Effect of Battery Performance on Determining CO_2 Emissions of Hybrid Electric Vehicles under Real-World Conditions

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Abstract

Hybrid electric vehicles (HEVs) can potentially reduce vehicle CO_2 emissions by further using recuperated kinetic vehicle energy stored as electric energy. This ability mainly depends on the type and layout of the electric storage device, its manufacturing deviation and in-use deterioration. The resulting performance affects net HEV CO_2 emissions in a certain driving pattern, described as equivalent to unchanged net energy content of that storage device. This energy content cannot be measured externally, demanding a correction procedure to determine net HEV CO_2 emissions from their raw CO_2 emissions. The present study investigates such effects on HEV CO_2 emissions based on chassis dynamometer test results with three identical in-use examples of a conventional HEV model featuring different mileages. Statutory and real-world driving cycles together with full electric vehicle operation modes have therefore been considered. It is shown that the individual drive battery performance of the single HEVs affects both their raw CO_2 emissions and the outcomes of the statutory correction procedure. The corrected CO_2 emissions of a HEV in any driving pattern resulting from this statutory procedure clearly underestimate their true level which can be only reproduced when account is taken on the individual HEV drive battery performance.

Introduction

Hybrid electric vehicles (HEVs) represent a promising approach to reducing vehicle exhaust emissions of CO_2. An additional electric powertrain including an energy storage device, typically a rechargeable drive battery or supercapacitors, is combined with a combustion engine to provide the desired overall vehicle power output. This configuration makes it possible both to design and employ the single powertrains in their most efficient operating conditions and to recuperate kinetic vehicle energy during deceleration for further use, leading to reduced overall CO_2 vehicle emissions (Sundström, 2009, Sundström et al., 2009, 2008). HEVs are categorized according to their capability for full electric driving (full hybrid) or not (mild hybrid) and whether they are externally rechargeable (plug-in hybrid) or not (conventional hybrid). However, such types of vehicles are expected to attain a considerable market share in the near future (Christidis et al., 2005, Duleep et al., 2004), also because of specific CO_2 vehicle emission reduction policies (An, 2007) and legislation such as in Europe (Regulation EC 443/2009) (Fontaras and Samaras, 2010), and first studies have already been carried out to determine their real-world pollutant emission performance (Fontaras et al., 2008). Furthermore, HEVs are assumed to open up the way towards electricity-based powertrain solutions such as electric or fuel cell vehicles (Van Mierlo et al., 2006).

A crucial feature of HEVs is the ability of their electric storage device to further use stored electric energy, because the latter then needs not be provided by the combustion engine and facilitates most savings in CO_2 emissions. When drive battery is employed, this battery performance generally depends on the battery technology used and its layout, but is also device-specific due to manufacturing deviation and in-use deterioration. However, net CO_2 emissions of a HEV in any driving pattern are affected because they are described as equivalent to the unchanged net energy content or state of charge (SOC) of its battery. Therefore, an adequate procedure for correcting the recorded raw CO_2 emissions of individual HEVs needs to be applied that reflects its true respective emission level, because battery SOC cannot be measured externally.

In order to study the effect of battery performance on determining net CO_2 emissions of HEVs under real-world conditions, an experimental investigation with three identical in-use examples of a conventional HEV model featuring different mileages has been conducted on a chassis dynamometer. Test runs with the statutory cycle for Europe NEDC and the real-world Common Artemis Driving Cycle (CADC) including urban, rural and motorway driving patterns have been performed together with constant-speed full electric driving and vehicle traction mode. The test results obtained are discussed in detail, highlighting the importance of including the individual HEV drive battery performance when determining true net CO_2 emissions in any driving pattern in contrast to the statutory correction procedure.

Methodology

Vehicle sample

The main characteristics of the three identical in-use examples of a particular HEV model selected for the test series with different mileages are summarized in Table 1. This HEV is categorized as a ‘conventional full hybrid’, i.e. the drive battery employed is not externally rechargeable but allows full electric vehicle operation in certain driving situations as well as assisting the combustion engine and recuperating kinetic vehicle energy during deceleration (Danisch and Goppelt, 2004). Therefore, a certain range of drive battery SOC is made available by this HEV, whereas when it reaches its lower limit recharging up to a higher level via the combustion engine is carried out. Under normal operating conditions, however, the overall HEV control system attempts to operate around a defined battery SOC level where the latter situation does not occur. Note that no particular servicing was carried out before the test runs except a general vehicle function check.

Table 1: Main characteristics of the considered vehicle sample; IC: internal combustion

characteristic			HEV A	HEV B	HEV C
vehicle	make & model	[-]		Toyota Prius II	
	inertia setting[a]	[kg]		1425	
	gearbox	[-]		CVT	
	certification class	[-]		Euro-4	
	1st certification	[-]	Feb 06	Aug 06	Jun 05
	mileage	[km]	32768	60761	104266
IC engine	displacement	[cm^3]		1497	
	rated power	[kW]		57	
electric motor	rated power	[kW]		50	
drive battery	type	[-]		NiMH	
	nominal voltage	[V]		201.6	
	number of cells	[-]		168	

[a] empty mass plus 100kg

Experimental Program

Several driving cycles were employed in the test series in order to determine the effect of battery performance on the CO_2 emissions of the selected HEVs. The statutory cold-start driving cycle for Europe (Council Directive 70/220/EEC) was included, as well as the real-world Common Artemis Driving Cycle (CADC). The warm-start CADC was derived from car driving behavior studies within the ARTEMIS research program, and its cycle sections represent European real-world urban, rural and motorway driving behavior for cars (André, 2004). Additionally, test runs with full electric driving and vehicle traction mode, simulating coasting conditions, were executed at a constant speed of 25 km h-1 to determine the resulting net battery charge flow when maximally discharging and charging the drive battery over its whole available SOC range.

The single cycle sections of the CADC were started with different initial battery SOC to investigate the sensitivity with regard to CO_2 emissions of each driving pattern on actual battery SOC and to further apply a correction method to determine net CO_2 emissions of the single HEVs as presented below. There, maximum and minimum initial battery SOC level have been considered that are defined by either having no more charge leading to the drive battery in vehicle traction mode or having the combustion engine started in full electric vehicle driving to ensure the minimum permitted SOC level, respectively. A medium initial battery SOC level between these two initial SOC levels has also been included, set identically for all tests using the respective information on the instrument panel of the individual vehicles. However, this initial SOC condition was not strictly adjustable. The test runs with the statutory cycle NEDC were all started with maximum battery SOC.

Experimental Setup

Figure 1 shows the overall experimental setup employed for the test series. The exhaust was sampled with a Constant Volume Sampling (CVS) system. Exhaust emissions of CO_2 were measured time-resolved and according to the statutory procedure specified in Council Directive 70/220/EEC of storing a sample of diluted exhaust in a tedlar gas sampling bag and analyzing its content offline after completion of the test run. In both cases an adequate exhaust gas analyzer (HORIBA AIA-110S) as specified by Council Directive 70/220/EEC was employed. The time-resolved drive battery wire current was measured with a clamp-on ammeter (LeCroy CP500) fulfilling the criteria specified in Regulation ECE R-101 of Council Directive 70/220/EEC together with the terminal voltage of the battery using differential probe analyzers (LeCroy ADP305), both recorded via a digital sampling oscilloscope (LeCroy WaveRunner 44Xi).

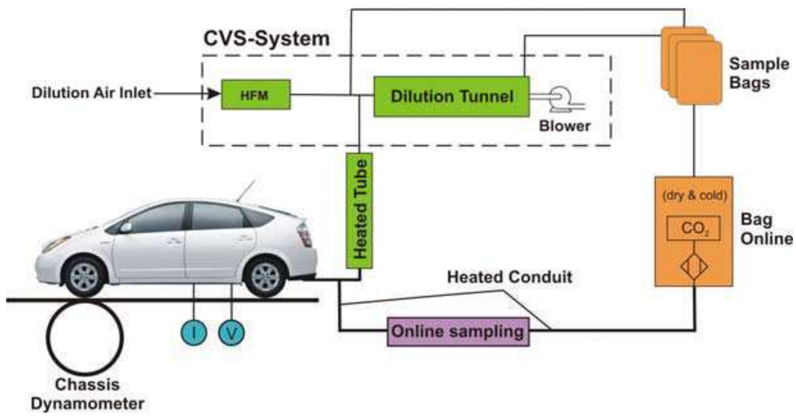

Figure 1 Schematic diagram of the test setup; HFM: hot-film air-mass flow meter; V: measurement of battery terminal voltage; I: measurement of battery wire current.

The chassis dynamometer and its settings were applied according to the provisions of Council Directive 70/220/EEC. The driving resistance of the vehicle was simulated using the respective coast-down data provided by the manufacturer, and the inertia settings were set at empty vehicle mass plus 100 kg payload. The ambient conditions of the test cell were set to 23°C temperature and 50% relative air humidity. All HEVs were operated with the same standard fuel with low sulfur content.

Correction of raw CO_2 emissions

Net emissions of CO_2 of a HEV in any driving pattern need to be described as equivalent to unchanged net energy content or state of charge (SOC) of the drive battery within the driving pattern in order to avoid any under- or overestimation. However, a driving pattern with unchanged net battery SOC is unlikely to be performed, and the resulting raw CO_2 emissions thus need to be adjusted. Because battery SOC cannot be measured externally, an adequate correction procedure has to be derived to achieve this aim.

The statutory procedure for correcting CO_2 emissions of conventional HEVs is described in Regulation ECE R-101 of Council Directive 70/220/EEC. The change in electric energy of the battery ΔE_{batt} is defined to be equivalent to the nominal battery energy content E_{TEbatt} weighted with the change in battery SOC and expressed by the product of the net charge flow Q recorded on the battery wire in a driving pattern and the battery nominal voltage:

$$\Delta E_{batt} = \Delta \mathrm{SOC}[-] \times E_{TEbatt} = Q \times V_{batt} \quad (1)$$

The measured charge balance Q is therefore the only indicator used to reflect changes in battery SOC. Given this, a number of n measurements in a certain driving pattern are executed with a particular HEV in order to obtain a data set of different raw CO_2 emissions M_i together with respective Q_i, whereas at least one of the latter should be negative in order to be able to derive a correction factor for CO_2 applying a linear regression on this data set:

$$K_{CO_2} = \frac{n \cdot \sum Q_i \times M_i - \sum Q_i \times \sum M_i}{n \cdot \sum Q_i^2 - \left(\sum Q_i\right)^2} \qquad (2)$$

This correction factor has to be provided by the manufacturer for certification purposes. The resulting net emissions of CO_2 M_0 from the raw emissions M of a particular HEV obtained in this certain driving pattern are then defined as:

$$M_0 = M - K_{CO_2} \times Q \qquad (3)$$

For this statutory procedure of describing battery ΔE_{batt} via ΔSOC and correcting HEV CO_2 emissions, two assumptions are made: first, it is assumed that the battery terminal voltage remains constant and equal to the battery nominal voltage. Secondly, no irreversibility during storage and further usage of the charge provided to the battery is implicitly assumed.

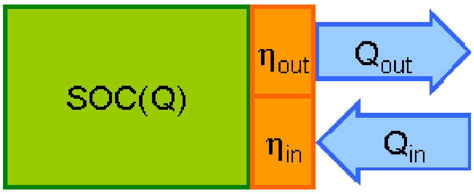

Figure 2: Schematic flow diagram of the charge flows of a HEV drive battery.

In real operation, however, neither of the two assumptions is likely to occur, in particular the charge provided to the battery Q_{in} and further used Q_{out} are to be efficiency-delimited as depicted in Figure 2. The single efficiencies η_{in} and η_{out} generally depend on actual SOC, current, voltage, temperature and state of deterioration of the battery. The resulting charge balance equivalent to battery ΔSOC in a driving pattern is then:

$$Q = \int \eta_{in}(t) \times \frac{dQ_{in}}{dt} \partial t - \int \frac{1}{\eta_{out}(t)} \times \frac{dQ_{out}}{dt} \partial t \qquad (4)$$

And when η_{in} and η_{out} are assumed to be constant, the relation between the charge flows provided to and further used from the battery per unit battery SOC can be expressed as:

$$Q_{out} = \eta_{in} \times \eta_{out} \times Q_{in} \qquad (5)$$

Therefore only the fraction $\eta_{in} \times \eta_{out}$ of the charge provided to the battery is further used, a characteristic that indicates the battery performance in terms of its individual ability to store and further use charge provided to the battery. This performance needs to be considered when using charge balance to describe battery SOC and subsequently to derive adequate correction factors to determine net CO_2 emissions of HEVs.

Results

Maximum battery charging and discharging

Several repetitions of test runs have been performed operating the single vehicles in full electric driving and vehicle traction mode at constant speed of 25 km h^{-1} utilizing their whole permitted battery SOC range. The resulting net charge flows when maximally charging and further discharging the same SOC range of the single vehicle drive batteries are presented in Figure 3. It can be seen there that the maximum amount of charge available from the single drive batteries decreases significantly with increasing vehicle mileage, indicating a possible deterioration effect caused by in-use ageing. The respective maximum amount of charge needed to be provided to the single batteries is also always substantially higher than the charge further available. This observation does not comply with vehicle mileage, leading to ratios of charge further used from and provided to the battery in this driving regime of 78%, 67% and 72% for HEV A, B and C, respectively, for the given driving pattern.

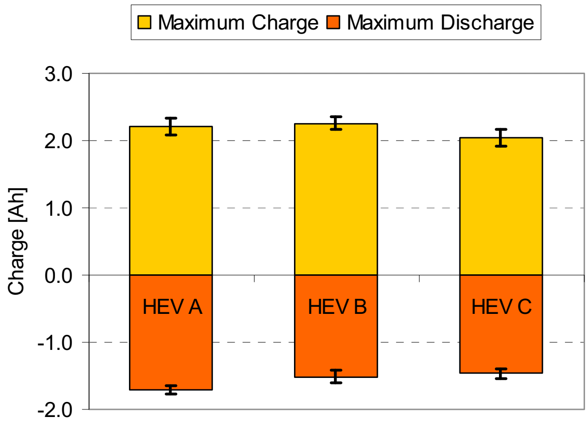

Figure 3: Maximum net charge flows provided to and further used from the individual batteries of the single HEVs in full electric driving and vehicle traction mode at 25 km h^{-1}.

As the battery demand was almost constant during full electric constant-speed operation of the vehicles, these ratios may represent the characteristic $\eta_{in} \times \eta_{out}$ of the single batteries and thus reflect the individual battery performance with respect to further using stored charge provided to the battery. These levels of performance are more likely to be affected by the number and depth of in-use battery charge and discharge cycles occurred than by battery ageing due to absolute vehicle mileage. The excess electric energy provided to the battery is assumed to be finally dissipated as heat via the air cooling system of the single vehicle's drive batteries.

Statutory emission performance

Figure 4 shows the single HEV emission performance in the driving cycle NEDC of raw and corrected CO_2 emissions according to the statutory correction procedure, employing the same correction factors for CO_2 provided by the HEV manufacturer for that cycle. No particular trends for the single HEVs can be detected from the raw CO_2 emissions, indicating that the low driving dynamics of the NEDC does not make great demands on their hybrid powertrains. All three vehicles exhibit final CO_2 emissions similar to the official value of 104 g km^{-1} CO_2 stated for this HEV model (Danisch and Goppelt, 2004) even though the chosen inertia settings exceed the respective certification specification by 65 kg.

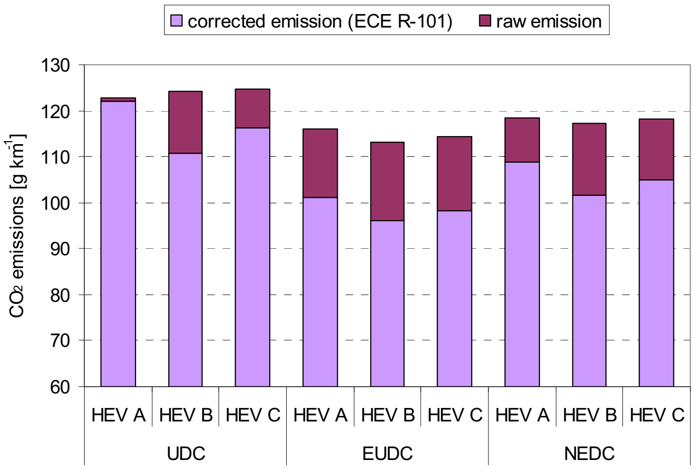

Figure 4: Raw and corrected CO_2 emissions according to the statutory correction procedure of the single HEVs in the statutory driving cycle NEDC started with maximum drive battery SOC.

But it can be seen that although these test runs have been started with a maximally charged drive battery, a correction towards lower CO_2 emissions already has to be applied in the first cycle section of the NEDC, named the Urban Driving Cycle (UDC). According to the correction methodology used, described above, this observation would imply an increase in battery SOC in the first cycle section UDC, which, however, cannot have occurred, as also indicated by the respective information on the instrument panel of the single vehicles.

This observation can be explained by the findings summarized in Figure 3. More charge than can be further used per unit SOC always has to be provided there to the drive batteries of the single HEVs, i.e. whenever these vehicles attempt to maintain a certain SOC level in regular driving conditions, as in the UDC, more charge will have to be provided to the battery than is effectively used. This circumstance distorts the outcomes of the statutory correction procedure, which does not consider any irreversibility in battery charge flow, resulting in the misleading indication that all the excess charge provided to the battery will be further available to save vehicle CO_2 emissions. Therefore, the single drive battery performance levels with regard to the ability to further use provided charge presented above are also reflected here: the lower the stated ratio is, the greater the resultant absolute statutory CO_2 correction.

Real-world emission performance

The test results for raw CO_2 emissions obtained for the different cycle sections of the CADC representing real-world urban, rural and motorway driving pattern, and started with minimum, medium and maximum battery SOC, are summarized in Figure 5. Strong influence of initial battery SOC on the resulting raw CO_2 emissions of the single HEVs can be stated in real-world urban driving in a range of around 30% to 40% of the average. This effect is less pronounced for rural driving and almost non-existent for motorway driving, indicating that hybrid electric driving of the HEVs considered is most effective in real-world urban driving patterns.

There also, raw HEV CO_2 emissions tend to increase with vehicle mileage for the different initial battery SOC conditions. The lower absolute amount of charge that the single drive batteries can facilitate with increased vehicle mileage, see Figure 3, is mainly responsible here, leading to more extensive demand on the combustion engine when performing this driving pattern.

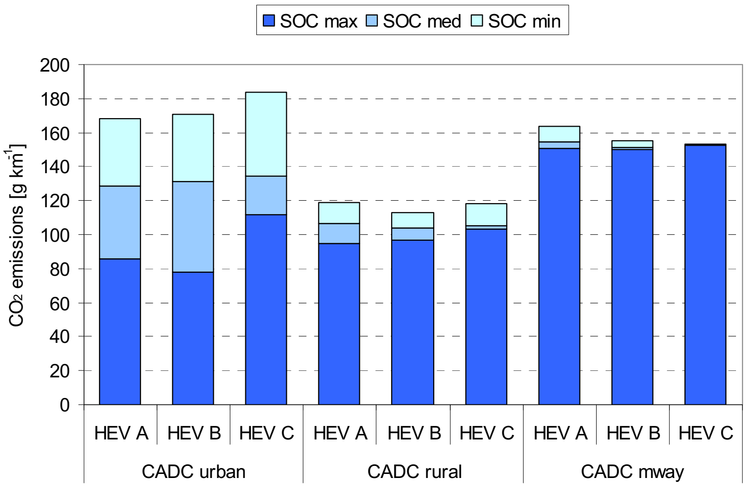

Figure 5: Raw CO_2 emissions of the single HEVs in the real-world driving cycle CADC started with maximum, medium and minimum drive battery SOC.

Given the data set for the CADC, the statutory procedure for deriving CO_2 correction factors according to Equation 2 is applied and the outcomes for the single HEVs are summarized in Figure 6 together with the respective range of measured raw CO_2 emissions shown in Figure 5. Again, HEV B features the largest correction in CO_2 emissions, especially for the urban section of the CADC, which is also assumed to be caused by its lowest drive battery performance of further using charge provided to the battery, see Figure 3. All the corrected CO_2 emissions tend to lie in the lower third of the total range of raw CO_2 emissions.

Additionally, corrected CO_2 emissions of the HEVs were calculated when applying the same correction procedure but weighting the measured charge flow with the ratios presented in Figure 3 to include the individual HEV drive battery performance, see Figure 6. These corrected emissions are up to around 25% higher than the outcomes of the statutory correction procedure and typically lie closer to the average of the range of their raw CO_2 emissions. The corrected emissions from the weighted method are therefore assumed to represent much better the true net CO_2 emissions of these HEVs. However they are not equivalent as they exceed the range of their measured raw CO_2 emissions in some cases. The cause for this circumstance is due to the fact that the individual HEV drive battery performance depends on the driving pattern, which determines the theoretically possible battery usage of an HEV. The ratio applied here stated in Figure 3 is thus most probably excessive because it has been derived from full electric vehicle operation that represents a more pronounced demand to the drive battery than in the driving patterns of the CADC.

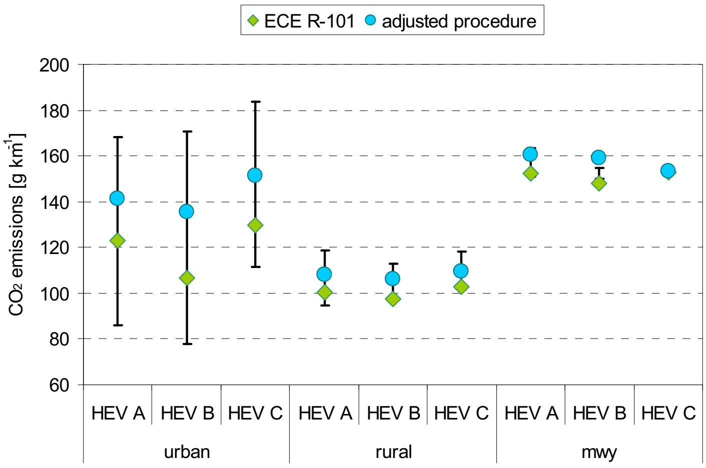

Figure 6 Corrected CO_2 emissions of the single HEVs in the real-world driving cycle CADC derived from the statutory correction method and an adjusted procedure with weighted charge flows; error bars represent the range of their raw measured CO_2 emissions.

Summary and Conclusions

The present experimental investigation with three examples of a conventional HEV offers varied insight into the effect of drive battery performance on determining CO_2 emissions of HEVs under real-world conditions. It is shown that the individual drive batteries of the single HEVs perform differently under equivalent driving conditions. First, the total charge output of the batteries is lower with increasing mileage and therefore most probably caused by in-use deterioration. Secondly, it is observed that only a fraction of the charge provided to the single drive batteries can always be further used per unit battery SOC, which also varies considerably for each battery. The latter circumstance is presumably to be attributed to the number and depth of in-use charge and discharge cycles performed by each battery.

These findings influence both the raw CO_2 emission performance of HEVs and particularly the outcomes of the statutory procedure for correcting HEV CO_2 emissions with respect to unchanged net battery energy content in a driving pattern. Because this procedure bases upon the measured charge flow but does not consider any irreversibility in further using the charge provided to the battery, the resulting corrected CO_2 emissions may considerably underestimate the true CO_2 emission level of a HEV in any driving cycle, as indicated by the present test results. The measured net battery charge flow within a driving pattern for itself does therefore not correctly indicate the effective change in energy content of the HEV drive battery.

It can be concluded that the individual HEV drive battery performance needs to be taken into account when determining true CO_2 emissions of a conventional HEV in any driving pattern. The most appropriate approach for it appears to be to have direct access to the battery SOC information of the HEV powertrain control system to apply to the respective correction procedure. Alternatively, subsequently repeating this pattern until stabilized CO_2 emissions are reached would also be feasible because the energy content of the drive battery of a conventional HEV is self-sustaining.

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