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Tailpipe Emissions of a Plug-in Hybrid Electric Vehicle in Cold Climate

H. Abediasl*, C.R. Koch and M. Shahbakhti

Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

Abstract

The transition to electrified powertrains, including hybrid and plug-in hybrid electric vehicles, requires a thorough understanding of their tailpipe emissions, especially in cold climates. Under low ambient temperatures, the energy consumption of these vehicles increases due to additional energy demands for battery thermal conditioning and cabin heating, contributing to higher tailpipe emissions. In this study, a plug-in hybrid electric vehicle (PHEV) was tested in real-world driving conditions on a 20 km route, covering both urban and highway areas in Edmonton, Canada. The vehicle was tested 107 times across two operational modes—charge-depleting and charge-sustaining—at ambient temperatures ranging from −25°C to 29°C. During the tests, vehicle operating parameters and energy consumption were recorded. In addition, a portable emissions measurement system (PEMS) was installed to measure tailpipe emissions of a test in charge-sustaining mode that relies mainly on the internal combustion engine.

The cold phase occurred before the engine coolant reached its warmed-up condition. This phase lasted only the first 300 seconds of the 40-minute trip. Despite its short duration, it accounted for 65% of NOx, 62% of CO, and 98% of unburned hydrocarbons (UHC) during a test conducted at the ambient temperature of −5°C. Moreover, at least 80% of these emissions occurred before the aftertreatment system reached its light-off temperature, emphasizing that cold operation of both the engine and aftertreatment system is the primary driver of tailpipe emissions. In charge-sustaining mode, lowering the ambient temperature from 28°C to −25°C increased the distance traveled with the engine on by 65%, due to higher energy demands. In charge-depleting mode, the engine remained mostly off at ambient temperatures above zero. However, at −23°C, up to 45% of the trip required engine involvement.

1 Introduction

Road transportation emissions are significantly influenced by ambient temperature, with emissions increasing in cold ambient conditions [1]. With recent advancements in powertrain electrification and the growing popularity of plug-in hybrid electric vehicles (PHEVs), the effect of cold climates on their performance, particularly in terms of emissions, needs to be studied in detail [2, 3]. PHEVs are equipped with both an internal combustion engine (ICE) and an electric battery and motor for powering the vehicle. They typically operate in either charge-sustaining or charge-depleting modes. In charge-sustaining mode, both the ICE and electric motor are involved in powering the vehicle while maintaining the battery state-of-charge (SOC) at a set level, with the ICE turning on and off intermittently. In charge-depleting mode, the vehicle prioritizes electric power and switches to the ICE when additional power is required or when the electric range becomes minimal [4]. In PHEVs, low ambient temperatures affect both the ICE and the electric powertrain, leading to higher energy consumption and contributing to increased tailpipe emissions. Laboratory testing in [5] revealed that PHEVs experience higher emissions and energy consumption in −7°C comapred to that in 23°C, to the extent that they can emit similar or even higher levels of pollutants than Euro 6 ICE vehicles under cold conditions.

Due to the strong dependency of vehicle operation on the driving cycle, real-world experimental results are more important compared to laboratory testing under standard drive cycles [6]. This shift has led to the incorporation of real-driving emissions (RDE) testing into standard vehicle emissions assessment procedures [7]. On-road testing of the Chevrolet Volt under extreme cold conditions (as low as −27°C) showed a 20–30%

*Corresponding author: abediasl@ualberta.ca

increase in fuel consumption in charge-sustaining mode compared to normal ambient conditions. In charge-depleting mode, electricity consumption increased by approximately 50% for highway driving and 100% for city driving at around 0°C [8]. Another real-world study on PHEVs operating in both charge-depleting and charge-sustaining modes showed that low ambient temperatures significantly increased energy consumption, with a more substantial rise in the charge-depleting mode. Specifically, reducing the ambient temperature from 28°C to −24°C led to a 350% increase in energy consumption in charge-depleting mode and an 85% increase in charge-sustaining mode [9]. While previous studies lacked tailpipe emission measurements, one study conducted on a PHEV in above-zero ambient temperatures measured tailpipe NOx emissions and found that they were primarily driven by the cold start emission peak during the initial activation of ICE, while the trip-average NOx emission factors remained at negligible levels [10].

The literature review reveals a gap in real-world experimental studies investigating the tailpipe emissions of PHEVs under cold climate conditions, particularly with a detailed focus on the cold phase of vehicle operation. To address this knowledge gap, the present study conducts real-world driving tests of a PHEV across a wide range of ambient temperatures from −25°C to 29°C. The study provides an experimental analysis of emissions, energy consumption, and key vehicle and aftertreatment system parameters.

2 Methodology

2.1 Test Vehicle and Driving Route

A 2021 Ford Escape PHEV (Fig. 1.a) was selected for this study due to its capability to operate under different powertrain modes involving both an ICE and an electric motor. The focus is on hybrid electric operation in two modes: charge-sustaining and charge-depleting. The vehicle was powered by a 123 kW ICE, and was capable of delivering maximum total power (ICE and electric motor) of 149 kW. The vehicle was equipped with a 14.4 kWh lithium-ion battery.

(a) (b)

Fig. 1: Experimental setup: a) Test vehicle used in this study, equipped with PEMS for tailpipe emission measurement; b) The 20 km driving route, comprising both urban and highway areas.

A test route was selected to cover various driving conditions (Fig. 1.b). This 20 km route typically took about 35 to 40 min to drive. Each round of driving the vehicle on this route was denoted as a "test" in this study. The drive cycle distance (20 km) was less than the PHEV charge-depletion range (61 km @ T_{amb} range from 20°C to 30°C). For consistency, all tests were began with the initial SOC of 77 ± 1%, and the cabin HVAC setting was constantly set to 25°C, and the fan speed was set to the second speed level. A total of 107 tests were conducted along the test route under varying ambient temperatures ranging from −25°C to 29°C, including 59 in the charge-sustaining mode and 48 in the charge-depleting mode.

2.2 Data Collection Setup

A CSS Electronics CANedge2 controller area network (CAN) data logger was used to collect data from the vehicle's on-board diagnostics (OBD) port, providing access to various telematics parameters. Additionally, in one of the tests conducted at an ambient temperature of −5°C, tailpipe emissions were measured using GlobalMRV Axion R/S portable emissions measurement system (PEMS). This device sampled emissions directly from the tailpipe at a rate of 1 Hz, capturing the concentrations of key gaseous pollutants, including CO_2, O_2, CO, NO, and unburned hydrocarbons (UHC). Each of these emission species concentrations was measured within an accuracy of 0.3%, 0.02%, 0.02%, 8 ppm and 25 ppm, respectively. The emission concentrations were then converted to mass flow rates using the exhaust flow rate data obtained from the OBD system.

3 Results and Discussion

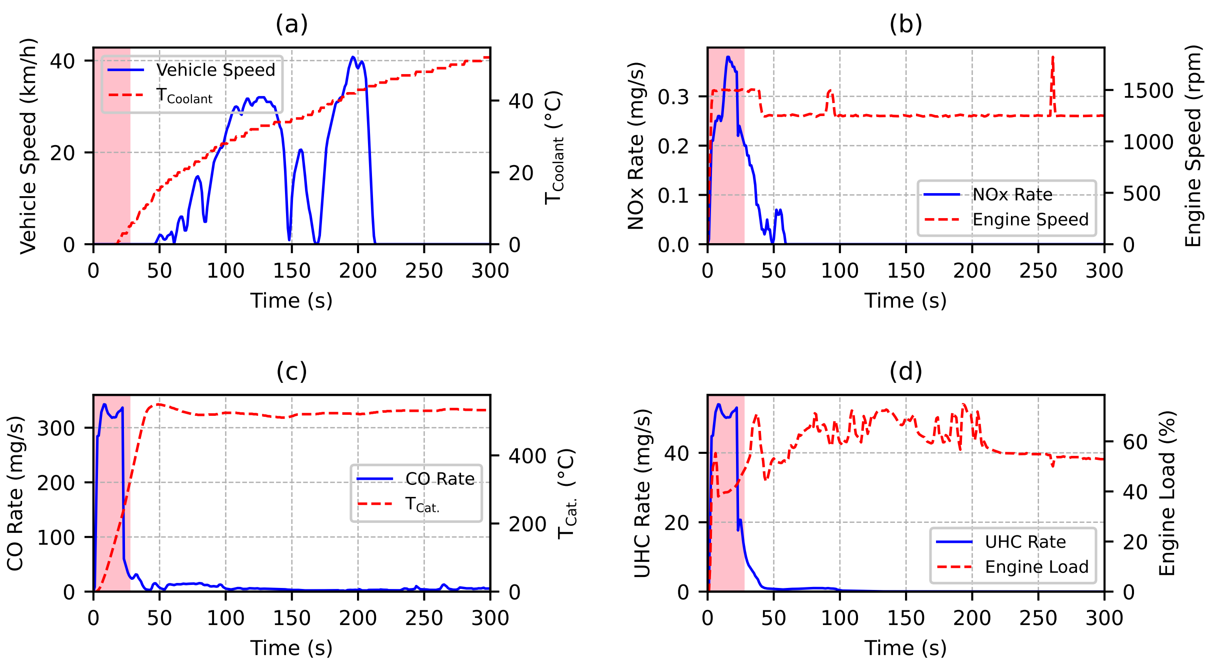


Fig. 2: Time-series of different vehicle parameters and emission rates, during cold phase of operation: a) vehicle speed and engine coolant temperature ($T_{Coolant}$), b) NOx rate and engine speed, c) CO rate and three-way catalyst temperature ($T_{Cat.}$), d) UHC rate and engine load. The shaded area at the beginning of the trip represents the light-off period. The vehicle operates in charge-sustaining mode at an ambient temperature of −5°C.

Fig. 2 presents the time series of emission rates and vehicle parameters during the first 300 seconds of operation. The vehicle operation before the engine coolant temperature ($T_{Coolant}$) reaches 70°C is often considered the cold phase period of operation [11]. As shown in Fig. 2.a and Fig. 2.c, both $T_{Coolant}$ and catalyst temperature ($T_{Cat.}$) rose during this phase, with $T_{Cat.}$ increasing more rapidly and reaching a steady-state temperature within the first 50 seconds. Aftertreatment systems require a minimum activation threshold—known as the light-off temperature (typically around 300°C)—to become effective [12]. The light-off region is shaded in Fig. 2, highlighting a period of elevated emission rates due to the inactivity of the aftertreatment system before $T_{Cat.}$ reaches 300°C. Even after light-off, emissions remained slightly elevated compared to the fully warmed-up condition, as the engine was still operating below its optimal temperature ($T_{Coolant}$ <70°C).

Even though the vehicle operated in hybrid electric mode, where the engine could turn off during idling, the engine remained on throughout the entire cold phase of operation, as shown in Fig. 2.b. During this phase, the engine mostly operated at a constant speed, known as the idling speed, which helped the engine and aftertreatment system warm up more quickly. This reduced excess emissions during the cold phase and light-off period. At the beginning of the cold phase operation (i.e., light-off condition), the engine idling speed was slightly higher (1500 rpm versus 1250 rpm) to provide more thermal energy for the aftertreatment system, facilitating a faster warm-up.

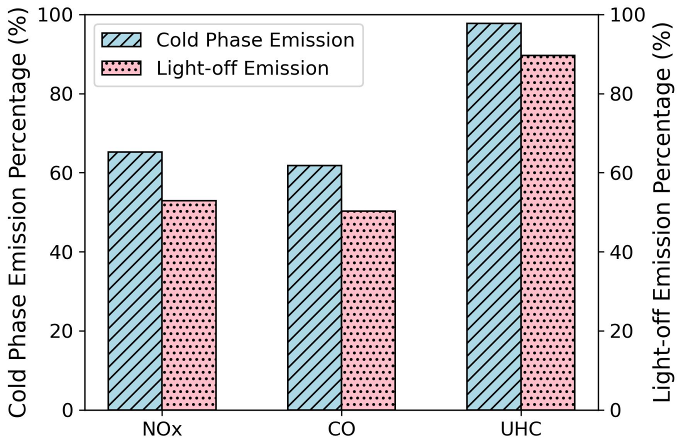
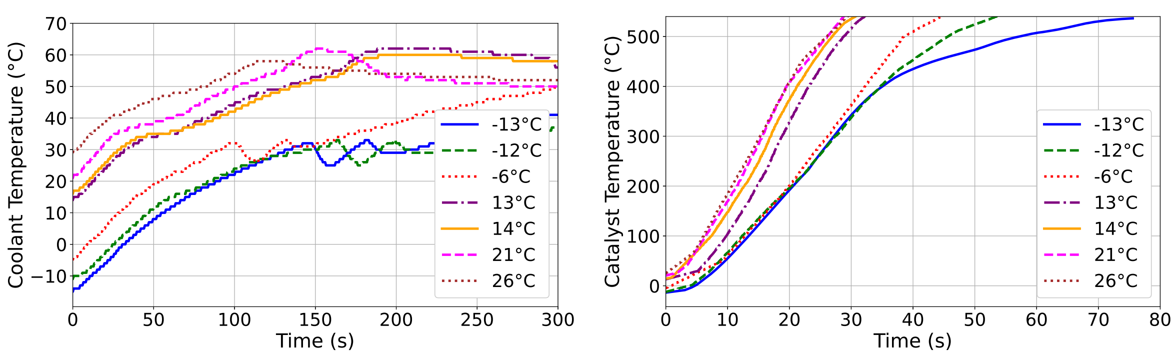


Fig. 3: The percentage of emissions during cold phase operation and catalyst light-off period, as observed in the specified drive cycle of this study. The vehicle operates in charge-sustaining mode, with an ambient temperature of $-5°C$.

Cold phase operation, where the engine and aftertreatment system operated at suboptimal efficiency, and particularly the light-off condition, where the $T_{Coolant}$ was below light-off temperature, accounted for a considerable share of emissions. This was more significant in hybrid electric operations, because during the warmed-up phase, the engine could even turn off, reducing emissions during that phase. However, in the cold phase, the engine remained on and continued emitting before reaching its optimal operating temperature. Fig. 3 shows the emission percentage in the cold phase and light-off condition for each of the NOx, CO, and UHC emissions. It can be seen that during the test drive cycle, at least 60% of the emissions occurred in the cold phase, and at least 50% were in the light-off condition. Notably, out of 40 minutes of testing, only 300 seconds were spent in the cold phase, and the light-off condition lasted for just the first 27 seconds.



(a)

(b)

Fig. 4: Vehicle warm-up in charge-sustaining mode at different ambient temperatures: a) Coolant temperature during the cold phase, b) Catalyst temperature during light-off time.

As noted earlier, the energy management system of hybrid electric powertrains uses the engine operation to facilitate warm-up, allowing the engine and aftertreatment system to reach their optimal operating temperatures as quickly as possible. Ambient temperature affects the warm-up time for both the engine and aftertreatment system, causing $T_{Coolant}$ and $T_{Cat.}$ to reach their optimal temperatures over a longer duration in colder ambient temperatures. Fig. 4.a shows the coolant warm-up process for different ambient temperatures during the cold phase of operation. It was observed that at an ambient temperature of $-13°C$, $T_{Coolant}$ after 300 seconds was around 40°C, while at an ambient temperature of 26°C, $T_{Coolant}$ reached around 60°C in about 120 seconds. Additionally, Fig. 4.b shows that the $T_{Cat.}$ light-off time nearly doubles at an ambient temperature of $-13°C$ compared to 26°C. This extended warm-up duration for both the engine and aftertreatment system results in higher emissions during the cold phase of operation as the ambient temperature decreases.

In addition to higher cold phase emissions in electrified powertrains in cold climate, the warm-up emissions are also affected by the ambient temperature and increased in low ambient temperatures. This is primarily because in both charge-sustaining and charge-depleting modes, the use of ICE is increased in lower ambient temperatures. The higher use of ICE is justified to provide additional energy needed for cabin heating as well as other additional required power in cold climate such as battery thermal conditioning. Fig. 5 shows the percentage of distance traveled with ICE on in different tests in different ambient temperatures. In charge-sustaining mode, at ambient temperatures above $-20°C$ where little to no cabin heating is needed—about 30% of the distance is traveled with the ICE on. As the ambient temperature drops, this percentage consistently increases due to higher energy demand. At $-25°C$, more than 90% of the distance is powered by the ICE. In charge-depleting mode, ICE involvement is minimal at temperatures above zero. It is only occasionally required during short bursts of high power demand. However, in subzero temperatures, the percentage of distance traveled with ICE on increases significantly. In some tests, up to 45% of the trip was powered with the engine on. More ICE involvement, leads to higher tailpipe emissions during the trip.

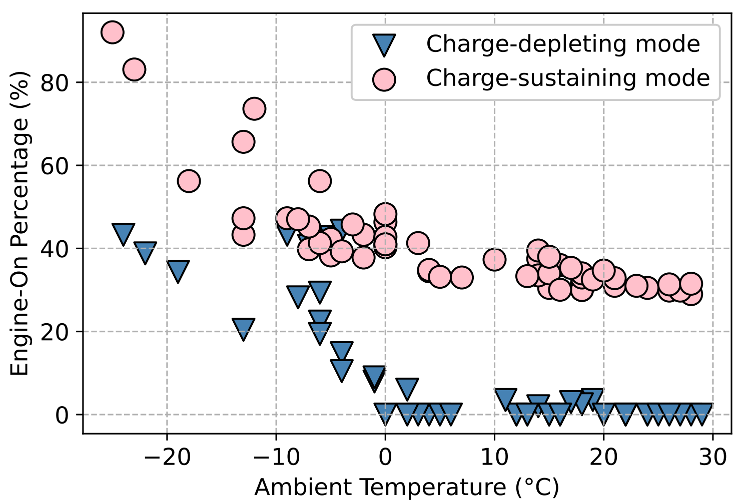


Fig. 5: Percentage of distance traveled with the engine on in charge-sustaining and charge-depleting modes across a range of ambient temperatures.

In addition to the cabin heating demand, another key reason for increased ICE engagement is the need to maintain coolant and aftertreatment system temperatures above critical thresholds to prevent excessive emissions. As illustrated in Fig. 6, the engine turns on frequently (indicated by spikes in engine load) to prevent the coolant and catalyst temperatures from falling below these thresholds.

4 Conclusion

A plug-in hybrid electric vehicle was tested across a wide range of ambient temperatures on a designated route. Energy consumption and other vehicle operational data were collected, along with real-driving tailpipe emissions. Effects of cold climates on emissions, with a specific focus on emissions during the cold phase of operation were investigated.

During the cold phase of operation (i.e., the first 300 seconds), when the engine coolant temperature is below optimal, the majority of tailpipe emissions—at least 60%—were produced. Moreover, at least 50% of the tailpipe emissions were emitted before the aftertreatment system reached its optimal temperature (i.e., 300°C).

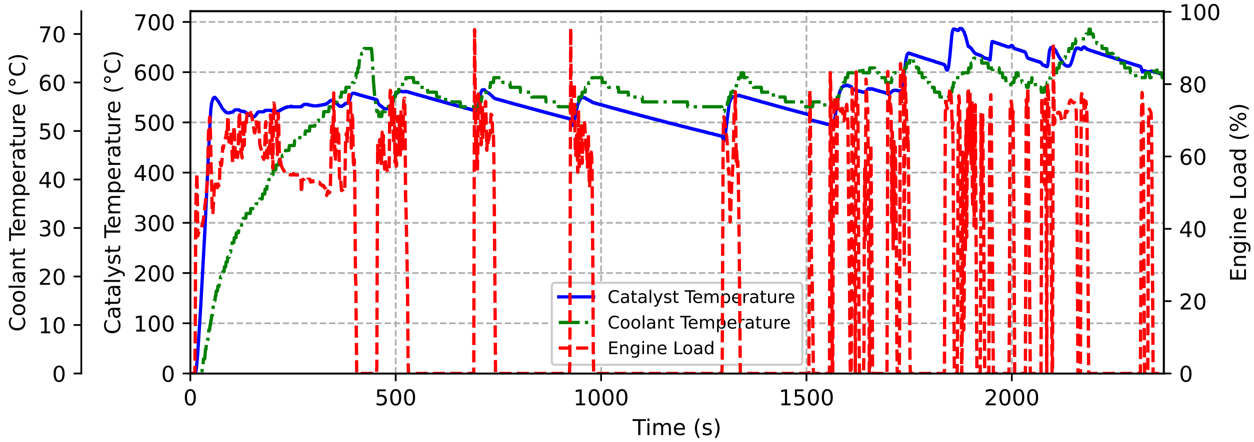


Fig. 6: Time-series of coolant temperature, catalyst temperature, and engine load for a whole trip. The vehicle operates in charge-sustaining mode at an ambient temperature of $-5°C$.

This highlighted that the warm-up period of the vehicle is the primary contributor of tailpipe emissions. The warm-up period for both the engine and aftertreatment system increased in low ambient temperatures. For example, the aftertreatment light-off period doubles when the ambient temperature decreases from $26°C$ to $-13°C$. In addition to cold phase emissions, cold climate also affects tailpipe emissions in electrified powertrains by increasing the involvement of the internal combustion engine to power the vehicle. In charge-sustaining mode, the distance traveled with the engine on increased by 65% when the temperature dropped from $28°C$ to $-25°C$. Even in charge-depleting mode, in which the vehicle primarily relies on its electric battery for power, nearly half of the trip required engine involvement at an ambient temperature of $-23°C$.

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