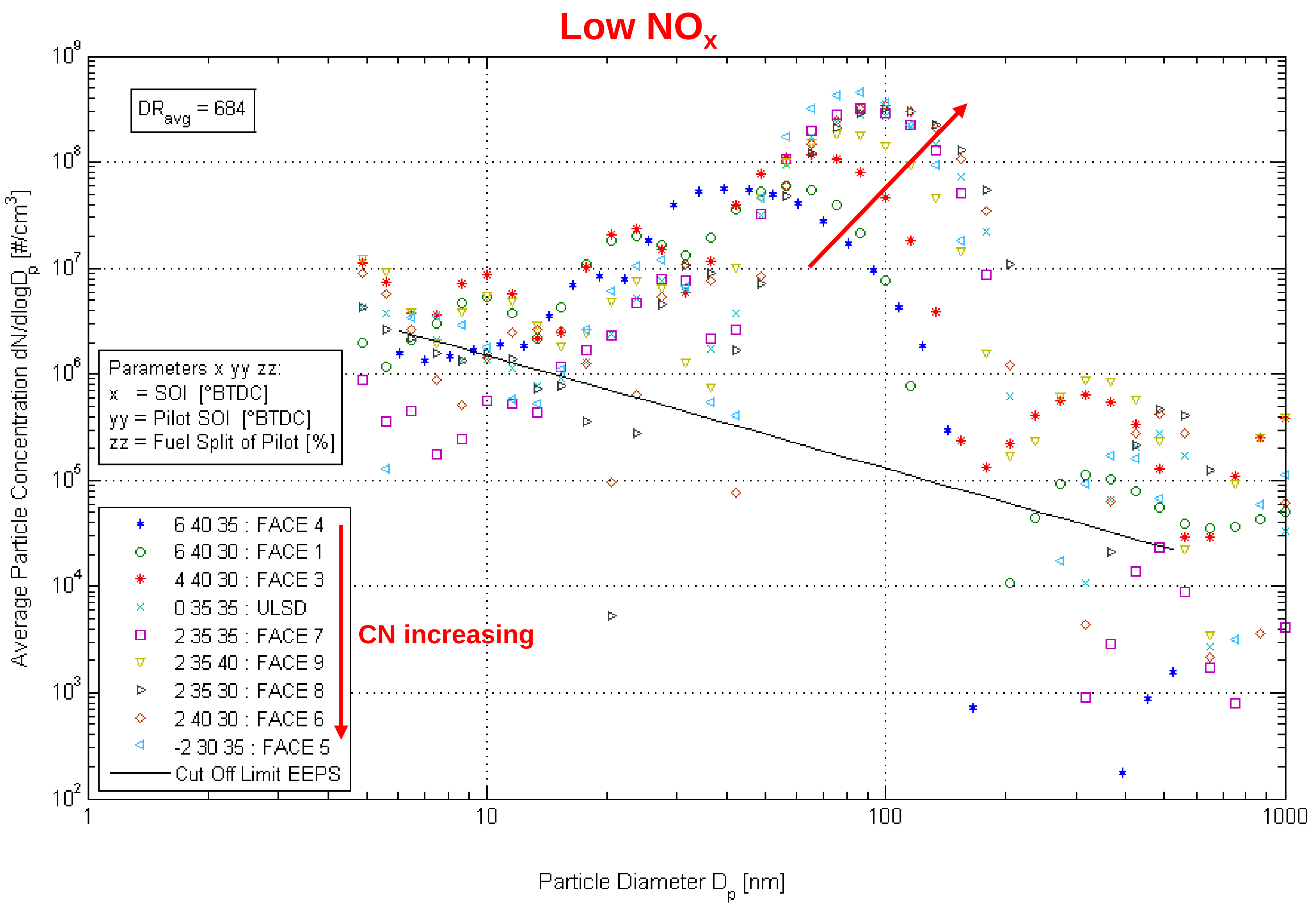




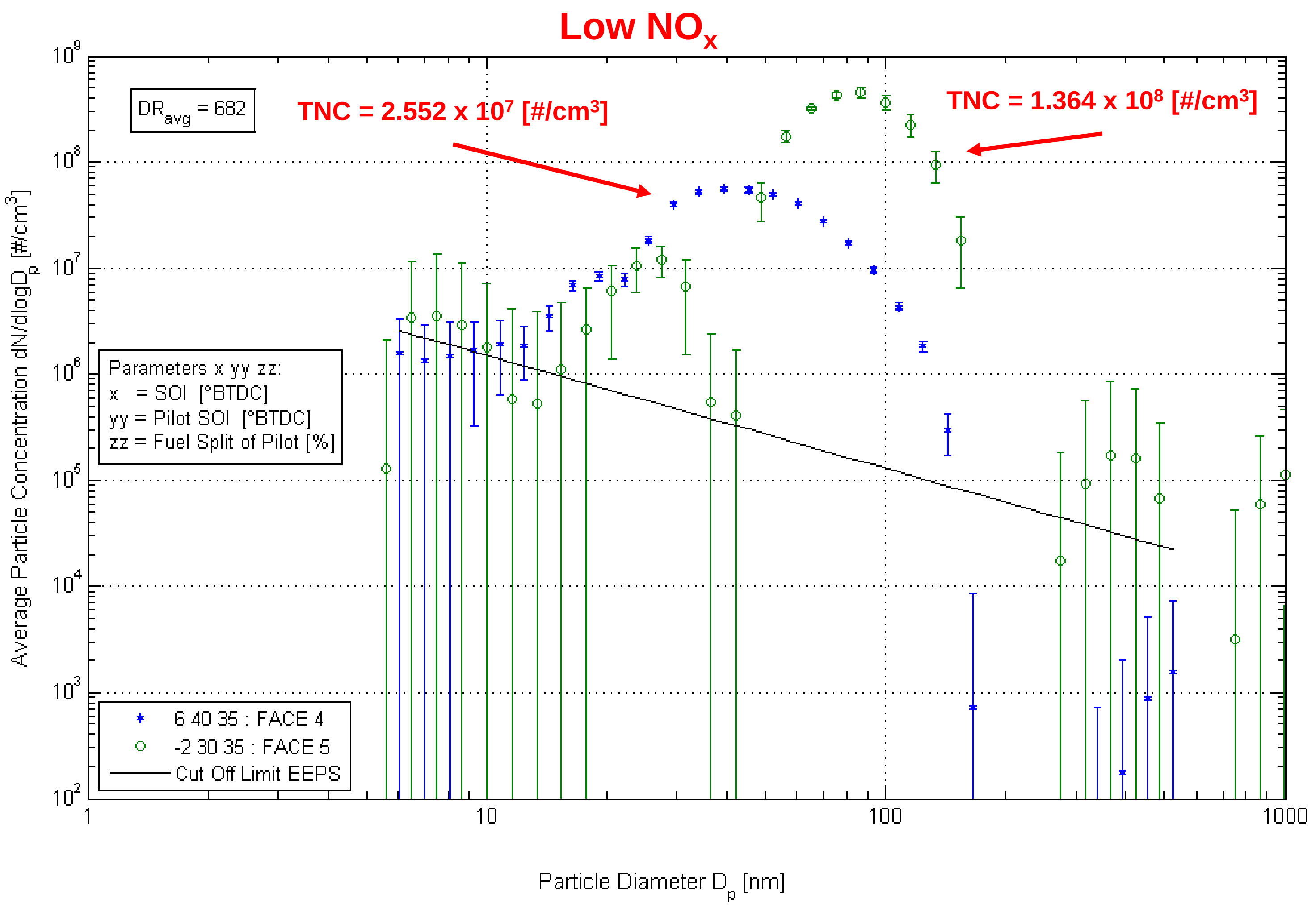
	Temperature [°C]	Dilution Ratio [-]	Residence Time [ms]
CVS Tunnel	31±2	≈ 10	6935
1st stage hot dilution	140±5	≈ 6	519
2nd stage cold dilution	25±5	≈ 11	373



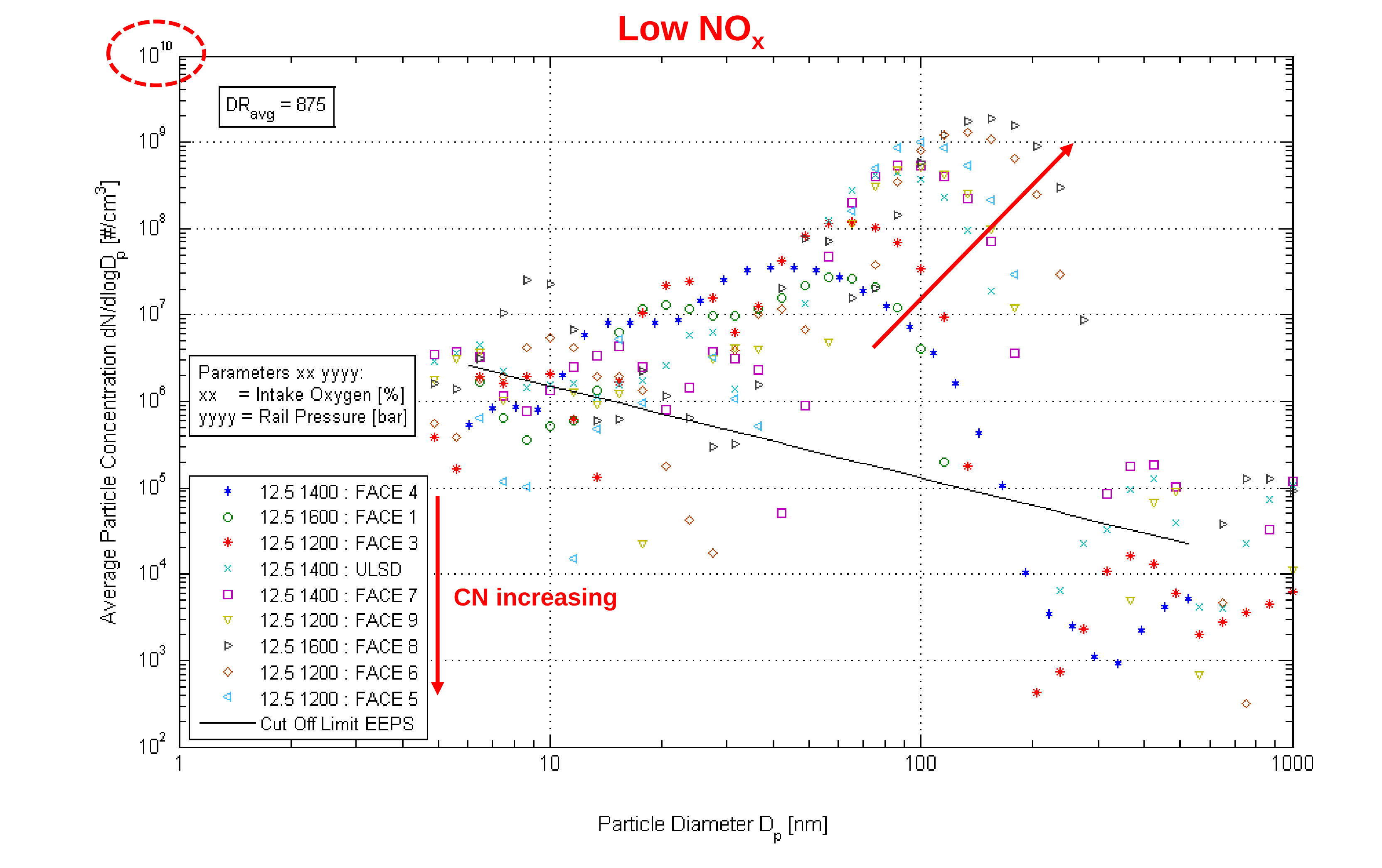
Results - Optimal Split Injection Tests



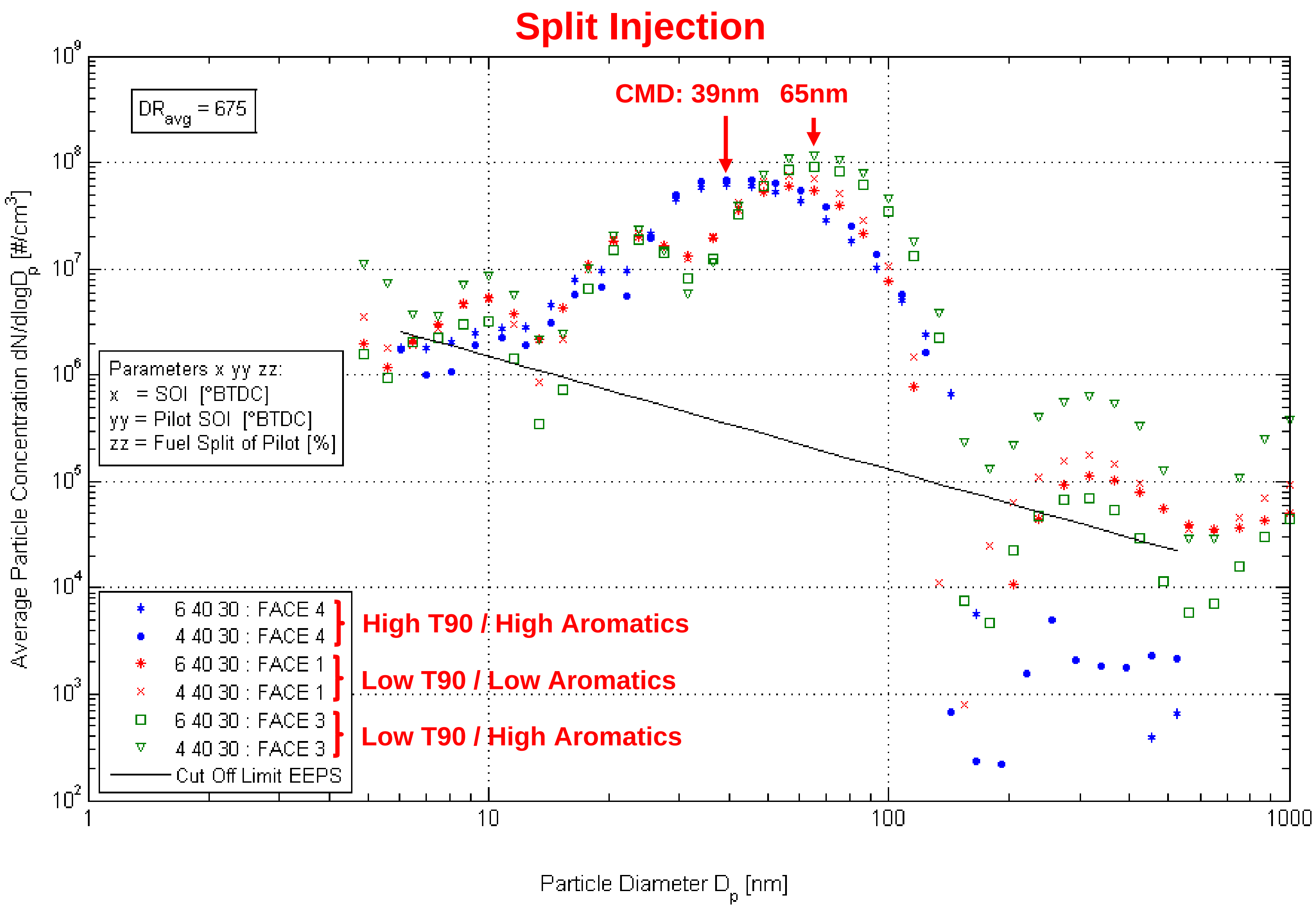
Results - Optimal Split Injection Tests



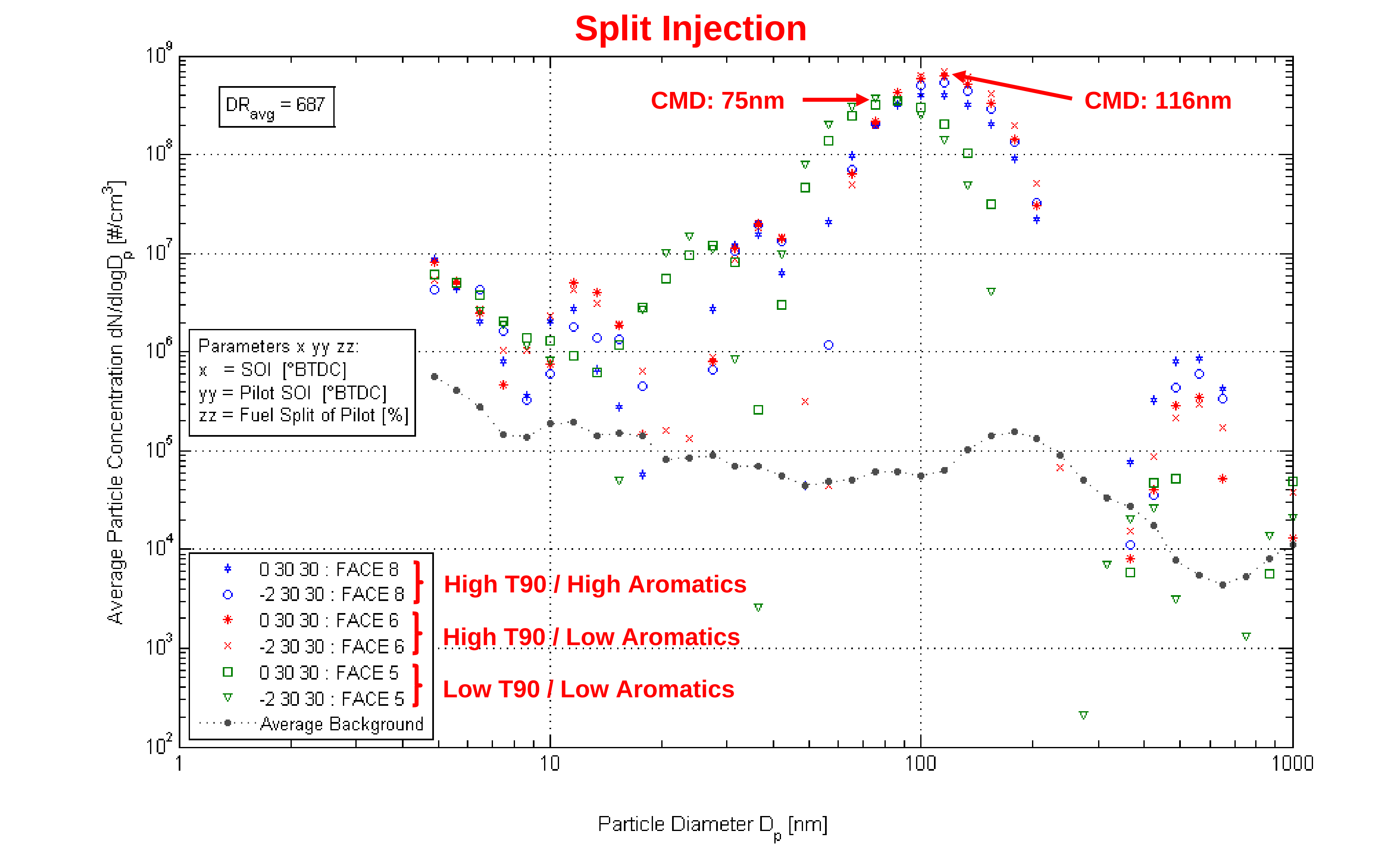
Results - Optimal Single Injection Tests



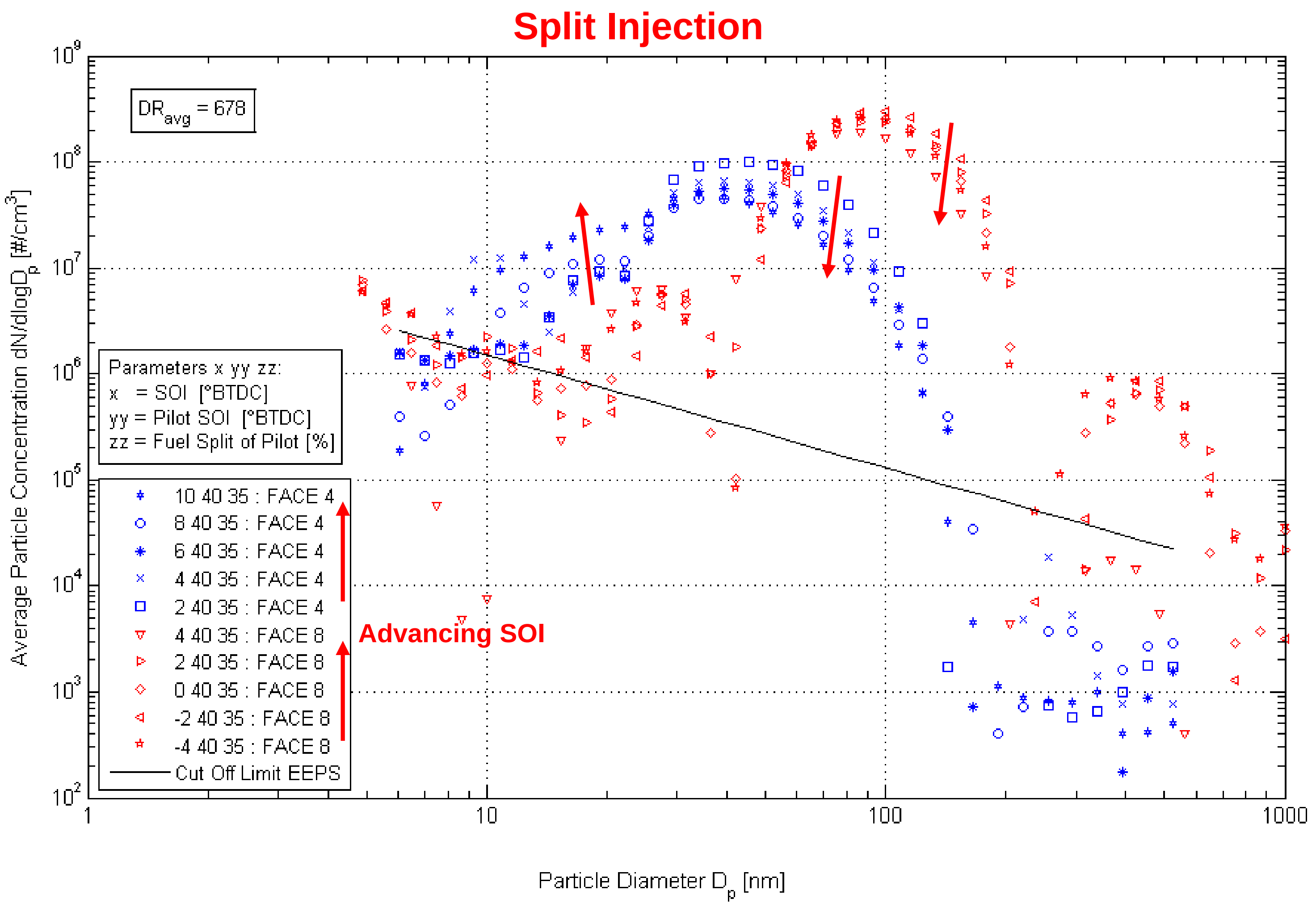
Results - Low Cetane Fuels



Results - High Cetane Fuels



Results - Injection Timing Comparison



Conclusions

- Particle number concentration increased with a simultaneous increase in particle diameter for both, single and split injection strategies in case of FACE diesel fuels with increasing CN for the low NO_x, low soot* and highest BTE* tests (*: not shown in this presentation)
- Particle number concentrations were higher for single injection compared to split injection strategy
- Low CN fuels exhibit wide particle number distributions whereas high CN fuels tend to have especially narrow accumulation modes

Conclusions (cont'd)

- CN had the highest effect, followed by T_{90}, and aromatic content; CN may mask the other 2 fuel properties
- The 90 percent distillation temperature had significant influence on the particle size distribution: the count mode diameter was found to be lower for low CN and high T_{90} fuels, and also lower for high CN and low T_{90} fuels
- Advancing the start of injection timing led to a decrease in particle number concentration, but a simultaneous increase in nanoparticle emissions was observed for low CN fuels

Thank You for Your Attention

CAFEE Center for Alternative Fuels, Engines and Emissions

Literature References:

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6) Storey, J.M.E., Lewis, S.A., Parks, J.E., Szybist, J.P., Barone, T.L., and Prikhodko, V.Y., "Mobile Source Air Toxics (MSATs) from High Efficiency Clean Combustion: Catalytic Exhaust Treatment Effects," SAE Int. J. Engines, vol. 1, pp. 1157-1166, 2008.
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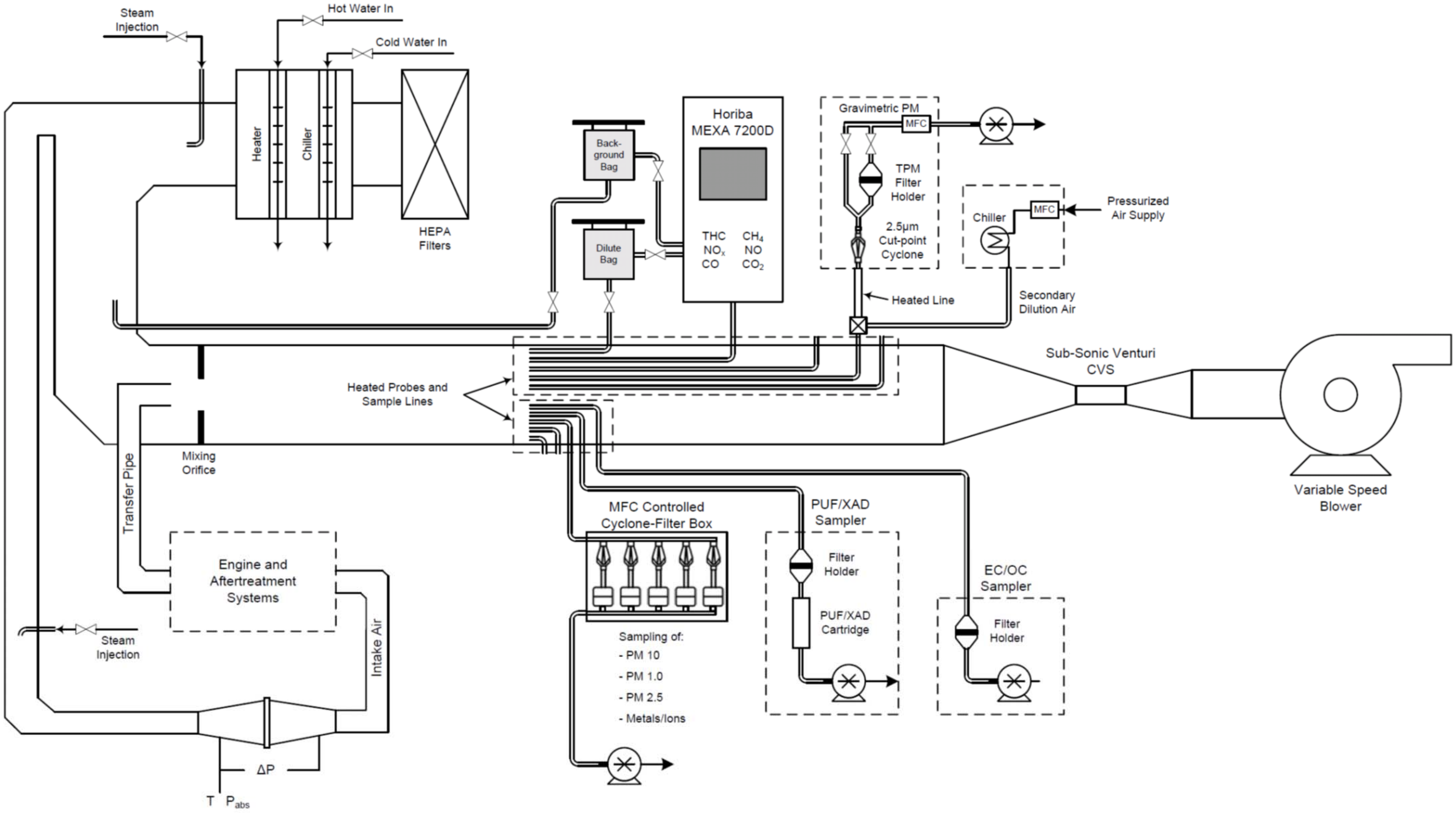
8) Balakrishnan, R., "Investigation of Particulate Matter Number Concentration and Size Distribution during Low Temperature Combustion," Master's Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, 2011.

Backup - 40 CFR 1065 Compliant Laboratory Setup



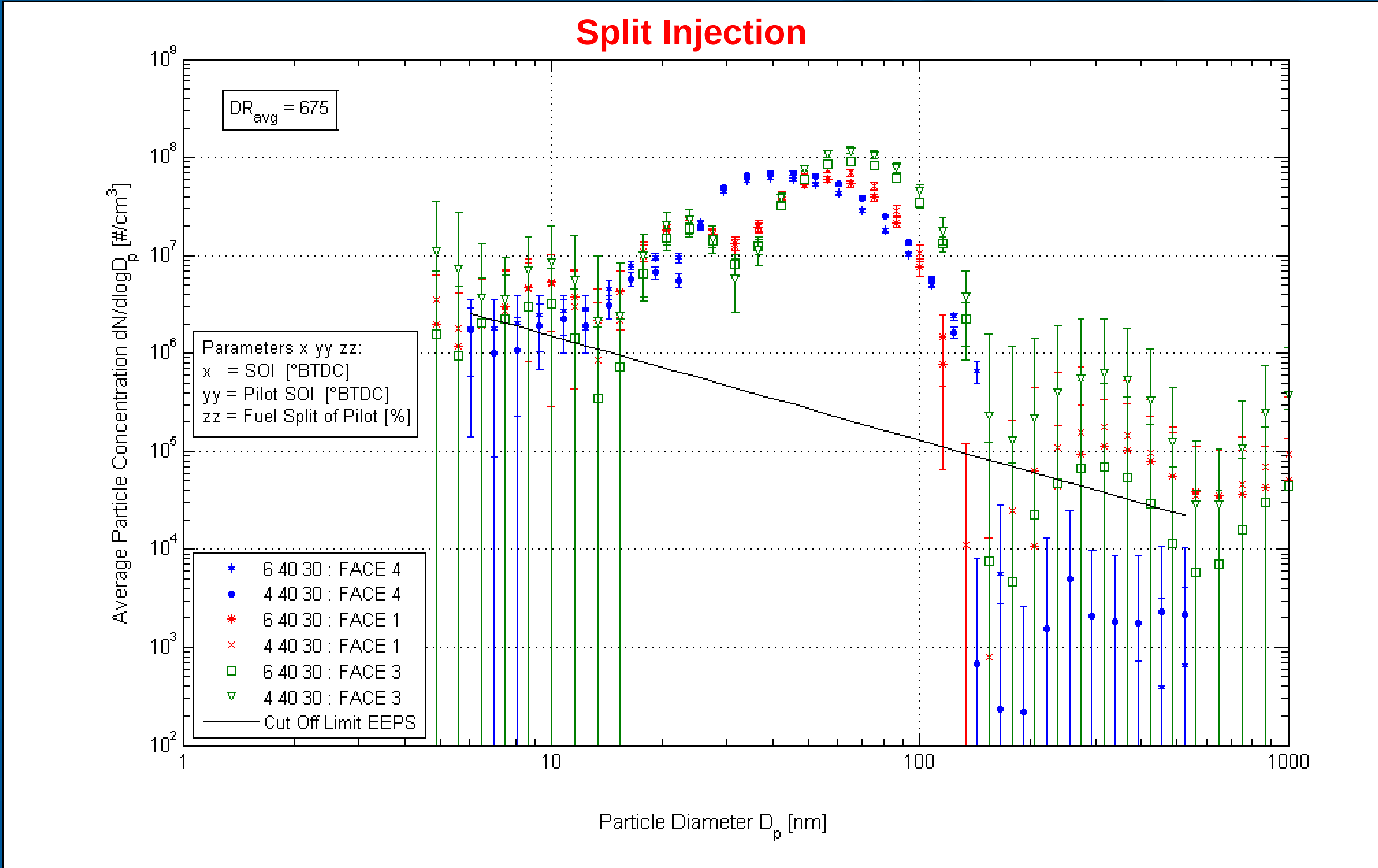
Backup - Emissions Comparison

Emissions Comparison of Optimal Split and Single Injection Tests for Low NO_x:

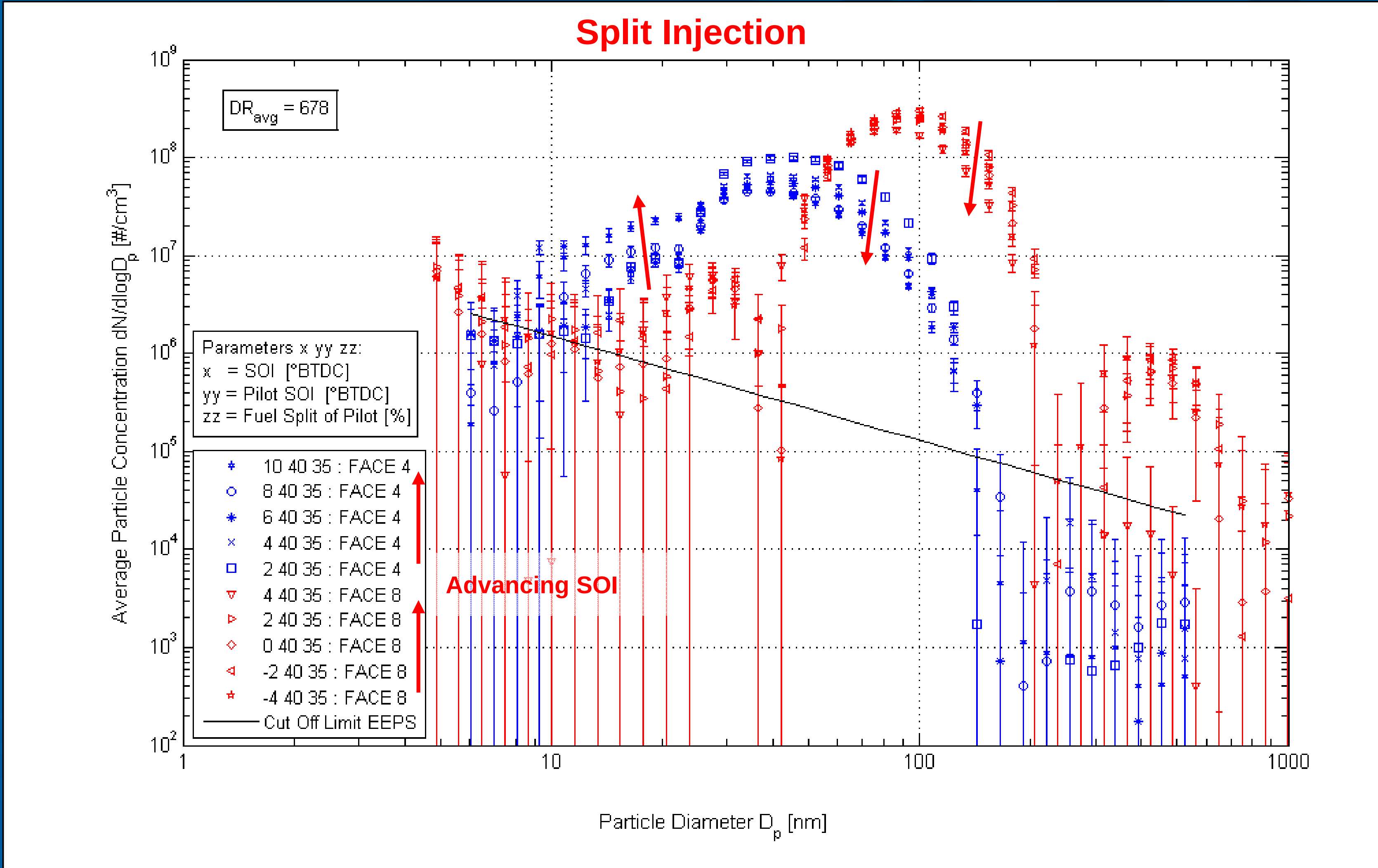
Fuel	Test #		HC [g/kWh]		NO_x [g/kWh]		CO [g/kWh]		Soot [mg/kWh]		BTE [%]	
	Split	*Single*	*Split*	*Single*	*Split*	*Single*	*Split*	*Single*	*Split*	*Single*	*Split*	*Single*
FACE 4	20	50	7.35	6.91	0.476	0.083	19.72	19.10	6.6	2.0	29.4	30.5
FACE 1	19	51	4.36	3.58	0.549	0.107	16.45	12.65	9.1	2.0	30.4	32.7
FACE 3	28	49	4.59	2.94	0.485	0.119	17.64	17.09	30.4	20.2	30.2	32.0
ULSD	29	50	1.90	1.30	0.438	0.134	10.18	10.93	138.6	103.3	31.4	33.4
FACE 7	20	50	1.77	1.38	0.501	0.137	10.11	13.73	161.8	168.7	31.1	32.1
FACE 9	21	49	1.86	1.12	0.599	0.182	9.72	10.37	128.6	266.8	31.7	33.7
FACE 8	13	51	1.38	1.11	0.575	0.186	7.37	15.02	314.0	924.9	31.8	32.2
FACE 6	16	49	1.82	1.02	0.460	0.159	11.56	15.54	264.2	749.4	31.8	33.0
FACE 5	29	49	1.09	1.12	0.384	0.122	6.63	13.83	131.8	271.9	31.5	33.5

Note: Split / Single = Split / Single Injection Strategy

Backup - Low Cetane Fuels



Backup - Injection Timing Comparison



Backup - Emissions Comparison

Emissions Comparison for Low and High CN and Varying SOI Timing:

	Test Parameters	TNC [#/cm^3]	HC [ppm]	HC [g/kWh]	NO_x [ppm]	NO_x [g/kWh]	CO [ppm]	CO [g/kWh]	BTE [%]
FACE 4	10 40 35*	2.640×10^7	1735	5.63	85.8	0.927	2325	15.12	29.1
	8 40 35*	2.232×10^7	1817	5.80	58.3	0.615	2653	17.11	29.4
	6 40 35*	2.552×10^7	2295	7.35	45.0	0.476	3056	19.72	29.4
	4 40 35*	3.217×10^7	2667	8.64	38.7	0.408	3540	22.88	28.8
	2 40 35*	4.584×10^7	2681	8.70	36.2	0.381	3634	23.73	28.3
FACE 8	4 40 35*	6.749×10^7	694	2.10	61.8	0.657	1689	10.73	31.4
	2 40 35*	8.923×10^7	804	2.52	54.2	0.586	1781	11.48	30.0
	0 40 35*	9.226×10^7	907	2.88	48.9	0.524	1762	11.45	29.2
	-2 40 35*	1.058×10^8	861	2.72	47.7	0.513	1689	10.96	28.9
	-4 40 35*	9.299×10^7	838	2.67	42.5	0.463	1816	11.98	28.9

** Note: Parameters x yy zz: x = SOI [°BTDC]; yy = Pilot SOI [°BTDC]; zz = Fuel Split of Pilot [%]*

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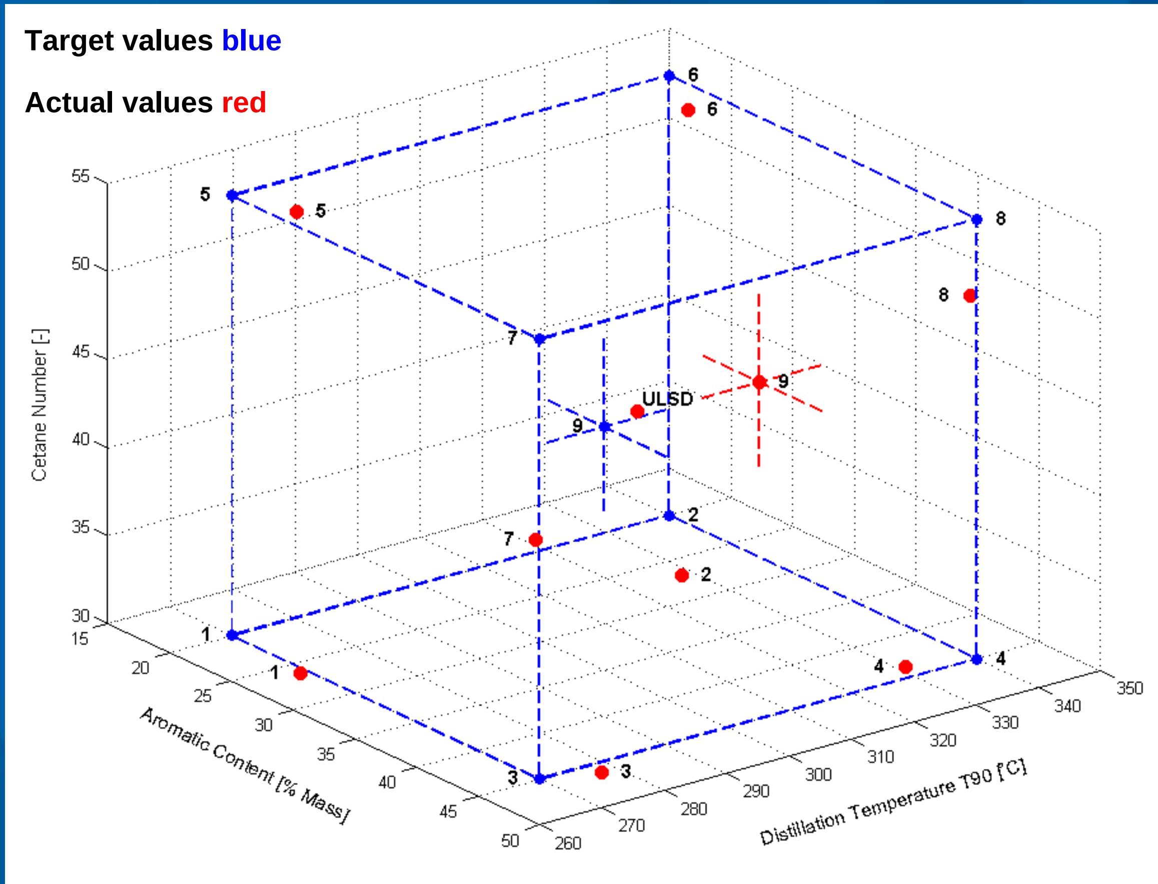
- Primary objective:
  - To study the effects of various FACE diesel fuels on the nanoparticle formation during LTC modes

- Specific objectives:
  - To assess the influence of the three main properties of FACE diesel fuel, CN, T_{90}, and aromatic content on particle concentration and size distributions during LTC operation
  - To investigate single and split injection strategies

Methodology - Fuel Properties



Target Fuel Properties:

Cetane Number	30 and 55
90% Distillation Temperature	270 and 340ºC
Aromatic Content	20 and 45% (mass)

Actual Fuel Properties:

Fuel	Cetane Number [-]	Aromatic Content [Mass %]	90% Distillation Temp. [ºC]
FACE 1	29.93	26.1	269
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FACE 8	50.00	43.5	342
FACE 9	44.95	37.0	321
ULSD	44.00	34.7	306

- FACE 2 was substituted by an ultra low sulfur (ULSD) 2007 certification fuel as a “check fuel”

Methodology - Injection Strategies/Test Selection

- Engine operating conditions for injection strategies:

Single Injection Strategy:

Engine Speed	2100rpm
BMEP	3.5bar
CA50	7°ATDC
Fuel Temperature	32°C*
Coolant Temperature	84°C*

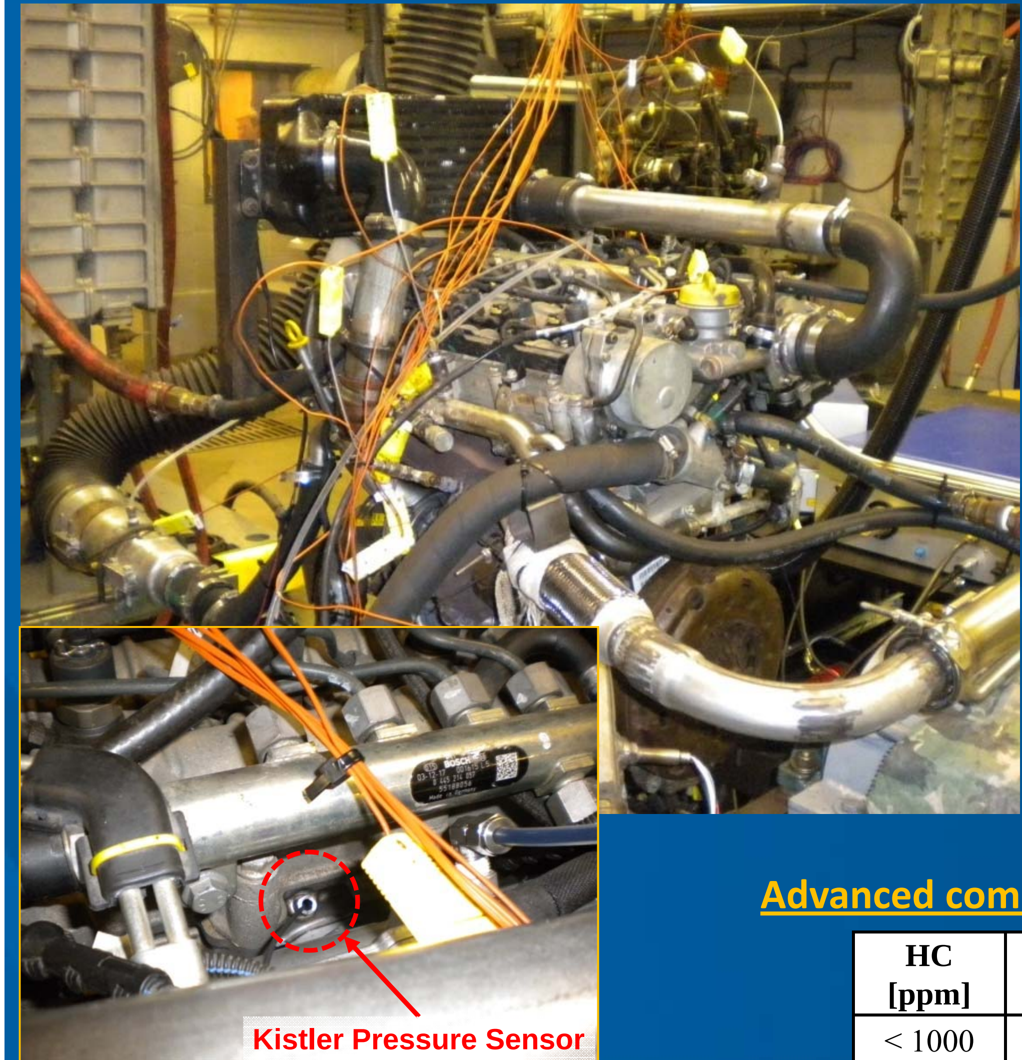
** Note: average value*

Split Injection Strategy:

Engine Speed	2100rpm
BMEP	3.5bar
Intake Oxygen Concentration	16%
Rail Pressure	1600bar
Fuel Temperature	31°C*
Coolant Temperature	86°C*

- Optimal Split and Single Injection Tests:
  - ➢ For first comparison, isolated the 10 tests with highest BTE, then selected:
    - – test with highest BTE -> "Highest BTE"
    - – test with lowest soot emissions -> "Low Soot"
    - – test with lowest NO_x emissions -> "Low NO_x"
- Low, Medium and High Cetane Fuel Comparison:
  - ➢ Blocked out predominant effect of CN
  - ➢ Investigated effects of T_{90} and aromatic content

Experimental Setup - Engine



Test Engine Specifications:

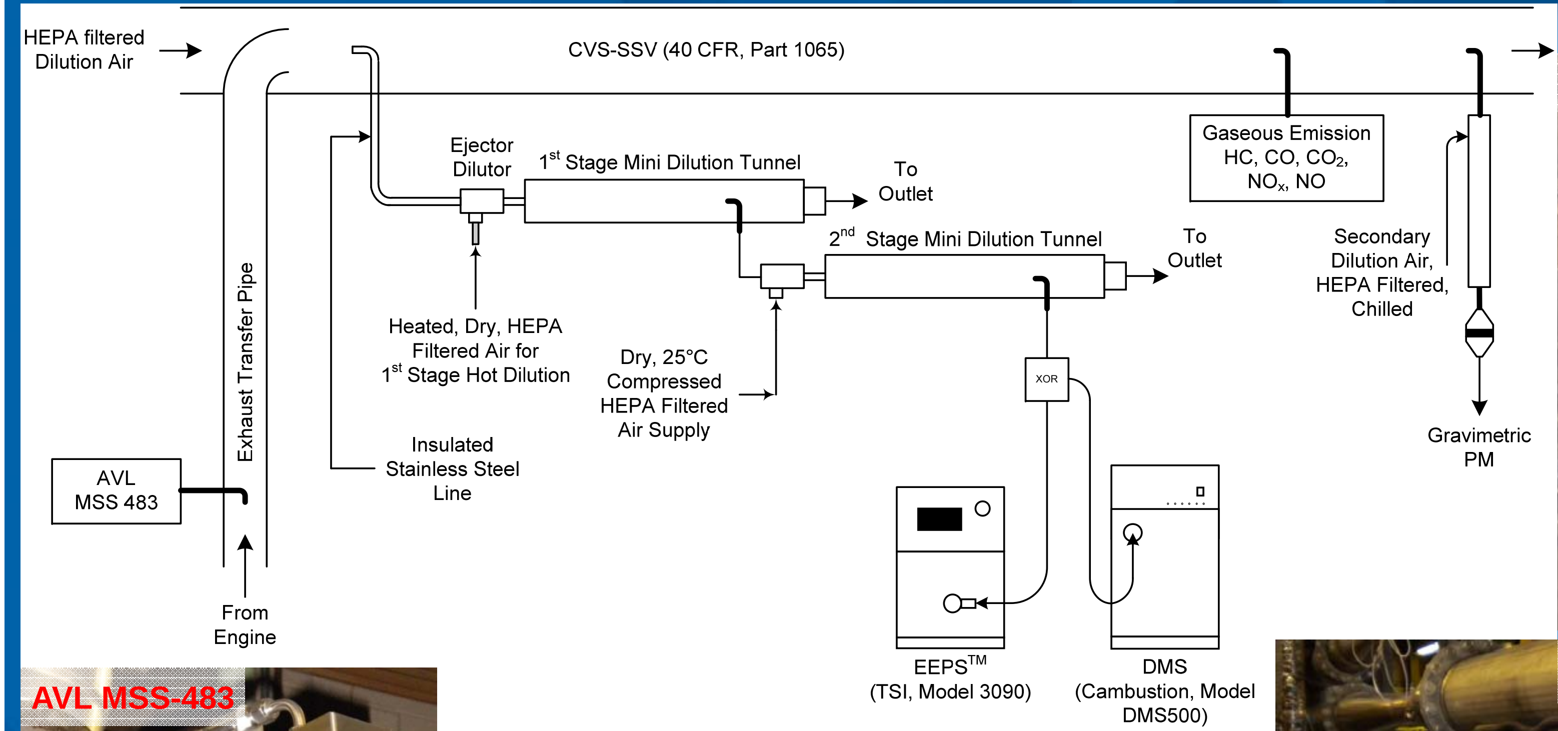
Type	CDTi Diesel Engine
Manufacturer	General Motors
Model	Z19DTH
Valve Configuration	4 Valves per Cylinder
Year	2005
Configuration	In-Line 4 Cylinder
Displacement	1.9L
Bore	82mm
Stroke	90.4mm
Compression Ratio	17.5:1
Turbocharger	Garret VGT (Intercooler)
Injection System	Common Rail
EGR	Cooled, External
Rated Power	110kW @ 4000rpm

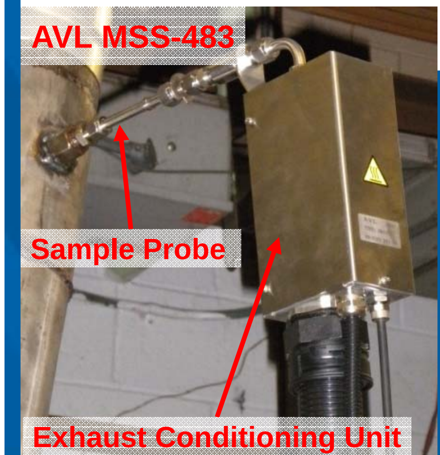
- Drivven Automotive Control ECU
- Intake and raw exhaust O_2 measurement ($MEXA$-720 ZrO_2-sensor) => EGR fraction
- Kistler in-cylinder pressure transducer

Advanced combustion criteria for GM Z19DTH engine:

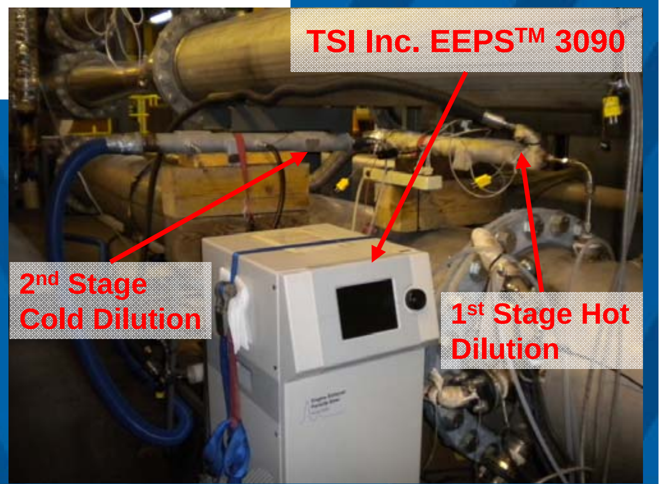
HC [ppm]	NO_x [ppm]	CO [ppm]	Soot [mg/m^3]	BTE [%]
< 1000	< 50	< 3000	< 10	> 30

Experimental Setup - PM Instrumentation

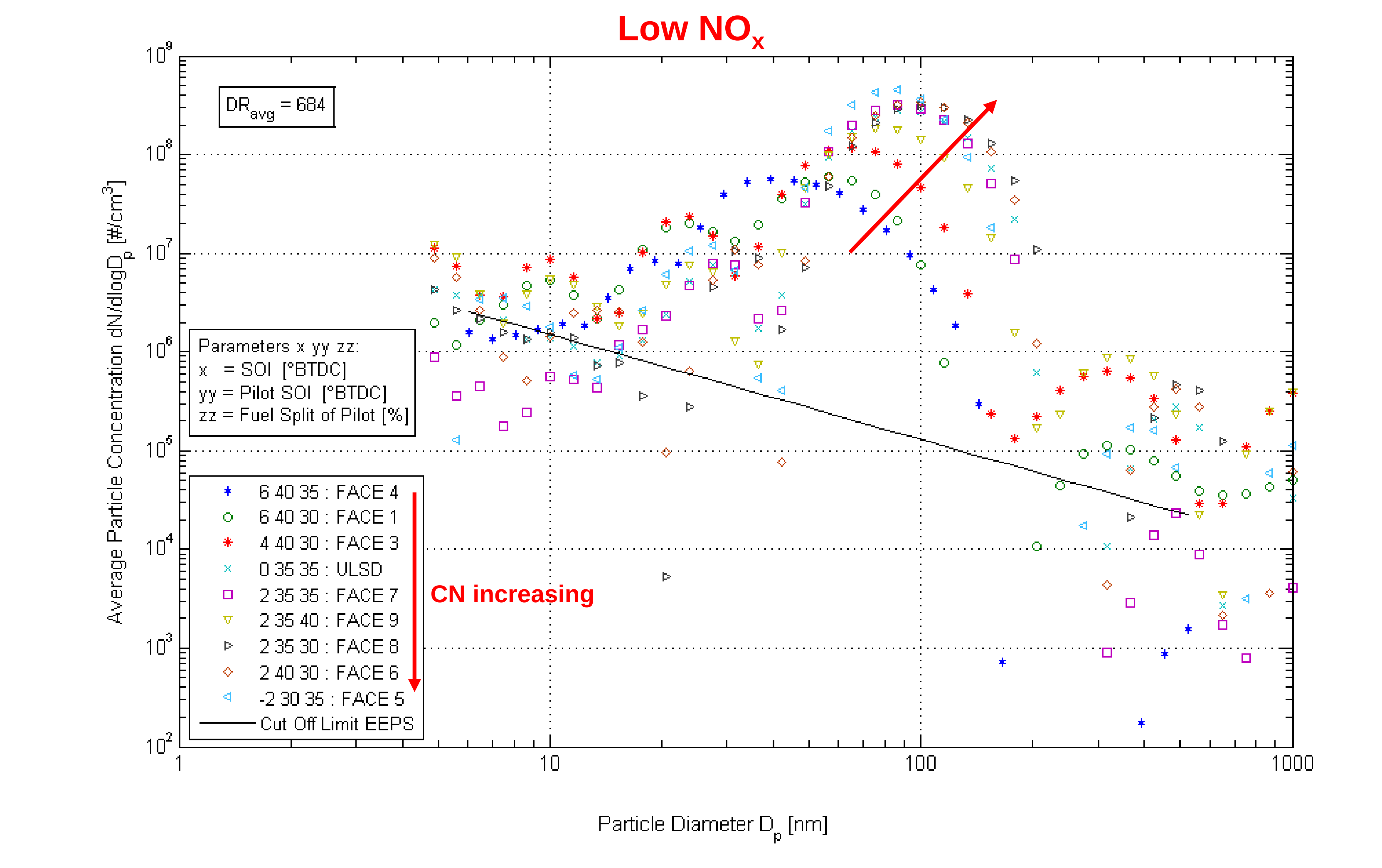




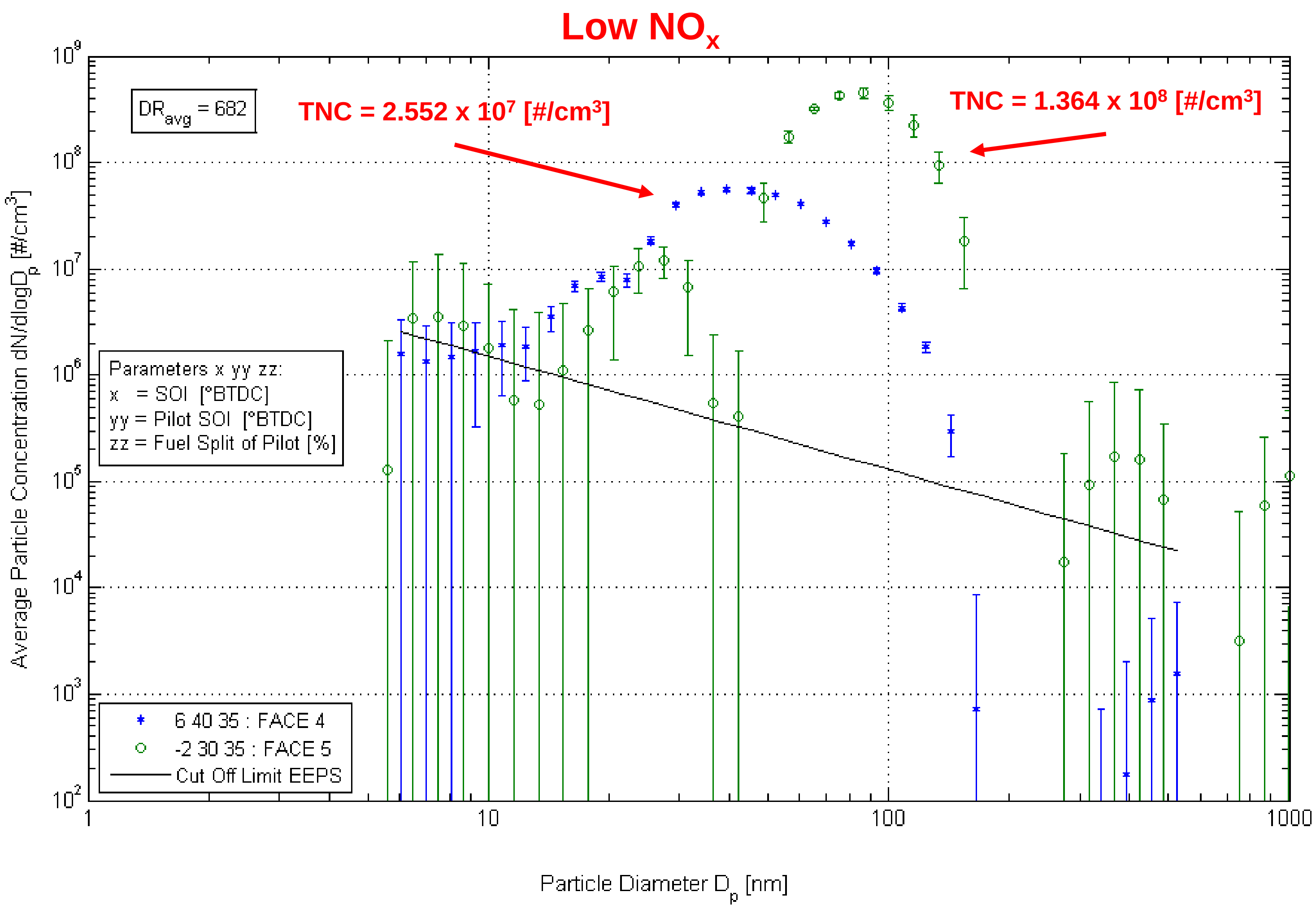
	Temperature [°C]	Dilution Ratio [-]	Residence Time [ms]
CVS Tunnel	31±2	≈ 10	6935
1st stage hot dilution	140±5	≈ 6	519
2nd stage cold dilution	25±5	≈ 11	373



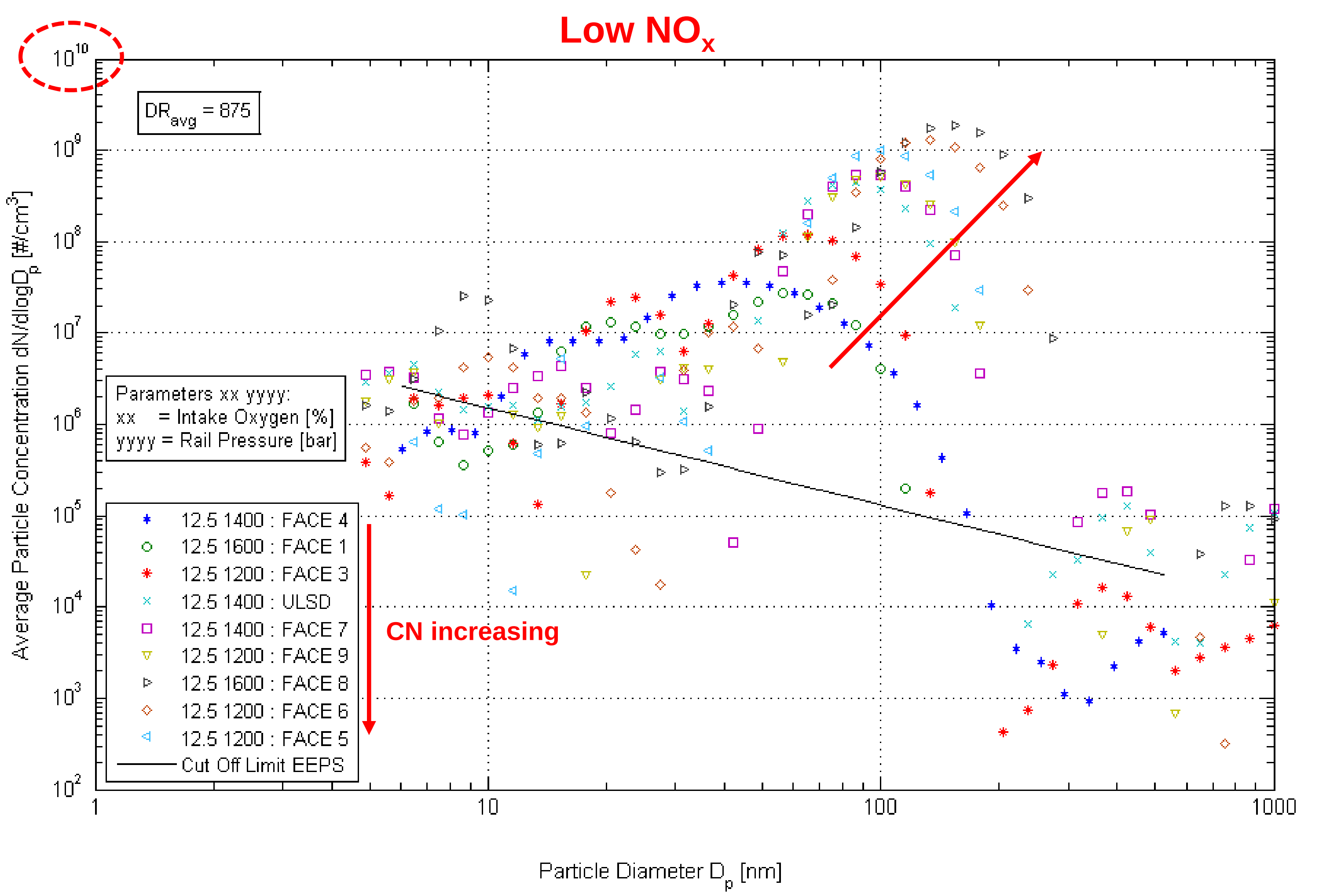
Results - Optimal Split Injection Tests



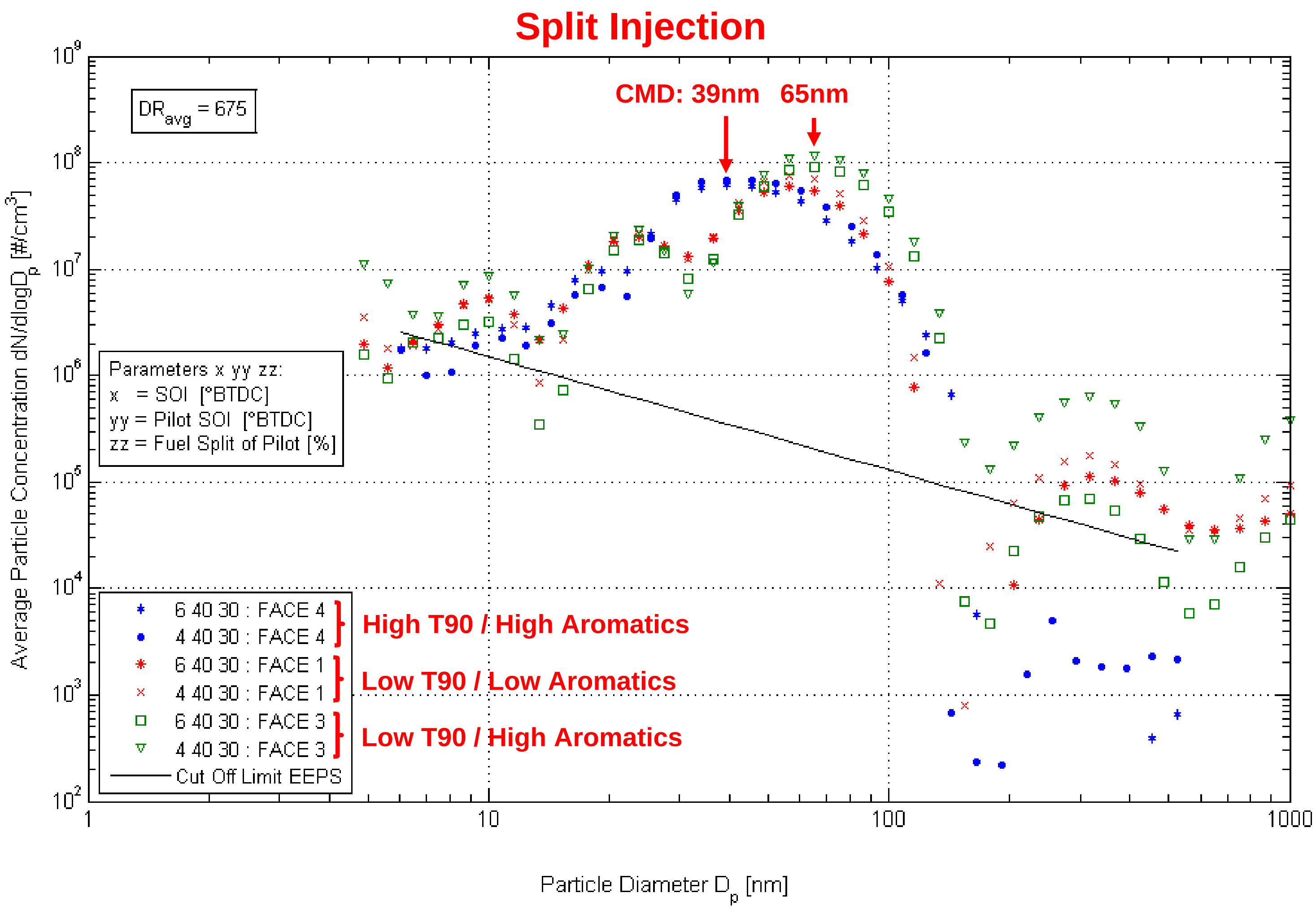
Results - Optimal Split Injection Tests



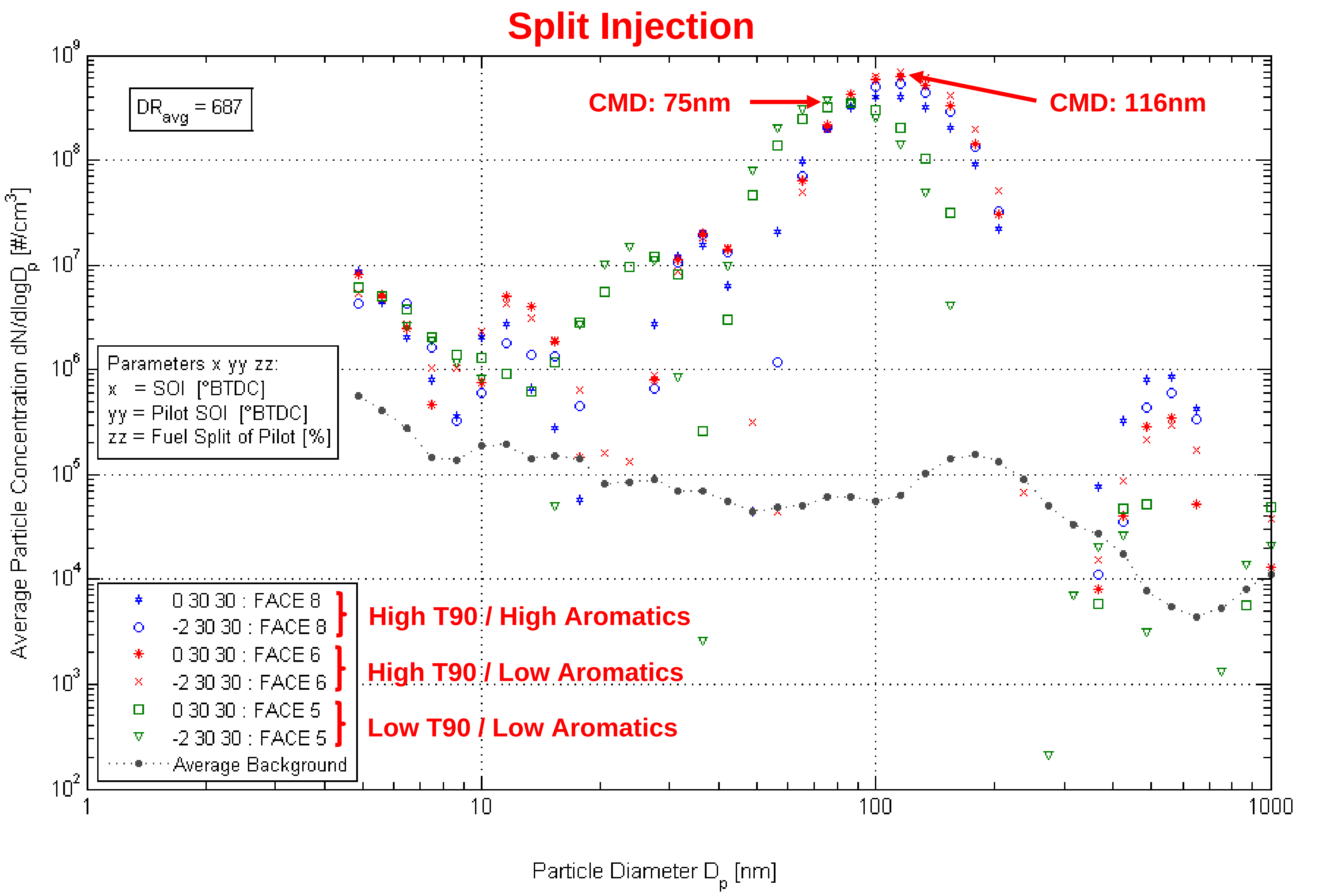
Results - Optimal Single Injection Tests



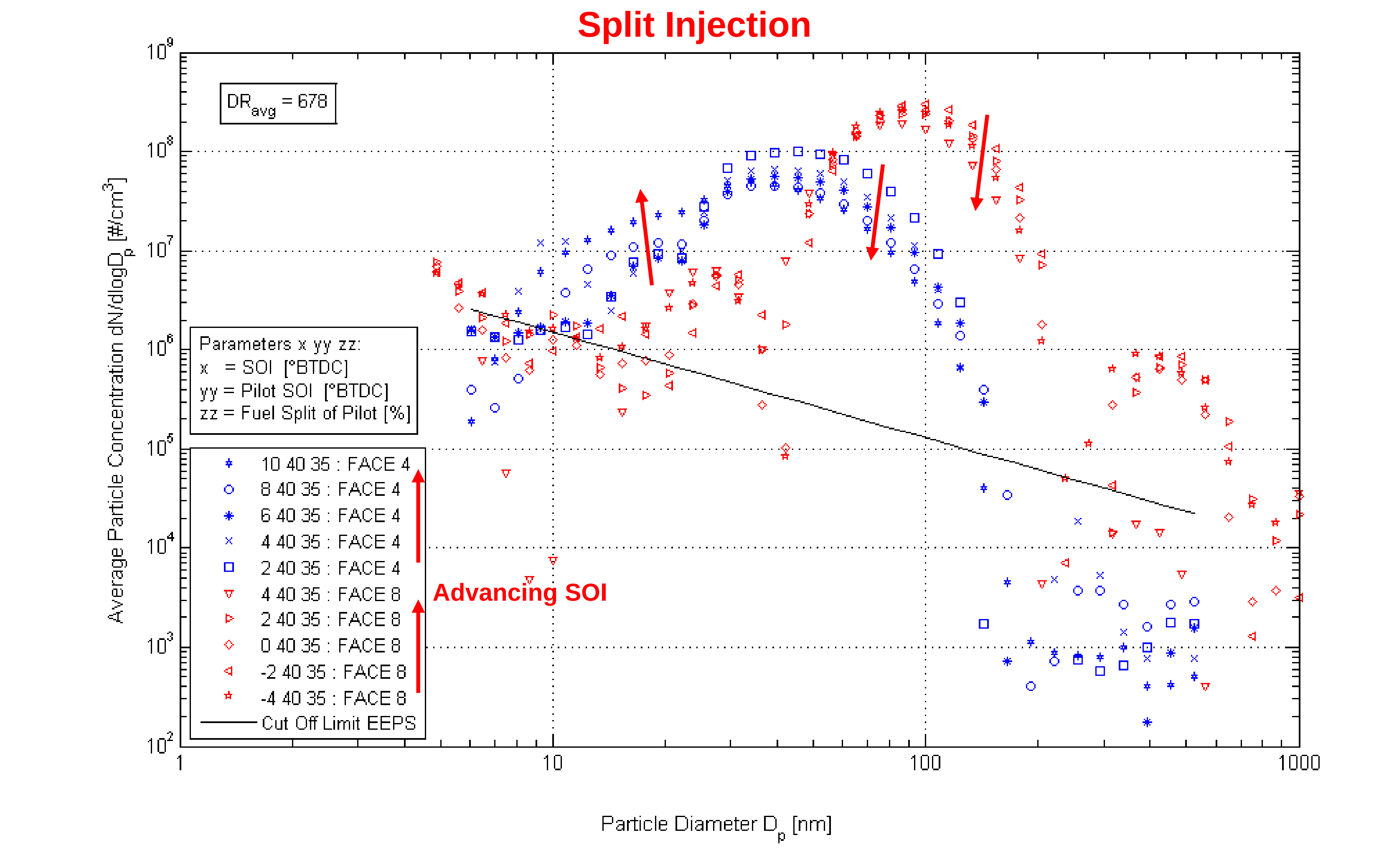
Results - Low Cetane Fuels



Results - High Cetane Fuels



Results - Injection Timing Comparison



Conclusions

- Particle number concentration increased with a simultaneous increase in particle diameter for both, single and split injection strategies in case of FACE diesel fuels with increasing CN for the low NO_x, low soot* and highest BTE* tests
(*: not shown in this presentation)
- Particle number concentrations were higher for single injection compared to split injection strategy
- Low CN fuels exhibit wide particle number distributions whereas high CN fuels tend to have especially narrow accumulation modes

Conclusions (cont'd)

- CN had the highest effect, followed by T_{90}, and aromatic content; CN may mask the other 2 fuel properties
- The 90 percent distillation temperature had significant influence on the particle size distribution: the count mode diameter was found to be lower for low CN and high T_{90} fuels, and also lower for high CN and low T_{90} fuels
- Advancing the start of injection timing led to a decrease in particle number concentration, but a simultaneous increase in nanoparticle emissions was observed for low CN fuels

Thank You for Your Attention

CAFEE Center for Alternative Fuels, Engines and Emissions

Literature References:

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2) Gallant, T., Franz, J.A., Alnajjar, M.S., Storey, J.M.E., Lewis, S.A., Sluder, C.S., Cannella, W.J., Fairbridge, C., Hager, D., Dettman, H., Luecke, J., Ratcliff, M.A., and Zigler, B.T., "Fuels for Advanced Combustion Engines Research Diesel Fuels: Analysis of Physical and Chemical Properties," SAE Int. J. Fuels Lubr., vol. 2, pp. 262-272, 2009.
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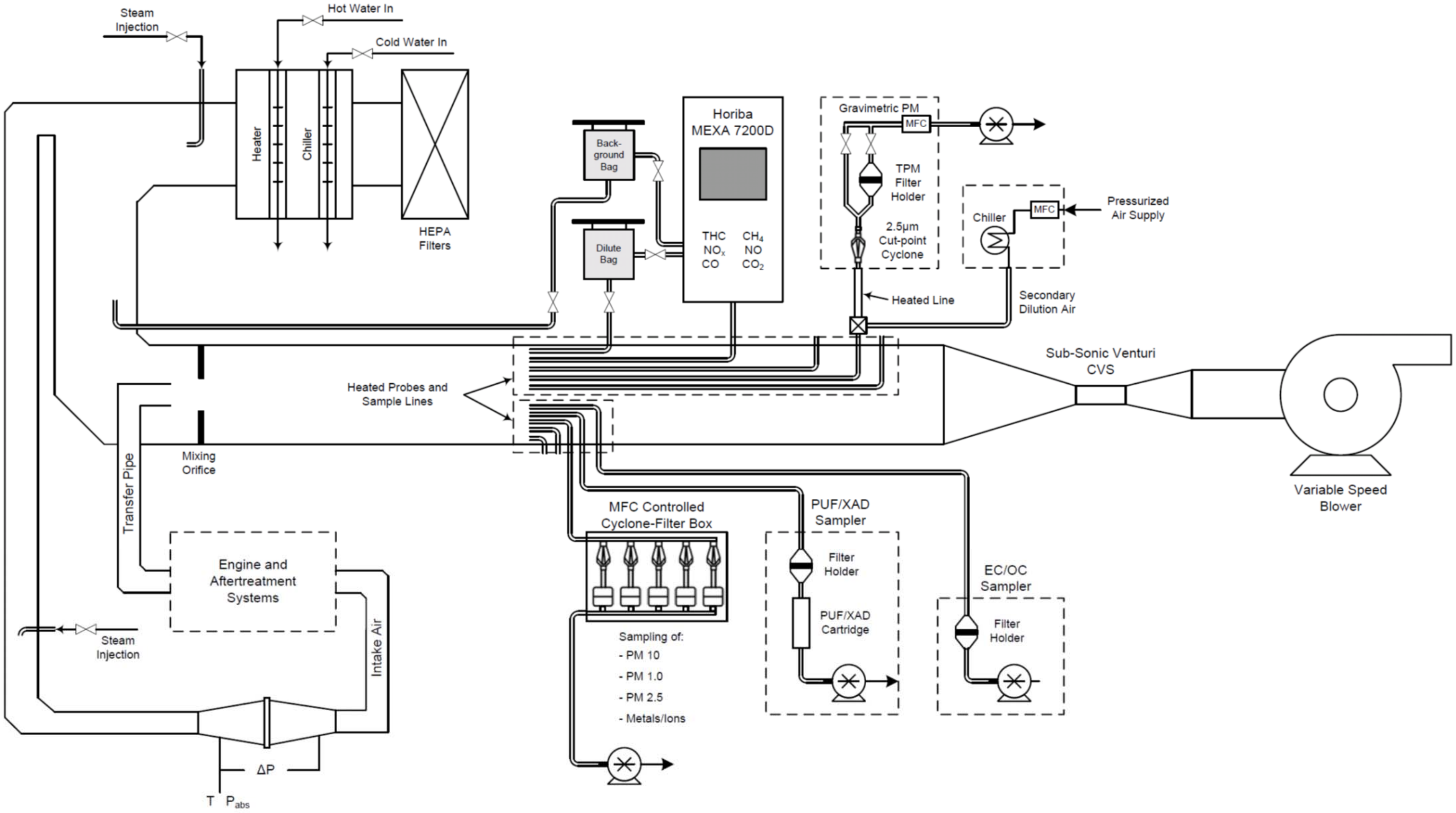
4) Hosseini, V., Neill, W., Guo, H., Dumitrescu, C.E., Chippior, W., Fairbridge, C., and Mitchell, K., "Effects of Cetane Number, Aromatic Content and 90% Distillation Temperature on HCCI Combustion of Diesel Fuels," SAE Technical Paper, 2010-01-2168, 2010.
5) De Ojeda, W., Bulicz, T., Han, X., Zheng, M., and Cornforth, F., "Impact of Fuel Properties on Diesel Low Temperature Combustion," SAE Int. J. Engines, vol. 4, pp. 188-201, 2011.
6) Storey, J.M.E., Lewis, S.A., Parks, J.E., Szybist, J.P., Barone, T.L., and Prikhodko, V.Y., "Mobile Source Air Toxics (MSATs) from High Efficiency Clean Combustion: Catalytic Exhaust Treatment Effects," SAE Int. J. Engines, vol. 1, pp. 1157-1166, 2008.
7) Natti, K.C., Henein, N.A., Poonawala, Y., and Bryzik, W., "Particulate Matter Characterization Studies in an HSDI Diesel Engine under Conventional and LTC Regime," SAE Int. J. Engines, vol. 1, pp. 735-745, 2008.
8) Balakrishnan, R., "Investigation of Particulate Matter Number Concentration and Size Distribution during Low Temperature Combustion," Master's Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, 2011.

Backup - 40 CFR 1065 Compliant Laboratory Setup



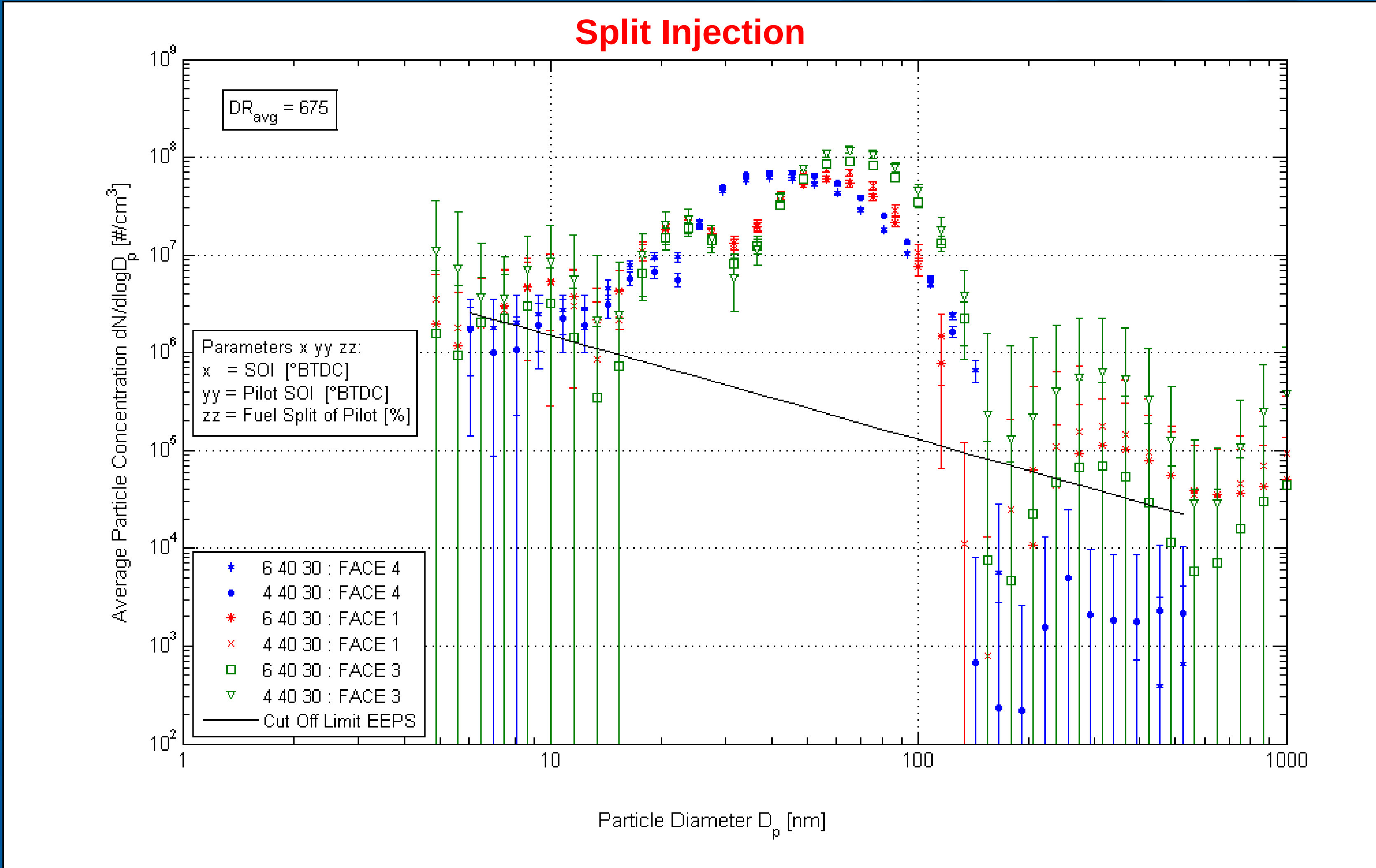
Backup - Emissions Comparison

Emissions Comparison of Optimal Split and Single Injection Tests for Low NO_x:

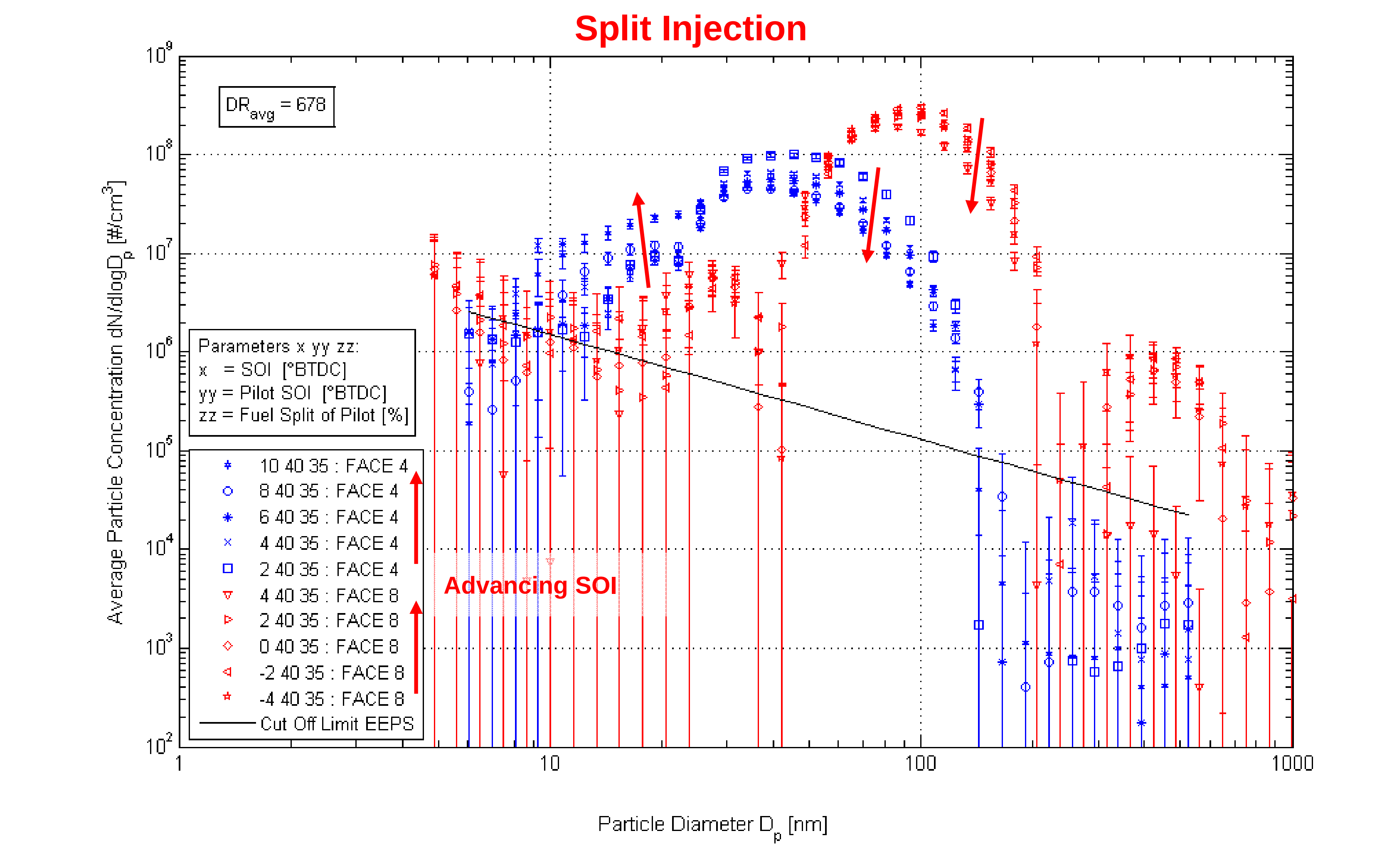
Fuel	Test #		HC [g/kWh]		NO_x [g/kWh]		CO [g/kWh]		Soot [mg/kWh]		BTE [%]	
	Split	*Single*	*Split*	*Single*	*Split*	*Single*	*Split*	*Single*	*Split*	*Single*	*Split*	*Single*
FACE 4	20	50	7.35	6.91	0.476	0.083	19.72	19.10	6.6	2.0	29.4	30.5
FACE 1	19	51	4.36	3.58	0.549	0.107	16.45	12.65	9.1	2.0	30.4	32.7
FACE 3	28	49	4.59	2.94	0.485	0.119	17.64	17.09	30.4	20.2	30.2	32.0
ULSD	29	50	1.90	1.30	0.438	0.134	10.18	10.93	138.6	103.3	31.4	33.4
FACE 7	20	50	1.77	1.38	0.501	0.137	10.11	13.73	161.8	168.7	31.1	32.1
FACE 9	21	49	1.86	1.12	0.599	0.182	9.72	10.37	128.6	266.8	31.7	33.7
FACE 8	13	51	1.38	1.11	0.575	0.186	7.37	15.02	314.0	924.9	31.8	32.2
FACE 6	16	49	1.82	1.02	0.460	0.159	11.56	15.54	264.2	749.4	31.8	33.0
FACE 5	29	49	1.09	1.12	0.384	0.122	6.63	13.83	131.8	271.9	31.5	33.5

Note: Split / Single = Split / Single Injection Strategy

Backup - Low Cetane Fuels



Backup - Injection Timing Comparison



Backup - Emissions Comparison

Emissions Comparison for Low and High CN and Varying SOI Timing:

	Test Parameters	TNC [#/cm^3]	HC [ppm]	HC [g/kWh]	NO_x [ppm]	NO_x [g/kWh]	CO [ppm]	CO [g/kWh]	BTE [%]
FACE 4	10 40 35*	2.640×10^7	1735	5.63	85.8	0.927	2325	15.12	29.1
	8 40 35*	2.232×10^7	1817	5.80	58.3	0.615	2653	17.11	29.4
	6 40 35*	2.552×10^7	2295	7.35	45.0	0.476	3056	19.72	29.4
	4 40 35*	3.217×10^7	2667	8.64	38.7	0.408	3540	22.88	28.8
	2 40 35*	4.584×10^7	2681	8.70	36.2	0.381	3634	23.73	28.3
FACE 8	4 40 35*	6.749×10^7	694	2.10	61.8	0.657	1689	10.73	31.4
	2 40 35*	8.923×10^7	804	2.52	54.2	0.586	1781	11.48	30.0
	0 40 35*	9.226×10^7	907	2.88	48.9	0.524	1762	11.45	29.2
	-2 40 35*	1.058×10^8	861	2.72	47.7	0.513	1689	10.96	28.9
	-4 40 35*	9.299×10^7	838	2.67	42.5	0.463	1816	11.98	28.9

** Note: Parameters x yy zz: x = SOI [°BTDC]; yy = Pilot SOI [°BTDC]; zz = Fuel Split of Pilot [%]*