On-Road Nanoparticle Measurements – Fuel and Oil Sulfur Effects

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Outline – On-road measurements of nucleation mode particles from a heavy-duty vehicle

- DPF equipped engines
  - Under on-road cruise conditions, nucleation mode particles downstream of a catalyzed DPF system are mainly sulfuric acid
  - Strong dependence on exhaust temperature
  - These particles constitute little particle mass
  - Analysis of 5 years of on-road particle measurements to determine influence of fuel, lubricating oil, trap type and trap age on nanoparticle emissions measured downstream of a heavy-duty vehicle operated under real-world highway cruise conditions*
- Heavy-duty engines without traps
  - Nucleation mode particles consist mainly of heavy hydrocarbons
  - Their formation is facilitated by sulfur in fuel
  - Strong dependence on ambient temperature
  - Results of recent on-road tests with LSD and ULSD

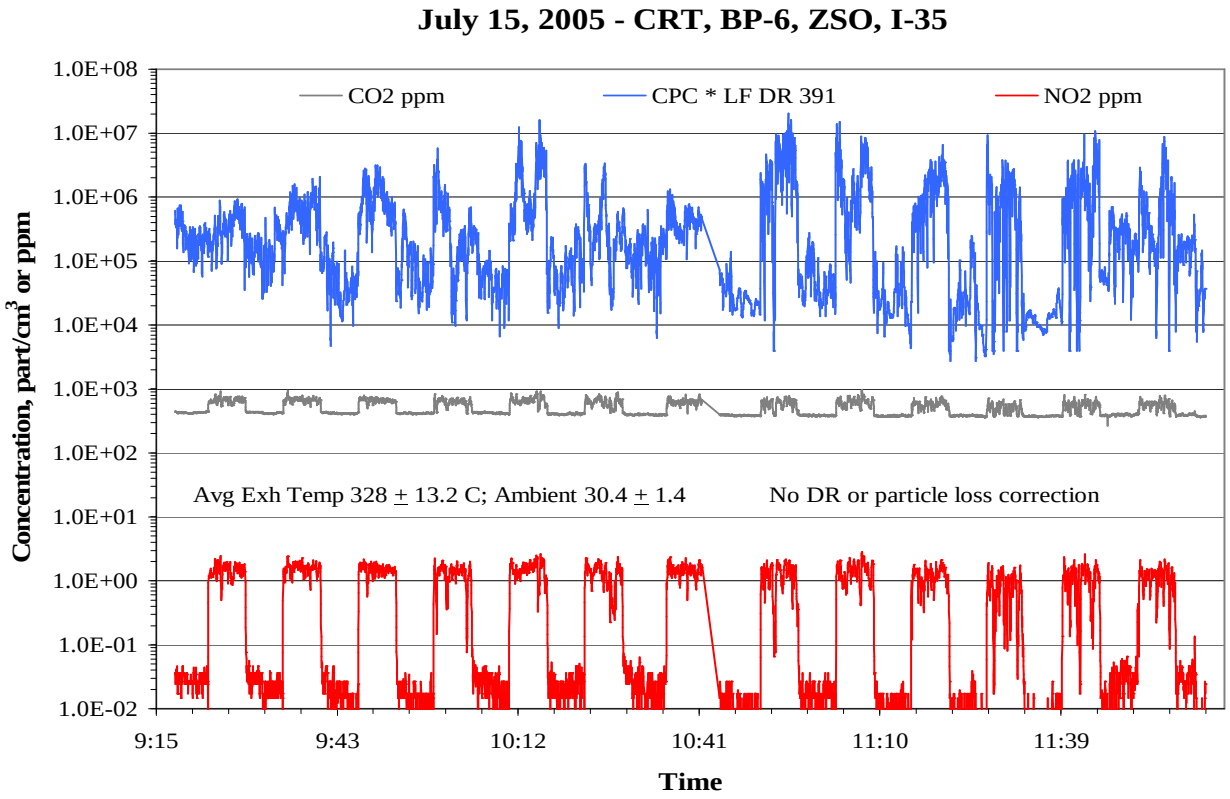
*D. B. Kittelson, W. F. Watts, J. P. Johnson, C. Thorne, C. McCann, M. Payne, S. Goodier, C. Warrens, H. Preston, U. Zink, D. Pickles, C. Goersmann, M. V. Twigg, A. P. Walker, and R. Boddy, 2007. Effect of Fuel and Lube Oil Sulfur on the Performance of a Diesel Exhaust Gas Continuously Regenerating Trap, to be submitted to EST.

UMN Mobile Emissions Laboratory (MEL)

Trial Sequence

Season	Trial	Fuel	Fuel S, ppm	Oil	Oil S, %
Fall 02	-5	BP-15	15	HSO	0.261
Fall 02	-4	BP-50	45	HSO	0.261
Summer 03	-3	BP-15	15	HSO	0.261
Summer 03	-2	BP-15	15	LSO	0.126
Summer 03	-1	BP-15	15	LSO	0.126
Summer 03	1	BP-50	45	HSO	0.261
Summer 04	4	BP-15	15	LSO	0.126
Summer 05	7	BP-6	4	ZSO	0.042
Summer 05	8	ECD	6	ZSO	0.042
Summer 05	9	BP-6	4	HSO	0.261
Summer 06	12	BP-50	45	HSO	0.261
Summer 06	13	ECD-1	6	VHSO	0.619
Summer 06	14	BP-6	4	LSO	0.142

How We Sample



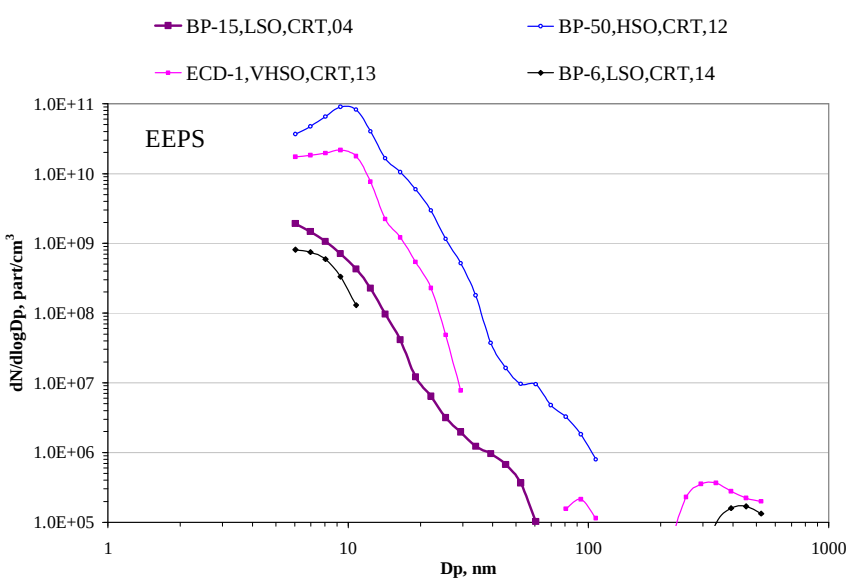
Summary - Number of Samples

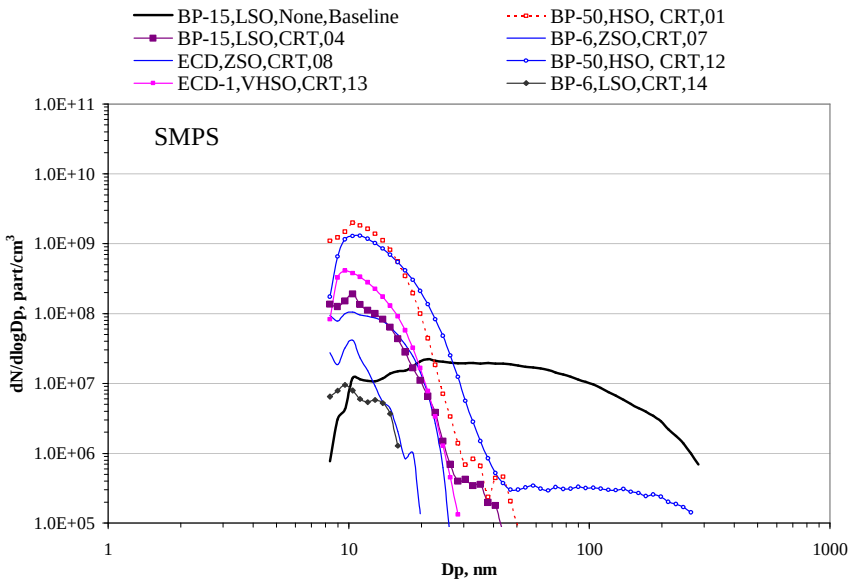
Trial	Fuel	Oil	Aftertreatment	Number of repetitions	Number of plume samples	Number of background samples	Number of SMPS background scans	Nuimber of plume SMPS scans
Baseline	BP-15	LSO	None	26	7877	14974	146	74
Trial 01	BP-50	HSO	CRT	28	8622	17896	160	80
Trial 02	BP-15	LSO	CCRT	72	22453	47314	433	214
Trial 03	BP-15	LSO	CRT + S-Trap	33	10361	20490	192	98
Trial 04	BP-15	LSO	CRT	57	17215	35184	350	169
Trial 05	BP-15	LSO	CRT + S-Trap	45	14436	30823	277	135
Trial 06	BP-15	LSO	CCRT	37	11615	23124	217	111
Trial 07	BP-6	ZSO	CRT	66	20943	44492	406	197
Trial 08	ECD	ZSO	CRT	38	12163	24831	229	113
Trial 09	BP-6	HSO	CRT	43	13882	26373	239	128
Trial 10	BP-50	ZSO	CRT + S-Trap	41	13168	28891	264	121
Trial 11	BP-50	HSO	CRT + S-Trap	60	18910	39326	358	178
Trial 12	BP-50	HSO	CRT	39	14456	29056	221	114
Trial 13	ECD-1	VHSO	CRT	40	14833	30386	239	119
Trial 14	BP-6	LSO	CRT	37	13091	26498	210	105

Test Condition – 105 ± 8 km/hr

Trial	Fuel	Oil	Aftertreatment	Dilution ratio	
				Avg	Std
Baseline	BP-15	LSO	None	477	91
Trial 01	BP-50	HSO	CRT	431	74
Trial 02	BP-15	LSO	CCRT	429	56
Trial 03	BP-15	LSO	CRT + S-Trap	340	33
Trial 04	BP-15	LSO	CRT	507	69
Trial 05	BP-15	LSO	CRT + S-Trap	406	24
Trial 06	BP-15	LSO	CCRT	400	48
Trial 07	BP-6	ZSO	CRT	381	60
Trial 08	ECD	ZSO	CRT	473	75
Trial 09	BP-6	HSO	CRT	379	39
Trial 10	BP-50	ZSO	CRT + S-Trap	416	52
Trial 11	BP-50	HSO	CRT + S-Trap	362	40
Trial 12	BP-50	HSO	CRT	385	21
Trial 13	ECD-1	VHSO	CRT	413	41
Trial 14	BP-6	LSO	CRT	516	89

SMPS and EEPS Size Distributions - CRT



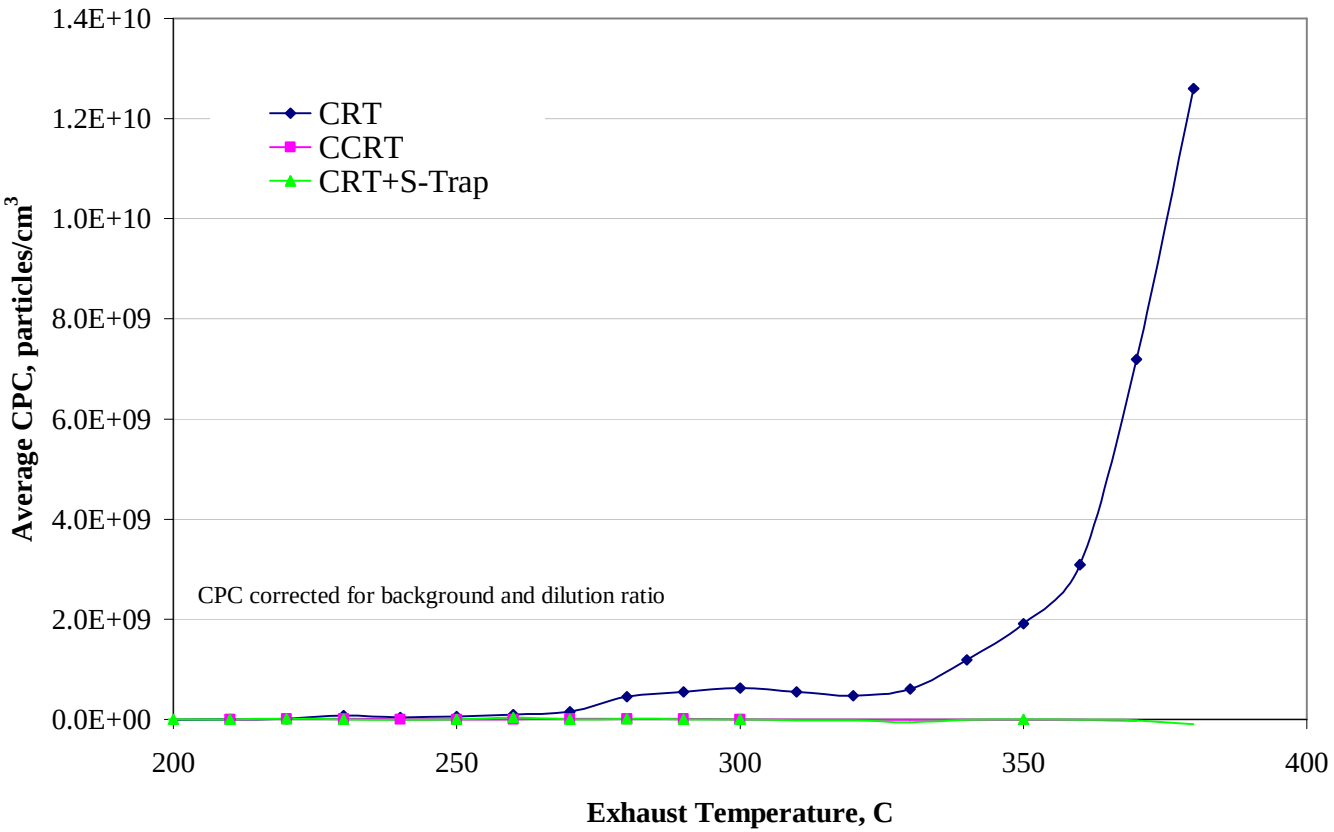


Note the much greater response of the EEPS to small particles under these transient conditions. The EEPS tracks well with the CPC on total number

Summary SMPS Statistics

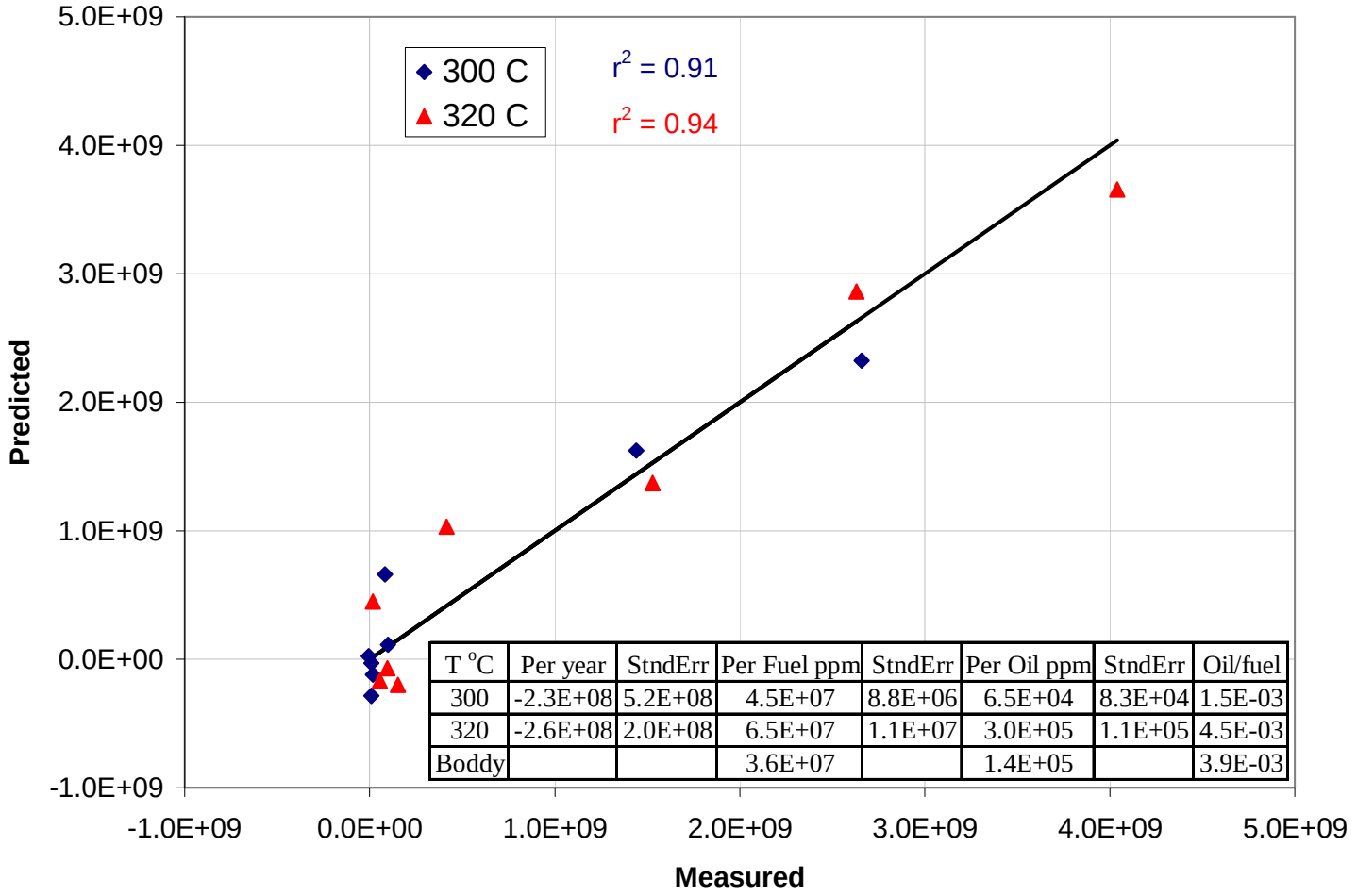
Trial	Fuel	Oil	Aftertreatment	Dilution ratio		CPC, part/cm^3		SMPS, part/cm^3		N/V	CPC/SMPS
				Avg	Std	Avg	Std	Avg	Std		
Baseline	BP-15	LSO	None	477	91	2.06E+07	1.20E+07	1.86E+07	6.21E+06	3.5E+03	1.10
Trial 01	BP-50	HSO	CRT	431	74	2.68E+09	5.02E+08	4.32E+08	2.79E+08	1.8E+06	6.20
Trial 02	BP-15	LSO	CCRT	429	56	-5.79E+06	1.43E+07	-2.11E+05	1.42E+05	-1.7E+04	27.46
Trial 03	BP-15	LSO	CRT + S-Trap	340	33	1.33E+07	4.17E+07	-9.32E+05	1.35E+06	7.1E+03	-14.31
Trial 04	BP-15	LSO	CRT	507	69	5.43E+08	1.85E+08	3.75E+07	1.62E+08	-1.4E+05	14.48
Trial 05	BP-15	LSO	CRT + S-Trap	406	24	-7.02E+07	1.13E+08	-7.65E+05	6.04E+05	7.5E+04	91.79
Trial 06	BP-15	LSO	CCRT	400	48	-8.22E+06	1.62E+07	-1.25E+06	2.71E+06	7.3E+03	6.58
Trial 07	BP-6	ZSO	CRT	381	60	3.88E+08	1.75E+08	2.88E+07	3.57E+07	-2.3E+05	13.50
Trial 08	ECD	ZSO	CRT	473	75	1.31E+08	1.25E+08	4.75E+06	9.55E+06	-3.3E+04	27.65
Trial 09	BP-6	HSO	CRT	379	39	1.04E+08	6.06E+07	2.75E+06	8.78E+06	-1.8E+04	37.72
Trial 10	BP-50	ZSO	CRT + S-Trap	416	52	-1.08E+07	6.53E+07	-1.12E+06	1.39E+06	6.0E+03	9.63
Trial 11	BP-50	HSO	CRT + S-Trap	362	40	-1.55E+07	1.87E+07	-1.62E+06	2.11E+06	9.5E+03	9.58
Trial 12	BP-50	HSO	CRT	385	21	2.17E+09	3.14E+08	3.16E+08	1.47E+08	4.2E+05	6.87
Trial 13	ECD-1	VHSO	CRT	413	41	1.23E+09	2.80E+08	7.97E+07	7.03E+09	1.8E+06	15.50
Trial 14	BP-6	LSO	CRT	516	89	1.55E+08	7.28E+07	1.16E+06	5.95E+05	-4.7E+03	134.08

Relationship Between Particle Concentration And Exhaust Temperature – CRT, CCRT, CRT + S-trap



- Averaging all tests shows the differences between the CRT and CCRT and CRT + S-trap.
- Data shown are for all runs regardless of fuel and lube

Correlate number emissions with age, fuel S, and oil S at constant binned T



T °C	Per year	StndErr	Per Fuel ppm	StndErr	Per Oil ppm	StndErr	Oil/fuel
300	-2.3E+08	5.2E+08	4.5E+07	8.8E+06	6.5E+04	8.3E+04	1.5E-03
320	-2.6E+08	2.0E+08	6.5E+07	1.1E+07	3.0E+05	1.1E+05	4.5E-03
Boddy			3.6E+07		1.4E+05		3.9E-03

Conclusions

- Nucleation mode particle formation by the CRT is strongly temperature dependent, but neither the CCRT nor the CRT plus S trap form particles detectable above background at any temperature in the range examined
- The formation of nucleation mode particles by the CRT is proportional to fuel S, oil S, but decreases with catalyst age.
  - For the conditions tested a 10 ppm S fuel would be expected to produce from 4 to 7 x 10^8 particles/cm^3
  - Particle formation per unit sulfur in the lube oil ranges from 0.15 - 0.45% of that per unit sulfur in the fuel.
    - For the conditions tested, the oil consumption of the Volvo is in the 0.05 - 0.15% of fuel consumption range. This suggest that S in the lube oil that is consumed is more effective at producing nuclei mode particles than the S in the fuel
    - For the conditions tested a 3000 ppm S lube oil would be expected to form as many particles as 4.5 to 13.5 ppm S fuel
- Other oil components may play a role, this is being examined by BP/Castrol

ON-ROAD EVALUTION OF LOW SULFUR AND ULTRA LOW SULFUR DIESEL FUEL

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through the University of Rochester

Fuel properties – fuel purchased from a local fuel supplier in the Rochester, NY area

Fuel	Sulfur mass, %	Density, g/mL	Kinematic viscosity	Aromatics, wt % ASTM D5186		
			@ 40^{o}C, cSt			
	ASTM D2622	ASTM D4052	ASTM D445	Total	Mono	Polynuclear
LSD	0.0263	0.8456	2.615	27.6	21.1	6.5
ULSD	0.0014	0.869	2.919	36.4	27.6	8.8

Daily test conditions – rural freeway driving near Rochester, NY

Date	Ambient temperature, °C		Dew point,	RH, %[1]	Wind direction[1]	Wind speed,	Condition[1]	Precipitation
	Avg	Std	Avg			km/hr[1]		
9/24/2006	22.6	1.5	14.1	60	WSW	40.40	PC	N/A
9/25/2996	18.2	2.3	8.6	66	W	18.90	MC	N/A
9/26/2006	18.0	1.7	8.4	65	W,WNW,NW	15.10	PC	N/A
9/27/2006	23.1	2.0	11.5	57	SSW	23.60	PC	N/A
9/28/2006	21.6	2.9	14.0	93	NW	8.20	LR	Rain
10/1/2006	16.6	1.9	12.7	77	WSW,SW,W	17.40	MC (LR)	N/A
10/2/2006	17.2	2.5	10.3	65	WSW,W,SW	13.20	SC	N/A
10/3/2006	17.6	1.9	16.4	89	VSW,SSW,S,WNW,V	15.40	LR	Rain
10/4/2006	18.2	2.0	16.6	88	SSW,SW	24.10	LR	Rain
10/5/2006	14.0	2.0	3.6	62	N,NNE,NE	20.10	MC	N/A
10/6/2006	13.4	2.7	4.9	62	E,NE,NNE,N	15.30	SC	N/A

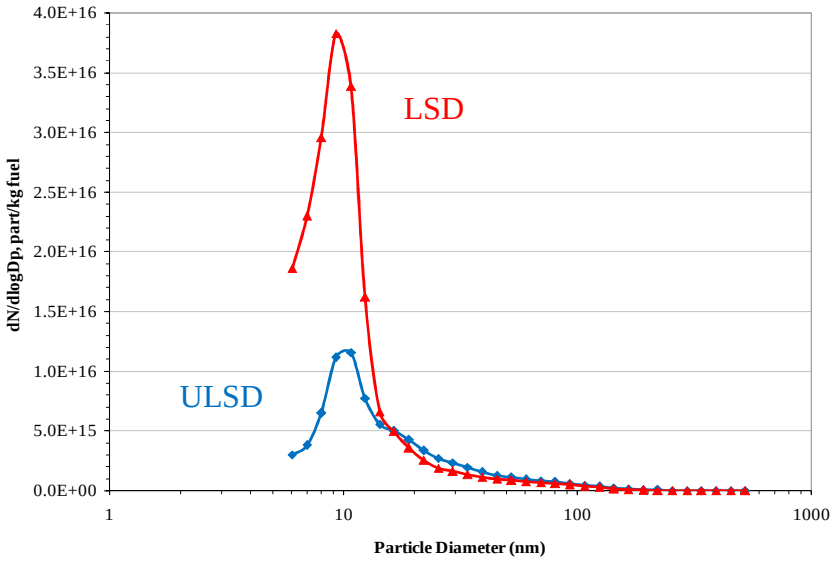
[1] Source www.wunderground.com for Rochester, NY- data averaged over test period

PC partly cloudy, MC mostly cloudy, LR light rain, SC scattered clouds, (LR) encountered on route

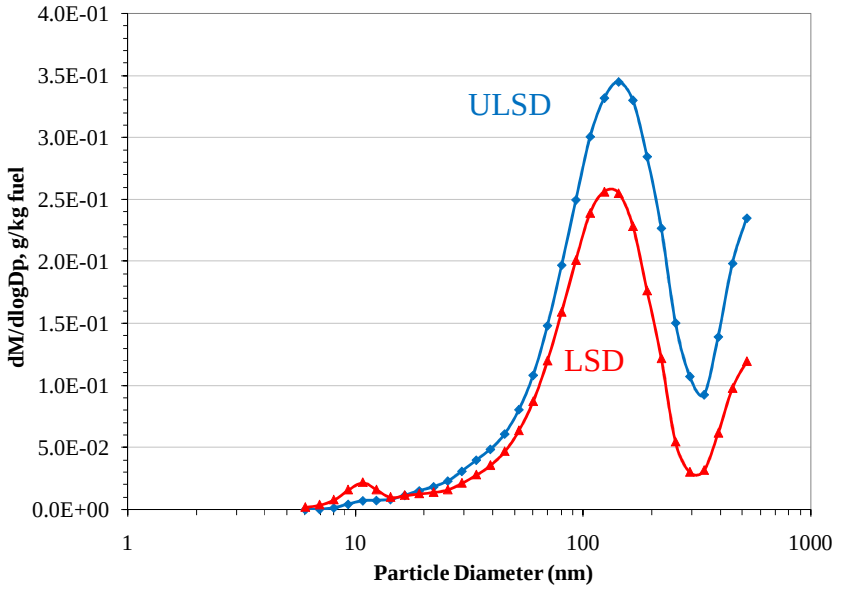
- Tests were run for approximately 6 hours per day
- The first week of testing was done with ULSD, the second with LSD
- The weather was not cooperative but this is *real-world* testing.

Fall 2006 on-road studies with LSD and USLD – sulfur influences nuclei mode and number, other properties mass

Weekly average fuel specific number size distributions (particles/kg fuel)

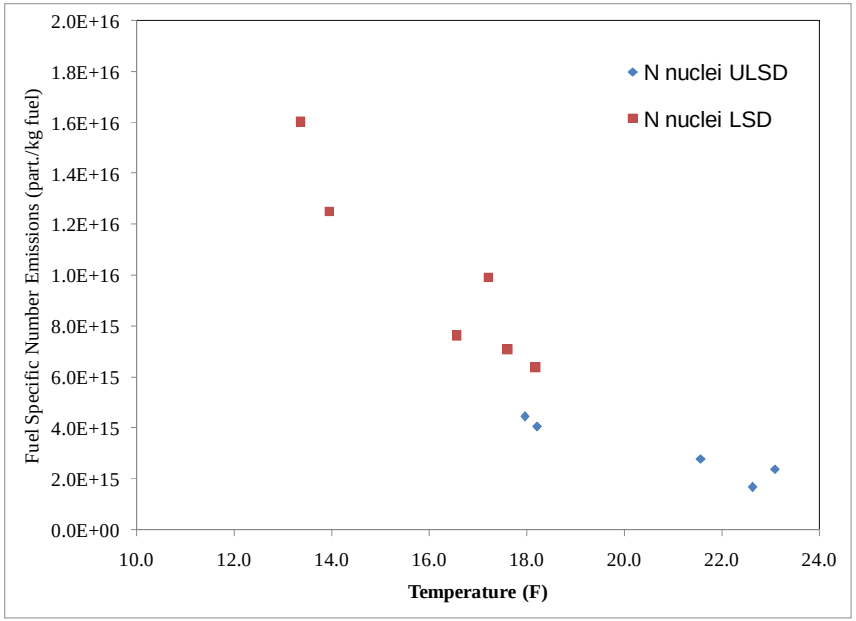


Weekly average fuel specific mass size distributions (g/kg fuel)

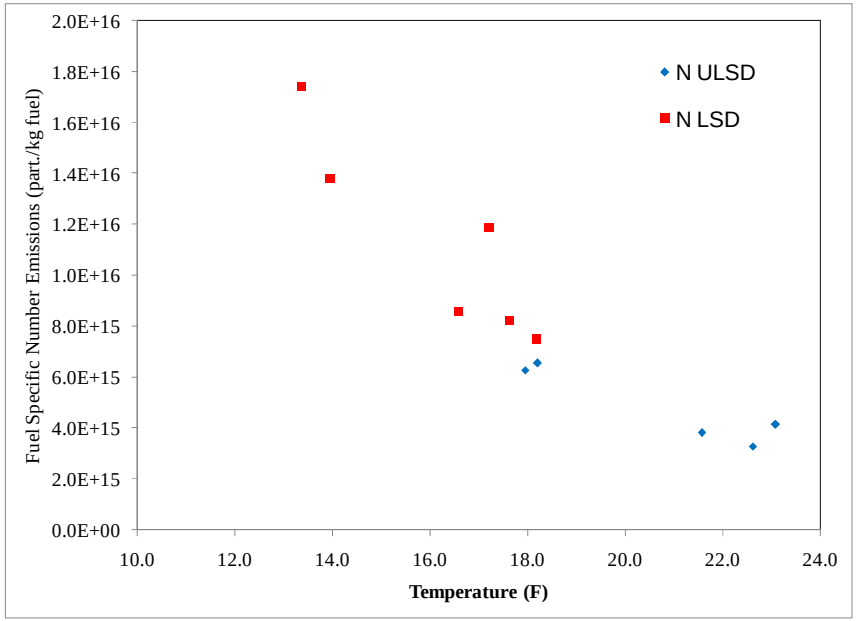


When daily temperature differences are taken into account there is surprisingly little difference in number emissions between the two fuels

Nuclei mode fuel specific number concentration (particles/kg fuel)

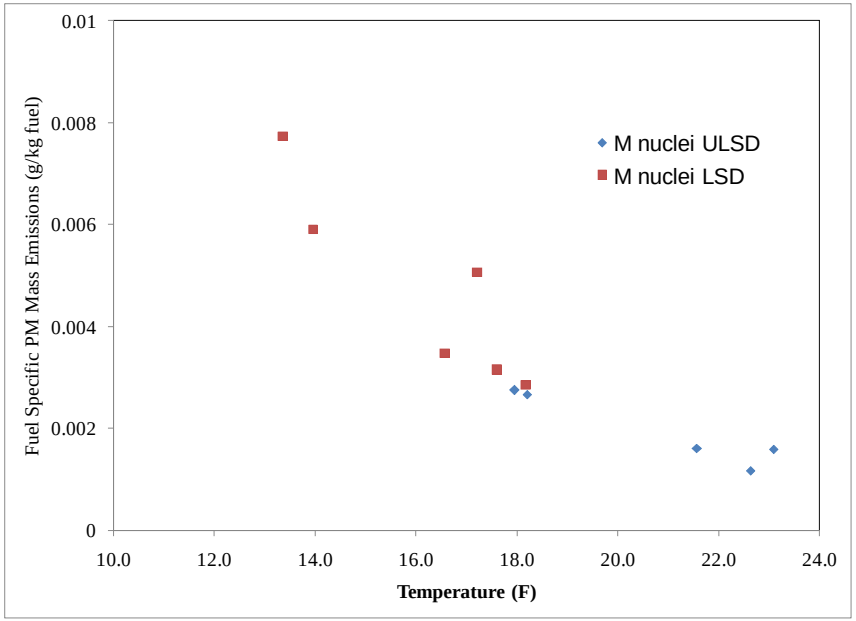


Total fuel specific number concentration (particles/kg fuel)

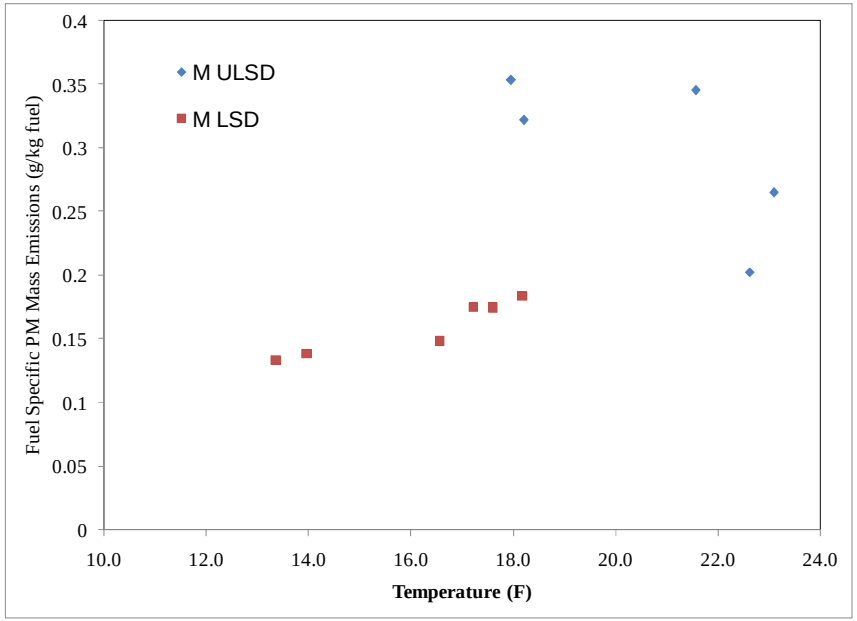


Nucleation mode mass showed a similar temperature dependence to number but no trend was evident for total PM

Nucleation mode fuel specific mass emissions (g/kg fuel)

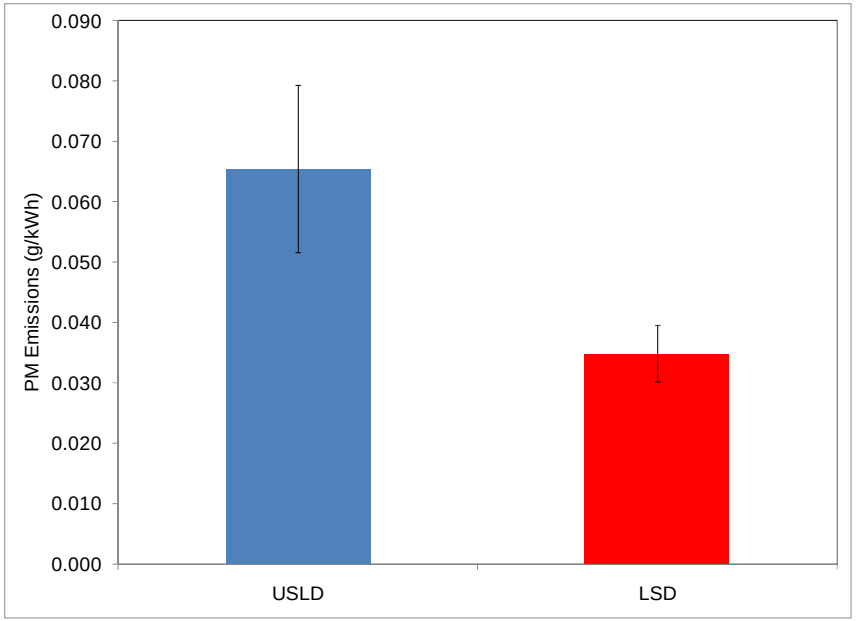


Total fuel specific PM mass emissions (g/kg fuel)

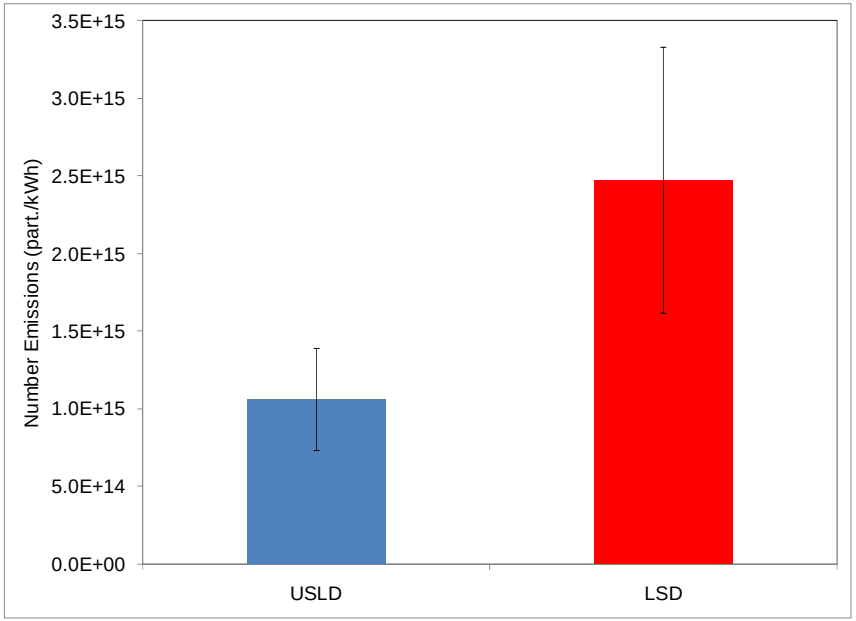


Weekly average mass and number emissions

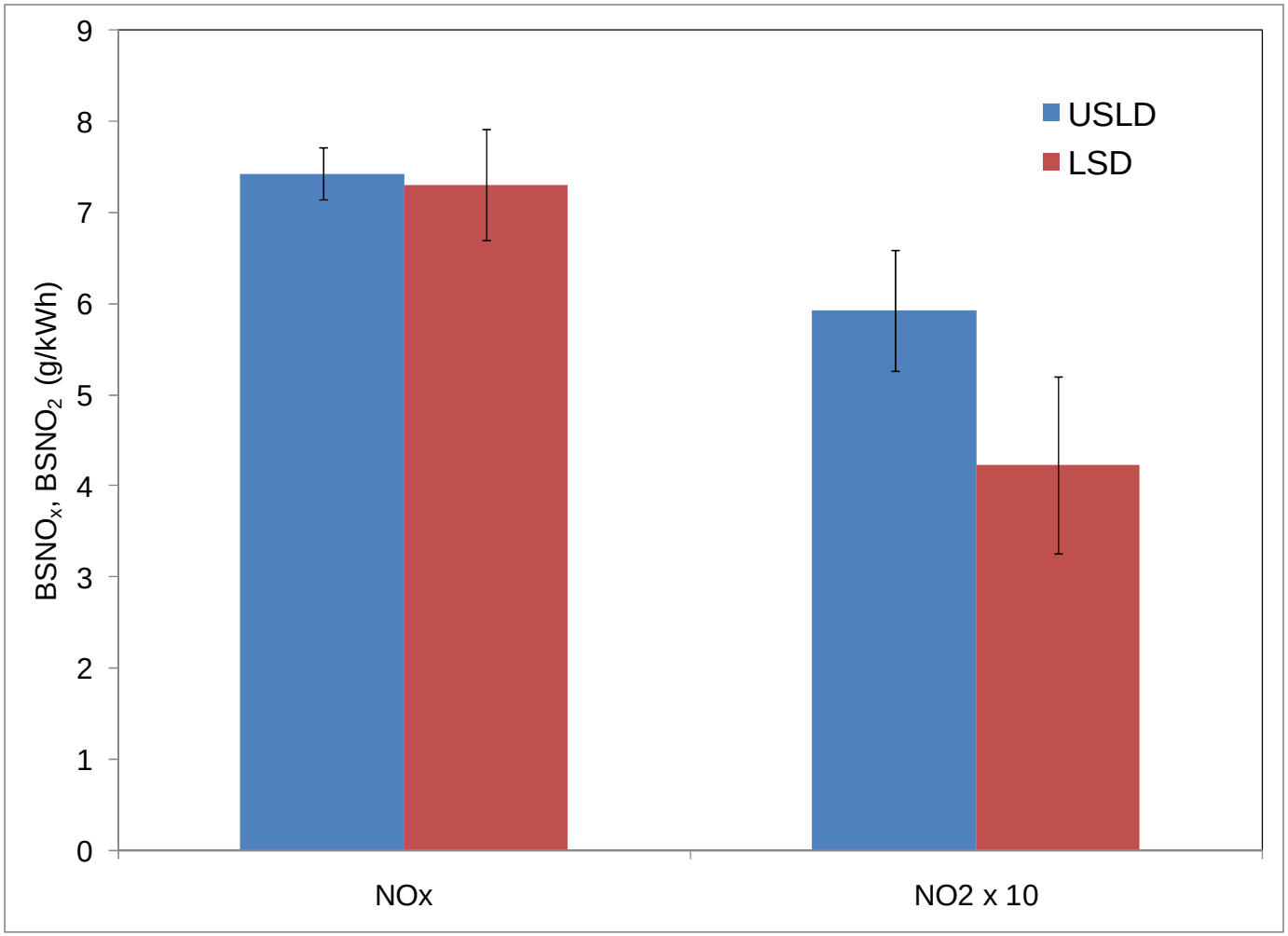
PM mass emissions (g/kWh)



Particle number emissions (particles/kWh)



NO_x emissions were similar for the two fuels but NO_2 was slightly higher with USLD



Conclusions

- The MEL is a useful platform for performing real-world emission tests
- However, real-world means real-world and ambient conditions introduce additional variables
- Two weeks of testing under highway cruise conditions revealed some interesting differences between commercial LSD and ULSD in a 2000 model year heavy-duty vehicle
  - Number emissions were slightly higher with LSD but ambient temperature had a stronger influence than fuel
  - Mass emissions were higher with USLD
  - These results suggest that the sulfur content of the fuel mainly influence the nucleation mode where most of the number is found while other properties like the aromatic content influence the accumulation mode where most of the mass is found
  - NO_x emissions were similar but USLD produced slightly more NO_2
  - ULSD has been introduced to allow the use of catalyzed aftertreatment but does not necessarily lead to reduced emissions with in use vehicles