Real-World Engine Cold Start and "Restart" Particle Number Emissions from a 2010 Hybrid and Comparable Conventional Vehicle

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ABSTRACT

Despite increasing popularity of hybrid-electric vehicles, few studies have compared their real-world particle emissions from internal combustion engine (ICE) cold starts and restarts, which have been shown to result in particulate number (PN) concentrations that exceed normal engine operations [1]. Tailpipe PN concentrations emitted from a conventional and hybrid 2010 Toyota Camry were quantified during 1 Hz sampling over 44 replicate runs of a 32-mile route in Chittenden County, Vermont using the Total On-board Tailpipe Emissions Measurement System. This study is the first to compare hybrid and conventional vehicle cold start emissions as well as quantify PN concentrations arising from hybrid engine restarts under a range of real-world driving ambient temperature (-10 to 41 ˚C) and road grade (-9 to 12%) conditions.

Cold start events averaged 9 seconds in duration, with total raw PN concentrations between 9.2E4 and 4.5E7 #/cm^3. Hybrid engine restart events were characterized over 25 runs. The hybrid ICE was off 20% to 50% of the total run time, with corresponding ICE restarts ranging between 42 and 118 events per run. The number of restarts increased at higher ambient temperature, but the PN concentration range per individual restart event did not vary. The mean hybrid restart total PN concentration was 4 times lower than those of hybrid cold starts. Hybrid cold start PN concentrations were on average 10% lower than those the conventional vehicle. Over the entire route, the mean hybrid PN concentration was 4 times higher than the conventional PN concentration.

INTRODUCTION

Light-duty hybrid vehicle “restarts” occur upon the re-ignition of the internal combustion engine (ICE) after a period engine-off, or electric-only, operation. This study examines the hypothesis that hybrid restart PN emissions can be modeled based upon the cold start emissions of comparable conventional vehicle. Previous work has identified the correlation between light-duty cold start events and elevated particulate concentrations. [2]. Though three-way catalysts remove up to 75% of hydrocarbon particle precursors during hot-stabilized operation [2], emissions control systems are not as effective under cold starts, as observed under an urban FTP 75 drive cycle, where more than 80% of total run hydrocarbon gaseous emissions were generated during cold start operation [3]. Similarly, elevated PN concentrations have been observed for restart events in city driving [1].

Recent studies provide evidence of correlation between exposure to particulate matter and increased rates of lung disease, cardiopulmonary disease, diminished childhood lung development and mortality [4, 5, 6]. Though motor vehicles are a significant source of particulate matter, laboratory vehicle exhaust emission testing, typically conducted under uniform conditions, fails to capture the full effect of variability experienced under real-world vehicle operating conditions. As hybrid vehicles make up an increasing proportion the vehicle fleet, their emissions behavior should be taken into account in emissions models, and engine restart events must be characterized in order to more acm3urately capture the effects upon emissions and fuel consumption. As part of a larger project designed to improve understanding of vehicular emissions under real-world driving conditions [1, 7], this study collected tailpipe emissions for two light-duty gasoline vehicles operating on a specified 32-mile driving route in Chittenden County, Vermont. This route included driving along a variety of road facilities, including approximately 8 miles along urban local collectors, 12 miles along the highway, 6 miles on rural collectors and 6 miles of urban arterial driving. The selection of the Toyota Camry for this study allowed for optimal comparison between a conventional vehicle and its hybrid equivalent in identifying particle number emissions associated with hybrid technology.

Studies on light-duty and heavy-duty hybrid vehicle effects on tailpipe emissions have yielded various results [8 - 12]. Increasing numbers of hybrid models entering the market with a multitude of transmission systems (series, parallel, planetary-combination) result in varying power demands placed upon the internal combustion engine (ICE), particularly under transient operating conditions. These differing power platforms also affect the operation of the ICE, notably the models which allow for the ICE to shutdown and operate under electric-drive-only during instances of low power demand, under certain speeds and sufficient battery state of charge. Zhai [13] identified specific thresholds of maximum speed and acceleration for ICE-off operation of a first generation Toyota Prius. Others studies have shown significant effects of temperature upon hybrid operation for a Toyota Prius and a Ford Escape on a NYC test cycle, a three-fold decrease in percent ICE-off in both vehicles with a temperature change from 20˚C to -18˚C [8]. This variability makes characterization of emission patterns particularly challenging.

Research on hybrid-electric vehicular particle total number concentrations is emergent. One study of light-duty vehicles under dynamometer testing showed similar emission patterns between conventional and hybrid vehicles, with particulate number emission rates increasing during acceleration and at high speeds [8]. Consistent with literature on conventional vehicle operation, emission rates were also higher during transient operation as compared to steady-state operation for all vehicles. Despite these similarities, differences in emission patterns were found for hybrid-electric vehicle designs that allow the ICE to turn off during electric-drive-only operation [1, 8]. Significantly elevated emissions were associated with ICE restart events immediately following electric-drive-only operation. Frequency of ICE restarts events has been positively correlated with higher particle number concentrations during city driving [1]. During engine ignition, fuel-rich conditions lead to an increase in unburned hydrocarbons, thus producing significantly higher particle numbers with an increase in the proportion of particles between 30 and 50 nanometers [2]. In urban environments, where engine restarts occur more frequently and with greater spatial density, elevated PN levels may have a significant adverse impact upon human health and the environment.

The purpose of this paper is to assess the potential influence of hybrid ICE restart events upon on air quality, to compare cold start PN emissions between comparable hybrid and conventional vehicles, and to quantify the effects of ambient conditions upon hybrid ICE operation. Whereas previous research has focused upon gas-phase emissions from numerical models [14], this study was conducted using on-board exhaust emissions measurement of particle number under real-world road and environmental conditions. Restart characterization is critical for developing better models of hybrid vehicle emissions at the project level and hot-spot analysis, particularly in low speed traffic conditions where a large number of hybrid vehicle restarts may occur simultaneously within a dense spatial configuration.

METHODOLOGY

Data Collection

This study used the University of Vermont's Total On-Board Tailpipe Emissions Measurement System (TOTEMS) instrumentation and protocols for the purposes of collecting 1-second measurements of particle *number* (PN) concentrations of exhaust pulled directly from the tailpipe [7]. The two vehicles used for data collection were similar in weight when fully instrumented (the hybrid 300 lb greater than the conventional), aerodynamic dimensions and mileage. The hybrid vehicle was equipped with a 147-horsepower, 2.4 liter gasoline powered engine, assisted with a 105 kW electric motor. The conventional vehicle was powered by a 169-horsepower, 2.5 liter gasoline engine. Both vehicles have 4 cylinders, with the hybrid ICE operating under the Atkinson cycle and the conventional ICE operating under the Otto cycle. Both vehicles were equipped with the same emissions control devices (warm-up catalyst and three-way catalyst, heated oxygen sensor), with EPA emissions ratings of Tier 2 Bin 3 for the hybrid and Tier 2 Bin 5 for the conventional.

Over the specific 32-mile driving route, in Chittenden County, Vermont, 25 hybrid and 19 conventional replicate sampling runs were conducted across an 18-month study period. A total of 41 cold start events were captured to characterize the temporal duration and magnitude of cold start PN concentrations for these two vehicles under a range of ambient conditions. ICE cold starts followed a minimum 12-h overnight soak. Cold start durations for both vehicles were computed as the time from the initial spike in particulate concentration above background until a point in time when PN concentration dropped below 20,000 $\#/cm^3$. Cold start total PN concentrations (TPN) were computed by integrating instantaneous PN over the cold start event duration. Similarly, total PN concentrations resulting from a total of 2115 hybrid ICE restart event were characterized using the mean duration (in seconds) of all hybrid and conventional cold starts.

A specially modified tailpipe adapter was developed to collect measurements of exhaust gas temperature and flow at the tailpipe through the use of a thermocouple and pitot tube [7]. Four differential pressure sensors of varying sensitivity were used to quantify exhaust flow rate, with a single sensor selected to predict instantaneous flow at standard volumetric conditions. This chosen flow rate is then adjusted to compensate for changes in the exhaust fluid volume due to exhaust temperature.

A TSI, Inc. EEPS Model 3090 was designed to measure the distribution and magnitude of particles ranging from 5.6 to 562 nanometers in diameter, sampling at a rate of 9.0 LPM. In tandem with the EEPS, the TSI, Inc. Ultrafine Condensation Particle Counter (UCPC) Model 3025A was instrumented to sample total particle concentration (PN/cm3) at a flow rate of 1.5 LPM. Tailpipe exhaust gas was drawn into a two-stage Matter Engineering, Inc. dilution system to achieve a final dilution ratio of 108. This dilution ratio was used to compute 1 sec instantaneous exhaust flow. Exhaust gases were maintained at 191 °C using an electrically heated line running from the tailpipe to the inlet of the dilution system. All electrical power demands of the onboard instrumentation were met by an independent 12-volt battery system so as not to place any auxiliary load on the vehicle. All PN concentrations reported here are uncorrected for dilution or EEPS instrument detection limits.

The vehicles were stored in an unheated laboratory when not in use, and pushed outdoors during tunnel blank sampling and vehicle cold starts were conducted outdoors in ambient conditions. During all sampling runs, the vehicle climate control was set to 70 °F to control for effects of auxiliary power demand from heating and cooling loads. (No sampling was conducted under the presence of precipitation). Both vehicle mileages did not exceed 8000 miles. Additional vehicle operating parameters were recorded using Toyota Techstream software (version 6.01.021), including ICE RPM, vehicle speed, ambient temperature, engine coolant temperature and calculated load. Ambient temperature and relative humidity were collected both inside the vehicle and outside (roof mounted) with two HOBOware pro devices (v2 U23-001).

Cold start Emissions Data Analysis

For this analysis, only EEPS raw particle number concentrations were used to characterize PN emissions because a significant proportion of the UCPC measurements exceeded the upper sampling limit of 10^5/cm3 limit during cold start and restart events. EEPS data were uncorrected for diffusion losses or instrument electrometer noise. Inherent to on-board measurement systems is a temporal lag between engine emissions and their measurement downstream of exhaust gas dilution, as well as with flow measurements made directly at the tailpipe. For cold start and restart emissions analysis, temporal alignment of the EEPS and the pitot tube differential pressure sensors was necessary. This multi-step process was performed manually based on the time of the initial ICE-on event of each instrument. First, the ambient temperature, relative humidity and exhaust temperature data were aligned with the pitot data by directly matching the time stamps of each instrument. The initial ICE-on datum was then determined from the exhaust flowrate, calculated from the most sensitive differential pressure sensor (i.e. the point when its voltage exceeded 5.4V, the lower limit of its operation). The EEPS and the UCPC had similar responses during engine-on events, where PN concentrations climbed from background (0 and 3500 #/cm^3) to maximum levels within two seconds. The cold start EEPS PN ICE-on datum was next identified using the first sampling datum exceeding 20,000 #/cm^3. The entire EEPS particle concentration data set and the exhaust flow rate data were thus aligned using the initial ICE-on datum. A cold start event was defined as all continuous EEPS emissions greater than 20,000 #/cm^3 following the initial ICE-on. The duration of each cold start event (in seconds) was measured, as well as cumulative particle concentration.

Hybrid Restart Emissions and Cumulative Particle Concentrations

Frequent hybrid restart events were recorded during the course of sampling across the entire 32-mile run. Identification of restart events was similar to the cold start characterization. First, all ICE-off events were tagged in the sampling run (not including the initial cold starts) as any data where the most sensitive differential pressure sensor was below 5.4 volts. The beginning of a restart event was identified as the point at which the most sensitive differential pressure sensor exceeded 5.4 volts immediately following a minimum two-second ICE-off period. Slightly different EEPS PN concentration thresholds were necessary to flag the ICE restarts, because not all restart events were observed to have significant increases in PN concentration compared to cold starts. A 10,000 PN/cm3 threshold was used to identify and align EEPS restart event PN concentrations. Hybrid restart event temporal durations were more difficult to characterize because the "end" of a restart was rarely followed by idling operation, as it was for cold starts. Hybrid restart durations were therefore designated based upon the mean combined (both) cold start duration of 9 seconds.

Total (cumulative) PN concentrations (TPN) were computed for each cold start event, each 8-s hybrid restart event, as well as cumulative total run duration. Also tabulated was the number of restarts per hybrid run, the mean ICE-off duration in seconds, and the total percent of ICE-off time during the full 32-mile route. T-tests from regressions developed to quantify the strength of relationships between PN and other measured variables were computed using an alpha = 0.05.

EXPERIMENTAL RESULTS

Summaries of all run data are provided in Tables 1 -3. Temperature ranges during cold starts ranged from -10 °C to 41°C. The mean ambient temperature for all hybrid sampling runs was higher than conventional sampling (18.4 °C compared to 13.9 °C). Mean run relative humidity was 47% during hybrid sampling and 50% during conventional sampling. Total run duration was similar across most runs ($mean_{hyb.}$ = 4698 s), with the exception of Runs 13, 38 and 39, which contained truncated data due to instrument malfunctions. Mean exhaust flowrates were generally higher in the conventional vehicle by a factor of 1.5 (see Tables 1 and 2)

Overall mean exhaust temperatures were nearly identical between conventional and hybrid ICE-on operation ($mean_{ICE\text{-}on}$ = 159 °C; see Figure 1). Hybrid ICE-off mean exhaust temperature was considerably lower ($mean_{ICE\text{-}off}$ = 103 °C), which can be explained by the cooling effects experienced during the ICE shutdown. No relationship was found between instantaneous PN concentrations and ambient relative humidity.

ICE-off duration and frequency varied considerably during hybrid runs (see Table 3 below), with ICE-off operation ranging from 20 to 50 percent of the total run time, and ICE-off durations from 2.6 s to 31.4 s, with an overall mean of 9.2 s. No significant relationship existed between ICE-off duration and PN emissions. The total number of ICE restart events per run ranged from 53 to 118 (not including partial run 13). Normalized restarts per hour of driving by run were weakly positively correlate with run mean ambient temperature (R^2 adj. = 0.256, $p<0.01$; see Figure 2). Mean run TPN concentrations were on average 3.8 times higher in the hybrid ($mean_{ICE\text{-}on} = 1.45 \times 10^4$ #/cm^3) than in the conventional vehicle.

ICE Cold Start and Restart Characterization

Conventional cold start TPN concentrations were, on average slightly higher in comparison with hybrid events ($mean_{conv.}$ = 8.29 x 10^5 #/cm^3, $mean_{hyb.}$ = 7.60 x 10^5 #/cm^3; Tables 1,2, and Figure 3), yet the hybrid cold starts had a standard deviation twice that of the conventional concentrations ($SD_{hyb.}$ = 1.02 x 10^6). Cold start exhaust flowrates were slightly higher in the conventional compared to the hybrid (804 Lpm and 684 Lpm, respectively). Mean cold start duration (meeting criteria where instantaneous #/cm^3 > 2x10^4) were similar between vehicles ($mean_{conv.}$ = 8.2 s, $mean_{hyb.}$ = 8.8 s).

Each vehicle's typical cold start exhibited similar temporal PN concentration patterns across the duration of the event (Figure 3), but there was a greater frequency of "paired" high emission events in the hybrid cold starts. This is seen in the increasing range of boxplot concentrations in hybrid cold start duration from second 10 to second 15 in Figure 3. These secondary emissions peaks may be explained by the physical operation of hybrid during cold start sampling. Hybrid ignition was turned on by the press of a button, and delays between ICE-on and "ignition on" could last several seconds. The vehicle operator, during these instances of extended delay between ignition-on and ICE-on, commenced the sampling run during some of the cold starts (i.e. pushed the accelerator to begin driving), which may have resulted in an additional load on the vehicle. Conventional vehicle cold start TPN concentrations showed a strong *negative correlation* with ambient temperature (R^2 adj. = 0.571, $p<0.001$; see Figure 4). This relationship was not repeated in the hybrid cold starts, where no strong correlation was observed (R^2 adj. = 0.091, $p<0.12$) although there was missing data for the hybrid vehicle at all temperatures.

Hybrid restart TPN concentrations were characterized using a mean combined cold start duration of 9 seconds. A total of 2115 hybrid vehicle restart events were characterized over 25 runs (see Table 3). Though no strong relationship existed between individual restart TPN concentrations and ambient temperature, at the mean run level there was a slight positive correlation between the two (R^2 adj. = 0.305, $p<0.01$). Cumulative hybrid restart TPN concentrations (the total particle number concentration resulting from all restarts for each run) were compared to the entire run cumulative TPN concentrations. These ratios ranged from 0.19 to 0.62, suggesting a significant cumulative contribution from all restart events to the total run PN emissions. These varying ratios also indicate a large difference *between runs* in the relative contribution of restart PN concentrations to the entire sampling run PN concentrations. Restart TPN concentrations were *significantly lower* than those of hybrid cold starts, by a factor of 4 on average. No strong relationship was observed between restart TPN concentrations and either ambient temperature or exhaust temperature.

DISCUSSION

The particle number data suggest that no differences exist in overall magnitude of cold start PN emissions between a hybrid and a comparable conventional vehicle. The overall trend in reduced cold start TPN concentration with increased ambient temperature, though not replicated to the same extent in hybrid cold start events, demonstrates a similarity between vehicle types during cold starts. The high number of outliers observed during restart PN emission events of 5 – 9 sec duration (see Figure 3) suggests that secondary PN emission events, not solely attributable to the ICE restart, may have occurred due to the additional engine loading as the vehicle is accelerated. This suggests that the temporal duration of PN emission events attributable to restarts may be shorter overall than cold starts.

Evidence from this study suggests that ambient temperature has little to no effect upon either conventional or hybrid vehicle PN concentrations, despite the considerable cooling of the exhaust control system seen during the hybrid ICE-off events. The results suggest that a) the engine-out PN emissions are relatively insensitive to changes in either the intake air temperature or the temperature of the engine block, or that b) the efficacy of the emissions control system in removing PN is largely insensitive to variation in the ambient temperature.

The cumulative impact of restart events upon cumulative run TPN concentrations is considerable. The four-fold higher mean PN concentration under hybrid ICE operation compared to the conventional highlights the importance of restart emissions. For all "on-network" operation (i.e. non-cold start), the data from the Camry vehicles suggest the following general model for predicting hybrid mean PN concentrations from data collected on a comparable conventional vehicle:

$$PN_{hybrid} = PN_{stabilized,hybrid} + PN_{restarts,\ hybrid}$$

and

$$PN_{hybrid} = 4(PN_{stabilized,conventional}) + 0.9(PN_{cold\ starts,conventional})$$

Where PN_{hybrid} is the total cumulative concentration of a hybrid run, $PN_{stablizied,}$ is the total contribution of stabilized ICE operation and $PN_{cold\ starts}$ is the total PN from cold starts. With this generalized model, it is possible to predict the typical PN concentrations of a future fleet composed of increasing proportions of hybrid vehicles using *only data from comparable conventional vehicles*. The implications of this preliminary model suggest that hybrid vehicles do not perform well in reducing particulate number emissions, and that further research is necessary to identify and measure the factors which impact PN emissions.

Previous research suggests that a weak relationship exists between engine load and PN concentrations. The differences in engine loading under transient operation, and from road grade at various points along the run, may have a significant effect upon the hybrid (ICE-off) operation and consequently the restart frequency. Since the hybrid drive system is constantly optimizing the transfer of energy between vehicle, battery system and the ICE, variation in engine speed across the duration of the run may be greater in the hybrid. In other words, overall differences between vehicles in patterns of engine loading may have a significant impact on exhaust flowrate.

Clearly, a more thorough measure of comparison can be had through the computation of PN emission rates (#/sec), thus providing greater temporal resolution for analysis of restart events and stabilized (non-restart) operating conditions. Hybrid exhaust flowrates were considerably lower than those of the conventional vehicle, by a factor of 1.5 (See Tables 1 and 2). This effect may be due to a) slightly smaller hybrid ICE, b) the optimization of engine speed by the hybrid power distribution system, which may result in lower overall engine speeds in the hybrid and c) the differences in power from the ICE of the hybrid compared to the conventional due to the difference in operation cycle (i.e. Atkinson vs. Otto). Though exhaust flowrate was computed at the disaggregate level, it was beyond the scope of this study to adequately verify the precise alignment of exhaust flowrate data with EEPS PN concentrations at 1 Hz resolution. Results of this study were based upon raw PN concentrations uncorrected for instrument detection limits and exhaust dilution ratio, but the relative error was considered small enough to allow for general comparisons to be made between vehicles across all runs. Taking these considerations into account, with a mean correction of 1.5 for the difference in run exhaust flowrates between vehicle types, the hybrid PN emissions still exceed those of the conventional by a factor of 2. This research points to an overall higher trend in hybrid PN emissions, for this route, than a comparable conventional vehicle.

Though there appears to be a positive correlation between ambient temperature and mean run restart TPN, there is no strong relationship between *frequency* of restarts and the proportion of total run TPN. This suggests that certain characteristics of individual runs (i.e. elevated traffic congestion on some runs which may lead to stop and go driving conditions) may have a greater impact upon PN concentrations than previously expected. Observed during this study was the impact of driving conditions upon the frequency of hybrid restarts. As previously stated, ICE-off was governed largely by speed criteria, and in this study no ICE-off were observed above 70 kph (43 mph). This results in specific sections of the run where the ICE is on continuously, notably the highway and rural arterial driving portions. As expected, city driving at lower speeds (within the range the ICE-off thresholds) results in the greatest number of engine restarts per distance traveled.

The large variation in the ratio between restart and cumulative run TPN concentrations again suggest that there are additional unmeasured factors which contribute to PN emissions patterns. Though no relationships were found between PN concentrations and ambient conditions of temperature and humidity, the relative young age of these vehicles may preclude observation of the greater ambient effects seen in older vehicles. As hybrid vehicle ICEs and emissions control systems begin to wear and malfunctions arise, the effects of temperature may become more apparent.

CONCLUSIONS

In this paper, cold starts were characterized in duration and magnitude between a hybrid vehicle and a comparable conventional vehicle across a range of ambient temperatures. Cold starts were overall not significantly different between vehicle types, yet a trend in overal reduction in total PN concentrations with increasing ambient temperature was observed. Cold start PN concentrations were typically four times greater than those of cold starts. No overall effect was seen between ambient temperature and the magnitude of total restart emissions, yet the proportion of cumulative PN concentration resulting directly from hybrid restart events were found to vary significantly between runs, suggesting that other factors related to vehicle operation have a greater effect on hybrid PN emissions than do ambient conditions. Overall, PN concentrations, at the run level, were significantly higher under hybrid ICE-on operation compared to the conventional operation.

From this study, a generalized model is developed to compare hybrid PN emissions at the run level using comparable conventional vehicle data. This model may be further refined with the inclusion of more vehicle operational data (speed, acceleration, road grade) and the alignment of exhaust flowrates to create disaggregate particulate number emission rates. The results of this study may have a significant impact in the development of better models of PN emissions, particularly in urban congested conditions where more frequent ICE restarts potentially lead to elevated emissions levels.

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TABLE 1 Conventional Vehicle Cold Start and Sampling Run Summary

Run	Total Duration (s)	Mean Ambient Temperature (C)	Cold Start Duration (s)	Cold Start Total PN Concentration (#/cc)	Run Total PN Concentration (#/cc)	Run Mean PN Conc. (#/cc)	Mean Exhaust Temperature (C)	Mean Exhaust Flowrate (Lpm)	Mean Relative Humidity (%)
5	4,456	1.5	10	1.64E+06	2.74E+07	6.1E+03	182	1,963	58
6	4,217	-1.2	9	1.37E+06	2.36E+07	5.6E+03	185	1,840	49
7	4,361	-4.7	9	1.08E+06	2.21E+07	5.1E+03	192	1,962	41
8	4,604	4.2	7	9.84E+05	1.88E+07	4.1E+03	186	1,903	46
9	4,409	2.5	7	7.06E+05	1.90E+07	4.3E+03	182	1,851	59
10	4,660	5.1	7	8.21E+05	1.82E+07	3.9E+03	172	1,786	53
11	4,723	2.9	7	6.65E+05	1.99E+07	4.2E+03	174	1,748	62
12	4,566	2.4	13	1.08E+06	2.29E+07	5.0E+03	181	1,910	50
32	5,318	20.2	6	2.82E+05	1.11E+07	2.1E+03	141	1,388	34
34	5,076	11.4	10	9.41E+05	8.94E+06	1.8E+03	--	N/A	55
35	4,613	7.4	13	1.68E+06	2.21E+07	4.8E+03	170	1,657	72
36	4,744	11.1	13	1.31E+06	1.60E+07	3.4E+03	110	1,382	42
37	4,569	8.6	12	1.17E+06	2.91E+07	6.4E+03	169	1,626	62
38	1,177	8.3	13	1.68E+06	8.65E+06	7.3E+03	107	--	51
39	3,611	4.4	7	7.40E+05	1.60E+07	4.4E+03	--	1,199	66
54	4,998	--	--	--	1.11E+07	2.2E+03	133	1,365	--
55	4,970	22.4	--	--	1.04E+07	2.1E+03	138	1,439	46
57	4,691	23.4	7	5.46E+05	1.05E+07	2.2E+03	139	1,516	50
59	4,753	26.9	8	6.60E+05	1.58E+07	3.3E+03	145	1,488	40
60	4,664	24.9	5	3.02E+05	8.77E+06	1.9E+03	148	1,621	52
61	4,681	31.0	5	3.26E+05	2.29E+07	4.9E+03	154	1,707	34
62	4,779	24.6	5	3.11E+05	1.04E+07	2.2E+03	142	1,495	48
63	4,859	33.1	6	3.52E+05	3.09E+07	6.4E+03	142	1,494	36
64	4,664	32.6	4	1.93E+05	1.53E+07	3.3E+03	141	1,576	47
65	5,104	31.0	5	2.44E+05	1.54E+07	3.0E+03	132	1,493	54
Mean	4,531	13.9	8.2	8.29E+05	1.74E+07	3.84E+03	155	1,626	50
S.D.	154	2.5	0.6	1.01E+05	1.31E+06	3.21E+02	5.1	44.8	2

TABLE 2 Hybrid Vehicle Cold Start and Sampling Run Summary

Run	Total Duration (s)	Mean Ambient Temp. (C)	Cold Start Duration (s)	Cold Start Total PN Conc. (#/cc)	Run Total PN Conc. (#/cc)	ICE-On Mean Exhaust Flowrate (Lpm)	ICE_On Mean Exhaust Temp. (C)	ICE_Off Mean Exhaust Temp. (C)	Mean Relative Humidity (%)
13	2,744	4.7	7	5.82E+05	3.09E+07	1,204	176	106	34
14	4,097	5.4	6	2.98E+05	3.41E+07	1,099	169	121	38
16	4,104	2.8	11	1.10E+06	3.85E+07	1,415	195	127	60
17	4,077	4.9	7	3.80E+05	2.15E+07	1,402	180	116	54
18	4,471	9.5	4	1.22E+05	2.47E+07	849	—	—	45
20	4,770	21.9	—	—	3.35E+07	987	154	92	41
21	4,492	22.0	—	—	3.68E+07	1,097	163	95	50
22	4,686	35.3	7	4.80E+05	7.30E+07	1,068	182	147	47
23	4,490	34.1	—	—	3.56E+07	1,067	175	101	45
24	5,098	35.6	—	—	6.27E+07	882	168	89	47
25	4,417	31.4	10	5.11E+05	4.17E+07	N/A	146	.	55
26	5,281	32.5	—	—	6.06E+07	927	167	99	47
27	4,892	27.5	—	—	3.23E+07	891	167	99	57
28	4,873	35.6	—	—	4.76E+07	711	153	153	39
29	4,674	33.9	—	—	4.98E+07	1,079	161	97	45
30	4,575	30.2	—	—	3.43E+07	1,059	161	92	56
40	—	—	11	6.98E+05	—	—	—	—	—
41	—	—	7	5.80E+05	—	—	—	—	—
42	4,854	4.5	5	1.97E+05	2.66E+07	997	161	105	57
43	4,939	4.1	4	9.22E+04	1.73E+07	919	150	98	56
45	4,473	-9.8	17	4.68E+06	4.59E+07	1,185	171	119	49
46	4,798	-1.0	15	5.88E+05	4.52E+07	994	153	99	24
47	4,495	2.0	6	2.61E+05	4.04E+07	1,159	153	105	32
48	4,803	9.0	11	6.21E+05	3.22E+07	912	148	96	40
49	4,716	10.0	—	—	2.86E+07	793	136	77	—
50	4,658	31.2	—	—	2.19E+07	1,195	113	76	—
51	4,160	12.3	10	5.95E+05	2.76E+07	1,019	148	83	34
52	4,706	8.3	12	9.08E+05	4.02E+07	936	140	86	68
53	4,737	2.5	10	9.95E+05	4.36E+07	999	144	90	30
Mean	4,698	18.4	9.2	7.60E+05	6.04E+07	1,033	159	103	46
S.D.	90	2.7	0.9	2.40E+05	2.50E+06	32	3.3	3.8	2.1

Note: Run 13 is a partial run.

TABLE 3 Hybrid ICE Restart Summary

Run	# ICE Resart Events	Restarts per hour	Mean Restart PN Conc. (#/cc)	Cumulative Restart PN Concentration (#/cc)	Ratio of Total Restart/Total Run PN	Percent ICE-off operation	Mean ICE Off Duration (s)	Mean ICE-On PN Conc. (#/cc)
13 *	42	55	2.69E+05	1.11E+07	0.36	29%	5.9	1.75E+04
14	85	75	2.06E+05	1.74E+07	0.51	34%	6.1	1.70E+04
16	87	76	1.71E+05	1.46E+07	0.38	33%	4.9	1.51E+04
17	42	37	2.01E+05	8.16E+06	0.38	20%	2.6	8.49E+03
18	84	68	1.70E+05	1.40E+07	0.57	39%	9.3	1.28E+04
20	108	81	1.84E+05	1.96E+07	0.58	41%	6.9	1.69E+04
21	88	70	1.92E+05	1.67E+07	0.45	39%	7.8	1.50E+04
22	86	66	2.33E+05	2.01E+07	0.28	38%	8.3	2.15E+04
23	92	73	2.06E+05	1.87E+07	0.52	38%	13.7	1.67E+04
24	89	61	2.08E+05	1.84E+07	0.29	44%	17.8	1.74E+04
26	118	80	2.34E+05	2.79E+07	0.46	42%	10.9	2.13E+04
27	99	72	1.89E+05	1.85E+07	0.57	41%	9.1	1.54E+04
28	105	78	2.27E+05	2.30E+07	0.48	42%	9.1	1.89E+04
29	112	86	2.26E+05	2.46E+07	0.49	39%	6.3	2.11E+04
30	89	70	2.36E+05	2.09E+07	0.61	42%	9.7	1.91E+04
43	73	53	6.50E+04	4.72E+06	0.27	42%	7.6	4.83E+03
45	73	59	1.61E+05	1.17E+07	0.25	33%	5.3	1.38E+04
46	84	63	1.38E+05	1.16E+07	0.26	38%	7	1.27E+04
47	53	42	1.43E+05	7.53E+06	0.19	21%	3.6	1.10E+04
48	87	65	1.06E+05	9.23E+06	0.29	42%	9	9.40E+03
49	85	61	1.32E+05	1.13E+07	0.40	46%	10.9	1.00E+04
50	83	57	1.41E+05	1.16E+07	0.53	50%	31.4	1.00E+04
51	72	62	1.81E+05	1.30E+07	0.47	39%	6.9	1.26E+04
52	101	76	1.26E+05	1.25E+07	0.31	43%	9.7	1.24E+04
53	79	60	1.86E+05	1.45E+07	0.33	36%	9.2	1.38E+04
Mean	85	66	1.81E+05	1.53E+07	0.41	38%	9.2	1.46E+04
S.D.	4	2	9.40E+03	1.13E+06	0.02	1%	1.1	8.55E+02

* Run 13 is a partial run.

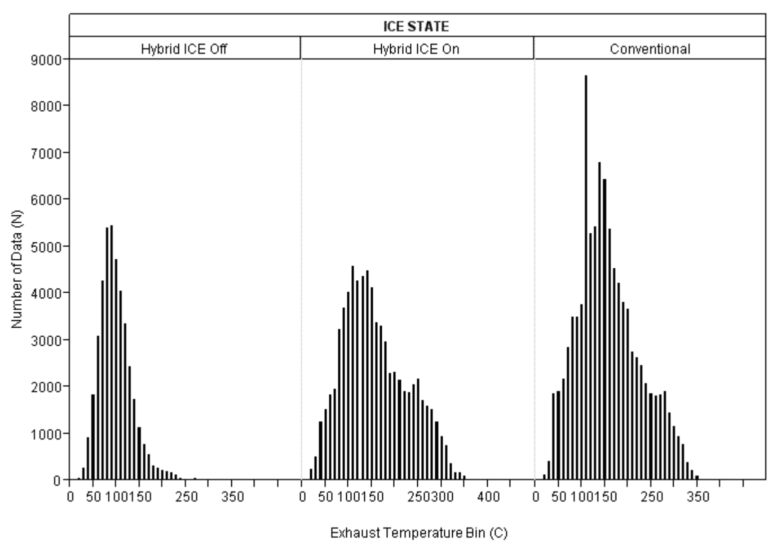

FIGURE 1 Histogram of Exhaust Temperature during a) Hybrid, ICE off b) Hybrid, ICE On and c) Conventional Operation

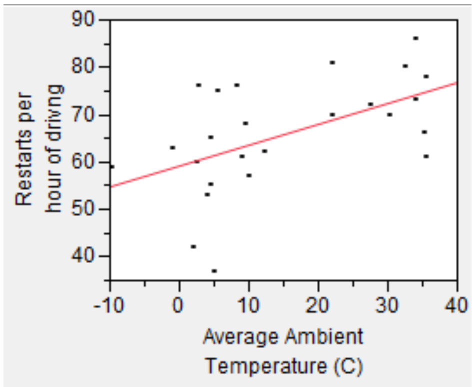

FIGURE 2 Regression of Number of Hybrid ICE Restarts per hour of driving vs. Ambient Temperature

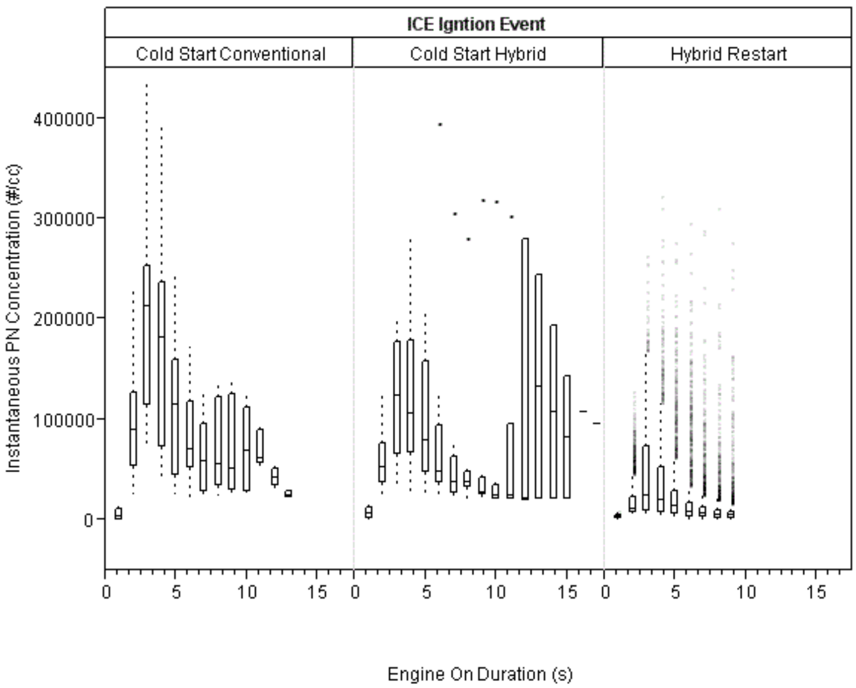

FIGURE 3 Instantaneous PN Concentrations as a function of ICE-On Event Duration for a) Conventional Cold Starts, b) Hybrid Cold Starts and c) Hybrid Restarts.

Note: The first second of each event is the background PN concentration before the ICE-On event.

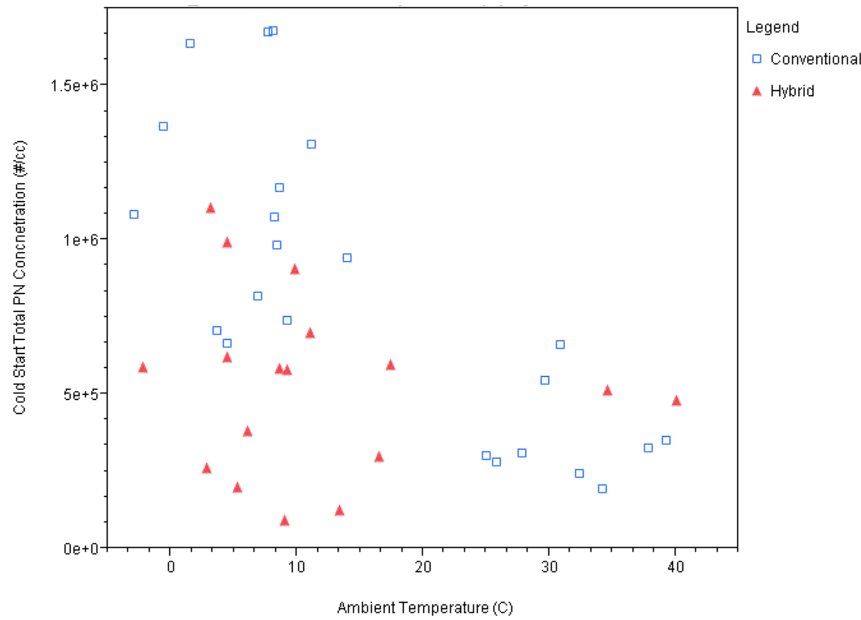

FIGURE 4 Cold Start Total PN Concentration as a function of Ambient Temperature for Conventional Vehicle (squares) and Hybrid Vehicle (triangles)

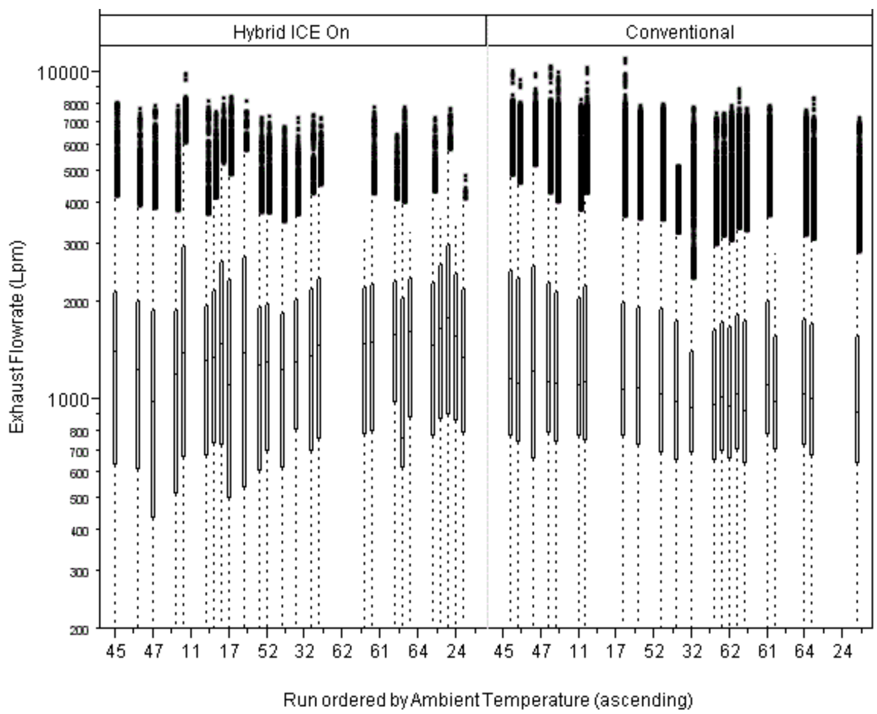

FIGURE 5 Exhaust Flowrate (log scale) for a) Hybrid ICE On and b) Conventional Operation as a function of Mean Run Ambient Temperature