Emissions during and Real-world Frequency of Heavy-duty Diesel Particulate Filter Regeneration

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Supporting Information.

3 pages

15 figures

3 tables

Description of DPF loading procedure

HDDVs were driven on the dynamometer to load their DPFs with engine particulate emissions. Note that this is in contrast to previous studies of regeneration emissions from these vehicles, in which the DPFs were loaded by extended idling and low-speed on-road driving with the tractor but no trailer.[1-3] In this study, PM accumulated on the DPFs during driving that involved repeated constant accelerations and decelerations from ~10 to ~25 to ~10 mph. A brief example of such driving is shown in Figure S1. Engine loadings, controlled by the resistive force of the dynamometer, were initially low, but after the first two tests were raised to the highest levels at which DPF temperature did not exceed ~200°C and thus passive regeneration of the DPF was assumed not to occur. It should be noted that this may have changed the composition of the engine-out PM. DPFs were loaded over driving distances ranging from 250 to 734 miles. After sufficient PM had accumulated in the DPF, a dashboard regeneration LED indicator illuminated. For the 2007 HDDV, after ~200 additional miles had been driven, this indicator switched from a solid to a flashing display. DPFs were regenerated after loading to either the solid or flashing light for the 2007 HDDV, or the solid light for the 2010 HDDV.

Description of real-time instrumentation

Emissions were quantified at the tailpipe with Semtech DS Portable Emissions Measurement System (PEMS, Sensors Incorporated, Saline, MI, USA). Undiluted tailpipe emissions that were quantified include CO, CO_2, NO, NO_X, and total hydrocarbons (THC). These emissions were introduced into a custom-made wind tunnel, operated at a flowrate of 9000 scfm, which diluted of tailpipe emissions by a factor of 15-30. Emissions were diluted with ambient air to simulate real-world conditions, and PM from this air was collected and analyzed with separate filters used to correct tunnel background concentrations for PM species. Gas-phase species were background-corrected by subtracting a 60-second average of tunnel concentrations immediately before the HDDV engine was started.

Real-time measurements of particle size distributions, black carbon (BC), and gas-phase species, as well as PM filter samples for chemical analysis, were collected through sampling ports on the tunnel. Particle size distributions were measured both with a scanning mobility particle sizer (SMPS model 3080, TSI, Shoreview, MN) and a Fast Mobility Particle Sizer (FMPS, model 3091, TSI). The SMPS was operated with sample and sheath flowrates of 0.3 and 3 lpm, respectively, and scans were repeated every 2 minutes and observed particles with mobility diameters from 10 to 414 nm. The FMPS measured size distributions from 5.6 to 560 nm at 1 Hz resolution. BC was measured with an aethalometer (model AE33, Magee Scientific, Berkeley, CA). CO and CO2 were measured with a Q-Trak (TSI).

Description of PM filter collection and analysis

PM filter samples were collected on 47mm filters, which were either PTFE (2 μm pore size, Whatman, UK) or quartz (Tissuquartz filters, Pall, Port Washington, NY). Samples were collected only when regeneration was occurring. For active regenerations, the beginning of each event was determined by the time when regeneration was initiated by the driver via the dashboard control. The end was determined by a decrease in the OBD-reported fuel rate (Fig. 2), which typically occurs approximately 45 minutes after initiation. For passive regenerations, events were initiated by raising vehicle speed (under load) to 50 mph, and considered complete when the vehicle speed returned to zero, typically 15-30 minutes after initiation (Figs S7-S9).

Quartz filters were pre-baked at 900°C for four hours. PTFE filters were analyzed for gravimetric mass (CARB test method MV-AEROSOL-145) and elemental composition by X-Ray Fluorescence (XRF, CARB test method MV-AEROSOL-156). Aqueous extracts were taken of the PTFE filters and analyzed by ion chromatography (IC, , CARB test method MV-AEROSOL-142) for inorganic ions including NH4+, Na+, SO42-, and NO3-. Elemental carbon (EC) and organic carbon (OC) were measured with thermo-optical carbon analysis of the quartz filters (CARB test method MV-AEROSOL-139). All analyses were performed by CARB's Aerosol Analysis and Methods Evaluation section in El Monte, CA.

For one experiment conducted on 9/22/2015, size-segregated PM was collected with a nano-MODUI cascade impactor (model 122R, MSP, Shoreview, MN). These samples were collected on PTFE substrates, and ranged in particle diameter from 10 nm to 18 µm. Particles larger than 56 nm were impacted onto the same type of 45-mm PTFE substrate given above, and smaller particles were collected onto 90-mm PTFE substrates (1 µm pore size, Pall). To ensure that sufficient mass was available for analyses on the day, after a passive regeneration of the DPF on the 2010 HDDV, two forced (active) regenerations were initiated. The PM collected by the nano-MOUDI includes all three of these events. Analyses of these samples was identical to that of the bulk PM samples described above.

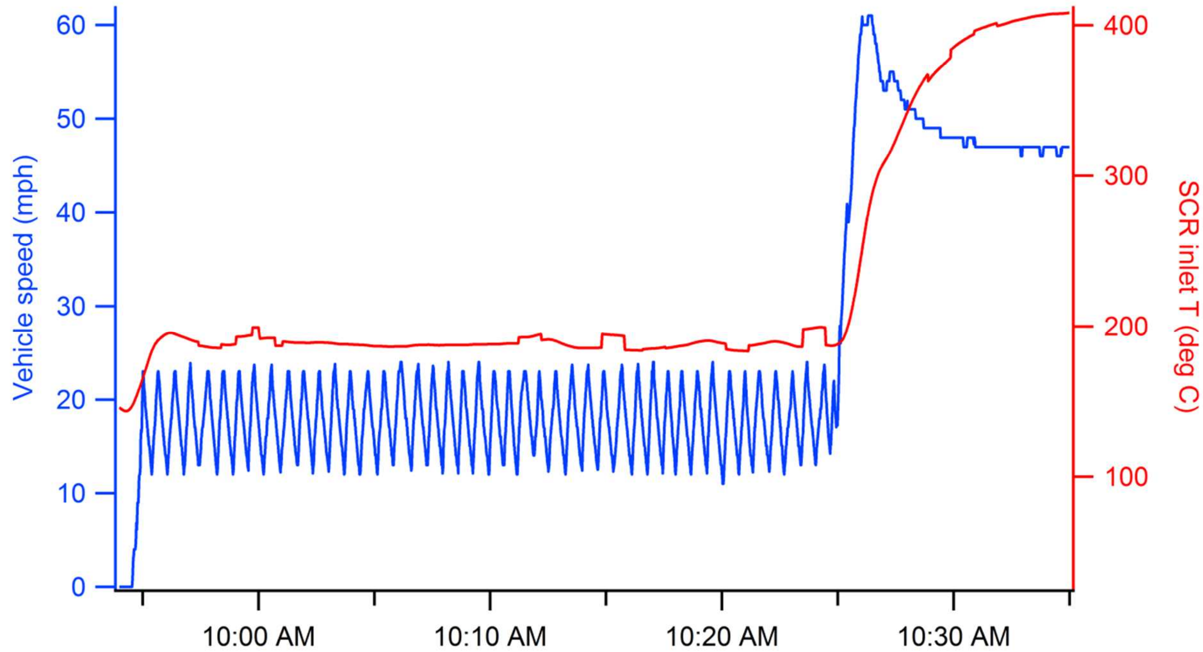


Figure S1. Typical pattern of acceleration/deceleration used to load HDDV DPFs with PM (through 10:25 AM), followed by an acceleration to highway speeds and associated increase in SCR inlet temperature.

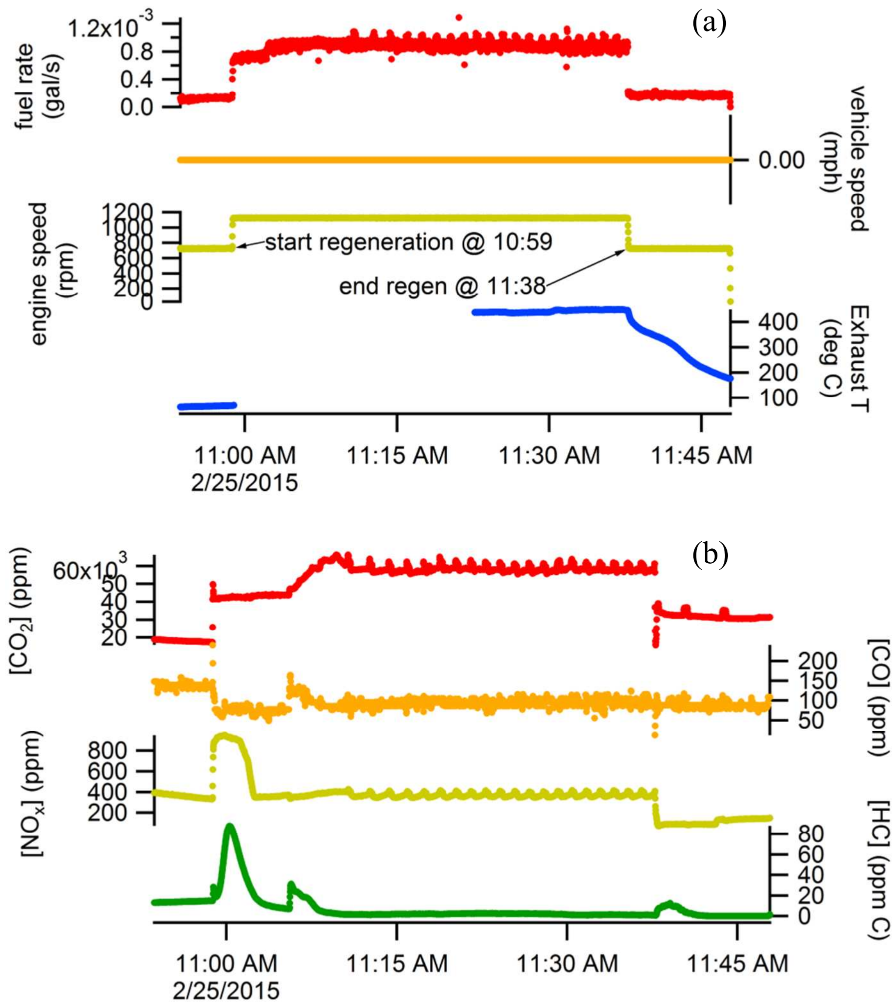


Figure S2. (a) Engine parameters and (b) emissions from a parked regeneration of the DPF from the 2007 HDDV performed on February 25, 2015.

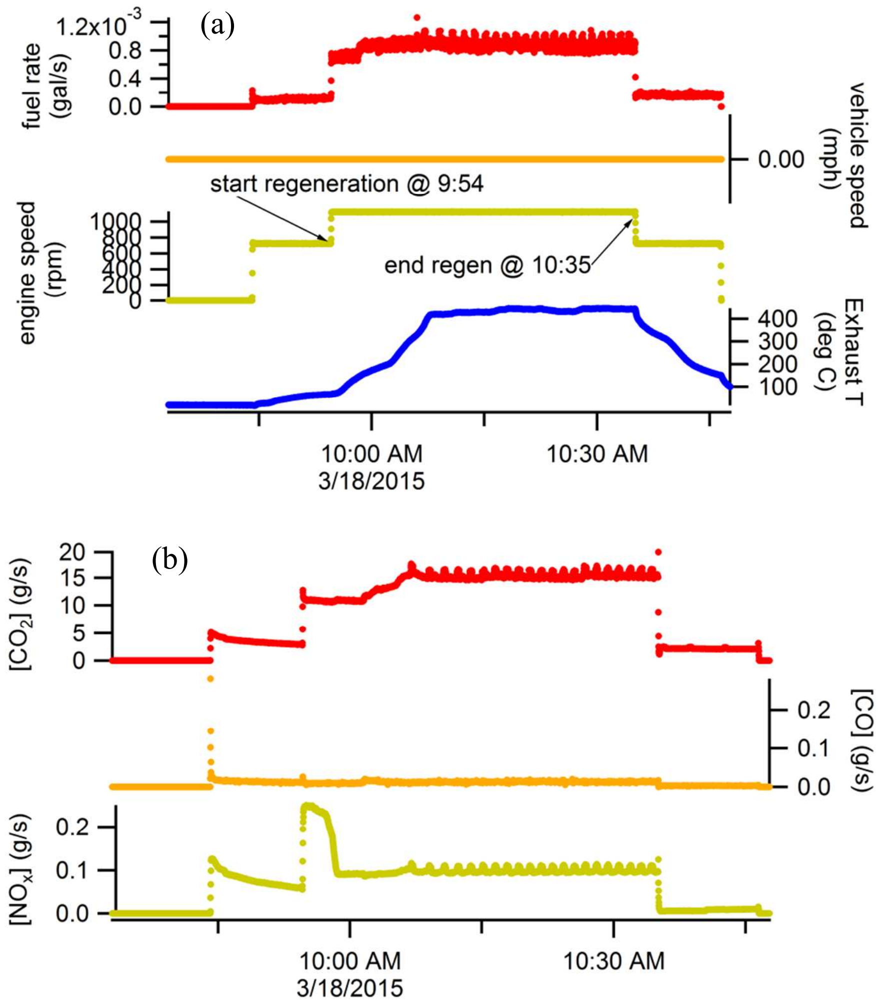


Figure S3. (a) Engine parameters and (b) emissions from a parked regeneration of the DPF from the 2007 HDDV performed on March 18, 2015.

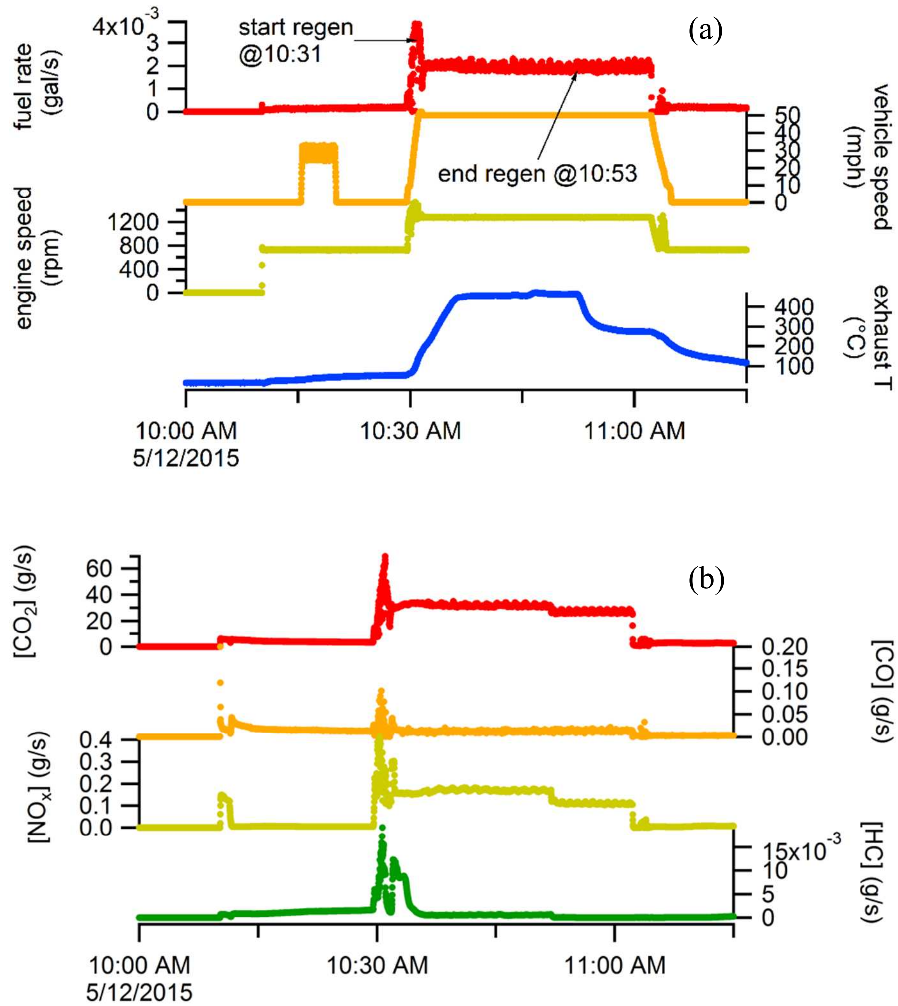
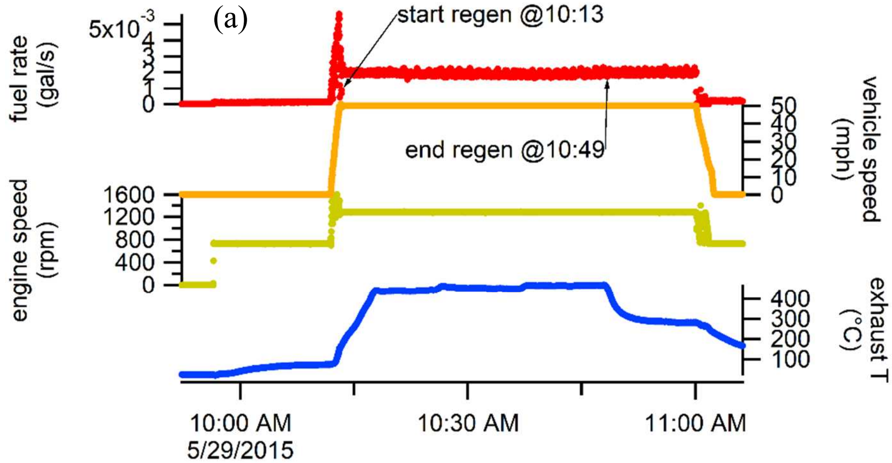


Figure S4. (a) Engine parameters and (b) emissions from a driving regeneration of the DPF from the 2007 HDDV performed on May 12, 2015.



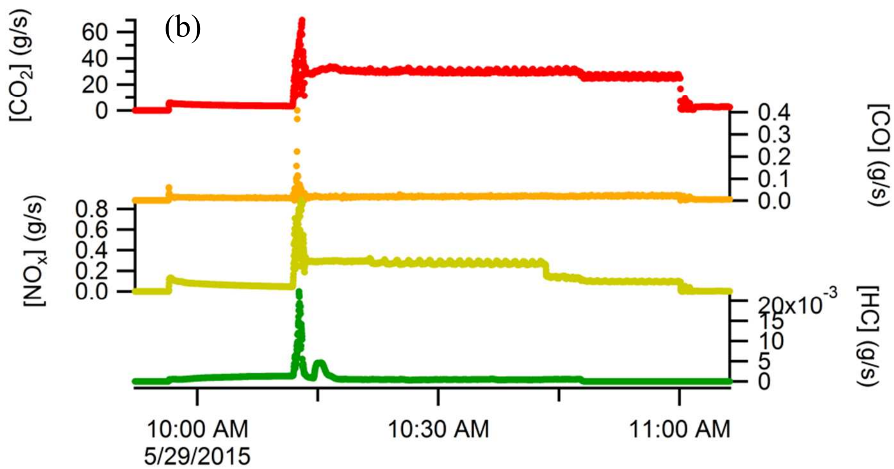


Figure S5. (a) Engine parameters and (b) emissions from a driving regeneration of the DPF from the 2007 HDDV performed on May 29, 2015.

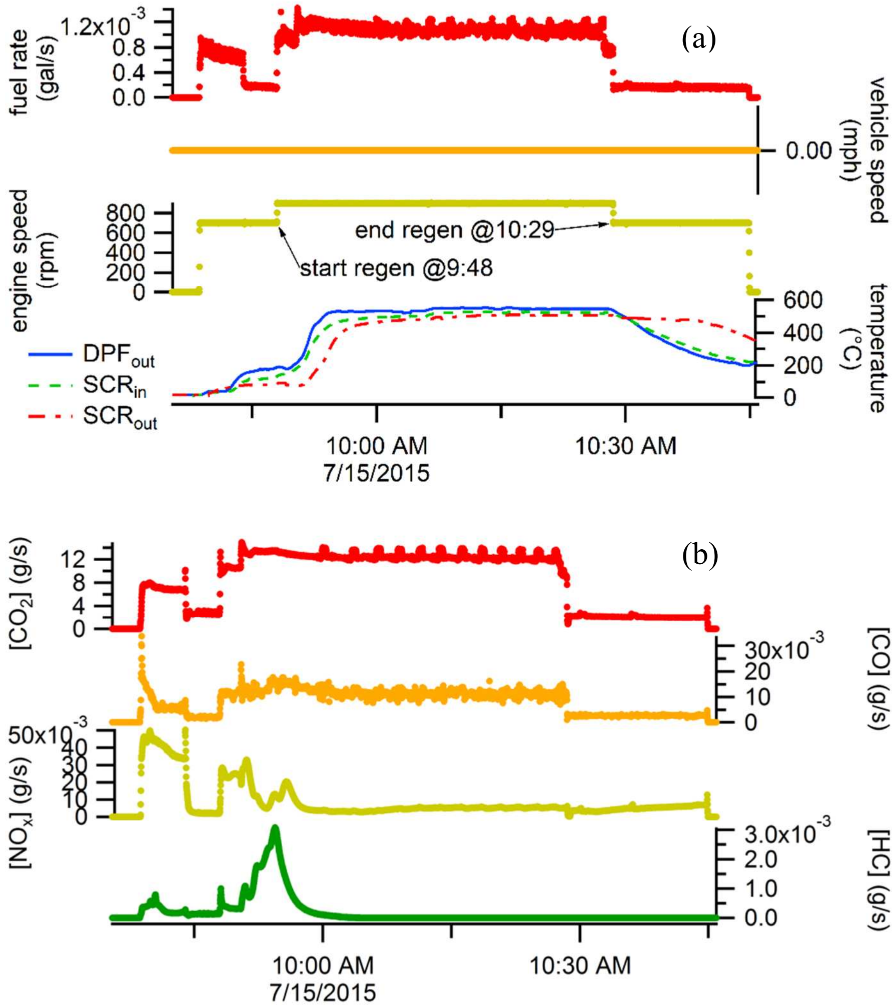


Figure S6. (a) Engine parameters and (b) emissions from a parked regeneration of the DPF from the 2010 HDDV performed on July 15, 2015.

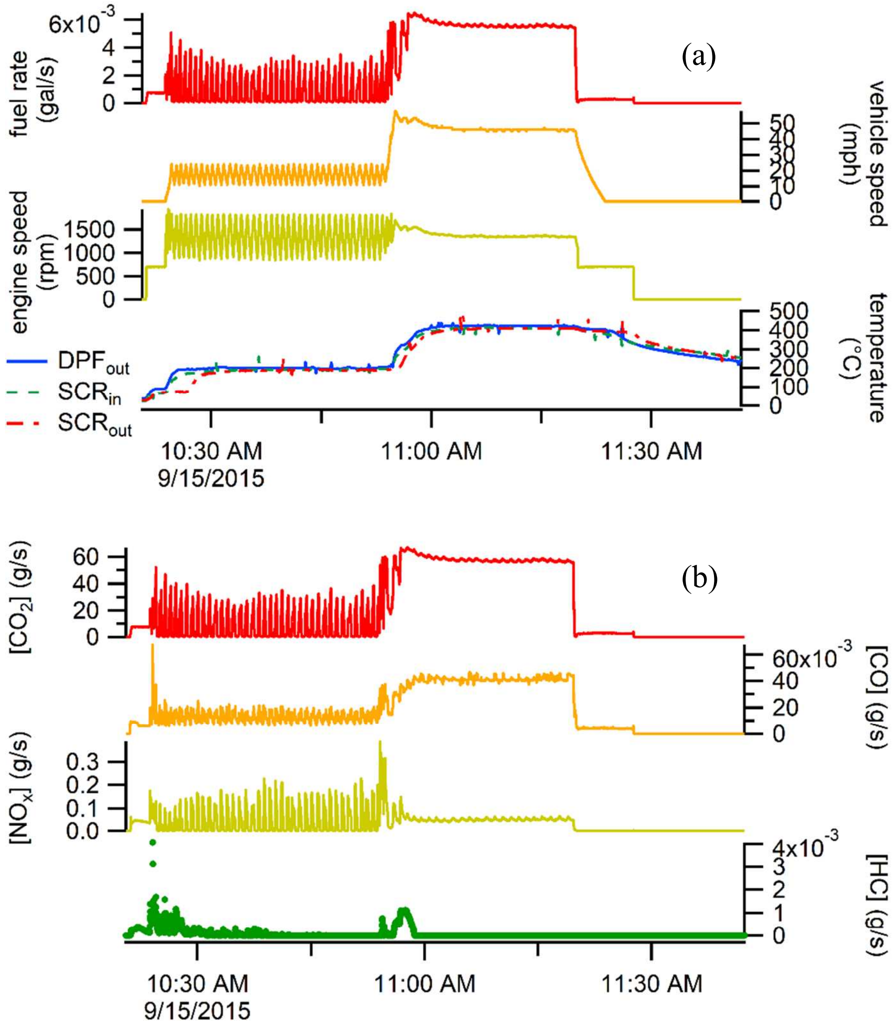


Figure S7. (a) Engine parameters and (b) emissions from a passive regeneration of the DPF from the 2010 HDDV performed on September 15, 2015.

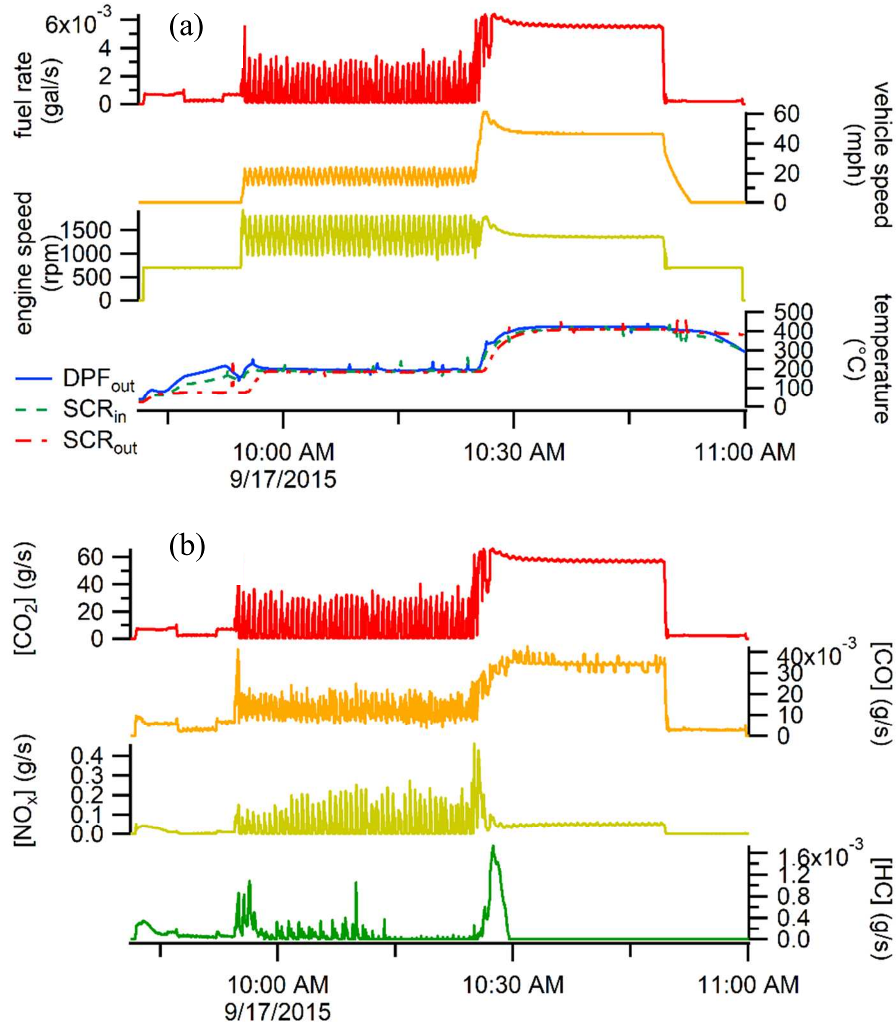
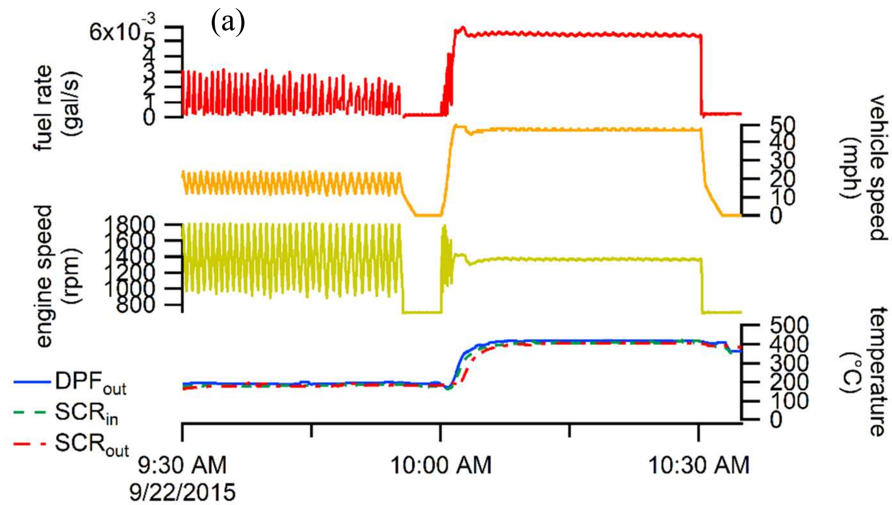


Figure S8. (a) Engine parameters and (b) emissions from a passive regeneration of the DPF from the 2010 HDDV performed on September 17, 2015.



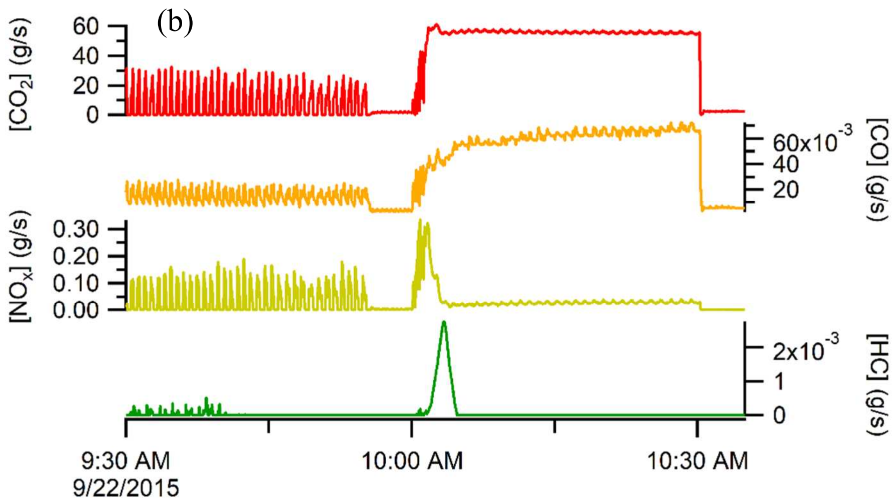


Figure S9. (a) Engine parameters and (b) emissions from a passive regeneration of the DPF from the 2010 HDDV performed on September 22, 2015.

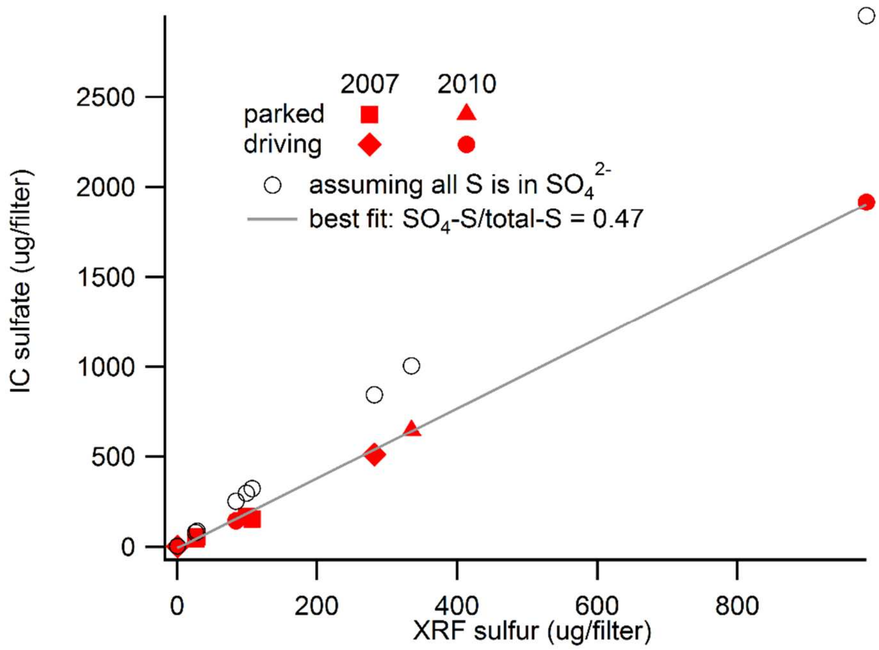


Figure S10. Sulfur detected by IC (as sulfate) vs detected by XRF.

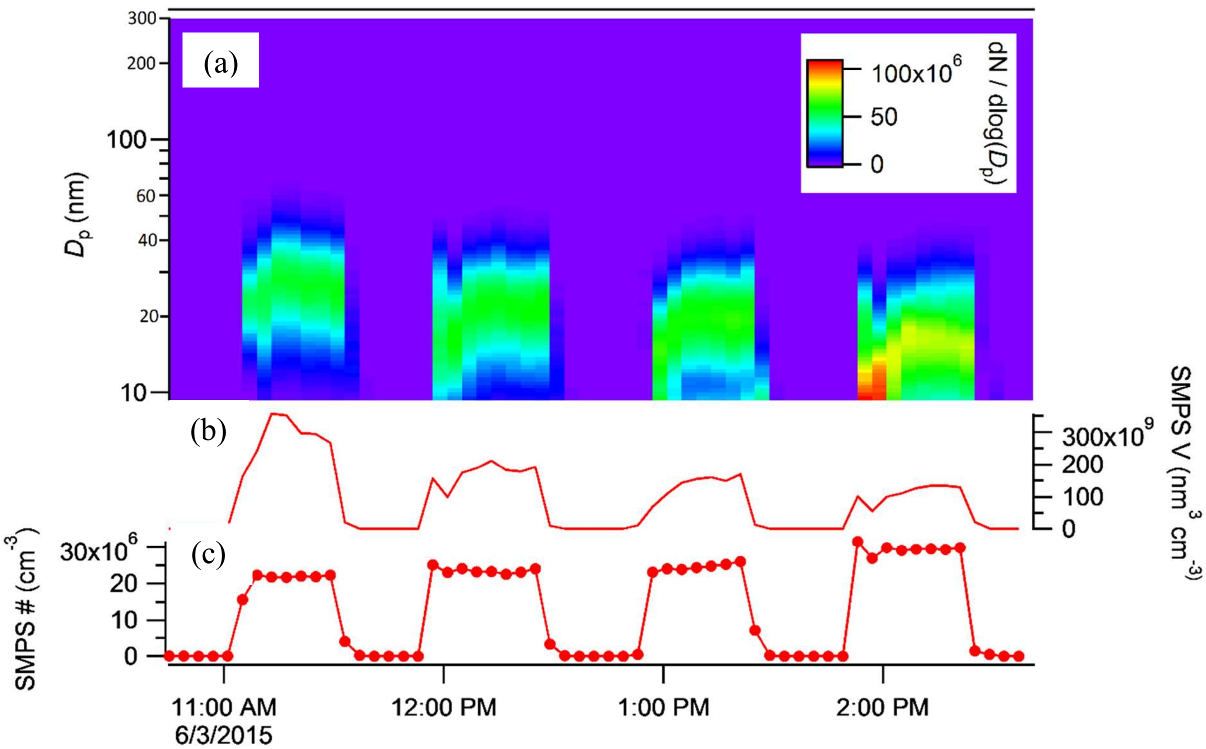


Figure S11. Results from four consecutive forced regenerations of the DPF on the 2007 HDDV. SMPS results are presented as (a) number size distributions, (b) total volume concentration, and (c) total number concentration.

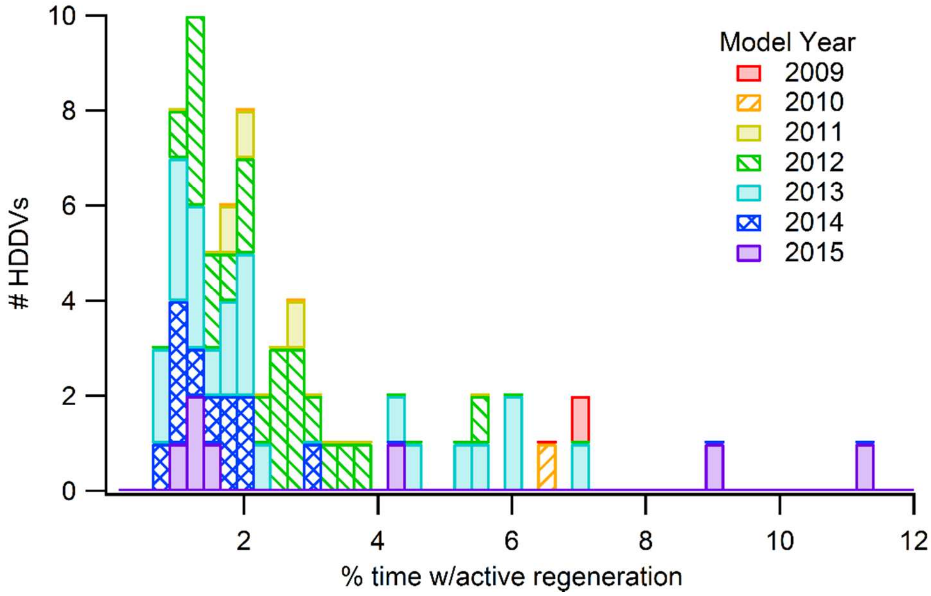


Figure S12. Histogram of the percentage of total running time that real-world vocational HDDVs underwent active DPF regeneration.

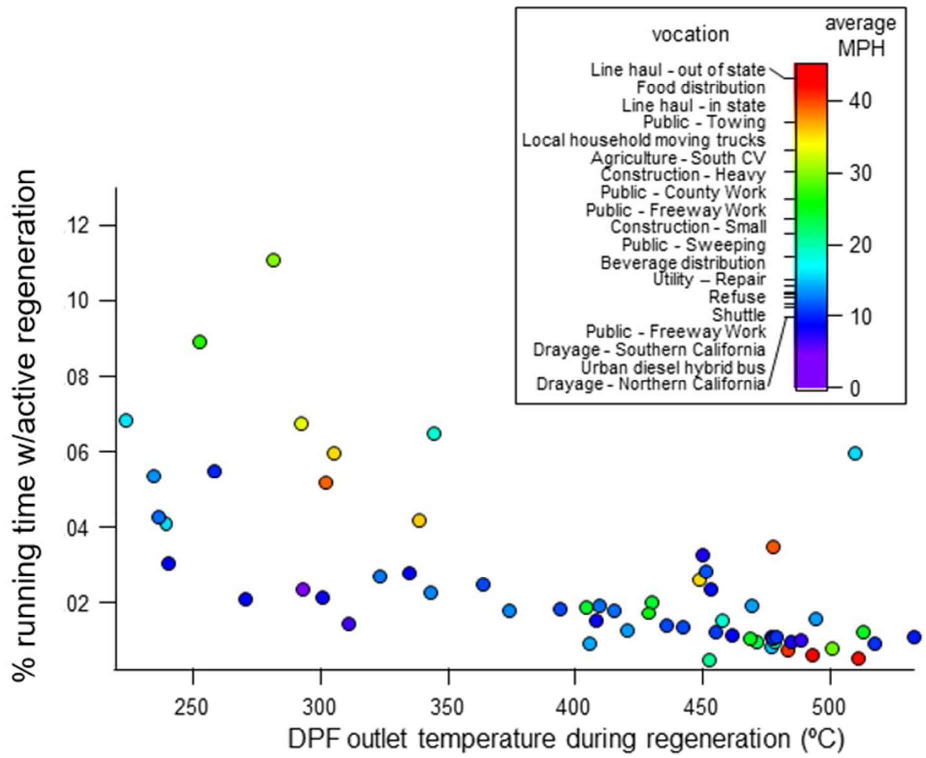


Figure S13. Percent of engine-on time in which active DPF regeneration was occurring vs. average DPF outlet temperature during regeneration.

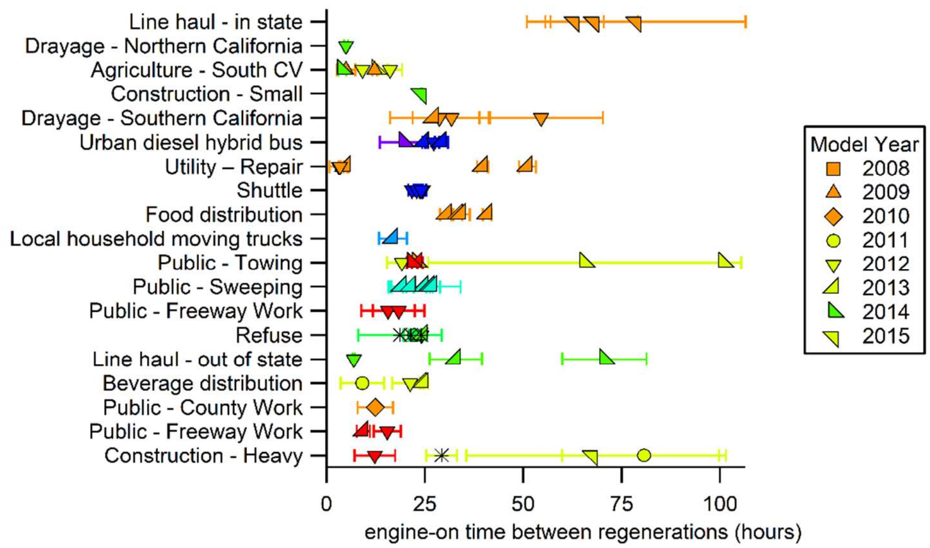


Figure S14. Average engine-on time between DPF regenerations, by HDDV vocation, model year (symbol), and OEM (color).

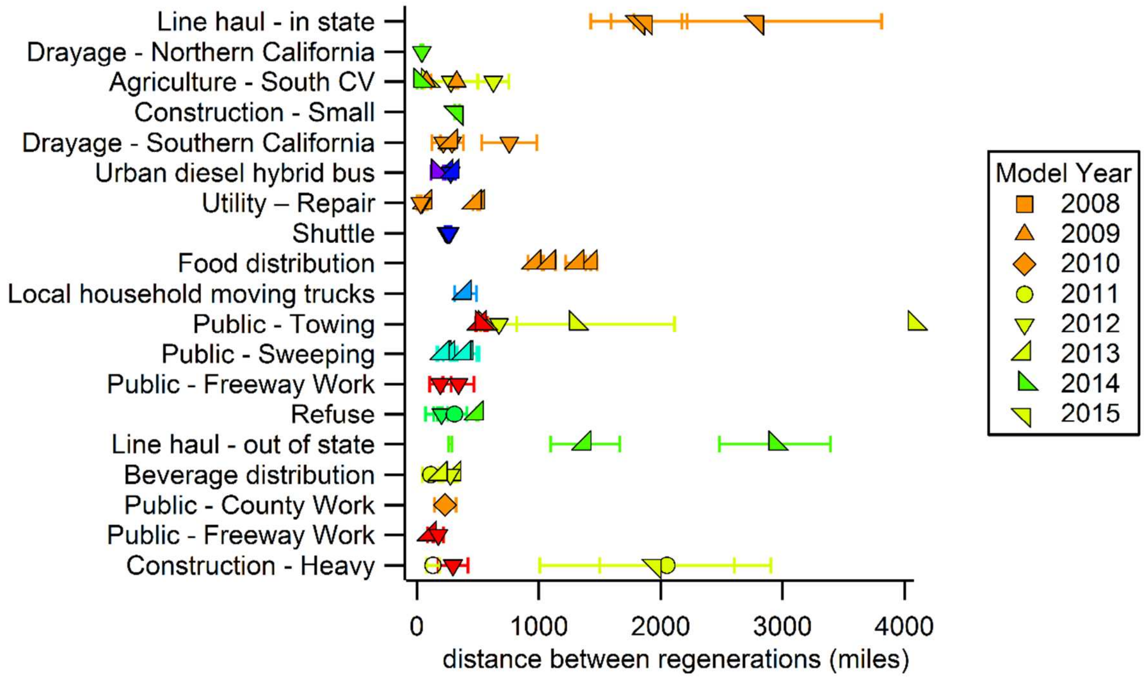


Figure S15. Average distance travelled between DPF regenerations, by HDDV vocation, model year (symbol), and OEM (color).

Table S1. Heavy-Duty Diesel Vehicle Specifications.

	HDDV #1	**HDDV #2**
Engine Model Year	2007	2010
Engine Make	Cummins	Cummins
Engine PM Certification	0.01 g/bhp-hr	0.01 g/bhp-hr
Engine NO_x Certification	1.2 g/bhp-hr	0.25 g/bhp-hr
Engine Displacement (L)	14.9	14.9
Chassis Model Year	2008	2011
Chassis Make	Kenworth	Kenworth
Chassis Model	T800	T800
Odometer reading	391,000	18,000
Aftertreatment Components	DPF + DOC	DPF + DOC + SCR

DPF: Diesel particulate filter; DOC: Diesel oxidation catalyst; SCR: Selective catalytic reduction

Table S2. Summary of active regeneration tests, emissions, and DPF loading conditions.

Test				Emissions								
2015 date	MY	type	LED[a]	PM	OC	EC	BC	SO_4	NH_4	DPF mass lost	Loading distance	Engine-out PM
				g	g	g	g	g	g	g	mi	mg/mi
2/25	2007	parked	flashing	0.72	0.085	0.017	0.003	0.63	0.17	168.4	343.0 [b]	491
3/18	2007	parked	flashing	0.98	0.030	0.049	0.037	0.62	0.16	137.1	250.0 [b]	548
4/23	2007	parked	flashing	5.40	0.158	0.024	0.060	2.89	0.20	136.5	570.2 [c]	239
5/12	2007	road	solid	1.87	0.057	0.016	0.047	0.93	0.08	100.9	381.0 [c]	265
5/29	2007	road	flashing	4.08	0.157	0.023	0.013	2.14	0.15	141.9	595.4 [c]	238
7/15	2010	parked	solid	2.61	0.126	0.056	0.160	1.49	0.20	120.3	525.7 [c]	229
8/5	2010	road	solid	16.33	0.321	0.247	1.249	6.16	0.29	93.6	734.0 [c]	128
8/26	2010	road	solid	9.44		0.218	0.519			87.0	689.0 [c]	126

[a] corresponding to SPN 3701, solid indicates “regeneration needed, lowest level” and flashing indicates “regeneration needed, moderate level”

[b] lower dynamometer tractive force used to ensure no passive regeneration

[c] dynamometer tractive force increased, but internal DPF temperature still kept below 250 °C

Table S3. Emissions and DPF mass lost during active regenerations. This is the same data as in Table S2, but grouped first by Model Year and then by type (parked or driving).

MY	**type**	***n***	**Emissions** PM	OC	EC	BC	SO_4	NH_4	**DPF mass lost**	**Engine -out PM**
			g	g	g	g	g	g	g	mg/mi
2007		5	2.6 ± 1.0[a]	0.10 ± 0.03	0.026 ± 0.007	0.32 ± 0.01	1.4 ± 0.5	0.15 ± 0.02	137 ± 12	356 ± 75
2010		3	9.5 ± 4.8	0.22 ± 0.14	0.17 ± 0.07	0.64 ± 0.39	3.8 ± 3.3	0.24 ± 0.06	110 ± 13	161 ± 42
	parked	4	2.4 ± 1.2	0.10 ± 0.03	0.036 ± 0.011	0.065 ± 0.039	1.4 ± 0.6	0.18 ± 0.01	141 ± 12	377 ± 96
	driving	4	7.9 ± 3.7	0.18 ± 0.09	0.13 ± 0.07	0.46 ± 0.33	3.1 ± 1.9	0.17 ± 0.07	106 ± 14	189 ± 42

[a] quoted uncertainty is the standard error

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(1) Dwyer, H.; Yoon, S.; Quiros, D.; Burnitzki, M.; Riemersma, R.; Chernich, D.; Collins, J.; Herner, J. Ambient Emission Measurements from Parked Regenerations of 2007 and 2010 Diesel Particulate Filters. *SAE Technical Paper* **2014**-01-2353.

(2) Quiros, D. C.; Yoon, S.; Dwyer, H. A.; Collins, J. F.; Zhu Y.; Huai T. Measuring particulate matter emissions during parked active diesel particulate filter regeneration of heavy-duty diesel trucks. *J. Aerosol Sci.* **2014,** *73*, 48-62.

(3) Yoon, S.; Quiros, D. C.; Dwyer, H. A.; Collins, J. F.; Burnitzki, M.; Chernich, D.; Herner, J. D. Characteristics of particle number and mass emissions during heavy-duty diesel truck parked active DPF regeneration in an ambient air dilution tunnel. *Atmos. Environ.* **2015**, *122*, 58-64.