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Emissions of PCDD/Fs, PCBs, and PAHs from a Modern Diesel Engine Equipped with Catalyzed Emission Control Systems

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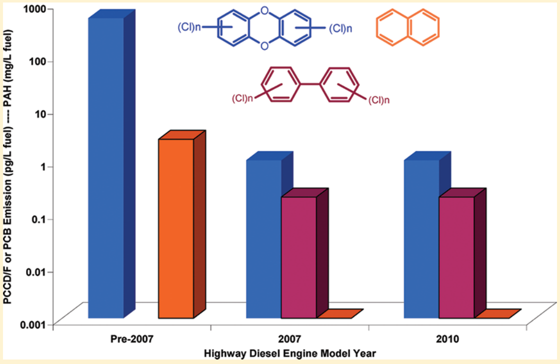
Supporting Information

ABSTRACT: Exhaust emissions of 17 2,3,7,8-substituted chlorinated dibenzo-*p*-dioxin/furan (CDD/F) congeners, tetra−octa CDD/F homologues, 12 2005 WHO chlorinated biphenyls (CB) congeners, mono−nona CB homologues, and 19 polycyclic aromatic hydrocarbons (PAHs) from a model year 2008 Cummins ISB engine were investigated. Testing included configurations composed of different combinations of aftertreatment including a diesel oxidation catalyst (DOC), catalyzed diesel particulate filter (CDPF), copper zeolite urea selective catalytic reduction (SCR), iron zeolite SCR, and ammonia slip catalyst. Results were compared to a baseline engine out configuration. Testing included the use of fuel that contained the maximum expected chlorine (Cl) concentration of U.S. highway diesel fuel and a Cl level 1.5 orders of magnitude above. Results indicate there is no risk for an increase in polychlorinated dibenzo-*p*-dioxin/furan and polychlorinated biphenyl emissions from modern diesel engines with catalyzed aftertreatment when compared to engine out emissions for configurations tested in this program. These results, along with PAH results, compare well with similar results from modern diesel engines in the literature. The results further indicate that polychlorinated dibenzo-*p*-dioxin/furan emissions from modern diesel engines both with and without aftertreatment are below historical values reported in the literature as well as the current inventory value.



INTRODUCTION

Recent changes in the emission standards for oxides of nitrogen (NO_x) and particulate matter (PM) from both highway and nonroad diesel engines have for the first time lead to the widespread use of aftertreatment systems to control the emissions from these engines. Engine manufacturers have employed the use of diesel oxidation catalysts (DOC), catalyzed diesel particulate filters (CDPF), and urea selective catalytic reduction (SCR) to meet these new emission standards.[1−3]

A limited number of dynamometer and tunnel studies have been performed on polychlorinated dibenzo-*p*-dioxin/furan (PCDD/F) emissions from diesel engines generating a wide range of emission results.[4−11] Diesel engines have been generally known to be emitters of hydrocarbons, which include polycyclic aromatic hydrocarbons (PAHs), nitro-polycyclic aromatic hydrocarbons, and PM with a significant fraction of elemental carbon.[12,13] The presence of these pollutants in combination with the availability of chlorine (Cl) primarily from the fuel may drive the formation of PCDD/Fs via either the precursor or de novo synthesis routes.[14] The current inventory value used by the United States Environmental Protection Agency (U.S. EPA) to approximate the PCDD/F emissions from diesel engines is 172 pg international toxic equivalency (I-TEQ)/km or approximately 946 pg I-TEQ/L fuel consumed when using a fuel economy factor of 5.5 km/L.[15,16]

Studies have shown that the use of DOCs and CDPFs for PM control have led to a greater than 90% decrease in hydrocarbons, specifically PAHs.[17] Recently, concern over the potential for increased PCDD/F formation in the catalyst systems of diesel engines was raised due to the introduction of copper zeolite (CuZ) urea SCR for NO_x control. At the time this study commenced, a comprehensive study of the emissions of PCDD/Fs and PCBs from these systems had not been performed. Recently, the results of two test programs similar in nature to the one described here for PCDD/F emissions have been published.[18,19]

Both reactor bench studies and studies involving municipal waste incinerators (MWIs) have shown that dioxin formation increases in the presence of copper (Cu).[20,21] Studies by Mayer and Heeb, et al. showed that the use of Cu fuel additives in the presence of high fuel Cl levels (up to 110 ppm) with an uncatalyzed diesel particulate filter (DPF) increased PCDD/F emission rates by up to 4 orders of magnitude.[22,23] Additional studies on MWIs, equipped with urea SCR utilizing V_2O_5 catalysts to reduce NO_x emissions, have shown that the presence of urea can reduce dioxin emission rates by up to 99.5%.[24,25]

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Based on the lack of data regarding the effect of CuZ urea SCR on PCDD/F emissions, the U.S. EPA initiated a test program to determine the effects of modern diesel engines and their catalyst systems on PCDD/F, PCB, and PAH emissions.

The objectives of this program were to (i) determine the 17 2,3,7,8-substituted congener and tetra−octa homologue CCD/F profiles including I-TEQ, the 12 2005 WHO congener and mono−nona homologue CB profiles including TEQ, and 19 PAH emissions from a modern diesel engine utilizing various catalyst configurations representing baseline, model year 2008, and various model year 2010 configurations, and (ii) determine whether the use of CuZ urea SCR poses a risk for increased PCDD/F formation when compared to the baseline.

EXPERIMENTAL METHODS

Test Configuration. Testing was performed at the U.S. EPA National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, MI using a Schenck AC dynamometer and STARS control system. The engine used to generate exhaust gas was a 280 hp, turbocharged, 2008 MY 6.7 L Cummins ISB equipped with electronically controlled high pressure common rail fuel injection, high pressure loop EGR, and a DOC/CDPF for PM control. The SCR urea dosing control system was designed by our lab to represent a production type urea dosing system and was active if noted in the test configuration description. The CDPF was active at all times when present and was passively regenerated.

To determine a maximum Cl content for the test fuel used in the program, a fuel survey was conducted of 20 ultralow sulfur (<15 ppm sulfur) pump diesel fuels from across the United States. Fuel was analyzed using Neutron Activation Analysis (NAA) by North Carolina State University's Department of Nuclear Engineering. Samples were irradiated for 180 s at 1 MW, followed by transfer to clean vials where they were decayed for 5 min and then counted for 10 min via gamma spectroscopy. The survey results ranged from 139 to 533 ppb Cl and averaged 150 ppb. Cummins Premium Blue CJ-4 lube oil and NALCO Stableguard 32.5% wt. urea solution in H_2O were also analyzed for Cl and Cu. The CJ-4 oil contained 96.3 ppm Cl and Cu was below the detection limit. The urea solution was found to contain 267 ppb Cl and 730 ppb of Cu. We chose to operate the engine on a fuel with a target Cl content of 600 ppb. The fuel was doped with 1-chlorohexadecane, chosen for its carbon chain length when compared to that of diesel fuel, and averaged 588 ppb Cl. Since Mayer and Heeb, et al. showed that increasing fuel Cl can lead to increases in PCDD/F emissions;[22,23] we doped the fuel to 10.3 ppm Cl to determine the sensitivity of CuZ urea SCR systems to Cl level. The test fuel properties can be found in Table S1 of the Supporting Information (SI).

The remaining possible source of Cl during combustion is the intake air. A survey of the Cl content of our intake air was not performed. Dyke, et al. showed that ambient Cl levels in their test facility were on the order of 0.35−2.5 ppb, averaging 1 ppb,[26] whereas Liu, et al. was below 2.4 ppb (below the detection limit using NIOSH method 6011).[19] Using Dyke's numbers as a worst case, assuming an average air-to-fuel ratio (AFR) of 20:1, the maximum Cl contribution to the combustion process expected from ambient air would be 50 ppb. Based on our fuel survey and the fuel Cl level that we chose to perform the majority of our testing at, we believe that we have adequately accounted for the worst case Cl contribution from ambient air, as well as fuel.

Steady-state testing was performed at 2275 rpm and engine power was adjusted as necessary from configuration to configuration to maintain a target exhaust gas or catalyst temperature. An overview of the conditions can be found in Table 1. The temperatures chosen have been shown to be the optimum temperature for PCDD/F formation over fly ash for Cu and Fe.[20] Steady-state tests that included CuZ and FeZ SCR catalysts were run without urea injection to worst case PCDD/F emissions. Transient testing was performed over the Heavy-Duty Diesel Engine Federal Test Procedure (HDDE-FTP) and a profile of engine speed, torque, and SCR catalyst temperature can be found in Figure S1 of the SI. A baseline engine out test was not run for the transient test cycle because the steady-state baseline run indicated that PCDD/F emissions were very low, at or near detection limits. For the transient testing performed here, 2 cold start and 46 hot start HDDE-FTPs were run for each sample taken affording a 1:23 ratio of cold to hot start tests.

SCR and ammonia slip catalysts (ASC) were supplied by Manufacturer of Emission Controls Association (MECA) member companies. The DOC and CDPF used were supplied with the engine. A description of the catalyst properties can be found in Table S2 of the SI.

During testing over steady-state cycles where a CDPF was not used, samples were taken from a constant-mass-flow dilution system using annular dilution to prevent rapid overloading of the sample train PM filter.[27] For all transient cycle tests and for all steady-state testing utilizing a CDPF, the exhaust was sampled directly from the exhaust system.

Sampling Procedure. PCDD/F, PCB, and PAH emissions were collected using a sampling system based on EPA method 23A.[28] A functional schematic of the sampling system can be found in Figure S2 of the SI. The system differs from Method 23A in that it uses a larger sorbent module design similar to that used by Method 20 to allow up to 50 g of XAD-2 resin; as well as a titanium (Ti) sample probe, filter holder, and condenser along with a nickel (Ni) sample module per EN 1948-1.[29,30] The larger sorbent module permits a higher sampled exhaust volume to ensure that there is no breakthrough due to the potential for high hydrocarbon concentrations. Ti and Ni sample train components were chosen for their durability and inertness toward catalyzation of PCDD/F formation. All joints were sealed with Teflon gaskets. A peristaltic pump was utilized to collect condensate from the water trap.

Samples were taken from the center of the dilution tunnel or exhaust pipe. Proportional sampling was maintained for both transient and steady-state testing, according to 40 CFR part 1065.545.[31] Exhaust flow was calculated from the intake air and fuel flow measurement. Sample flow was calculated by taking the difference between the total flow through the sampler and makeup flow, taking into account the water that condensed and was removed from the sample flow when passing through the condenser. The sampler total flow was controlled with a positive displacement pump while the makeup flow was measured with a laminar flow element and controlled using a proportional valve. Each test required 16 h of sampling.

Particulate Matter was collected onto a 110 mm Pall Tissuquartz filter (7 mil thickness) supported by a perforated titanium disk. Filters were precleaned via Soxhlet extraction with methylene chloride for 24 h and dried over dry nitrogen. The sample probe and filter holder maintained a temperature of 191 °C over the test. The inlet and outlet cones were sealed with a Ti gasket. Non-CDPF tests required multiple filter changes (up to 45) to

Table 1. Catalyst Configuration as it Relates to Test Cycle, Engine Power, Exhaust Temperature, and Fuel Cl Level

	catalysts									
test configuration	DOC/ CDPF	CuZ	FeZ	ASC	urea injection	test cycle	engine power (Hp)	exhaust temperature (°C)	exhaust dilution	target fuel Cl level (ppm)
SS engine out						steady-state	130	300	√	0.6
SS CuZ SCR HT		√				steady-state	125	320	√	0.6
SS CuZ SCR LT		√				steady-state	105	300	√	0.6
SS FeZ SCR			√			steady-state	130	350	√	0.6
SS DOC+CDPF	√					steady-state	130	300		0.6
T DOC+CDPF+CuZ SCR+ASC+urea	√	√		√	√	HDDE-FTP	variable	250 - 350		0.6
T DOC+CDPF+FeZ SCR+ASC+urea	√		√	√	√	HDDE-FTP	variable	250 - 350		0.6
T DOC+CDPF	√					HDDE-FTP	variable	250 - 350		0.6
T DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	√	√		√	√	HDDE-FTP	variable	250 - 350		10.0

prevent loss of sample flow due to an increase in back pressure (60 kPa limit) from the PM collected.

Gaseous phase PCDD/Fs, PCBs, and PAHs were collected on 40−50 g of XAD-2 located in between 3 in. diameter polyurethane foam (PUF) plugs. A perforated Teflon disk held the downstream PUF plug in place. The module was located downstream of the condenser and both were submersed in a water bath controlled to achieve a sample gas temperature of 5 ± 1 °C at the module outlet. A leak check was performed between the inlet of the sample probe and the outlet of the sample flow control hardware before each test. The target sample flow rate through the module was 200 slpm for the steady-state tests and 1.35% of the exhaust flow for transient testing, averaging 70 slpm. Target total sample volumes were 192 m^3 for the steady-state and 65 m^3 for transient tests. These volumes represent a 64 and 21 fold increase in total sample volume targeted by Method 23A.

Sample Preparation and Analysis. All sample preparation and analysis were carried out by Analytical Perspectives, Inc. (Wilmington, NC), an NELAC accredited lab. PUF and XAD-2 were cleaned via a series of Soxhlet extractions: 8 h water, 22 h methanol, 22 h methylene chloride, and 22 h toluene followed by drying over nitrogen. Sample preparation was carried out according to an enhanced version of EPA method 8290a, taking into consideration ARB methods 428 and 429, and has been previously described.[32−35] Briefly, the sample train wetted surfaces were rinsed with acetone followed by toluene post test. The volumes were reduced as needed using a Kuderna-Danish concentrator and added to the extraction solvents before extraction was initiated. To accommodate the Soxhlet extractions of PCDD/Fs, PCBs, and PAHs from a single sample, two 16 h extractions were employed; the first using hexane and the second using toluene. For all tests that incorporated the use of a DOC+ CDPF, the PUF, XAD-2, rinse, and PM filter were extracted together. For all other tests, due to the number of PM filters used over the 16 h test (up to 45), the PM filters were extracted and analyzed in a single batch, separate from the PUF and XAD-2. The results were then combined with the results from PUF/ XAD-2/rinse and reported as a single value for each congener. A description of the process can be found in the SI.

Isotopic dilution was used throughout the test program, including the use of isotopically labeled surrogate, internal, alternate, and recovery standards. The isotopic standards were obtained from Cambridge Isotope Laboratories (Andover, MS) and a list can be found in Tables S4, S5, and S6 of the SI. Surrogate standard recoveries were typically in the 70−130% range and support work by Ryan, et al. that showed higher sample volumes can be attained without affecting sample recovery.[10]

For this testing total tetra−octa CDD/F homologue and mono−nona CB homologue plus PCB-209 totals were measured. Seventeen individual 2,3,7,8-substituted CDD/F congeners were measured to determine I-TEQ. Twelve individual PCB congeners that are considered to be "dioxin-like", referring both to their toxicity and structural features which make them similar to 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), were measured to determine WHO 2005 TEQ. These "dioxin-like" PCB congeners have 4−7 Cl substituents; with both para, 2 or more meta, and up to 1 of the ortho positions chlorinated. The 19 PAHs measured were a subset of urban hazardous air pollutants (HAPs) incorporating six of seven PAHs that EPA has designated as mobile source air toxics. These seven PAHs are benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, chrysene, indeno(1,2,3-cd)pyrene), and 7,12-dimethylbenz(a)anthracene (not measured).[36]

The analytical protocols and quality control methodology, including the use of batch control spikes and method blanks, for the analysis of PCDD/Fs have been previously described by Tondeur, et al.[37] Those used for PCB and PAH analyses are similar to the PCDD/Fs with the following exceptions: PCB analysis utilized an SPB-Octyl GC column and the temperature profile used was a variation of EPA method 1668b,[38] and the PAH analysis utilized a temperature profile that was a variation of ARB method 429.[34] Detection limits were determined based on considerations laid out by Keith[39] and have been described by Liu.[19]

Field and media blanks were taken throughout the testing to determine the contribution of the media and environment to the actual test results. A single media blank consisting of PM filter/PUF/ XAD-2 was analyzed for every five tests, whereas a field blank accompanied each test module and was analyzed to determine the effects on the module from environmental exposure.

For tests where a CDPF was not in the exhaust system, dilution tunnel blanks were run to determine the contributions to the test results from dilution air and the interaction of the diluted exhaust with

Table 2. Sampling and Engine Operation Data for All Test Configurations

test configuration	number of valid repeats PCDD/Fs	number of valid repeats PCBs and PAHs	average total engine work (hp-hr)	average brake-specific fuel consumption (L/hp-hr)	average sampler total volume (m^3)	average total CVS volume (m^3)	average total exhaust volume (m^3)
SS Engine Out	14	17	2123	0.199	172	49 152	12 033
SS CuZ SCR HT	9	9	1927	0.199	137	46 782	9339
SS CuZ SCR LT	5	5	1806	0.205	192	51 766	8500
SS FeZ SCR	5	5	2150	0.200	192	51 863	10 516
SS DOC+CDPF	5	5	2285	0.203	192	n/a	9429
T DOC+CDPF+CuZ SCR+ASC+urea	5	5	883	0.223	67	n/a	4873
T DOC+CDPF+FeZ SCR+ASC+urea	5	5	884	0.224	65	n/a	4822
T DOC+CDPF	5	5	883	0.226	67	n/a	4883
T DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	5	5	881	0.226	66	n/a	4854

the dilution tunnel walls. No corrections were made for media or environmental contributions, including dilution air, to the test results.

RESULTS AND DISCUSSION

The sampling and engine operation data can be found in Table 2. The information provided is averaged across all of the test runs for a given test configuration. Emission results for a selection of test configurations for NO_x, HC, CO, and PM are presented in Table S3 of the SI. The results indicate that modern diesel emission control technology is very effective at significantly reducing NO_x, HC, CO, and PM emissions, showing greater than 90% reduction with the PM emissions approaching zero.

Replicate testing was performed to assess measurement variability. In one instance, three of the SS Engine Out results for PCDD/Fs were deemed outliers at the upper 0.1% significance level utilizing a one-sided *t* test when the standard deviation is calculated from the same sample, as described in ASTM E178-08.[40] The outlier values were 254.7, 43.0, and 9.7 pg I-TEQ/hp-hr, where nondetect equals zero (ND = 0)). The reason for these outliers cannot be confirmed, but we believe that it may be due to sample contamination as the 2,3,7,8-substituted CCD/F congener and tetra−octa CCD/F homologue profiles are dominated by furans in these tests at levels which are not seen in any of the other SS Engine Out tests.

For the results presented here, any estimated maximum possible concentrations (EMPC) are reported in the results. EMPC is used for a result where a peak is detected that does not meet all of the criteria for qualitative determination of the congener (most commonly the ion abundance ratio outside the allowed theoretical range of ±15%). The reported EMPC concentration represents an upper bound on the congener concentration.

PCDD/Fs. PCDD/F emission factor data in pg I-TEQ/L fuel consumed for all configurations tested are shown with the 95% confidence interval (student *t* test assuming a normal distribution) in Figure 1. Additionally, the average emission results and detection limits with standard deviation for all 2,3,7,8-substitued CCD/F congeners and tetra−octa substituted CCD/F homologues, along with I-TEQ emissions can be found in Tables S8−S12 in the SI.

A review of the I-TEQ results across all steady-state configurations tested indicate that the results are not statistically significant where ND = 0, but a significant difference is observed when comparing the SS Engine Out and SS DOC+CDPF results where nondetect equals detection limit (ND = DL). It should be noted that the detection limit, which can be influenced by many factors, varied from about 0.1 to 9 pg/L fuel consumed for the varying 2,3,7,8-substituted CCD/F congeners and this uncertainty may be just as likely accountable for the apparent reduction in I-TEQ as the oxidative function of the DOC+CDPF. This may also account for the statistically significant higher I-TEQ for the SS CuZ SCR HT and LT results when compared to SS Engine Out and SS DOC+CDPF. For 2,3,7,8-substituted CDD/F congeners, 1,2,3,4,6,7,8-HpCDD, OCDD, and furan emissions are driving the reported I-TEQ for ND=0, with almost all of the emissions just above the detections limit (OCDD being the exception). The tetra−octa CDD/F homologue totals are comparable within a level of chlorination and are dominated by tetra and penta CDF homologues.

The results for the transient configurations tested are similar to those for the steady-state configurations, indicating that the transient results are not statistically significant where ND = 0. A statistically significant difference is observed when comparing T DOC+CDPF+CuZ+ASC+urea with a fuel Cl content of 0.6 ppm to a fuel Cl content of 10 ppm where ND = DL. Again, here we believe that this difference is due to the variability associated with the detection limit. For the 2,3,7,8-substituted CDD/F congeners; 1,2,3,4,6,7,8-HpCDD, OCDD, 2,3,4,7,8-PeCDF, and 1,2,3,4,6,7,8-HpCDF emissions are driving the reported I-TEQ for ND = 0, with all but the OCDD emissions at just above the detection limit. The tetra−octa CDD/F homologue totals are comparable within a level of chlorination with the exception of the DOC+CDPF+CuZ+ASC+urea, which exhibited higher emissions of tetra−octa CDD/Fs in almost every class, and are dominated by tetra and penta CDF homologues.

When comparing I-TEQ results across all of the configurations tested, even with the statistical significance across some of the results, the results are all well within the same range. Further, emission patterns of 2,3,7,8-substituted CDD/F congeners are comparable across the range.

Historically, PCDD/F emission factor data availability is limited. However, some studies have been done and have produced the following emission factors: 70 − 80 pg I-TEQ/L fuel consumed from diesel truck engines in Germany,[4] 10 pg I-TEQ/L fuel

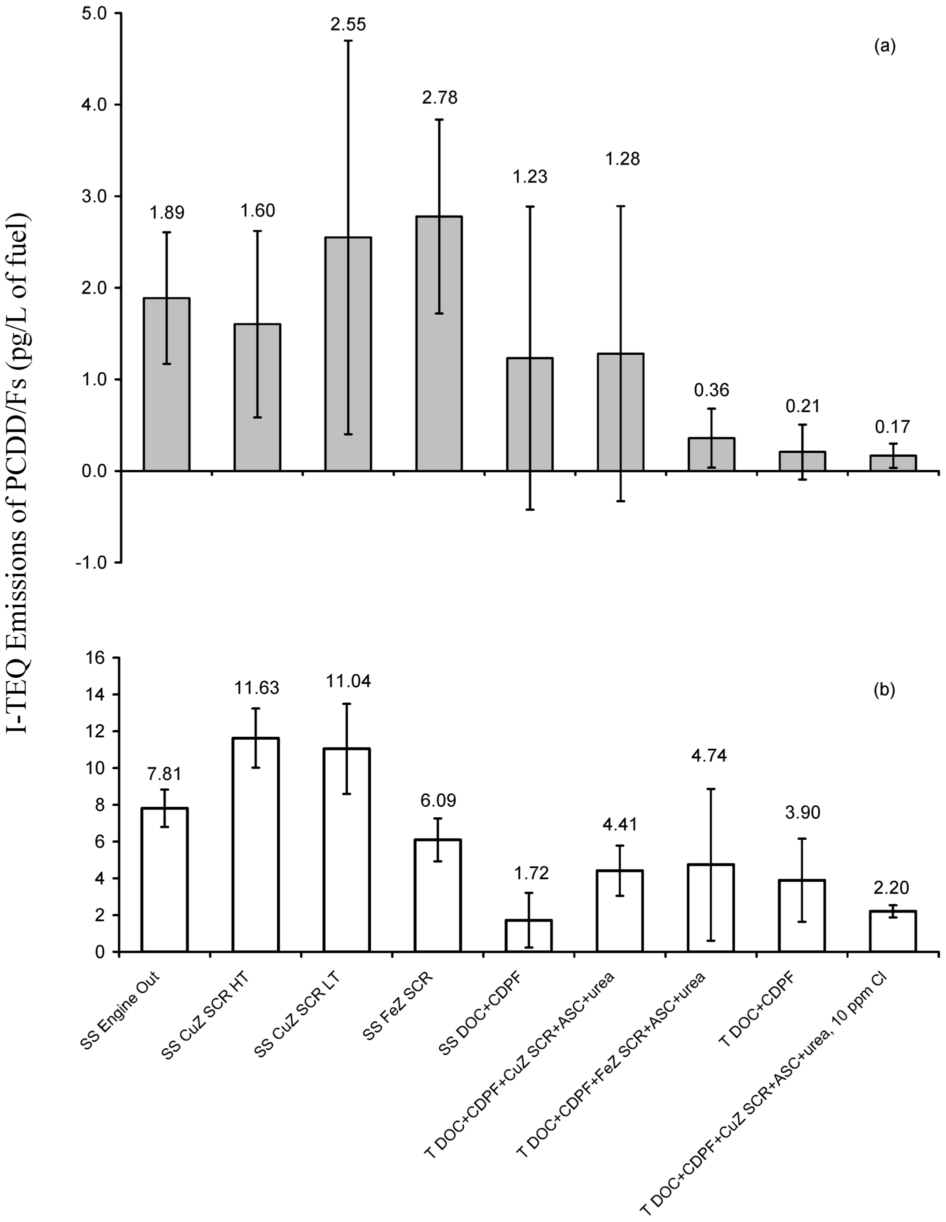

Figure 1. Average PCDD/F I-TEQ emission values with ±95% C.I. ND = 0, EMPC = EMPC (a) and ND = DL, EMPC = EMPC (b) for all of the configurations tested.

consumed from diesel bus plume emissions,[5] 77 pg I-TEQ/L fuel consumed from a load carrying diesel engine,[6] 52 000 pg Nordic TEQ/L fuel consumed on the up hill portion and 3960 pg Nordic TEQ/L fuel consumed on the down hill portion of a Nordic tunnel study (assuming 5.5 km/L fuel economy),[7] 65 pg I-TEQ/L fuel consumed from a tunnel study in Antwerp Belgium,[8] 946 ± 400 pg I-TEQ/L fuel consumed from a tunnel study in Baltimore, MD (assuming 5.5 km/L fuel economy) which is the inventory value for highway diesel trucks in the United States,[15,16] 160 pg I-TEQ/L fuel consumed with an upper limit of 583 pg I-TEQ/L fuel consumed (assuming 5.5 km/L fuel economy) from an on-road study,[10] and 127 ± 121 pg I-TEQ/L fuel consumed for a high mileage engine, 44 ± 11 pg I-TEQ/L fuel consumed for a newly rebuilt engine, and 88 ± 72 pg I-TEQ/L fuel consumed for a newly rebuilt engine operating on low sulfur diesel fuel (assuming 5.5 km/L fuel economy) during an on-road study.[11]

More recently, Liu et al. and Hovemann et al. published results for a modern diesel engines equipped with emission control system configurations similar to those tested in this program. For results reported by Liu et al., for ND = 0, engine out emissions were 0.31 pg WHO 1998 TEQ/hp-hr, 0.13 pg WHO 1998 TEQ/hp-hr for DOC+CDPF, and 0.12 pg WHO 1998 TEQ/hp-hr for DOC+CDPF+CuZ SCR+urea for steady-state engine operation. The results also indicated that fuel doped to 8.4 ppm Cl did not yield an increase in PCDD/F formation.[19] Results reported by Hovemann et al. for ND = 0 showed emission factors of 0.11 pg/m^3 over steady-state operation for SCR temperatures ranging from 200 to 450 °C and 0.10 pg/m^3 over transient operation for DOC+CuZ+urea.[18]

When considering the literature, the results from this test program for configurations that represent 2007 (T DOC+CDPF) and 2010 (T DOC+CDPF+CuZ+ASC+urea) era emission control systems are at 0.21 pg I-TEQ/L fuel consumed with the upper limit of the 95% confidence interval at 0.51 pg I-TEQ/L fuel consumed (0.05 ± 0.07 pg I-TEQ/hp-hr, 0.01 ± 0.01 pg I-TEQ/m^3) and 1.28 pg I-TEQ/L fuel consumed with the upper limit of the 95% confidence interval at 2.89 pg I-TEQ/L fuel consumed (0.29 ± 0.36 pg I-TEQ/hp-hr, 0.05 ± 0.06 pg I-TEQ/m^3), respectively (ND =0) and are 1−4 orders of magnitude below the historic and inventory values at the upper limit, even with ND = DL. This suggests that for a modern diesel engine, both with and without catalytic exhaust treatment, PCDD/F emissions are near zero levels.

One remaining question is whether or not 2007 and 2010 type emission control systems have a positive or negative influence on PCDD/F emissions from heavy-duty diesel engines. For the results presented here, 2,3,7,8 substituted CCD/F congeners reported as detects are just above the detection limit making a direct homologue or I-TEQ comparison among the different test configurations difficult. Where the tetra−octa CDD/F homologue groups are above the detection limits, the emission levels are still very low and the associated uncertainty again make comparison difficult. For reported I-TEQ results where ND = DL, in all configurations except SS DOC+CDPF, the detection limits contribute to greater than 50% of the final I-TEQ value with the detection limit variability driving the uncertainty in comparison of these I-TEQ values.

In results from Liu et al., detects indicated a reduction in 1,2,3,4,6,7,8-HpCDD, OCDD, 2,3,7,8-TCDF, and 1998 WHO TEQ on the order of 50% when comparing the engine out to DOC+CDPF+CuZ+urea configurations and showed an average decrease of 60% across all tetra−octa CDD/F homologues.[19] Results from Hovemann et al. only give composite I-TEQ results and these results do not show a discernible pattern of increasing or decreasing I-TEQ for any of the configurations tested.[18]

Based on Liu's results, we conclude that it may be possible to discern the differences in PCDD/F emissions from engines equipped with modern diesel emission control systems, however as our work and that of Hovemann et al. have shown, the emissions of PCDD/Fs from these modern engines are so low that making an accurate comparison of different test configurations is difficult, even with today's ultra trace analytical techniques.

The results indicate that the heterogeneous processes of de novo and precursor formation of PCDD/Fs, if occurring, are minimal. Further, the addition of Cu into the exhaust stream as a flow through exhaust aftertreatment does not appear to have an effect on PCDD/F formation, indicating that the conditions as they exist are not optimal for formation, even in the presence of elevated Cl levels. This could be due to lack of precursor availability, residence time over the catalyst, or the availability of Cu sites in the catalyst matrix. Further, the addition of the DOC +CDPF+ASC+urea to the CuZ catalyst should work to further reduce PCDD/Fs. As evident from the PAH results discussed later in this paper, catalysts utilizing platinum group metals are highly effective at facilitating the chemical mechanisms of oxidation, hydrogenolysis, and thermal decomposition; eliminating >90% of hydrocarbons from the exhaust stream. The presence of urea decomposition products has been shown to reduce PCDD/F formation in MWIs by chemically altering precursors to benzonitriles, benzylamines, and pyridines.[41] Based on the presence of these components starting in 2007 (DOC+CDPF) and 2010 (DOC+CDPF+urea), we would expect the amount of any PCDD/F emitted from the engine to decrease, even in the presence of a CuZ SCR catalyst.

PCBs. PCB emission factor data in pg I-TEQ/L fuel consumed for all configurations tested are shown with the 95% confidence interval (student *t* test assuming a normal distribution) in Figure 2. Additionally, the average emission results and detection limits with standard deviation for all 2005 WHO CB congeners and mono−nona substituted CB homologues plus PCB-209, along with 2005 WHO TEQ emissions can be found in Tables S13−S17 in the SI.

A review of the 2005 WHO TEQ results across all configurations tested indicate that some of the results are statistically significant where ND = 0 and ND = DL. It should be noted that the detection limit, which can be influenced by many factors, expressed variability similar to that discussed for PCDD/Fs for the varying 2005 WHO CB congeners. Further the reported standard deviations across all of the 2005 WHO CB congeners and the mono−nona substituted CB homologues plus PCB-209 are large when compared to the average.

The two configurations whose results stand out statistically from the others are the SS CuZ SCR LT and T DOC+CDPF +CuZ SCR+ASC+urea, 10 ppm Cl configurations. The 2005 WHO TEQ value for SS CuZ SCR LT is 2 orders of magnitude higher than all of the other configurations tested where DL = 0. This configuration was identical to the SS CuZ SCR HT configuration except for the power setting, which was 20 Hp lower for the LT configuration. An analysis of the congeners emitted above the detection limit for the HT and LT SS CuZ SCR configurations indicate that while the HT configuration TEQ was driven by PCBs 105 and 118, the LT configuration TEQ was driven by emissions of 8 of the 11 PCBs that are part of the TEQ determination, with the primary drivers being the emission of PCB-126 which has the highest toxic equivalency factor (TEF) of 0.1 and PCB-169 (TEF of 0.03), which together accounted for greater than 98% of the TEQ value. It should also be noted that PCB-126 and PCB-169 were reported as nondetects for all other steady-state configurations tested and the reported average emission values for the SS CuZ SCR LT configuration are below the DL for the SS Engine Out and SS CuZ SCR HT configurations. Mono−nona substituted CB homologues plus PCB-209 emissions for both SS CuZ SCR HT and LT configurations were comparable. Analysis of the T DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl configuration emission profile indicated that TEQ was driven by emissions of PCB-126 and PCB-169 which were very close to the detection limit. These two congeners were reported as nondetects for the other transient configurations and the reported emission values for PCB-126 and PCB-169 are below the detection limits for these other test configurations. Mono−nona substituted CB homologues plus PCB-209 emissions for all transient configurations were comparable.

It should be noted that the dilution air background should be taken into consideration when assessing the PCB results. The tunnel blanks reported an average PCB value of 0.03 ± 0.013 pg WHO 2005 TEQ/L fuel consumed at the 95% confidence interval, which can be a significant source of PCBs for this testing when exhaust dilution is utilized, however it does not account for the high TEQ emission results for the SS CuZ SCR LT tests.

A review of the literature did not reveal any prior work that undertook measurement of PCBs from diesel engine emissions nor is there a current mobile source inventory value available. While the PCB data presented here has measurement uncertainty associated with the low levels detected, we believe that the

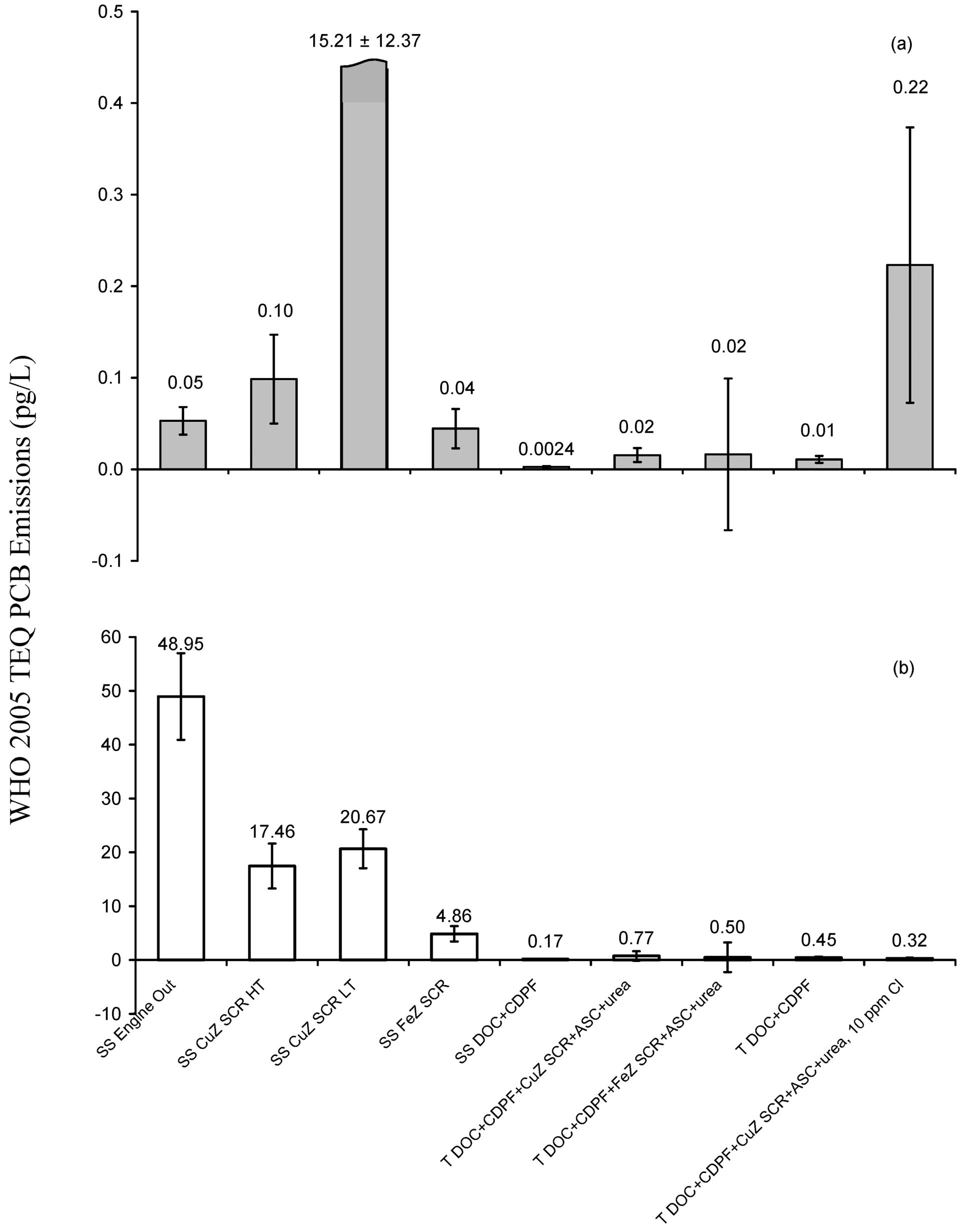

Figure 2. Average PCB 2005 WHO TEQ emission values with ±95% C.I. ND = 0, EMPC = EMPC (a) and ND = DL, EMPC = EMPC (b) for all of the configurations tested.

values presented with the upper limit of the 95% confidence interval can be used to provide a worst case estimate of PCB emissions from diesel engines, 0.01 pg I-TEQ/L fuel consumed (upper limit of the 95% confidence interval at 0.014 pg I-TEQ/L) for a 2007 era system and 0.02 pg I-TEQ/L fuel consumed (upper limit of the 95% confidence interval at 0.03 pg I-TEQ/L) for a 2010 era system. Further we believe that the mechanisms for the formation and destruction of PCBs in diesel combustion and over the aftertreatment systems are similar in nature to what we have described for PCDD/Fs. Overall these results suggest that for a modern diesel engine, both with and without aftertreatment, PCB emissions are near zero levels.

PAHs. Average PAH emission factor data, including standard deviation, in ng/hp-hr for steady-state and transient test configurations are shown in Tables S18−S22 of the SI.

The PAH results within a given configuration show consistent results for repeat tests. The data show that there is no relative increase in PAH formation when comparing the SS Engine Out configuration to the results of the SS CuZ SCR tests. Interestingly, the results for the SS FeZ SCR configuration indicate order(s) of magnitude reduction in 11 of the 19 PAH measured. The authors are not aware of any properties associated with the FeZ catalyst that would facilitate this reduction, nor are we aware of any similar findings in the literature. The results also show that the presence of platinum group metals in the DOC and CDPF in the SS DOC +CDPF configuration reduces all of the PAHs measured here by at least 99.6% when compared to SS Engine Out, which is consistent with previously published results.[17] The use of a DOC+CDPF essentially eliminated all of the PAHs within our ability to measure them during both steady-state and transient operation. These results are consistent with what would be expected from the oxidative functionality of catalysts utilizing platinum group metals and supports our belief that the high oxidative efficiency observed for PAHs would also be observed for PCDD/Fs and PCBs if the emissions of these compounds were sufficiently high enough in the SS Engine Out baseline configuration to denote the reduction.

Overall, the results of our testing show that PCDD/F emissions appear to be unaffected by the use of catalytic exhaust treatment when compared to the baseline SS Engine Out configuration within our ability to measure PCDD/Fs. Further, when compared to other historical data [3−11,15,16] and more recent testing on modern diesel engines,[18,19] the emission factor results suggest a 1 to 4 order of magnitude reduction in PCDD/F emissions from diesel engines and suggest that modern diesel engines are a minor contributor to the PCDD/F inventory when compared to stationary sources.[16] At this time, it is not clear if the reduction is due to improvements in diesel engine combustion technology, including higher fuel injection pressures, improved piston skirt/ring pack design, and improved cylinder machining tolerance; or improvements in the sampling and analytical methodologies which included repeat testing, high sample flow rates, and long test durations.

Further, the results indicated that the presence of Cu in the form of CuZ as a flow through exhaust aftertreatment, has no adverse effect on PCDD/F formation from modern diesel engines at fuel and ambient air Cl concentrations that represent levels expected to be encountered during normal engine operation, as well as at the elevated fuel Cl level tested.

The PCB results suggest that modern diesel engines are not a significant source of PCB emissions and that the inclusion of catalytic exhaust aftertreatment does not increase the PCB emissions from the engine. The results also show that the PAH emissions are unaffected by the presence of CuZ as a flow through exhaust aftertreatment, and the presence of a highly effective oxidation catalyst in the DOC+CDPF oxidizes at least 99.6% of the PAHs in the exhaust.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Catalyst properties; test fuel properties; emission results for criteria pollutants; transient engine speed, torque, and catalyst temperature; sampler diagram; list of isotopically labeled standards; PCDD/F test results in pg I-TEQ/L fuel consumed; PCDD/F test results in pg I-TEQ/m^3; PCB test results in pg WHO 2005 TEQ/L fuel consumed; PCB test results in pg WHO 2005 TEQ/m^3; average PCDD/F emissions data with standard deviation for 2,3,7,8-substituted congeners and tetra−octa homologues, average PCB emissions data with standard deviation for 2005 WHO congeners and mono−nona homologues plus PCB-209, and PAH emissions data with standard deviation in ng/L fuel consumed and ng/m^3.This material is available free of charge via the Internet at http://pubs.acs.org.

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Supporting Information

Emissions of PCDD/Fs, PCBs, and PAHs from a Modern Diesel Engine Equipped with Catalyzed Emission Control Systems

Christopher A. Laroo, Charles R. Schenk, L. James Sanchez, Joseph McDonald

36 Pages
2 Figures
31 Tables

Table S1. Test Fuel Properties

test method	result
Net Heat of Combustion, ASTM D3338-92 (MJ/kg)	42.86
Density @ 15.5 ºC (g/cm^3), ASTM D4052	0.8519
Cetane Number, ASTM D613	44.1
Cetane Index, ASTM D976	44.4
Olefins, by FIA, ASTM D1319-93 (% Vol.)	0.8
Aromatics, by FIA, ASTM D1319-93 (% Vol.)	29.7
Sulfur, ASTM D2622 (ppm mass)	8.2
Carbon, ASTM D5291 (% mass)	87.05
Distillation Properties, ASTM D86	
IBP (ºC):	177
10 % (ºC):	205
50 % (ºC):	243
90 % (ºC):	295
End Point (ºC):	322
Residue Diesel (mL):	0.9
Recovery:	98.6%

Table S2. Catalyst Properties

catalyst type	cell density (cpsi)	wall thickness (mil)	volume (L)	zeolite type	PGM[a] ratio[b]	PGM[a] loading (g/L)
DOC	400	4	4.25		4.4:1:0	1.3
CDPF	200	12	11.5		1:0:0	0.19
FeZ SCR	300	5	12.75	Fe-Y-exchanged		
ASC for FeZ SCR	300	5	4.25		1:0:0	0.18
CuZ SCR	300	5	12.75	Cu-Y-exchanged		
ASC for CuZ SCR	300	5	4.25		1:0:0	0.18

[a] PGM stands for Platinum Group Metals which consists of platinum, palladium, and rhodium.
[b] PGM ratio is defined as Pt:Pd:Rh.

Table S3. Emission Results for a Selection of Test Configurations

test configuration	NOx (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	PM (g/hp-hr)
SS Engine Out	1.66	0.06	0.40	
SS DOC+CDPF	1.40	0.00	0.02	
T DOC+CDPF	1.81	0.07	0.04	0.002
T DOC+CDPF+CuZ SCR+ASC+urea	0.08	0.06	0.04	0.002

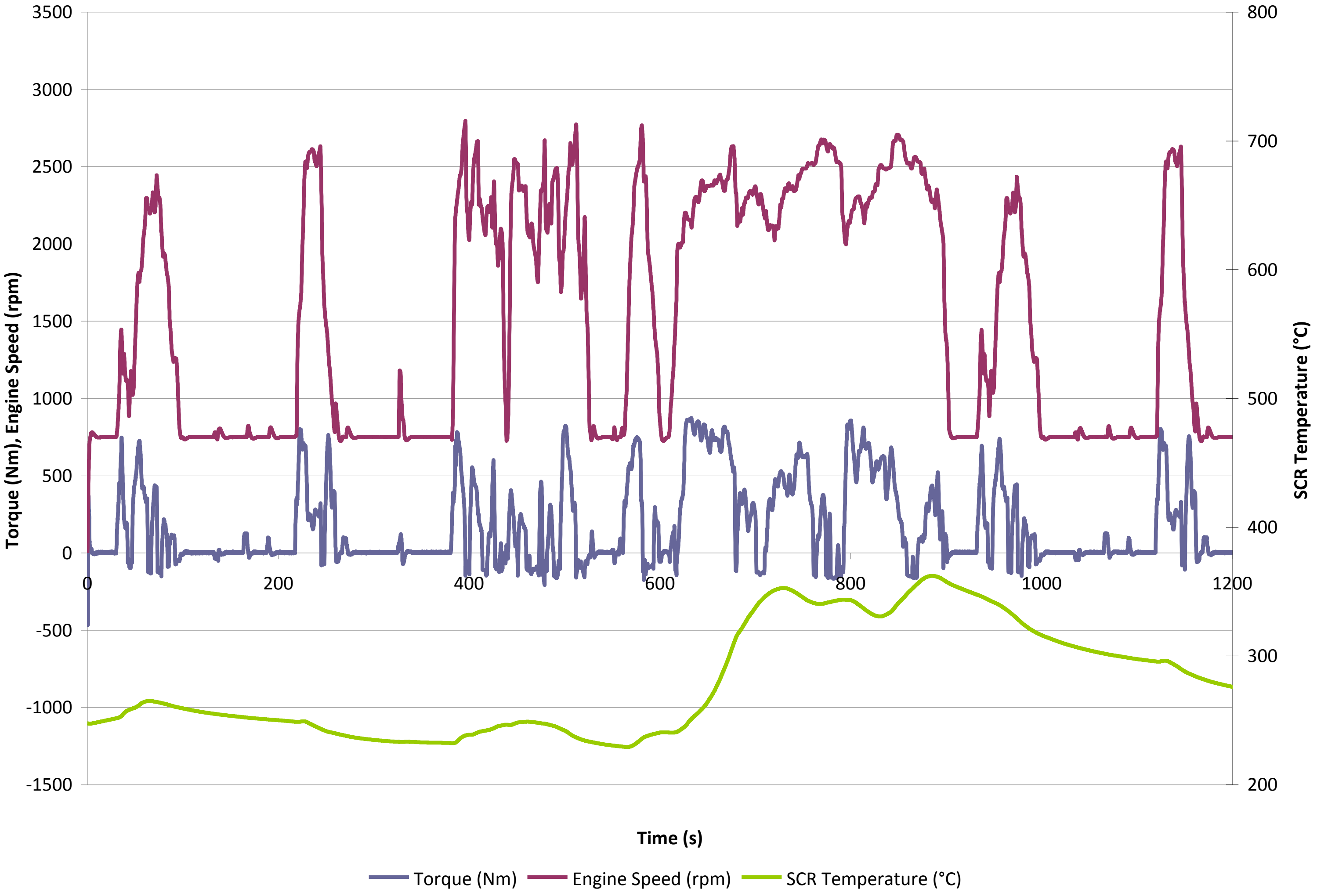

Figure S1. Engine speed and torque along with SCR catalyst temperature over the hot start HDDE-FTP.

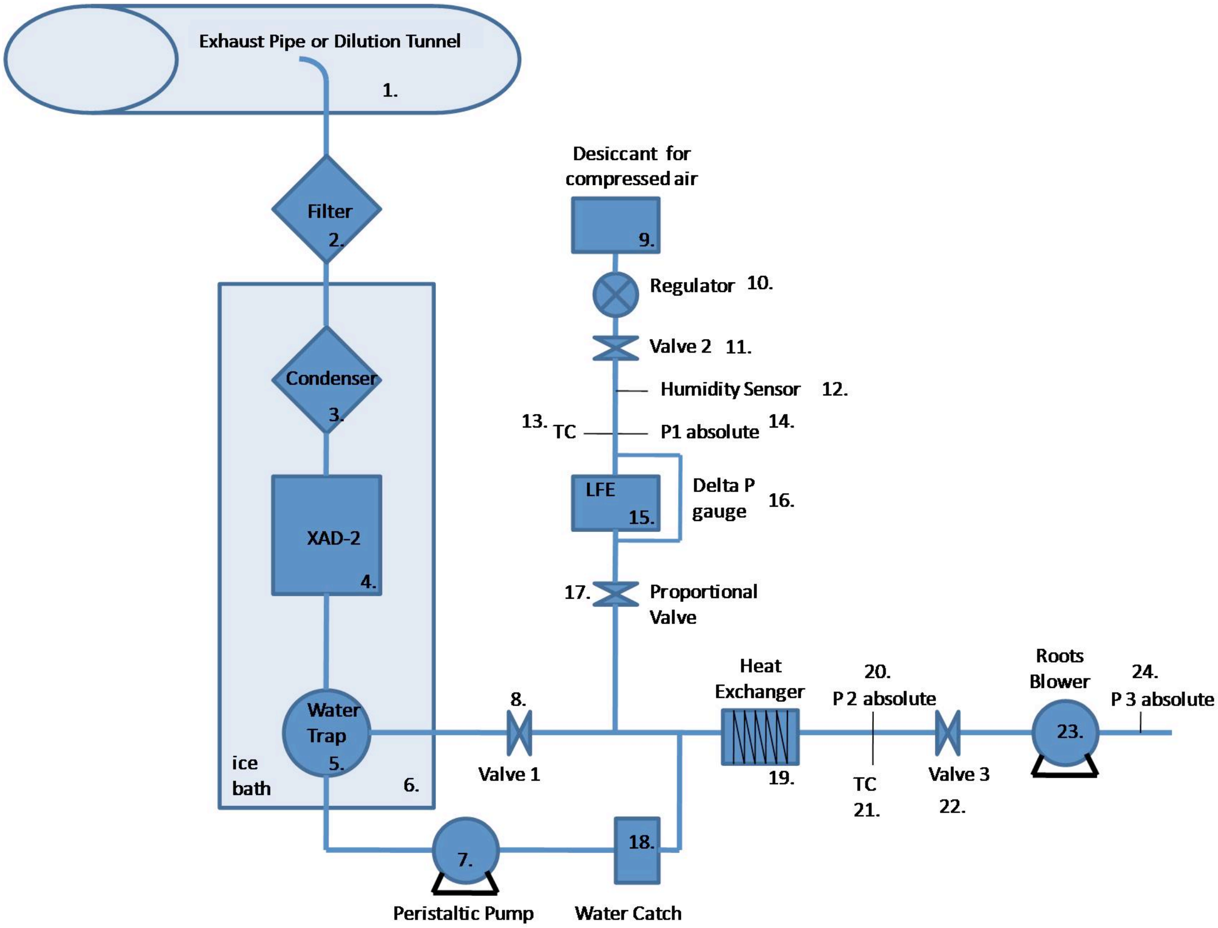

Figure S2. Schematic of the sampling system used in this test program. A description is given below for each of the numbered components:

1. Exhaust pipe or dilution tunnel: The point at which the raw or diluted exhaust sample is extracted.
2. Heated filter: Collects particulate matter from exhaust, heated to 191 ±11°C, constructed from titanium.
3. Condenser coil: Used to rapidly cool the exhaust sample, constructed from titanium.
4. Holder for XAD-2 resin, constructed from nickel.
5. Water Trap: Collects the water that condenses out of the exhaust, constructed from 316-stainless steel.
6. Ice bath: Used to cool the exhaust gas to 5 °C before it reaches the XAD-2.
7. Peristaltic pump: Used to remove water from the water trap.
8. Valve: Closes off the sample train from the rest of the system.
9. Desiccant: Removes water, oil and particles from house supplied compressed air.
10. Regulator: Used to set the desired pressure of air at the LFE inlet.
11. Valve: Used to perform leak check.
12. Humidity sensor: Used to verify that all of the water is removed from the compressed air.
13. Temperature sensor: Used for calculation of make up air flow rate.

14. Pressure sensor: Used for calculation of make up air flow rate.
15. Laminar Flow Element: Used to measure make up air flow rate.
16. Differential pressure sensor: Used for calculation of make up air flow rate.
17. Proportional valve: Used to control the make up air flow rate.
18. Water catch: Used to collect water removed from exhaust.
19. Heat exchanger: increases the gas temperature to ambient to simplify the flow calculations for the total flow.
20. Pressure sensor: Used for calculation of total flow rate.
21. Thermocouple: Used for calculation of total flow rate.
22. Valve: Used to perform leak check.
23. Roots Blower: Used to control and measure total flow rate.
24. Pressure Sensor: Used for calculation of total flow rate.

Table S4. List of Isotopically Labeled PCDD/F Standards Used for Sample Analysis

PCDD/F

Surrogate Standards

$^{37}Cl_4$-2,3,7,8-TCDD
$^{13}C_{12}$-1,2,3,4,7-PeCDD
$^{13}C_{12}$-1,2,3,4,6-PeCDF
$^{13}C_{12}$-1,2,3,4,6,9-HxCDF
$^{13}C_{12}$-1,2,3,4,6,8,9-HpCDF

Internal Standards

$^{13}C_{12}$-2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD)
$^{13}C_{12}$-1,2,3,7,8-Pentachlorodibenzo-p-dioxin (PeCDD)
$^{13}C_{12}$-1,2,3,4,7,8-Hexachlorodibenzo-p-dioxin (HxCDD)
$^{13}C_{12}$-1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin (HxCDD)
$^{13}C_{12}$-1,2,3,7,8,9-Hexachlorodibenzo-p-dioxin (HxCDD)
$^{13}C_{12}$-1,2,3,4,6,7,8-Heptachlorodibenzo-p-dioxin (HpCDD)
$^{13}C_{12}$-Octachlorodibenzo-p-dioxin (OCDD)
$^{13}C_{12}$-2,3,7,8-Tetrachlorodibenzofuran (TCDF)
$^{13}C_{12}$-1,2,3,7,8-Pentachlorodibenzofuran (PeCDF)
$^{13}C_{12}$-2,3,4,7,8-Pentachlorodibenzofuran (PeCDF)
$^{13}C_{12}$-1,2,3,4,7,8-Hexachlorodibenzofuran (HxCDF)
$^{13}C_{12}$-1,2,3,6,7,8-Hexachlorodibenzofuran (HxCDF)
$^{13}C_{12}$-1,2,3,7,8,9-Hexachlorodibenzofuran (HxCDF)
$^{13}C_{12}$-2,3,4,6,7,8-Hexachlorodibenzofuran (HxCDF)
$^{13}C_{12}$-1,2,3,4,6,7,8-Heptachlorodibenzofuran (HpCDF)
$^{13}C_{12}$-1,2,3,4,7,8,9-Heptachlorodibenzofuran (HpCDF)
$^{13}C_{12}$-Octachlorodibenzofuran (OCDF)

Alternate Standards

$^{13}C_{12}$-1,3,6,8-Tetrachlorodibenzo-p-dioxin
$^{13}C_{12}$-1,3,6,8-Tetrachlorodibenzofuran

Recovery Standards

$^{13}C_{12}$-1,2,3,4-Tetrachlorodibenzo-p-dioxin
$^{13}C_{12}$-1,2,3,4,6,7-Hexachlorodibenzo-p-dioxin
$^{13}C_{12}$-1,2,3,4-Tetrachlorodibenzofuran

Table S5. List of Isotopically Labeled PCB Standards Used for Sample Analysis

PCB

Internal Standards

$^{13}C_{12}$-2-Monochlorobiphenyl (PCB-1)
$^{13}C_{12}$- 4-Monochlorobiphenyl (PCB-3)
$^{13}C_{12}$-2,2'-Dichlorobiphenyl (PCB-4)
$^{13}C_{12}$-4,4'-Dichlorobiphenyl (PCB-15)
$^{13}C_{12}$-2,2',6-Trichlorobiphenyl (PCB-19)
$^{13}C_{12}$-3,4,4'-Trichlorobiphenyl (PCB-37)
$^{13}C_{12}$-2,2',6,6'-Tetrachlorobiphenyl (PCB-54)
$^{13}C_{12}$-3,3',4,4'-Tetrachlorobiphenyl (PCB-77)
$^{13}C_{12}$-3,4,4',5-Tetrachlorobiphenyl (PCB-81)
$^{13}C_{12}$-2,2',4,6,6'-Pentachlorobiphenyl (PCB-104)
$^{13}C_{12}$-2,3,3',4,4'-Pentachlorobiphenyl (PCB-105)
$^{13}C_{12}$-2,3,4,4',5-Pentachlorobiphenyl (PCB-114)
$^{13}C_{12}$-2,3,4,4',5-Pentachlorobiphenyl (PCB-115)
$^{13}C_{12}$-2,3',4,4',5-Pentachlorobiphenyl (PCB-118)
$^{13}C_{12}$-2',3,4,4',5-Pentachlorobiphenyl (PCB-123)
$^{13}C_{12}$-3,3',4,4',5-Pentachlorobiphenyl (PCB-126)
$^{13}C_{12}$-2,2',4,4',6,6'-Hexachlorobiphenyl (PCB-155)
$^{13}C_{12}$-2,3,3',4,4',5-Hexachlorobiphenyl (PCB-156)
$^{13}C_{12}$-2,3,3',4,4',5'-Hexachlorobiphenyl (PCB-157)
$^{13}C_{12}$-2,3',4,4',5,5'-Hexachlorobiphenyl (PCB-167)
$^{13}C_{12}$-3,3',4,4',5,5'-Hexachlorobiphenyl (PCB-169)
$^{13}C_{12}$-2,2',3,3',4,4',5- Heptachlorobiphenyl (PCB-170)
$^{13}C_{12}$-2,2',3,4,4',5,5'- Heptachlorobiphenyl (PCB-180)
$^{13}C_{12}$-2,3,3',4,4',5,5'- Heptachlorobiphenyl (PCB-189)

Surrogate Standards

$^{13}C_{12}$-2,4,4'-Trichlorobiphenyl (PCB-28)
$^{13}C_{12}$-2,3,3',5,5'-Pentachlorobiphenyl (PCB-111)
$^{13}C_{12}$-2,2',3,3',5,5',6-Heptachlorobiphenyl (PCB-178)

Alternate Standards

none

Recovery Standards

$^{13}C_{12}$-2,5- Dichlorobiphenyl (PCB-9)
$^{13}C_{12}$-2,2',5,5'-Tetrachlorobiphenyl (PCB-52)
$^{13}C_{12}$-2,2',4,5,5'-Pentachlorobiphenyl (PCB-101)
$^{13}C_{12}$-2,2',3,4,4',5'-Hexachlorobiphenyl (PCB-138)
$^{13}C_{12}$-2,2',3,3',4,4',5,5'-Octachlorobiphenyl (PCB-194)

$^{13}C_{12}$-2,2',3,3',5,5',6,6'-Octachlorobiphenyl (PCB-202)
$^{13}C_{12}$-2,3,3',4,4',5,5',6-Octachlorobiphenyl (PCB-205)
$^{13}C_{12}$-2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl (PCB-206)
$^{13}C_{12}$-2,2',3,3',4,5,5',6,6'-Nonachlorobiphenyl (PCB-208)
$^{13}C_{12}$-2,2',3,3',4,4',5,5',6,6'-Decachlorobiphenyl (PCB-209)

Table S6. List of Isotopically Labeled PAH Standards Used for Sample Analysis

PAH	
Surrogate Standards	Alternate Standards
d_{10}-Fluorene	d_{10}-Anthracene
d_{14}-Terphenyl	
	Recovery Standards
Internal Standards	d_{10}-2-Methylnaphthalene
$^{13}C_6$-Naphthalene	d_{10}-Acenaphthene
$^{13}C_6$-2-Methylnaphthalene	d_{10}-Pyrene
$^{13}C_6$-Acenaphthylene	d_{12}-Benzo(a)Pyrene
$^{13}C_6$-Acenaphthene	
$^{13}C_6$-Fluorene	
$^{13}C_6$-Phenanthrene	
$^{13}C_6$-Anthracene	
$^{13}C_6$-Fluoranthene	
$^{13}C_3$-Pyrene	
$^{13}C_6$-Benzo(a)anthracene	
$^{13}C_6$-Benzo(b)fluoranthene	
$^{13}C_6$-Benzo(k)fluoranthene	
$^{13}C_4$-Benzo(a)pyrene	
$^{13}C_4$-Benzo(e)Pyrene	
d_{12}-Perylene	
$^{13}C_6$-Ideno(1,2,3-c,d)pyrene	
$^{13}C_6$-Dibenz(a,h)anthracene	
$^{13}C_{12}$-Benzo(g,h,i)perylene	
$^{13}C_x$-Chrysene	

Note Regarding the Averaging of Reported Emission Factors and Detection Limits (Tables S7 – S31)

The following describes how the PCDD/F, PCB, and PAH emission factors and detection limits were averaged for the different test configurations (Note, all EMPCs were reported as detects for these test results). The same methodology applies for determination of the standard deviation as well:

Test Configurations without a DOC+CDPF
For testing without a DOC+CDPF where exhaust dilution was utilized, the filters had to be extracted separately from the PUF/XAD-2/rinsate. For these test results, emissions above the detection limit were summed for an individual test (filter result + PUF/XAD-2/rinsate result) for each individual congener. If a given congener emission result was reported as a non-detect for both the PM and PUF/XAD-2/rinsate, the higher of the two non-detect results was reported, as the summing of two non-detects would have artificially elevated the detection limit. For instances where a given congener emission resulted in a non-detect for the PM result and was above the detection limit for the PUF/XAD-2/rinsate (or vice versa), each result was reported. These individual test results for emissions above the detection limit and non-detects were grouped and averaged to create emission and non-detect results for the given congener. Where a non-detect is reported as "-", all individual tests reported results as a detect for that congener. Where a standard deviation is reported as "-", only one value was reported as the detect or non-detect. The average values for the 2,3,7,8-substituted CDD/F congeners and 2005 WHO PCB congeners were then used to calculate I-TEQ and 2005 WHO TEQ respectively with non-detects reported as 0, 0.5*DL, and DL

Test Configurations with a DOC+CDPF
For testing with a DOC+CDPF where exhaust dilution was not utilized, the filters were extracted with the PUF/XAD-2/rinsate. For these test results, emissions above the detection limit were averaged across all of the tests for each individual congener. For instances where a given congener emission resulted in a non-detect, the non-detects were averaged across all of the tests for each individual congener. Where a non-detect is reported as "-", all individual tests reported results as a detect for that congener. Where a standard deviation is reported as "-", only one value was reported as the detect or non-detect. The average values for the 2,3,7,8-substituted CDD/F congeners and 2005 WHO PCB congeners were then used to calculate I-TEQ and 2005 WHO TEQ respectively with non-detects reported as 0, 0.5*DL, and DL.

Table S7. PCDD/F Emission Factor Results in I-TEQ pg/L and pg/m^3, ND = 0 and EMPC = EMPC

	pg/L			pg/m^3		
test configuration	range of I-TEQ	average I-TEQ	± 95% C.I.	range of I-TEQ	average I-TEQ	± 95% C.I.
SS engine out	0.75 – 4.42	1.89	0.72	0.04 – 0.21	0.09	0.03
SS CuZ SCR HT	0.55 – 4.73	1.60	1.02	0.02 – 0.16	0.07	0.04
SS CuZ SCR LT	0.49 – 4.54	2.55	2.15	0.02 – 0.21	0.12	0.1
SS FeZ SCR	1.85 – 3.80	2.78	1.06	0.09 – 0.18	0.12	0.05
SS DOC+CDPF	0.30 – 3.46	1.23	1.66	0.01 – 0.17	0.06	0.08
T DOC+CDPF+CuZ SCR+ASC+urea	0.04 – 3.18	1.28	1.61	0.0 – 0.13	0.05	0.06
T DOC+CDPF+FeZ SCR+ASC+urea	0.04 – 0.58	0.36	0.32	0.01 – 0.02	0.01	0.01
T DOC+CDPF	0.0 – 0.49	0.21	0.30	0.0 – 0.02	0.01	0.01
T DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	0.04 – 0.35	0.17	0.13	0.0 – 0.01	0.01	0.01
Tunnel Blank	0.0 – 0.85	0.30	0.55	0.0 – 0.01	0.003	0.005
Field Blank	0.0 – 0.57	0.09	0.05	0.0 – 0.03	0.004	0.002

Table S8. Average PCDD/F Emissions in pg/L fuel consumed – 2,3,7,8-substituted Congeners and Homologues by Class for Steady-state Tests, EMPC=EMPC

	concentration									
	engine out (n=14)		CuZ SCR HT (n=9)		CuZ SCR LT (n=5)		FeZ SCR (n=5)		DOC+CDPF (n=5)	
	pg/L		pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	ND	-	ND	-	ND	-	ND	-	0.08	0.15
1,2,3,7,8-PeCDD	ND	-	ND	-	ND	-	ND	-	0.20	0.22
1,2,3,4,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-	0.07	-
1,2,3,6,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-	0.06	-
1,2,3,7,8,9-HxCDD	ND	-	ND	-	ND	-	ND	-	ND	-
1,2,3,4,6,7,8-HpCDD	2.46	2.32	2.97	3.68	3.48	6.08	0.70	0.65	0.34	0.09
OCDD	10.15	5.36	22.20	31.87	13.47	4.91	3.70	2.79	0.66	0.06
2,3,7,8-TCDF	7.98	2.02	8.05	3.59	6.38	1.65	0.23	0.51	1.47	2.04
1,2,3,7,8-PeCDF	0.40	0.67	1.09	1.63	ND	-	0.27	0.37	0.99	1.22
2,3,4,7,8-PeCDF	0.91	1.26	0.83	1.35	3.53	3.46	5.19	1.38	1.41	1.37
1,2,3,4,7,8-HxCDF	1.61	2.39	1.37	1.18	ND	-	0.78	0.72	0.41	0.32
1,2,3,6,7,8-HxCDF	0.71	1.39	0.51	0.78	ND	-	0.46	0.65	0.43	0.31
2,3,4,6,7,8-HxCDF	0.96	1.28	0.49	0.77	0.92	2.05	ND	-	0.45	0.40
1,2,3,7,8,9-HxCDF	0.17	0.64	0.14	0.42	ND	-	ND	-	ND	-
1,2,3,4,6,7,8-HpCDF	20.70	48.17	2.57	2.46	0.81	1.80	1.25	1.05	0.54	0.21
1,2,3,4,7,8,9-HpCDF	0.21	0.78	ND	-	ND	-	ND	-	0.17	0.08
OCDF	23.25	49.09	1.53	4.60	1.31	2.94	0.97	1.33	0.35	0.08
Total TCDDs	6.90	3.99	10.70	7.18	ND	-	33.63	49.24	227.26	184.03
Total PeCDD	ND	-	ND	-	ND	-	2.43	5.43	7.12	3.34
Total HxCDD	ND	-	0.18	0.55	ND	-	1.65	1.91	0.75	0.91
Total HpCDD	5.24	5.62	9.46	12.04	7.72	10.66	1.97	1.18	0.66	0.21
Total TCDF	259.72	54.78	344.00	117.80	177.17	17.79	95.32	28.70	433.55	252.63
Total PeCDF	42.39	105.13	23.96	21.45	6.18	1.37	14.48	6.56	22.49	16.43
Total HxCDF	6.37	8.33	4.62	4.63	2.12	4.75	3.35	4.84	4.83	3.85
Total HpCDF	21.75	47.81	2.94	2.93	0.81	1.80	0.90	0.84	1.15	0.60
ITEF TEQ (ND=0)	1.89	1.25	1.60	1.32	2.55	1.73	2.78	0.85	1.23	1.33
ITEF TEQ (ND=DL/2)	4.85	3.09	6.62	3.08	6.80	1.17	4.44	0.71	1.48	1.27
ITEF TEQ (ND=DL)	7.81	5.08	11.63	6.12	11.04	1.33	6.09	0.99	1.72	1.20

Table S9. Average PCDD/F Detection Limits in pg/L fuel consumed – 2,3,7,8-substituted Congeners and Homologues by Class for Steady-state Tests

	detection limit									
	engine out (n=14)		CuZ SCR HT (n=9)		CuZ SCR LT (n=5)		FeZ SCR (n=5)		DOC+CDPF (n=5)	
	pg/L		pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	1.41	0.76	3.12	1.14	2.95	0.45	1.31	0.31	0.21	0.03
1,2,3,7,8-PeCDD	2.75	1.68	4.23	1.58	3.15	0.30	1.25	0.32	0.23	0.07
1,2,3,4,7,8-HxCDD	3.67	1.69	4.96	2.60	4.37	0.47	1.38	0.37	0.23	0.03
1,2,3,6,7,8-HxCDD	3.76	1.67	4.85	2.70	4.52	0.42	1.38	0.37	0.23	0.02
1,2,3,7,8,9-HxCDD	4.11	1.86	5.49	3.21	4.73	0.46	1.61	0.43	0.26	0.02
1,2,3,4,6,7,8-HpCDD	2.90	1.90	4.46	2.26	4.40	0.87	1.66	0.45	0.29	-
OCDD	4.21	2.63	8.88	4.80	6.88	0.80	3.02	1.03	0.50	0.01
2,3,7,8-TCDF	1.33	0.59	2.83	1.69	2.38	0.40	0.95	0.28	0.17	-
1,2,3,7,8-PeCDF	2.11	1.35	3.06	1.22	2.31	0.17	0.79	0.22	0.12	-
2,3,4,7,8-PeCDF	1.83	1.01	3.10	1.10	2.04	0.45	0.84	0.04	-	-
1,2,3,4,7,8-HxCDF	1.81	0.70	2.64	2.15	2.63	0.36	0.71	0.26	0.14	-
1,2,3,6,7,8-HxCDF	1.89	1.05	2.42	1.89	2.56	0.20	0.71	0.24	0.12	-
2,3,4,6,7,8-HxCDF	1.78	0.61	2.52	2.00	2.64	0.19	0.83	0.25	0.13	-
1,2,3,7,8,9-HxCDF	2.65	1.37	3.97	3.54	3.22	0.32	1.17	0.37	0.23	0.03
1,2,3,4,6,7,8-HpCDF	2.71	2.35	2.26	2.11	2.69	0.57	0.96	0.11	-	-
1,2,3,4,7,8,9-HpCDF	4.01	3.55	3.82	2.68	3.90	1.00	1.30	0.34	0.27	0.02
OCDF	4.03	4.13	8.27	4.29	5.45	1.30	2.27	0.77	0.55	-
Total TCDDs	1.41	0.60	2.52	0.68	2.95	0.45	0.79	-	-	-
Total PeCDD	2.85	1.66	4.23	1.58	3.15	0.30	1.20	0.34	-	-
Total HxCDD	3.84	1.74	5.09	2.84	4.52	0.43	1.41	0.47	0.37	0.16
Total HpCDD	2.61	1.92	4.85	2.16	4.40	0.87	1.66	0.45	0.29	-
Total TCDF	-	-	-	-	-	-	-	-	-	-
Total PeCDF	2.64	1.50	2.76	0.92	2.04	0.37	-	-	-	-
Total HxCDF	1.91	0.75	3.24	2.29	2.73	0.23	0.84	0.23	-	-
Total HpCDF	3.18	2.80	2.89	2.46	3.19	0.78	1.33	0.25	0.36	-

Table S10. Average PCDD/F Emissions in pg/L fuel consumed – 2,3,7,8-substituted Congeners and Homologues by Class for Transient Tests, EMPC=EMPC, n=5 for each configuration

	concentration							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,7,8-PeCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,4,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,6,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,7,8,9-HxCDD	ND	-	ND	-	0.20	-	ND	-
1,2,3,4,6,7,8-HpCDD	5.02	2.27	1.46	1.01	1.24	1.48	2.01	0.24
OCDD	33.48	8.17	8.36	4.87	4.46	0.81	6.06	0.74
2,3,7,8-TCDF	0.24	-	ND	-	ND	-	ND	-
1,2,3,7,8-PeCDF	0.51	0.22	ND	-	ND	-	ND	-
2,3,4,7,8-PeCDF	1.56	1.31	0.60	0.22	0.30	0.17	ND	-
1,2,3,4,7,8-HxCDF	1.06	1.08	0.16	-	ND	-	0.79	0.45
1,2,3,6,7,8-HxCDF	1.17	1.00	ND	-	ND	-	0.31	0.18
2,3,4,6,7,8-HxCDF	0.86	0.98	ND	-	ND	-	ND	-
1,2,3,7,8,9-HxCDF	ND	-	ND	-	ND	-	ND	-
1,2,3,4,6,7,8-HpCDF	4.77	4.32	1.26	0.70	1.44	0.49	2.44	0.94
1,2,3,4,7,8,9-HpCDF	0.28	-	ND	-	ND	-	ND	-
OCDF	8.33	5.04	5.19	3.37	3.39	1.41	4.55	2.35
Total TCDDs	1.01	1.21	ND	-	ND	-	0.45	0.31
Total PeCDD	ND	-	0.37	-	ND	-	0.91	0.19
Total HxCDD	1.35	-	ND	-	0.20	-	ND	-
Total HpCDD	9.27	4.03	2.10	1.94	1.58	1.36	3.48	1.03
Total TCDF	7.70	12.44	ND	-	0.44	0.58	0.66	1.65
Total PeCDF	8.95	12.38	0.60	0.22	0.30	0.17	0.11	-
Total HxCDF	8.94	14.91	0.31	-	ND	-	1.92	1.58
Total HpCDF	8.74	7.40	1.26	0.70	1.44	0.49	2.78	1.63
ITEF TEQ (ND=0)	1.28	1.30	0.36	0.26	0.21	0.24	0.17	0.11
ITEF TEQ (ND=DL/2)	2.85	1.13	2.55	1.59	2.05	0.85	1.18	0.17
ITEF TEQ (ND=DL)	4.41	1.10	4.74	3.33	3.90	1.82	2.20	0.27

Table S11. Average PCDD/F Detection Limits in pg/L fuel consumed – 2,3,7,8-substituted Congeners and Homologues by Class for Transient Tests, n=5 for each configuration

	detection limit							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	1.19	0.34	1.72	1.47	1.31	0.71	0.77	0.10
1,2,3,7,8-PeCDD	1.29	0.30	1.71	1.43	1.43	0.77	0.80	0.18
1,2,3,4,7,8-HxCDD	1.37	0.33	1.53	1.19	1.48	0.70	0.79	0.09
1,2,3,6,7,8-HxCDD	1.34	0.34	1.54	1.18	1.45	0.73	0.83	0.09
1,2,3,7,8,9-HxCDD	1.38	0.34	1.77	1.28	1.86	0.70	0.94	0.10
1,2,3,4,6,7,8-HpCDD	-	-	3.42	2.56	1.52	0.24	-	-
OCDD	-	-	-	-	7.02	-	-	-
2,3,7,8-TCDF	0.76	0.16	1.01	0.76	0.85	0.42	0.48	0.04
1,2,3,7,8-PeCDF	0.95	0.22	0.95	0.63	1.02	0.52	0.59	0.07
2,3,4,7,8-PeCDF	0.76	0.03	1.30	1.00	1.20	0.61	0.55	0.06
1,2,3,4,7,8-HxCDF	0.98	0.16	1.04	0.88	0.91	0.39	0.48	-
1,2,3,6,7,8-HxCDF	0.87	0.14	0.94	0.75	0.86	0.42	0.61	0.10
2,3,4,6,7,8-HxCDF	0.89	0.08	1.04	0.95	0.88	0.47	0.62	0.09
1,2,3,7,8,9-HxCDF	1.03	0.20	1.42	1.29	1.22	0.54	0.79	0.15
1,2,3,4,6,7,8-HpCDF	-	-	2.01	1.68	2.18	-	-	-
1,2,3,4,7,8,9-HpCDF	1.27	0.17	1.92	1.67	1.60	0.94	0.81	0.11
OCDF	-	-	1.78	-	6.25	-	-	-
Total TCDDs	1.34	0.30	1.71	1.48	1.31	0.71	0.77	0.14
Total PeCDD	1.29	0.30	1.92	1.56	1.43	0.77	0.67	0.04
Total HxCDD	1.44	0.32	1.60	1.20	1.72	0.67	0.85	0.09
Total HpCDD	-	-	3.42	2.56	1.52	0.24	-	-
Total TCDF	0.75	0.06	1.01	0.76	1.02	0.46	0.50	0.04
Total PeCDF	0.79	0.02	1.32	1.01	1.23	0.57	0.55	0.06
Total HxCDF	0.91	0.09	1.18	1.04	0.95	0.45	0.54	-
Total HpCDF	-	-	2.50	2.07	2.62	-	-	-

Table S12. Average PCDD/F and PCB Tunnel Blank Results in pg/L fuel consumed – 2,3,7,8-substituted Congeners and Homologues by Class (PCDD/F) and 2005 WHO Congeners and Homologues by Class (PCB), EMPC=EMPC, n=5

	concentration pg/L		detection limit pg/L	
compound	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	ND	-	1.84	0.09
1,2,3,7,8-PeCDD	ND	-	1.74	0.31
1,2,3,4,7,8-HxCDD	ND	-	1.75	0.15
1,2,3,6,7,8-HxCDD	ND	-	1.89	0.18
1,2,3,7,8,9-HxCDD	ND	-	1.91	0.22
1,2,3,4,6,7,8-HpCDD	ND	-	1.89	0.27
OCDD	1.51	-	3.67	0.32
2,3,7,8-TCDF	ND	-	0.94	0.07
1,2,3,7,8-PeCDF	ND	-	0.92	0.07
2,3,4,7,8-PeCDF	0.64	0.16	0.89	0.04
1,2,3,4,7,8-HxCDF	ND	-	1.04	0.15
1,2,3,6,7,8-HxCDF	ND	-	0.94	0.15
2,3,4,6,7,8-HxCDF	ND	-	0.98	0.12
1,2,3,7,8,9-HxCDF	ND	-	1.44	0.27
1,2,3,4,6,7,8-HpCDF	ND	-	1.10	0.19
1,2,3,4,7,8,9-HpCDF	ND	-	1.41	0.16
OCDF	ND	-	2.93	0.33
Total TCDDs	3.02	7.5	62.77	105.4
Total PeCDD	ND	-	1.86	0.41
Total HxCDD	ND	-	1.84	0.18
Total HpCDD	ND	-	1.89	0.27
Total TCDF	9.40	9.2	-	-
Total PeCDF	0.64	0.16	0.92	0.05
Total HxCDF	ND	-	1.08	0.16
Total HpCDF	ND	-	1.25	0.17
ITEF TEQ (ND=0)	0.32	0.46		
ITEF TEQ (ND=DL/2)	2.49	0.26		
ITEF TEQ (ND=DL)	4.67	0.20		

	concentration pg/L		detection limit pg/L	
compound	average	standard deviation	average	standard deviation
PCB-77	34.3	9.3	-	-
PCB-81	ND	-	2.70	0.49
PCB-105	201.1	68.7	-	-
PCB-114	18.6	6.3	-	-
PCB-118	729.1	239.7	-	-
PCB-123	12.4	4.3	4.16	-
PCB-126	ND	-	3.56	0.49
PCB-156/157	39.5	11.2	-	-
PCB-167	18.0	4.2	-	-
PCB-169	ND	-	2.76	0.30
PCB-189	3.0	0.55	1.72	-
Total Mono-CBs	1,225	457.3	-	-
Total Di-CBs	7,309	3,331	-	-
Total Tri-CBs	10,993	5,613	-	-
Total Tetra-CBs	23,667	18,127	-	-
Total Penta-CBs	14,817	5,323	-	-
Total Hexa-CBs	6,151	1,943	-	-
Total Hepta-CBs	1,816	481.6	-	-
Total Octa-CBs	362.9	86.0	-	-
Total Nona-CBs	63.1	18.3	-	-
PCB-209	8.0	5.6	3.56	-
WHO 2005 TEQ (ND=0)	0.03	0.01		
WHO 2005 TEQ (ND=DL/2)	0.25	0.03		
WHO 2005 TEQ (ND=DL)	0.47	0.05		

Table S13. PCB Emission Factor Results in I-TEQ pg/L and pg/m^3, ND = 0 and EMPC = EMPC

	pg/L			pg/m^3		
test configuration	range of I-TEQ	average I-TEQ	± 95% C.I.	range of I-TEQ	average I-TEQ	± 95% C.I.
SS engine out	0.02 – 0.12	0.05	0.02	0.0011 – 0.0059	0.0003	0.0001
SS CuZ SCR HT	0.03 – 0.24	0.10	0.05	0.0014 – 0.0082	0.0041	0.0017
SS CuZ SCR LT	4.19 – 29.34	15.21	12.37	0.19 – 1.33	0.69	0.56
SS FeZ SCR	0.02 – 0.05	0.04	0.02	0.0011 – 0.0032	0.002	0.001
SS DOC+CDPF	0.001 – 0.003	0.00	0.00	0.0001 – 0.0002	0.0001	0.00005
T DOC+CDPF+CuZ SCR+ASC+urea	0.01 – 0.02	0.02	0.01	0.0003 – 0.0010	0.0006	0.0003
T DOC+CDPF+FeZ SCR+ASC+urea	0.01 – 0.03	0.02	0.08	0.0 – 0.0011	0.0007	0.0005
T DOC+CDPF	0.01 – 0.02	0.01	0.00	0.0003 – 0.0006	0.0004	0.0002
T DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	0.09 – 0.39	0.22	0.15	0.0036 – 0.0162	0.0092	0.0062
Tunnel Blank	0.02 – 0.05	0.032	0.013	0.0002 – 0.0004	0.0003	0.0001
Field Blank	0.0 – 0.01	0.003	0.001	0.0 – 0.0005	0.0002	0.0001

Table S14. Average PCB Emissions in pg/L fuel consumed – 2005 WHO Congeners and Homologues by Class for Steady-state Tests, EMPC=EMPC

	concentration									
	engine out (n=17)		CuZ SCR HT (n=9)		CuZ SCR LT (n=5)		FeZ SCR (n=5)		DOC+CDPF (n=5)	
	pg/L		pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	23.3	29.4	66.3	88.0	273.3	93.6	61.4	20.9	2.9	2.8
PCB-81	ND	-	ND	-	85.3	45.6	ND	-	ND	-
PCB-105	430.2	452.9	971.2	540.3	1130	827.7	334.3	157.5	13.7	4.9
PCB-114	ND	-	ND	-	147.4	100.7	20.1	7.3	0.4	-
PCB-118	1255	502.1	1998	1,227	3408	3,146	858.8	324.2	36.1	10.3
PCB-123	ND	-	ND	-	146.8	78.1	8.5	11.7	13.5	5.0
PCB-126	ND	-	ND	-	98.8	83.1	ND	-	ND	-
PCB-156/157	ND	-	95.1	207.0	349.8	145.3	41.1	14.9	5.0	2.6
PCB-167	ND	-	ND	-	161.9	84.5	15.4	10.2	3.1	2.0
PCB-169	ND	-	ND	-	170.5	57.8	ND	-	ND	-
PCB-189	ND	-	ND	-	140.2	39.9	ND	-	ND	-
Total Mono-CBs	1,664	2,509	61,803	17,596	36,825	7,306	1645	642.0	142.8	113.0
Total Di-CBs	31,646	90,527	12,061	4,440	16,314	10,069	7,626	3,290	2,151	705.2
Total Tri-CBs	10,218	6,994	18,017	7,088	23,859	17,082	11,122	3,385	6,248	1,497
Total Tetra-CBs	96,796	135,509	164,598	193,800	122,638	83,942	36,256	22,078	290,355	73,062
Total Penta-CBs	20,121	11,417	28,126	15,218	57,384	61,160	14,959	3,169	1,451	447.7
Total Hexa-CBs	10,173	7,516	11,205	7,378	26,396	25,116	5,655	1,226	511.3	124.9
Total Hepta-CBs	2,796	3,401	2,645	1,371	7,590	6,518	1,859	531.2	299.2	153.3
Total Octa-CBs	221.2	880.3	125.6	191.3	1,397	951.9	324.1	127.9	27.8	15.2
Total Nona-CBs	18.8	77.5	ND	-	338.3	153.8	34.2	35.8	ND	-
PCB-209	ND	-	ND	-	192.8	51.4	1.6	3.6	ND	-
WHO 2005 TEQ (ND=0)	0.05	-	0.10	0.1	15.2	10.0	0.04	-	0.002	0.001
WHO 2005 TEQ (ND=DL/2)	24.5	5.5	8.8	3.6	17.9	8.4	2.5	0.6	0.06	0.03
WHO 2005 TEQ (ND=DL)	48.9	11.0	17.46	7.2	20.7	7.0	4.86	1.1	0.12	0.05

Table S15. Average PCB Detection Limits in pg/L fuel consumed – 2005 WHO Congeners and Homologues by Class for Steady-state Tests

	detection limit									
	engine out (n=14)		CuZ SCR HT (n=9)		CuZ SCR LT (n=5)		FeZ SCR (n=5)		DOC+CDPF (n=5)	
	pg/L		pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	453.8	119.1	200.8	43.2	-	-	30.5	4.9	2.9	1.0
PCB-81	401.2	79.1	210.6	54.5	61.0	43.4	31.3	4.2	2.6	0.62
PCB-105	291.5	160.2	14.1	-	-	-	-	-	-	-
PCB-114	228.4	120.9	110.2	49.3	14.4	5.0	38.6	9.3	0.8	0.22
PCB-118	114.6	-	-	-	-	-	-	-	-	-
PCB-123	245.3	133.9	117.3	52.9	16.4	-	40.7	9.4	-	-
PCB-126	350.2	80.1	115.0	65.2	39.7	16.2	33.8	5.7	1.2	0.30
PCB-156/157	494.9	136.0	162.2	90.7	-	-	60.9	21.2	-	-
PCB-167	398.2	124.3	165.4	56.9	31.8	-	41.9	13.3	1.1	-
PCB-169	454.9	127.5	191.9	61.6	48.7	-	47.4	15.9	1.6	0.75
PCB-189	238.5	77.3	87.3	30.8	33.4	-	30.0	8.3	1.1	0.39
Total Mono-CBs	1029	146.5	-	-	-	-	-	-	-	-
Total Di-CBs	-	-	-	-	-	-	-	-	-	-
Total Tri-CBs	-	-	-	-	-	-	-	-	-	-
Total Tetra-CBs	-	-	-	-	-	-	-	-	-	-
Total Penta-CBs	-	-	-	-	-	-	-	-	-	-
Total Hexa-CBs	-	-	-	-	-	-	-	-	-	-
Total Hepta-CBs	53.5	2.0	50.5	-	-	-	-	-	-	-
Total Octa-CBs	283.0	166.2	83.6	59.0	-	-	53.4	15.8	-	-
Total Nona-CBs	331.5	159.6	200.9	67.8	23.6	-	61.2	13.2	2.9	0.65
PCB-209	323.8	134.3	211.4	63.8	13.5	-	54.9	9.9	1.0	0.22

Table S16. Average PCB Emissions in pg/L fuel consumed – 2005 WHO Congeners and Homologues by Class for Transient Tests, EMPC=EMPC, n=5 for each configuration

	concentration							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	12.3	7.6	14.1	3.5	13.0	1.2	13.8	3.9
PCB-81	ND	-	ND	-	ND	-	0.30	-
PCB-105	106.5	44.7	117.3	39.0	80.2	27.3	81.7	24.2
PCB-114	5.6	3.2	6.8	6.6	2.9	1.6	6.6	2.1
PCB-118	313.1	117.9	331.4	193.3	196.2	63.7	221.6	92.3
PCB-123	3.4	2.1	5.2	4.1	0.79	-	4.5	1.7
PCB-126	ND	-	ND	-	ND	-	1.0	0.59
PCB-156/157	32.0	10.2	26.3	2.8	25.9	7.3	28.3	7.1
PCB-167	10.8	5.6	8.4	1.1	9.9	3.7	11.6	3.0
PCB-169	ND	-	ND	-	ND	-	3.70	0.78
PCB-189	1.8	1.5	ND	-	ND	-	3.4	0.81
Total Mono-CBs	7,552	15,651	261.6	254.2	187.3	75.9	829.5	412.5
Total Di-CBs	40,855	86,735	2,232	1,953	2,000	915.0	2,120	544.1
Total Tri-CBs	52,501	111,721	3,364	3,035	2,324	1,335	2,162	1,400
Total Tetra-CBs	11,027	17,937	5,578	6,930	2,829	1,424	2,514	1,386
Total Penta-CBs	2,554	949.3	4,507	4,970	1,858	788.9	2,069	1,266
Total Hexa-CBs	1,940	525.8	2,158	1,090	1,606	571.1	1,833	667.1
Total Hepta-CBs	1,033	265.6	889.2	63.6	877.2	232.8	1,075	325.4
Total Octa-CBs	271.7	118.5	182.7	8.4	143.5	39.4	273.5	50.5
Total Nona-CBs	27.6	20.5	12.8	6.7	13.3	2.4	22.6	8.1
PCB-209	3.6	3.9	1.53	-	4.12	3.3	5.9	1.3
WHO 2005 TEQ (ND=0)	0.02	0.01	0.02	0.01	0.01	0.003	0.22	0.12
WHO 2005 TEQ (ND=DL/2)	0.39	0.35	0.26	0.16	0.23	0.08	0.27	0.10
WHO 2005 TEQ (ND=DL)	0.77	0.70	0.50	0.31	0.45	0.15	0.32	0.08

Table S17. Average PCB Detection Limits in pg/L fuel consumed – 2005 WHO Congeners and Homologues by Class for Transient Tests, n=5 for each configuration

	detection limit							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/L		pg/L		pg/L		pg/L	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	35.1	-	-	-	-	-	-	-
PCB-81	9.9	12.9	2.7	2.10	2.4	0.54	1.6	0.31
PCB-105	-	-	-	-	-	-	-	-
PCB-114	8.8	7.5	7.1	-	3.1	0.55	-	-
PCB-118	-	-	-	-	-	-	-	-
PCB-123	9.2	8.2	7.1	-	2.7	0.45	-	-
PCB-126	5.5	4.7	3.6	2.21	3.1	1.12	1.01	0.27
PCB-156/157	-	-	-	-	-	-	-	-
PCB-167	18.7	-	7.9	-	-	-	-	-
PCB-169	6.4	7.4	4.1	3.15	4.2	1.30	-	-
PCB-189	7.8	8.2	3.2	2.26	2.2	0.77	-	-
Total Mono-CBs	-	-	-	-	-	-	-	-
Total Di-CBs	-	-	-	-	-	-	-	-
Total Tri-CBs	-	-	-	-	-	-	-	-
Total Tetra-CBs	-	-	-	-	-	-	-	-
Total Penta-CBs	-	-	-	-	-	-	-	-
Total Hexa-CBs	-	-	-	-	-	-	-	-
Total Hepta-CBs	-	-	-	-	-	-	-	-
Total Octa-CBs	-	-	-	-	-	-	-	-
Total Nona-CBs	33.8	-	11.3	-	-	-	-	-
PCB-209	-	-	5.1	-	3.3	1.01	-	-

Table S18. PAH Emission Factor Results for Steady-state Engine Out and CuZ SCR HT Tests

	concentration							
	SS engine out (n=17)				SS CuZ SCR HT (n=9)			
	ng/L		ng/m^3		ng/L		ng/m^3	
analyte	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
Naphthalene	1,084,405	398,586	52,283	19,137	1,299,934	78,195	55,590	6,829
2-Methylnaphthalene	815,442	250,816	39,338	12,204	410,175	141,400	16,946	3,511
Acenaphthylene	67,988	6,108	3,275	284.5	32,966	8,773	1,373	174.2
Acenaphthene	18,605	5,535	896.9	266.1	2,475	839.6	102.5	21.3
Fluorene	68,149	27,840	3,281	1,339	16,737	6,890	686.6	176.7
Phenanthrene	186,268	25,928	8,989	1,363	210,057	33,673	8,872	852.6
Anthracene	14,707	2,111	708.4	99.4	4,017	1,674	164.6	45.2
Fluoranthene	10,345	1,555	498.7	77.2	8,497	1,003	360.1	27.2
Pyrene	22,980	5,249	1,107	252.1	5,778	1,238	243.6	37.3
Benzo(a)Anthracene	1,214	100.4	58.5	5.1	493.2	42.7	21.2	3.9
Chrysene	1,299	148.4	62.6	7.1	734.4	41.6	31.3	3.1
Benzo(b)Fluoranthene	699.7	176.8	33.6	8.1	600.7	55.8	25.9	4.9
Benzo(k)Fluoranthene	261.1	87.7	12.5	4.0	182.6	30.2	7.9	1.9
Benzo(e)Pyrene	589.9	68.2	28.4	2.9	302.1	27.5	13.0	2.5
Benzo(a)Pyrene	586.6	108.0	28.2	4.8	404.1	59.5	17.5	4.0
Perylene	108.1	10.9	5.2	0.5	59.4	11.8	2.6	0.8
Indeno(1,2,3-c,d)Pyrene	509.1	330.4	24.5	15.7	540.9	190.3	23.5	10.0
Dibenzo(a,h)Anthracene	88.3	61.2	4.2	2.9	72.0	10.4	3.1	0.7
Benzo(g,h,i)Perylene	846.1	979.5	40.5	46.2	658.5	226.8	28.9	12.3

Table S19. PAH Emission Factor Results for Steady-state CuZ SCR LT and FeZ SCR Tests

	concentration							
	SS CuZ SCR LT (n=5)				SS FeZ SCR (n=5)			
	ng/L		ng/m^3		ng/L		ng/m^3	
analyte	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
Naphthalene	2,399,417	271,776	109,326	12,777	13,732	4,233	619.9	231.1
2-Methylnaphthalene	630,964	84,075	28,742	3,841	6,610	1,433	297.9	85.1
Acenaphthylene	43,746	6,013	1,993	277.2	1,105	124.0	49.7	10.1
Acenaphthene	3,698	2,422	168.1	109.3	249.3	81.3	11.1	4.0
Fluorene	20,472	4,775	932.8	218.8	586.4	147.0	26.1	7.0
Phenanthrene	361,051	35,615	16,444	1,590	3,295	711.2	145.7	27.6
Anthracene	8,667	2,043	395.0	94.0	275.9	23.3	12.4	2.4
Fluoranthene	13,959	1,753	635.7	78.4	640.7	74.0	28.8	5.5
Pyrene	10,369	2,197	472.1	98.9	790.9	98.8	35.5	6.7
Benzo(a)Anthracene	803.8	133.7	36.6	5.9	350.5	47.4	15.7	3.0
Chrysene	1,099	163.1	50.0	7.3	323.9	45.0	14.5	2.7
Benzo(b)Fluoranthene	547.3	87.7	24.9	4.0	567.1	199.6	25.3	9.7
Benzo(k)Fluoranthene	202.7	19.5	9.2	0.9	185.0	65.1	8.2	2.9
Benzo(e)Pyrene	386.0	67.7	17.6	3.0	299.3	112.3	13.2	5.1
Benzo(a)Pyrene	435.9	59.7	19.8	2.6	553.9	229.5	23.6	6.1
Perylene	80.0	12.4	3.6	0.5	120.6	40.4	5.3	1.4
Indeno(1,2,3-c,d)Pyrene	498.6	38.7	22.7	1.7	337.3	230.0	13.4	3.8
Dibenzo(a,h)Anthracene	73.2	7.1	3.3	0.3	71.7	43.3	2.9	0.7
Benzo(g,h,i)Perylene	797.8	159.3	36.3	7.0	569.3	395.3	22.6	7.2

Table S20. PAH Emission Factor Results for Steady-state DOC+CDPF and Tunnel Blank Tests

	concentration							
	SS DOC+CDPF (n=5)				tunnel blank (n=5)			
	ng/L		ng/m^3		ng/L		ng/m^3	
analyte	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
Naphthalene	1,644	1,836	81.3	91.8	44.3	10.7	63.9	14.4
2-Methylnaphthalene	76.8	58.2	3.8	2.9	22.3	3.8	32.2	4.8
Acenaphthylene	3.4	4.3	0.2	0.2	0.083	0.01	0.1	0.02
Acenaphthene	2.9	0.2	0.1	0.009	2.3	1.0	3.3	1.5
Fluorene	13.3	2.3	0.7	0.12	3.3	1.4	4.8	2.1
Phenanthrene	78.8	59.8	3.9	3.0	7.9	3.4	11.4	5.2
Anthracene	2.8	2.4	0.1	0.12	0.080	0.02	0.1	0.03
Fluoranthene	15.9	6.0	0.8	0.3	1.004	0.2	1.4	0.2
Pyrene	10.8	5.1	0.5	0.2	0.344	0.1	0.5	0.10
Benzo(a)Anthracene	0.9	1.1	0.05	0.05	0.008	0.003	0.012	0.004
Chrysene	0.8	0.9	0.04	0.04	0.014	0.003	0.021	0.005
Benzo(b)Fluoranthene	2.3	3.5	0.1	0.2	0.017	0.005	0.024	0.007
Benzo(k)Fluoranthene	0.9	1.6	0.04	0.08	0.006	0.002	0.009	0.003
Benzo(e)Pyrene	1.5	1.8	0.1	0.09	0.011	0.003	0.016	0.004
Benzo(a)Pyrene	0.4	0.8	0.02	0.04	0.007	0.002	0.010	0.003
Perylene	0.1	0.2	0.004	0.01	0.011	0.01	0.016	0.013
Indeno(1,2,3-c,d)Pyrene	1.0	1.6	0.05	0.1	0.008	0.002	0.012	0.003
Dibenzo(a,h)Anthracene	0.2	0.3	0.01	0.02	ND	-	ND	-
Benzo(g,h,i)Perylene	1.6	1.8	0.1	0.1	0.012	0.003	0.018	0.004

Table S21. PAH Emission Factor Results for Transient DOC+CDPF+CuZ SCR+ASC+urea and DOC+CDPF+FeZ SCR+ASC+urea Tests

	concentration							
	FTP DOC+CDPF+CuZ SCR+ASC+urea (n=5)				FTP DOC+CDPF+FeZ SCR+ASC+urea (n=5)			
	ng/L		ng/m^3		ng/L		ng/m^3	
analyte	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
Naphthalene	846.5	207.5	34.1	8.1	2,323	1,503	95.6	62.2
2-Methylnaphthalene	171.3	41.5	6.9	1.7	522.1	549.2	21.4	22.4
Acenaphthylene	5.7	0.9	0.2	0.04	8.6	11.3	0.4	0.5
Acenaphthene	23.1	1.4	0.9	0.1	31.2	7.7	1.3	0.3
Fluorene	59.3	19.9	2.4	0.8	61.8	24.7	2.5	1.0
Phenanthrene	223.8	34.7	9.0	1.4	220.9	66.8	9.1	2.7
Anthracene	9.5	5.0	0.4	0.2	7.8	9.4	0.3	0.4
Fluoranthene	52.4	5.9	2.1	0.3	52.9	13.3	2.2	0.6
Pyrene	60.9	47.9	2.5	1.9	34.0	11.7	1.4	0.5
Benzo(a)Anthracene	1.4	0.4	0.1	0.02	1.6	1.8	0.1	0.07
Chrysene	2.5	0.9	0.1	0.04	1.5	0.3	0.1	0.01
Benzo(b)Fluoranthene	3.0	1.0	0.1	0.04	2.2	1.0	0.1	0.04
Benzo(k)Fluoranthene	0.8	0.2	0.03	0.007	0.6	0.3	0.02	0.01
Benzo(e)Pyrene	2.1	0.9	0.1	0.04	1.3	0.3	0.1	0.01
Benzo(a)Pyrene	0.8	0.3	0.03	0.01	0.4	0.2	0.02	0.01
Perylene	0.4	0.1	0.02	0.004	0.1	0.1	0.004	0.004
Indeno(1,2,3-c,d)Pyrene	0.9	0.3	0.04	0.01	0.5	0.3	0.02	0.01
Dibenzo(a,h)Anthracene	ND	-	ND	-	ND	-	ND	-
Benzo(g,h,i)Perylene	1.7	0.6	0.1	0.02	0.9	0.5	0.04	0.02

Table S22. PAH Emission Factor Results for Transient DOC+CDPF and DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl Tests

	concentration							
	FTP DOC+CDPF (n=5)				FTP DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl (n=5)			
	ng/L		ng/m^3		ng/L		ng/m^3	
analyte	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
Naphthalene	2,103	503.2	85.9	20.8	1,487	2,468	61.2	101.7
2-Methylnaphthalene	556.1	270.4	22.8	11.2	535.9	847.8	22.0	34.9
Acenaphthylene	5.7	1.6	0.2	0.06	6.3	7.5	0.3	0.3
Acenaphthene	28.0	11.9	1.1	0.5	33.1	23.3	1.4	1.0
Fluorene	65.3	30.9	2.7	1.3	59.7	32.0	2.5	1.3
Phenanthrene	251.5	74.7	10.3	3.1	195.3	69.1	8.0	2.9
Anthracene	5.5	1.8	0.2	0.07	7.1	2.3	0.3	0.09
Fluoranthene	55.9	11.1	2.3	0.5	48.3	11.2	2.0	0.5
Pyrene	40.1	26.6	1.6	1.1	29.6	8.1	1.2	0.3
Benzo(a)Anthracene	0.9	0.2	0.04	0.009	1.2	1.3	0.05	0.05
Chrysene	2.6	0.5	0.1	0.02	1.9	1.2	0.1	0.05
Benzo(b)Fluoranthene	3.0	0.4	0.1	0.02	2.9	2.5	0.1	0.10
Benzo(k)Fluoranthene	1.0	0.2	0.04	0.006	1.3	1.2	0.1	0.05
Benzo(e)Pyrene	2.0	0.2	0.1	0.01	1.8	1.4	0.1	0.06
Benzo(a)Pyrene	0.8	0.5	0.03	0.02	1.1	1.4	0.05	0.06
Perylene	0.2	0.2	0.01	0.01	0.9	1.5	0.04	0.06
Indeno(1,2,3-c,d)Pyrene	1.0	0.6	0.04	0.02	1.3	1.4	0.1	0.06
Dibenzo(a,h)Anthracene	0.1	0.1	0.002	0.005	0.2	0.3	0.01	0.01
Benzo(g,h,i)Perylene	2.3	0.9	0.1	0.04	1.9	1.5	0.1	0.1

Table S23. Average PCDD/F Emissions in pg/m^3 – 2,3,7,8-substituted Congeners and Homologues by Class for Steady-state Tests, EMPC=EMPC

	concentration									
	engine out (n=14) pg/m^3		CuZ SCR HT (n=9) pg/m^3		CuZ SCR LT (n=5) pg/m^3		FeZ SCR (n=5) pg/m^3		DOC+CDPF (n=5) pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	ND	-	ND	-	ND	-	ND	-	0.004	0.01
1,2,3,7,8-PeCDD	ND	-	ND	-	ND	-	ND	-	0.01	0.01
1,2,3,4,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-	0.01	-
1,2,3,6,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-	0.01	-
1,2,3,7,8,9-HxCDD	ND	-	ND	-	ND	-	ND	-	ND	ND
1,2,3,4,6,7,8-HpCDD	0.12	0.11	0.12	0.13	0.16	0.28	0.03	0.03	0.02	0.004
OCDD	0.49	0.26	0.87	1.08	0.61	0.23	0.17	0.14	0.03	0.003
2,3,7,8-TCDF	0.38	0.10	0.33	0.10	0.29	0.08	0.01	0.02	0.07	0.10
1,2,3,7,8-PeCDF	0.02	0.03	0.04	0.06	ND	-	0.01	0.02	0.05	0.06
2,3,4,7,8-PeCDF	0.04	0.06	0.03	0.05	0.16	0.16	0.23	0.07	0.07	0.07
1,2,3,4,7,8-HxCDF	0.08	0.11	0.06	0.05	ND	-	0.04	0.04	0.02	0.02
1,2,3,6,7,8-HxCDF	0.03	0.07	0.02	0.03	ND	0.00	0.02	0.03	0.02	0.02
2,3,4,6,7,8-HxCDF	0.05	0.06	0.02	0.03	0.04	0.09	ND	-	0.02	0.02
1,2,3,7,8,9-HxCDF	0.01	0.03	0.01	0.02	ND	-	ND	-	ND	-
1,2,3,4,6,7,8-HpCDF	1.00	2.31	0.10	0.09	0.04	0.08	0.06	0.05	0.03	0.01
1,2,3,4,7,8,9-HpCDF	0.01	0.04	ND	-	ND	-	ND	-	0.01	0.004
OCDF	1.12	2.36	0.05	0.16	0.06	0.13	0.05	0.07	0.02	0.004
Total TCDDs	0.33	0.19	0.44	0.28	ND	-	1.60	2.40	11.21	9.14
Total PeCDD	ND	-	ND	-	ND	-	0.12	0.26	0.35	0.17
Total HxCDD	ND	-	0.01	0.03	ND	-	0.07	0.09	0.04	0.05
Total HpCDD	0.25	0.27	0.37	0.41	0.35	0.49	0.09	0.05	0.03	0.01
Total TCDF	12.48	2.49	14.31	3.13	8.07	0.81	4.35	1.69	21.36	12.68
Total PeCDF	2.06	5.14	0.95	0.70	0.28	0.06	0.66	0.34	1.11	0.82
Total HxCDF	0.31	0.40	0.19	0.18	0.10	0.22	0.15	0.24	0.24	0.19
Total HpCDF	1.05	2.30	0.12	0.11	0.04	0.08	0.04	0.04	0.06	0.03
ITEF TEQ (ND=0)	0.09	0.06	0.07	0.05	0.12	0.08	0.12	0.04	0.06	0.07
ITEF TEQ (ND=DL/2)	0.24	0.15	0.28	0.11	0.31	0.05	0.20	0.06	0.07	0.06
ITEF TEQ (ND=DL)	0.38	0.25	0.49	0.23	0.50	0.06	0.28	0.09	0.08	0.06

Table S24. Average PCDD/F Detection Limits in pg/m^3 – 2,3,7,8-substituted Congeners and Homologues by Class for Steady-state Tests

	detection limit									
	engine out (n=14) pg/m^3		CuZ SCR HT (n=9) pg/m^3		CuZ SCR LT (n=5) pg/m^3		FeZ SCR (n=5) pg/m^3		DOC+CDPF (n=5) pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	0.07	0.04	0.13	0.04	0.13	0.02	0.06	0.02	0.01	0.002
1,2,3,7,8-PeCDD	0.13	0.08	0.18	0.06	0.14	0.01	0.06	0.02	0.01	0.004
1,2,3,4,7,8-HxCDD	0.18	0.08	0.21	0.10	0.20	0.02	0.06	0.03	0.01	0.002
1,2,3,6,7,8-HxCDD	0.18	0.08	0.20	0.11	0.21	0.02	0.06	0.03	0.01	0.001
1,2,3,7,8,9-HxCDD	0.20	0.09	0.23	0.13	0.22	0.02	0.07	0.03	0.01	0.001
1,2,3,4,6,7,8-HpCDD	0.14	0.09	0.19	0.10	0.20	0.04	0.08	0.03	0.01	-
OCDD	0.20	0.13	0.37	0.19	0.31	0.04	0.14	0.07	0.02	0.001
2,3,7,8-TCDF	0.06	0.03	0.12	0.06	0.11	0.02	0.04	0.02	0.01	-
1,2,3,7,8-PeCDF	0.10	0.06	0.13	0.04	0.11	0.01	0.04	0.01	0.01	-
2,3,4,7,8-PeCDF	0.09	0.05	0.13	0.04	0.09	0.02	0.04	0.002	-	-
1,2,3,4,7,8-HxCDF	0.09	0.03	0.11	0.10	0.12	0.02	0.03	0.02	0.01	-
1,2,3,6,7,8-HxCDF	0.09	0.05	0.10	0.09	0.12	0.01	0.03	0.02	0.01	-
2,3,4,6,7,8-HxCDF	0.09	0.03	0.11	0.09	0.12	0.01	0.04	0.02	0.01	-
1,2,3,7,8,9-HxCDF	0.13	0.07	0.17	0.16	0.15	0.02	0.05	0.02	0.01	0.002
1,2,3,4,6,7,8-HpCDF	0.13	0.11	0.10	0.08	0.12	0.03	0.04	0.02	-	-
1,2,3,4,7,8,9-HpCDF	0.19	0.17	0.16	0.10	0.18	0.04	0.06	0.02	0.01	0.001
OCDF	0.20	0.20	0.36	0.21	0.25	0.06	0.10	0.05	0.03	-
Total TCDDs	0.07	0.03	0.10	0.03	0.13	0.02	0.04	-	-	-
Total PeCDD	0.14	0.08	0.18	0.06	0.14	0.01	0.06	0.03	-	-
Total HxCDD	0.19	0.08	0.21	0.11	0.21	0.02	0.06	0.03	0.02	0.008
Total HpCDD	0.13	0.09	0.21	0.10	0.20	0.04	0.08	0.03	0.01	-
Total TCDF	-	-	-	-	-	-	-	-	-	-
Total PeCDF	0.13	0.07	0.12	0.03	0.09	0.02	-	-	-	-
Total HxCDF	0.09	0.04	0.14	0.11	0.12	0.01	0.04	0.02	-	-
Total HpCDF	0.15	0.13	0.12	0.10	0.15	0.03	0.06	0.02	0.02	-

Table S25. Average PCDD/F Emissions in pg/m^3 – 2,3,7,8-substituted Congeners and Homologues by Class for Transient Tests, EMPC=EMPC, n=5 for each configuration

	concentration							
	DOC+CDPF+CuZ SCR+ASC+urea pg/m^3		DOC+CDPF+FeZ SCR+ASC+urea pg/m^3		DOC+CDPF pg/m^3		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,7,8-PeCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,4,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,6,7,8-HxCDD	ND	-	ND	-	ND	-	ND	-
1,2,3,7,8,9-HxCDD	ND	-	ND	-	0.01	-	ND	-
1,2,3,4,6,7,8-HpCDD	0.20	0.09	0.06	0.04	0.05	0.06	0.08	0.01
OCDD	1.35	0.34	0.34	0.20	0.18	0.03	0.25	0.03
2,3,7,8-TCDF	0.01	-	ND	-	ND	-	ND	-
1,2,3,7,8-PeCDF	0.02	0.01	ND	-	ND	-	ND	-
2,3,4,7,8-PeCDF	0.06	0.05	0.02	0.009	0.01	0.01	ND	-
1,2,3,4,7,8-HxCDF	0.04	0.04	0.01	-	ND	-	0.03	0.02
1,2,3,6,7,8-HxCDF	0.05	0.04	ND	-	ND	-	0.01	0.01
2,3,4,6,7,8-HxCDF	0.03	0.04	ND	-	ND	-	ND	-
1,2,3,7,8,9-HxCDF	ND	-	ND	-	ND	-	ND	-
1,2,3,4,6,7,8-HpCDF	0.19	0.18	0.05	0.03	0.06	0.02	0.10	0.04
1,2,3,4,7,8,9-HpCDF	0.01	-	ND	-	ND	-	ND	-
OCDF	0.34	0.21	0.21	0.14	0.14	0.06	0.19	0.10
Total TCDDs	0.04	0.05	ND	-	ND	-	0.02	0.01
Total PeCDD	ND	-	0.02	-	ND	-	0.04	0.01
Total HxCDD	0.06	-	ND	-	0.01	-	ND	-
Total HpCDD	0.38	0.17	0.09	0.08	0.06	0.06	0.14	0.04
Total TCDF	0.31	0.49	ND	-	0.02	0.02	0.03	0.07
Total PeCDF	0.36	0.49	0.02	0.009	0.01	0.01	0.005	-
Total HxCDF	0.36	0.59	0.01	-	ND	-	0.08	0.06
Total HpCDF	0.35	0.30	0.05	0.03	0.06	0.02	0.11	0.07
ITEF TEQ (ND=0)	0.05	0.05	0.01	0.01	0.01	0.01	0.01	0.004
ITEF TEQ (ND=DL/2)	0.11	0.05	0.10	0.07	0.08	0.03	0.05	0.01
ITEF TEQ (ND=DL)	0.18	0.04	0.20	0.14	0.16	0.07	0.09	0.01

Table S26. Average PCDD/F Detection Limits in pg/m^3 – 2,3,7,8-substituted Congeners and Homologues by Class for Transient Tests, n=5 for each configuration

	detection limit							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/m^3		pg/m^3		pg/m^3		pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	0.05	0.01	0.07	0.06	0.05	0.03	0.03	0.004
1,2,3,7,8-PeCDD	0.05	0.01	0.07	0.06	0.06	0.03	0.03	0.007
1,2,3,4,7,8-HxCDD	0.06	0.01	0.06	0.05	0.06	0.03	0.03	0.003
1,2,3,6,7,8-HxCDD	0.05	0.01	0.06	0.05	0.06	0.03	0.03	0.003
1,2,3,7,8,9-HxCDD	0.06	0.01	0.07	0.05	0.08	0.03	0.04	0.004
1,2,3,4,6,7,8-HpCDD	-	-	0.14	0.11	0.06	0.01	-	-
OCDD	-	-	-	-	0.29	-	-	-
2,3,7,8-TCDF	0.03	0.01	0.04	0.03	0.03	0.02	0.02	0.001
1,2,3,7,8-PeCDF	0.04	0.01	0.04	0.03	0.04	0.02	0.02	0.003
2,3,4,7,8-PeCDF	0.03	0.001	0.05	0.04	0.05	0.02	0.02	0.003
1,2,3,4,7,8-HxCDF	0.04	0.01	0.04	0.04	0.04	0.02	0.02	-
1,2,3,6,7,8-HxCDF	0.04	0.01	0.04	0.03	0.04	0.02	0.03	0.004
2,3,4,6,7,8-HxCDF	0.04	0.004	0.04	0.04	0.04	0.02	0.03	0.004
1,2,3,7,8,9-HxCDF	0.04	0.01	0.06	0.05	0.05	0.02	0.03	0.006
1,2,3,4,6,7,8-HpCDF	-	-	0.08	0.07	0.09	-	-	-
1,2,3,4,7,8,9-HpCDF	0.05	0.01	0.08	0.07	0.07	0.04	0.03	0.005
OCDF	-	-	0.07	-	0.26	-	-	-
Total TCDDs	0.05	0.01	0.07	0.06	0.05	0.03	0.03	0.006
Total PeCDD	0.05	0.01	0.08	0.06	0.06	0.03	0.03	0.002
Total HxCDD	0.06	0.01	0.07	0.05	0.07	0.03	0.03	0.003
Total HpCDD	-	-	0.14	0.11	0.06	0.01	-	-
Total TCDF	0.03	0.002	0.04	0.03	0.04	0.02	0.02	0.001
Total PeCDF	0.03	0.001	0.05	0.04	0.05	0.02	0.02	0.002
Total HxCDF	0.04	0.004	0.05	0.04	0.04	0.02	0.02	-
Total HpCDF	-	-	0.10	0.09	0.11	-	-	-

Table S27. Average PCB Emissions in pg/m^3 – 2005 WHO Congeners and Homologues by Class for Steady-state Tests, EMPC=EMPC

	concentration									
	engine out (n=14) pg/m^3		CuZ SCR HT (n=9) pg/m^3		CuZ SCR LT (n=5) pg/m^3		FeZ SCR (n=5) pg/m^3		DOC+CDPF (n=5) pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	1.1	1.4	2.6	3.1	12.4	4.2	2.8	1.2	0.1	0.14
PCB-81	ND	-	ND	-	3.9	2.1	ND	-	ND	-
PCB-105	20.8	22.1	41.2	22.0	51.3	37.4	14.6	6.8	0.7	0.25
PCB-114	ND	-	ND	-	6.7	4.5	0.90	0.37	0.02	-
PCB-118	60.5	24.5	82.7	42.0	154.8	142.1	38.0	15.0	1.8	0.52
PCB-123	ND	-	ND	-	6.7	3.5	0.32	0.48	0.7	0.25
PCB-126	ND	-	ND	-	4.5	3.8	ND	-	ND	-
PCB-156/157	ND	-	4.1	9.3	15.9	6.5	1.8	0.73	0.2	0.13
PCB-167	ND	-	ND	-	7.4	3.8	0.66	0.45	0.2	0.10
PCB-169	ND	-	ND	-	7.8	2.6	ND	-	ND	-
PCB-189	ND	-	ND	-	6.4	1.8	ND	-	ND	-
Total Mono-CBs	80.6	121.8	2680	916.7	1676	321.0	73.3	31.4	7.0	5.6
Total Di-CBs	1,535	4,401	510.5	190.2	741.6	454.1	338.4	157.0	105.7	35.1
Total Tri-CBs	493.7	339.5	750.4	250.7	1,084	770.6	494.7	162.5	307.1	75.7
Total Tetra-CBs	4,643	6,487	6,566	7,180	5,589	3,840	1,618	1,134	14,278	3,722
Total Penta-CBs	970.5	556.1	1152	461.3	2606	2,765	666.4	155.7	71.3	22.4
Total Hexa-CBs	490.8	364.6	464.8	254.1	1199	1,135	251.8	59.2	25.1	6.3
Total Hepta-CBs	135.2	164.2	111.2	48.6	344.7	294.4	82.3	23.9	14.7	7.6
Total Octa-CBs	10.7	42.4	5.1	7.2	63.5	43.0	14.3	6.1	1.4	0.75
Total Nona-CBs	0.91	3.7	ND	-	15.4	6.9	1.3	1.4	ND	-
PCB-209	ND	-	ND	-	8.8	2.3	0.08	0.18	ND	-
WHO 2005 TEQ (ND=0)	0.003	-	0.004	-	0.69	0.45	0.002	-	0.0001	0.00004
WHO 2005 TEQ (ND=DL/2)	1.2	0.27	0.36	0.11	0.82	0.38	0.11	-	0.003	0.001
WHO 2005 TEQ (ND=DL)	2.4	0.53	0.72	0.21	0.94	0.31	0.21	-	0.006	0.003

Table S28. Average PCB Detection Limits in pg/m^3 – 2005 WHO Congeners and Homologues by Class for Steady-state Tests

	detection limit									
	engine out (n=14) pg/m^3		CuZ SCR HT (n=9) pg/m^3		CuZ SCR LT (n=5) pg/m^3		FeZ SCR (n=5) pg/m^3		DOC+CDPF (n=5) pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	21.8	5.5	8.8	1.7	-	-	1.4	0.22	0.14	0.05
PCB-81	19.3	3.8	8.9	1.9	2.8	2.0	1.4	0.27	0.13	0.03
PCB-105	14.1	7.8	0.55	-	-	-	-	-	-	-
PCB-114	11.0	5.9	4.6	1.8	0.65	0.22	1.7	0.18	0.04	0.01
PCB-118	5.5	-	-	-	-	-	-	-	-	-
PCB-123	11.8	6.5	4.9	1.9	0.74	-	1.8	0.20	-	-
PCB-126	16.9	3.9	4.7	2.0	1.8	0.74	1.5	0.22	0.06	0.01
PCB-156/157	23.8	6.4	6.9	3.5	-	-	2.6	0.27	-	-
PCB-167	19.2	5.8	7.0	2.0	1.4	-	1.8	0.28	0.05	-
PCB-169	21.9	6.0	8.0	1.8	2.2	-	2.0	0.16	0.08	0.04
PCB-189	11.5	3.8	3.6	1.0	1.5	-	1.3	0.19	0.05	0.02
Total Mono-CBs	50.0	6.9	-	-	-	-	-	-	-	-
Total Di-CBs	-	-	-	-	-	-	-	-	-	-
Total Tri-CBs	-	-	-	-	-	-	-	-	-	-
Total Tetra-CBs	-	-	-	-	-	-	-	-	-	-
Total Penta-CBs	-	-	-	-	-	-	-	-	-	-
Total Hexa-CBs	-	-	-	-	-	-	-	-	-	-
Total Hepta-CBs	2.5	0.08	2.3	-	-	-	-	-	-	-
Total Octa-CBs	13.6	8.0	3.6	2.6	-	-	2.1	0.22	-	-
Total Nona-CBs	16.0	7.8	8.6	3.2	1.1	-	2.7	0.44	0.14	0.03
PCB-209	15.7	6.6	9.0	3.0	0.61	-	2.5	0.58	0.05	0.01

Table S29. Average PCB Emissions in pg/m^3 – 2005 WHO Congeners and Homologues by Class for Transient Tests, EMPC=EMPC, n=5 for each configuration

	concentration							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/m^3		pg/m^3		pg/m^3		pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	0.50	0.3	0.58	0.14	0.53	0.05	0.56	0.16
PCB-81	ND	-	ND	-	ND	-	0.01	-
PCB-105	4.3	1.9	4.8	1.6	3.3	1.1	3.4	1.00
PCB-114	0.23	0.13	0.28	0.27	0.12	0.07	0.27	0.09
PCB-118	12.7	4.9	13.6	7.8	8.0	2.6	9.1	3.8
PCB-123	0.14	0.09	0.21	0.16	0.03	-	0.19	0.07
PCB-126	ND	-	ND	-	ND	-	0.04	0.02
PCB-156/157	1.3	0.43	1.1	0.12	1.1	0.30	1.2	0.29
PCB-167	0.43	0.23	0.35	0.04	0.41	0.15	0.48	0.12
PCB-169	ND	-	ND	-	ND	-	0.15	0.03
PCB-189	0.07	0.06	ND	-	ND	-	0.14	0.03
Total Mono-CBs	304.0	629.4	10.7	10.3	7.7	3.1	34.0	17.0
Total Di-CBs	1,644	3,488	91.5	79.4	81.8	37.5	87.1	22.5
Total Tri-CBs	2,113	4,493	137.9	123.5	94.9	54.5	88.8	57.6
Total Tetra-CBs	444.6	721.0	228.3	282.4	115.5	58.1	103.3	57.2
Total Penta-CBs	103.4	38.9	184.6	202.4	75.9	32.3	85.0	52.3
Total Hexa-CBs	78.5	21.8	88.6	44.1	65.6	23.5	75.3	27.6
Total Hepta-CBs	41.8	10.8	36.6	2.4	35.9	9.6	44.2	13.5
Total Octa-CBs	11.0	4.8	7.5	0.35	5.9	1.6	11.2	2.1
Total Nona-CBs	1.1	0.82	0.53	0.28	0.54	0.10	0.93	0.34
PCB-209	0.15	0.16	0.06	-	0.17	0.14	0.24	0.05
WHO 2005 TEQ (ND=0)	0.001	0.0003	0.001	0.0003	0.0004	0.0001	0.01	0.01
WHO 2005 TEQ (ND=DL/2)	0.02	0.01	0.01	0.01	0.01	0.003	0.01	0.004
WHO 2005 TEQ (ND=DL)	0.03	0.03	0.02	0.01	0.02	0.01	0.01	0.003

Table S30. Average PCB Detection Limits in pg/m^3 – 2005 WHO Congeners and Homologues by Class for Transient Tests, n=5 for each configuration

	detection limit							
	DOC+CDPF+CuZ SCR+ASC+urea		DOC+CDPF+FeZ SCR+ASC+urea		DOC+CDPF		DOC+CDPF+CuZ SCR+ASC+urea, 10 ppm Cl	
	pg/m^3		pg/m^3		pg/m^3		pg/m^3	
compound	average	standard deviation	average	standard deviation	average	standard deviation	average	standard deviation
PCB-77	1.4	-	-	-	-	-	-	-
PCB-81	0.40	0.53	0.11	0.09	0.10	0.02	0.07	0.01
PCB-105	-	-	-	-	-	-	-	-
PCB-114	0.36	0.31	0.29	-	0.12	0.02	-	-
PCB-118	-	-	-	-	-	-	-	-
PCB-123	0.38	0.33	0.29	-	0.11	0.02	-	-
PCB-126	0.22	0.19	0.15	0.09	0.13	0.05	0.04	0.01
PCB-156/157	-	-	-	-	-	-	-	-
PCB-167	0.76	-	0.33	-	-	-	-	-
PCB-169	0.26	0.30	0.17	0.13	0.17	0.05	-	-
PCB-189	0.32	0.34	0.13	0.09	0.09	0.03	-	-
Total Mono-CBs	-	-	-	-	-	-	-	-
Total Di-CBs	-	-	-	-	-	-	-	-
Total Tri-CBs	-	-	-	-	-	-	-	-
Total Tetra-CBs	-	-	-	-	-	-	-	-
Total Penta-CBs	-	-	-	-	-	-	-	-
Total Hexa-CBs	-	-	-	-	-	-	-	-
Total Hepta-CBs	-	-	-	-	-	-	-	-
Total Octa-CBs	-	-	-	-	-	-	-	-
Total Nona-CBs	1.38	-	0.46	-	-	-	-	-
PCB-209	-	-	0.21	-	0.13	0.04	-	-

Table S31. Average PCDD/F and PCB Tunnel Blank Results in pg/m^3 – 2,3,7,8-substituted Congeners and Homologues by Class (PCDD/F) and 2005 WHO Congeners and Homologues by Class (PCB), EMPC=EMPC, n=5

compound	concentration pg/m^3		detection limit pg/m^3	
	average	standard deviation	average	standard deviation
2,3,7,8-TCDD	ND	-	0.02	0.001
1,2,3,7,8-PeCDD	ND	-	0.02	0.003
1,2,3,4,7,8-HxCDD	ND	-	0.02	0.001
1,2,3,6,7,8-HxCDD	ND	-	0.02	0.002
1,2,3,7,8,9-HxCDD	ND	-	0.02	0.002
1,2,3,4,6,7,8-HpCDD	ND	-	0.02	0.002
OCDD	0.01	-	0.03	0.003
2,3,7,8-TCDF	ND	-	0.01	0.001
1,2,3,7,8-PeCDF	ND	-	0.01	0.001
2,3,4,7,8-PeCDF	0.01	0.001	0.01	0.0003
1,2,3,4,7,8-HxCDF	ND	-	0.01	0.001
1,2,3,6,7,8-HxCDF	ND	-	0.01	0.001
2,3,4,6,7,8-HxCDF	ND	-	0.01	0.001
1,2,3,7,8,9-HxCDF	ND	-	0.01	0.002
1,2,3,4,6,7,8-HpCDF	ND	-	0.01	0.002
1,2,3,4,7,8,9-HpCDF	ND	-	0.01	0.001
OCDF	ND	-	0.03	0.003
Total TCDDs	0.03	0.07	0.54	0.91
Total PeCDD	ND	-	0.02	0.004
Total HxCDD	ND	-	0.02	0.002
Total HpCDD	ND	-	0.02	0.002
Total TCDF	0.08	0.08	-	-
Total PeCDF	0.01	0.001	0.01	0.0004
Total HxCDF	ND	-	0.01	0.001
Total HpCDF	ND	-	0.01	0.001
ITEF TEQ (ND=0)	0.003	0.004		
ITEF TEQ (ND=DL/2)	0.02	0.002		
ITEF TEQ (ND=DL)	0.04	0.002		

compound	concentration pg/m^3		detection limit pg/m^3	
	average	standard deviation	average	standard deviation
PCB-77	0.30	0.08	-	-
PCB-81	ND	-	0.02	0.004
PCB-105	1.74	0.60	-	-
PCB-114	0.16	0.05	-	-
PCB-118	6.32	2.1	-	-
PCB-123	0.11	0.04	0.04	-
PCB-126	ND	-	0.03	0.004
PCB-156/157	0.34	0.10	-	-
PCB-167	0.16	0.04	-	-
PCB-169	ND	-	0.02	0.003
PCB-189	0.03	0.005	0.01	-
Total Mono-CBs	10.62	4.0	-	-
Total Di-CBs	63.34	28.9	-	-
Total Tri-CBs	95.27	48.6	-	-
Total Tetra-CBs	205.1	157.1	-	-
Total Penta-CBs	128.4	46.1	-	-
Total Hexa-CBs	53.30	16.8	-	-
Total Hepta-CBs	15.73	4.2	-	-
Total Octa-CBs	3.14	0.75	-	-
Total Nona-CBs	0.55	0.16	-	-
PCB-209	0.07	0.05	0.03	-
WHO 2005 TEQ (ND=0)	0.03	0.0001		
WHO 2005 TEQ (ND=DL/2)	0.25	0.0002		
WHO 2005 TEQ (ND=DL)	0.47	0.0005		