Title

Emissions from Plug-in Hybrid Electric Vehicle (PHEV) During Real World Driving Under Various Weather Conditions

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A Research Report from the National Center for Sustainable Transportation

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U.S. Department of Transportation (USDOT) Disclaimer

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EXECUTIVE SUMMARY

Exposure to particulate matter (PM) and pollutant gas (NO_x) is associated with increased cardiopulmonary morbidity and mortality. Mobile source emissions contribute to PM and NOx emissions significantly in urban areas. Hybrid Electric Vehicles (HEVs) plays an important role to reduce emissions. While sales of electric vehicles has been increasing, electric vehicles have to overcome issues with charging time, driving range, and production/sales cost for more widespread market penetration. Hybrid electric vehicles have a potential to serve as a bridge technology between current internal combustion engine powered vehicles and zero emissions vehicles such as electric vehicles and fuel cell vehicles.

Current regulations require emissions to be tested on a chassis dynamometer. However, it is known that on-road emissions can be quite different from that those measured on regulatory driving cycles in the lab. In this study, emissions from two HEVs with different combustion technologies (gasoline direction injection vs port fuel injection) were compared using PEMS (portable emissions measurement system) and tailpipe sensors under cold weather conditions.

The study has found the frequency and duration of re-ignition events vary depending on the type of HEV. Prius (PFI HEV) showed more frequent re-ignition events compared to Sonata (GDI HEV) for both city and highway driving conditions. Prius re-ignited almost every one minute while Sonata re-ignited every two minutes on average during the city driving condition. Re-ignition events affected emissions profile significantly during the city driving condition. As a result, Prius showed higher NOx emissions during the city driving condition while Sonata showed higher NOx emissions during the cold-cold start and highway driving condition. For PM emissions, PFI technology is known to make minimal amount of soot which is shown in the cold-cold start result while GDI technology is more prone to generating soot. This gap is reduced in city and highway driving condition due to more frequent re-ignition events of the PFI HEV (referring to Prius).

Future studies should include more vehicles to understand whether the re-ignition events are vehicle specific or technology specific.

Introduction

Plug-in hybrid electric vehicle (PHEV) are regarded as a key technology to reduce the impact of internal combustion engine on air pollution and greenhouse gasses. PHEV has advantage in market penetration due to its lower cost and higher driving range compared to EV. On the other hand, PHEV still emits air pollutants due to the presence internal combustion engine.

PHEV has improved energy efficiency by switching the driving power between a battery and an internal combustion engine. This allows the engine cold-start to take place multiple times and it is expected to become more severe under cold weather conditions. This project aims to understand and evaluate the occurrence of cold-restart (or re-ignition event) and cold-cold-restart with respect to emissions under real world driving conditions.

Research Goal and Objectives

In this study, we characterized emissions from a PFI and a GDI light-duty gasoline HEV tested during real-world driving under cold weather (-7 ^{o}C ~ -0 ^{o}C). We compared emissions from two different types of HEV with respect to particle number (PN), particulate mass (PM mass), and NOx. Specific objectives of this research include:

1. Compare cold weather on-road emissions between a PFI engine and a GDI engine powered HEV under cold weather conditions.
2. Characterize and compare “Cold cold” starts with “re-ignition events” on city and highway driving routes.
3. Evaluate the impact of “re-ignition” events on PM and NOx emissions.

Vehicle Selection and Experimental Setup

Vehicles

Two HEVs with different types of engines, PFI and GDI, were used in this study. A 2016 Toyota Prius (PFI) and a 2015 Hyundai Sonata (GDI) were recruited based on availability near the test location in Minnesota. The specification of the vehicles are presented in Table 1.

Table 1. Hybrid electric vehicle specifications

Vehicle Specifications		
HEV types	Toyota Prius	Hyundai Sonata
Year	2016	2015
Engine Type	1.8L, 121 hp	2.4L, 199 hp
MPG	54 city, 50 highway	36 city, 40 highway
Electric motor	60 hp	47 hp
Battery output	45 kW	47 kW
Battery capacity	1 kWh	1.6 kWh
Fuel injection	PFI	GDI

Experimental Setup

The primary instrument used to monitor the vehicle's status was an On-Board Diagnostic II (OBDII) Pro Scan Tool that queries 16 different parameters per second. The OBD II Scan Tool is operated by a laptop that records the data, using UC Riverside's College of Engineering Center for Environmental Research and Technology (CE-CERT) developed software Mobile Energy Emission Telematics System, M.E.E.T.S. Parameter Identifications (PIDs) were queried and recorded at roughly 0.5 Hz. The Primary parameters monitored were the vehicle speed, RPM, the state of charge (SOC) of the battery, and four kinds of temperatures (e.g., ambient, intake air, engine cooling, and catalyst).

A TSI, Inc. EEPS Model 3090 was used to measure particle size distributions ranging from 5.6 to 562 nm, sampling at a rate of 1Hz. The e-FilterTM (Dekati®) was also employed to measure particle concentrations up to 10^8 particles/cm^3 for average 70 nm particles in real-time. In the e-Filter's real-time detection module, the sample first passes through a miniature diffusion charger with 0.5 LPM of sampling flow rate, where particles gain a known amount of positive charge. The charger is currently controlled maintaining a 1 µA current with 2.5 kV charger voltage. A smaller voltage trap field is located right after the charger. It is used to remove excessive ions generated in the charger. In this study, the minimum trap voltage that was used is 10 V, and this voltage setting removes all ions and particles < 5nm from the sample. It should be noted gravimetric filter sample, which is available as a companion-sampling device, was not taken.

The dilution system for particle measurement includes two separate components, the rotating disk thermos-diluter (RDTD; Model 379020A, TSI, Inc.) and thermal conditional air supply evaporation tube (ASET; Model 379030, TSI, Inc.) are designed to work together, providing first stage (RDTD) and second stage (ASET) in one self-contained device. Where the RDTD's main purpose is to dilute the raw exhaust gas, the ASET provides the flow rate required by the connected particle instruments. The ASET draws diluted exhaust from the RDTD at a constant flow of 1.0 LPM. This dilution stream is sent through a HEPA filter, ensuring no outside influence from ambient particulate matter. Two different heating temperature of RDTD and ASET were selected in this study. The RDTD and ASET heated to an ambient temperature in order to measure the total particle number (TPN) of exhaust gas from the vehicles. Volatile particles were removed through thermal treatment using a volatile particle remover (VPR), includes an initial hot dilution (150 oC) stage with an RDTD, followed by an ASET heated to a 300 oC wall temperature, letting through only solid particles (SPN) for measurement.

Furthermore, the exhaust gas from the RDTD is mixed with the ambient air dilution stream, creating the first stage of diluted gas with two different dilution ratio of 1:15.6 (TPN) and 1:20.6 (SPN). The diluted gas then enters the evaporation tube which is also heated to ambient and 300 ^oC. At the outlet of evaporation tube, the second stage of dilution takes place with a dilution ratio of 1: 8.0, resulting in the total dilution ratio of 1:110(TPN) and 1:160 (SPN).

Figure 1 and 2 show the on-road emission measurement setup. First, raw exhaust gas is sampled via a thermally insulated short probe, placed in the center of the tailpipe adapter. The sample probe draws an exhaust sample from the tailpipe of a vehicle and transport it to the dilution system via a heated sample line. The transport line from the sample probe to the 1st stage RDTD was heated by the heat controller (MAKE) at 150 ^oC. The second stage dilution is at room temperature and the diluted exhaust travels through an 85 cm long section of 0.64 cm silicone conductive tubing. From this tube, the exhaust was split, first to the EEPS at 10 LPM, then to the e-Filter at 0.5 LPM. The NTK sensors (PM and NOx) vertically embedded into the tailpipe adapter which can directly detect the raw exhaust emissions from the both vehicles. During the measurement of the e-Filter and NTK, data are saved to a micro SD memory card at a 1-second resolution, and then the data is sent to the device via USB port. All of the instruments are supplied by two 12 V battery packs (separate deep cycle marine batteries) and an onboard DC-AC converter to provide 240 V AC necessary for instrument operation. They provided electricity approximately for 1-2 hours of operation of instruments.

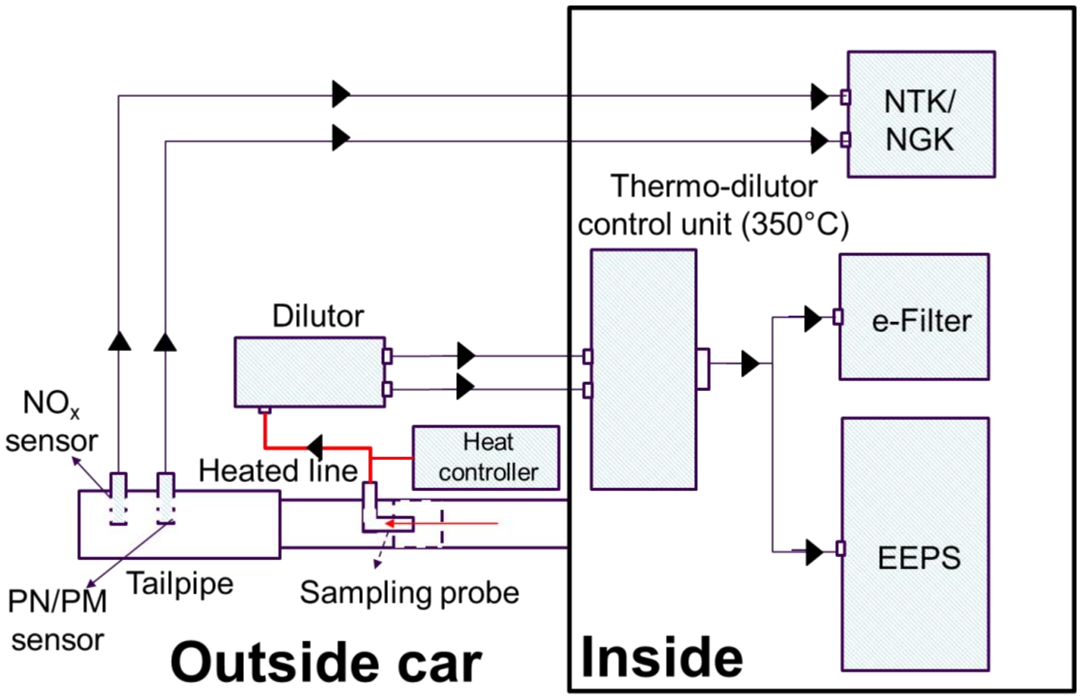

Figure 1. Schematic diagram of on-road emission test system

Figure 2. PEMS equipped two vehicle with associated components

Driving Route and Test Procedure

Routes

Two different driving routes were selected for city and highway real-world driving conditions. The highway driving route consists of a 58.6-mile within Bloomington from 35W to 434W highway route (Figure 3a). The city driving route consists of a 27.7-mile loop through the downtown of Minneapolis (Figure 3b) to investigate emissions during engine "re-ignition" events. The topography of the road is almost flat which means that there has no significant uphill or downhill. An EM-406 SiRF III GPS system was used to provide time, latitude, speed, longitude and geographical position. Data was logged at 1 Hz and stored onto a compact SD memory card.

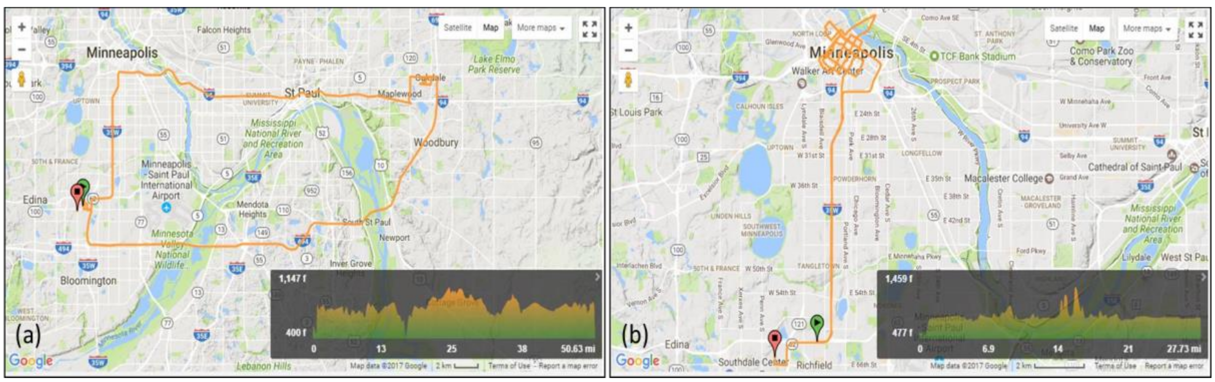

Figure 3. Map and nations of driving route; (a) Highway, (b) City

Test Procedure

A full run consists of 5 steps as follows:

1) Overnight soak at the outside at least 8 to 12 hours,
2) 10 minutes warm up for of EEPS, NTK and Rotating disk dilution and 30 minutes warm up for e-filter using separate battery packs from the vehicle battery pack,
3) Collection of instrument blanks and tunnel blanks for 2 minutes before the start of the engine,
4) Cold-cold engine start and measure the emissions for 5 minutes during the idle condition, and
5) Start driving a designed route (highway and city) and carry out on-road tests.

Table 2 summarizes the testing date and driving conditions for two vehicles.

Table 2. Sampling schedule

Vehicles	Date	Experimental conditions			Driving route
Toyota HEV	02.22	Test	Ambient / 350 °C	TPN/SPN	Random
	02.23	Test	Ambient / 350 °C	TPN/SPN	Random
	02.24	Test	Ambient / 350 °C	TPN/SPN	Route-a
	02.25	Cold-cold-start	Ambient	TPN/SPN	Route-a
	02.26	Cold-cold-start	350 °C	SPN	Route-a
	02.27	Cold-cold-start	Ambient	TPN	Route-b
	02.28	Cold-cold-start	350 °C	SPN	Route-b
Sonata HEV	03.01	Test	Ambient / 350 °C	TPN/SPN	Route-a and b
	03.02	Cold-cold-start	Ambient	TPN	Route-a
	03.03	Cold-cold-start	350 °C	SPN	Route-a
	03.04	Cold-cold-start	Ambient	TPN	Route-b
	03.05	Cold-cold-start	350 °C	SPN	Route-b

Results

Cold-Cold Start

Figure 4 compares particle concentrations measured by EEPS during the cold-cold start for the PFI engine (Figure 4a) and GDI engine (Figure 4b) HEVs. A GDI engine HEV showed higher particle concentrations, almost 8-times more than that of PFI engine HEV. The PFI engine HEV started at the time 200s and the vehicle started moving meaning accelerating at the time 250s. Particle concentration during acceleration was higher than that during the cold-cold start.

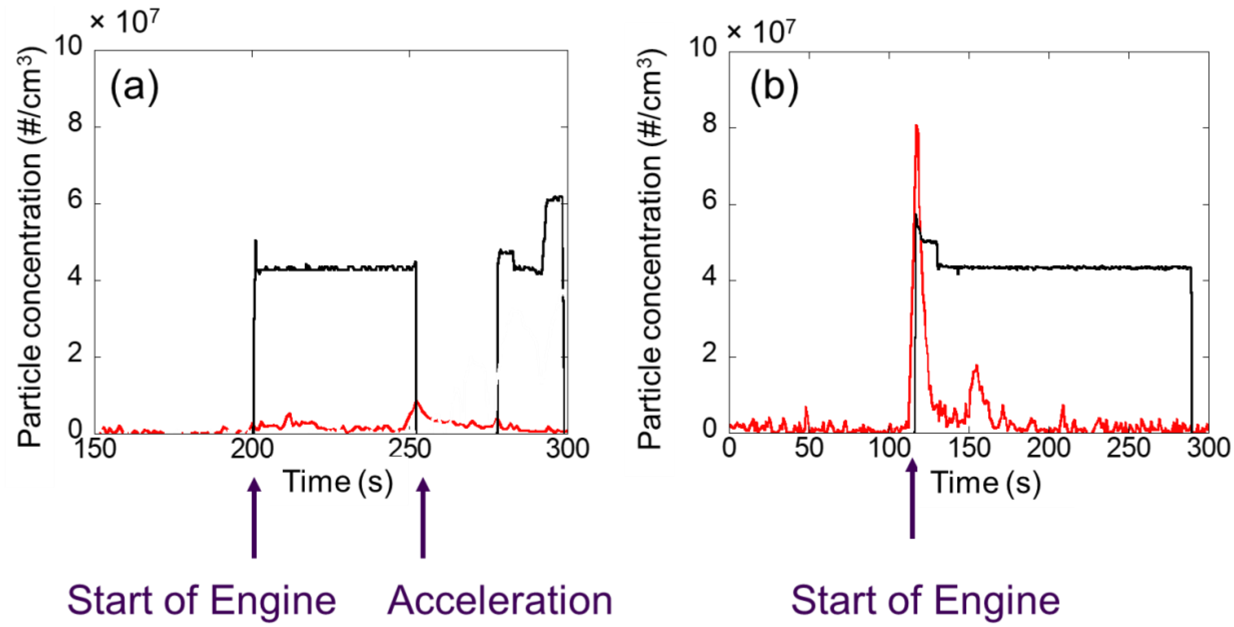

Figure 4. The particle concentration in cold-cold start (a) PFI engine, (b) GDI engine

Frequency and Duration of the Re-ignition Events

Figure 5 shows that the duration and frequency of the re-ignition events for Prius and Sonata HEV. In general, the re-ignition events were more frequent during city driving compared to highway driving. Prius showed more frequent re-ignition events compared to Sonata HEV. Prius HEV showed the most frequent re-ignition event with the shortest duration time during the city driving. Sonata HEV showed the least frequent re-ignition event with the longest duration time during the highway driving.

The results are very intriguing because battery capacity, battery power, and motor power output shown in Table 1 are comparable and not significantly different. The results suggest more studies are needed to understand CS mode, re-ignition events, power management of HEV vehicles. The variation and distribution of frequency and duration of re-ignition events lead significant different in HEV exhaust emissions.

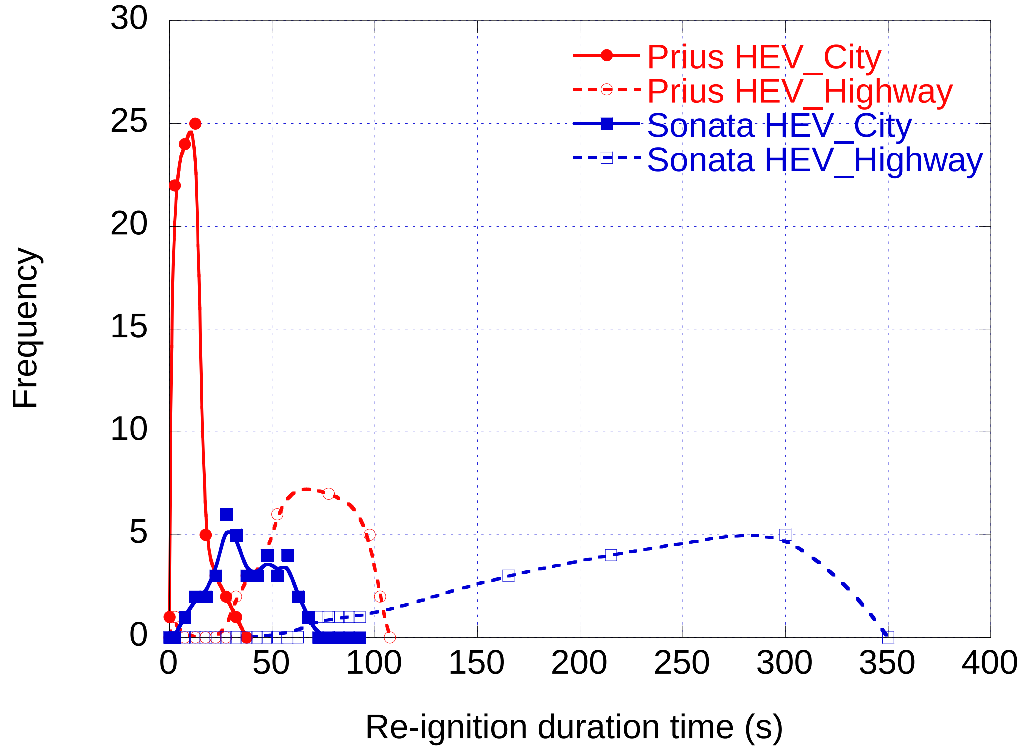

Figure 5. Frequency and duration of re-ignition events for Prius and Sonata HEV

Particle Emissions

Toyota and Sonata HEV have shown quite different emission trends. Figure 6 and Figure 7 show that about 90 % of high emission events occurred as a result of re-ignition events during city driving. The particles were emitted when the events occurred and the duration of the event was typically around 60 s or less and it was at a high frequency of almost every 1-min for Prius HEV (see Figure 6). Sonata HEV showed higher particle concentration with longer duration (75s) and less frequent (every 2 min) re-ignition events as shown in Figure 7.

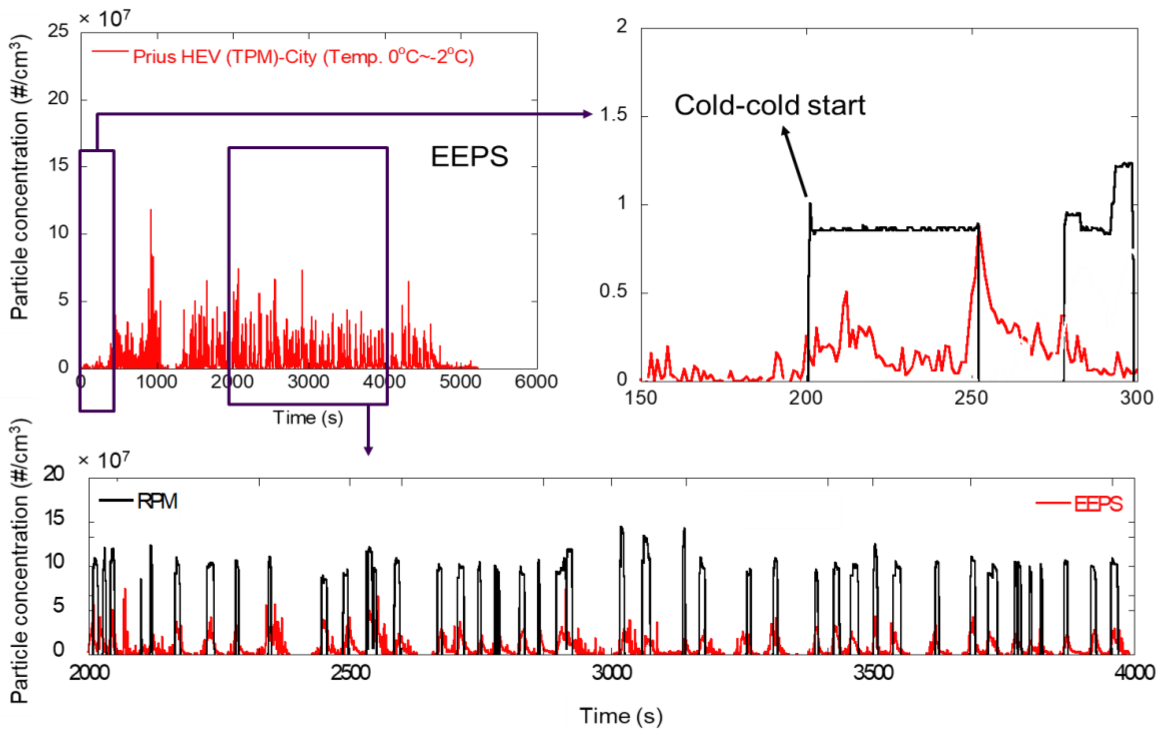

Figure 6. The emission of particle concentration for Prius HEV in city driving condition

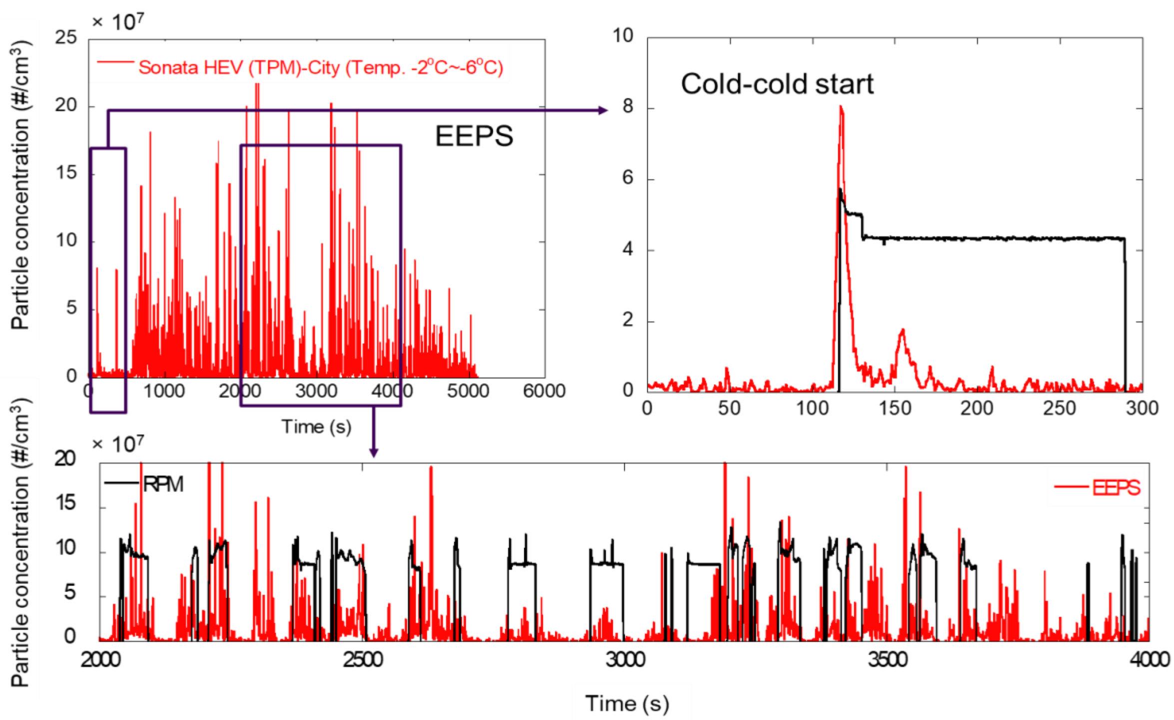

Figure 7. The emission of particle concentration for Sonata HEV in city driving condition

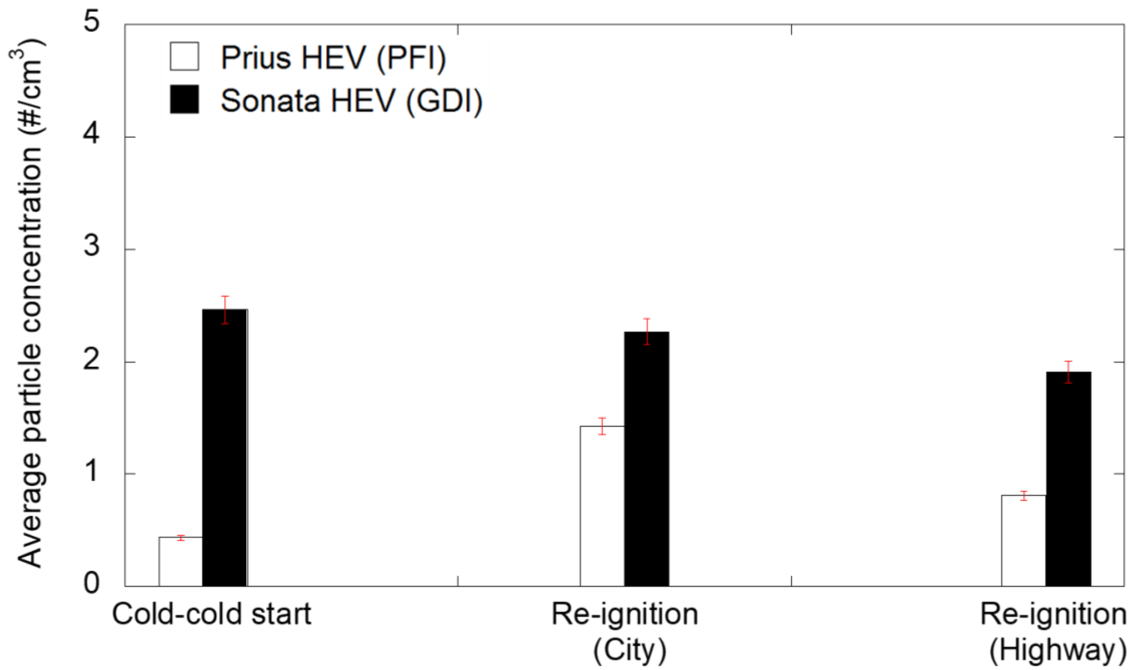

Figure 8. Comparison of total concentration of particles with cold start and re-ignition of two routes between two HEV.

Figure 8 compares average particle concentrations for the PFI and GDI engines during the test. In general, GDI HEV showed higher average particle concentrations than PFI HEV during all test conditions. Particle emissions from GDI HEV was much higher than that of PFI HEV during cold-cold start and this is somewhat expected considering the difference in injection and resulting combustion characteristics of the two technologies. It is noteworthy that PFI HEV emitted only ~35% less than that of GDI HEV during the re-ignition events of the city driving condition regardless of the difference in combustion technologies. Re-ignition events occur when there is a lack of power and often upon the re-ignition the engine is under transient condition for acceleration of the vehicle. This probably puts the PFI engine more soot emitting. On the other hand, GDI HEV emits more than twice compared to PFI HEV during the highway driving condition reflecting less severity of acceleration.

NOx Emissions

Catalyst light-off temperatures

Fresh catalysts may light-off close to 200°C, with aged ones closer to 300°C or higher. The average light-off temperature at which the catalytic begins to function ranges from 200 to 300 °C. Figure 9 shows that catalyst temperatures for the both HEVs in this study. The result shows that the catalyst temperatures of the two HEVs were always much higher than that of light-off temperature during the city driving condition. It appears that we measured the temperature of the close-couple catalyst for GDI HEV and that of underfloor catalyst for PFI HEV.

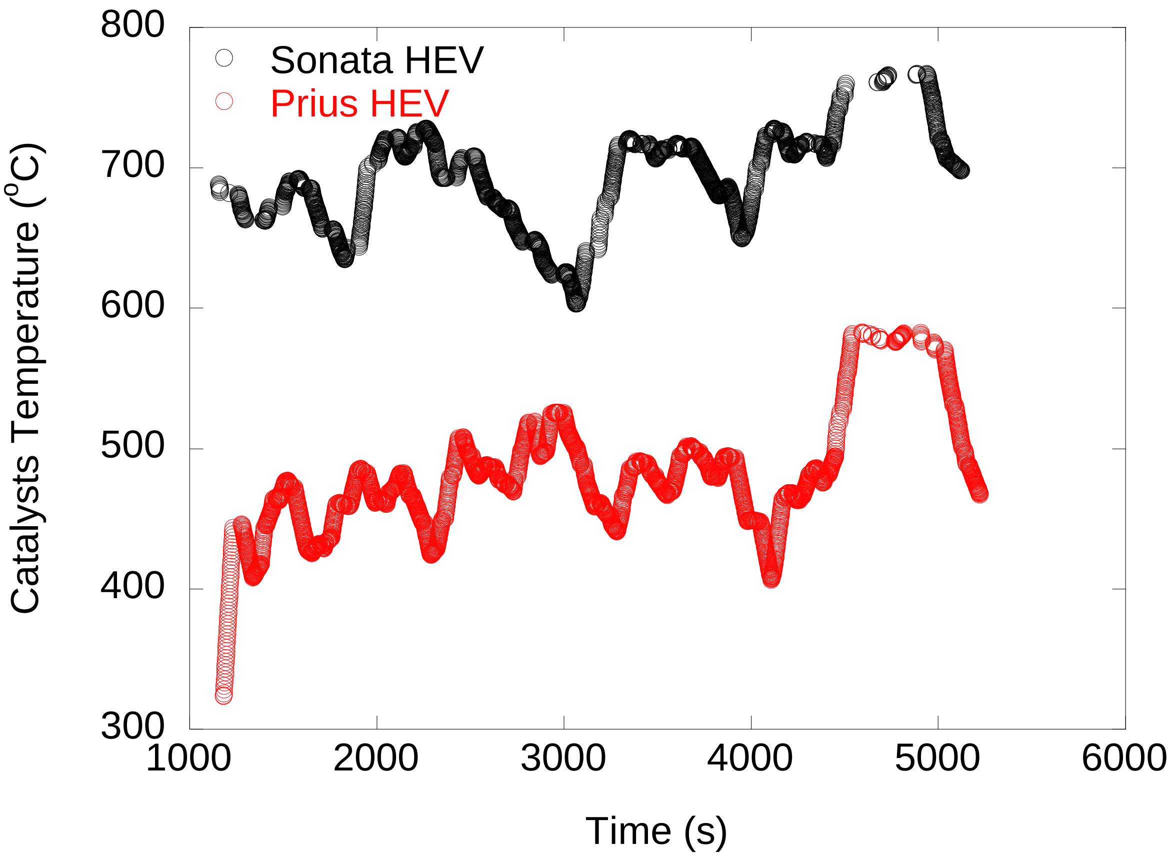

Figure 9. The different range of catalyst light-off temperature between two HEV

The emissions of NOx concentration for Prius and Sonata during city driving conditions

NOx emission was measured using a NGK/NTK NOx sensor installed in the tailpipe. Figure 10 and Figure 11 show that the NOx emitted from Prius and Sonata HEV during the city driving condition. What is noteworthy is that NOx emission increases during the re-ignition event. Prius HEV showed higher NOx concentrations than those of Sonata HEV during city cycle despite that Prius was tested at lower ambient temperature conditions (-4 ^{o}C). While NGK/NTK NOx sensors used in other studies showed no zero drift and good transient response, we observed the sensor we used have an electric drift. The NGK/NTK sensor was calibrated by the manufacturer before it was used for the test. We subtracted background noise (or drift signal) to calculate route average and cumulative NOx emissions.

Figure 12 compared average NOx concentrations between Prius and Sonata HEV during cold-cold start, city and highway driving routes. The results show that the Sonata HEV emitted higher NOx concentration during cold-cold start and highway driving condition. Interestingly Prius showed higher NOx concentration during city driving condition. We attribute this dramatic difference to the frequency and duration of re-ignition events. Prius had more frequent and shorter duration of re-ignition event during the city driving condition.

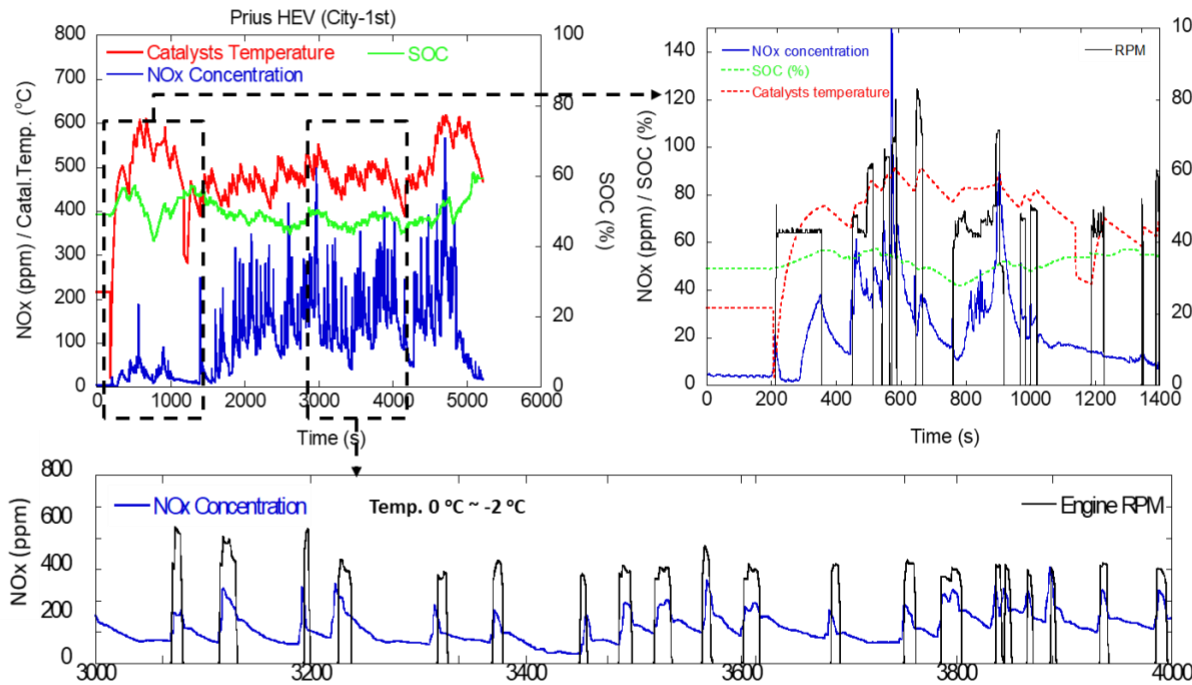

Figure 10. Re-ignition events with NOx increase during cold-cold start and stop-and-go city route (3000-4000s) for Prius HEV

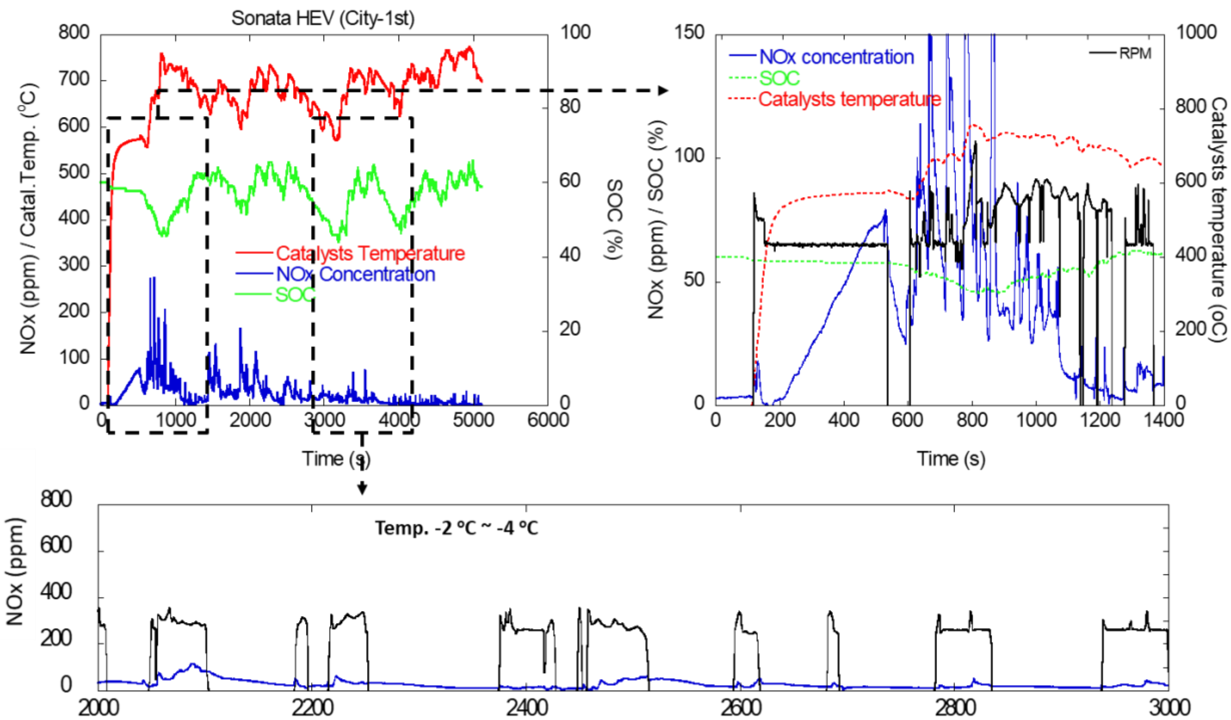

Figure 11. Re-ignition events with NOx increase during cold-cold start and stop-and-go city route (3000-4000s) for Sonata HEV

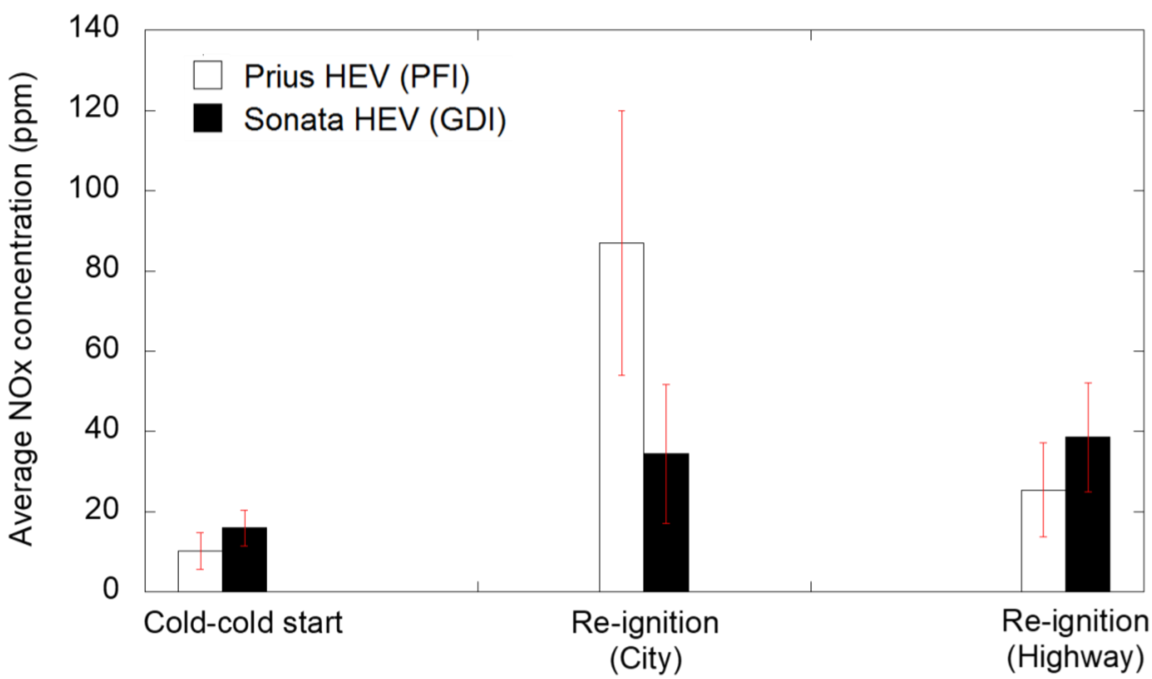

Figure 12. Comparison of toatal NOx concentrations with cold start and re-ignition of two routes between two HEV

Concluding Remarks

HEV and PHEV are bridging technologies between BEV (battery electric vehicle) and conventional engine powered vehicle technologies. HEV is a key component of sustainable transportation due to its long driving range, low greenhouse emissions, and high-energy efficiency. The result of the study highlights that emissions from HEV engine can vary significantly depending on technologies and power management strategies. The study also suggests more emissions under cold weather conditions. It is encouraged to conduct more comprehensive studies with more vehicles and tests in the future studies to understand variations of HEV emissions and promote development technologies to further reduce emissions from HEVs.