Hybrid Vehicle Performance Measurement: a New Challenge in Standardization

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Abstract

The definition of performance measurement standards for hybrid electric vehicles is one of the main challenges faced by standardization committees. The plethora of hybrid drivetrain topologies and drivetrain strategies which are implemented by the manufacturers make it quite difficult to define one comprehensive test procedure which allows to compare the vehicles between them on one hand and with battery-electric or thermal vehicles on the other hand. The paper will highlight the situation in the field, taking into account ongoing standardization work, and will give a number of recommendations for future developments. The particular situation of light-duty versus heavy-duty vehicles will be taken into account.

Keywords: standardization, regulation, HEV

1. Performance standards for light duty vehicles

1.1 Introduction

The definition of a universal performance standard for a hybrid vehicle is not a straightforward issue.
A first thing to be considered is the possible availability of different driver-selected operation modes in the same vehicle. To get an overall assessment, it is essential that all available modes (for as far as they are compatible with test cycles) are measured,
For “pure-electric” (with the APU switched off) or “pure thermal” (with the electric drive train not intervening in traction) modes, if any, relevant measuring procedures for respectively electric [1] and thermal vehicles [2] should be used, with however the same speed cycles (e.g. the New European Driving Cycle, NEDC) to be used where applicable to allow comparison among all modes.

For the hybrid driving modes however, the main issue concerning the measurement of the energy consumption is the consideration of the state-of-charge (SOC) of the on-board rechargeable energy storage system (RESS) during the test. In order for the test being valid, it is of course essential that the SOC of the RESS is the same before and after the test, otherwise the energy consumption measured will not be the real energy consumption used to propel the vehicle.
The evolution of the SOC is strongly dependent on the configuration of the HEV and its control strategy.
One can make the distinction between several possible cases:

- whether or not the HEV is externally chargeable;
- whether or not the APU is designed to deliver a constant output power;
- what is the typical application profile for the vehicle.

1.2Externally chargeable hybrid

The externally chargeable HEV, also known as “plug-in hybrid”, presents the following application profiles:
Battery-electric vehicle with “range extender” APU; for such vehicle, electric operation will be the principal mode, with hybrid mode used occasionally when the need arises to cover a longer distance.
Hybrid vehicle with zero-emission capability; for such vehicle, hybrid operation will be the principal mode, with electric mode used for example in city centres or other sensitive environments.

Test procedures for these types of HEV should take into account both electric and hybrid operation modes:

For electric operation, without APU use: measurement of the range and energy consumption can be performed according to the procedures for battery-electric vehicles (ISO 8714). The RESS should be fully charged at the beginning of the test, and recharged from the grid after the full range has been covered in order to measure the electricity consumption.
For hybrid operation, both fuel and electricity consumption have to be measured. Taking into account the practical use of a plug-in hybrid vehicle, where the user will charge the vehicle from the grid overnight, using energy which is cheaper and more environmentally friendly than when recharging from the APU, it is reasonable here to perform a test with the initial SOC at 100%, and with the RESS being fully recharged from the grid at the end of the test. This procedure has been described in the SAE J1711 standard, where it is called the FCT-HEV test [3], with the initial SOC at 100 % and with the RESS recharged from the grid at the end of the test.

1.3Non-externally charged hybrid

For non-externally chargeable HEV, the energy consumption to be measured is on the level of the APU fuel supply. Due to the variety of drive train structures and control strategies envisageable, it is difficult to put forward one standard procedure which would fit for all.
The most critical point in the testing procedure is the SOC balance over the test: if the SOC before or after the test is not the same, the measured fuel consumption is not equivalent to the energy needed to propel the vehicle through the test cycle, since either part of it has been used to recharge the RESS or part of the driving energy has been provided by the discharge of the RESS. This is illustrated in Figure 1 [4]: only in the middle case will the fuel consumption be relevant for the energy consumption over the cycle.

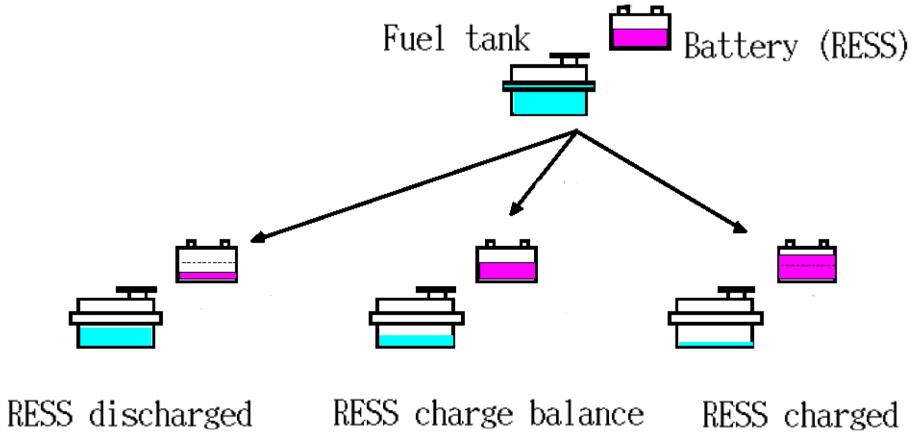

Figure 1: Charge balance

It is thus necessary to measure the energy flows going in and out of the RESS, and to define an acceptable energy balance level. An acceptable energy change of ± 1% can be considered an accurate enough choice; the 1% being the ration of the difference in stored RESS electrical energy to the total fuel energy consumed over the cycle, as shown in formula (1). This value has been brought forward in standards, such as SAE J1711 [3].

$$\left| \frac{(\Delta_{Stored\ Electrical Energy})}{Total\ Fuel\ Energy} \right| \leq 1\% \quad (1)$$

For the cases where the value of change is greater than 1% but lower than 5%, a correction procedure based on linear interpolation between several tests has been proposed in SAE J2711 [5].The principle of such interpolation is shown in Figure 2 [6]. It is clear that such a correction procedure is to be considered an approximation however, and a trade-off has to be found between accuracy of the measurement results on one hand and complexity (i.e. cost!) of the test procedure on the other hand.

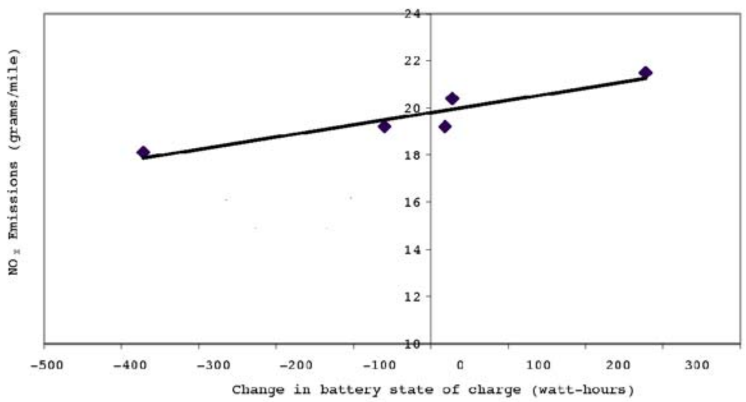

Figure 2: SOC correction by interpolation

It may be necessary though for a HEV to extend the test cycle. A standard urban European test cycle for example, as defined in ISO 8714 [1], only covers a distance of 11 km, which, due to the "time constant" of the energy balance strategy which may be embedded in the drive train control system, may not be sufficient to achieve a RESS SOC balance within the desired limits; in this case several cycles should be performed, adding basic cycles until the desired level is achieved.

Another issue to be taken into account is the initial SOC for the test. For this type of vehicle, it is most likely less than 100 %. The influence of the initial SOC is also dependent of the drive train strategy; and unless one wants to extend the number of tests (and hence their expense) considerably, it seems acceptable to start the test with a SOC level stated by the manufacturer, which could be between certain limits however (e.g. typically between 40 % and 80 %). Such approach is reflected in standards already, such as SAE J1711 (PCT-HEV test) and EN1986-2 [7].

1.4General remarks

The general trend for the definition of performance test cycles for hybrid road vehicles is to adapt, wherever possible, the existing test procedures for ICE vehicles and more particularly to use the same test cycles. Although such procedure allows for easy comparison between vehicles (either ICE or hybrid), one has to take into account that the usual reference cycles do not represent a true image of traffic, and that consumption and emission values in real traffic will be consistently higher. [8, 9] This is mainly due to the lack of dynamics represented in current driving cycles (e.g. the European cycle from ECE-83 or the Japanese 10-mode and 15-mode cycles, which are of a rather simple trapezoid structure). It might thus be advisable to define test cycles which are more realistic than the ones now in use; this however should take into account the actual differences between traffic conditions and driving style which exist in different parts of the world.
The non-representativeness of usual test cycles, particularly of those of a simple structure, also has to be considered in the light of manufacturers fine-tuning their vehicles to yield optimal results on that particular cycle, in which case the values obtained and published may be less representative for real traffic conditions, and their information value for the vehicle user (consumer) may be limited.

2. Performance standards for heavy duty vehicles

2.1Generalities

Heavy-duty vehicles like buses and trucks represent a large application field of hybrid drive technology. Testing procedures for consumption and emission of hybrid heavy-duty vehicles are not so straightforward however: whileas for light-duty vehicles they can be derived using existing test cycles for conventional vehicles, this does not apply for heavy-duty vehicles, where the standard test methods for conventional vehicles are based on engine bench tests (e.g. the European Stationary Cycle 13-mode test [10], illustrated in Figure 3 introduced by the directive 96/96/EC), which can not be meaningfully applied to hybrid vehicles, since in these vehicles the instantaneous behaviour of the engine is decoupled from the instantaneous road load, and the standard set of measuring points and their weighting may not apply.[11]

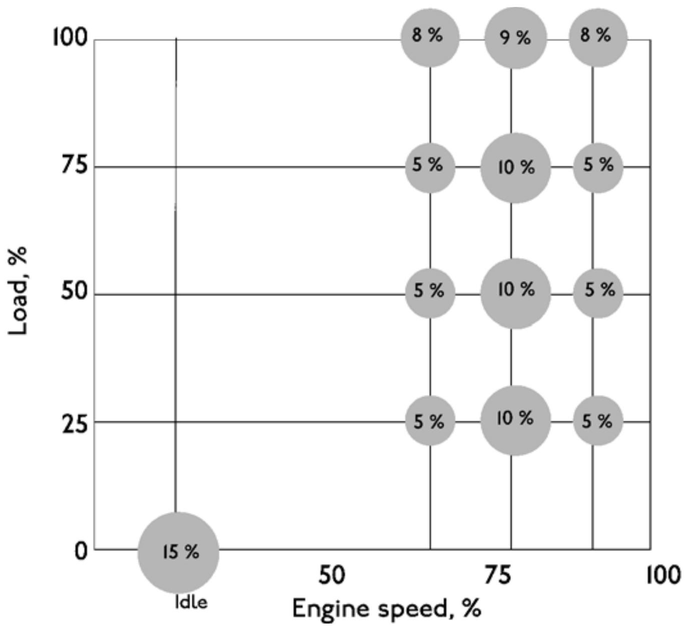

Figure 3: European Stationary Cycle 13-mode test

A particular approach is thus necessary; according to the drive train strategy, the following cases can be distinguished, taking into account the output power and set point of the APU:

2.2APU delivering a constant power

This is typically the case for series hybrid city buses; this configuration allows the APU to be operated at is optimal point, minimizing energy consumption. Since the APU output power (and hence its consumption and emissions) is constant, it can be easily characterized on an engine test bench, using a single operation point (Figure 4).
A vehicle test however is recommendable to show the concordance between APU behaviour on and off the vehicle. Furthermore, the behaviour of the APU with a fully charged RESS (in which case the APU may have its output power reduced or where it may be switched off) should be investigated.

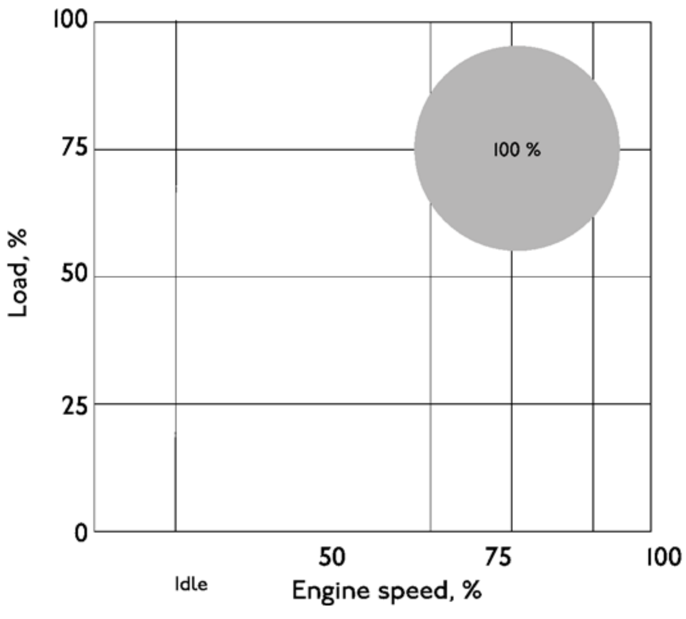

Figure 4: APU delivering a constant power

2.3APU having a limited number of operating points

Also this case can be easily described by a bench test focusing on a limited number of operating points. Figure 5 shows an example where the APU engine is operated at constant speed, but with different torque outputs. In order for the test to be relevant, the appropriate points have to be chosen for the measurement.

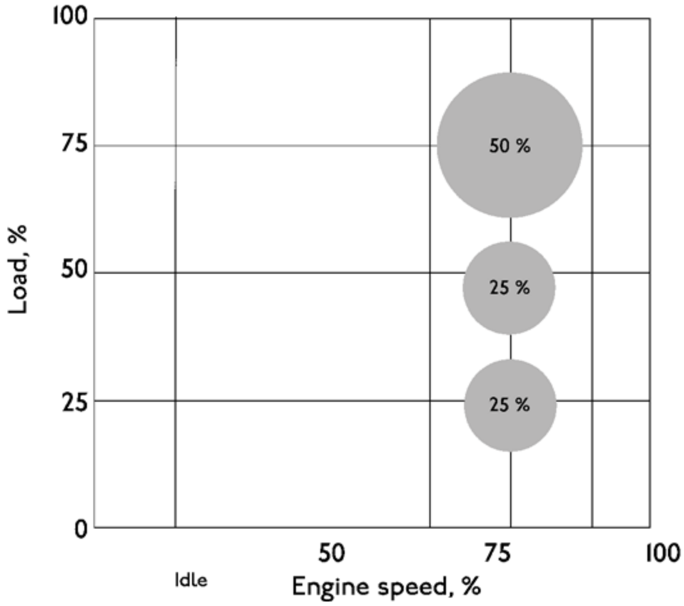

Figure 5: APU with fixed operation points

2.4APU delivering a dynamic power

In this case, which is obviously a more complicated one, the actual operating point of the APU is defined by the drive train strategy. A reliable test in this case would necessitate the knowledge of the typical operation of the APU. This necessitates performing a cycle test corresponding to an actual road cycle in order to know the dynamic operation range in order to define relevant points for bench testing the APU. Figure 6 shows an example, where relevant points are identified within the operation range of the engine.

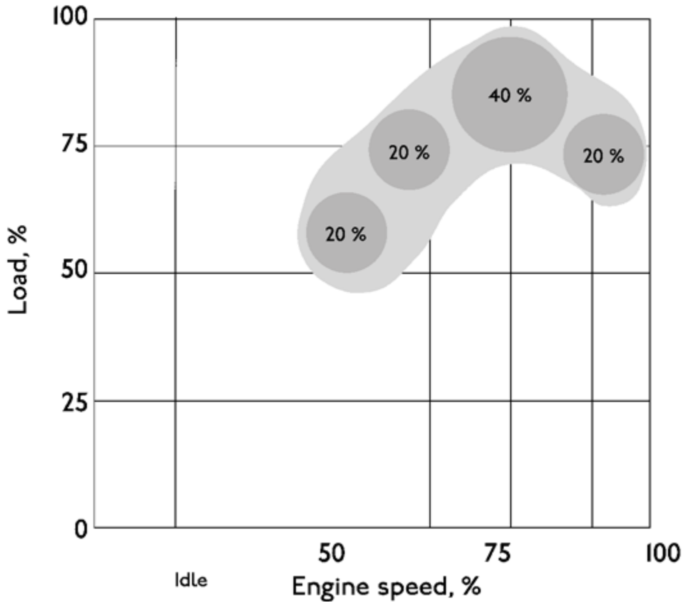

Figure 6: APU with fixed operation points

The actual points to allow relevant measurements are dependent on the drive train strategy and do not necessarily correspond with the standard reference points for ICE engines (Figure 3); if one wants to base the test on these points, it may be necessary to adapt the weighting of the individual operating points according to their relevance in the use cycle of the considered APU.

2.5General remarks

It is clear that when one desires to have really representative engine tests, the tests to be performed and the measurement points to be selected and weighted will have to be customized for each vehicle taking into account the underlying drive train strategy. This customizing however requires a thorough knowledge of the control strategy and the underlying parameters, knowledge which vehicle manufacturers usually consider as proprietary and anxiously guard. A legal obligation, such as the conformity to type approval regulations, could be an useful means to have such information disclosed.

One could state that the use of customized engine tests would disallow a valid comparison between engines. However, taking into account that the use of the engine will be specific for each HEV and that the generic engine test (designed for ICE vehicle) is ill-suited for testing HEV engines, it is clear that the engine should be tested in a mode of operation which mimics its actual use in the vehicle. When adopting customized tests, care should be taken however that test conditions proposed by manufacturers do represent actual operating conditions of the equipment and are not selected in order to influence the test results.

Just as with the light duty vehicles (cf. above), the real value of the considered tests, i.e. their relevance to actual vehicle operation, should be taken into account. Engines also can be fine-tuned to yield optimal emission and consumption values for a certain test; an engine designed for a hybrid vehicle APU and fine-tuned for its actual points of operation may perform poorly on a “standard” test not reflecting its use pattern. This of course puts into question the whole concept of standardized engine tests.

3. Fuel and electricity consumption

A hybrid vehicle which is externally chargeable will have two consumption values: one electric (kWh/100 km) and one fuel (l/100 km). One could desire to have a single comprehensive value however, and try to calculate electricity consumption back to fuel consumption. This is for example proposed in SAE J2711, where the following calculation is proposed: [5]

$$FE_e = \frac{HV_{FuelOil} \times E_G \times E_T \times E_C}{E_U \times K_3} \qquad (2)$$

where

- FE_e is the electric fuel economy in diesel equivalent (miles per gallon)
- $HV_{FuelOil}$ is the lower calorific value of diesel fuel
- E_G is the electricity generation efficiency (35%)
- E_T is the transmission efficiency (90%)
- E_C is the charging efficiency (70%)
- E_U is the energy consumption measured at the grid (kWh/mile)

- K_3 is a conversion factor (3412 BTU/kWh)

This formula is flawed and will present a much too low value: on one hand the generation efficiency E_G is with 35% very low; state-of-the-art electric power plants have easily efficiencies exceeding 55%. The transmission efficiency E_T is also rather low, in practice they can be 92 to 95%. On the other hand, the charging efficiency E_C should be deleted from the formula: since the consumption E_U is measured at the grid, upstream from the charger, the losses in the charger and the battery are already included.
Emission values from the electricity consumption can be traced back to the electricity generation plant and added to the exhaust emissions. Taking into account local utility emissions will yield different results in each location however, and it is not a straightforward process to link a consumer of electricity to a specific generation plant, in order to make a precise calculation of primary energy consumption and emissions, due to the interconnection on the electric distribution grid.
Several approaches to the problem of linking electricity consumers to power plants have been made in recent studies. [12, 13] The most interesting solution is a corollary of the ongoing liberalization of the (European) electricity market, which allows the consumer to choose his electricity supplier and enables specifically the purchase of “green” current from renewable sources, which would then be effectively zero-emission.
An alternative approach, consisting in determining the APU output emissions as if the RESS would be charged by the APU only and not from the grid, also proposed in SAE J2711 [5], will also yield a too high consumption value, due to the in nearly all cases lower efficiency and higher emissions of the on-board APU compared to an electric power plant.
It thus seems more advisable not to try to combine fuel and electricity consumption in one overall consumption figure, except in singular cases where the origin of the electricity used is fully known (e.g. renewable energy sources).
Furthermore, the juxtaposition of an electricity consumption figure with a fuel consumption figure is more interesting for the vehicle user, who usually acquires these energies from different sources and is thus enable to assess the economic impact (i.e. consumption cost) of the vehicle.

4. Conclusions

The development of performance standards and measurement procedures for hybrid electric road vehicles is a key element in allowing these vehicles to be deployed on a global market and to assess their energetical and environmental benefits in a clear and objective manner.
For light-duty vehicles, international standardization work is making progress in defining test procedures allowing to take into account the energy balance within the vehicle and to obtain a valuable comparison.
For heavy-duty vehicles, the definition of suitable engine tests taking into account the specific use of a combustion engine in a hybrid vehicle still has to be defined.
In both cases however, the general representativeness of test procedures and standard test cycles should be taken into account, and the definition of realistic vehicle or engine tests, allowing to make a clear correlation with energy consumption or emissions in real traffic conditions remains an issue to be worked out. Future standardization and regulation work should be oriented towards resolving these issues, particularly in the light of defining “global technical regulations”, which are key elements to allow the deployment of advanced environmentally friendly vehicle technologies on a global scale.

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