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Evaluating the Effects of Ambient Temperature and Drive Cycle on the Performance of a PHEV Prius Driven On-Road and on a Chassis Dynamometer

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Abstract

An aftermarket PHEV Toyota Prius was tested on a chassis dynamometer at average temperatures of 25°C and -10°C and under various drive cycles. These tests were carried out to quantify the performance of a parallel PHEV based on ambient temperature and geographic-specific driving behaviour. Performance was evaluated in terms of emission rates, UBE, pack utilization energy, and charge depletion range. Cold temperatures had similar effects on PHEVs as they do on ICEs and HEVs. Depletion range was highly dependent on the design of the vehicle. The HWFETx2 drive cycle resulted in a 20% higher depletion range than most other drive cycles due to increased contribution from the ICE. Based on these results, pack utilization energy and UBE are a better proxy for evaluating the performance of PHEVs in comparison to charge depletion range.

Keywords: PHEV, Battery, Emissions, Vehicle Performance

1 Introduction

Plug-in hybrid electric vehicles (PHEVs) have begun to infiltrate the commercial market in recent years. Prior to 2010, Li-ion vehicle conversions were the primary source of PHEV vehicles found on roads. More recently, vehicles such as the Chevrolet Volt and the Nissan Leaf have enjoyed critical success and have paved the way for EVs to become more prominent in today's economy. In the near future, Ford will introduce the 2012 PHEV Focus, while BMW will present the PHEV IE8 in 2014, to name a few. This surge in PHEV usage can be attributed to government initiatives promoting the research and production of electric vehicles. In fact, the U.S. Government has a goal to have one million electric vehicles in the market by 2015 [1]. Although these goals are highly optimistic, it shows the U.S. governments' commitment to the success of electric vehicles.

Several studies show that the adoption of PHEVs into the current market would result in a decrease in CO_2 emissions, lowered oil demand, and a considerable savings in fuel cost [2-4]. Since the possible environmental and economic benefits of PHEV introduction have already been considered, it is important to investigate the viability of implementing PHEV technology in various geographical environments.

This study aims to quantify the effects of the variation of ambient temperature on the Li-ion battery pack in a PHEV Prius and the overall performance of PHEVs. The study will also consider the effects of drive cycles on PHEV performance. Vehicle performance will be gauged by comparing emission rate, charge depletion range, charge sustaining energy, and fuel economy between average winter (-10°C) and summer (25°C) temperatures.

The effect of temperature on Li-ion batteries has already been well-documented [5]; however, although battery performance and end of life (EOL) are negatively affected, these findings have yet to be directly applied to PHEV performance. The results from this study will provide a more empirical relationship between temperature and PHEV vehicle performance.

It is also widely known that drive cycle has a significant effect on the performance of a vehicle. This effect is exaggerated in PHEVs because the power contribution from the battery is highly dependant on driving behaviour. This paper aims to demonstrate that PHEV testing should also be conducted using drive cycles representing driving behaviour demonstrated in a particular location. Combined with the effects of temperature, the results from this study can be used to assess the practicality of employing PHEVs in Eastern Ontario using the current available technology.

2 Methods

Tailpipe emissions were measured from a PHEV Prius while driven on-road and on a chassis dynamometer, with the use of climate control. In addition, the vehicle was fuelled with appropriate commercial gasoline for each ambient temperature. During summer tests, standard commercial gasoline was used. For winter tests, winter grade commercial gasoline was used.

During each test, the vehicle was operated in charge depletion mode. After a 12 minute hot soak, the drive cycle was repeated. This method was repeated until the Li-ion battery was fully depleted. The vehicle would then switch to the NiMh battery and would operate in charge-sustaining mode for one final cycle repeat. This method is called a battery depletion test, and is used to calculate the depletion range of the Li-ion battery, as well as the total energy discharge. The performance of the vehicle can also be evaluated during different modes of operation using this method of testing.

2.1 Vehicle Specifications

The test vehicle used in this study is a second generation Toyota Prius obtained by Environment Canada in 2008. The Prius was converted into a PHEV by installing a Hymotion Li-ion battery developed by A123 Systems. The vehicle specifications are found in Table 1.

Table 1: PHEV Prius Specifications

Make / Model	**Toyota Prius**
Vehicle Type	Plug In Hybrid Electric
After Market Parts	A123 Systems Hymotion L5
ESS Capacity	Li-ion 5kWh, NiMh 1.3kWh
ESS Type	NiMh + Li-ion
Model Year	2009
Test Weight	3729 lb

The PHEV Li-ion battery operates in parallel with the ICE and the HEV battery. The Li-ion battery is always operating in charge depletion mode, and is used to assist the ICE. Since this is a parallel operation, the on-board diagnostic systems play a major role in determining the contribution of the Li-ion battery.

2.2 Chassis Dynamometer vs. On-Road Tests

The chassis dynamometer tests follow the procedure of the US EPA Code of Federal

Table 2: Comparison of On-road and Chassis Dynamometer Drive cycles

Drive Cycle	Ave Speed (kph)	Stdev. Speed (kph)	Max Speed (kph)	Max Accel. (kph/s)	Max Decel (kph/s)	Total time (s)	Idle time (s)	Total Dist. (km)	No. of Idle Periods
On-Road Highway	58.9 ± 0.79	21.93 ± 1.92	78.6 ± 1.82	5.63 ± 0.71	-6.50 ± 1.02	1242 ± 16.52	18.13 ± 12.88	20.3 ± 0.0	3.75 ± 1.28
HWFETx2	77.1	17.6	96.4	5.15	-5.31	1530	22.00	33.0	2.00
On-Road City	38.6 ± 6.55	22.7 ± 1.81	79.9 ± 7.01	8.64 ± 4.19	-11.2 ± 3.72	1388 ± 71	182.7 ± 205.9	14.94 ± 0.03	7.78 ± 2.07
LA4 (UDDS)	31.5	23.7	91.2	5.30	-5.30	1370	260	12.0	18

Regulations Title 40 Part 86. The LA4 drive cycle was used to simulate city driving behaviour, and the HWFETx2 was used to simulate driving conditions at higher speeds.

On-road tests were designed to simulate Ottawa driving behaviour. Table 2 provides a comparison between the dynamometer and on-road drive cycles. These averaged values were obtained using the recorded speed-time trace for each test.

It was found that average speed of the on-road highway routes is nearly three quarters of the average speed recorded in the HWFETx2, respectively. The total distance and maximum speeds were determined to be 20.3 km and 78.6 km/h, which is 61.5% and 81.5% of the same values for the HWFETx2. The maximum acceleration was 5.63 ± 0.71 kph/s, and the maximum deceleration was -6.50 ± 1.02 kph/s. These values for acceleration and deceleration were relatively close to HWFETx2 tests, which are 5.15 kph/s and -5.31kph/s, respectively. The number of idle periods for the on-road test was 3.75 ± 1.28, which is near the value of 2 for the HWFETx2. Overall, it was determined that the driving behaviour for the on-road tests were similar to the HWFETx2, but is carried out at a lower speed.

The on-road city test was determined to be very comparable to the LA4 for average speed, total time, idle time, and distance. The average speed for the on-road city tests were 38.6 ± 6.55 kph, compared to 31.5 kph for the LA4. Total time and idle time were 1388 ± 71 and 182.70 ± 205.97 seconds for the on-road city test. The values for these parameters in the LA4 are 1370 and 260 seconds, respectively. However, the on-road test has a maximum speed nearly 12% lower than the dynamometer test. On average, the maximum acceleration and deceleration were 63% and 111% larger in comparison to the LA4. It was also determined that the LA4 had, on average, 10 more idle periods than the on-road test.

As expected, the on-road routes are subject to far more variability in comparison to chassis dynamometer tests, particularly for the on-road city drive cycle. Figure 1 shows the speed-time trace for the on-road city drive cycle. The variation between tests is easily observed, even within the first 4 minutes of the test. The effect of traffic lights, vehicle congestion, and many other extraneous factors has a significant impact on the repeatability of the test. This is evident by looking at the variation of the on-road city test parameters found in Table 2. The variations in average speed, maximum speed, average acceleration and deceleration, idle time, and idle periods can range between 17-112% of the average value.

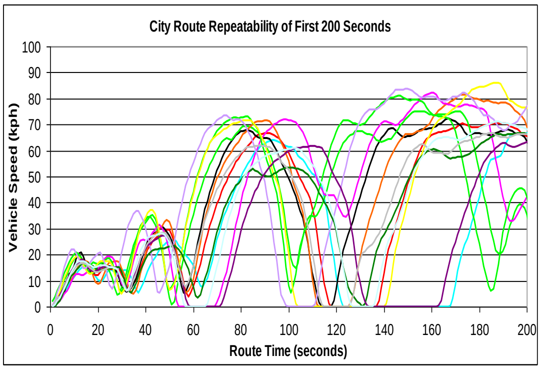


Figure 1: Speed-time traces for the first 200 seconds of the on-road city drive cycle

Figure 2 shows multiple speed-time traces for the highway on-road drive cycle. This drive cycle shows a significant improvement in repeatability in comparison to the on-road city cycle. The variability between maximum speed, average speed, and other values listed in table 2 range between 1.3 – 71.1%, which is significantly lower than the range for the on-road city tests. The speed-time traces illustrate that all on-road tests exhibit a similar pattern.

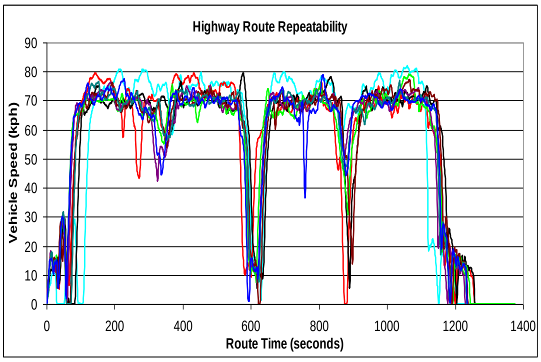


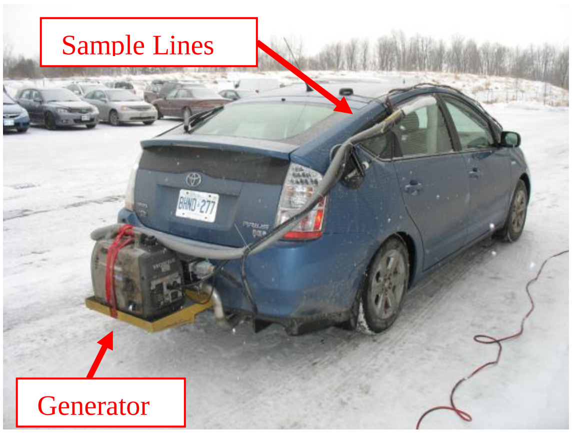
Figure 2: Speed-time trace for the on-road highway drive cycle

Although the on-road highway drive cycle is much more repeatable than the on-road city cycle, the variations in test parameters are still relatively significant for on-road drive cycles in general. This demonstrates just one of the inherent benefits of using chassis dynamometer tests, especially in the case of simulating city driving.

2.3 Sample Measurement

As previously mentioned, chassis dynamometer tests were carried out following the procedure outlined in the US EPA CFR. A constant volume sampling (CVS) system was used collect, dilute and sample CO, CO_2, NO_x, and THC emissions. A HIOKI 3193 Power HiTester unit was used to measure both the Li-ion and NiMh battery voltage, current, power and integrated energy.

Second-by-second exhaust concentrations of O_2 CO, CO_2, NO_x, and THC were measured using a SEMTECH-DS^{TM} and Sensors high speed exhaust flow meter (EFM-HS). The same unit is also used to record the exhaust flow, ambient temperature and pressure, relative humidity, speed, altitude, fuel consumption, and total distance travelled. A Kvaser Memorator reads CANbus signals, and records battery temperature, engine RPM, and battery SOC (both Li-ion and NiMH, depending on vehicle mode). A GRAPHTEC unit is used to measure the temperature of the cabin, engine and catalyst, as well as ambient conditions. The HIOKI 3193 Power HiTester is used to measure the electrical output of both the Li-ion and Ni-MH batteries. These instruments are powered by a generator that was mounted onto the back of the Prius. A photograph of the test set up is provided in figure 3.



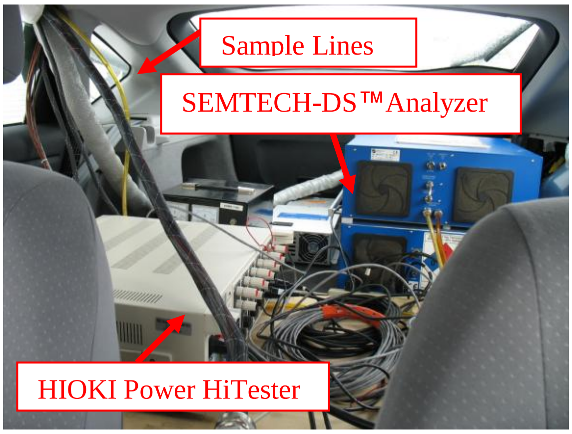


Figure 3: Photographs and description of on-road Prius test set-up with instrumentation

The SEMTECH-DS^{TM} flow meter is attached to the exhaust tailpipe, which draws a small amount of sample while simultaneously measuring the exhaust flow rate. The sample is then transported through a heated line into the analyzer, which is connected to a laptop that records various gas concentrations using Sensor Tech Inc. software. The HIOKI Power HiTester records electrical output using a LabView program developed by Argonne National Laboratories [6].

It should be noted that the SEMTECH-DS™ analyzer has some inherent differences in measurement accuracy when compared to CVS system. To obtain a comparison between the two methods, both analyzers were run in parallel during a series of dynamometer tests. From these tests, it was found that the SEMTECH-DS™ provided an adequate representation of CO emissions when concentrations were high. However, as the engine warmed up and CO concentrations reached the lower detection limit, CO emissions factors measured by the SEMTECH-DS™ were found to be 800% and higher than the values obtained by the CVS system. Similarly, NO_x emission factors measured by the SEMTECH-DS™ had a tendency to be much higher than the values measured by CVS system during the first cycle repeat, when concentrations were low. NO_x concentrations are typically lowest during cold starts. However, when the engine warmed up and NO_x concentrations reached higher values, the SEMTECH-DS™ provides very accurate results.

As is the case with any measurement instrument, the SEMTECH-DS™ analyzer may experience a drift over the duration of the test. At lower concentrations, this drift effect tends to have a larger effect on the measured concentrations. As a result, the SEMTECH-DS™ would report higher

modal values for CO and NO_x concentrations. This problem would be resolved by recalibrating the instrument between on-road cycle repeats, as is completed with the measurement instruments in the test cell. However, re-calibration of the SEMTECH-DS™ takes at least one hour, much longer than the recalibration of the CVS system. Re-calibrating the SEMTECH-DS™ between cycle repeats cannot be completed during the 12 minute soak period that is allowed between tests.
Another issue is that the SEMTECH-DS™ system must be calibrated with gases with higher concentrations than the calibration gases for the CVS system. This is done to accurately capture the large spikes in tailpipe emissions caused by cold starts, periods of high acceleration, and other high-emission scenarios. Since the range of the measurements is very large, low concentration data is less accurate. Therefore, it can be concluded that the accuracy of the SEMTECH-DS™ is negatively affected when measuring low concentrations on high range settings.

3 Results

Vehicle performance can be evaluated in many different ways. One goal of this study is to quantify the energy efficiency of a PHEV vehicle. The fuel efficiency of a conventional ICE is typically measured by fuel consumption, in L/100km, mpg, etc. For a PHEV, the energy efficiency of the battery must be combined with the fuel efficiency of the engine. The cycle energy intensity is used to quantify the amount of energy used during a particular drive cycle. This is measured in Wh/km, and takes into account the battery energy and the energy gained from the combustion of fuel.
PHEV performance was heavily influenced by the effects of temperature and drive cycle. This section of the report quantifies the effect of these parameters on emission rates and vehicle performance.

3.1 Effect of Ambient Temperature

3.1.1 Vehicle Performance

Although they are more efficient than ICEs, battery powered vehicles have inherent losses as well. Therefore, identifying how efficient the battery operates at various temperatures is important to evaluating the performance of a PHEV. It is also important to determine the distance that the vehicle can travel before the Li-ion battery is depleted.
The discharge efficiency of the Li-ion battery can be determined by comparing the UBE with the nominal battery capacity. The UBE is obtained by integrating the total power output of the battery over the length of the depletion test. The charge depletion ranges for the tests were obtained by determining at what distance the Li-ion battery was depleted, or when the vehicle switched to HEV mode. This was calculated by aligning the data from the HIOKI power measurements with the speed-time trace, noting at what time the Li-ion discharge was reduced to zero, and calculating the total distance at that time.
Test results showed that the vehicle would switch to HEV mode when the SOC of the Li-ion battery reached 21.5%. According to the battery specifications, the nominal battery capacity is 5 kWh. Ideally, this means that there would be 3.925 kWh of UBE if the battery was discharging 100% efficiently. Values for the actual UBE are

Table 3: Fuel consumption, cycle energy intensity, Li-ion battery energy consumption, charge depletion range, and UBE for the LA4 and HWFET drive cycles tested at -10ºC and 25ºC

		Fuel Consumption (L/100km)				Cycle Energy Intensity (Wh/km)			
		Repeat 1	*Repeat 2*	*Repeat 3*	*Repeat 4*	*Repeat 1*	*Repeat 2*	*Repeat 3*	*Repeat 4*
LA4	*Cold*	5.71	3.42	3.72	5.99	106.93	111.24	108.72	30.34
LA4	*Warm*	1.88	1.76	3.47	5.02	124.57	118.90	16.63	23.96
HWFETx2	*Cold*	3.48	4.28	4.83	-	83.77	72.45	18.10	-
HWFETx2	*Warm*	2.46	4.40	4.91	-	98.10	21.06	23.44	-

		Hymotion Consumption (Wh/km)				Depletion Range (km)	UBE (kWh)
		Repeat 1	*Repeat 2*	*Repeat 3*	*Repeat 4*	*Overall Test*	*Overall Test*
LA4	*Cold*	80.07	95.15	91.20	2.14	36.95	3.24
LA4	*Warm*	115.62	110.51	0.08	0.00	35.44	2.73
HWFETx2	*Cold*	67.57	24.09	0.51	-	47.01	3.06
HWFETx2	*Warm*	86.37	0.07	0.00	-	46.09	2.86

presented in Table 3.

The data indicates that the cold temperature LA4 test had the highest UBE, at a total value of 3.24 kWh. Therefore, the Li-ion battery is operating at a pack utilization energy of 82.5%. The lowest value for UBE, 2.73kWh, was measured during the warm temperature LA4 tests. This corresponds to a pack utilization energy of 69.6%. The same trend between warm and cold temperature was observed in HWFETx2 tests (pack utilization energy of 78.0% vs 72.9% for cold and warm tests, respectively.

Charge depletion range is often a parameter that is used as a basis for comparing electric vehicles. It was interesting to note that the charge depletion range for HWFETx2 tests were, on average, 21.4-23.1% higher than LA4 tests at both cold and warm temperatures. Although this may seem counterintuitive, it is important to note that unlike a series hybrid, parallel hyrids use the Li-ion battery to aid the ICE in generating power for the vehicle. This battery is optimized for energy density, so that the vehicle can travel longer distances using battery power. However, the ICE is used primarily during sections of high power demand. Since the vehicle is operating at a higher average speed in the HWFETx2 test, more power is required to move the vehicle. As a result, the ICE is used more, which is indicated by decreased values for Li-ion battery consumption. Li-ion battery consumption was found to be 15.6-25.3% lower for cold and warm temperature HWFETx2 tests compared to the LA4 tests, respectively.

3.1.2 Criteria Emissions

Battery depletion test results held at various ambient temperatures are summarized in the following section. As previously mentioned, these tests involve driving the vehicle for several repeat cycles until the battery is fully depleted. Figures 4, 5, 6, and 7 provide the average emission factors for various air pollutants for each test cycle sequence. The value on the graph for the first test cycle sequence represents the average emission factor during the first cycle repeat. The values for the second test cycle sequence represent the average emission factor for the second cycle repeat performed after a 12 minute hot soak, and so forth. It is also important to note that LA4 battery depletion tests lasted four cycle repeats, whereas the HWFETx2 test lasted three cycle repeats.

Figure 4 presents the average CO_2 emission factors observed for each test cycle. The concentration of CO_2 at the tailpipe is dependant on the completeness of combustion and is always directly related to fuel consumption. The efficiency of the three-way catalyst (WTC), which is related to catalyst temperature, also has an effect on tailpipe CO_2 concentrations.

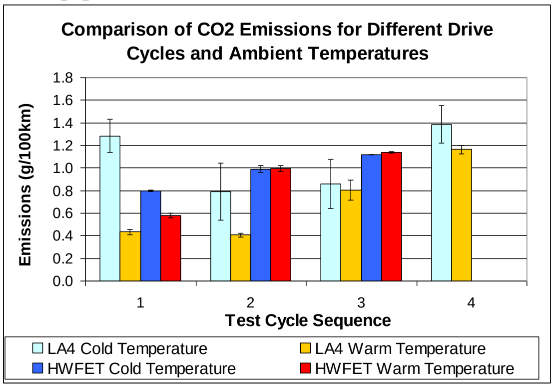


Figure 4: CO_2 Emission factors for dynamometer tests performed at -10 ºC and 25 ºC

For the LA4 drive cycle, cold temperature CO_2 emission rates were much higher than warm temperatures during the first two cycle repeats. The difference is lessened for the last the two cycle repeats, although the cold temperature CO_2 emission rate remains slightly higher; HWFETx2 tests also showed a similar trend. During the first cycle, CO_2 emissions were higher for cold temperatures than warm temperatures. During the next two cycle repeats, the CO_2 emissions were relatively similar between cold and warm temperature tests. This is consistent with the values for fuel consumption. It was found that CO_2 emissions are not different at a statistically significant level when the difference between the fuel consumption was 10% or less.

In contrast to CO_2, emission factors for CO were found to be radically different between cold and warm temperature tests. The test results for CO emission factors are summarized in Figure 5.

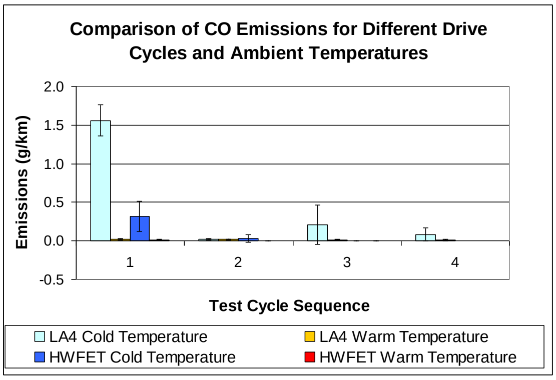


Figure 5: CO Emission factors for dynamometer tests performed at -10 ºC and 25 ºC

Warm temperature dynamometer tests resulted in CO emission factors ranging from 0.01-0.02 g/km, with very little deviation in values. Cold temperature tests showed a very significant increase, reaching a value of 0.32 ± 0.20 g/km and 1.56 ± 0.21 g/km for HWFETx2 and LA4 tests, respectively; this indicates that start-up emissions for the PHEV Prius are still subject to incomplete combustion at cold temperatures. This is an example of a “first test effect”, where the first cycle repeat shows different behaviour in comparison to other cycle repeats.

NO_x is formed primarily when the engine temperature is high. Therefore, during a cold start, we expect the NO_x concentrations to be at their lowest. Figure 6 summarizes the average emission factors for NO_x for all four types of tests.

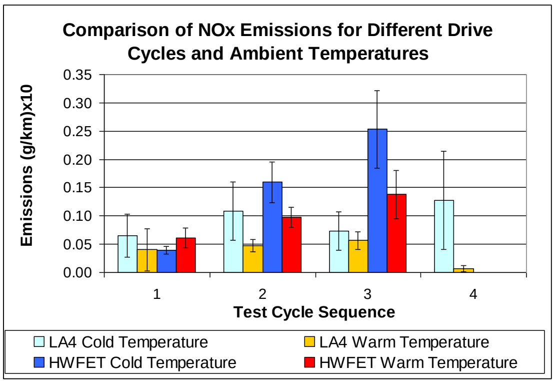


Figure 6: NO_x Emission factors for dynamometer tests performed at -10 ºC and 25 ºC

The results show that during the first cycle repeat, NO_x concentrations are generally very low. This is due to the low temperature of the engine during the cold start. As the car is subjected to more cycle repeats, the engine warms up, resulting in more NO_x formation. It was also found that in most cases, the HWFETx2 drive cycle produced more NO_x in comparison to the LA4 drive cycles. For the HWFETx2 cycles, the engine is operating more intensely because of the higher average speed. As a result, the engine reaches higher temperatures and more NO_x is formed during combustion.

The last pollutant that was measured was THC. The emission factors for THC are reported in Figure 7. The first cycle repeat for the cold temperature LA4 drive cycle produced the highest THC emission rates, averaging approximately 4.10 g/km. The first cycle repeat of the cold temperature HWFETx2 also produced a substantial THC emission factor of approximately 0.88 g/km.

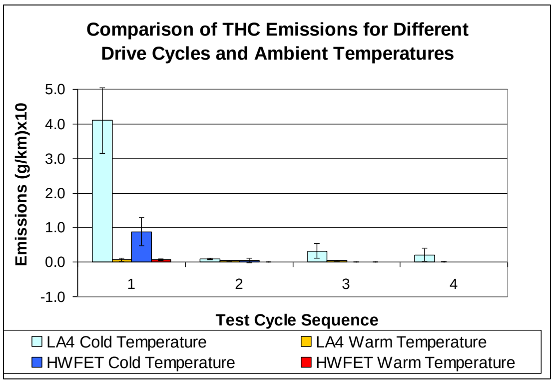


Figure 7: THC Emission factors for dynamometer tests performed at -10 ºC and 25 ºC

This first test effect is a result of the initial temperature of the engine during the cold temperature tests. As well as inhibiting complete combustion cold temperatures reduce the efficiency of the TWC. These factors result in an increased amount of unburned hydrocarbons leaving the tailpipe during the first test. As expected, the THC emissions correlate very strongly with CO emissions, since both pollutants are affected by the same processes.

Overall, it was found that cold operating temperatures tend to exaggerate the first test effect for all measured pollutants. This is comparable to cold temperature effects experienced by ICEs and HEVs and is primarily a result of lower engine and catalyst temperatures during the first cold start. Combustion is much less efficient at cold temperatures, leading to increased hydrocarbon and carbon monoxide formation [7]. The thermo-chemical processes that govern the three-way catalytic converters are also negatively affected by the lower cold start temperatures, leading to higher tailpipe pollutant concentrations. These temperature-dependant processes are found not only for ICEs and HEVs, but in PHEVs as well. Therefore, these similar first test effects are expected, and were observed, in the PHEV evaluation.

3.2 Effect of Drive cycle

Driving behaviour makes a significant impact on the tailpipe emissions and vehicle performance. This section quantifies the differences in these parameters based on two dynamometer drive cycles (LA4 and HWFETx2) and two on-road drive cycles (City and Highway). When comparing the results for different driving behaviour, it is important to consider the difference between the drive cycles. These results are all obtained at an average temperature of 25ºC.

3.2.1 Vehicle Performance

Vehicle performance parameters for various drive cycles are summarized in Table 4. Once again, the charge depletion ranges for the HWFETx2 dynamometer test cycles were significantly higher than the on-road highway tests; however, as was mentioned in section 3.1.1, this is primarily a result of a decreased Li-ion battery consumption in relation to ICE power contribution for the HWFETx2 tests. In contrast to the high-speed drive cycles, the LA4 and on-road city test cycles showed similar depletion ranges and fuel consumption. The differences between these two parameters were 6.66% for charge depletion range, and between approximately 2-25% for fuel consumption. The differences between these parameters for the high speed drive cycles were much larger: 30.6% for charge depletion range and between 12.2-41.9% for fuel consumption. This is a possible indication that the LA4 is more representative of Ottawa city driving. Conversely, this would mean that the HWFETx2 is not as representative of Ottawa driving behaviour.

UBE for the LA4 and HWFETx2 tests were 19.9% and 16.6% lower than their on-road counterparts. As a result, the Li-ion battery would deplete shortly into the third cycle repeat for the LA4, and shortly into the second cycle repeat for the HWFETx2. The lower UBE indicates that the Li-ion battery discharged less efficiently in the dynamometer tests in comparison to the on-road tests. Higher average speeds in the HWFETx2 and increased stop-and-go behaviour in the LA4 are possible reasons why the battery did not operate as efficiently in the dynamometer tests. Liaw et al. explains that batteries operating under a higher-than-average discharge rate may not discharge at an optimum efficiency. [8]. There are also models that predict this type of behaviour, as seen in a study by V. Johnson [9]. Therefore, the increased speed and start-and-stop behaviour likely caused the batteries to have lower UBE for those tests.

3.2.2 Emission Rates

Figure 8 shows the CO_2 emission factors for dynamometer and on-road tests carried out at an average temperature of 25°C.

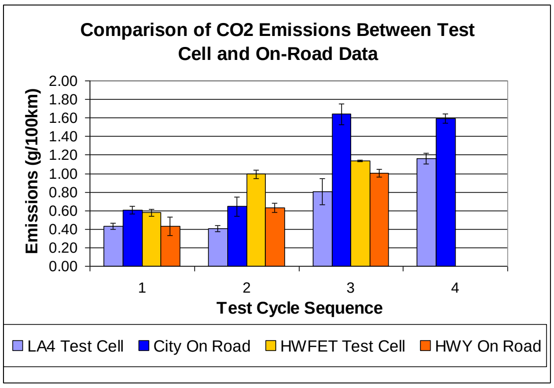


Figure 8: CO_2 emission factors for the PHEV Prius operating under various drive cycles performed at 25ºC

CO_2 emissions were highest for the HWFETx2 tests, consistent with the fuel consumption values in Table 4. These emission rates were higher than the CO_2 emission rates for the on-road highway tests for all three cycle repeats. During the first test, the high fuel consumption is representative of the higher average speed in the HWFETx2 drive cycle compared to other drive cycles. The third cycle repeat also showed slightly higher CO_2

Table 4: Fuel consumption, cycle energy intensity, Li-ion battery energy consumption, charge depletion range, and UBE for the on-road and chassis dynamometer drive cycles at 25ºC

	Fuel Consumption (L/100km)				Cycle Energy Intensity (Wh/km)			
	Repeat 1	Repeat 2	Repeat 3	Repeat 4	Repeat 1	Repeat 2	Repeat 3	Repeat 4
LA4	1.88	1.76	3.47	5.02	124.57	118.90	16.63	23.96
On-road City	2.10	1.72	4.37	4.24	109.38	105.04	37.83	18.63
HWFETx2	2.46	4.40	4.91	-	98.10	21.06	23.44	-
On-road Highway	1.88	2.56	4.32	-	110.85	72.45	18.10	-

	Hymotion Consumption (Wh/km)				Depletion Range (km)	UBE (kWh)
	Repeat 1	Repeat 2	Repeat 3	Repeat 4	Overall Test	Overall Test
LA4	115.62	110.51	0.08	0.00	35.44	2.73
On-road City	99.41	96.87	16.98	-1.58	33.08	3.27
HWFETx2	86.37	0.07	0.00	-	46.09	2.86
On-road Highway	101.98	65.82	2.58	-	31.97	3.33

emissions for the HWFETx2. The large difference in the second cycle repeat is a result of the Li-ion battery typically depleting shortly into the second HWFETx2 repeat. Therefore, the vehicle would be running in HEV mode for the majority of that test, thus leading to increased fuel consumption.

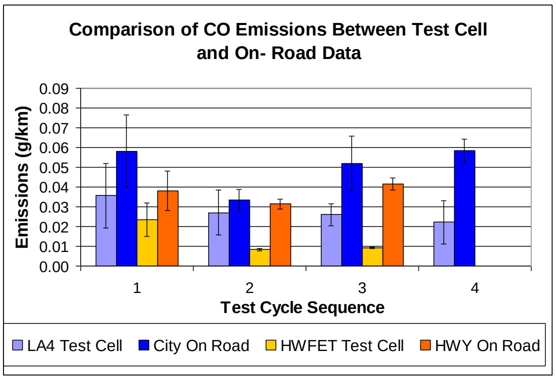


Figure 9: CO emission factors for the PHEV Prius operating under various drive cycles performed at 25ºC

In Figure 9, the emission rates of CO are summarized. CO emissions behaved as expected; that is, they are higher during cold start and higher in drive cycles where the primary source of energy is the ICE. Hot-start CO emissions for cycle repeat 2 of the on-road city tests were 43% lower than the hot-start emissions for cycle repeat 4. Cold start emissions were also 43% higher than the hot-start emissions from the second cycle repeat.

It was also found that the CO emission rates are higher for on-road tests in comparison to their chassis dynamometer cycle counterparts. In the city tests, dynamometer CO emission rates are be between 20-55.6% lower than on-road CO emission rates. This difference is even larger for the highway tests, with differences in dynamometer CO emission rates ranging between 33.3-85.7% lower than those for on-road tests. This discrepancy, however, is partially due to the nature of the SEMTECH-DS™ measurements. As mentioned in section 2.3, the SEMTECH-DS™ has a tendency to over-predict emissions at lower concentrations. Tailpipe emission concentrations of CO are very low after the catalytic converter has warmed up. Therefore, the SEMTECH-DS™ continuously over-predicts for a long period of time during the on-road test. This could be a reason why the CO concentration measurements are higher during on-road tests.

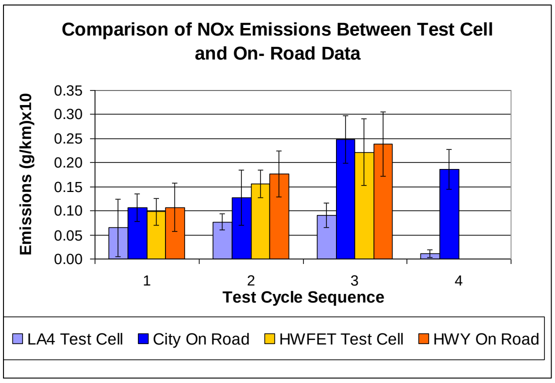


Figure 10: NO_x emission factors for the PHEV Prius operating under various drive cycles performed at 25ºC

Figure 10 summarizes the comparison between NO_x emission rates for chassis dynamometer and on-road drive cycle tests. For the highway tests, NO_x emission rates increased with each cycle repeat. The HWFETx2 produced NO_x emission factors of 0.010, 0.016, and 0.022 (g/km) for repeats 1, 2 and 3, respectively. On-road highway tests had very similar results; producing NO_x emission factors of 0.011, 0.018, and 0.024 (g/km) for repeats 1, 2 and 3, respectively. The increase in emission rate with cycle repeat is due to the increasing temperature of the engine as the car is driven for longer periods of time. In addition, NO_x emissions increase as the vehicle uses the ICE more often for generating power.

Contrary to the high-speed cycles, the on-road city and LA4 drive cycles have very different NO_x emissions for all cycle repeats.

Another issue is that the NO_x emissions varied largely from test to test. Reported average emission rates produced standard deviations that ranged between 22.2%-100% of the total values. This variation is a result of emission factors close to the detection limit of the SEMTECH-DS™,

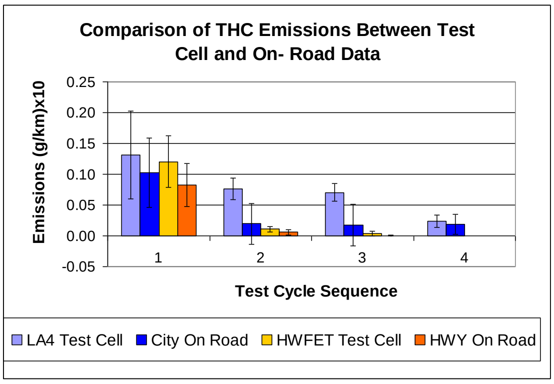


Figure 11: THC emission factors for the PHEV Prius operating under various drive cycles performed at 25ºC

Warm temperature THC emission factors showed a significant amount of variation for the first cycle repeat of each set of tests. The cold start THC emission factors were the highest, and decreased for each subsequent cycle repeat. It was also found that for each cycle repeat, the LA4 showed the highest amount of THC concentration. This is primarily due to the increased idling time and idling periods that are observed in the LA4 drive cycle.

When considering route performance, it was confirmed that there are significant differences between highway and city drive cycles. It was also found that there are some inherent differences in emissions when comparing chassis dynamometer and on-road results. Some of these inconsistencies are due to difficulties in measurement. However, many of these differences can also be attributed to the differences between the on-road and chassis dynamometer drive cycles.

4 Conclusions and Future Work

It was found that the differences in route characteristics were the major cause of discrepancy in PHEV emission rates and performance between on-road and chassis dynamometer results. These differences are due to the nature of driving in Ottawa, Ontario, and how this is different than the driving patterns used in the CFR procedure. The on-road city and LA4 drive cycles showed the greatest discrepancies in emissions, whereas the on-road highway and the HWFETx2 showed the greatest discrepancies in battery performance. On-road emission factors of CO and NO_x were much higher than chassis dynamometer emission factors. THC, on the other hand, was much higher in the LA4 drive cycle due to increased idling time. When comparing the on-road highway and the HWFETx2, the HWFETx2 had much higher average speeds. This causes the engine to be used more as it operates to supplement the power generation in parallel to the battery. As a result, the battery lasts longer, but resulted in 16% less energy discharged during the HWFETx2 tests.

The effects of drive cycles were also studied. Overall, the HWFETx2 dynamometer test showed a higher charge depletion range than its on-road counterpart. The depletion range was, on average, 30.6% larger for the HWFETx2 when compared to the on-road highway drive cycle. However, it was also found that this increase in the charge depletion range were correlated with an 18.1% decrease in Li-ion battery consumption per kilometre, as well as a 16-6% decrease in UBE. The values for depletion range and fuel consumption were similar between the LA4 and the on-road city drive cycles. However, the LA4 pack utilization energy was equal to 69.6%, much smaller in comparison to the 83.3% pack utilization energy obtained during the on-road city route. Therefore, although the depletion range was similar between the city and LA4 drive cycles, the battery was operating almost 15% less efficiently.

Temperature had a similar effect on PHEVs as it has on other types of light duty vehicles. Colder temperatures resulted in higher CO and THC emissions, which show that the tailpipe pollutants are heavily affected by the catalyst performance. Less NO_x was formed under colder temperatures. Cold engine temperatures limited the amount of NO_x being formed. Fuel consumption increased with decreasing temperatures. Battery discharge rate was much faster at higher temperatures, but the overall energy consumption was better at low temperatures.

Based on these results, it was found that for post-production PHEVs, charge depletion range is subject to the manufacturer's battery design and corresponding battery control unit. This prevents depletion range to be used an accurate measure of battery efficiency. Instead, discharge efficiency and battery consumption should be used as a proxy for PHEV performance evaluation.

There were significant differences in PHEV performance between the chassis dynamometer drive cycles and the on-road tests carried out in Ottawa. Emissions and vehicle performance are highly dependent on these parameters, and are even more influential to PHEV performance. This indicates that, in concordance with standardized vehicle testing procedures, the specific driving behaviour for various geographical locations should also be considered when evaluating the performance of PHEVs.

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No Photo

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