Effect of Low Ambient Temperature on Fuel Consumption and Emissions of Hybrid Electric Vehicles in Real-World Conditions

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Abstract

Hybrid electric vehicles (HEVs) can potentially reduce vehicle fuel consumption and CO_2 emissions by using recuperated kinetic vehicle energy stored as electric energy in a hybrid system battery (HSB). Low ambient temperatures can affect the overall HEV powertrain operation under warm-up and hot driving conditions and, consequently, affect fuel consumption and emission performance. The present study investigates the influence of low ambient temperatures on HEV fuel consumption and pollutant and CO_2 emissions for five in-use HEV models. Chassis dynamometer measurements have been conducted at different set ambient temperatures using a real-world driving cycle suitable for investigating vehicle cold-start emissions. The main observation is that the amount of HEV cold-start extra emissions (CSEEs) of regulated pollutants are reduced by 30% to 85% on average in comparison to sample CSEEs of conventional gasoline vehicles. The results for HEV CSEEs of CO_2 and fuel consumption are mainly similar to those of conventional gasoline vehicles except for CSEEs of some HEVs at the ambient temperature of 23°C. There, increased CSEEs are observed that exceed maximum sample CSEEs of conventional gasoline vehicles, reaching values for CO_2 between 155 [g/start] and 300 [g/start] even though the test runs were initiated with maximum initial state of charge (SOC) of the HSB. Because SOC of the HSB considerably influences the fuel consumption of HEVs, this aspect should be further investigated in regard to the effect of low ambient temperatures on HEV fuel consumption and CO_2 emissions. Moreover, no particular influence of low ambient temperatures on HSB performance was observed during hot-phase operation.

Introduction

Hybrid electric vehicles (HEVs) represent a promising approach to reduce vehicle fuel consumption and exhaust emissions of CO_2. An additional electric powertrain including an energy storage device, typically a rechargeable battery or super capacitors, is combined with an internal combustion engine to provide the desired overall vehicle power output. This configuration makes it possible to design and employ the internal combustion engine in its most efficient operating conditions and to recuperate kinetic vehicle energy during deceleration for further use, which leads to reduced overall CO_2 vehicle emissions (Sundström, 2009, Sundström et al., 2010, Sundström et al., 2008). Initial studies have already been conducted to determine the real-world pollutant emission performance of HEVs (Fontaras et al., 2008).

In general, emissions during cold start become particularly relevant in comparison to hot emissions for modern vehicles with state-of-the art aftertreatment systems, especially for low ambient temperatures (Weilenmann et al., 2009). The time elapsed until hot operation of both the aftertreatment system and the powertrain is achieved determines the cold-start extra emissions (CSEEs) of the vehicle. The specific attribute of HEV powertrains of providing electrical assistance to the combustion engine can therefore influence this heating-up and the resulting HEV CSEEs, particularly in the case of full HEVs because of the possibly intermittent operation of its combustion engine. Furthermore, the operational performance of the hybrid system battery (HSB) employed in HEV powertrains may be affected by low ambient temperatures, which can also lead to increased fuel consumption and CO_2 emissions. In this regard, field tests to investigate the real-world fuel economy of HEVs and PHEVs in low ambient temperature conditions have already been conducted (Laurikko and Pellikka, 2010), and the results show that important fuel savings can be achieved with such vehicles at low ambient temperatures depending on their layout and operation.

Methodology

Testing

The main characteristics of the five in-use HEV models selected for the test series are summarized in Table 1. HEVs 1 to 3 represent three identical examples of a single HEV model (Danisch and Goppelt, 2004) with different mileages. All of the HEVs used in this study are categorized as full hybrids except HEV 5, which is a mild hybrid (not capable of full electric driving).

Table 1: Main characteristics of the considered vehicle sample. cert.: certification; cat.: category; IC: internal combustion; HSB: hybrid system battery; nom.: nominal; no.: number.

characteristic			HEV 1	HEV 2	HEV 3	HEV 4	HEV 5
vehicle	make	[-]	Toyota			Toyota	Honda
	model		Prius II			GS450h	Insight
	inertia	[kg]	1425			2030	1301
	gearbox	[-]	CVT			CVT	CVT
	cert. cat.	[-]	Euro-4			Euro-4	Euro-5
	1st cert.	[-]	Feb 06	Aug 06	Jun 05	Feb 07	May 09
	mileage	[km]	32768	60761	104266	22335	2756
IC engine	displacement	[cm^3]	1497			3456	1339
	rated power	[kW]	57			218	65
electric motor	rated power	[kW]	50			147	10
HSB	type	[-]	NiMH			NiMH	NiMH
	nom. voltage	[V]	201.6			288	100
	no. of cells	[-]	168			240	84
level of hybridization		[-]	full			full	mild

The repetitive cold-start real-world driving cycle Inrets Urbain Fluid Court (IUFC15) was used for this investigation. This cycle consists of 15 repetitions of a short representative European real-world urban driving pattern (sub-cycles) (Joumard et al., 2007, Andre, 2004). This enables the acquisition of pollutant emissions for each sub-cycle during warm-up and additionally ensures that enough hot-phase sub-cycle repetitions are carried out to derive representative average hot stabilized emissions (Weilenmann et al., 2009, Favez et al., 2009).

Single test runs have been executed at ambient temperatures of 23°C, 8°C and -7°C for each HEV after soak times of more than 12 hours. The HEVs were preconditioned to the maximum initial state of charge (SOC) of their HSBs, defined by having no additional charge leading to the HSB in constant-speed vehicle traction mode, which simulates coasting conditions. This start-up SOC configuration of the HSB avoids any HSB recharging process by the combustion engine during vehicle cold start and, consequently, considerable additional CO_2 emissions that would distort the envisaged CSEE estimation for HEVs (Alvarez et al., 2010). In such vehicle cold start conditions, the operation of the combustion engine of HEVs is only adjusted to additionally heat up the powertrain and aftertreatment system, making its operational demand most comparable to conventional vehicles. Furthermore, the air conditioning systems of the HEVs were turned off during the test runs because its operation considerably affects fuel consumption and CO_2 emissions (Alvarez et al., 2010, Fontaras et al., 2008).

Exhaust emissions of regulated pollutants and CO_2 were measured according to the statutory procedure specified in Council Directive 70/220/EEC. Time-resolved measurements of raw exhaust pollutant and CO_2 emissions were also performed, using adequate exhaust gas analyzers as specified by Council Directive 70/220/EEC. The fuel consumption was then calculated from the measured emissions of regulated pollutants. The time-resolved HSB wire current was measured with a clamp-on ammeter (LeCroy CP500) to meet the criteria specified

in Regulation ECE R-101 of Council Directive 70/220/EEC. In addition, the terminal voltage of the HSB was measured using differential probe analyzers (LeCroy ADP305). Both measurements were recorded with a digital sampling oscilloscope. All HEVs were operated with the same standard fuel with low sulfur content.

CSEE estimation

The effect of low ambient temperatures on the fuel consumption and pollutant and CO_2 emissions of the considered HEVs was assessed by determining the respective cold-start extra emissions (CSEEs) for the test runs at the different ambient temperatures. Out of the different methods to determine CSEEs, the so-called sub-cycle method is selected because it is best suited for vehicles like HEVs with unsteady hot emissions (Weilenmann et al., 2009, Favez et al., 2009): The emission results are separated into a warm-up phase and a hot phase, depending on the mean CO_2 emission performance in the single sub-cycles, which are calculated out of the measured time-resolved CO_2 emission measurement. The average hot stabilized emissions of the hot phase are then subtracted from the respective sub-cycle emissions of the warm-up phase to obtain absolute CSEEs in grams per start.

Results

CSEEs of regulated pollutants

The CSEEs of regulated pollutants obtained for the single HEVs at the different ambient temperatures are summarized in Figure 1 and compared to mean CSEEs of six gasoline vehicles of the certification category Euro-4 (G4), which were obtained within an earlier study (Weilenmann et al., 2009). The average pollutant CSEEs of the selected HEVs are 30% to 85% smaller compared to the average CSEEs of the G4 sample. This performance is particularly remarkable for HC emissions, where most values for the HEVs are even below the minimum of the G4 sample.

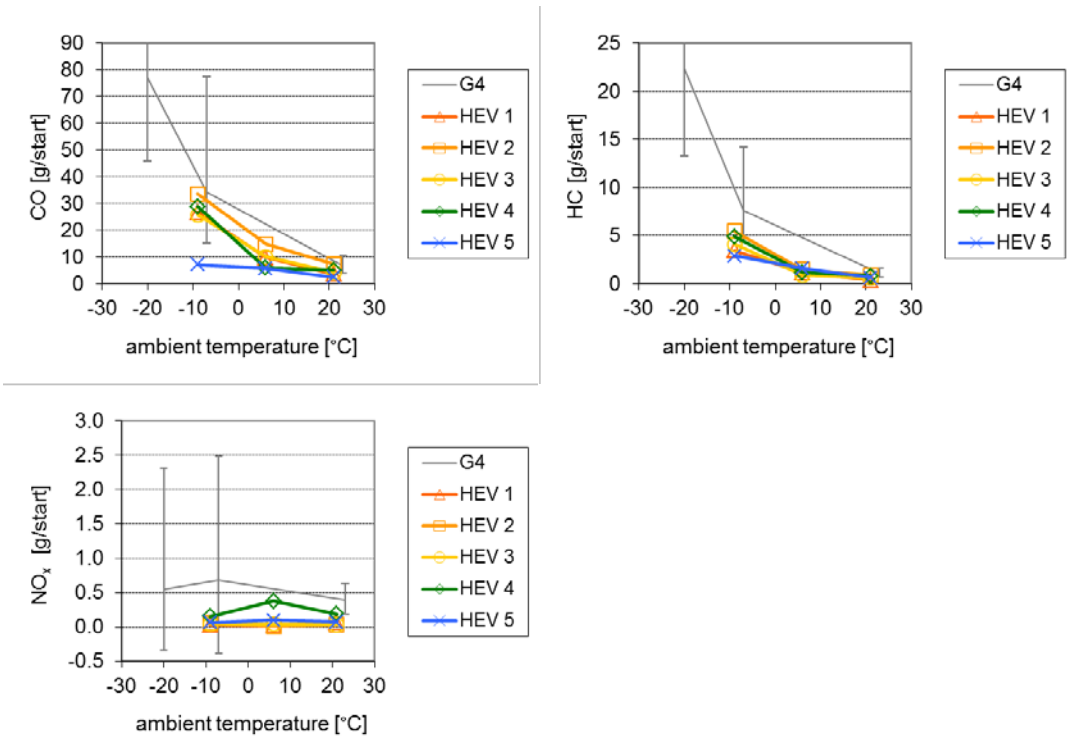

Figure 1: Measured CSEEs of regulated pollutants of the selected HEVs for the different ambient temperatures compared to the average CSEEs of a sample of Euro-4 gasoline vehicles (Weilenmann et al., 2009). The error bars represent maximum and minimum sample emissions.

These observations highlight the good emission performance for pollutant CSEEs of HEVs. A specific advantage of HEV powertrains is assumed to be responsible here: the ability of the

electric drivetrain to assist the combustion engine when providing drive energy allows adjusting the operation of the latter during cold start to heat up the three-way catalyst with minimal emissions. This heating-up occurs without the excessive formation of pollutants because peak load demands to the combustion engine are avoided thanks to the electric assistance, especially for full HEVs. The observed pollutant CSEEs of HEVs are in line with the overall good pollutant emission performance of HEVs in real-world driving conditions compared to gasoline vehicles (Fontaras et al., 2008). In that study, little influence of the initial SOC of the HSB on regulated pollutant emissions is also reported for cold-started driving cycles, which indicates that their CSEEs may not vary considerably on account of initial SOC of the HSB.

CSEEs of CO2 and fuel consumption

The CSEE of CO_2 and fuel consumption for the different ambient temperatures are given in Figure 2. In contrast to the CSEEs of regulated pollutants, the HEV CSEEs of CO_2 and fuel consumption are mainly similar to the respective sample CSEEs of the gasoline vehicles G4 (Weilenmann et al., 2009). The CSEEs of some HEVs exceed the average sample emissions of the G4 sample and even their maximum sample emissions at the ambient temperature of 23°C. A specific attribute of HEV powertrains can again explain this finding: the measured hot stabilized emissions of CO_2 and fuel consumption of HEVs are reduced in comparison to the respective average sample emissions of G4 due to the electric assistance, but the particular fuel used to overcome the increased friction in the cold engine remains approximately the same. This circumstance influences the respective CSEEs more than it does for gasoline vehicles, which leads to increased CSEEs for HEVs.

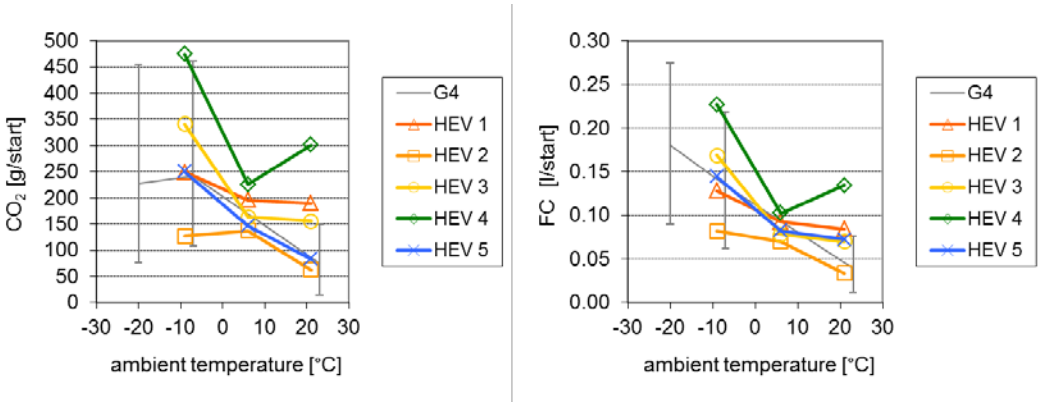

Figure 2: Measured CSEEs of CO_2 and fuel consumption of the selected HEVs for the different ambient temperatures compared to average CSEE of a sample of Euro-4 gasoline vehicles (Weilenmann et al., 2009). The error bars represent the maximum and minimum sample emissions.

Furthermore, a significant drop in the CSEEs is also detected for HEV 2 at -7°C and 23°C and for HEV 4 at 8°C ambient temperature. In those instances, a pronounced short-term use of electric energy out of the HSB for full electric driving is observed in one of the sub-cycles during the warm-up phase, which results in lower overall CO_2 emissions and fuel consumption for this period and, consequently, lower CSEEs. This occurrence may be rather exceptional and mainly due to the uncommon initial maximum SOC of the HSB. However, the resulting CO_2 emissions and fuel consumption are also considered to be representative for the respective HEV operation. In contrast, the mild hybridized HEV 5, which operates most similar as conventional gasoline vehicles, features almost identical CSEEs compared to sample CSEEs of the G4 vehicles.

The CSEEs of CO_2 and fuel consumption presented in Figure 2 are to be judged optimistically because the test runs were started with fully charged HSB (Alvarez et al., 2010).

Hot-phase HEV operation

Another interesting aspect is the hot-phase operation of the HEV powertrains at different ambient conditions because varying ambient temperatures may affect the underlying electrochemical processes in the HSB. Consequently, the resulting CO_2 emissions and fuel consumption can also be affected (Alvarez et al., 2010, Fontaras et al., 2008). Therefore, the

average electric drive energy provided from and recuperated to the HSB in full electric vehicle operation was determined for the selected HEVs in the hot-phase sub-cycles of the IUFC15 at the different ambient temperatures, see Figure 3. No particular differences in the HSB performance are observed during these driving conditions for the different ambient temperatures. A slight trend towards reduced performance with lower ambient temperatures can only be observed for HEV 1, but is not statistically significant. This slight trend is reflected in the clearly steeper increase of the average hot-phase CO_2 emissions of HEV 1 for lower ambient temperatures compared to those of the other HEVs and the G4 sample, see Figure 4. In general, however, a significant influence of low ambient temperatures on the HSB performance of the selected HEVs resulting in more pronounced CO_2 emissions and fuel consumption can be excluded given the test results.

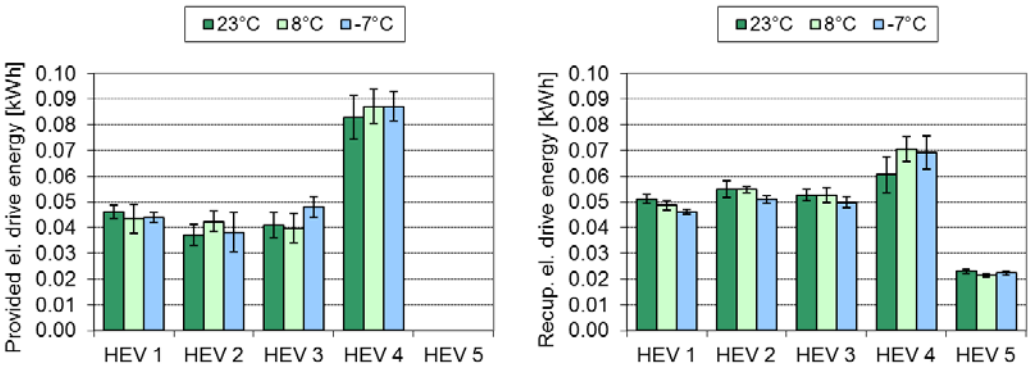

Figure 3: Average and standard deviation of electric drive energy provided from (left) and recuperated to (right) the HSB in full electric vehicle operation determined in the hot-phase sub-cycles of the IUFC15 cycle for the selected HEVs at the different ambient temperatures; abs.: absolute; el.: electric; recup.: recuperated.

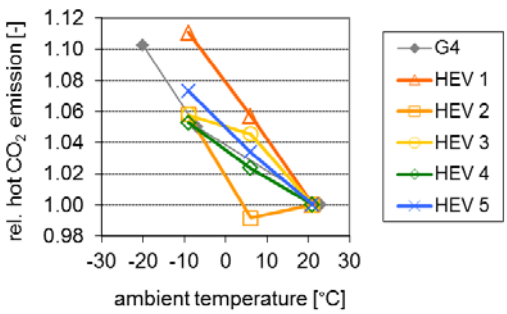

Figure 4: Relative average hot-phase CO_2 emissions of the selected HEVs and of the G4 sample in the IUFC15 cycle for the different ambient temperatures.

Summary and conclusions

The present experimental investigation with five in-use HEVs offers insight into the effect of low ambient temperatures on their fuel consumption and pollutant and CO_2 emissions in real-world driving conditions. The test results show that the CSEEs of regulated pollutants of HEVs are reduced by 30% to 85% on average in comparison to sample CSEEs of conventional gasoline vehicles of the same certification category. In contrast, the CSEEs of CO_2 and fuel consumption are mainly similar to those of conventional gasoline except for the test results at the ambient temperature of 23°C, where some HEVs feature further increased CSEEs.

Both observations are explained by the specific attributes of HEV powertrains, in which the electric assistance to the combustion engine allows a heating-up without high loads that cause pronounced amounts of pollutants during that period. But the extra fuel used during warm-up becomes more relevant because the engine runs a longer percentage of time than in hot driving.

It can be concluded that the CSEE of HEVs show the same (relative) trend over temperature as the CSEE of gasoline vehicles. The CSEEs for CO_2 and fuel consumption are assumed to be particularly sensitive to the initial SOC of the HSB, because the latter considerably influences the fuel consumption of HEVs (Alvarez et al., 2010, Fontaras et al., 2008). This aspect should at least be taken into account or further investigated to evaluate in detail the influence of low ambient temperatures on fuel consumption of HEVs. Moreover, no particular influence of low ambient temperatures on fuel consumption and CO_2 emissions are observed in hot-phase driving conditions.

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