22PFL-071

Plug-in Hybrid Vehicle Thermal Management and System Operation in Real-World Conditions

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Abstract

Plug-in hybrid electric vehicles (PHEVs) use stored electrical energy from electrical grids as well as chemical energy from fuel as energy sources for propulsion and various auxiliary loads. Using their electrified powertrains, PHEVs are designed to achieve improved overall efficiency and lower emissions compared to conventional internal combustion engine vehicles (ICEVs). Real-world conditions may, however, require significant thermal management energy, lowering PHEV efficiency and increasing their tailpipe emissions. A series of on-road tests were completed in Canadian summer and winter conditions to characterize the operation of four 2018 model-year PHEVs: a minivan, an SUV, and two hatchbacks. Their respective thermal management equipment and associated control strategies are discussed in this paper. Vehicle equipment included electric air-conditioning systems, electric coolant heaters, advanced heat pump systems, and conventional heater core-based systems. The results are analyzed in terms of operation strategy, thermal management loads, tailpipe CO_2 emissions, and various electric range metrics. In summertime, all vehicles were able to run all-electrically for significant distances, thanks to their electric air-conditioning systems. In wintertime, the two vehicles with electric coolant heaters immediately started their engines to boost heat production, but also used stored electrical energy to provide heat and/or propulsion. One vehicle had an advanced heat pump system, which allowed it to run all-electrically for significant portions of winter testing (albeit for shorter distances than in summer testing). The remaining test vehicle had no electrical heating capability, and thus required engine operation whenever cabin heat was needed, but blended-in electrical energy for propulsion when possible.

Introduction

Plug-in hybrid electric vehicles (PHEVs) have the ability to plug into the electrical grid to charge, storing electricity in their on-board rechargeable energy storage system (RESS), generally made up of high-voltage batteries. This stored energy may allow the vehicle to run on electricity alone for a limited all-electric range (AER), or it can be used to assist in propulsion, heating, cooling, and accessory loads as needed. When a vehicle's stored battery energy generally decreases without being fully replenished by internal combustion engine (ICE) use or regenerative braking, it is considered to be in charge depleting (CD) operation [1]. In real-world conditions, high power demands and climate control operation during CD mode may require gasoline engine operation in addition to electrical operation (this is often referred to as "blended" operation) [2]. Once stored battery energy has been depleted to a manufacturer-selected level while operating in CD mode, a PHEV can fall back into a charge-sustaining (CS) mode, like a typical hybrid electric vehicle (HEV), obtaining its required propulsion and accessory energy from the combustion of on-board fuel [1]. In CS mode, the battery may be used during regenerative braking to recapture kinetic energy that would otherwise be wasted, or to allow for efficient operation of the ICE using strategies such as intermittent engine shut down or load shifting, leading to improved efficiency and emissions when compared to an ICE-only vehicle [2]. Unlike in CD mode, in CS mode the state of charge (SOC) of the battery remains relatively consistent over time [1]. Using its hybrid drivetrain and advanced control strategies, a PHEV can achieve better overall efficiency (in both CD and CS modes) than a conventional ICE vehicle in many types of driving conditions [3].

Conventional ICE vehicles (ICEVs) use belt-driven air-conditioning (A/C) compressor systems for cooling the cabin in hot weather. These systems require the use of the engine to operate the air-conditioning compressor via the accessory belt. In cold weather, a conventional ICEV uses waste-heat from its engine for cabin heating; since the ICE operates at all times its waste heat is always available. In contrast, HEVs and PHEVs often operate their engines intermittently in order to save fuel (while battery electric vehicles, BEVs, do not have combustion engines at all). Alternative heating and cooling systems are often used on HEVs and PHEVs to provide cabin comfort and battery conditioning without the need for engine operation.

The preferred cooling option for HEVs, PHEVs, and BEVs is an electric air-conditioning system. In this system, the A/C compressor, instead of being belt-driven by the engine, is driven by an electric motor. This electric motor is supplied with high-voltage electricity from the main battery (or via the powertrain system through regenerative braking or electricity generation, as needed). An electric A/C compressor can run whenever cooling is required, without the need to use an ICE, thus enabling all-electric vehicle operation in hot weather.

Both electricity from the battery pack (or powertrain system) and engine waste heat (through a conventional heater core) can be used to provide cabin heating for HEVs and PHEVs (whereas BEVs can only use electrical heating systems or electrical system waste heat to supply cabin heating). Electrical heating methods can be further sub-divided into two most commonly used technologies: resistance heating and heat pump systems.

Electrical resistance heating uses electricity to create heat directly. In electric vehicles, resistive heating is often provided by a Positive Temperature Coefficient (PTC) type heater, whether this is a coolant heater or a direct air heater. Heat from a coolant heater is transferred to a circulating fluid, which can be used to heat the cabin and/or battery pack [4]. Alternatively, PTC heaters can be placed in the cabin air stream to heat the cabin air directly [4], however none of the test vehicles included in this paper used this method.

Heat pump systems consist of a compressor (usually the same electrically-driven compressor used for air-conditioning but converted to heating mode using a reversing valve) that circulates a working fluid (called a refrigerant) through heat exchangers and valves to effectively extract heat from the ambient air and deliver it to the cabin and/or battery pack [5]. The main advantage of heat pump systems over electrical resistance heating is that by extracting thermal energy from the ambient air and delivering this energy, along with the compressor energy, to the required location, heat pumps can provide the same amount of useful heat while using less electrical energy than an equivalently-powerful resistance heating system [5]. Heat pump systems are, however, more complex than resistance heaters, which can entail additional initial purchase and maintenance costs [6]. Heat pump systems may also require additional backup systems (for example, engine waste-heat recovery or resistance heating systems) because they cannot typically operate efficiently when ambient temperatures are very low [5].

A PHEV's ability to use stored electrical energy for propulsion or to power auxiliary loads, such as heating and cooling, can lead to improvements in energy consumption and emissions when compared to ICEVs. However, heating and cooling loads may become significant components of a PHEV's energy use during hot summer and cold winter days, which are both common throughout Canada, reducing this efficiency advantage and the PHEV's all-electric driving range. This study compares current PHEV cabin heating and cooling technologies and associated control strategies in terms of their effects on vehicle operation, electrical energy consumption, tailpipe CO_2 emissions, and various electric range metrics. To quantify these effects, the team investigated the operation of four 2018 model year PHEVs on-road in Canadian summer and winter conditions. The test vehicles included several body styles (a minivan, an SUV, and two hatchbacks) as well as different cabin heating technologies (electric coolant heaters, reversible heat pumps, and conventional heater cores).

Vehicle Descriptions

All four test vehicles use complex two (or three) motor drivetrain systems that allow the optimization of fuel consumption during driving using parallel or series hybrid strategies. All test vehicles also use electric A/C compressors for cooling in hot weather. Their heating systems, however, applied several different technologies.

Vehicle 1 is a PHEV minivan. For heating it uses an electric resistance "coolant heater" to heat a circulating fluid, which then heats the cabin air and the battery pack if engine waste heat is not available or is not sufficient to meet heating needs.

Vehicle 2 is a PHEV SUV with an independent rear motor to allow all-wheel drive (AWD) capability. Its heating system is of the same type as that of Vehicle 1.

Vehicle 3 is a PHEV hatchback. It uses an electric heat pump system for cabin heating, which can operate effectively down to a temperature of -10°C [5]. Below this temperature, the gasoline engine must be started when heating is required and replaces the heat pump as the source of cabin heating. Using a reversing valve and associated piping, the heat pump system also operates as the air-conditioning system in hot weather and can provide dehumidification without the use of an additional electric resistance heating system [5].

Vehicle 4 is another PHEV hatchback which uses one main traction motor and a secondary starter motor/generator unit. This is the only vehicle of the four models tested that uses a gasoline direct injection (GDI) engine rather than a port fuel injection (PFI) engine. The vehicle does not include electrical cabin heating for cold weather operation. This means that when cabin heating is required, the gasoline engine must be started to provide heat through the conventional heater core. During this time, the associated mechanical engine power output is used to propel the vehicle and/or to generate electricity for the battery and on-board systems. Additional test vehicle specifications are included in Table 1.

Table 1: Test Vehicle Specifications

Parameter	**Vehicle 1**	**Vehicle 2**	**Vehicle 3**	**Vehicle 4**
Model Year	2018	2018	2018	2018
Curb Weight (lb)	5021	4292	3365	3318
GVWR (lb)	6300	5225	N/A	4343
Drivetrain	FWD	AWD	FWD	FWD
Cabin Heating Type	Coolant Heater	Coolant Heater	Heat Pump	No Electrical Heater
Battery Description	Li-ion, 96 cells, 360V	Li-ion, 300V	Li-ion, 351.5V	Li-ion, 360V
Battery Capacity (kWh)	16	12	8.8	8.9
Engine Description	3.6L V-6	2.0L i-4	1.8L i-4	1.6L i-4
Fuel Injection Type	Port fuel injection	Port fuel injection	Port fuel injection	Gasoline direct inj.
Rated Electric Range (km) [7]	53	35	40	47
Electric (CD) Mode Fuel Consumption (L/100km e) [7]	2.8 (249 Wh/km)	3.2 (277 Wh/km)	1.8 (158 Wh/km)	2.0 (177 Wh/km)
Gasoline-only (CS) Fuel Consumption (L/100km) (City/Hwy/Combined) [7]	7.3/7.2/7.3	9.4/9.0/9.2	4.3/4.4/4.3	4.4/4.6/4.5
Rated CO2 Emissions (g/km) [7]	66	108	49	46

Methods

Instrumentation

The instruments used to collect test data during this project are listed in Table 2 and included an electrical power analyzer with clamp-on current probes and a Portable Emissions Measurement System (PEMS) with an exhaust flow meter (EFM) and a condensation particle number (CPN) counter.

Table 2: Instrumentation Summary

Instrument	**Parameters**	**Units**	**Ranges**	**Make/Model**
Power Analyzer	Current Voltage	A V	0-1000 0-1000	Hioki PW6001-16
Current Probes	Current	A	0-200 0-500	Hioki CT6843/5
PEMS	CO CO2 NO NO2	ppm % v ppm ppm	8 18 3000 1000	Sensors Inc. LDV
EFM	Exhaust Mass Flow	kg/hr	17-550	Sensors Inc. EFM4

CPN	Particle-Concentration	#/cm^3	0-1x10^4	Sensors Inc. CPN

Test Routes

Two test routes were selected for on-road operation during this project, the COMBO route and the RDE route. Both of these cycles were treated as “cold-start” tests, where the vehicles were soaked at ambient temperatures overnight and were not driven or started prior to the start of the test. The vehicles were also charged from the electrical grid prior to testing and began each test day with a fully-charged main battery.

COMBO Route

The on-road COMBO route includes driving segments in different parts of the city of Ottawa, Canada. During testing, the COMBO route was driven twice in succession with a 10-30 minute break between loops, referred to in its entirety as the COMBOx2 route, or individually as COMBO “Round 1” (R1) and COMBO “Round 2” (R2). Each individual COMBO Round begins and ends at the ERMS lab, and consists of five distinct segments (known as “Modes” M1-5) that circle a large area of the city. The segments are characterized in Table 3.

Table 3: COMBO route segment specifications

Mode	Type	Distance [km]	Speed limits [km/h]	Stops
M1	Arterial/rural	6.6	60-80	Some
M2	City	5.0	50-60	Frequent
M3	City Centre	2.7	40-50	Frequent
M4	Expressway	15.4	80-100	Few
M5	Arterial/rural	13.2	60-80	Some

RDE Route

The Real Driving Emissions (RDE) route was created based on the requirements of the European Euro 6 emissions regulations for light duty vehicles [8] because there is currently no common North American standard for on-road test route creation. The RDE test route begins at the ERMS facility in Ottawa and consists of several distinct segments, characterized in Table 4. A fourth segment has been added to the test procedure as a “return to base” (RTB) mode, which follows much of the M2 rural route in reverse, in order to capture the energy used on the way back to the test facility for energy consumption calculation purposes.

Table 4: RDE route segment specifications

Mode	Type	Distance [km]	Speed limits [km/h]	Stops
M1	Urban	20.4	40-60	Frequent
M2	Rural	19.4	60-80	Some
M3	Motorway	37.8	80-100	Very few
RTB	Rural	14.6	60-80	Some

Test Fuel

All vehicles were tested using a combination of electricity and Tier 2 gasoline certification fuel; see Table 5 for the gasoline specifications. Prior to testing, all vehicles were fuel-exchanged to use this test fuel, and were topped-up with it as needed during testing.

Table 5: Tier 2 Certification Gasoline Specifications

Parameter	Value
Density @15°C (kg/m^3)	743.2
Fuel Fraction Carbon (FFC)	0.8660
Net Heating Value (MJ/kg)	42.9 (18459 BTU/lb)
Net Heating Value (kWh/gal$_{US}$)	33.54

Electrical Charging Procedure

The test vehicles were set to charge within 3 hours of completing the daily testing by plugging them into an outdoor Level 2 (208V AC) electric vehicle supply equipment (EVSE) unit via an SAE J1772 connector. The vehicles charged overnight in ambient conditions in both winter and summer, and charging energy was monitored using the Hioki power analyzer. The outdoor EVSE units are rated to 32 Amps at 208-240 Volts and were supplied with 208 V electricity by the grid.

Even though many PHEVs feature the ability to pre-warm their cabin and batteries, this functionality was not used during testing in order to simulate a “worst-case” cold-start scenario. Therefore, the vehicles’ batteries and cabin were allowed to soak at ambient temperatures until the start of each test day.

Test Matrix

The number of completed tests for this program are shown in the test matrix in Table 6. Originally, the team aimed to conduct 3 repeats for each test condition, but due to delays, inclement weather and instrument failures, fewer repeats were completed for some test conditions. Vehicle 4, in particular, was only tested in winter and only on the RDE route.

Table 6: Test Matrix

Vehicle	COMBOx2		RDE	
	SUMMER	WINTER	SUMMER	WINTER
1	3	3	1	2
2	3	3	1	1
3	3	5	3	0
4	0	0	0	3

Vehicle Heating and Cooling Settings

The vehicle heating, ventilation, and air-conditioning (HVAC) system settings were selected based on the United States Code of Federal Regulations (CFR) Title 40, Part 1066.710 [9], which attempts to simulate typical real-world user behaviour. The temperature set point for both summer and winter was 22°C (72°F) and the fan speed was set to automatic. The fan mode was set to automatic for the summer testing, such that the vehicle would determine which fan outlets to use. In winter, the fan mode was set to “defrost” at the beginning of each test day.

Calculations

Most of the calculation methods used in this report have been adapted from the “SAE J1711 Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles” [10]. However, this recommended practice includes only analysis methods for chassis dynamometer test programs, which use specific and repeated drive cycles. The calculations used in this study are based on the J1711 methods but have been modified to account for the use of on-road test procedures with non-repeated test cycles.

Electrical Energy Consumption (AC and DC)

The direct current (DC) energy (E_{DC}) used by the vehicle (or any of the vehicle’s systems) is the cumulative DC energy measured by the power analyzer over the test. The DC energy consumption (EC_{DC}) is the E_{DC} divided by the distance travelled. The ratio of the overall AC test energy, E_{AC}, (obtained by monitoring the grid energy sent to the vehicle during charging) to the overall test E_{DC} can be used to transform the individual DC values to AC values. This ratio of E_{AC} to E_{DC} is also referred to as the Recharge Allocation Factor (RAF) [11].

For the Daily Operation Comparisons shown in the results section, the RESS Energy refers to the DC energy output from the battery. The AC energy consumption (EC_{AC}) values shown in the comparison tables in the RESS and Thermal Management Electrical Energy Consumption section, however, have been converted to AC values using the RAF.

Fuel Mass Flow Rate

The fuel mass flow rate in grams/s was calculated using the tailpipe emissions of carbon-containing exhaust species and the fuel fraction carbon (FFC). Unfortunately, a separate PEMS module for measuring total hydrocarbon emissions was not available during testing, therefore only emissions of carbon monoxide and carbon dioxide contributed to these carbon-balance calculations. This omission is not expected to have had a large effect on the results as the authors estimate that total hydrocarbons would contribute much less than 1% to the calculated fuel mass flow rate.

Actual Charge Depleting Range (Rcda)

In the SAE J1711 standard, the Actual Charge Depleting Range, or Rcda, is defined as the “estimated distance at which the RESS [Rechargeable Energy Storage System] has exhausted the off-board charged energy” [10]. In other words, this is the point at which the vehicle transitions from charge-depleting (CD) to charge-sustaining (CS) operation. However, the Rcda was designed to be determined by running a repeated test cycle on a chassis dynamometer, and not using on-road driving with variable driving conditions.

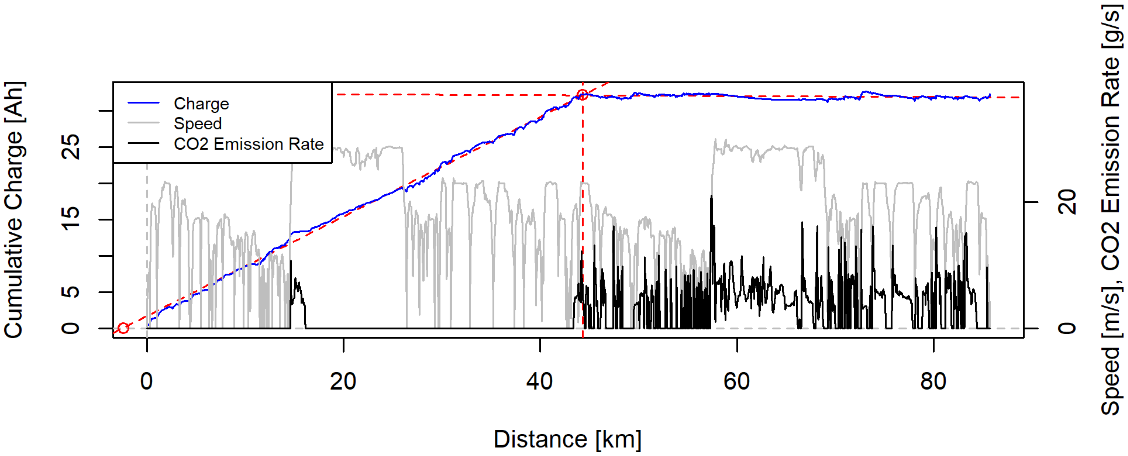

Figure 1: Example modified Rcda determination plot

To allow for the determination of an Rcda in an on-road situation, a modified method of determining this metric has been developed and is illustrated in Figure 1. Figure 1 shows the cumulative electrical charge (in Ah) output from the RESS against the distance traveled by the vehicle, along with the vehicle speed and tailpipe CO_2 emission rate (a proxy for ICE usage) for context.

The dotted red lines in Figure 1 represent linear lines of best fit to the cumulative charge during CD and CS operation. The CD line of best fit takes into account the values that are between 20 and 80 percent of the final cumulative charge for the test day, while the CS line of best fit takes into account any values that are above 98% of the final cumulative charge value. The x-axis value obtained at the intersection of these two lines is considered to be the Rcda of the test. A vertical red dotted line shows the location of this intersection and the associated Rcda value in km at this point on the x-axis.

For the CD line of best fit, the 20% lower limit for cumulative charge values was chosen to avoid including initial CS gasoline engine operation, which tended to occur during start-up of some vehicles in cold weather. It was thought that the inclusion of this operation would have skewed the slope of the line of best fit, leading to artificially long Rcda values. On the other end, the 80% upper limit for the CD line of best fit was chosen to avoid including the transition between CD and CS operation, which is not always sharply defined, in the calculation. Including this transition would also be expected to overly increase the Rcda values. For the purposes of Rcda determination, vehicle CD operation was always considered to start at 0 km even if the intersection of the CD line of best fit did not intersect the x-axis at the zero point.

The electric-only portion of the Rcda was defined as the portion of the Rcda that only the electrical systems were active and the gasoline engine was off, this is denoted in the full results table as $Rcda_{elec}$.

Equivalent All-Electric Range (EAER)

By definition, the All-Electric Range of a PHEV is the distance driven up to the first start-up of its ICE [10]. This is a useful metric for PHEVs that run all-electrically for their entire CD operation, but is not particularly useful for PHEVs that use blended CD operation. The Equivalent All-Electric Range (EAER) was created to quantify the estimated utility of such vehicles [12]. This metric was also designed to be determined using repeated cycles while testing vehicles on a chassis dynamometer. In order to quantify the EAER based on on-road testing, the EAER has been modified to the following form:

$$EAER = R_{cda} * \frac{(FC_{CS,Rcda} - FC_{CD,Rcda})}{FC_{CS,Rcda}} \quad \text{Eq.1}$$

Where $FC_{cs,Rcda}$ is the fuel consumption of the vehicle during CS mode (after having reached the Rcda) and $FC_{CD,Rcda}$ is the fuel consumption of the vehicle during CD mode (before having reached the Rcda).

Using this modified version of the EAER, we can compare the electric operation of vehicles that ran all-electrically to those that used blended operation during CD mode. In winter, additional caution should be taken when interpreting EAER results, however, since the use of electric heating along with the gasoline engine lowered some vehicles' calculated EAER significantly.

Results and Discussion

Test Cycle Statistics

Table 7 shows average test cycle statistics for each of the on-road route segments driven during testing. These average values combine the data for all vehicles in both summer and winter driving conditions. Abbreviations include "C" for COMBO route, "R" for RDE route, and "D" for full-day.

Urban segments have lower average speeds and higher kinetic intensities (kinetic intensity is a calculated cycle metric that attempts to quantify a cycle's potential benefits for vehicle electrification [13]) while highway segments have higher average speeds and lower kinetic intensities. Rural segments have both moderate average speeds and moderate kinetic intensities.

Table 7: Test Cycle Statistics, average of all test days

Cyc	M	Dist [km]	Kinetic Intensity [1/km]	Avg Driving Spd [km/h]	Avg Accel [m/s^2]	Idle Time [%]
C	M1	6.6	0.75	45.0	0.54	25.2
C	M2	5.0	1.06	39.0	0.49	24.7
C	M3	2.7	2.63	25.6	0.51	20.9
C	M4	15.4	0.22	70.7	0.41	14.2
C	M5	13.2	0.50	52.0	0.52	20.8
C	D	85.4	0.43	50.4	0.41	28.1
R	M1	20.6	0.86	42.4	0.49	14.7
R	M2	19.2	0.36	60.6	0.44	13.0
R	M3	37.8	0.07	89.3	0.29	1.1
R	RTB	14.6	0.29	61.3	0.42	12.6
R	D	86.5[1]	0.22	63.1	0.40	14.7

Daily Operation Comparisons

Major differences in operating strategy were observed between different test vehicles and different seasons. The operation of Vehicle 1 on two example test days is shown in Figure 2, contrasting summer and winter operation over the COMBOx2 route. On the left hand side, a summer test shows primarily electric operation for the duration of CD operation (very little fuel flow and low cumulative CO_2 emissions). Conversely, winter operation on the right hand side shows the immediate start-up of the gasoline engine and continued blended gas-electric operation for much of the CD mode. After the marked Rcda transition point, the vehicle ran in CS mode with significant engine operation during both summer and winter tests.

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[1] The average distance for the full-day RDE route is less than the sum of the individual segments because the RTB segment was missed on several occasions during data collection, skewing the daily distance result.

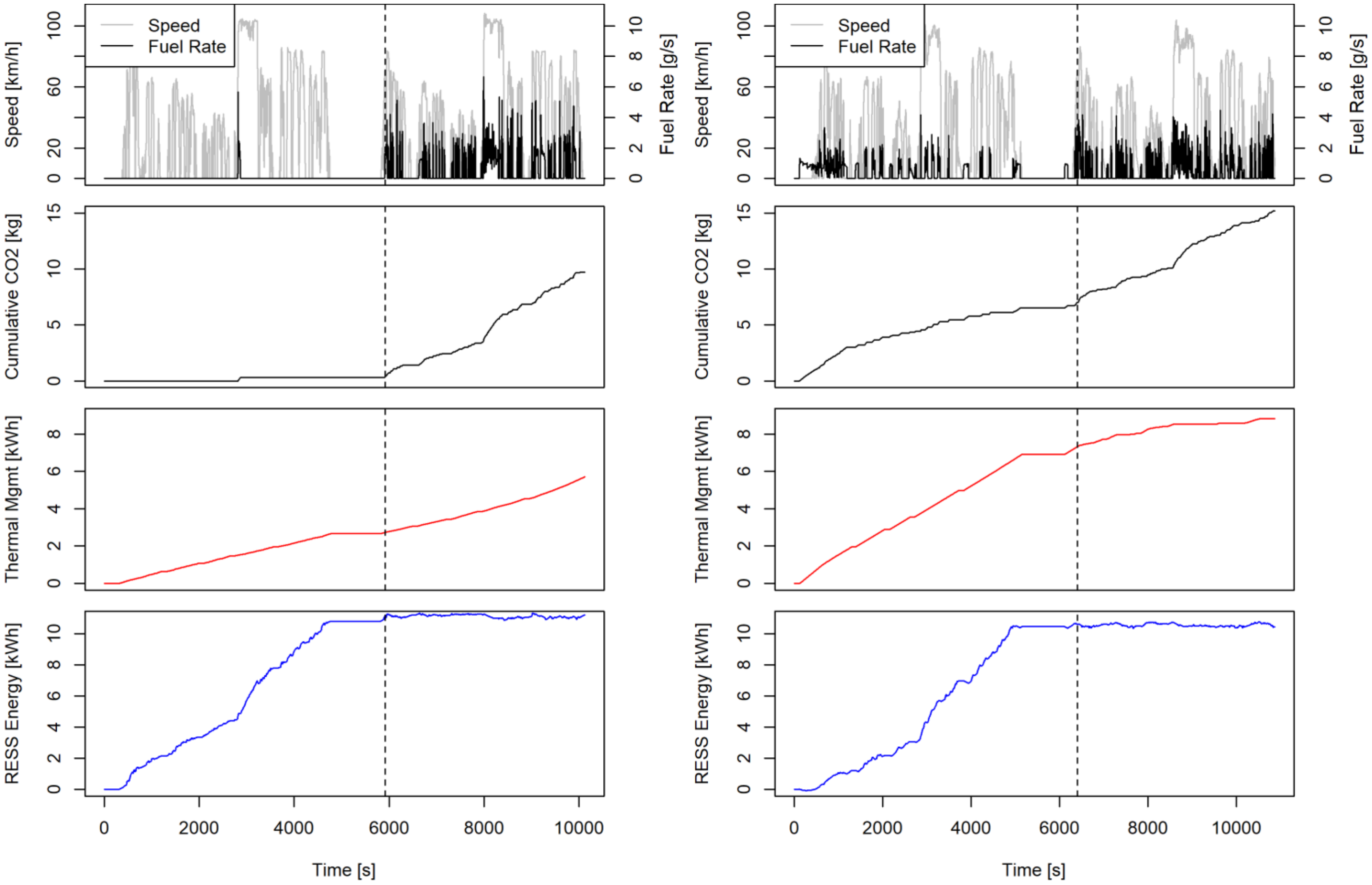

Figure 2: Vehicle 1 COMBOx2 route, summer (left) and winter (right) operation comparison, the dotted line shows the estimated transition point between CD and CS operation, known as the Rcda

The cumulative tailpipe CO_2 emissions for summer testing were minimal during the mostly-electric initial CD mode, while significant CO_2 was emitted during the winter season's blended CD mode. CS mode showed similar CO_2 emissions rates for both seasons (similar slopes of the cumulative emissions lines). Overall, the winter test result shows significantly higher total tailpipe CO_2 emissions at the end of the day.

The thermal management energy consumed during the summer was mostly used for electric A/C operation, with some additional electric coolant heater use during all-electric operation for dehumidification purposes. This electric A/C use continued during CS operation but engine heat was used instead of electric heat for dehumidification. A/C energy consumption increased over the course of the day, likely due to increasing ambient temperatures and potentially higher solar loading.

In winter, most thermal management energy was consumed by the electric coolant heater. Even though the gasoline engine was started at the beginning of this cycle, Vehicle 1 used its electric coolant heater to provide cabin heat in addition to the engine, to warm the vehicle as quickly as possible after the cold start. Vehicle 2 also used a similar heating strategy in winter. Overall, the cumulative amount of energy used for thermal management was higher in winter than in summer.

The RESS energy use in both seasons shows a clear transition between CD and CS operation. The length of time (and distance) spent in CD mode was similar for both the summer and winter tests; however, the vehicle achieved much greater electric operating range (whether considering $\text{Rcda}_{\text{elec}}$, AER or EAER) in summer, running all-electrically for most of the first half of the test day. In winter, the blended hybrid operating strategy and higher thermal management energy requirements reduced this electric-only range.

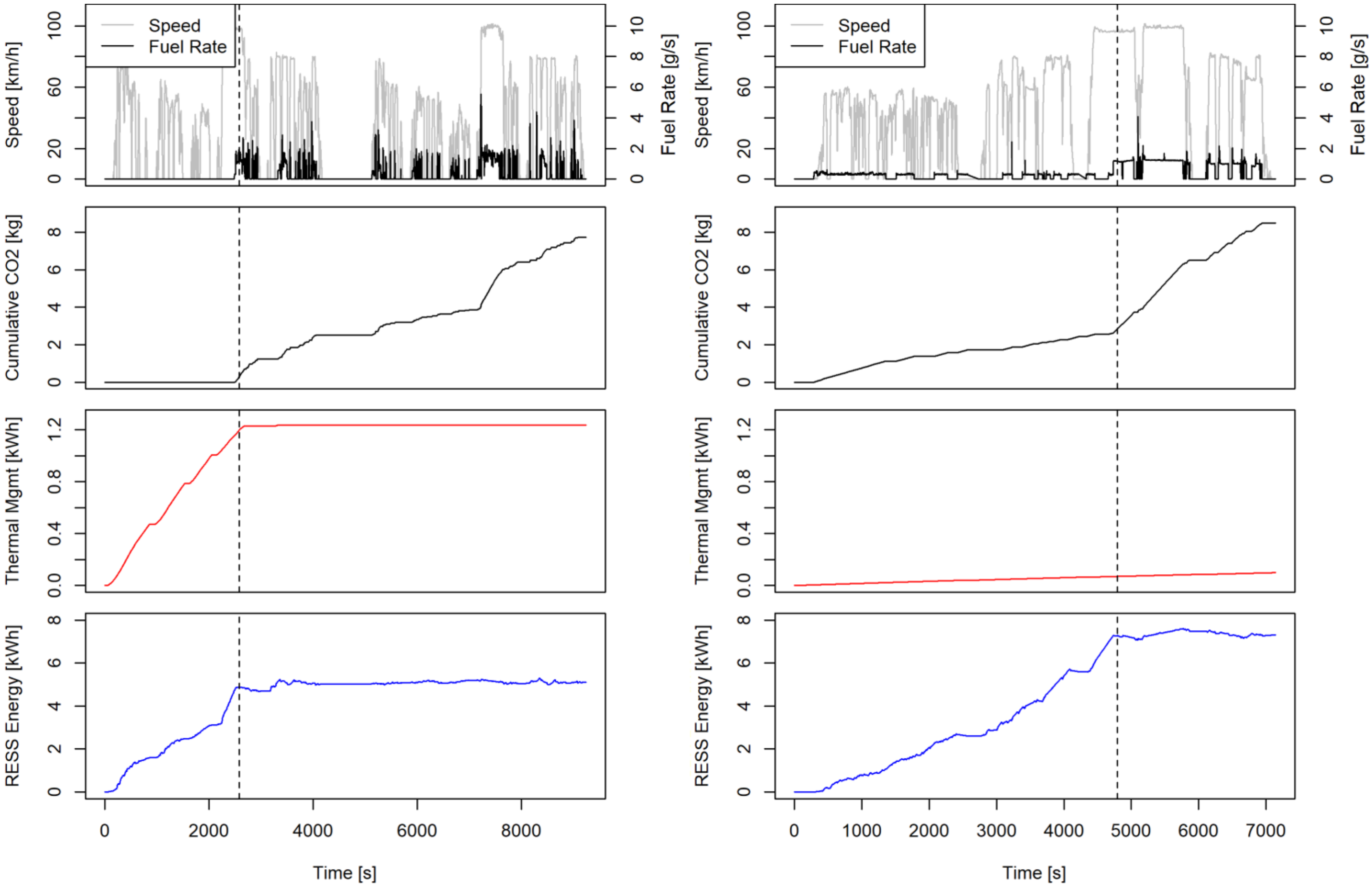

Figure 3: Vehicle 3 COMBOx2 route (left) and Vehicle 4 RDE route (right) winter operation comparison, the dotted line shows the estimated Rcda, the transition point between CD and CS operation

Figure 3 shows a comparison between different vehicles instead of different seasons. A Vehicle 3 winter test day is shown on the left hand side while a Vehicle 4 winter test day is on the right. Unfortunately, these two vehicles completed winter testing on different test cycles (COMBOx2 only for Vehicle 3 and RDE only for Vehicle 4). However, these two test days are compared to show general operational differences rather than exact performance metrics.

One of the most obvious differences between these two tests is that Vehicle 3 used significant amounts of electrical energy for thermal management purposes during CD operation, while Vehicle 4 did not. Vehicle 3 includes a heat pump for cold-weather cabin heating, while Vehicle 4 does not have any electrical cabin heating capability. The small amount of thermal management energy used by Vehicle 4 was due to usage of the A/C compressor, likely for dehumidification.

Vehicle 3 (with its heat pump system) was also able to run fully-electrically for the first portion of the test day. Vehicle 4 (without additional electric cabin heating) started its engine immediately at the start of the test and ran primarily in a low engine power, series-hybrid, blended gas-electric mode during CD operation.

Since Vehicle 4 was using its gasoline engine during CD mode, the Rcda (and the time taken to reach this transition point) was extended compared to if it had operated all-electrically. However, this also resulted in increased CD-mode CO_2 emissions when compared to Vehicle 3. Modeling studies have pointed out that blended gas-electric operation during CD-mode can be effective at reducing overall fuel use and tailpipe CO_2 emissions (similarly to all-electric operation in CD-mode), assuming that the distance driven is sufficient to deplete the battery and obtain the benefit of the stored electrical energy from the RESS [2]. With short-distance trips (less than the Rcda) and frequent charging opportunities, maximizing all-electric operation (as Vehicle 3 does with its heat pump system) would likely lead to lower fuel use and tailpipe CO_2 emissions. Since both test days included significantly longer driving distances than the Rcda ranges of the respective test vehicles, both strategies resulted in similar overall tailpipe CO_2 emissions of about 90 g/km for each test vehicle. Granted, these values were obtained on different test cycles and so are not directly comparable, but do show that the vehicles can obtain similar magnitudes of tailpipe CO_2 emissions values when driven on-road even though they employ significantly different operating strategies.

The electric-only portion of the actual all-electric range ($Rcda_{elec}$) during CD mode on these test days was similar in value for both vehicles even though their operating strategies were completely different. Once the cabin had warmed up sufficiently, Vehicle 4 was able to run all-electrically for short periods. Vehicle 3 exhibited decreased electric-only operating range in winter when compared to its summer operation, mostly due to the higher loads from thermal management systems in winter. Unfortunately, Vehicle 4 was not tested in summer so no comparison was possible.

RESS and Thermal Management Electrical Energy Consumption

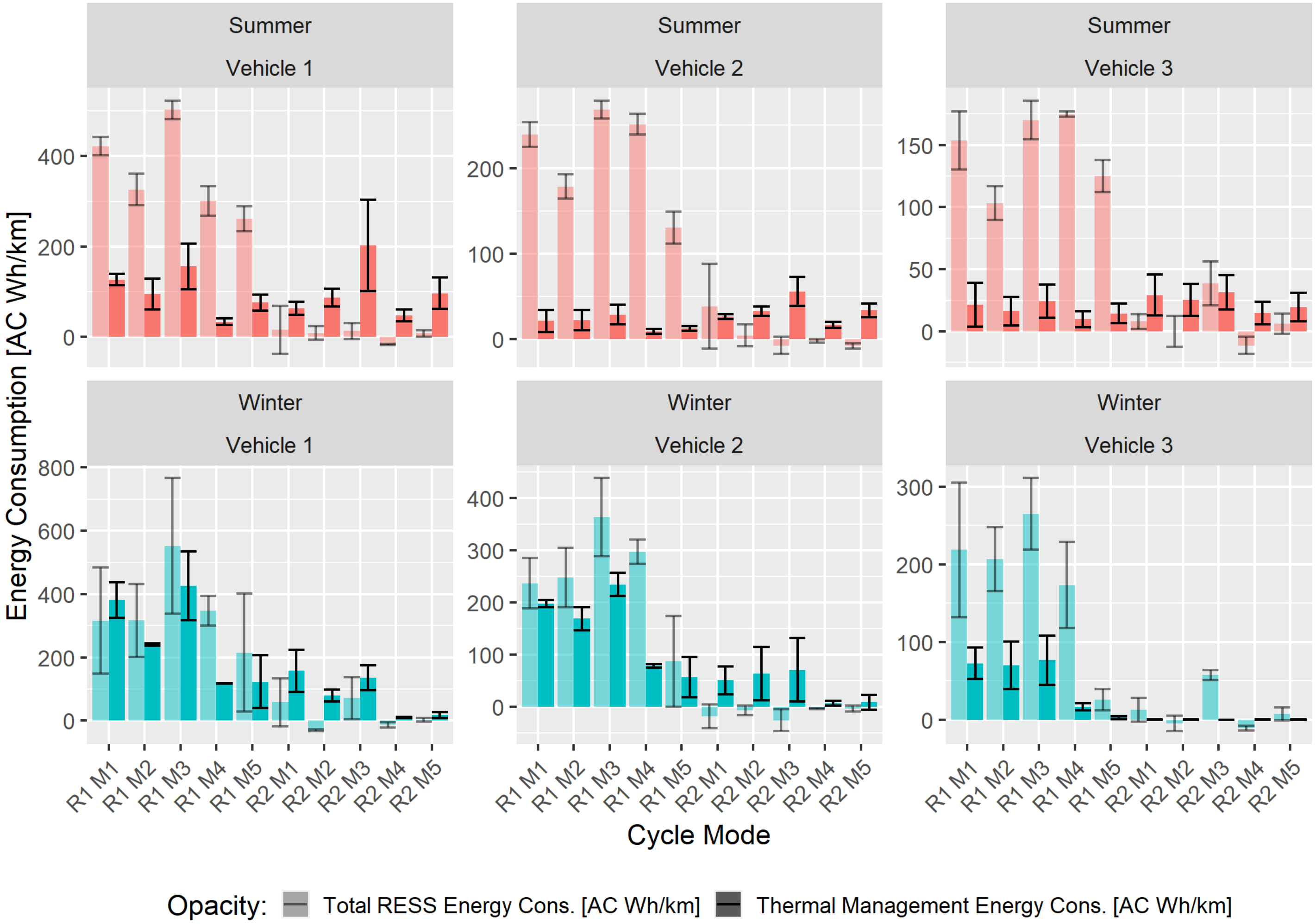

Figure 4: RESS and thermal management electrical energy consumption, vehicles 1, 2, and 3, in summer and winter, Rounds 1 and 2 of the COMBOx2 cycle

The total RESS electrical energy consumption for each vehicle during each test mode of the COMBOx2 cycle is shown in Figure 4, along with the corresponding thermal management energy consumption (both in AC Wh/km). The RESS electrical energy consumption includes all energy in or out of the main battery pack (by convention, negative RESS energy consumption means the battery was charged by the vehicle during the test mode). Thermal management energy can be provided by the main battery or by the electric motors when used as generators during driving and regenerative braking. Since heating or cooling energy need not come directly from the battery, the thermal management electrical energy consumption can be higher than the overall RESS electrical energy consumption of the vehicle. The error bars show the standard deviation of each mean column value.

As expected, total RESS electrical energy consumption for each vehicle was higher during CD operation (first portion of the test day) than during CS operation, in which the overall battery electrical energy consumption is close to zero as the vehicle's propulsion and auxiliary energy come predominantly from gasoline.

As evident in Figure 4, the cabin and battery thermal management loads can lead to significant electrical energy consumption during PHEV operation, especially in winter (when comparing seasons, note that the magnitude of the y-axis scales in the winter charts are about double those for summer due to the differences in test results). In summer, A/C cooling loads were relatively consistent throughout the test day. In contrast, winter electrical heating loads were greatly reduced due to greater engine operation during CS mode (in the latter portion of the test day) since the engine provides waste heat for thermal management purposes.

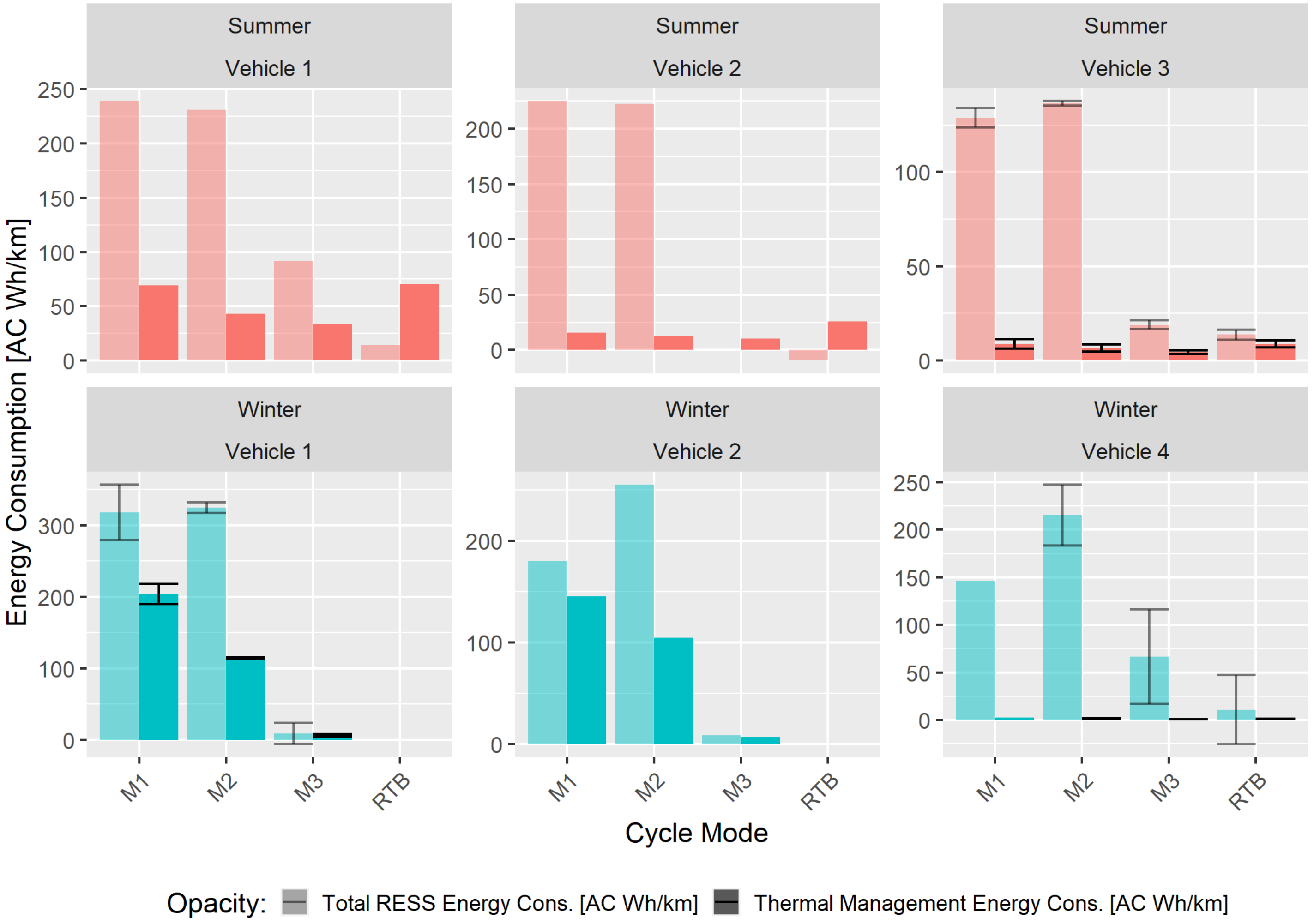

Figure 5: RESS and thermal management energy consumption, vehicles 1, 2, and 3 in summer, vehicles 1, 2, and 4 in winter, RDE cycle

Figure 5 shows the total RESS AC energy consumption of each available test vehicle during each mode of the RDE test cycle in summer and winter, adjacent to the thermal management AC energy consumption for each mode. Similarities to the COMBOx2 cycle results include the fact that the initial electrical cooling loads for Vehicles 1 and 2 in summer were generally lower in value than their electrical heating loads in winter testing. An exception to this trend is Vehicle 4, which does not have an electric cabin heater and so could not use any stored electricity to heat the cabin (thus measuring zero electrical heating loads in winter). The total RESS energy consumption shown for Vehicle 4 was instead made up of a mixture of vehicle propulsion usage and low-voltage accessory usage, with slight A/C compressor usage (for dehumidification purposes).

Vehicle 4 also showed a large amount of variability in its total RESS energy consumption during the test segments. This can be attributed to the different control strategies it employed during different test conditions, as the ambient temperature varied significantly during this vehicle's testing. Out of the three test days completed, two days began with blended CD operation using the gasoline engine in series-hybrid mode to provide additional energy to the electric motors and to provide heat to the cabin directly. The third test day, having a much lower ambient temperature, caused the vehicle to start the test in what appeared to be CS-type operation, maintaining full battery SOC through increased usage of the gasoline engine until the cabin had sufficiently warmed up. Only then did the vehicle start to use CD operation to obtain the full benefit of its stored electrical energy. Unfortunately, data collection errors in mode 1 on two test days caused incomplete results. Therefore, only a single test day's data is shown in the first bar of the graph for Vehicle 4. Tailpipe CO_2 shown for this vehicle in the next section does not have this issue since it was captured by a separate instrument.

Tailpipe CO_2 Emissions

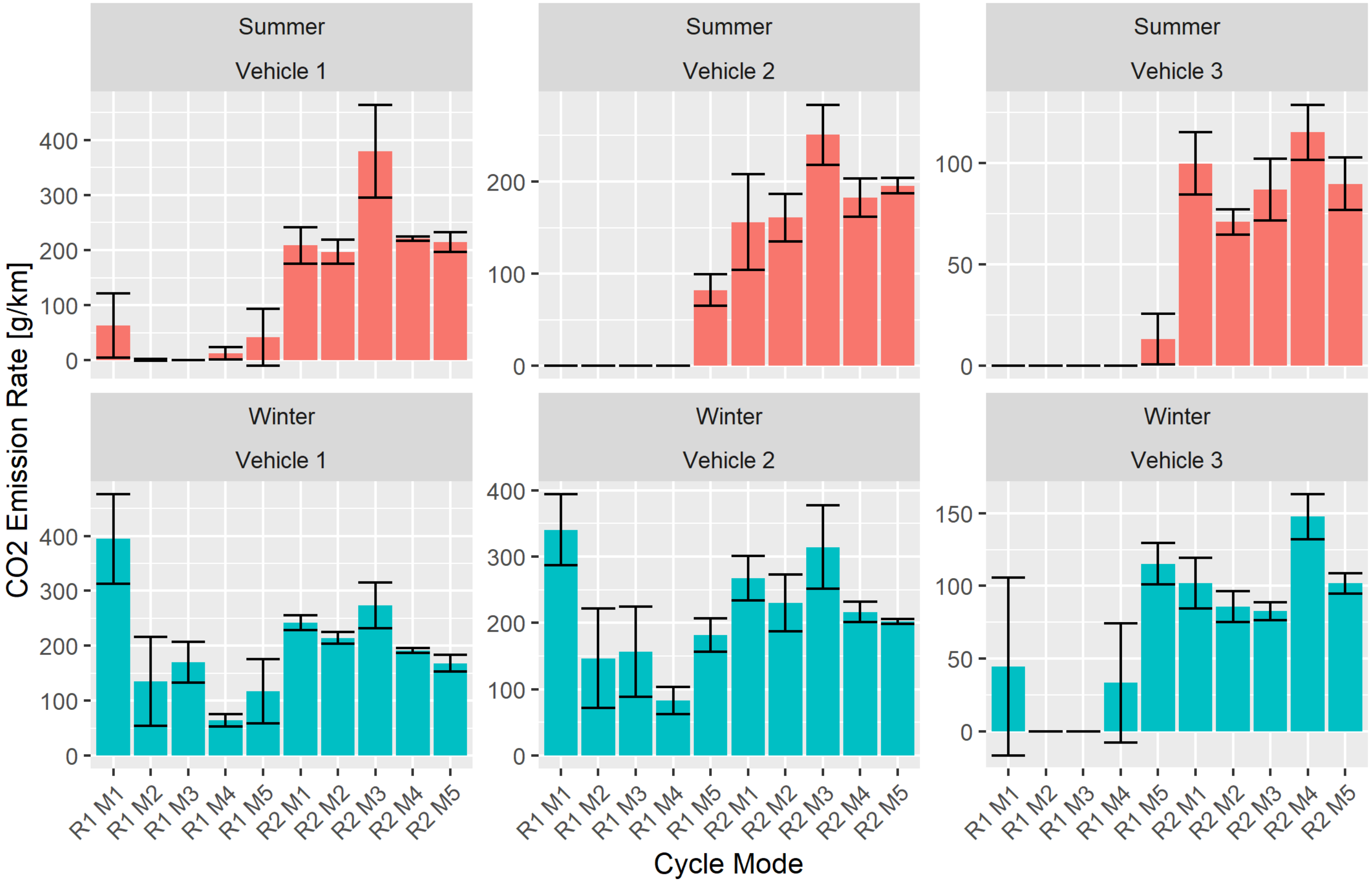

Figure 6: Tailpipe CO_2 emissions rates for each Round and Mode of the COMBOx2 cycle in winter and summer for vehicles 1-3

The CO_2 emission rate of test vehicles 1, 2, and 3 varied depending on the season and test mode, as shown in Figure 6 for the COMBOx2 cycle (note that Vehicle 4 was only tested on the RDE cycle in winter and is shown only in Figure 7). In summer testing, all vehicles were able to operate all-electrically for a significant initial portion of each test day. The minivan (Vehicle 1) did start its ICE at the beginning of some hot summer test days while the SUV (Vehicle 2) and hatchback (Vehicle 3) ran all-electrically on start-up. This led to very low COMBOx2 route tailpipe CO_2 emissions for all tested vehicles in summer. In order to maximize GHG reductions, a low-carbon source of electricity would ideally be used to charge the vehicles. The values shown in Figure 6 do not account for CO_2 emissions from electricity generation or gasoline production.

In wintertime, the CO_2 emissions for the first mode of the COMBOx2 route for vehicles 1 and 2 were very high. This was because the vehicles immediately started their gasoline engines to heat their cabins (which were soaked overnight at ambient temperatures). Vehicle 3 showed a significantly different control strategy, with very low or no tailpipe CO_2 emissions in the first few test modes in winter due to large amounts of all-electric operation. This all-electric operation was likely possible due to the use of the heat pump system and because the smaller hatchback vehicle likely had lower cabin heating loads.

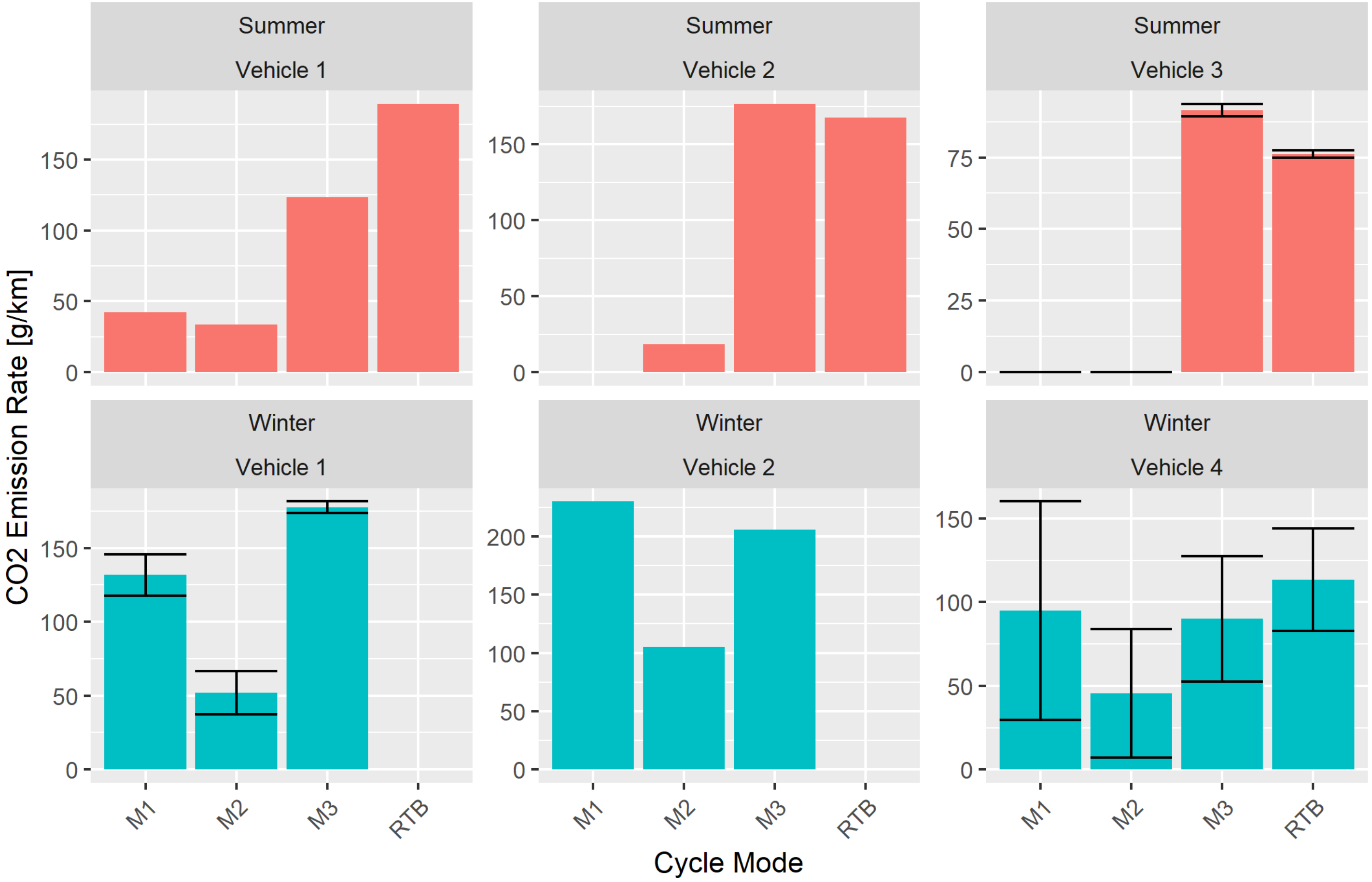

Figure 7: Tailpipe CO_2 emissions rates for each mode of the RDE cycle for vehicles 1, 2, and 3 in summer and for vehicles 1, 2, and 4 in winter

Figure 7 shows the tailpipe CO_2 emissions rate for the available test vehicles over the RDE test cycle (Vehicle 4 was not tested on the RDE in summer while Vehicle 3 did not complete winter RDE testing). Similar trends are visible here when compared to the COMBOx2 cycle. For example, modes 1 and 2 of the RDE cycle showed very low tailpipe CO_2 emissions in the summer for all vehicles. In the winter, Vehicles 1 and 2 once again started their gas engines immediately in order to heat the cabin, while showing lower emissions in the subsequent mode 2 due to additional electric energy usage and lower cabin heating requirements. Vehicle 4 has no electric cabin heating capability, and therefore had to use the gasoline engine to provide all cabin heat required in winter. Vehicle 4 therefore shows high tailpipe CO_2 emissions during RDE M1 when cabin heating requirements were the highest. The CO_2 emissions were lower during M2 when additional electrical energy was blended into operation and cabin heating requirements were lower. Vehicle 4's M3 and RTB CO_2 emissions were higher than M2 due to the vehicle operating mostly in CS mode for these cycles.

There was a high level of variability in the mode-by-mode CO_2 emissions for Vehicle 4. As explained in the previous section, this is because the test day temperatures were significantly different (with an average temperature below -19°C for one day, and greater than +3°C for another test day). In all winter test days, Vehicle 4's engine was started immediately upon starting the test, to heat the cabin. However, in extremely cold weather (-19°C), the vehicle's hybrid system ran in parallel-hybrid mode to start, using the gasoline engine to propel the vehicle and heat the cabin, and thus leading to higher CO_2 emissions in M1. The emissions on this day tapered off significantly in M2 when the vehicle reverted to series-hybrid operation, lowering the average power output of the engine. On moderately cold (-6°C) and warm (3°C plus) test days, the vehicle immediately started the engine but ran in series-hybrid mode upon start-up, lowering ICE power output and CO_2 emissions in M1 compared to the -19°C test day. However, running in low-power series-hybrid mode instead of high-power parallel-hybrid mode on start-up saved less battery energy for propulsion in M2 (thus increasing ICE operation and CO_2 emissions in M2 when compared to the -19°C test day).

Full Results Table

Table 8 is a full results table for each complete test day with the actual charge depleting range (Rcda) and the portion of this driving that was completed without using the gasoline engine ($Rcda_{elec}$). The table also includes the All-Electric Range (AER), the distance driven before the first start of the ICE (which can occur prior to battery depletion due to high accessory demand or high throttle input), and the Equivalent All-Electric Range (EAER). The EAER was estimated using a modified method as described in the Calculations section. The Recharge Allocation Factor (RAF) is the ratio of the AC electrical energy consumed to the DC electrical energy consumed, and was used to convert DC values to AC values for the results in previous sections.

Only one test day is shown for Vehicle 4 since errors in Mode 1 on two of three test days meant that complete daily data was only available for this single test day.

Table 8: Overall Results Table

Vehicle [#]	Cycle Type	Season	Date	Avg Temp [C]	Distance [km]	Rcda [km]	Rcda$_{elec}$ [km]	AER [km]	EAER [km]	RAF [-]	E_{DC} [Wh]	E_{AC} [Wh]
Vehicle 1	Combo	Summer	2019-06-26	20.7	85.7	39.6	38.3	0.0	34.6	1.26	10959	13826
Vehicle 1	Combo	Summer	2019-06-27	30.3	85.8	40.9	38.9	0.0	37.2	1.24	11050	13703
Vehicle 1	Combo	Summer	2019-07-02	32.3	85.7	44.3	41.8	14.6	41.4	1.25	11198	13997
Vehicle 1	Combo	Winter	2020-01-15	2.7	86.6	25.8	22.9	0.0	10.2	1.35	10211	13816
Vehicle 1	Combo	Winter	2020-01-19	-9.1	86.4	44.3	26.1	0.0	6.2	1.30	10436	13597
Vehicle 1	Combo	Winter	2020-01-20	-9.2	86.2	46.4	28.1	0.0	9.4	1.28	10344	13231
Vehicle 1	RDE	Summer	2019-07-05	32.8	92.2	54.7	50.2	0.0	43.3	1.25	10425	13031
Vehicle 1	RDE	Winter	2020-01-21	1.5	77.7	34.7	29.0	0.0	18.9	1.27	10444	13220
Vehicle 1	RDE	Winter	2020-01-22	-0.9	77.7	41.0	30.4	0.0	16.6	1.23	10632	13102
Vehicle 2	Combo	Summer	2019-07-30	27.0	85.7	37.2	36.7	36.7	37.0	1.21	7308	8852
Vehicle 2	Combo	Summer	2019-08-01	27.1	85.6	38.4	38.4	38.8	38.4	1.22	7324	8938
Vehicle 2	Combo	Summer	2019-08-02	27.7	85.7	40.3	40.3	40.5	40.3	1.22	7299	8893
Vehicle 2	Combo	Winter	2019-02-26	-14.6	86.7	36.8	20.7	0.0	10.9	1.29	6880	8882
Vehicle 2	Combo	Winter	2019-03-01	-7.0	88.5	28.2	21.9	0.0	14.1	1.30	6742	8772
Vehicle 2	RDE	Summer	2019-08-06	26.8	92.3	38.8	38.7	38.7	38.8	1.21	7238	8773
Vehicle 2	RDE	Winter	2019-02-27	-15.0	77.7	40.1	20.2	0.0	5.2	1.36	6599	8992
Vehicle 3	Combo	Summer	2019-07-12	22.6	85.7	41.4	41.4	43.2	41.4	1.19	5273	6286
Vehicle 3	Combo	Summer	2019-07-16	28.3	85.6	41.2	40.7	40.7	40.9	1.19	5409	6420
Vehicle 3	Combo	Summer	2019-07-19	31.4	85.7	39.4	39.4	39.7	39.4	1.22	5335	6483
Vehicle 3	Combo	Winter	2019-03-19	-3.8	85.7	22.4	19.2	18.6	18.3	1.23	5121	6314
Vehicle 3	Combo	Winter	2019-03-20	1.6	85.7	31.1	27.3	0.4	23.4	1.20	5380	6456
Vehicle 3	Combo	Winter	2019-03-21	6.0	84.0	33.1	31.6	31.5	27.0	1.19	5208	6172
Vehicle 3	Combo	Winter	2019-03-25	-4.8	85.8	24.2	20.8	20.8	20.5	1.23	5105	6266
Vehicle 3	Combo	Winter	2019-03-26	-4.0	83.2	29.5	26.4	0.5	22.8	1.19	5192	6192
Vehicle 3	RDE	Summer	2019-07-23	25.2	92.3	46.7	44.3	44.3	44.8	1.19	5158	6149
Vehicle 3	RDE	Summer	2019-07-24	24.2	92.3	45.7	43.1	43.1	43.6	1.16	5367	6225
Vehicle 3	RDE	Summer	2019-07-25	26.3	92.3	46.8	44.2	44.2	44.7	1.16	5341	6222
Vehicle 4	RDE	Winter	2020-02-19	-6.3	93.0	51.9	21.5	0.0	30.1	1.18	7301	8648

Conclusions

This project investigated the system operation, thermal management energy consumption, CO_2 emissions, and electric range of four PHEVs on-road in Canadian summer and winter conditions. The test vehicles included a minivan with an electric coolant heater, an SUV with an electric coolant heater, a hatchback with a heat pump system, and a hatchback with no electric-only cabin heating capability. All test vehicles were equipped with electric air-conditioning compressors for cooling in hot weather. Furthermore, all test vehicles were driven on pre-determined routes (one or both of the COMBOx2 and RDE cycles) around the city of Ottawa and started each test with a fully-charged high-voltage battery.

In summer, all vehicles were able to run all-electrically for a significant distance at the start of each test day. They used their electric air-conditioning systems to allow cabin cooling without the use of a belt-driven A/C compressor (which would require the use of the ICE). While operating in all-electric mode, the vehicles emitted no tailpipe CO_2 emissions.

In wintertime, significant initial thermal management loads for Vehicles 1 and 2 (minivan and SUV) caused the immediate start-up of their ICEs. Both engine waste heat and electric coolant heaters were used to heat the cabin as quickly as possible, leading to increased CO_2 emissions and increased thermal management energy consumption for the first portion of each test day. As this initial heating load tapered off with cabin temperatures reaching their set points, these vehicles were able to use stored battery energy to both propel the vehicles and provide additional cabin heating using their electric coolant heaters, until the batteries were depleted. ICE operation was also blended in during CD mode, providing additional heating and propulsion. After switching to CS mode, the electric heating load tapered off since increased ICE waste heat could be used to meet the majority of heating requirements. Using the electrically-powered cabin pre-heating techniques commonly available with plug-in vehicles could significantly decrease the start-up fuel consumption penalty seen when driving these two vehicles in winter, but this was not quantified in this study.

In contrast, Vehicle 3 was able to run in all-electric mode upon start-up on mild and moderately-cold winter days. On colder test days, the ICE started up initially but then quickly stopped, still allowing significant all-electric operation during CD mode. The heat pump system (which can heat more efficiently than a similarly-sized electric resistance heater), the lower heating demands from such a smaller vehicle (compared to Vehicles 1 and 2), and the prioritization of all-electric operation for this vehicle led to its ability to run fully electrically during CD operation in winter. This all-electric CD distance driven in winter was reduced when compared to its summer electric range, in part due to the higher thermal management electrical loads required for heating compared to those for cooling. If driven for short distances and charged frequently from a low-carbon electricity source, the all-electric winter driving capability of this vehicle could lead to significant fuel savings and CO_2 emissions reductions when compared to PHEVs with more blended-type control strategies.

Vehicle 4 was the only vehicle in this study that did not provide any means of heating the cabin using electricity. Therefore, the ICE started whenever cabin heating was required during winter testing. During this time, the ICE was also used to either generate electricity or to propel the vehicle directly while providing cabin heat in either scenario. Depending on driving style, battery state of charge, and ambient conditions, the vehicle automatically used whichever of these hybrid operation strategies (series or parallel) it deemed appropriate. Stored electrical energy from the RESS was used to propel the vehicle and to supply other accessory loads during blended CD operation. ICE heat was also used for cabin heating in CS mode. The initial start-up CO_2 emissions were negatively impacted by the lack of all-electric cabin heating ability, but over distances greater than the Rcda this effect was less significant, as the stored battery energy was eventually fully utilized to assist with propulsion and accessory loads during CD mode instead of for cabin heating. CS mode operation was similar to that of the other test vehicles, with frequent engine use being required to drive the vehicle, and thus waste heat was available for cabin heating in winter CS operation as well. Unlike all the other test vehicles in this study, Vehicle 4 would not be able to benefit from cabin pre-heating while plugged into the electrical grid unless an electric cabin heating method was added to its heating system.

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Acknowledgments

The authors gratefully acknowledge the work of David Buote, Luca Paradiso, Maurice Osbourne, Aidu Qi, and Vinay Sharma of the Emissions Research and Measurement Section of Environment and Climate Change Canada for undertaking the work described in this report. Funding and support for this work was provided by Transport Canada’s ecoTechnology for Vehicles Program, Natural Resources Canada’s Program of Energy Research and Development (Electric Mobility Project EM9), and Environment and Climate Change Canada.

Appendix A: List of Abbreviations

AC – Alternating Current (electricity)
A/C – Air Conditioning
AER – All-Electric Range
BEV – Battery Electric Vehicle
CD – Charge-Depleting
COMBO – Driving route around the city of Ottawa, starting and ending at the ERMS facility
COMBOx2 – Daily route consisting of twice the COMBO driving route
CFR – Code of Federal Regulations of the United States of America
CPN – Condensation Particle Number counter
CS – Charge-Sustaining
DC – Direct Current (electricity)
E_{AC} – Alternating Current Energy
EAER – Equivalent All-Electric Range
EC_{AC} – Alternating Current Energy Consumption
EC_{DC} – Direct Current Energy Consumption
ECCC – Environment and Climate Change Canada
E_{DC} – Direct Current Energy
EFM – Exhaust Flow Meter
ERMS – Emissions Research and Measurement Section (of Environment and Climate Change Canada)
EVSE – Electric Vehicle Supply Equipment
FC – Fuel Consumption
FFC – Fuel Fraction Carbon
GDI – Gasoline Direct Injection
HEV – Hybrid Electric Vehicle
HVAC – Heating, Ventilation, and Air Conditioning
ICE – Internal Combustion Engine
ICEV – Internal Combustion Engine Vehicle
M# – Mode (Modes 1-5 for the COMBO route and 1-3 for the RDE route)
NHV – Net Heating Value of a test fuel
PEMS – Portable Emissions Measurement System
PFI – Port Fuel Injection
PHEV – Plug-in Hybrid Electric Vehicle
PTC – Positive Temperature Coefficient (a type of heater sometimes used for vehicle cabin heating)
R1 or R2 – Round 1 or Round 2, of the COMBOx2 route
RAF – Recharge Allocation Factor
Rcda – Actual Charge-Depleting Range
$Rcda_{elec}$ – Electric-only portion of the Rcda
RDE – Real Driving Emissions (in this work, this refers to a test route modeled on the Euro VI on-road driving test procedure)
RESS – Rechargeable Energy Storage System (in this work, this refers to the vehicle’s main traction battery)
RTB – Return-to-Base (in this work, this refers to an additional Mode added to the RDE route)
SAE – Society of Automotive Engineers
SOC – State of Charge (of the RESS)
SUV – Sport Utility Vehicle