SUPPLEMENTAL INFORMATION

Variability of Particle Number Emissions from Diesel and Hybrid Diesel-Electric Buses in Real Driving Conditions

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Summary of Supplemental Information

Total Pages: 18

Number of Figures: 10

Number of Tables: 17

This **SUPPLEMENTAL INFORMATION** provides detailed testing schedule information, specifications for the two bus technologies, additional route average operating parameters, graphs of average particle concentration for each bus run, model diagnostic tests, fixed effects for interaction parameters, and differences in least-square means.

Table S-1. Specifications of Conventional Diesel and Hybrid Diesel-Electric Buses Tested

Specification	Conventional Diesel (CD)	Hybrid Diesel-Electric (HDE)
Engine	2002 Detroit Diesel Series 40E	2003 Cummins ISL 280
# cylinders, displacement (L)	6 cyl., 8.7 L	6 cyl., 8.9 L
Transmission	Allison B400R Automatic	Allison EP 40
Rated Power @ 2000 RPM, bhp (kW)	280 (205)	289 (205)
Peak Torque, lb-ft (N-m)	900 (1166)	900 (1220)
Combustion/Fuel System	Direct Injection	Electronic Timing Control
Exhaust Aftertreatment	Phase I - II: single-brick DOC; Phase III: Englehard DPX	Phase I-II: dual-brick DOC Phase III: Johnson-Matthew CRT DPF
Electric motors	N/A	Two Concentric AC Induction Motors
Battery	N/A	Sealed Nickel-Metal Hydride
Bus mileage prior to testing, mi	78,400 (201) 67,000 (202)	29,600 (H301) 28,800 (H302)
Weight, kg	13,086 (empty)	13,318 (empty)

Table S-2. Summary of Testing Days Used in Statistical Analysis

	CD Bus 1	CD Bus 2	HDE Bus1	HDE Bus 2
Phase I				
Fuel: No. 1 Diesel	23-Jan	11-Feb	6-Jan	27-Feb
Aftertreatment: DOC	30-Jan	13-Feb [a]	21-Jan	30-Apr
Ambient Temperature Range:	23-Apr	18-Feb [b]	16-Apr	
(-9.4 to 22.8 ^{o}C)		28-Apr	21-Apr	
		26-May		
		27-May		
Phase II				
Fuel: ULSD	6-Aug	20-Sep	29-Jul	25-Aug
Aftertreatment: DOC	10-Aug	21-Sep	3-Aug	26-Aug
Ambient Temperature Range:			4-Aug	
(18.2 to 29.4 ^{o}C)				
Phase III				
Fuel: ULSD	20-Oct	9-Nov	12-Oct [c]	2-Nov
Aftertreatment: DOC+DPF	25-Oct	10-Nov	13-Oct	3-Nov
Ambient Temperature Range:			15-Oct	
(0.6 to 18.9 ^{o}C)				

[a] Missing Avon Inbound and Farmington Inbound runs. [b] Each inbound and outbound run was made twice (16 runs) [c] Missing Enfield runs

Details on Experimental Data

Table S-2 contains the testing schedule, bus number, fuel/aftertreatment configuration. Figures S-1 through S-6 graphically display the average particle number concentration as recorded on each bus run for each day of testing.

On February 18th, two complete runs were made, providing an additional set of replications (2 inbound and 2 outbound runs for each route). On two days of the study, issues arose that prevented all of the routes to be recorded, or caused the recorded data to be unrepresentative of true conditions. On February 13th, the air compressor used with the dilution system failed before the Avon Inbound and Farmington Inbound routes could be measured. On October 12th all of the routes except the Enfield route were measured. The remaining data that was correctly recorded for these days was included in the statistical analysis.

Several testing days were not included in the statistical analysis due to issues with the sampling equipment that yielded unrepresentative measurements of the true particle number concentration. On May 28th and June 2nd the desiccant became saturated from rain, this erroneously affected the formation of particles on all routes. On November 16th and 17th there was excessive vibration on the HDE buses, which caused the ELPI to yield erroneously high counts to be recorded for these two days, except for the Farmington route, which may have been because the bus was operating at lower speeds. More complete information on the testing setup and schedule is available in Holmen *et al.* (*9*)

Table S-3. Table 1. Engine Speed by Routes for both Bus Technologies [a]

	Conventional			Hybrid Diesel-Electric		
Engine Speed (rpm)	Average	St. Dev	(Min/Max)	Average	St. Dev	(Min/Max)
Avon Down	1340	72	(1182/1471)	1454	145	(1236/1762)
Avon Up	1591	67	(1473/1689)	1841	61	(1722/1975)
Enfield	1963	57	(1868/2048)	1873	83	(1734/2039)
Farmington	1055	26	(978/1089)	993	20	(961/1048)

[a] Route parameters are recorded second-by-second using a Vansco USB Data Link Adapter on all 4 buses from April 16 onward. 9 pre-April testing days are not included, and 1 Enfield run from Nov. 9 is missing. [b] The listed values are averages, standard deviations, minimums and maximums of averages. The second-by-second data is averaged for each route, and then the average, minimum, and maximum across all test runs were calculated.

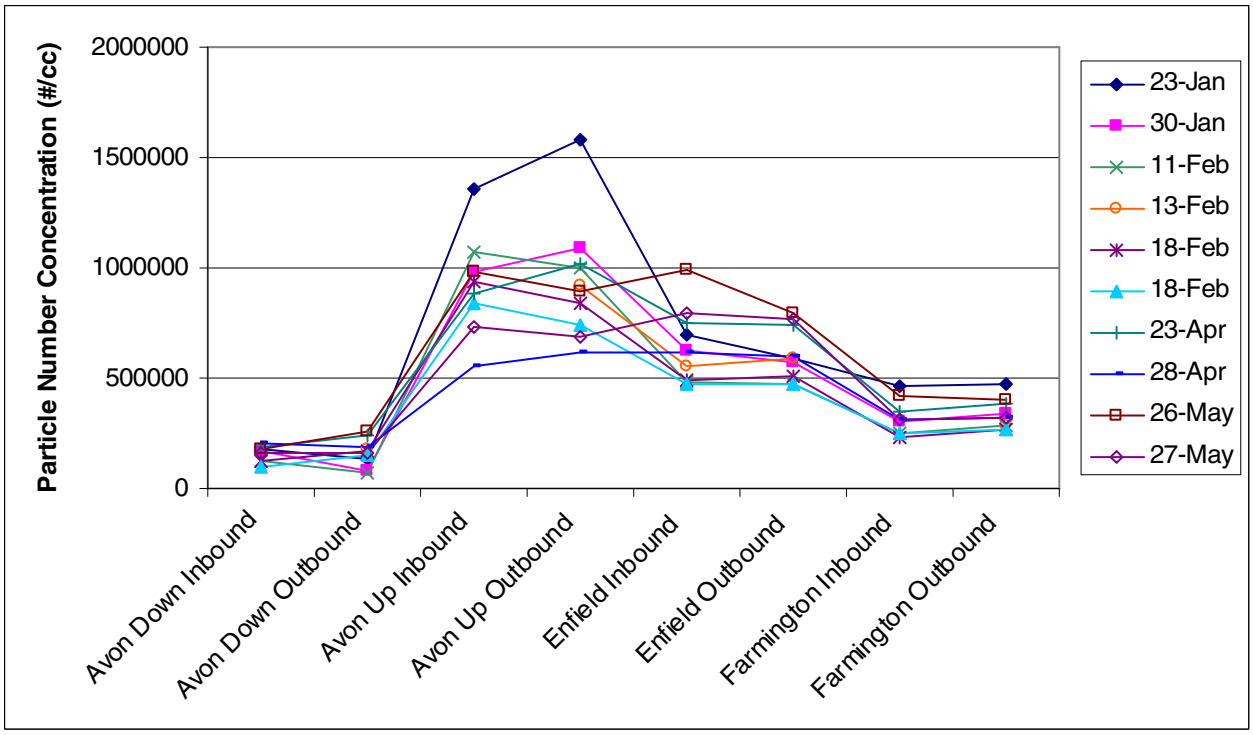

Figure S-1. Particle Number Concentrations according to Route and Testing Day for Conventional Diesel Buses on No. 1 Diesel Fuel

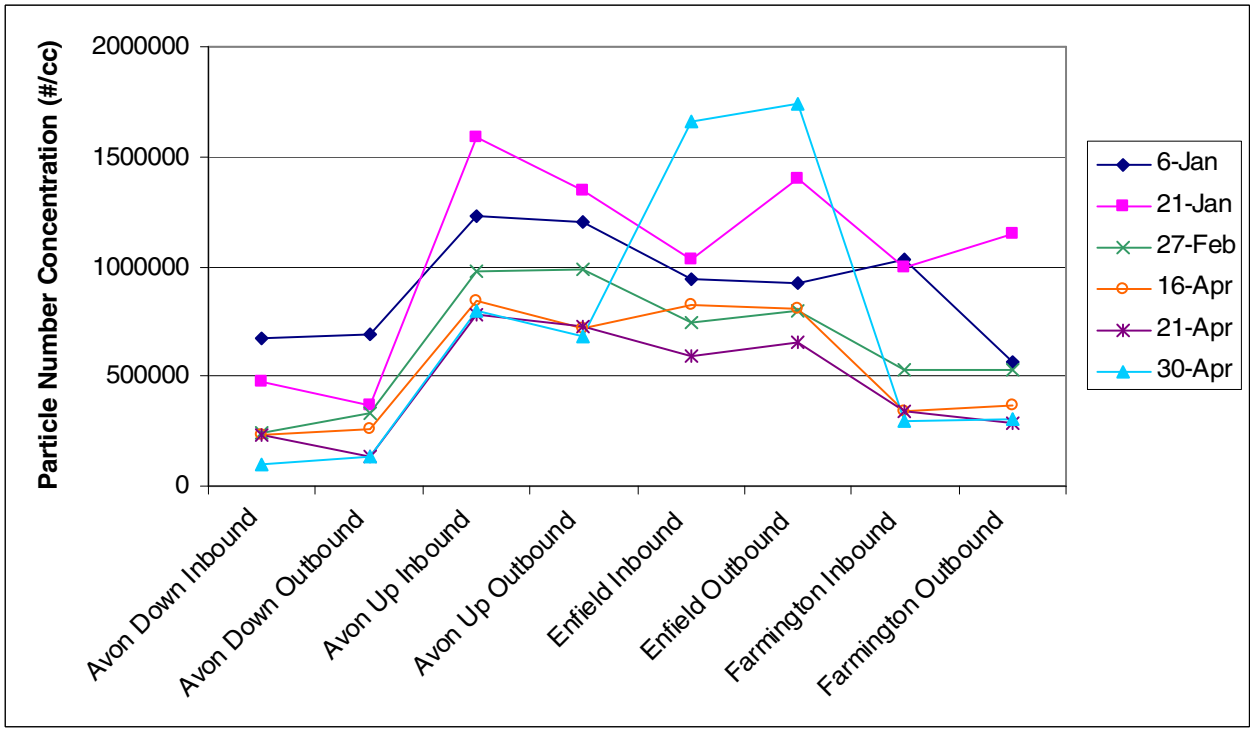

Figure S-2. Particle Number Concentrations according to Route and Testing Day for Hybrid Diesel-Electric Buses on No. 1 Diesel Fuel

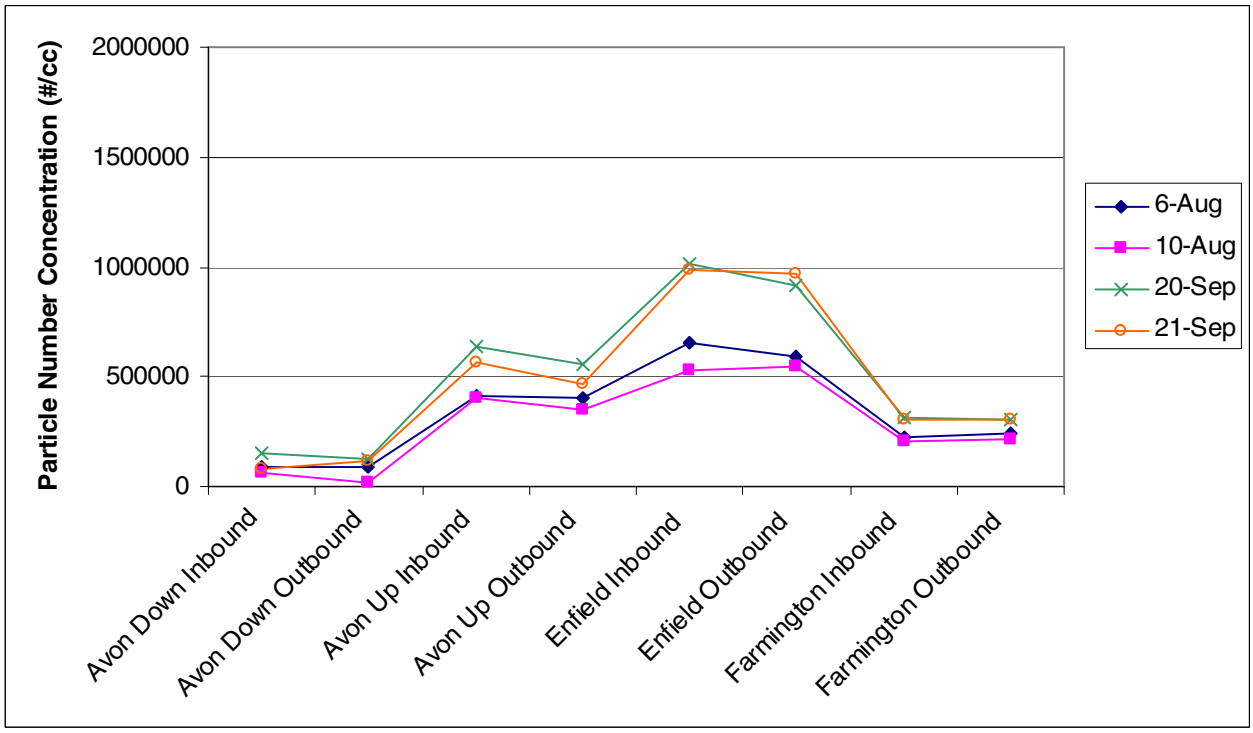

Figure S-3. Particle Number Concentrations according to Route and Testing Day for Conventional Diesel Buses on ULSD fuel

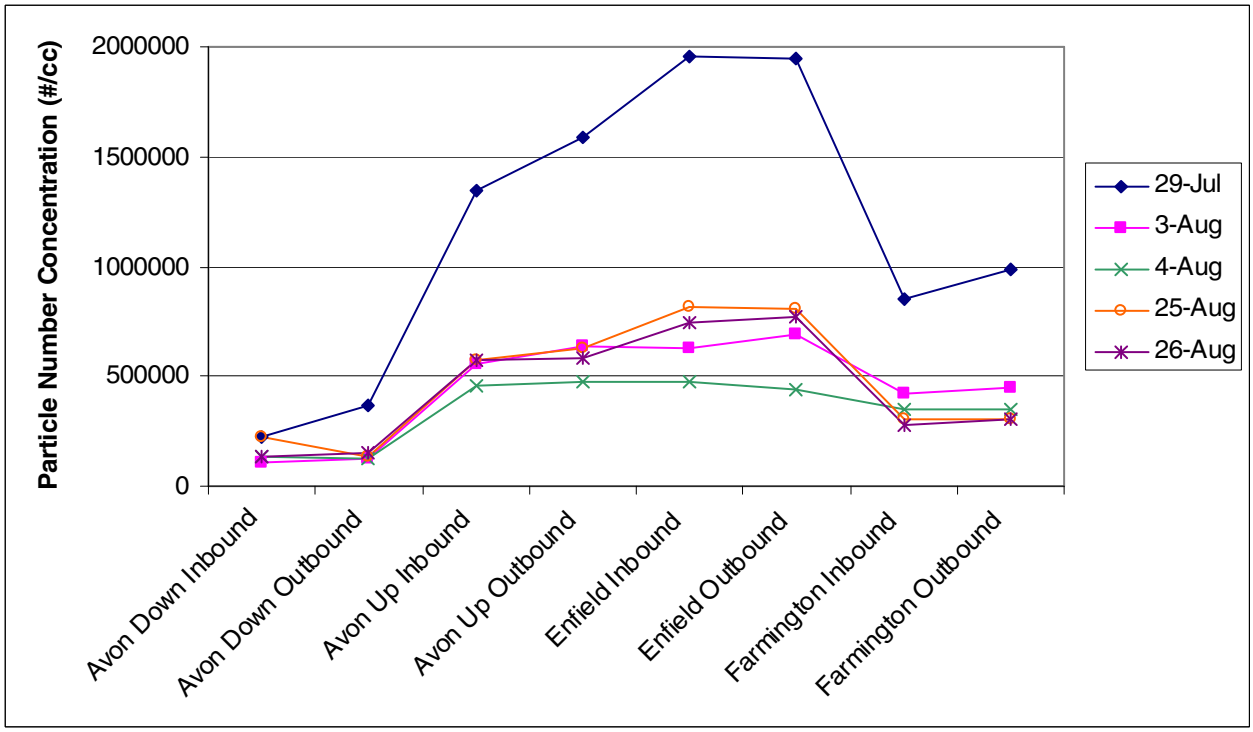

Figure S-4. Particle Number Concentrations according to Route and Testing Day for Hybrid Diesel-Electric Buses on ULSD fuel

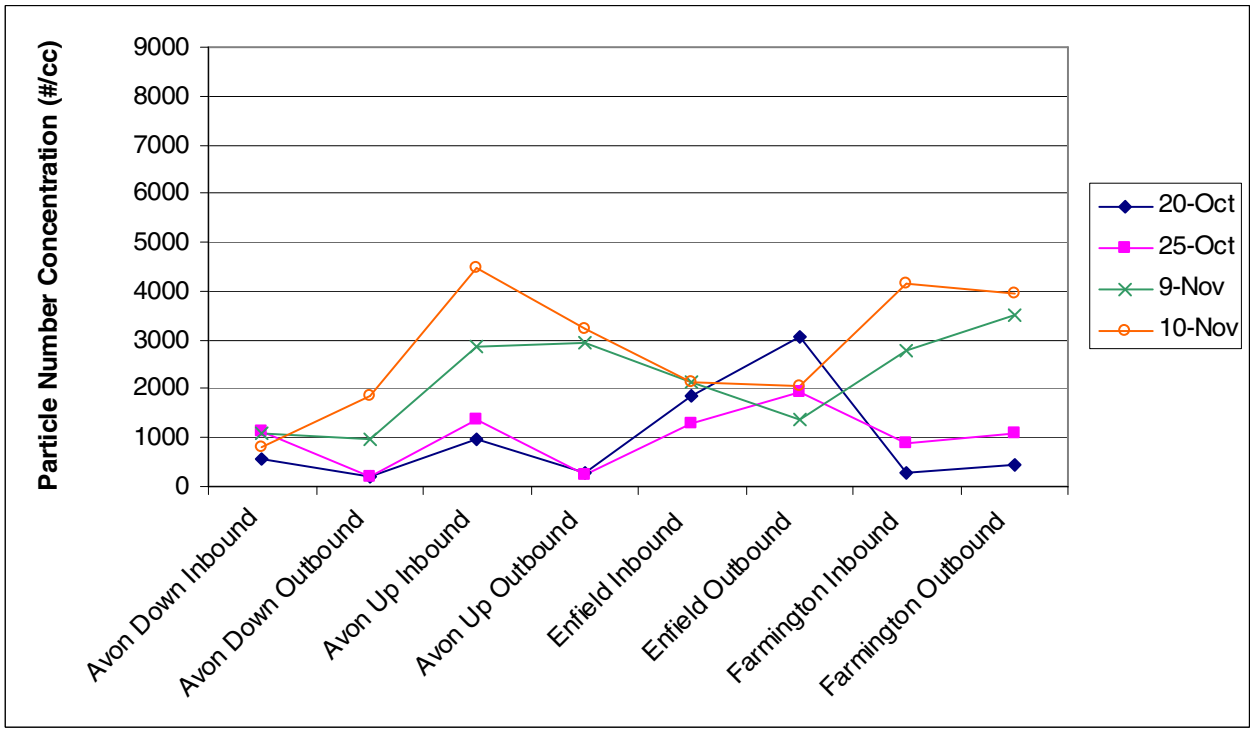

Figure S-5. Particle Number Concentrations according to Route and Testing Day for Conventional Diesel Buses on ULSD with Diesel Particulate Filters

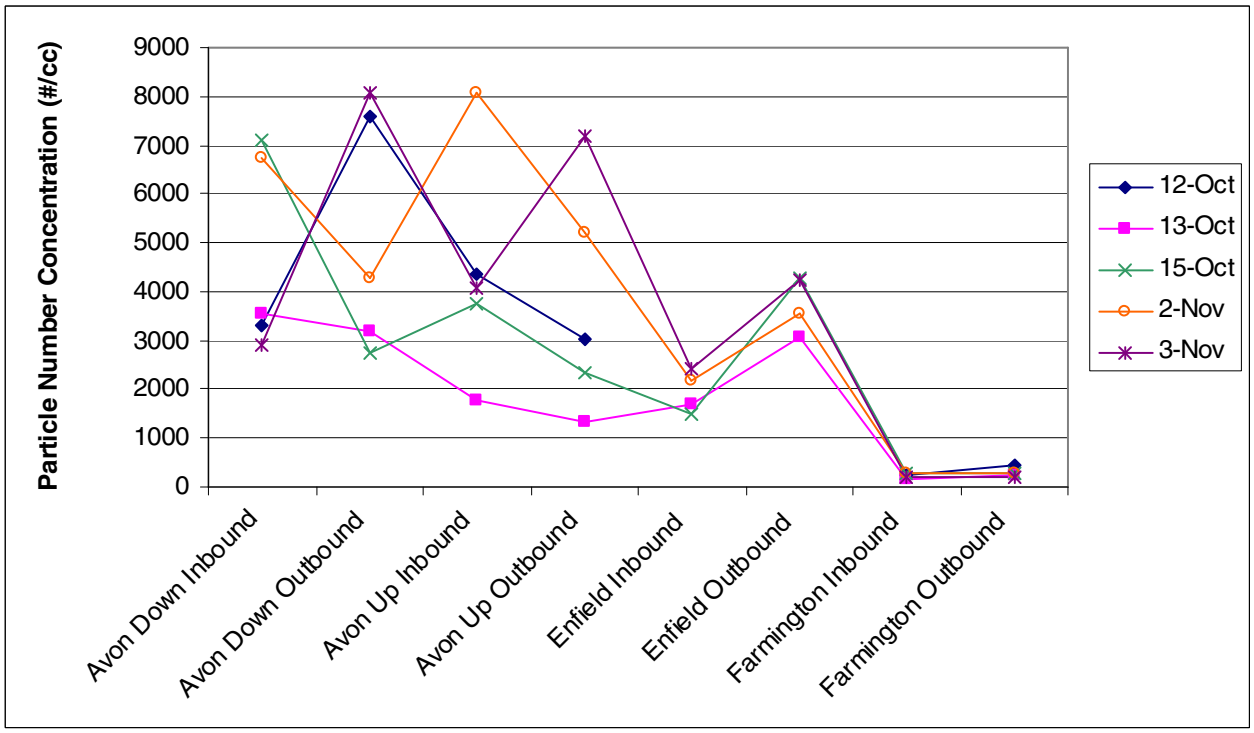

Figure S-6. Particle Number Concentrations according to Route and Testing Day for Hybrid Diesel-Electric Buses on ULSD with Diesel Particulate Filters

Model Diagnostic Tests

The statistics for the model fit with homogeneous residuals are shown in Table S-4. In Figure S-7, the conditional studentized residuals from the full interaction model are plotted alongside the predicted emissions. The conditional studentized residuals account for both the random and fixed effects, and are corrected by their estimated standard error (*10*). The predicted values are clearly divided into two groups; the lower values correspond to the particle number emissions recorded from buses outfitted with the DPF. These have a noticeably higher variation than for the concentrations without DPFs. This property violates the model assumption that the residuals errors are independent and identically distributed.

Table S-4. Homogeneous Residual Model Fit Statistics

-2 Res Log Likelihood	6.8
AIC (smaller is better)	12.8
AICC (smaller is better)	12.9
BIC (smaller is better)	6.8

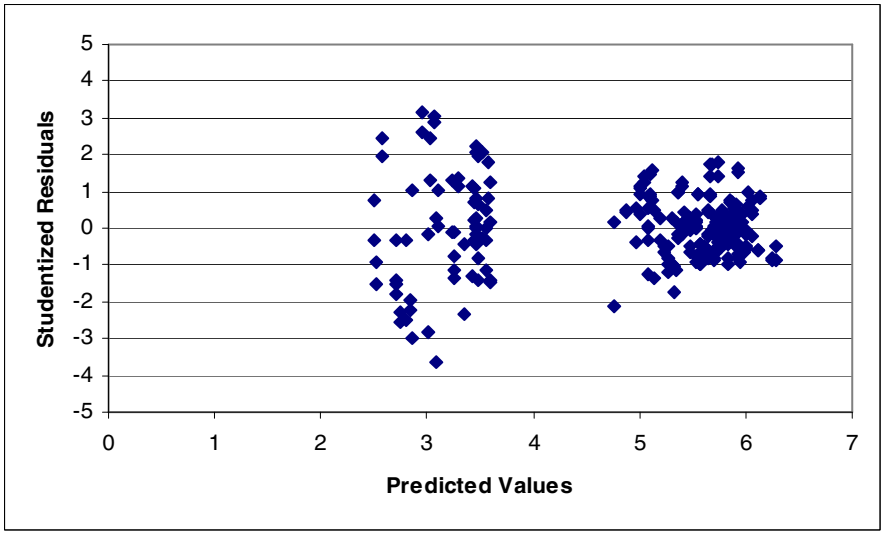

Figure S-7. Residuals from Homogeneous Residual Variance

To assure that the residuals are independent and identically distributed, we first implemented an alternative model that estimates a separate residual variance for the buses with and without DPFs (heterogeneous residual structure). The likelihood and other fit statistics are shown in Table S-5, which shows an increase in fit for all of the criteria. A likelihood ratio test determined that the heterogeneous residual model provides a significant increase in the goodness-of-fit (p-value <0.0001). Figure S-8 plots the studentized residuals from the alternative model that estimated separate residual variances for the DOC and DOC+DPF treatments. By implementing a heterogeneous residual structure the studentized residuals have more comparable variances.

The studentized residuals are useful for detecting outliers. Figure S-8 contains several residuals that are at least 3 standard errors from the mean, with one value almost 5 standard errors from the mean values. The experimental information was reviewed from these days to see if there were experimental errors that would warrant their removing from the analysis. No evidence was found that would suggest that the data points were unrepresentative of the testing measurements.

Table S-5. Heterogeneous Residual Model Fit Statistics (Residuals Grouped according to DPF and DOC treatments)

-2 Res Log Likelihood	-124.7
AIC (smaller is better)	-116.7
AICC (smaller is better)	-116.5
BIC (smaller is better)	-124.7

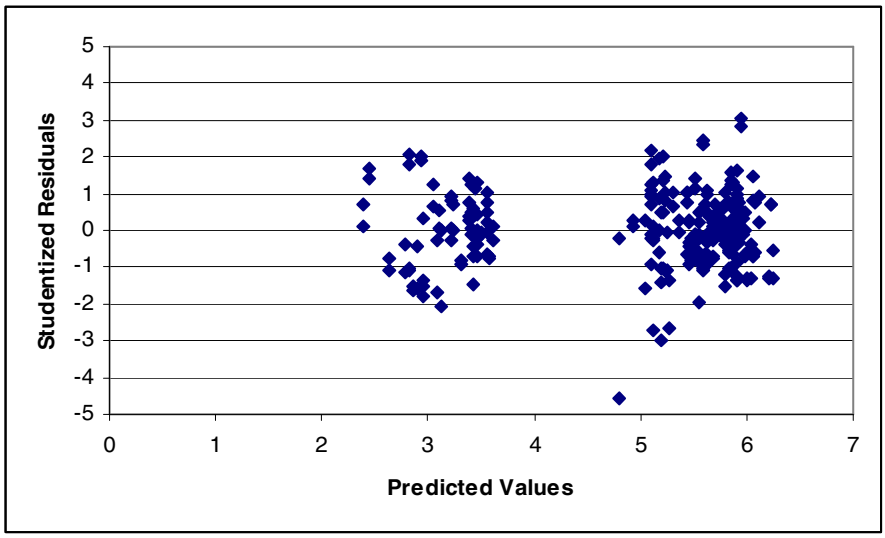

Figure S-8. Residuals from Heterogeneous Residual Variances Grouped According to DOC and DPF treatments

Next, we implemented a third model that estimated separate variance for the DPF treatment, as well as separate variances for each route under the DOC treatment (total of 5 residual variance terms). The fit statistics of the model were all improved as shown in Table S-6. A likelihood ratio test determined that the third model provided a significant increase in fit (p-value <0.0001) over the previous model. All studentized residuals were within 3 standard errors as shown in Figure S-9. Standard normality tests were used to test if the residuals pass the normality assumptions in Table S-5 through S-9. All of the statistics are insignificant, meaning that the null hypothesis of normally distributed errors was not rejected for each residual group. By implementing the current heterogeneous residual structure, the large variability of the data was able to be modeled accurately without having to remove influential outliers.

Table S-6. Heterogeneous Residual Model Fit Statistics (Residuals Grouped according to DPF and each route with DOC treatment)

-2 Res Log Likelihood	-171.0
AIC (smaller is better)	-157.0
AICC (smaller is better)	-156.5
BIC (smaller is better)	-171.0

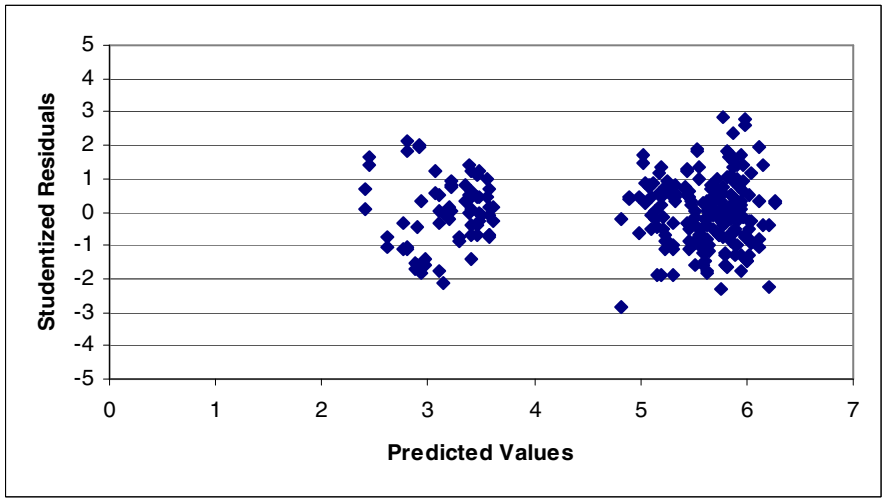

Figure S-9. Residuals from Heterogeneous Residual Variances Grouped According to DOC and DPF, an Each Route with the DOC Treatment

Table S-5. Normality Tests for Residuals from Avon Down + DOC treatment

Test	Statistic		p Value	
Shapiro-Wilk	W	0.973963	Pr < W	0.3455
Kolmogorov-Smirnov	D	0.096256	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.062684	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.389508	Pr > A-Sq	>0.2500

Table S-6. Normality Tests for residuals from Avon Up + DOC treatment

Test	Statistic		p Value	
Shapiro-Wilk	W	0.98518	Pr < W	0.7890
Kolmogorov-Smirnov	D	0.058678	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.018977	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.174784	Pr > A-Sq	>0.2500

Table S-7. Normality Tests for residuals from Enfield + DOC treatment

Test	Statistic		p Value	
Shapiro-Wilk	W	0.964446	Pr < W	0.1365
Kolmogorov-Smirnov	D	0.09405	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.054703	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.416065	Pr > A-Sq	>0.2500

Table S-8. Normality Tests for residuals from Farmington + DOC treatment

Test	Statistic		p Value	
Shapiro-Wilk	W	0.979072	Pr < W	0.5270
Kolmogorov-Smirnov	D	0.059585	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.026199	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.219712	Pr > A-Sq	>0.2500

Table S-9. Normality Tests for residuals from DPF treatment

Test	Statistic		p Value	
Shapiro-Wilk	W	0.986493	Pr < W	0.6560
Kolmogorov-Smirnov	D	0.047477	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.021333	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.181594	Pr > A-Sq	>0.2500

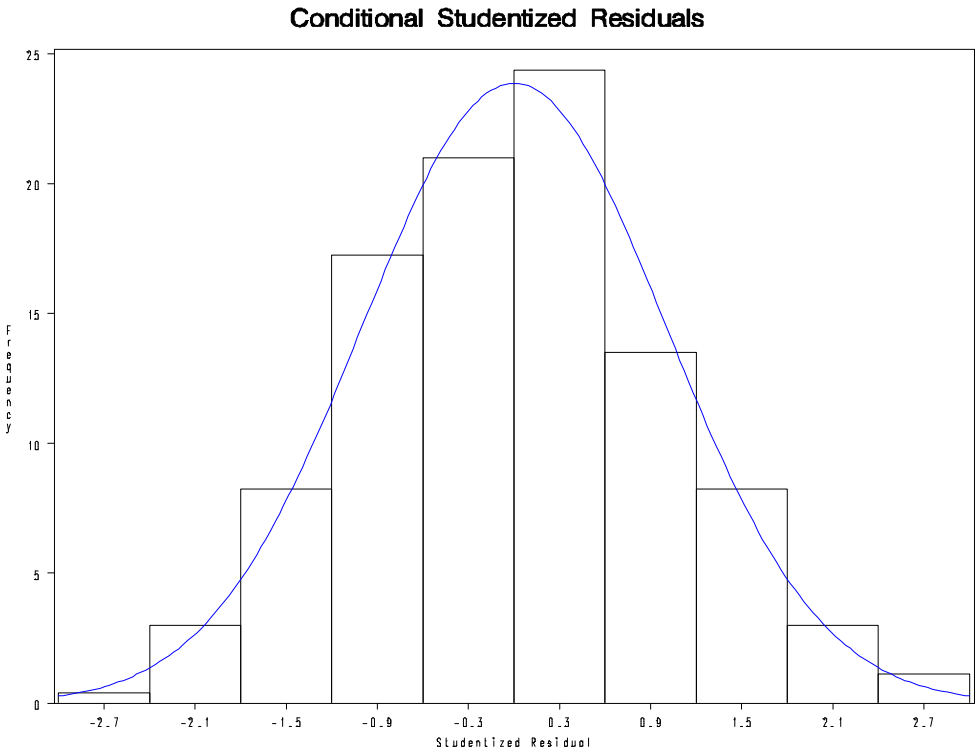

Figure S-10. Histogram of Conditional Studentized Residuals with Heterogeneous Residuals Variances for the DPF Treatment, and each route under the DOC treatment.

Table S-10. Type 3 Tests of Fixed Effects.

Effect	Num DF	Den DF	F Value	Pr > F
Tech	1	2	13.93	0.0649
Fuel	1	22	0.03	0.8555
Aftertreatment	1	22	180.53	<.0001
Driver	1	22	4.89	0.0378
Temperature	1	222	14.48	0.0002
Route	3	222	27.77	<.0001
Tech*Fuel	1	22	0.54	0.4706
Tech*Aftertreatment	1	22	0.67	0.4225
Tech*Route	3	222	9.42	<.0001
Route*Driver	3	222	27.27	<.0001
Temperature*Aftertreatment	1	222	3.37	0.0677
Route*Aftertreatment	3	222	17.55	<.0001

Table S-11 Fixed Effect Parameters (Including Interaction Effects) according to baseline case of: CD bus, ULSD fuel, DOC aftertreatment, Post-April Driver, and Farmington Route

Effect			Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept			5.6842	0.08533	2	66.61	0.0002
Tech	HDE		0.2878	0.08205	2	3.51	0.0725
Tech	CD		0	.	.	.	.
Fuel	#1 D		0.02634	0.08156	22	0.32	0.7497
Fuel	ULSD		0	.	.	.	.
Aftertreatment	DOC+DPF		-2.7605	0.1740	22	-15.86	<.0001
Aftertreatment	DOC		0	.	.	.	.
Driver	Pre-April 1		-0.1823	0.08592	22	-2.12	0.0454
Driver	Post-April 1		0	.	.	.	.
Temperature			-0.01390	0.002614	222	-5.32	<.0001
Route	Avon_down		-0.4276	0.04405	222	-9.71	<.0001
Route	Avon_up		0.3376	0.02267	222	14.89	<.0001
Route	Enfield		0.4062	0.03014	222	13.48	<.0001
Route	Farmington		0	.	.	.	.
Tech*Fuel	#1 D	HDE	-0.07592	0.1034	22	-0.73	0.4706
Tech*Fuel	ULSD	HDE	0	.	.	.	.
Tech*Fuel	#1 D	CD	0	.	.	.	.
Tech*Fuel	ULSD	CD	0	.	.	.	.
Tech*Aftertreatment	DOC+DPF	HDE	0.1379	0.1687	22	0.82	0.4225
Tech*Aftertreatment	DOC	HDE	0	.	.	.	.
Tech*Aftertreatment	DOC+DPF	CD	0	.	.	.	.
Tech*Aftertreatment	DOC	CD	0	.	.	.	.
Tech*Route	Avon_down	HDE	0.1139	0.05493	222	2.07	0.0392
Tech*Route	Avon_up	HDE	-0.1054	0.02864	222	-3.68	0.0003
Tech*Route	Enfield	HDE	-0.05744	0.03792	222	-1.51	0.1313
Tech*Route	Farmington	HDE	0	.	.	.	.
Tech*Route	Avon_down	CD	0	.	.	.	.
Tech*Route	Avon_up	CD	0	.	.	.	.
Tech*Route	Enfield	CD	0	.	.	.	.

Effect			Estimate	Standard Error	DF	t Value	Pr > |t|
Tech*Route	Farmington	CD	0	.	.	.	.
Route*Driver	Avon_down	Pre-April 1	0.06316	0.05903	222	1.07	0.2858
Route*Driver	Avon_down	Post-April 1	0	.	.	.	.
Route*Driver	Avon_up	Pre-April 1	0.1116	0.03014	222	3.70	0.0003
Route*Driver	Avon_up	Post-April 1	0	.	.	.	.
Route*Driver	Enfield	Pre-April 1	-0.1833	0.03982	222	-4.60	<.0001
Route*Driver	Enfield	Post-April 1	0	.	.	.	.
Route*Driver	Farmington	Pre-April 1	0	.	.	.	.
Route*Driver	Farmington	Post-April 1	0	.	.	.	.
Temperature*After	DOC+DPF		-0.02595	0.01414	222	-1.84	0.0677
Temperature*After	DOC		0	.	.	.	.
Route*Aftertreatment	Avon_down	DOC+DPF	0.9180	0.1299	222	7.07	<.0001
Route*Aftertreatment	Avon_down	DOC	0	.	.	.	.
Route*Aftertreatment	Avon_up	DOC+DPF	0.3514	0.1264	222	2.78	0.0059
Route*Aftertreatment	Avon_up	DOC	0	.	.	.	.
Route*Aftertreatment	Enfield	DOC+DPF	0.2520	0.1317	222	1.91	0.0570
Route*Aftertreatment	Enfield	DOC	0	.	.	.	.
Route*Aftertreatment	Farmington	DOC+DPF	0	.	.	.	.
Route*Aftertreatment	Farmington	DOC	0	.	.	.	.

Differences in Least Square means
The simulation method within SAS® is used to compute the adjusted *p*-values.

Table S-12. Differences of Tech×Fuel Least Square Means

Effect	Tech	Fuel	_Tech	_Fuel	Estimate	StdErr	DF	tValue	Adjp
Tech*Fuel	HDE	#1 D	HDE	ULSD	-0.04958	0.08156	22	-0.61	0.9271
Tech*Fuel	CD	#1 D	CD	ULSD	0.02634	0.08156	22	0.32	0.9874
Tech*Fuel	HDE	#1 D	CD	#1 D	0.2686	0.1083	22	2.48	0.0212
Tech*Fuel	HDE	ULSD	CD	ULSD	0.3446	0.08437	22	4.08	0.0005

Table S-13. Differences of Tech×Aftertreatment Least Square Means

Effect	Tech	After	_Tech	_After	Estimate	StdErr	DF	tValue	Adjp
Tech*After	HDE	DOC+DPF	HDE	DOC	-2.5699	0.1036	22	-24.81	<.0001
Tech*After	CD	DOC+DPF	CD	DOC	-2.7078	0.1340	22	-20.21	<.0001
Tech*After	HDE	DOC+DPF	CD	DOC+DPF	0.3755	0.1574	22	2.39	0.0261
Tech*After	HDE	DOC	CD	DOC	0.2376	0.05428	22	4.38	0.0002

Table S-14. Differences of Tech×Route Least Square Means

Effect	Tech	Route	_Tech	_Route	Estimate	StdErr	DF	tValue	Adjp
Tech*Route	HDE	Avon_down	HDE	Avon_up	-0.2867	0.07196	222	-3.98	0.0018
Tech*Route	HDE	Avon_down	HDE	Enfield	-0.2062	0.07611	222	-2.71	0.0900
Tech*Route	HDE	Avon_down	HDE	Farmington	0.1769	0.07332	222	2.41	0.1747
Tech*Route	HDE	Avon_up	HDE	Enfield	0.08053	0.06862	222	1.17	0.8758
Tech*Route	HDE	Avon_up	HDE	Farmington	0.4636	0.06564	222	7.06	<.0001
Tech*Route	HDE	Enfield	HDE	Farmington	0.3831	0.07010	222	5.47	<.0001
Tech*Route	CD	Avon_down	CD	Avon_up	-0.5060	0.07028	222	-7.20	<.0001
Tech*Route	CD	Avon_down	CD	Enfield	-0.3775	0.07354	222	-5.13	<.0001
Tech*Route	CD	Avon_down	CD	Farmington	0.06302	0.07142	222	0.88	0.9627
Tech*Route	CD	Avon_up	CD	Enfield	0.1285	0.06751	222	1.90	0.4357
Tech*Route	CD	Avon_up	CD	Farmington	0.5690	0.06507	222	8.75	<.0001
Tech*Route	CD	Enfield	CD	Farmington	0.4406	0.06869	222	6.41	<.0001
Tech*Route	HDE	Avon_down	CD	Avon_down	0.4328	0.09243	222	4.68	0.0001
Tech*Route	HDE	Avon_up	CD	Avon_up	0.2134	0.08303	222	2.57	0.1254
Tech*Route	HDE	Enfield	CD	Enfield	0.2614	0.08582	222	3.05	0.0388
Tech*Route	HDE	Farmington	CD	Farmington	0.3188	0.08491	222	3.75	0.0034

Table S-15. Differences of Route×Driver Least Square Means

Effect	Route	Driver	_Route	_Driver	Estimate	StdErr	DF	tValue	Adjp
Route*Driver	Avon_down	Pre-April 1	Avon_down	Post-April 1	-0.1191	0.09738	222	-1.22	0.8539
Route*Driver	Avon_up	Pre-April 1	Avon_up	Post-April 1	-0.07073	0.08310	222	-0.85	0.9695
Route*Driver	Enfield	Pre-April 1	Enfield	Post-April 1	-0.3656	0.08680	222	-4.21	<.0001
Route*Driver	Farmington	Pre-April 1	Farmington	Post-April 1	-0.1823	0.08592	222	-2.12	0.3129
Route*Driver	Avon_down	Pre-April 1	Avon_up	Pre-April 1	-0.4206	0.07837	222	-5.37	<.0001
Route*Driver	Avon_down	Pre-April 1	Enfield	Pre-April 1	-0.1686	0.08321	222	-2.03	0.3684
Route*Driver	Avon_down	Pre-April 1	Farmington	Pre-April 1	0.1516	0.08057	222	1.88	0.4593
Route*Driver	Avon_down	Post-April 1	Avon_up	Post-April 1	-0.3722	0.06463	222	-5.76	<.0001
Route*Driver	Avon_down	Post-April 1	Enfield	Post-April 1	-0.4151	0.06720	222	-6.18	<.0001
Route*Driver	Avon_down	Post-April 1	Farmington	Post-April 1	0.08840	0.06495	222	1.36	0.7848
Route*Driver	Avon_up	Pre-April 1	Enfield	Pre-April 1	0.2520	0.07083	222	3.56	0.0084
Route*Driver	Avon_up	Pre-April 1	Farmington	Pre-April 1	0.5721	0.06775	222	8.44	<.0001
Route*Driver	Avon_up	Post-April 1	Enfield	Post-April 1	-0.04293	0.06554	222	-0.66	0.9924
Route*Driver	Avon_up	Post-April 1	Farmington	Post-April 1	0.4606	0.06322	222	7.28	<.0001
Route*Driver	Enfield	Pre-April 1	Farmington	Pre-April 1	0.3202	0.07327	222	4.37	0.0002
Route*Driver	Enfield	Post-April 1	Farmington	Post-April 1	0.5035	0.06585	222	7.65	<.0001

Table S-16. Differences of Route×Aftertreatment Least Square Means

Effect	Route	After	_Route	_After	Estimate	StdErr	DF	tValue	Adjp
Route*After	Avon_down	DOC+DPF	Avon_up	DOC+DPF	-0.1130	0.1281	222	-0.88	0.9833
Route*After	Avon_down	DOC+DPF	Enfield	DOC+DPF	0.04119	0.1331	222	0.31	1.0000
Route*After	Avon_down	DOC+DPF	Farmington	DOC+DPF	0.5790	0.1286	222	4.50	<.0001
Route*After	Avon_down	DOC	Avon_up	DOC	-0.6797	0.02743	222	-24.78	<.0001
Route*After	Avon_down	DOC	Enfield	DOC	-0.6249	0.03036	222	-20.58	<.0001
Route*After	Avon_down	DOC	Farmington	DOC	-0.3390	0.02952	222	-11.49	<.0001
Route*After	Avon_up	DOC+DPF	Enfield	DOC+DPF	0.1542	0.1307	222	1.18	0.9173
Route*After	Avon_up	DOC+DPF	Farmington	DOC+DPF	0.6920	0.1261	222	5.49	<.0001
Route*After	Avon_up	DOC	Enfield	DOC	0.05481	0.01666	222	3.29	0.0180
Route*After	Avon_up	DOC	Farmington	DOC	0.3406	0.01507	222	22.60	<.0001
Route*After	Enfield	DOC+DPF	Farmington	DOC+DPF	0.5378	0.1311	222	4.10	0.0014
Route*After	Enfield	DOC	Farmington	DOC	0.2858	0.01991	222	14.36	<.0001
Route*After	Avon_down	DOC+DPF	Avon_down	DOC	-2.1012	0.1177	222	-17.85	<.0001
Route*After	Avon_up	DOC+DPF	Avon_up	DOC	-2.6678	0.1139	222	-23.41	<.0001
Route*After	Enfield	DOC+DPF	Enfield	DOC	-2.7672	0.1202	222	-23.03	<.0001
Route*After	Farmington	DOC+DPF	Farmington	DOC	-3.0192	0.1147	222	-26.33	<.0001

Table S-17. Type 3 Tests of Fixed Effects for Model that does not include Bus and Day Random Effects (Compare with Table S-10)

Effect	Num DF	Den DF	F Value	Pr > F
Tech	1	246	29.79	<.0001
Fuel	1	246	0.08	0.7821
Aftertreatment	1	246	294.12	<.0001
Driver	1	246	7.02	0.0086
Temperature	1	246	23.02	<.0001
Route	3	246	26.88	<.0001
Tech*Fuel	1	246	0.39	0.5306
Tech*Aftertreatment	1	246	2.22	0.1376
Tech*Route	3	246	4.29	0.0057
Route*Driver	3	246	10.00	<.0001
Temperature*Aftertreatment	1	246	7.54	0.0065
Route*Aftertreatment	3	246	17.65	<.0001