atmosphere

Contribution of Cold Starts to Real-World Trip Emissions for Light-Duty Gasoline Vehicles

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The supporting information includes: Details of hot-stabilized routes, driving cold start route, instruments, data analysis and quality assurance; Summary of vehicle characteristics and ambient conditions during measurement; Idle cold start durations for each measured vehicle; Time to accumulate 90% of idle cold start increment; Driving cold start increments for the five measured vehicles; Cold start emissions for the "five and drive" scenario; Relationship between vehicle characteristics and ambient conditions versus idle cold start durations, idle cold start increments, and idle cold start CSCs; Cold start contributions for emissions of CO_2, CO, HC, and NO_x for Routes A, C, 1, and 3; Cold start equivalent distances.

Hot-Stabilized Routes in Raleigh and Research Triangle Park Area

The hot-stabilized running measurement was conducted in the Raleigh and Research Triangle Park (RTP) area, NC [37]. Each vehicle was driven for 110 miles on four two-way routes, shown in Figure S1. Routes A and C are alternative paths between North Carolina State University (NCSU) and North Raleigh (NR), and Routes 1 and 3 are alternative paths between NR and RTP. Route A has approximately 10.1 miles for each of outbound and inbound trips. Route A includes all local roads, such as Hillsborough St., W. Morgan St., Capital Blvd, and Six Forks Rd. Route C has approximately 11.2 miles for each of outbound and inbound trips. Route C includes a portion of highway Interstate 440 and a portion of local roads such as Hillsborough St. and Six Forks Rd. Route 1 has approximately 16.3 miles for each of outbound and inbound trips. Route 1 includes a major portion of Interstate 540 and a small portion of local roads such as six forks Rd. and Davis Dr. Route 3 has approximately 17.6 miles for each of outbound and inbound trips. Route 3 includes all local roads such as saw mill Rd., Lynn Rd., Glenwood Ave., and TW Alexander Dr.

Driving Cold Start Routes in Raleigh Area

The driving cold start circuit route in Raleigh, NC area is shown in Figure S2. The route is approximately 4.2 miles in length, and the typical driving time is 10 minutes per circuit. The route is comprised of local road such as Clarks Branch Dr., Fairbanks Dr., Pinecrest Rd., Toscana Dr., Glenwood Ave., Ebenezer Church Rd., and Eden Park Dr.

Instruments Calibration and Validation

Prior to each day of measurement, the portable emission measurement system (PEMS) was calibrated using a BAR 97 High standard gas cylinder. The gas cylinder contains known concentrations of carbon monoxide (CO), hydrocarbon (HC), nitric oxide (NO), carbon dioxide (CO_2), and oxygen (O_2). During the measurements, the two gas analyzers periodically zeroed every 10 minutes on a staggered schedule using ambient air to prevent drift.

Battelle compared the exhaust concentrations between the same model PEMS and reference method instruments based on dynamometer tests [38]. The cycle average emission rates for CO_2, CO and nitrogen oxides (NO_x) were within 10% between these methods. The HC emission rates from NDIR are lower than for the reference method by a factor of approximately two. This bias for HC emission rates was expected because non-dispersive infrared (NDIR) is known to respond well to straight-chain alkanes but not for other types of HC, whereas the reference flame ionization detection (FID) method better characterizes total HC [40,41]. However, FID requires a hydrogen fuel source which is a potential safety concern for on-board measurements. Therefore, , the FID method was not used.

Data Synchronization, Analysis, and Quality Assurance

For both cold start and hot-stabilized measurements, the measured emission concentrations from PEMS and engine activity from on-board diagnostics (OBD) were time-aligned prior to emission rates analysis. The exhaust concentrations were time-aligned with OBD first, using concentration of CO or NO from PEMS and engine speed from OBD as indicators. The cold start period starts when the engine starts.

For quality assurance, the combined data set for a vehicle run was screened to check for errors or possible problems. NCSU has developed a PEMS quality assurance software in LabVIEW. Raw data from the PEMS runs through this software to identify data quality problems. Where possible, such problems are corrected. If correction is not possible, then the errant data are omitted from the final database used for analysis [43].

Typical errors include both gas benches zeroing and unusual air to fuel ratio (AFR). During measurement, the two gas benches in the PEMS were zeroed every 10 minutes. While zeroing, the gas bench intakes ambient air instead of tailpipe exhaust to prevent instrument drift. Data during the zeroing process were not used for analysis. Whenever both two gas benches were zeroing, there was no valid data for that period. Unusual AFR was defined when the AFR value exceed a threshold, which is typically 150. When the AFR exceeds 150, there could be fuel cut-off.

Emission Rates Estimates

Emission rates were estimated at 1 Hz for cold start and hot stabilized driving. For 26 out of 37 vehicles, the 1 Hz exhaust flow rates were estimated based on mass fuel flow (MFF), mole fractions of CO_2, CO, and HC in the exhaust, and molecular weight of fuel [43,44]. For the other 10 vehicles, neither MFF nor mass air flow (MAF) was reported. For these vehicles, the speed-density method was used to estimate MAF based on the ideal gas law, taking into account engine speed in revolutions per minute (RPM), manifold absolute pressure (MAP), intake air temperature (IAT), engine displacement, engine compression ratio, and volumetric efficiency (VE) [43,44,49,50]. VE is the ratio of actual to theoretical mass flow. AFR was inferred from the measured exhaust gas concentrations, and MFF was subsequently estimated using estimated MAF and AFR. VE was calibrated so that the total estimated MFF was equal to the actual fuel consumption subject to a constraint that VE is less than or equal to 0.95. Exhaust flow rates were then estimated. For all vehicles, based on estimated exhaust flow rate, mole fraction of each pollutant in the exhaust, and molecular weight for each pollutant, time-based emission rates were estimated.[S1]

For each of the 37 measured vehicles, the actual fuel use was compared with the estimated fuel use. The actual fuel use was recorded at the gas station. The estimated fuel use was calculated based on modal fuel use rates in each of the VSP modes and the distribution of time in each VSP mode based on the vehicle's measured driving cycle. Table S2 summarizes the actual fuel use, estimated fuel use, and the ratio of actual to estimated fuel use for each of the vehicles. On average of all 37 measured vehicles, the ratio of actual to estimated fuel use was 1.02±0.02, which is an indication that the estimated fuel use was in good quality.

The 95% confidence intervals (CIs) on the mean of measured cold start increments for the 37 vehicles are shown in main paper Table 1. The lower bound of the 95% CIs for some pollutant would be smaller than 0 if estimated analytically based on mean, standard deviation, and sample size, which is physically impossible. Therefore, these 95% CIs are based on bootstrap [51].

Measured Cold Start Vehicles

Idling cold starts were measured for 37 LDGVs, including 18 passenger cars (PCs) and 19 passenger trucks (PTs), as shown in Table S1. PCs include sedans and coupes. PTs include sport utility vehicles (SUVs), pickups, and minivans. These vehicles include 2000 to 2016 model years, 1.4 liter to 5.3 liter engines, 1,070 kg to 2,520 kg curb weights, and 54 miles to approximately 157,000 miles accumulated driving. For each vehicle, an idle cold start measurement was conducted. Ambient temperature for the cold start measurements ranged from 30 °F to 90 °F, and relative humidity ranged from 30% to 100%.

Five of the 37 LDGVs were also measured for driving cold start. These five vehicles include a 2014 Ford Focus, a 2015 Ford Fusion, a 2015 Chevrolet Tahoe, a 2015 Ford F150, and a 2016 Kia Sedona.

Cold Start Duration

Table S3 summarizes the fuel use, CO, HC, NO_x, and CO_2 cold start duration and corresponding scenario categories for each vehicle based on idle cold start measurement. These are quantified based on the scenarios described in the main paper. For the 37 vehicles, the average cold start durations, plus or minus 95% confidence intervals, for fuel use, CO emissions, HC emissions, NO_x emissions, and CO_2 emissions are 690±100 seconds, 340±110 seconds, 330±110 seconds, 390±130 seconds, and 690±100 seconds, respectively.

Table S4 summarizes the cold start duration to accumulate 90% of the cold start increment. Most of the cold start increment accrues soon after the engine start. The time need to accumulate 90% of the cold start increments were used and discussed in the main paper. For example, the time need to accumulate 90% of the cold start increments, plus or minus a 95% confidence interval, for fuel use, CO emissions, HC emissions, NO_x emissions, and CO_2 emissions are 400±80 seconds, 150±70 seconds, 330±100 seconds, 120±70 seconds, and 400±80 seconds, respectively. Because most of the cold start durations shown in Table S3 were 900 seconds (as quantified in Scenario 2), it is difficult to correlate factors that may have effect on cold start duration. The cold start duration to accumulate 90% of cold start increment is used to evaluate the effect of engine displacement, vehicle mileage, ambient temperature, and relative humidity on the cold start durations, as shown later in Figures S3 through S6.

Driving Cold Start Increments

Table S5 summarizes fuel use, CO, HC, NO_x, and CO_2 emissions for the five vehicles that were measured for driving cold start. Each vehicle was driven on a circuit route (shown in Figure S2) immediately after engine start, followed by one or more circuits on the same route. The first circuit is cold start circuit and the following are hot-stabilized circuits. The trip total emissions for the cold start circuit and for the average of hot-stabilized circuits are summarized in Table S5 for each vehicle. The driving cold start increments are estimated as the difference in trip total emissions between cold start circuit and hot-stabilized circuit averages.

The CO driving cold start increment is higher than the idle cold start increment by a factor of 4, with an inter-vehicle range of 0.9 to 25. The HC driving cold start increment was greater than the idle cold start increment by an average factor of 2.1 with an inter-vehicle range of 0.1 to 3.6. The NO_x driving cold start was higher than that for idle cold start by an average factor of 10.2, with an inter-vehicle range of 5.0 to 85.

The driving cold start increments can be evaluated by comparing the cold start lap and hot-stabilized lap total emissions. On average of the 5 vehicles, the average fuel use driving cold start increment was 56 grams. The average hot-stabilized lap total fuel use was 644 grams. Thus, the average fuel use driving cold start increment was equivalent to approximately 0.09 laps of hot-stabilized driving. Similarly, the average CO driving cold start increment was 7.0 grams, which was equivalent to approximately 3.3 laps of hot-stabilized driving. The average HC driving cold start increment was 0.73 grams, which was equivalent to approximately 8.5 laps of hot-stabilized driving. The average NO_x driving cold start increment was 0.79 grams, which was equivalent to approximately 2.9 laps of hot-stabilized driving.

Figures S3 to S4, S7 to S8, S9 to S10, S11 to S12, and S13 to S14 show the engine variables and measured exhaust concentrations versus distance for the Ford Focus, the Ford Fusion, the Chevrolet Tahoe, the Ford F150, and the Kia Sedona, respectively. The purpose of these figures is to compare the driving cold start versus the hot-stabilized operation for the same route. For all five vehicles, the speed versus distance profiles are approximately the same for the cold start and hot-stabilized laps, indicating repeatability of the driving cycle. The catalyst reached light-off temperature during the cold start lap. Thus, the cold start typically end within the cold start lap. For the exhaust flow rates and the fuel use rates, typically the cold start lap has similar rates compared to the hot-stabilized rates, but there are several points at which the rates in the cold start lap are higher than for the hot-stabilized lap. Concentrations of CO, HC, and NO_x were significantly higher for the cold start lap compared to the hot-stabilized lap, particularly at the beginning of the cold start lap as well as for several seconds of higher concentrations at different locations during the lap for some vehicles prior to the catalyst reaching light-off temperature. Overall, the higher fuel use and emission rates for the driving cold start compared to hot-stabilized operations are a result of significant higher exhaust concentrations in combination with slightly higher exhaust flow rates.

Figures S5 and S6 show the different engine variables and measured exhaust concentrations versus distance for the Ford Focus during the "five-and-drive" measurement. For this case, the vehicle was idled for five minutes, prior to being driven on the cold start lap. Table S6 shows the measured fuel use and emissions for 3 different cold start scenarios for the 2014 Ford Focus: five-and-drive, 15 minutes idling, and driving. Based on comparing the total emissions during the five minutes of idling and the increment during driving, the "five and drive" case had approximately half the CO, a third of the HC, and a quarter of the NO_x emissions compared to the driving case. However, because of the five minutes of no driving, the total fuel use and CO_2 emissions attributed to the start during the "five and drive" case was approximately twice as high as for driving. Thus, a hybrid start strategy of idling followed by driving can help reduce exhaust emissions of some pollutants with the tradeoff of more fuel consumption and higher greenhouse gas emissions.

Factors Affecting Cold Start Duration and Increment

To evaluate factors that may affect cold start duration and increment, Figures S15 through S18 summarize the relationship between idle cold start duration to accumulate 90% of idle cold start increment and each of engine displacement, mileage, temperature, and relative humidity, respectively. Figures S19 through S22 summarizes the relationship between cold start increments and each of engine displacement, mileage, temperature, and relative humidity, respectively.

The idle cold start duration for NO_x emissions to accumulate 90% of the cold start increment is weakly proportional to vehicle mileage, with a statistically significant R^2 of approximately 0.22, but is not sensitive to engine displacement, temperature, or relative humidity. For fuel use, CO and HC, no statistically significant relationships were found with respect to engine displacement, age, mileage, temperature, and relative humidity.

The cold start fuel use increments significantly increase as ambient temperature decreases, but are not significantly correlated with engine displacement, age, mileage, or relative humidity. Cold start HC increments significantly increase with increasing engine displacement, but are not sensitive to mileage or ambient conditions. Cold start CO and NO_x increments significantly increase with increasing mileage and decrease with ambient temperature, but are not significantly sensitive to engine displacement or relative humidity. Trends in these significant relationships with ambient temperature agree with previous studies [6,13]. However, since the ambient temperature range in this study were bounded to above -1 °C while the previous study controlled the ambient temperature to as low as -20 °C, the relationship between cold start increments and temperature here may be weak. The key factors that affect the cold start increments of fuel use and emissions of particular pollutants may differ.

Cold Start Contributions for All Measured Vehicles

To evaluate factors that may effect idle cold start contributions, Figures S23 through S26 summarize the relationship between idle cold start contribution and each of engine displacement, mileage, temperature, and relative humidity, respectively.

The idle CSCs for CO_2, CO, and HC emissions are weakly negatively proportional to ambient temperature with a statistically significant R^2 of approximately 0.22, 0.25, and 0.22, respectively, but are not sensitive to engine displacement, mileage, or relative humidity. For NO_x, no statistically significant relationships were found with respect to engine displacement, age, mileage, temperature, and relative humidity.

To evaluate idle cold start contribution for the vehicles for measured idle cold start, Figures S27 through S30 show cumulative distribution functions of the estimated CSCs averaged over outbound and inbound trips for each of Route A, C, 1, and 3, respectively. Each data point represents one vehicle. On average of all vehicles, Route A has the highest average CSCs for CO, HC, NO_x, and CO_2, which are 59%, 63%, 24%, and 5.5%, respectively. Route 1 has the lowest average CSC of 40% for CO and Route 3 has the lowest average CSCs of 41%, 14%, and 3.4% for HC, NO_x, and CO_2, respectively.

Figure S31 summarizes the idle cold start contribution based on 15 minutes idle total emissions and hot-stabilized trip total emissions. On average of all vehicles, the CSCs averaged 48%±9% for CO, 52%±7% for HC, 19%±6% for NO_x, and 16%±1% for CO_2. For CO, HC, and NO_x, the idle CSCs based on 15 minutes idle total emissions are approximately the same compared to the idle CSCs based on only idle cold start increments, within 3 percentage points. For CO_2, the CSCs based on 15 minutes idle total emissions are significantly higher compared to the CSCs based on only idle cold start increments. The amount of CO_2 emitted during the 15 minutes idling comprises a significant proportion of trip total CO_2 emissions.

Cold Start Equivalent Distance for All Measured Vehicles

Cold start equivalent distance (CSED) can be developed to supplement CSC. The idle CSED was estimated based on the ratio of idle cold start increment to the average hot-stabilized emission rate per one km of vehicle travel. Similarly, the driving CSED was estimated based on the ratio of driving cold start increment to the average hot-stabilized emission rates per one km of vehicle travel.

The CO, HC, NO_x, and CO_2 idle CSEDs, on average of all vehicles, range from 140 km to 470 km, 40 km to 160 km, 5.6 km to 13 km, and 0.93 km to 1.1 km, respectively, depending on the route. For some vehicles, the one-way route total hot-stabilized emissions are very low, such that the cold start increment contributes a large proportion of total emissions. Thus, the idle CSED can be very high for some cases. The differences in route distance and route typical traveling speed are key reasons for differences in hot-stabilized trip emissions, which lead to differences in idle CSEDs. On average of all vehicles and all routes, the idle CO and HC cold start increments are each equivalent to a hot-stabilized driving distance of approximately 20 km. The idle NO_x cold start increments are equivalent to a hot-stabilized distance of approximately 5.5 km.

For the vehicles with both driving and idling cold start measurements, the driving CO, HC, NO_x, and CO_2 CSEDs were higher compared to idling CSEDs by average factors of approximately 8.5, 1.5, 8.5, and 2.0, respectively.

Table S1. Cold Start Measurement – Summary of Measured Vehicle Year, Make, Model, Test Date, Engine Displacement, Mileage, and Ambient Conditions.

Year	Make	Model	Type[a]	Test Date	Age	Engine Displacement	Mileage	Amb. Temp.	Relative Humidity
						(L)	(mile)	(°F)	(%)
2000	Pontiac	Grand Prix	PC	2/17/2013	13	3.8	109,128	30	37
2001	Mazda	Protégé	PC	2/16/2013	12	2.0	157,245	36	90
2004	Pontiac	Grand Am GT	PC	2/16/2013	9	3.4	93,237	36	92
2005	Mazda	6	PC	11/11/2012	7	2.3	79,164	73	44
2008	Honda	Fit	PC	11/11/2012	4	1.5	55,531	73	44
2008	Chevy	Impala	PC	6/9/2013	5	3.5	98,244	79	81
2011	Chevy	HHR	PC	12/19/2011	0	2.2	21,072	48	52
2011	Toyota	Camry	PC	12/20/2011	0	2.5	8,827	57	50
2012	Nissan	Versa	PC	12/16/2011	0	1.8	615	57	80
2012	Fiat	500	PC	1/28/2012	0	1.4	12,875	41	50
2012	Toyota	Camry	PC	10/1/2012	0	2.5	18,752	66	81
2012	Nissan	Rogue	PC	2/16/2013	0	2.5	6,980	36	92
2012	Ford	Fusion	PC	5/29/2013	0	2.5	26,024	86	35
2012	Dodge	Avenger	PC	6/21/2013	0	2.4	38,502	90	45
2013	Chevy	Impala	PC	2/23/2013	0	3.6	8,176	38	60
2013	Ford	Fusion	PC	2/24/2013	0	2.5	42,966	48	30
2014	Ford	Focus	PC	3/7/2013	2	2.0	36,276	54	64
2015	Ford	Fusion	PC	9/17/2015	0	2.5	54	67	70
2002	Chevy	Silverado	PT	11/11/2012	10	4.8	154,475	68	38
2002	Lexus	RX300	PT	11/6/2012	10	3.0	135,784	47	54
2002	Jeep	Wrangler (1)	PT	11/11/2012	10	4.0	90,284	72	36
2002	Jeep	Wrangler (2)	PT	2/16/2013	11	4.0	136,114	42	75
2004	Toyota	Tacoma	PT	11/11/2012	8	4.0	136,211	50	75
2004	Chevy	Trailblazer	PT	2/16/2013	9	4.2	99,758	41	76
2006	Dodge	Caravan	PT	6/1/2013	7	3.3	123,927	86	46
2008	Nissan	Xterra	PT	2/16/2013	5	4.0	47,807	36	91
2010	Chevy	Silverado	PT	9/17/2012	2	4.8	26,551	79	72
2011	Ford	XL150 (1)	PT	9/17/2012	1	5.0	28,779	64	97
2011	Ford	XL150 (2)	PT	9/19/2012	1	5.0	17,208	64	97
2012	Toyota	Sienna	PT	5/20/2013	1	3.5	35,376	78	76
2013	GMC	Yukon	PT	9/29/2012	0	5.3	4,089	63	100
2013	GMC	Terrain	PT	5/16/2013	0	2.4	10,268	87	66
2014	Chrysler	Town and Country	PT	9/27/2014	0	3.6	13,442	60	90
2014	Buick	Encore	PT	10/26/2014	0	1.8	12,237	60	40
2015	Chevy	Tahoe	PT	9/11/2015	0	5.3	19,213	79	77
2015	Ford	F150	PT	9/14/2015	0	5.0	11,960	63	63
2016	Kia	Sedona	PT	9/19/2015	0	3.3	103	67	67

[a] Vehicle Type: PC = Passenger Car; PT = Passenger Truck.

Table S2. Actual Fuel Use and Estimated Fuel Use for Each Vehicle during the Hot-Stabilized Measurement.

Year	Make	Model	Actual Fuel Use	Estimated Fuel Use
2000	Pontiac	Grand Prix	5.516	5.121
2001	Mazda	Protégé	3.737	4.161
2004	Pontiac	Grand Am GT	4.972	4.811
2005	Mazda	6	4.253	4.215
2008	Honda	Fit	4.243	3.970
2008	Chevy	Impala	6.122	5.586
2011	Chevy	HHR	7.156	6.785
2011	Toyota	Camry	4.194	3.667
2012	Nissan	Versa	4.392	4.380
2012	Fiat	500	3.963	3.590
2012	Toyota	Camry	3.698	3.386
2012	Nissan	Rogue	5.215	5.056
2012	Ford	Fusion	3.935	4.427
2012	Dodge	Avenger	4.251	4.457
2013	Chevy	Impala	5.108	5.199
2013	Ford	Fusion	3.939	4.101
2014	Ford	Focus	3.865	3.276
2015	Ford	Fusion	4.990	5.071
2002	Chevy	Silverado	6.982	6.272
2002	Lexus	RX300	6.220	5.917
2002	Jeep	Wrangler (1)	9.709	10.659
2002	Jeep	Wrangler (2)	6.978	6.679
2004	Toyota	Tacoma	6.489	6.261
2004	Chevy	Trailblazer	6.714	6.692
2006	Dodge	Caravan	6.307	6.567
2008	Nissan	Xterra	7.143	6.698
2010	Chevy	Silverado	10.500	9.802
2011	Ford	XL150 (1)	9.200	9.517
2011	Ford	XL150 (2)	9.000	8.865
2012	Toyota	Sienna	5.884	5.968
2013	GMC	Yukon	8.421	8.233
2013	GMC	Terrain	4.825	4.657
2014	Chrysler	Town and Country	6.094	6.065
2014	Buick	Encore	4.365	4.474
2015	Chevy	Tahoe	n/a	6.678
2015	Ford	F150	6.623	6.621
2016	Kia	Sedona	5.833	5.819
	Average		5.857	5.751
	Standard Deviation		1.811	1.841
	95% Confidence Interval		0.613	0.623

Table S3. Cold Start Measurement – Summary of Idle Cold Start Duration and Scenario Categories for Each Vehicle and Each of Fuel Use and Pollutants.

Year	Make	Model	Cold Start Duration (s)[a,b]					Scenario Category				
			Fuel	CO	HC	NO_x	CO_2	Fuel	CO	HC	NO_x	CO_2
2000	Pontiac	Grand Prix	900	220	900	900	900	2	1	3	3	2
2001	Mazda	Protégé	900	758	900	900	900	2	3	3	3	2
2004	Pontiac	Grand Am GT	900	239	270	900	900	2	3	1	3	2
2005	Mazda	6	900	316	900	900	900	2	3	3	3	2
2008	Honda	Fit	137	90	130	82	137	1	1	1	1	1
2008	Chevy	Impala	330	76	900	110	330	1	1	3	1	1
2011	Chevy	HHR	900	400	436	900	900	2	3	1	3	2
2011	Toyota	Camry	900	295	578	486	900	2	3	1	3	2
2012	Nissan	Versa	900	900	900	900	900	2	3	3	3	2
2012	Fiat	500	900	81	900	900	900	2	1	3	3	2
2012	Toyota	Camry	900	300	900	150	900	2	3	3	1	2
2012	Nissan	Rogue	550	900	335	84	550	1	3	1	1	1
2012	Ford	Fusion	900	180	900	50	900	2	1	3	1	2
2012	Dodge	Avenger	400	900	900	122	400	1	3	3	1	1
2013	Chevy	Impala	550	112	900	900	550	1	1	3	3	1
2013	Ford	Fusion	900	168	273	900	900	2	1	1	3	2
2014	Ford	Focus	349	900	900	94	349	1	3	3	1	1
2015	Ford	Fusion	38	41	145	36	38	1	1	1	1	1
2002	Chevy	Silverado	900	455	900	900	900	2	3	3	3	2
2002	Lexus	RX300	900	330	314	900	900	2	1	1	3	2
2002	Jeep	Wrangler (1)	337	52	900	900	337	1	1	3	3	1
2002	Jeep	Wrangler (2)	900	90	205	900	900	2	1	1	3	2
2004	Toyota	Tacoma	522	255	115	900	522	1	3	1	3	1
2004	Chevy	Trailblazer	900	724	900	900	900	2	1	2	3	2
2006	Dodge	Caravan	900	900	900	180	900	2	3	3	1	2
2008	Nissan	Xterra	598	900	900	88	598	1	3	3	1	1
2010	Chevy	Silverado	900	900	900	900	900	2	3	2	3	2
2011	Ford	XL150 (1)	900	900	900	900	900	2	3	2	3	2
2011	Ford	XL150 (2)	900	900	900	900	900	2	3	2	3	2
2012	Toyota	Sienna	900	270	900	35	900	2	1	3	1	2
2013	GMC	Yukon	300	788	900	900	300	1	1	2	3	1
2013	GMC	Terrain	900	260	420	35	900	2	1	1	1	2
2014	Chrysler	Town and Country	900	395	121	138	900	2	1	1	1	2
2014	Buick	Encore	900	75	270	250	900	2	1	1	1	2
2015	Chevy	Tahoe	84	264	837	247	84	1	3	3	3	1
2015	Ford	F150	569	869	900	791	569	1	3	3	3	1
2016	Kia	Sedona	193	900	900	18	193	1	3	3	1	1

[a] The cold start duration was quantified based on scenarios described in the main paper.

Table S4. Idle Cold Start Measurement – Summary of Time to Accumulate 90% of Cold Start Increment for Each Vehicle and Each of Fuel Use and Pollutants.

Year	Make	Model	Time to Accumulate 90% of Cold Start Increment (s)				
			Fuel	CO	HC	NO_x	CO_2
2000	Pontiac	Grand Prix	487	151	377	770	487
2001	Mazda	Protégé	480	327	332	101	480
2004	Pontiac	Grand Am GT	331	50	107	654	331
2005	Mazda	6	313	76	547	58	313
2008	Honda	Fit	49	19	51	60	49
2008	Chevy	Impala	196	8	763	68	196
2011	Chevy	HHR	701	102	185	113	701
2011	Toyota	Camry	518	253	303	25	518
2012	Nissan	Versa	227	69	193	187	227
2012	Fiat	500	255	13	101	89	255
2012	Toyota	Camry	568	194	277	48	568
2012	Nissan	Rogue	355	704	112	56	355
2012	Ford	Fusion	220	20	759	13	220
2012	Dodge	Avenger	250	75	110	50	250
2013	Chevy	Impala	296	17	52	15	296
2013	Ford	Fusion	532	16	122	27	532
2014	Ford	Focus	263	806	821	58	263
2015	Ford	Fusion	30	15	34	13	30
2002	Chevy	Silverado	602	185	420	207	602
2002	Lexus	RX300	603	90	199	92	603
2002	Jeep	Wrangler (1)	205	6	609	119	205
2002	Jeep	Wrangler (2)	665	47	68	679	665
2004	Toyota	Tacoma	334	25	27	50	334
2004	Chevy	Trailblazer	700	205	596	244	700
2006	Dodge	Caravan	643	90	95	50	643
2008	Nissan	Xterra	265	25	649	67	265
2010	Chevy	Silverado	448	179	506	24	448
2011	Ford	XL150 (1)	503	114	798	15	503
2011	Ford	XL150 (2)	663	596	800	13	663
2012	Toyota	Sienna	384	59	123	10	384
2013	GMC	Yukon	123	13	483	44	123
2013	GMC	Terrain	638	18	298	22	638
2014	Chrysler	Town and Country	808	22	27	29	808
2014	Buick	Encore	748	23	94	132	748
2015	Chevy	Tahoe	45	242	344	8	45
2015	Ford	F150	367	24	631	20	367
2016	Kia	Sedona	113	506	49	14	113

[a] The approach to steady-state time is approximate time when the fuel use or emission rates approach steady-state, regardless of comparison to hot-stabilized idling rates.

Table S5. Circuit Driving Cold Start Emissions and Hot-Stabilized Circuit Average Emissions and Driving Cold Start Increments for the Four Vehicles on Driving Cold Start Measurements.

Vehicle	Circuit	Number of Circuits	Fuel Use (g)	CO (g)	HC (g)	NO_x (g)	CO_2 (kg)
2014 Ford Focus	Cold Start Circuit Trip Total	1	511	18	0.77	1.14	1.6
	Hot-Stabilized Circuits Average Trip Total	3	435	11	0.039	0.35	1.4
	Cold Start Increment		77	7.0	0.73	0.79	0.2
2015 Ford Fusion	Cold Start Circuit Trip Total	1	622	12	0.043	0.21	2.0
	Hot-Stabilized Circuits Average Trip Total	1	514	1.7	0.022	0.11	1.6
	Cold Start Increment		108	10	0.021	0.10	0.4
2015 Chevy Tahoe	Cold Start Circuit Trip Total	1	815	15	0.71	0.29	2.6
	Hot-Stabilized Circuits Average Trip Total	7	717	0.71	0.083	0.13	2.3
	Cold Start Increment		98	14	0.63	0.16	0.
2015 Ford F150	Cold Start Circuit Trip Total	1	825	14	0.65	0.78	2.6
	Hot-Stabilized Circuits Average Trip Total	1	784	1.2	0.027	0.084	2.5
	Cold Start Increment		41	13	0.62	0.70	0.1
2016 Kia Sedona	Cold Start Circuit Trip Total	1	728	2.7	0.17	0.51	2.3
	Hot-Stabilized Circuits Average Trip Total	3	682	0.6	0.008	0.04	2.2
	Cold Start Increment		46	2.1	0.16	0.47	0.1
Average	Cold Start Circuit Trip Total		700	12.3	0.47	0.59	2.2
	Hot-Stabilized Circuits Average Trip Total		644	2.8	0.051	0.15	2.0
	Cold Start Increment		56	9.5	0.42	0.44	0.2

Table S6. Emissions for Different Cold Start Scenarios for the 2014 Ford Focus.

Scenario	Summarizing Amount	Fuel Use (g)	CO (g)	HC (g)	NO_x (g)	CO_2 (kg)
Idling Cold Start	15 min idling total	264	3.3	0.41	0.072	0.83
Five-and-Drive[a]	5 min idling total + driving increment	137	3.9	0.22	0.19	0.43
Driving Cold Start	Driving increment	77	7.0	0.73	0.79	0.20

[a] The five-and-drive measurement includes five minutes of idle following by driving after an engine cold start.

Table S7. Idle Cold Start Increment, Hot-Stabilized Trip Total Emissions, and Cold Start Contributions for Each Trip, based on Measured Idle Cold Start and Hot-Stabilized Operation.

Cold Start or Route	CO		HC		NO_x		CO_2	
	Total[a] (g)	CSC[b]	Total (g)	CSC	Total (g)	CSC	Total (kg)	CSC
Cold Start Increment	4.4		0.26		0.060		0.18	
A_out Trip Total	9.1	33%	0.093	74%	0.22	22%	4.7	4%
A_in Trip Total	20	18%	0.35	43%	0.60	9%	4.5	4%
C_out Trip Total	19	19%	0.18	60%	0.53	10%	4.5	4%
C_in Trip Total	30	13%	0.21	56%	0.98	6%	4.1	4%
1_out Trip Total	7.9	36%	0.27	49%	0.84	7%	5.1	3%
1_in Trip Total	9.6	31%	0.17	60%	1.0	6%	5.4	3%
3_out Trip Total	30	13%	0.34	43%	0.99	6%	6.5	3%
3_in Trip Total	32	12%	0.44	37%	1.0	6%	6.9	3%
Hot-Stabilized Average Trip Total [c]	20	18%	0.26	50%	0.77	7.2%	5.2	3.3%
Hot-Stabilized 95% CI[d]	8.5	7.8%	0.096	19%	0.24	2.3%	0.84	0.5%

[a] *Total hot-stabilized trip emissions without cold start for each trip.*

[b] *CSC = Cold Start Contribution, which is the cold start increment divided by the sum of cold start increment and hot-stabilized trip total.*

[c] *The average is the average value for 8 trips.*

[d] *95% CI = 95% Confidence Interval*

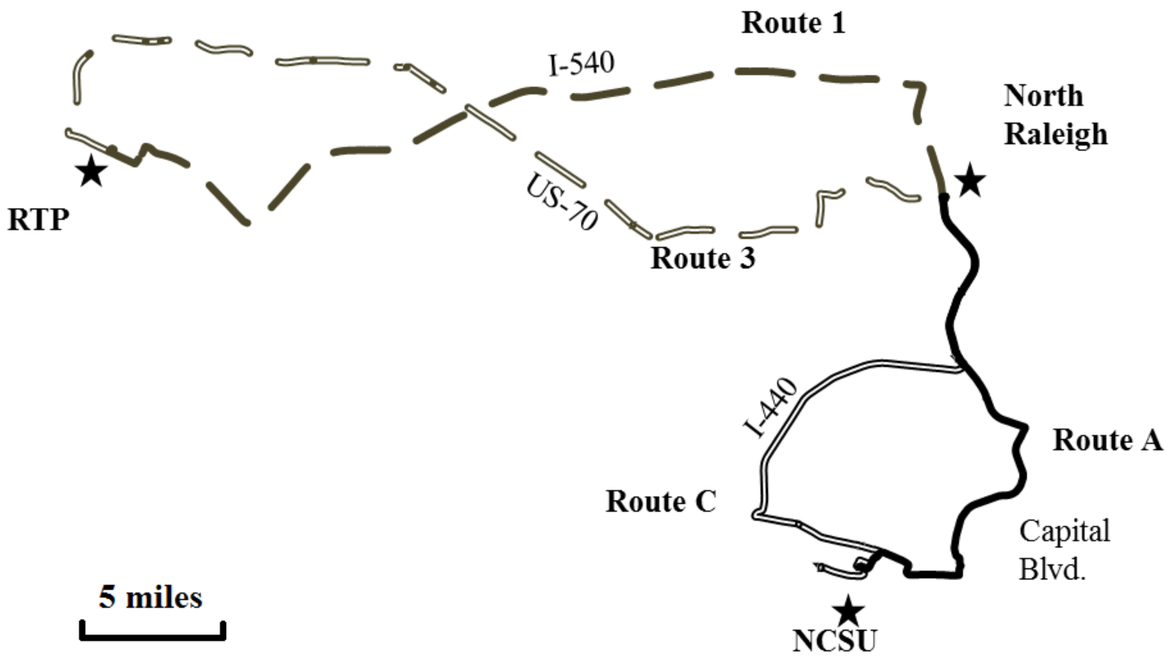

Figure S1. Maps For the Four Routes in Raleigh and Research Triangle Park Area in NC Used for Hot-Stabilized Operation Measurements.

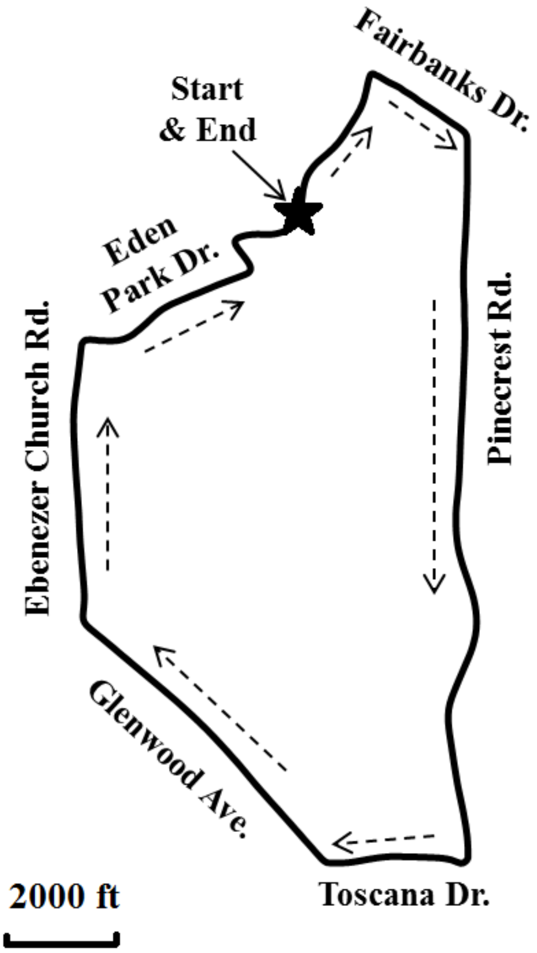

Figure S2. Map for Driving Cold Start Measurement in Raleigh, NC Area.

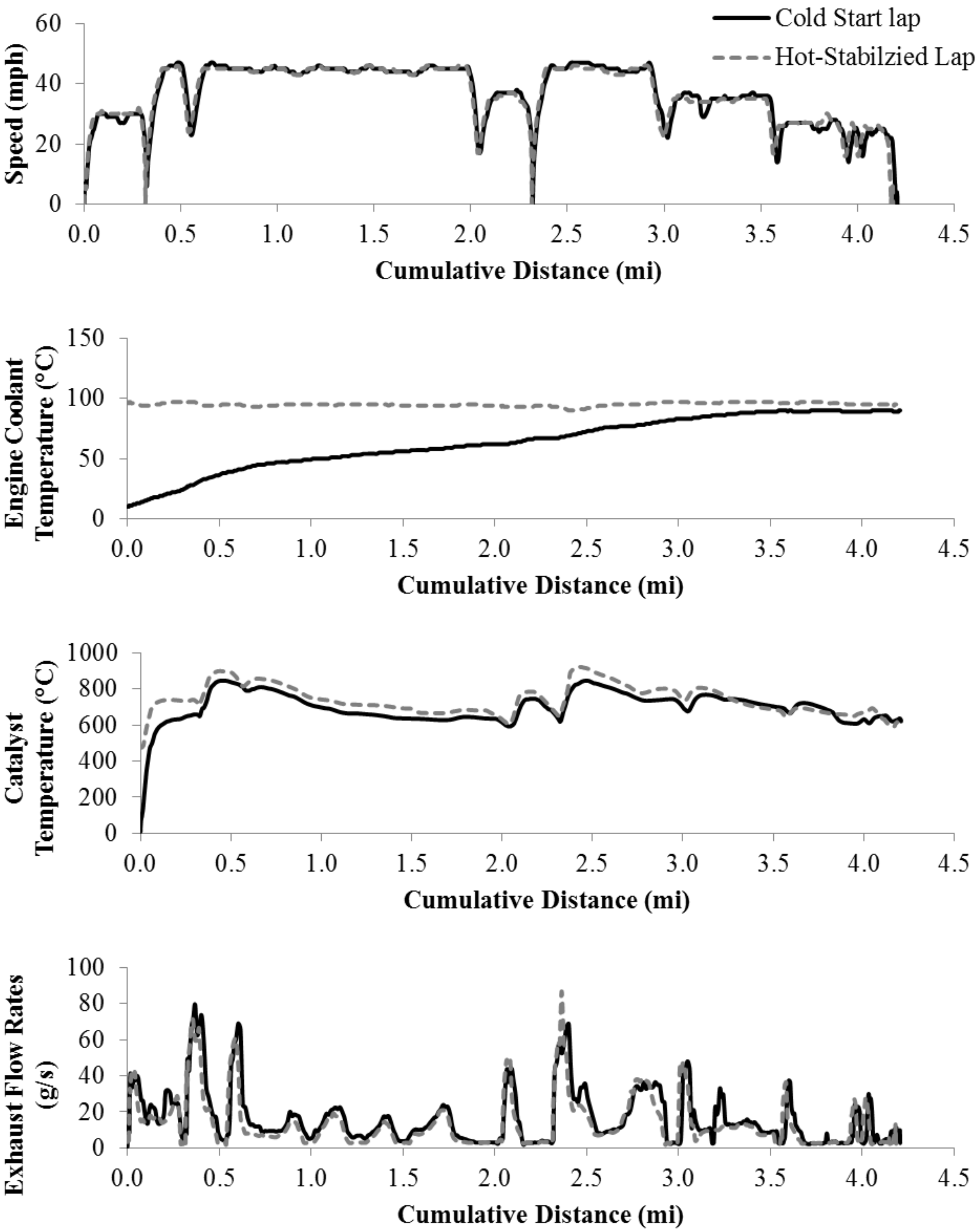

Figure S3. Speed, Engine Coolant Temperature, Catalyst Temperature, and Exhaust Flow Rate versus Cumulative Distance during Driving Cold Start Measurement for the 2014 Ford Focus.

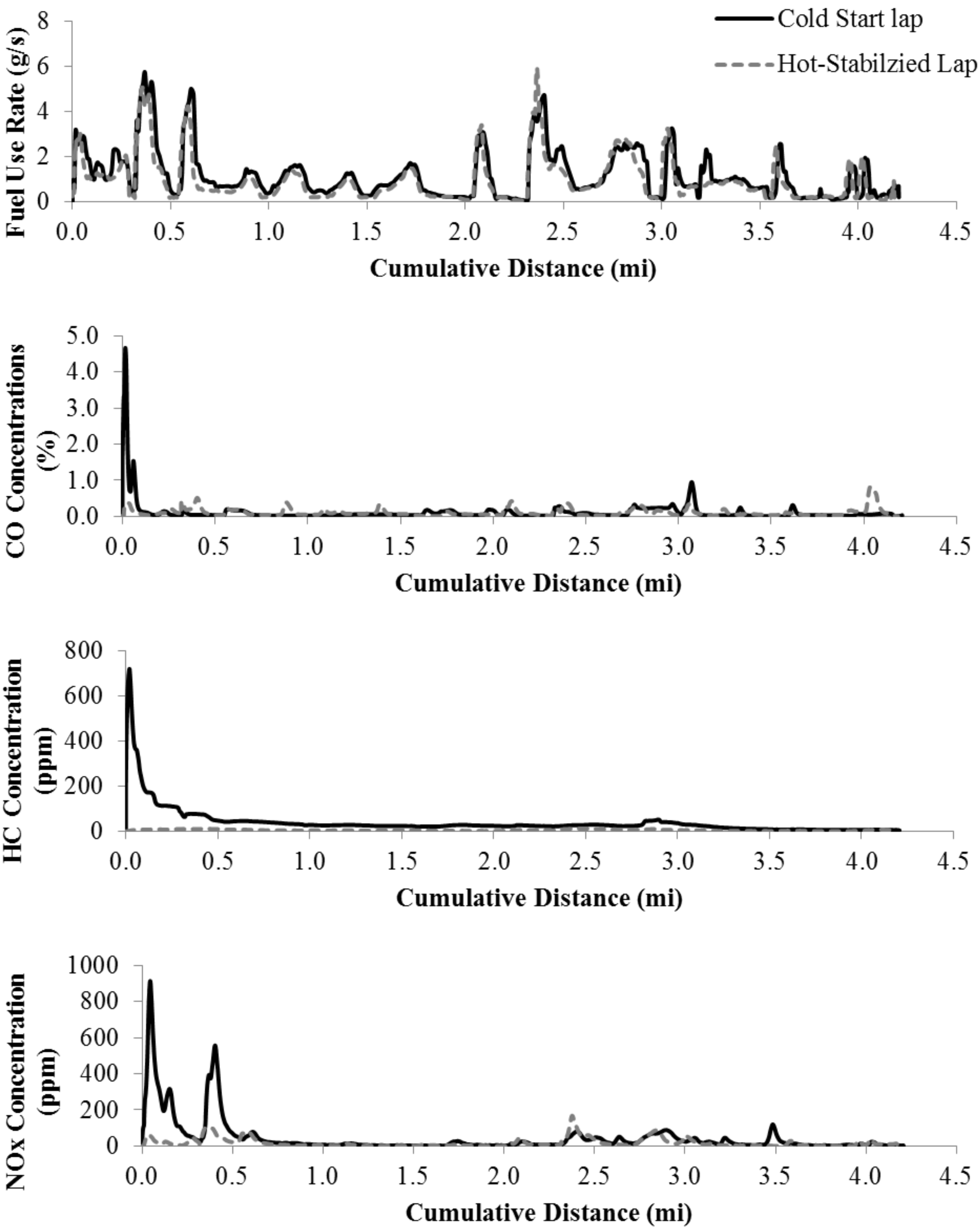

Figure S4. Fuel Use Rates and Emission Concentrations versus Cumulative Distance during Driving Cold Start Measurement for the 2014 Ford Focus.

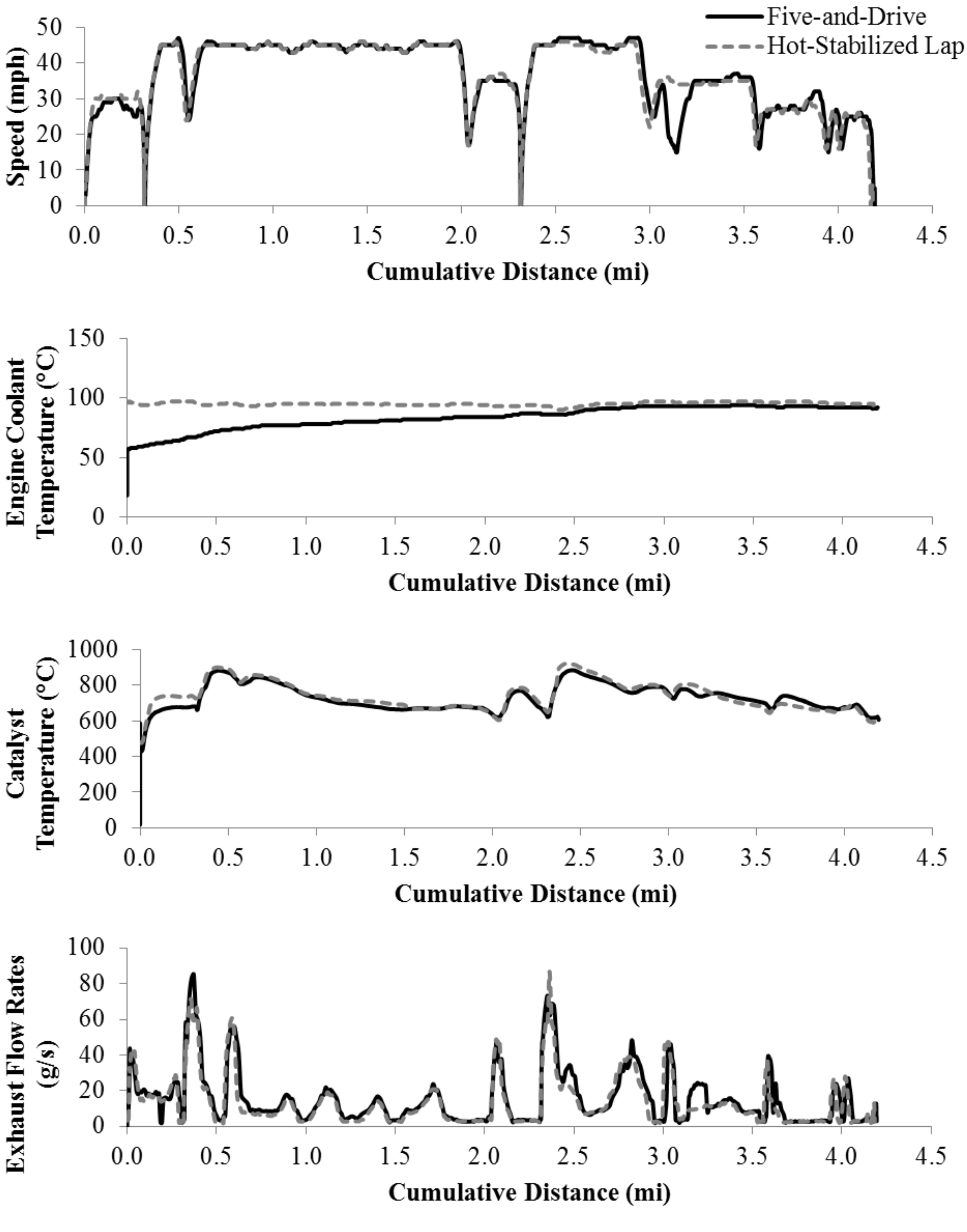

Figure S5. Speed, Engine Coolant Temperature, Catalyst Temperature, and Exhaust Flow Rate versus Cumulative Distance during Five-and-Drive Cold Start Measurement for the 2014 Ford Focus.

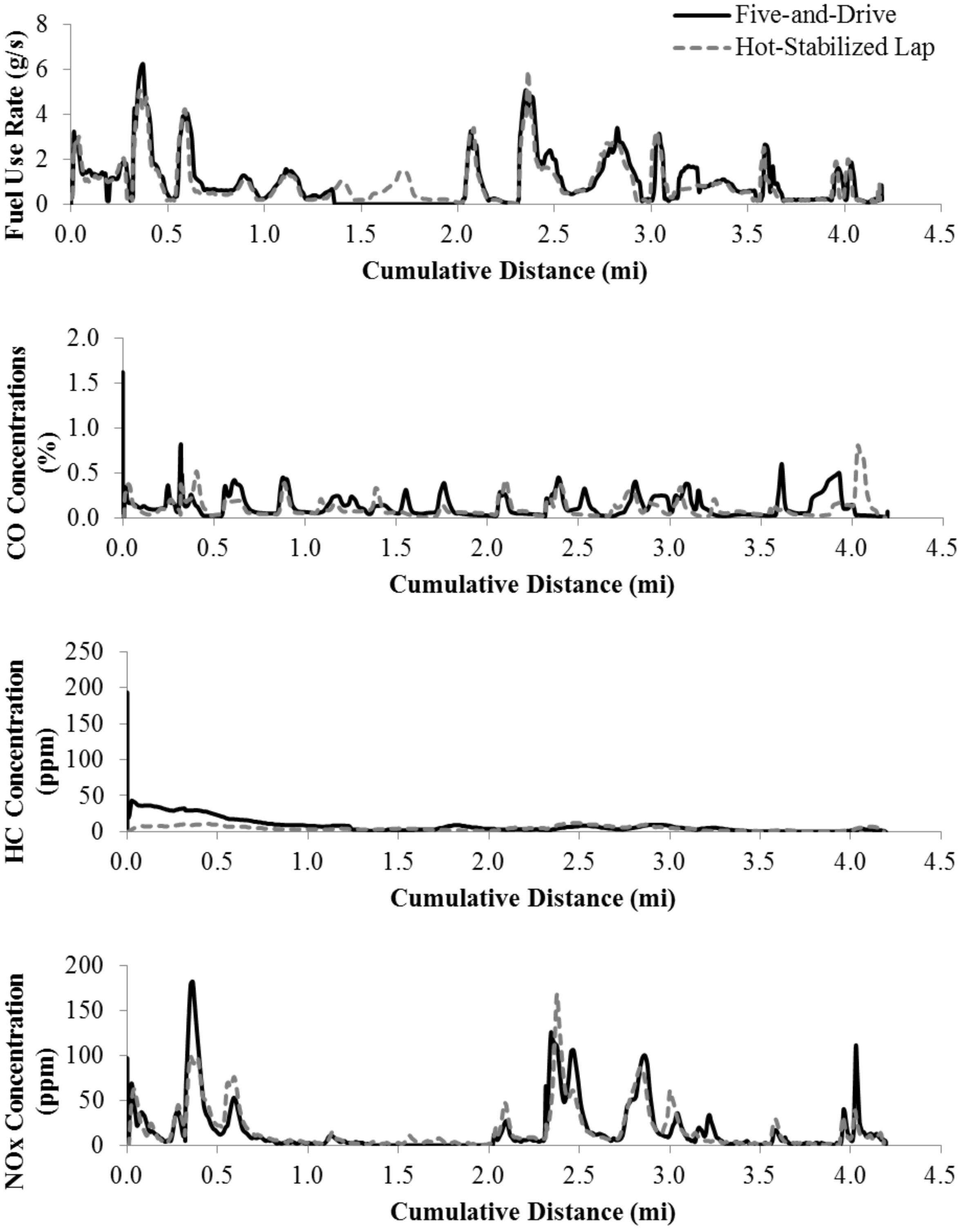

Figure S6. Fuel Use Rates and Emission Concentrations versus Cumulative Distance during Five-and-Drive Cold Start Measurement for the 2014 Ford Focus.

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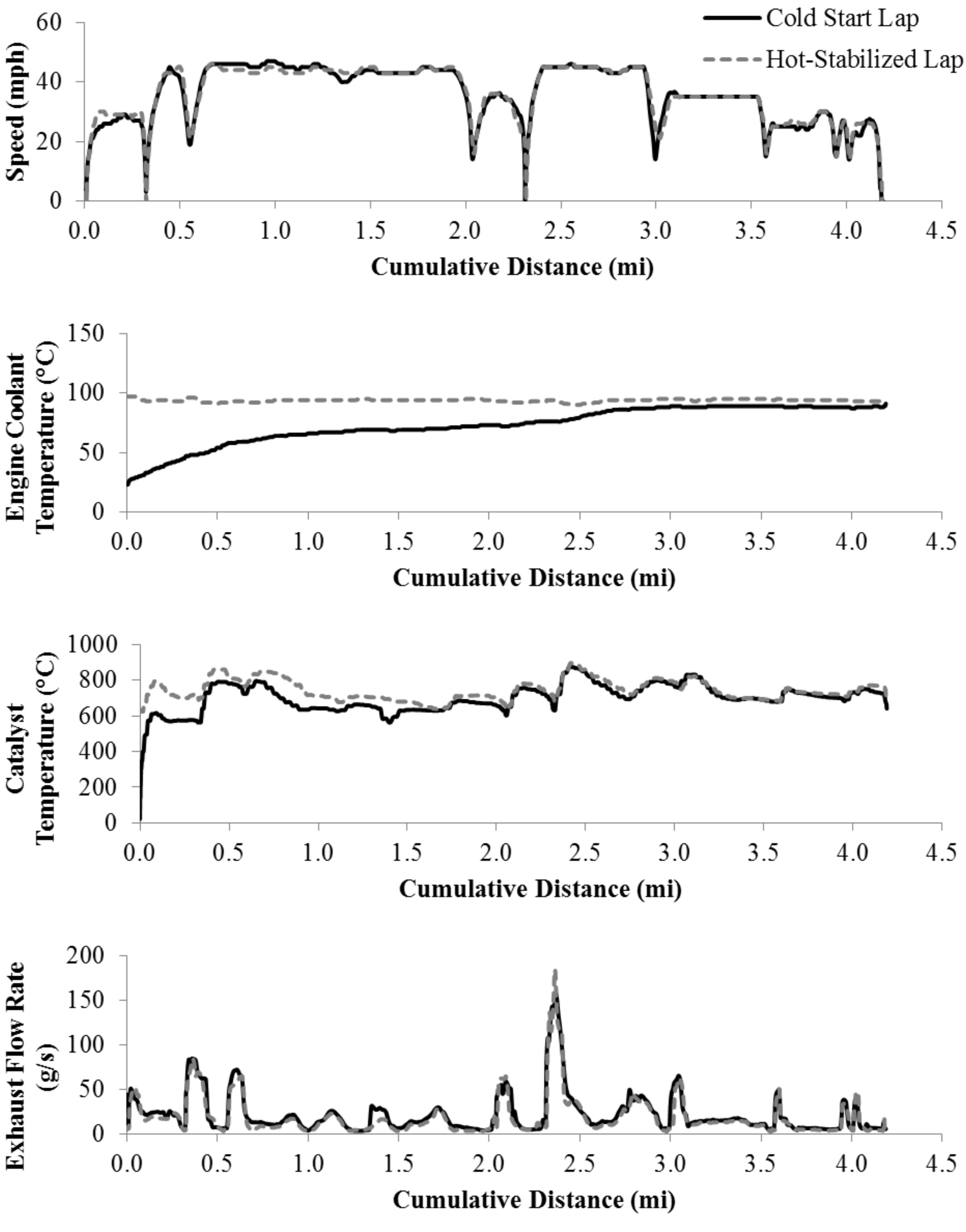

Figure S7. Speed, Engine Coolant Temperature, Catalyst Temperature, and Exhaust Flow Rate versus Cumulative Distance during Driving Cold Start Measurement for the 2015 Ford Fusion.

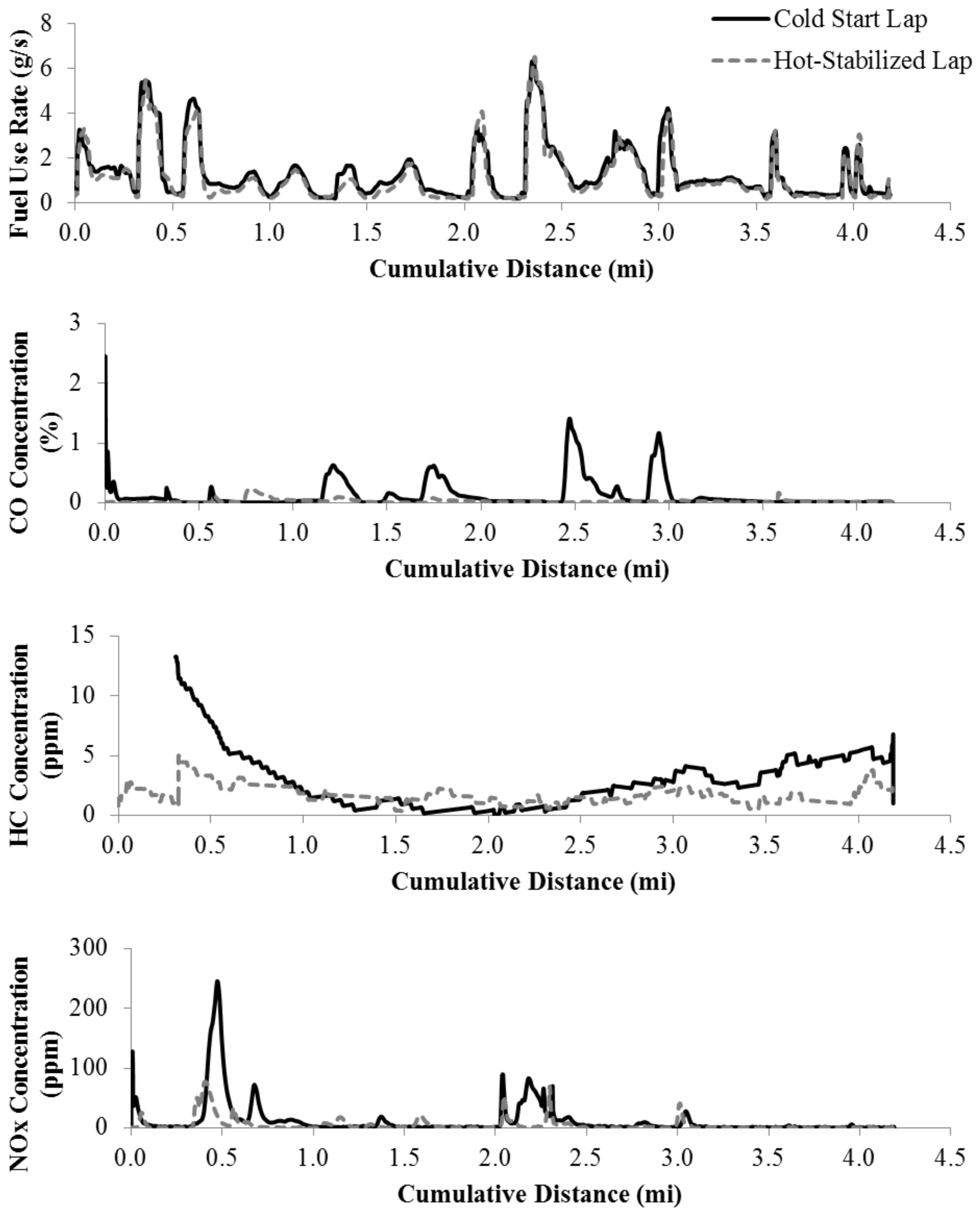

Figure S8. Fuel Use Rates and Emission Concentrations versus Cumulative Distance during Driving Cold Start Measurement for the 2015 Ford Fusion.

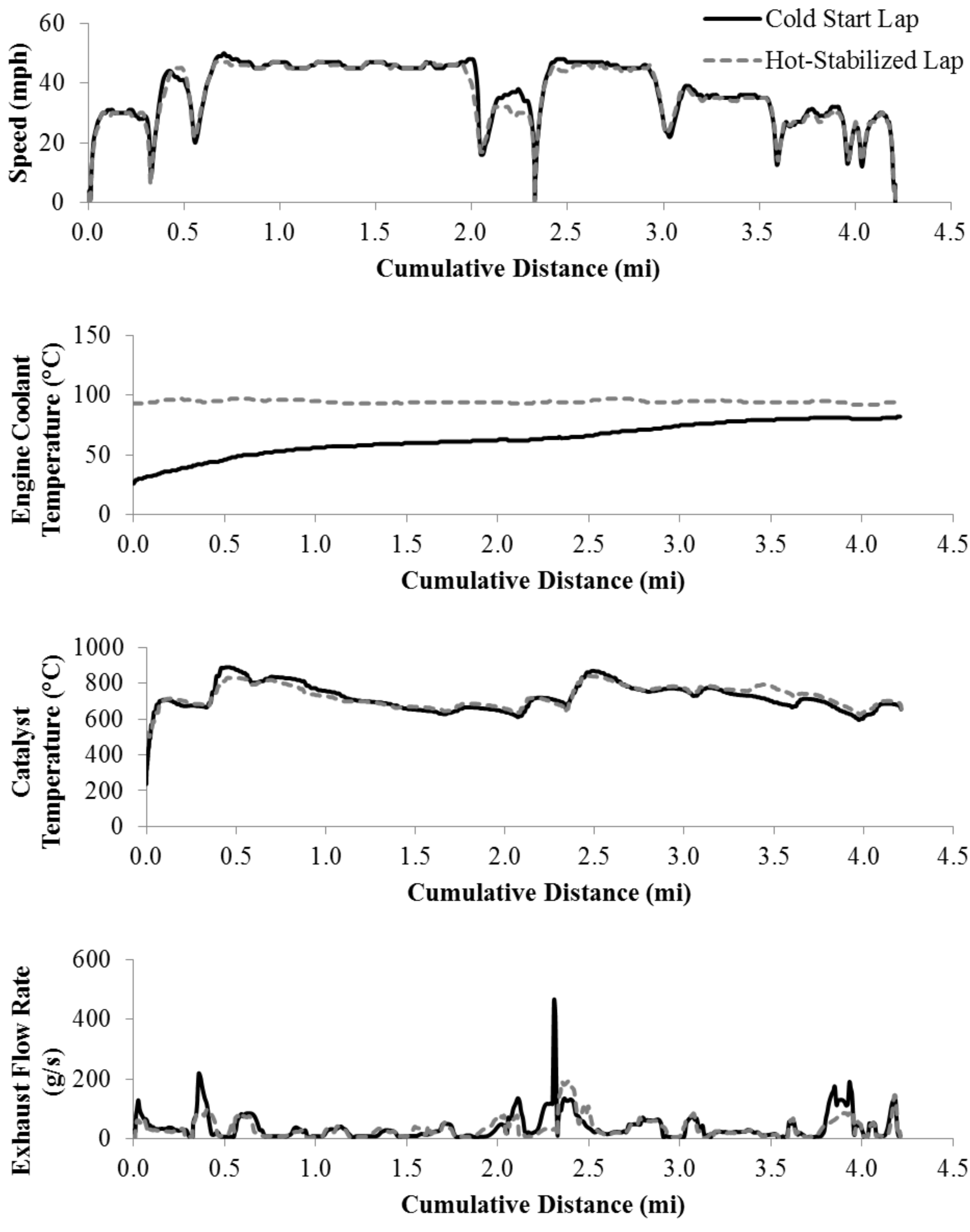

Figure S9. Speed, Engine Coolant Temperature, Catalyst Temperature, and Exhaust Flow Rate versus Cumulative Distance during Driving Cold Start Measurement for the 2015 Chevrolet Tahoe.

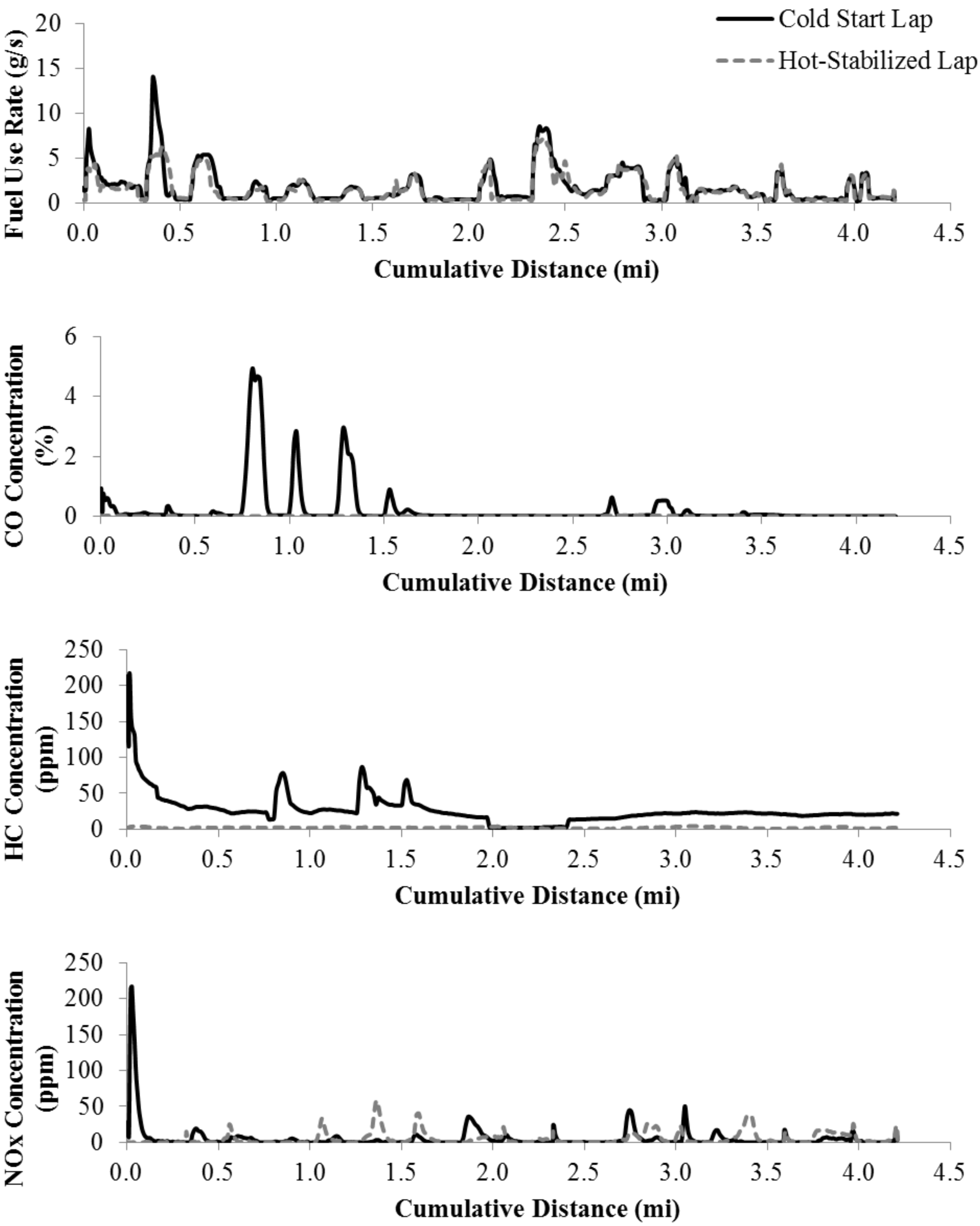

Figure S10. Fuel Use Rates and Emission Concentrations versus Cumulative Distance during Driving Cold Start Measurement for the 2015 Chevrolet Tahoe.

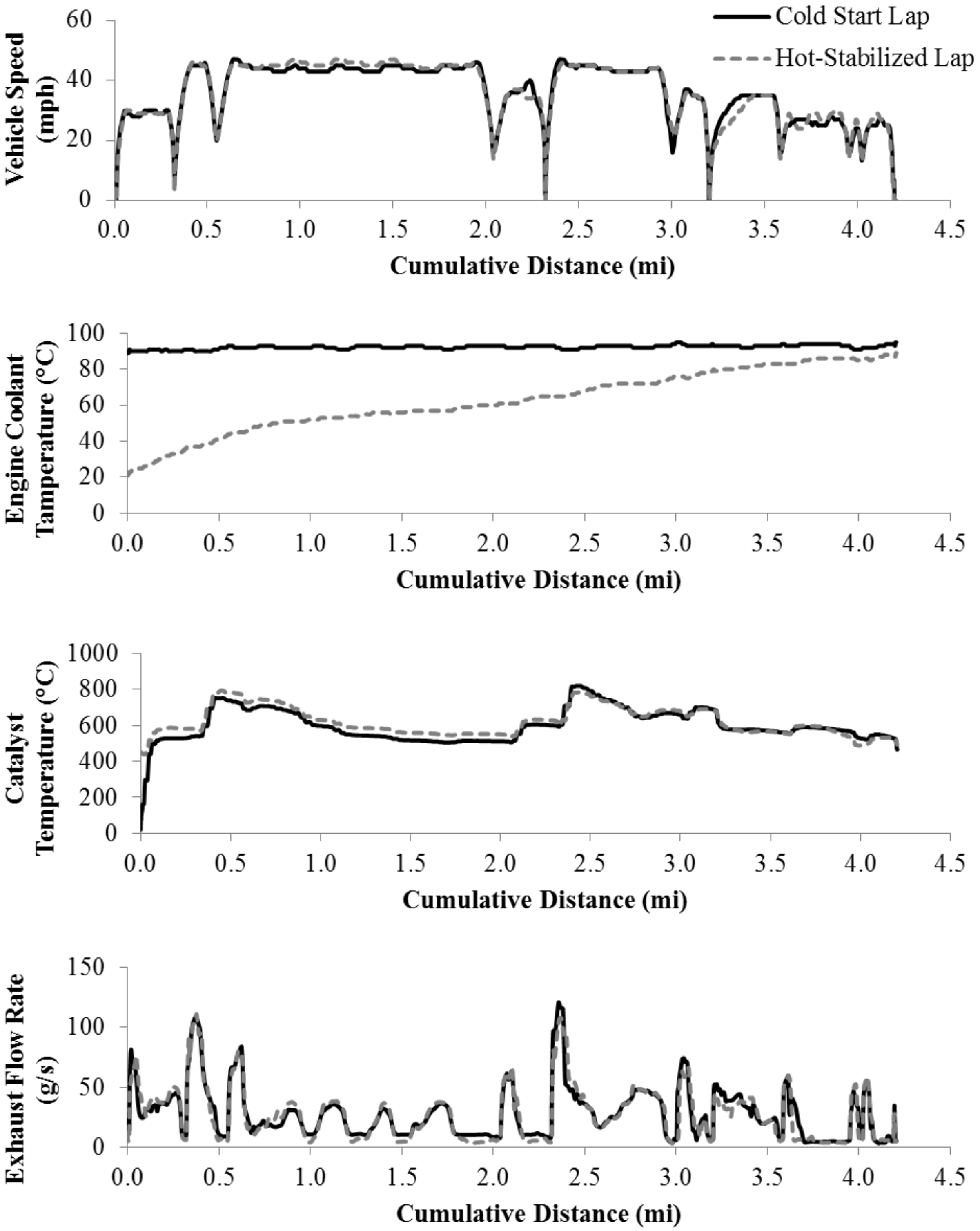

Figure S11. Speed, Engine Coolant Temperature, Catalyst Temperature, and Exhaust Flow Rate versus Cumulative Distance during Driving Cold Start Measurement for the 2015 Ford F150.

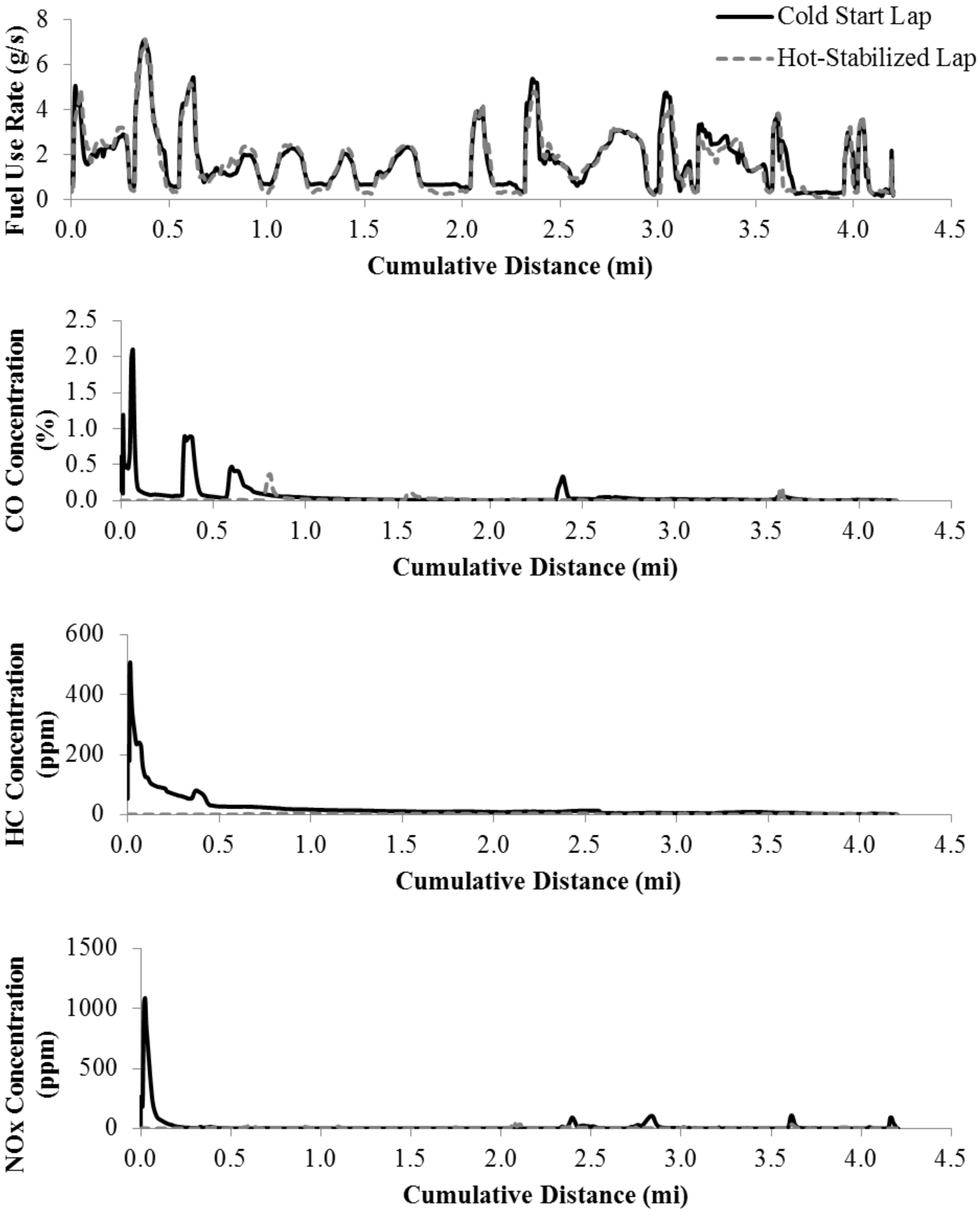

Figure S12. Fuel Use Rates and Emission Concentrations versus Cumulative Distance during Driving Cold Start Measurement for the 2015 Ford F150.

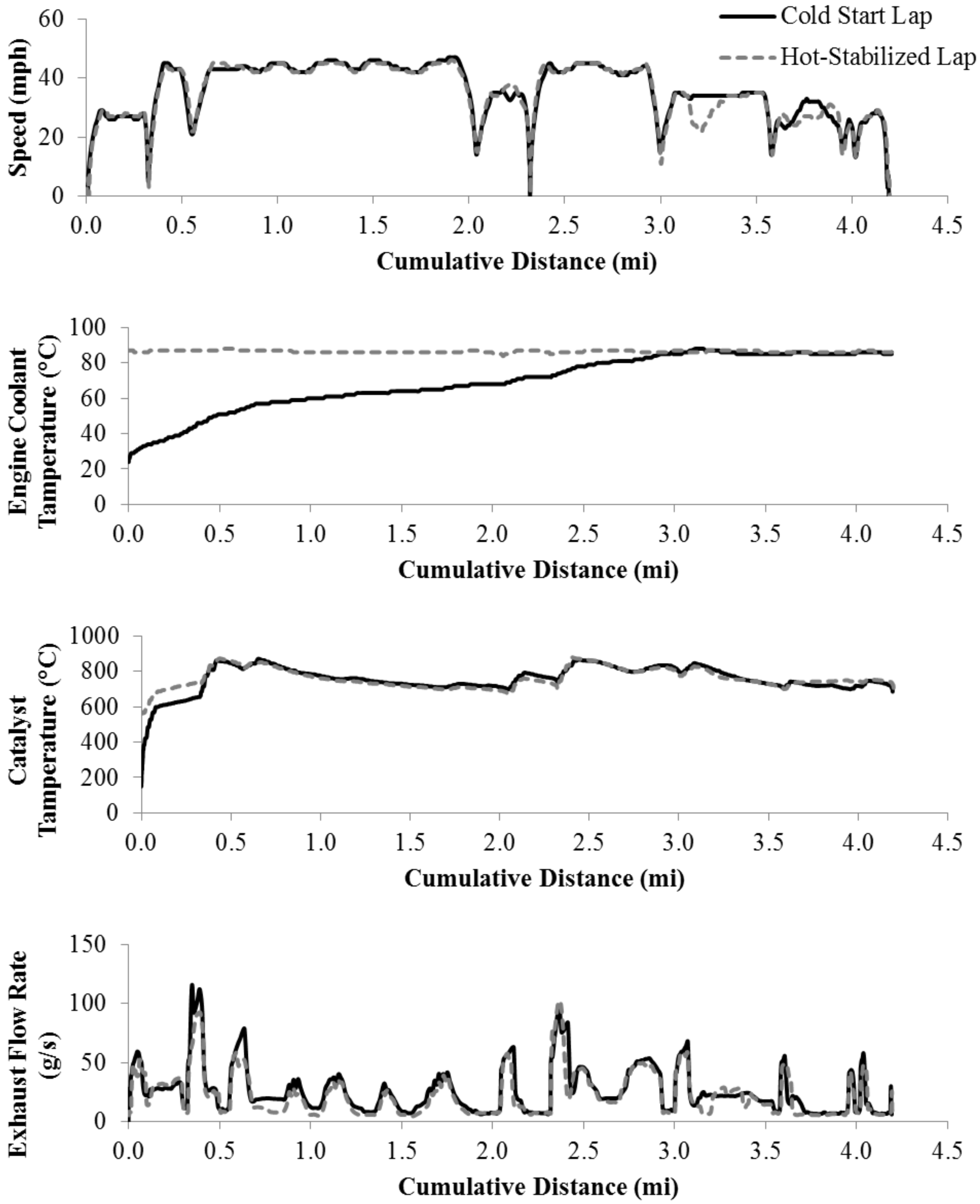

Figure S13. Speed, Engine Coolant Temperature, Catalyst Temperature, and Exhaust Flow Rate versus Cumulative Distance during Driving Cold Start Measurement for the 2016 Kia Sedona.

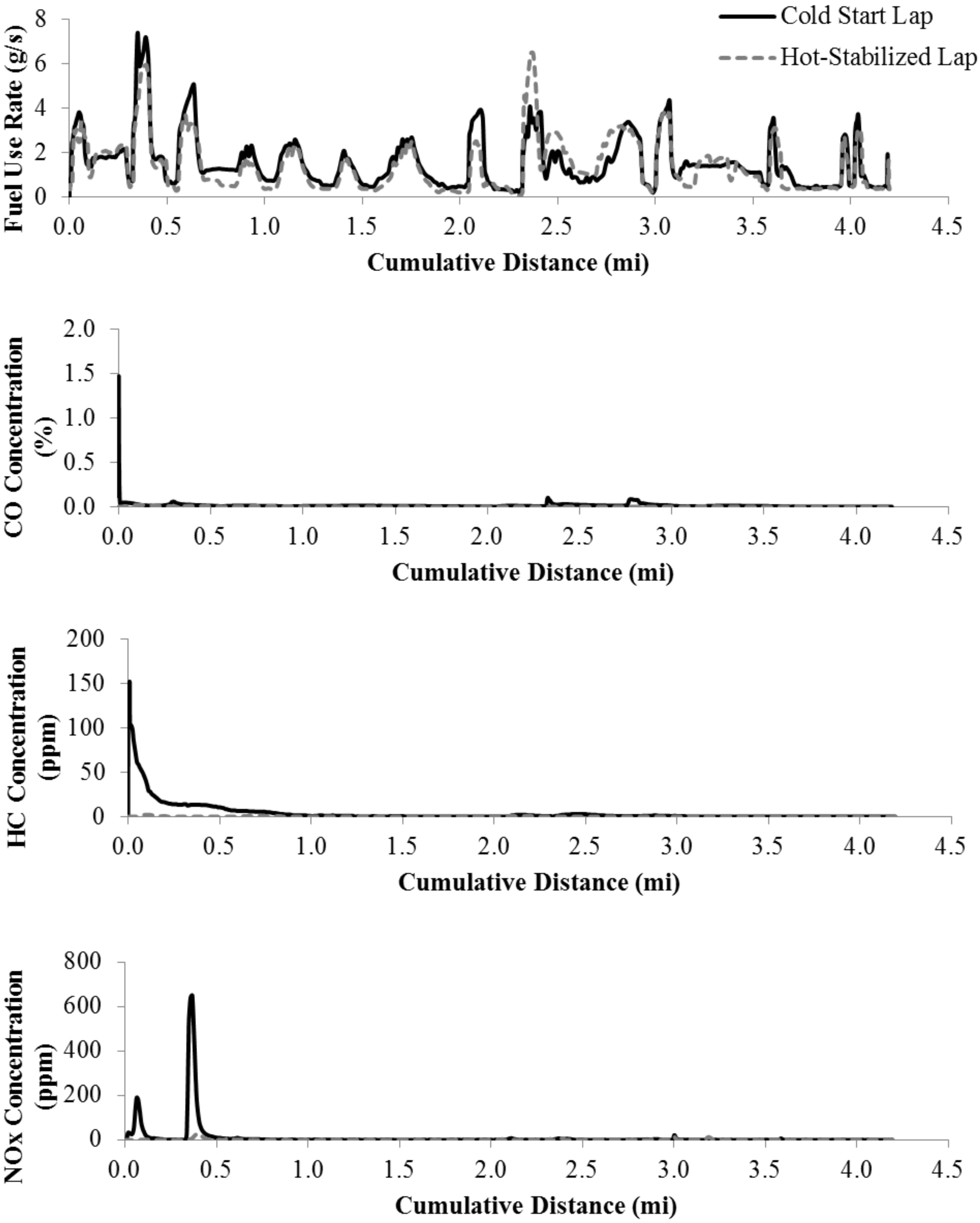

Figure S14. Fuel Use Rates and Emission Concentrations versus Cumulative Distance during Driving Cold Start Measurement for the 2016 Kia Sedona.

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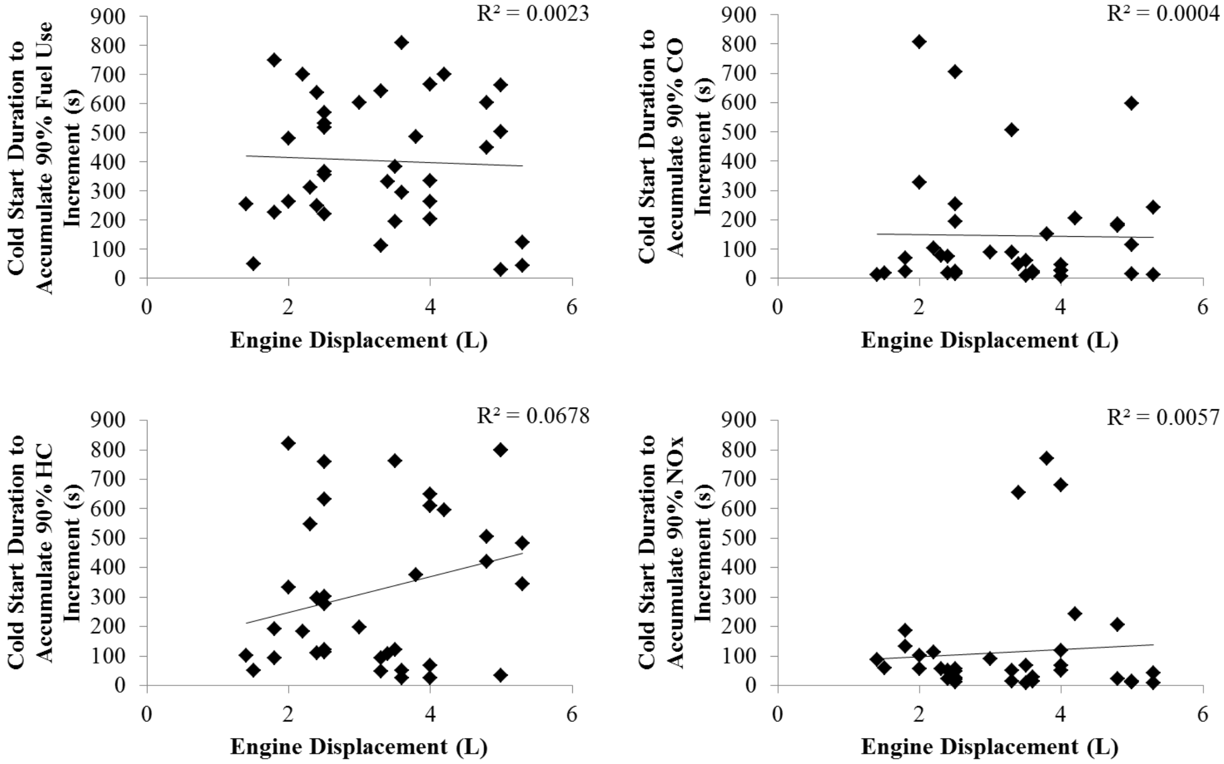

Figure S15. Scatter Plot of Cold Start Duration to Accumulate 90% Cold Start Increment versus Engine Displacement for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with engine displacement were observed for each of cold start approach to steady-state time for fuel use, CO, HC, and NO_x.

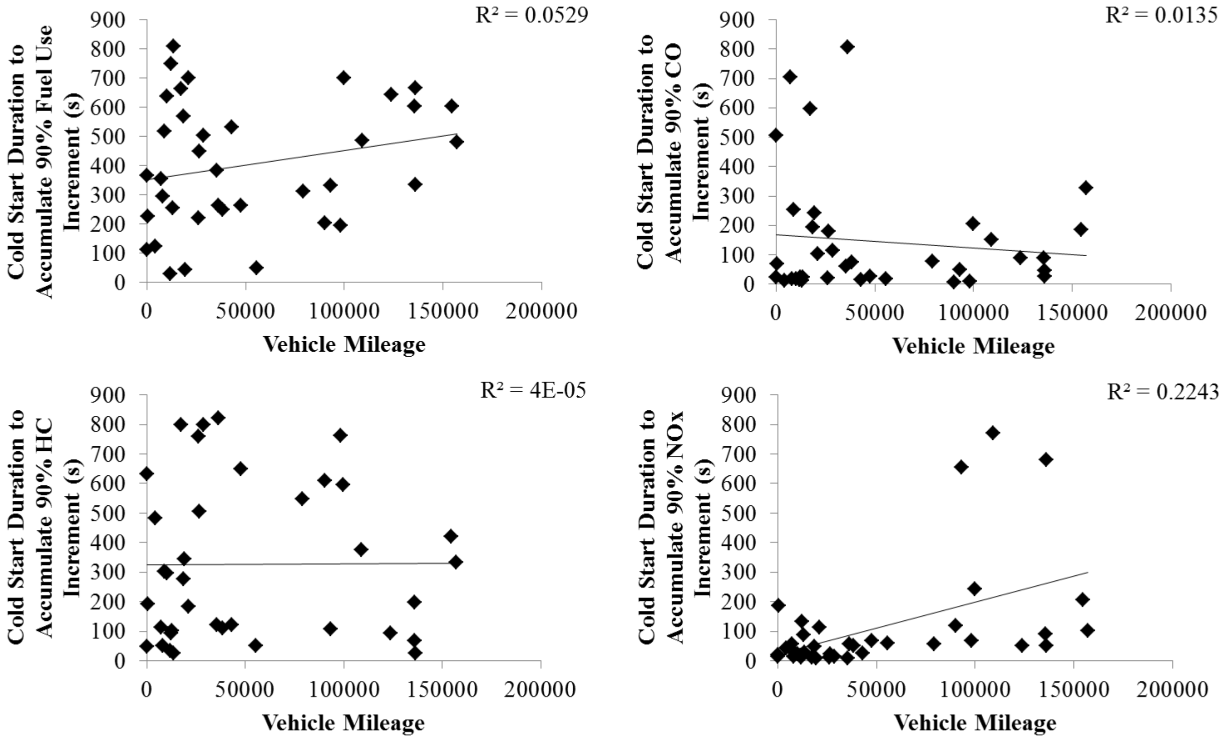

Figure S16. Scatter Plot of Cold Start Duration to Accumulate 90% Cold Start Increment versus Vehicle Mileage for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

NO_x approach to steady-state time statistically significantly linearly increases with vehicle mileage, with an R-square of 0.22. No statistically significant linear relationships with vehicle mileage were observed for each of cold start approach to steady-state time for fuel use, CO, and HC.

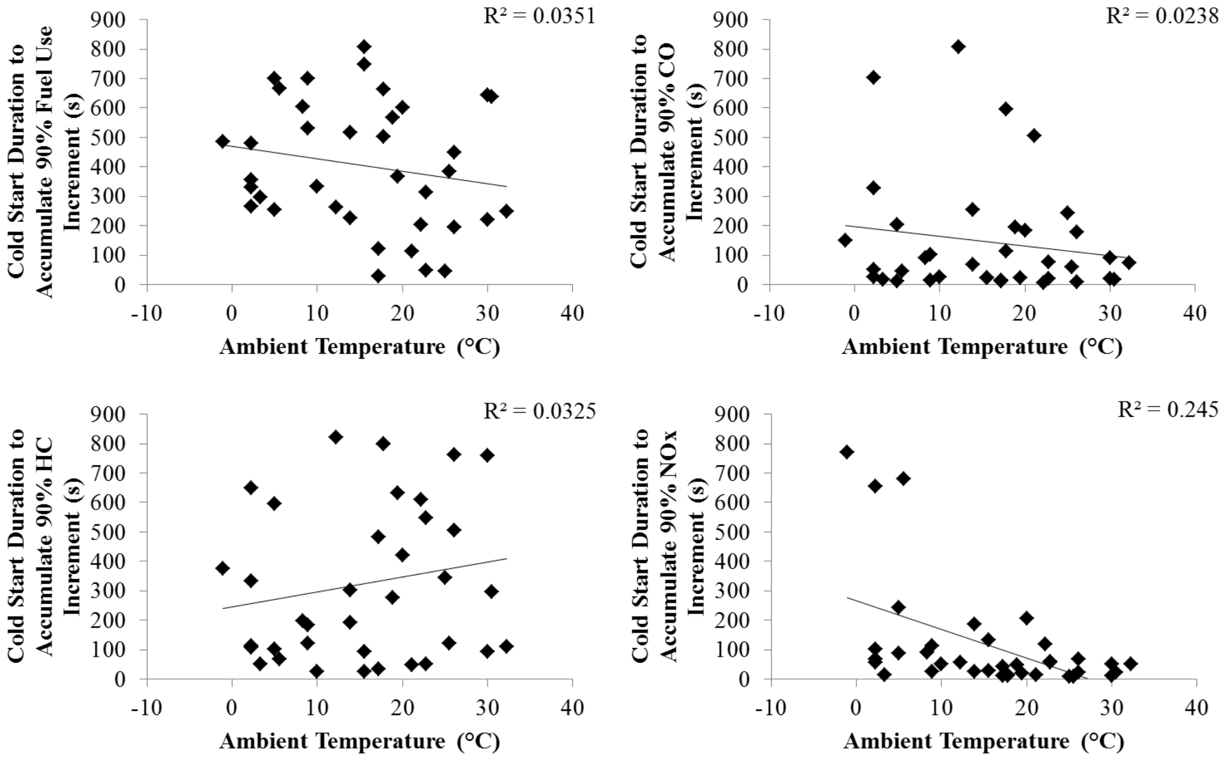

Figure S17. Scatter Plot of Cold Start Duration to Accumulate 90% Cold Start Increment versus Ambient Temperature for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with ambient temperature were observed for each of cold start approach to steady-state time for CO, HC, and NO_x.

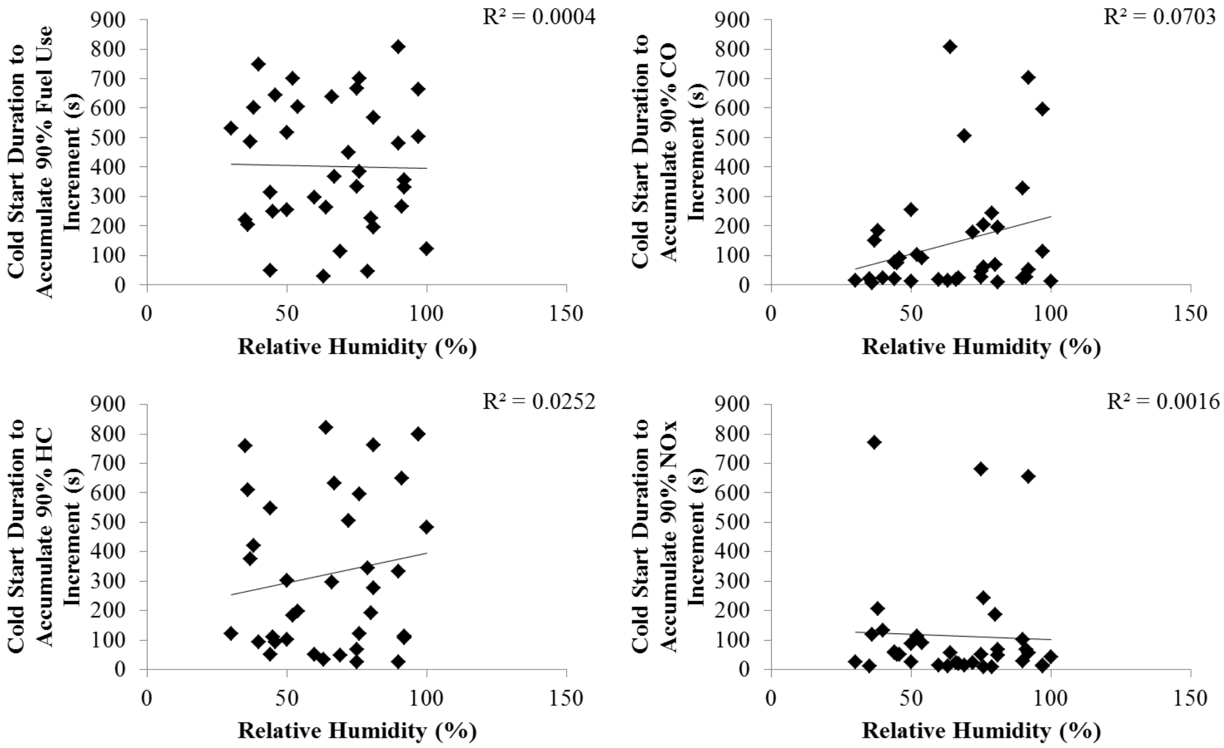

Figure S18. Scatter Plot of Cold Start Duration to Accumulate 90% Cold Start Increment versus Relative Humidity for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with relative humidity were observed for each of cold start approach to steady-state time for fuel use, CO, HC, and NO_x.

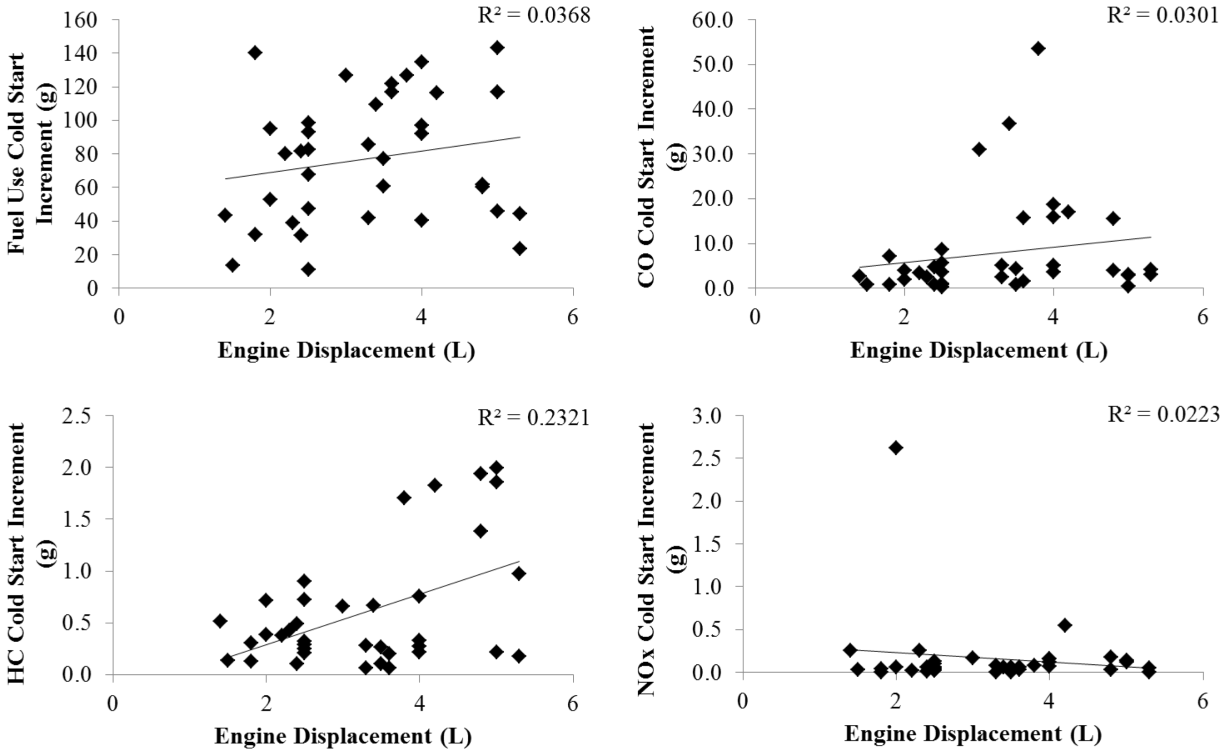

Figure S19. Scatter Plot of Cold Start Increment versus Engine Displacement for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

HC cold start increment statistically significantly linearly increases with engine displacement, with an R-square of 0.23. No statistically significant linear relationships with engine displacement were observed for each of cold start increment for fuel use, CO, and NO_x.

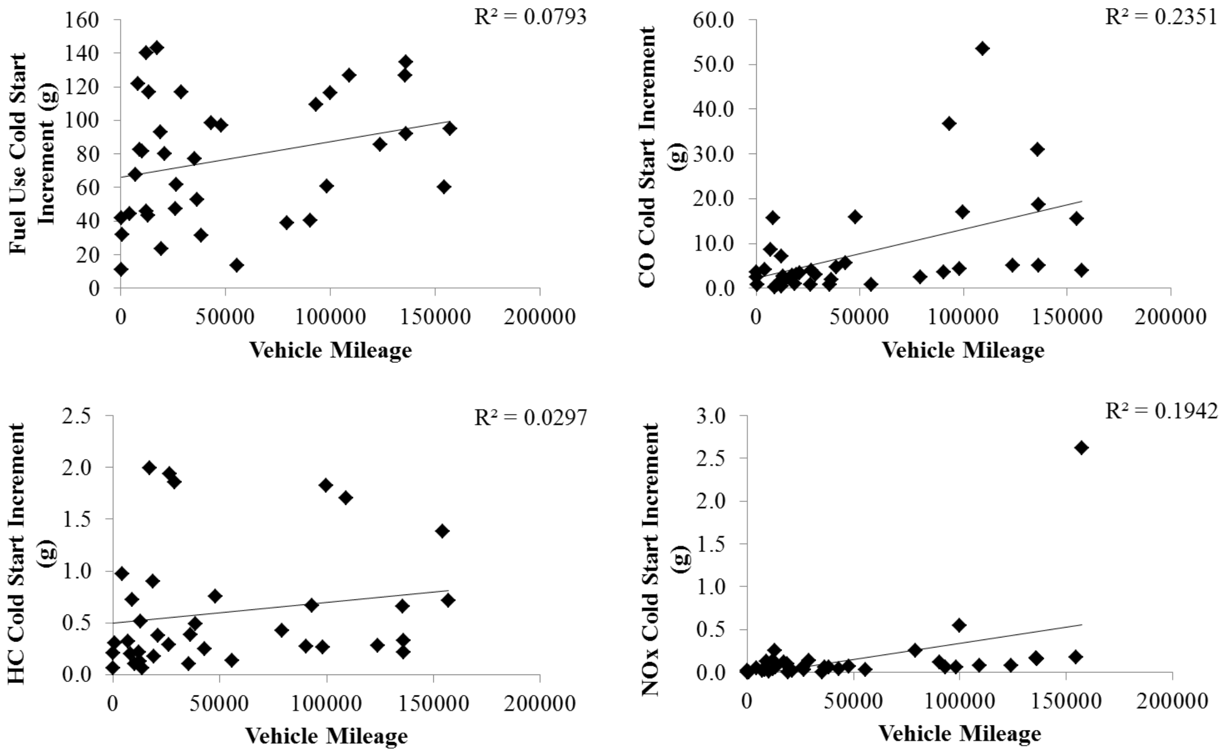

Figure S20. Scatter Plot of Cold Start Increment versus Vehicle Mileage for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

CO and NO_x cold start increment statistically significantly linearly increases with vehicle mileage, with R-squares of 0.23 and 0.19, respectively. No statistically significant linear relationships with vehicle mileage were observed for each of cold start increment for fuel use and HC.

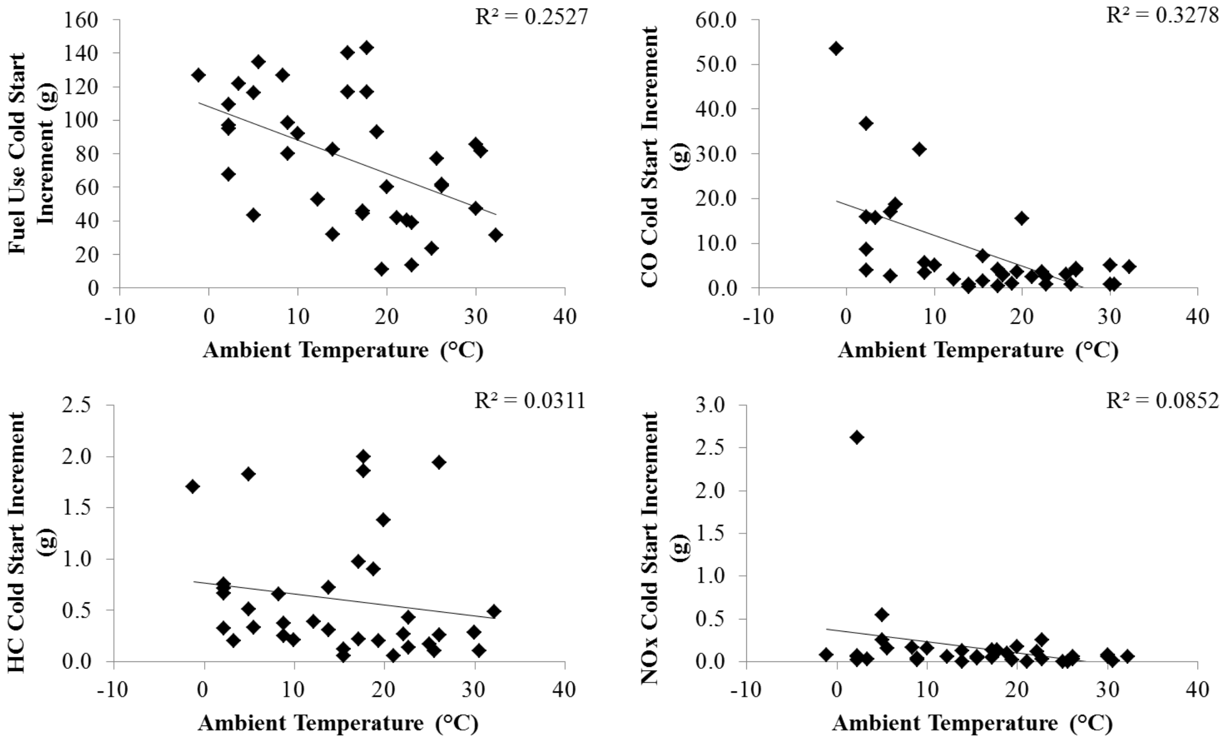

Figure S21. Scatter Plot of Cold Start Increment versus Ambient Temperature for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

Fuel use and CO cold start increments statistically significantly linearly decrease with ambient temperatures, with R-squares of 0.26 and 0.34, respectively. No statistically significant linear relationships with ambient temperature were observed for each of cold start increment for HC and NO_x.

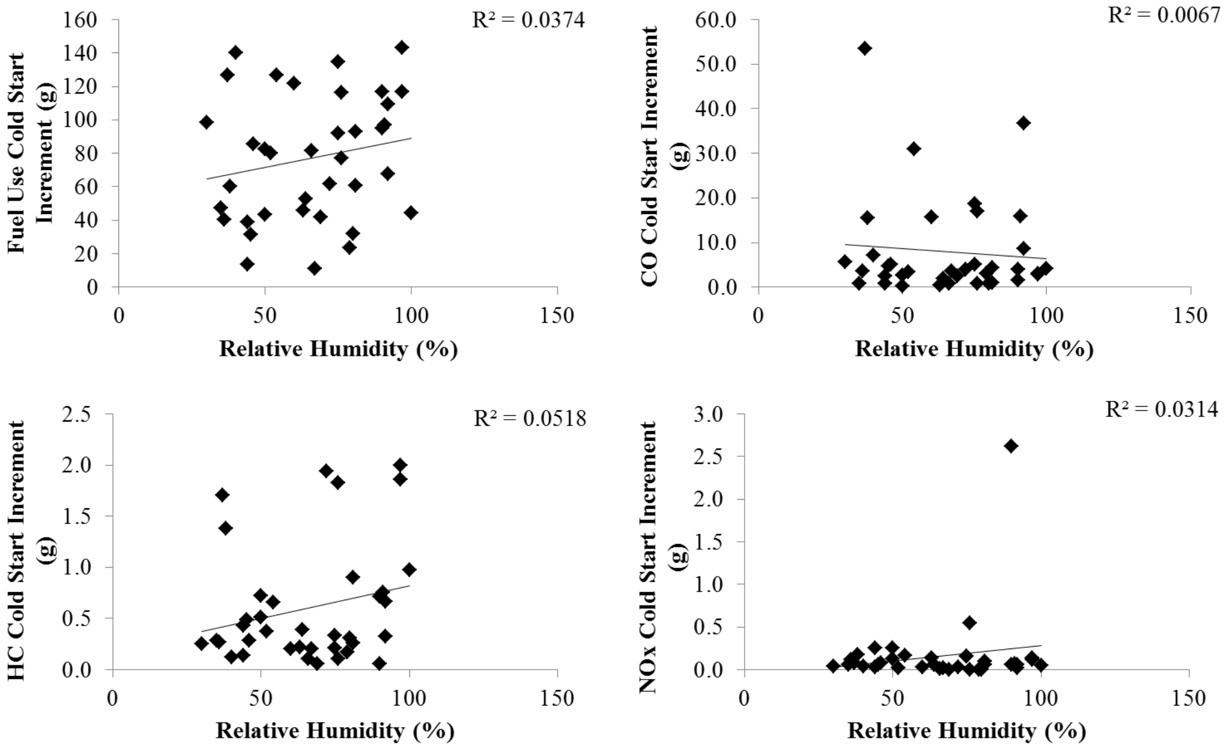

Figure S22. Scatter Plot of Cold Start Increment versus Relative Humidity for All Measured Vehicles for Each of Fuel Use, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with relative humidity were observed for each of cold start increment for fuel use, CO, HC, and NO_x.

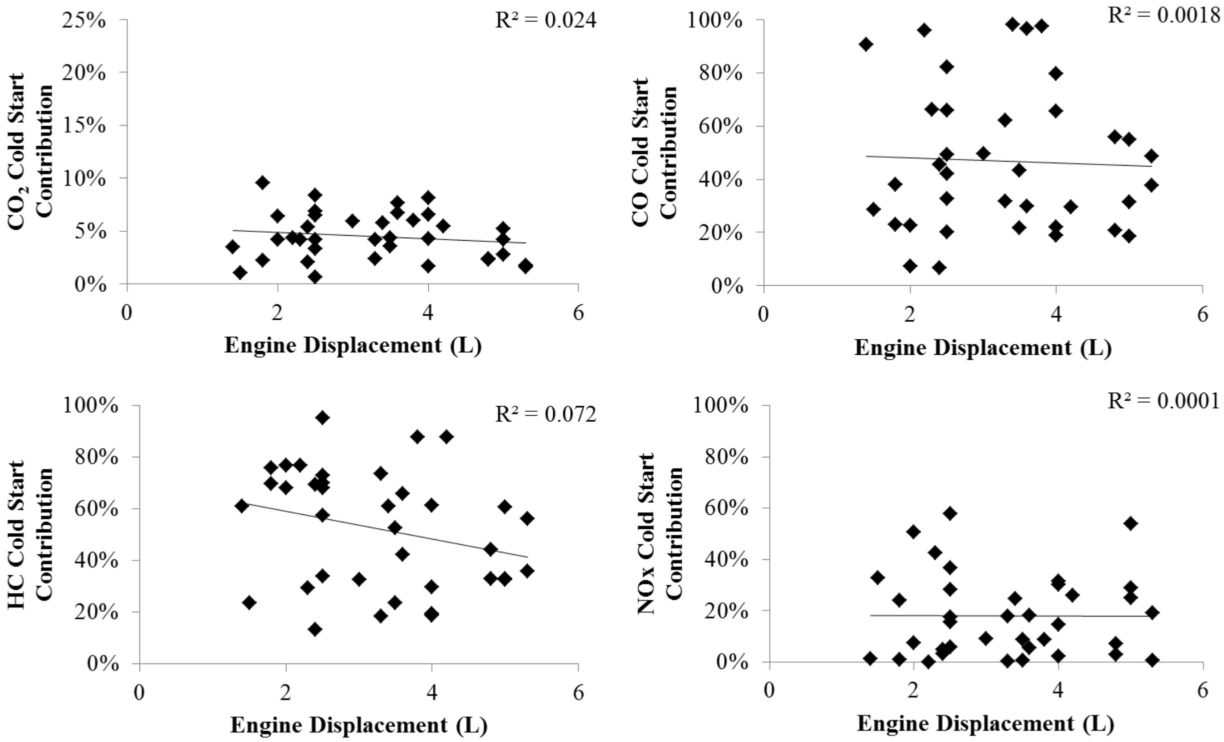

Figure S23. Scatter Plot of Idle Cold Start Contribution versus Engine Displacement for All Measured Vehicles for Each of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with engine displacement were observed for each of idle cold start contributions for CO_2, CO, HC, and NO_x.

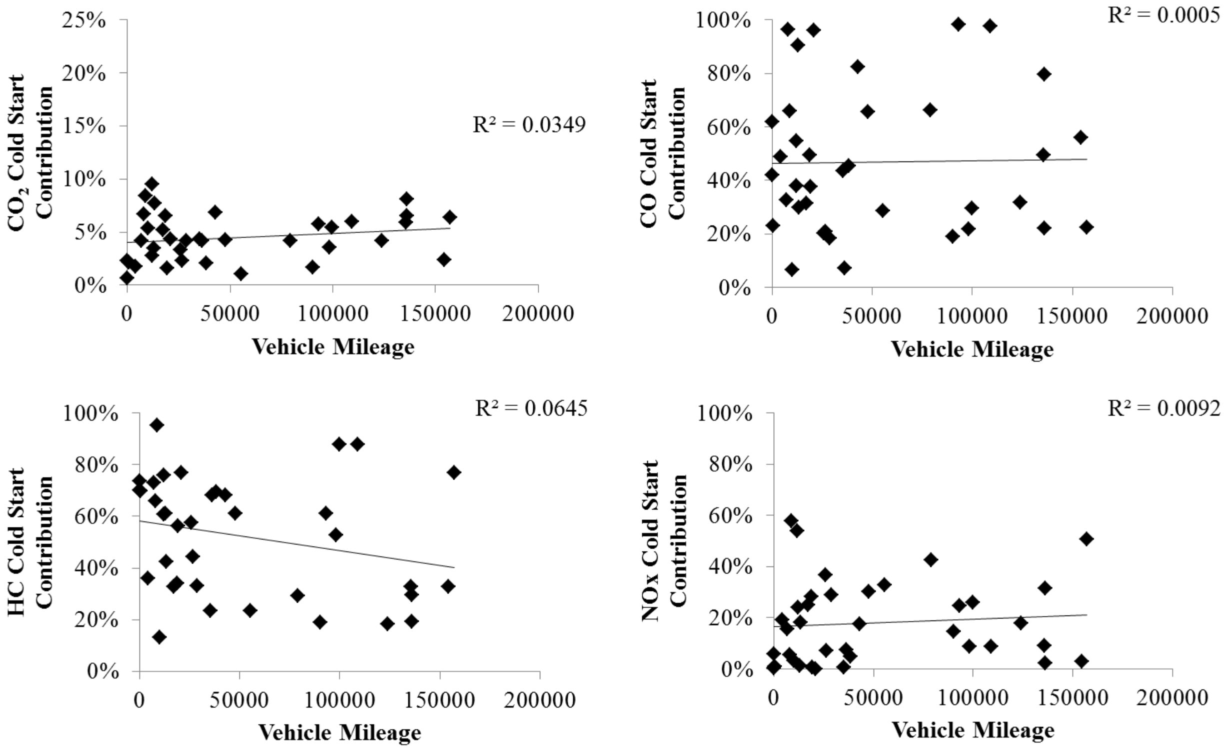

Figure S24. Scatter Plot of Idle Cold Start Contribution versus Vehicle Mileage for All Measured Vehicles for Each of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with vehicle mileage were observed for each of idle cold start contributions for CO_2, CO, HC, and NO_x.

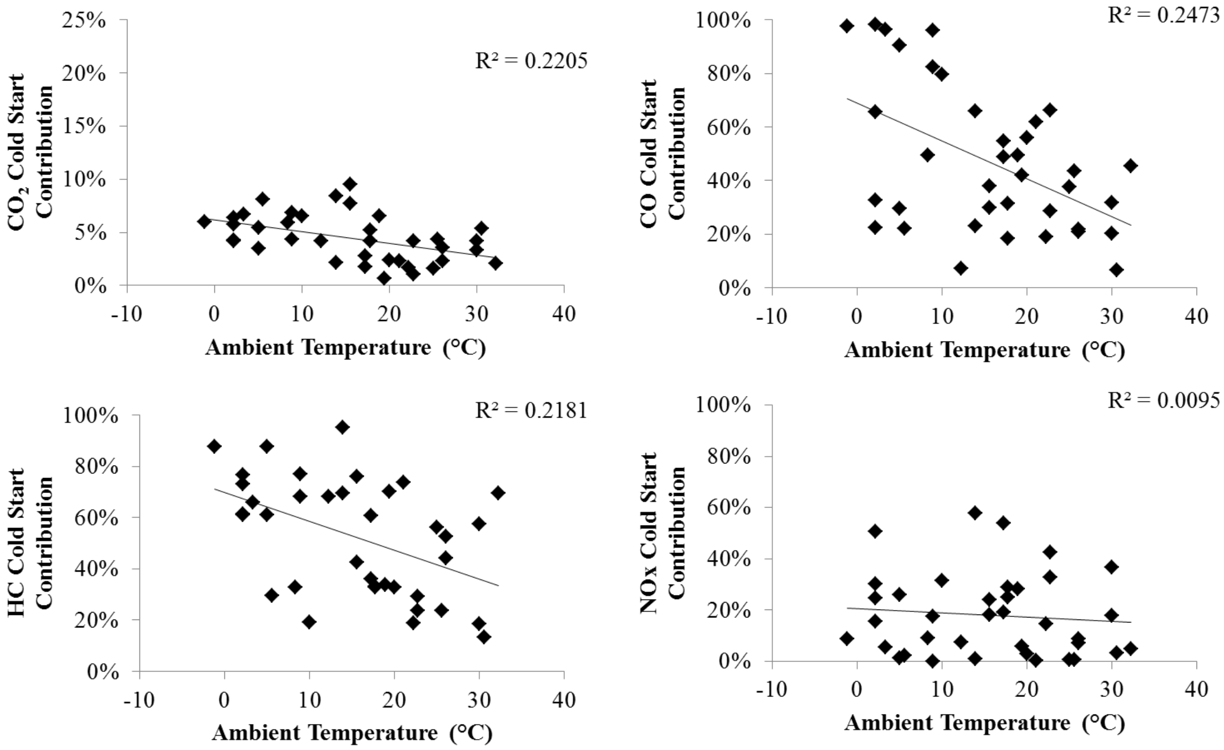

Figure S25. Scatter Plot of Idle Cold Start Contribution versus Ambient Temperature for All Measured Vehicles for Each of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

CO_2, CO, and HC idle cold start contributions statistically significantly linearly decrease with ambient temperatures, with R-squares of 0.22, 0.25, and 0.22, respectively. No statistically significant linear relationships with ambient temperature were observed for idle cold start contributions for NO_x.

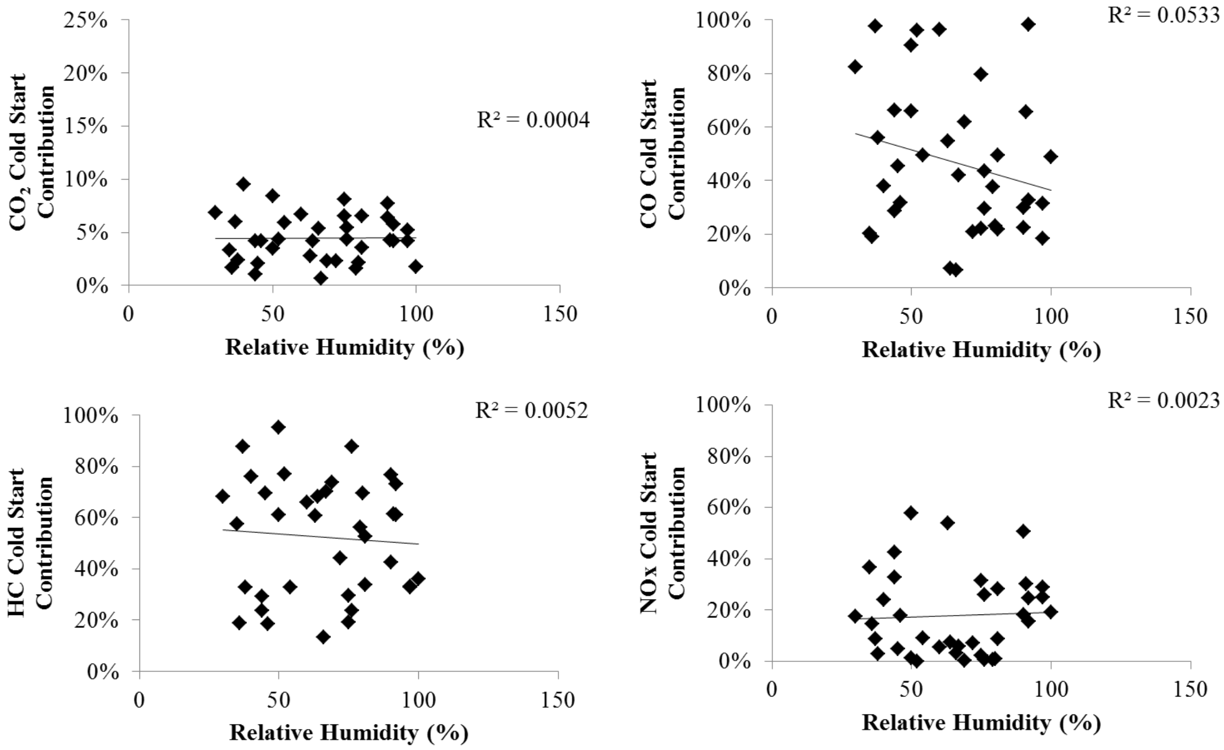

Figure S26. Scatter Plot of Idle Cold Start Contribution versus Relative Humidity for All Measured Vehicles for Each of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

No statistically significant linear relationships with relative humidity were observed for each of idle cold start contributions for CO_2, CO, HC, and NO_x.

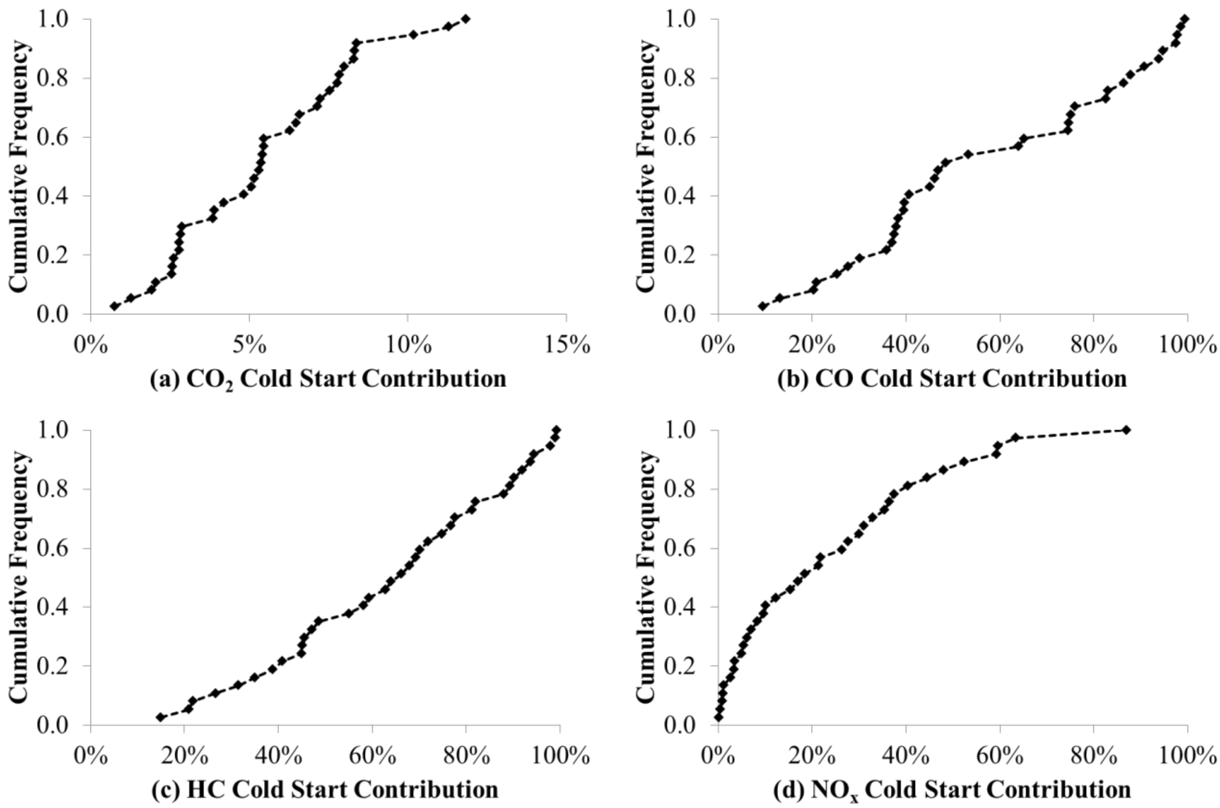

Figure S27. Cumulative Frequency of Cold Start Contributions of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Based on Measured Data for Route A. Each Point Represents One Vehicle, with Average Cold Start Contribution over 2 one-way trips of Route A. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

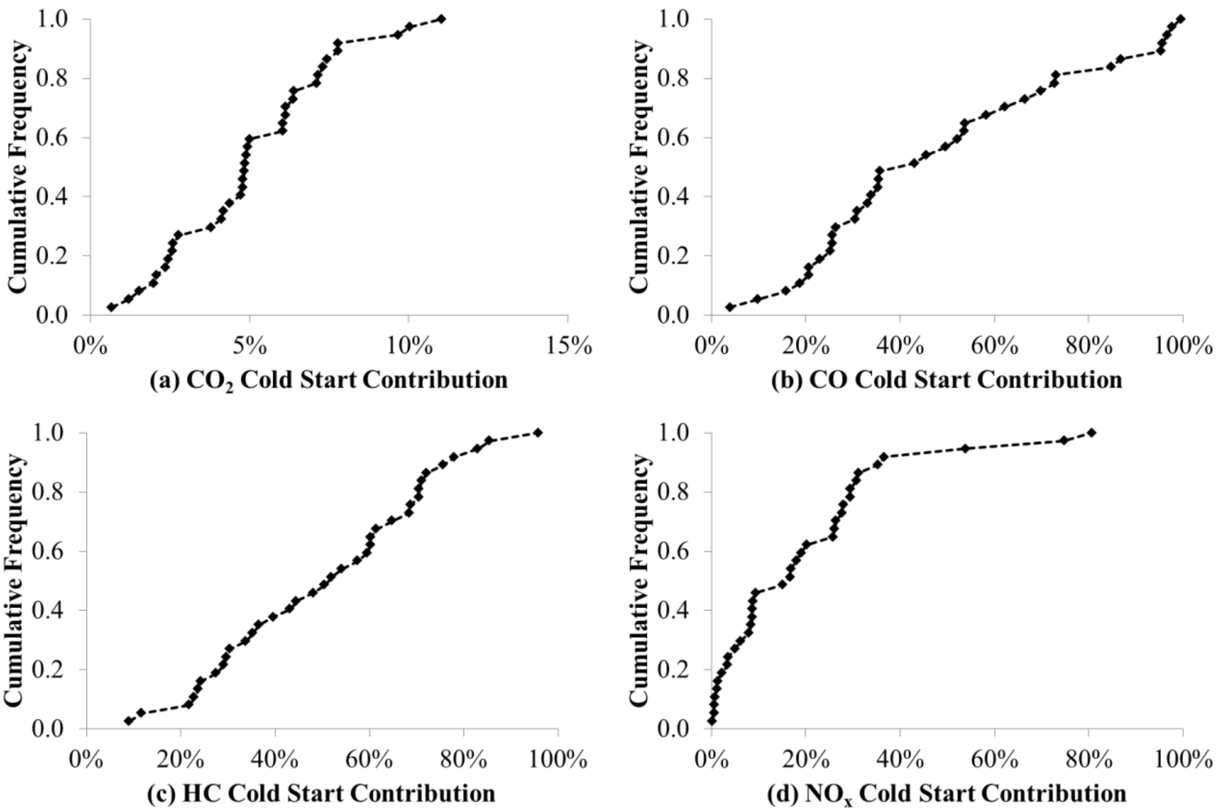

Figure S28. Cumulative Frequency of Cold Start Contributions of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Based on Measured Data for Route C. Each Point Represents One Vehicle, with Average Cold Start Contribution over 2 one-way trips of Route C. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

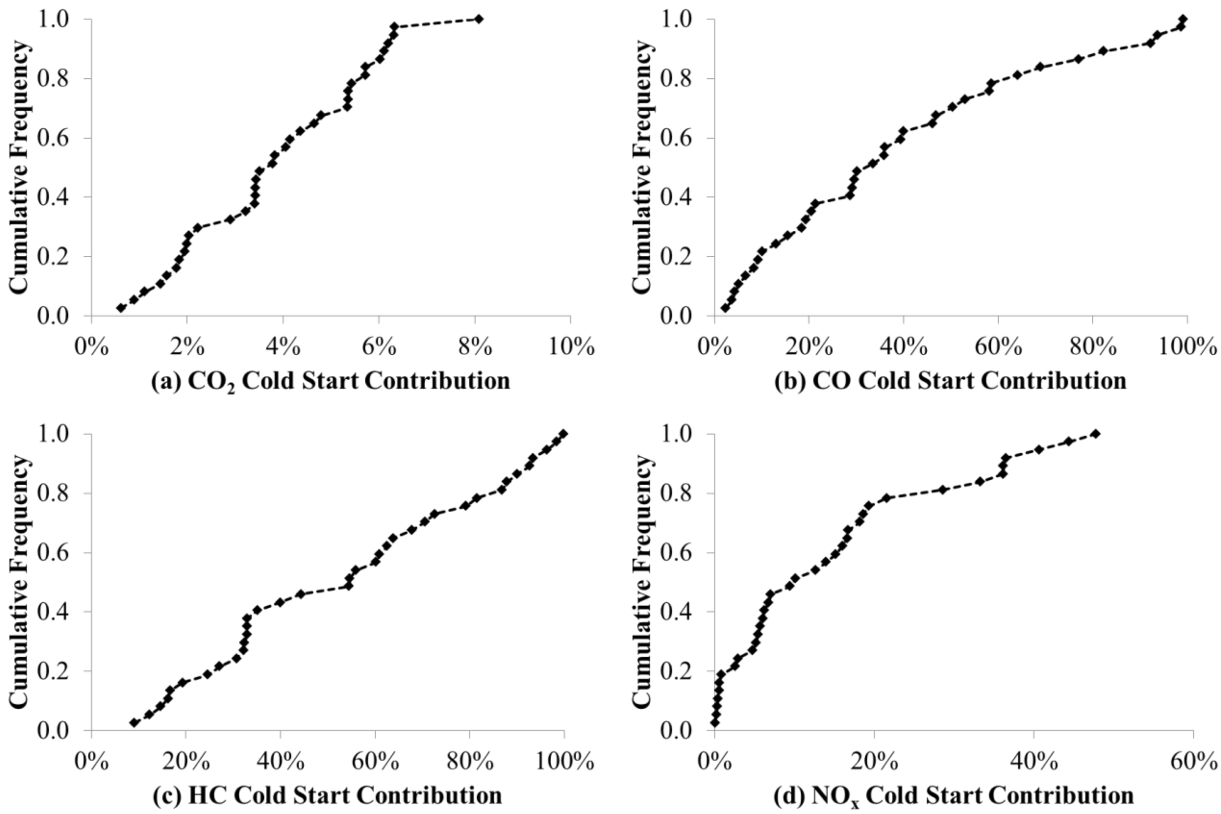

Figure S29. Cumulative Frequency of Cold Start Contributions of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Based on Measured Data for Route 1. Each Point Represents One Vehicle, with Average Cold Start Contribution over 2 one-way trips of Route 1. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

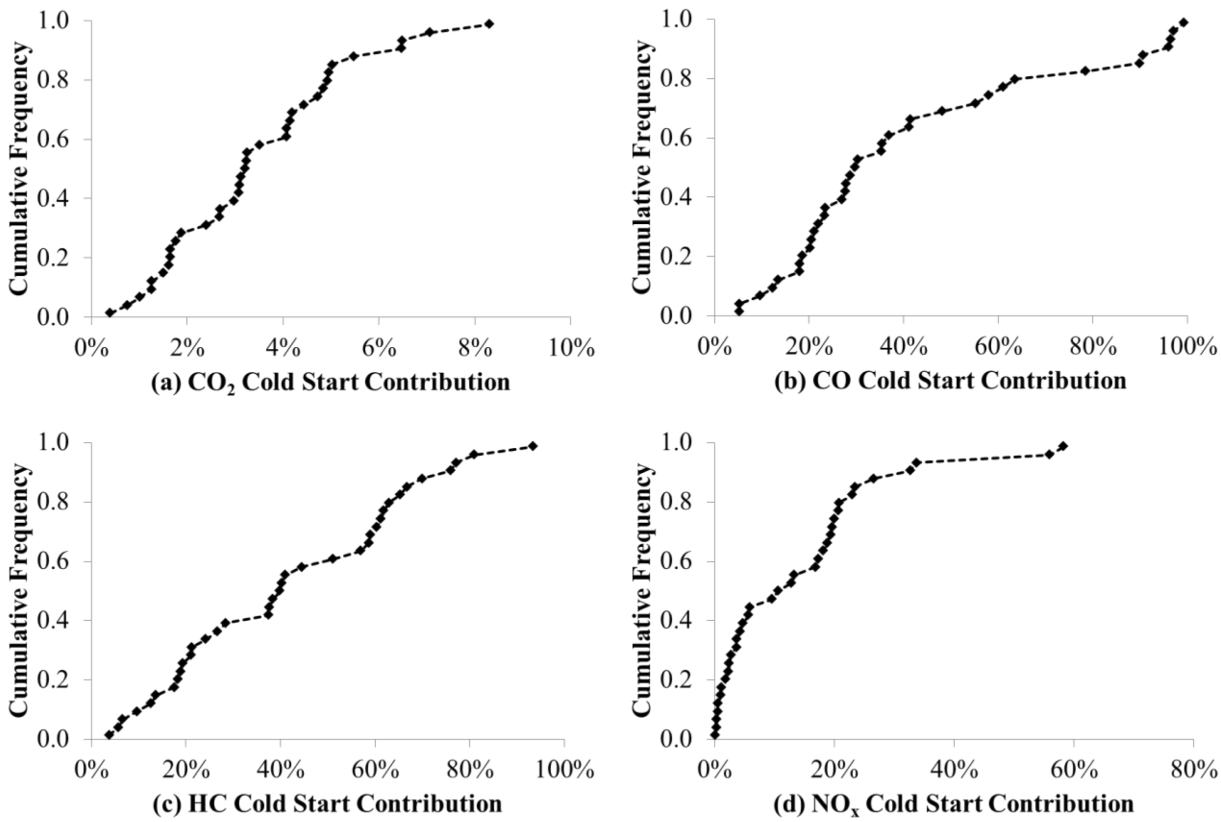

Figure S30. Cumulative Frequency of Cold Start Contributions of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Based on Measured Data for Route 3. Each Point Represents One Vehicle, with Average Cold Start Contribution over 2 one-way trips of Route 3. Each Panel Includes 37 Points with Each Point Represent One Vehicle.

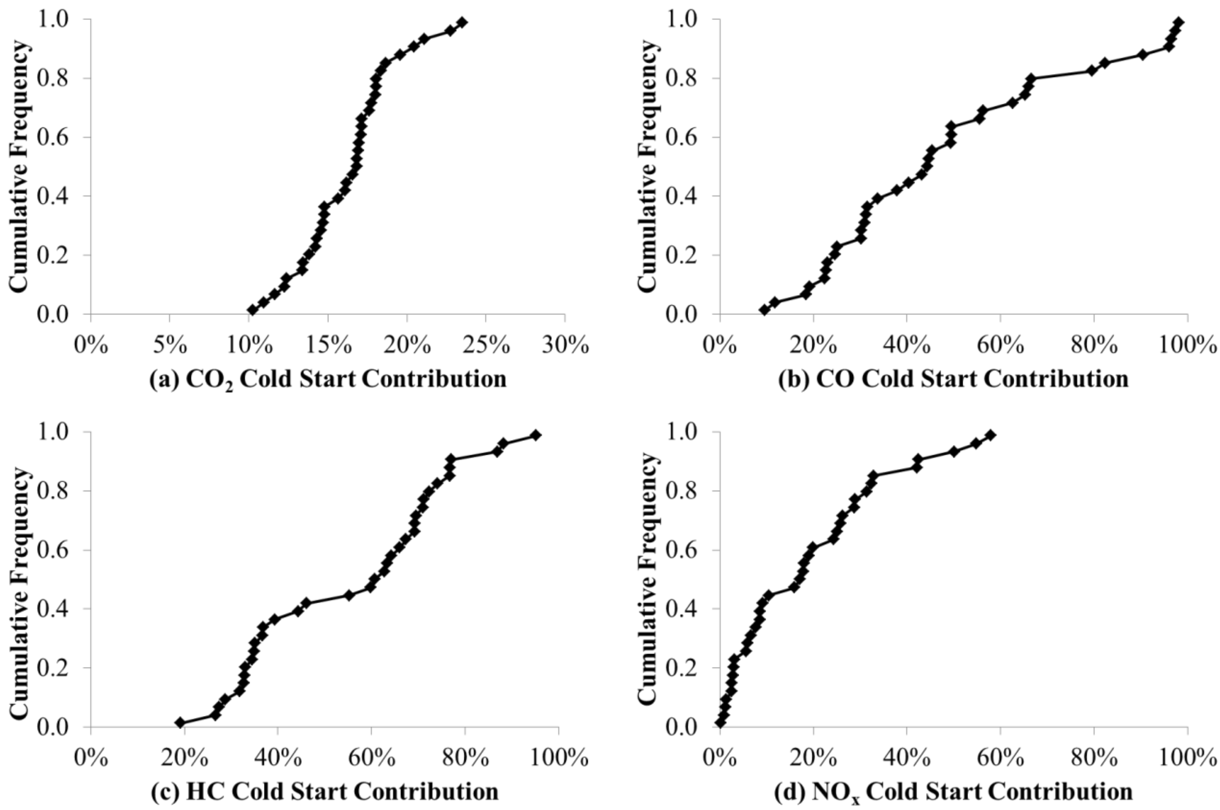

Figure S31. Cumulative Frequency of Idle Cold Start Contributions of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Based on 15 Minutes Idling Total Emissions. Each Panel Includes 37 Points. Each Point Represents One Vehicle, with Average Cold Start Contribution over 8 One-Way Trips.

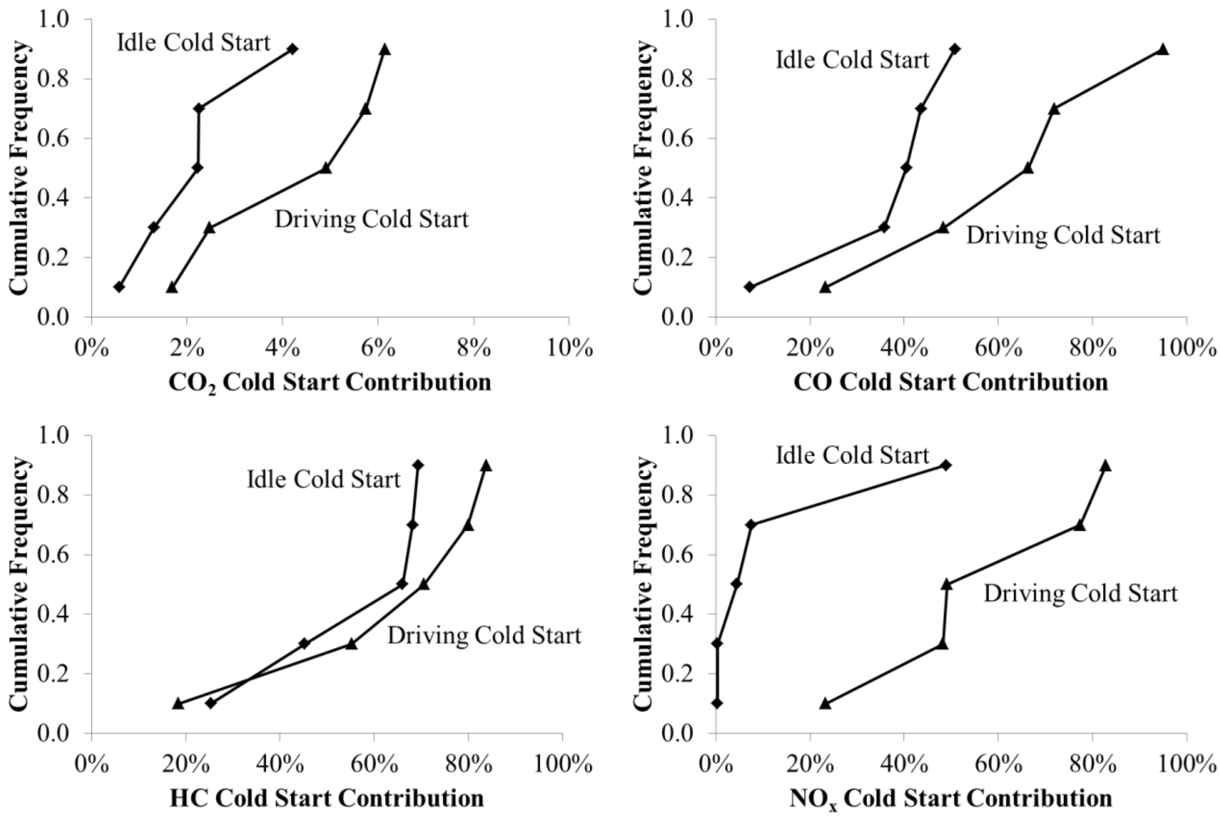

Figure S32. Cumulative Frequency of Idle versus Driving Cold Start Contributions of Carbon Dioxide, Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Based on Measured Data and MOVES Estimates. Each Panel Includes 5 Points. Each Point Represents One Vehicle that was Measured for Both Idle and Driving Cold Start, with Average Cold Start Contribution over 8 One-Way Trips.