Potentials of predictive control strategies

Potential analysis using a global energetic optimum

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***Abstract*— In the case of a hybrid vehicle, two drive units are available to propel the vehicle. In order to maximize efficiency, the control strategy has to adjust the power of the two energy storage devices in each time step in such a way that optimal efficiency is achieved for a driven cycle. If the cycle is not known, the drives have to be coordinated on the basis of a fixed parameterization. If, however, the strategy has predictive information, the operation point selection can be optimized. In this article, the local optimal equivalent consumption minimization strategy (ECMS) is compared with the respective global optimal control strategy (GOCS) in both WLTP and customer operation. The method for determining the global optimum is explained. Hybridization with an internal combustion engine (ICE) and a fuel cell (FC) as well as with and without plug-in capability are considered. Zero emission zones (ZEZ) also play an important role in the context of prediction. In this case, vehicles with ICE are forced to operate electrically. In fact, the forced electric drive is a constraint for the optimization, which can have a negative impact on CO_2 emissions. That impact is quantified using the mentioned customer cycle.**

Keywords—control strategy; global optimum; hybrid; fuel cell; zero emission zones; customer cycle; plug-in

I. INTRODUCTION

Hybrid powertrains have two energy storage units, which can be used alternately to drive the vehicle. Hybrid electric vehicles (HEV) have an internal combustion engine (ICE) and at least one electric machine (EM). Fuel cell vehicles (FCEV) also have a hybrid powertrain. Although the wheel is always exclusively driven by an EM, it can be propelled either by the fuel cell (FC) or the battery or a combination of both. The efficiency characteristics of the drive units are very different. A control strategy should therefore control the drivetrain in such a way that the lowest possible fuel consumption is achieved. If the complete cycle is known, a global energy optimum can be calculated for a certain powertrain configuration. This represents the maximum achievable potential for the powertrain.

Basically, a distinction has to be made between HEV and plug-in HEV (PHEV) or FCEV and plug-in FCEV (PFCEV). While the fuel consumption is to be minimized under the constraint of state of charge (SOC) neutrality over the cycle, the PHEV or PFCEV is designed to minimize fuel consumption and SOC at the end of the cycle at the same time. In the following article, the potential of a predictive control strategy is shown on the basis of the comparison of a global optimal control strategy (GOCS) and the local optimal equivalent consumption minimization strategy (ECMS) without prediction. Since it is a new method, GOCS is presented first. Nevertheless, the fundamentals have already been published in [1]. The current operational strategy is an extension of the previous work by [1].

II. GLOBAL OPTIMAL CONTROL STRATEGY

A. Introduction

The global energy optimum of a hybrid drive represents the potential for an existing powertrain and also for an existing control strategy. Furthermore, when comparing different drive concepts, a global optimum ensures that a conceptual efficiency comparison is not influenced by the control strategy used. That application is particularly relevant in the context of powertrain synthesis. In order to be able to evaluate a variety of concepts, the control strategy has to offer a low calculation time. This is usually not the case when using a global optimal method known in the literature (dynamic programming as in [2], [3], [4] or [5]). The control strategy presented in this paper and in [1] has a significant advantage over previous methods since the calculation time is at or below a local optimal control strategy. This is achieved by a systematic approach in which the control strategy consists of successive phases: 1. Optimal ICE / FC operation, 2. Boosting (if necessary), 3. Optimal recuperation, 4. Optimal load decrease as a consequence of recuperation, 5. Optimal load decrease as a consequence of load increase and 6. Optimal load increase up to the desired SOC.

As already described in [1], the driving cycle needs to be known and all possible operation point combinations have to be calculated at the beginning. Therefore, the optimization problem has to be discretized. The simulation model used works at operating temperature and quasi-stationary. Moreover, the battery capacity is considered to be unrestricted. Additionally, the dependency of the battery efficiency on the SOC cannot be taken into account. However, an SOC curve is calculated on the basis of the selected operating points. From this, it can be determined which battery capacity would have been necessary for optimal operation of the hybrid powertrain. The method can be applied to all hybrid topologies and hybridization levels (HEV, PHEV, FCEV and PFCEV). The phases of the control strategy are described below.

B. Optimal ICE / FC operation

First, the hybrid powertrain is operated conventionally, which means hybrid functions are not used yet. In this case, the fuel power P_{fuel} is minimized at every time step. Additionally, the battery may be charged at most. Ideally, a battery neutral operation is achieved as described in [1]. However, there are powertrain concepts that cannot avoid charging the battery in any driving situation. For example, this is the case for an FCEV since the FC has to provide a certain minimum power and has no idle operation like an ICE. In order to be able to identify an optimal consumption in ICE / FC operation for such concepts, unavoidable charging of the battery has to be permitted. The auxiliary consumers (Aux) are also initially supplied by the ICE or the FC.

$$min(P_{Fuel}),\ P_{Bat} \leq 0 \tag{1}$$

By applying (1), the fuel-optimized ICE / FC operation is obtained in each time step of the driving cycle. In the case of a HEV or PHEV, this means that the ICE is ideally operated along the line of its optimal efficiency by the transmission. This idealized operation is shown in Fig. 1.

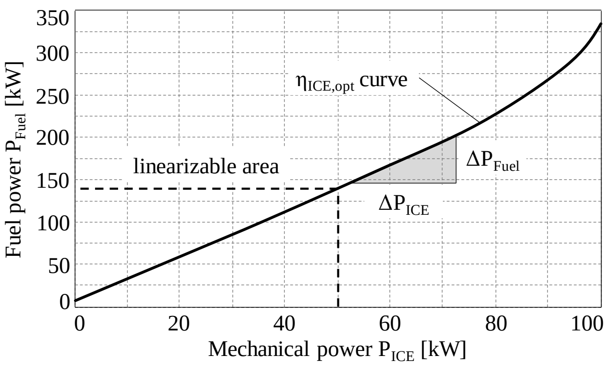

Fig. 1. Fuel power P_{Fuel} as a function of the mechanical ICE power P_{ICE} for optimal efficiency operation

A FC cannot be combined with a transmission. As a result, a certain fuel power is demanded for a certain electrical power as long as the FC is operated along a constant current-voltage curve. Fig. 2 shows the tank capacity as a function of the electrical power of the fuel cell.

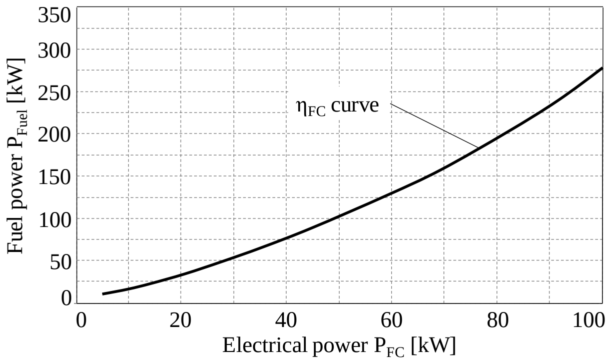

Fig. 2. Fuel power P_{Fuel} as a function of the electrical fuel cell power P_{FC}

C. Boosting

If the cycle cannot be handled by the ICE or the FC alone, additional battery power has to be provided. However, the battery power is minimized in this phase. This means that, initially, the power demand is covered by the ICE or the FC as much as possible. If the battery power was set beyond the minimum, this would already lead to a load decrease, which will be applied later. Equation (2) applies for boosting.

$$min(P_{Bat}),\ P_{Fuel} > 0 \tag{2}$$

D. Optimal recuperation

In this phase, the battery is to be charged as much as possible under the constraint that fuel power is zero (ICE is dragged or deactivated). Therefore, (3) applies during recuperation.

$$min(P_{Bat}),\ P_{Fuel} = 0 \tag{3}$$

Now the battery is charged. In the following, the electrical energy can be used for optimal load decrease as a consequence of recuperation.

E. Optimal load decrease as a consequence of recuperation

In case of an optimal load decrease, the existing electrical energy is used in such a way that a maximum reduction of fuel power is achieved with a specific battery power in a certain time step. The optimal load decrease as a consequence of recuperation is carried out until the recuperated energy is completely converted. After this phase, the end SOC is on the level of the start SOC if the battery was not charged during the optimal ICE / FC operation. Equation (4) applies.

$$min(|\Delta P_{Bat} / \Delta P_{Fuel}|),\ \Delta P_{Bat} > 0 \tag{4}$$

The maximum amount of load decrease is electric driving. In case of a HEV, electric driving is beneficial up to relatively high ICE power compared to load decrease without deactivating the ICE. This is illustrated in Fig. 3.

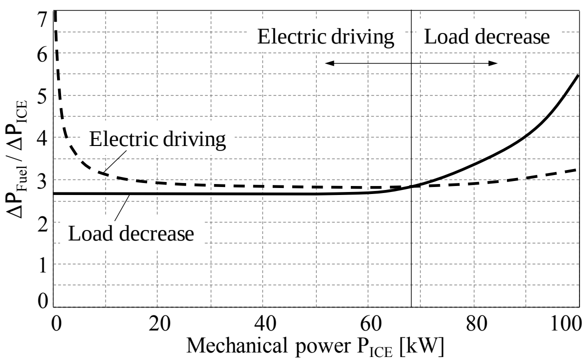

Fig. 3. Optimal load decrease and electrical driving for optimal ICE operation

In contrast, a FC load decrease without deactivating the FC is beneficial over a very wide power range. Only in the lowest power range electric driving results in higher fuel savings. This is illustrated in Fig. 4.

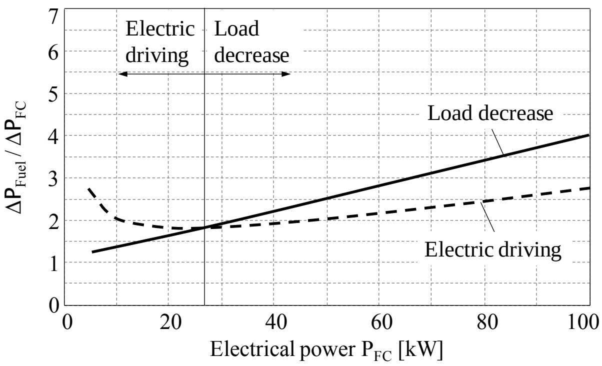

Fig. 4. Optimal load decrease and electric driving for a FC

F. *Optimal load decrease as a consequence of load increase*

Although load decrease as a consequence of recuperation usually contributes to the greatest extent to the saving of a hybrid drive, the overall efficiency can be further increased by the combination of load decrease and load increase. The battery is further discharged, whereby different intensities are possible. This makes it possible to investigate how sensible the fuel consumption is to different intensities of load decrease as a consequence of load increase, which means additional charging of the battery by the ICE or the FC. However, the optimum does not have to be determined iteratively. It is only necessary to decrease the load sufficiently, as the load increase will automatically reduce phases of load decrease until the optimum is achieved. Firstly, with (4), the same relation applies as before for the optimal load decrease as a consequence of recuperation.

G. *Optimal load increase*

In the last step, load increase is used to compensate the discharge of the battery, which has previously passed beyond the nominal SOC, until the desired SOC is obtained at the end of the cycle. For HEV and FCEV, this means that the SOC at the end of the cycle corresponds to the start SOC (SOC neutrality). For PHEV or PFCEV, discharging the battery is desired when it is charged externally. Therefore, a target SOC is defined. In general, the load increase for one cycle is controlled in such a way that a maximum battery charging power ($P_{Bat} < 0$) is achieved for a certain amount of fuel power for the considered time step. Equation (5) applies.

$$max(|\Delta P_{Bat} / \Delta P_{Fuel}|),\ \Delta P_{Bat} < 0 \tag{5}$$

Fig. 5 shows the possible consumption reduction through load increase for a HEV in case of an optimal ICE operation. It can be seen that electric driving as a result of load increase is beneficial at low ICE power. In addition, it is worthwhile to avoid peak power points of the ICE and to carry out load decrease with recharged energy. For the load increase, a constant efficiency is assumed in this case.

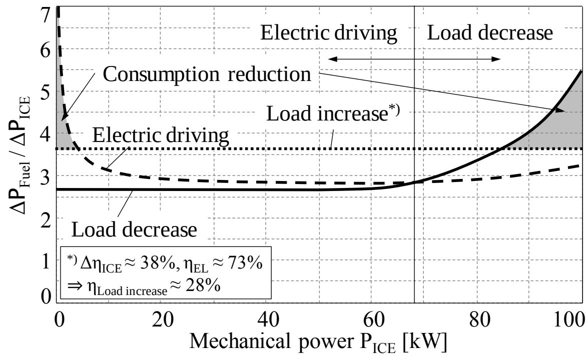

Fig. 5. Consumption reduction of load decrease or electric driving as a consequence of load increase for optimal ICE operation

In case of the FC, Fig. 6 shows that load increase can achieve consumption reduction in a very wide operation range. Basically, it can be derived that the FC is operated optimally around its best efficiency point. This is valid for the case that the cycle profile offers phases of low loads where optimal load increase is possible. A similar relation also applies to serial hybrids.

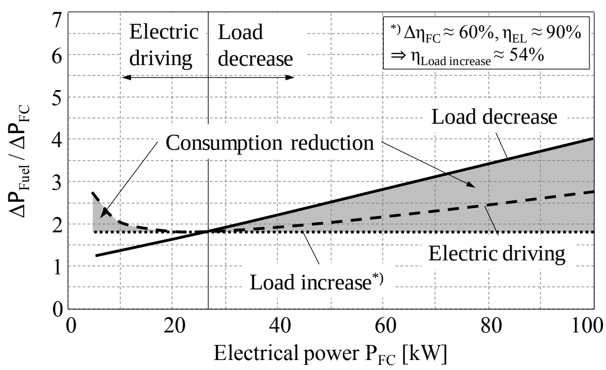

Fig. 6. Consumption reduction through load decrease and electric driving as a consequence of load increase for a FC

III. Local optimal control strategy

As compared to the GOCS, the ECMS is used as a local optimum operating strategy as described in [2], [6] or [7] in a similar form. This leads to an operating point selection in accordance with equation (6) in each time step.

$$min(P_{EC}) = min(P_{Fuel} + (k_{E0} + k_{E1} \cdot \Delta E_{Bat}) \cdot P_{Bat}) \qquad (6)$$

The concept of the ECMS is to make chemical fuel power (P_{Fuel}) with electric battery power (P_{Bat}) comparable by an equivalence factor ($k_{E0} + k_{E1} \cdot \Delta E_{Bat}$). This consists of a constant component k_{E0} and a SOC dependent component $k_{E1} \cdot \Delta E_{Bat}$. Instead of the relative SOC, an absolute value ΔE_{Bat} is used which is independent from the battery capacity. For a SOC neutral operation, the cycle is simulated several times and k_{E0} is adjusted after each cycle until chemical and electrical energy are balanced. The equivalence factor k_{E0} is influenced by the efficiency of the energy converters and the recuperation potential of the cycle. The SOC dependent component $k_{E1} \cdot \Delta E_{Bat}$ ensures that a SOC neutral solution can be found. If the actual SOC deviates from the target SOC, the weighting of the energies is influenced.

Since an adaptation of the equivalence factors requires a known cycle profile, constant parameterizations, which are determined on the basis of the WLTP for the different powertrains, are used for the presented vehicles. In the case of the PHEV and the PFCEV, it is not necessary to select different parameter settings for electric and hybrid operation. Due to the SOC-dependent component $k_{E1} \cdot \Delta E_{Bat}$, the electric drive mode is selected automatically at the beginning of the cycle since the start SOC is significantly above the target SOC. Thus, the local optimal control strategy with fixed equivalence factors is similar to the behavior of a heuristic control strategy as currently implemented in series HEV or PHEV. Based on local optimization, it is a benchmark for control strategies without prediction. This provides a good basis for further potential analysis.

IV. Vehicle parameters

The vehicle concepts examined in this article are presented below (TABLE I.). The HEV and PHEV are P2 topologies with a 6-speed dual clutch transmission (DCT). The two powertrains differ regarding the maximum power of the electric drive, as shown in TABLE I. In addition, different vehicle masses were defined in order to take account of the various drivetrain and energy storage concepts. Further vehicle parameters, e.g. the aerodynamics or the wheel bearing friction, were assumed constant. For vehicles with FC, the same EM is used both for FCEV and PFCEV. This is possible because in the FCEV, the EM has to guarantee the full driving operation anyway. The EM is coupled to a single speed transmission (SST). The auxiliary power P_{Aux} has been assumed to be the same for all concepts and is set to be slightly higher than on the test bench in order to consider comfort and infotainment systems used in reality.

TABLE I. Vehicle and Powertrain Parameters

Vehicle and powertrain parameters					
Parameter	***Unit***	***HEV***	***PHEV***	***FCEV***	***PFCEV***
Vehicle mass	kg	1400	1500	1700	1800
$c_D \cdot A$	m²	0.59	0.59	0.59	0.59
Friction force F_{Fric}	N	40	40	40	40
Rolling resistance coefficient f_{R0}	-	$8 \cdot 10^{-3}$	$8 \cdot 10^{-3}$	$8 \cdot 10^{-3}$	$8 \cdot 10^{-3}$
P_{ICE} / P_{FC}	kW	100	100	100	100
P_{EM}	kW	40	80	120	120
E_{Bat}	kWh	2	8	4	10
P_{Bat}	kW	40	80	60	120
Transmission	-	6G DCT	6G DCT	SST	SST
P_{Aux}	W	400	400	400	400

Fig. 7 illustrates the topology of the HEV and the PHEV. Fig. 8 illustrates the topology of the FCEV and the PFCEV. In general, it is a vehicle with front-wheel drive. The figures are reduced to the drive units. Other components, such as power electronics, electrical connections or the tanks, are neglected in the pictures.

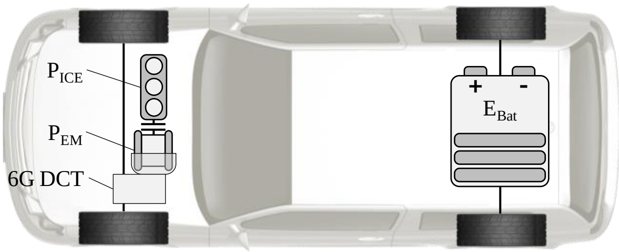

Fig. 7. Schematic representation of the topology of HEV and PHEV

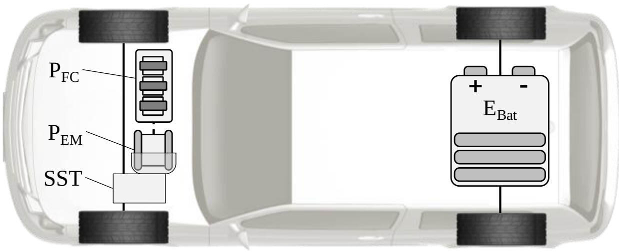

Fig. 8. Schematic representation of the topology of FCEV and PFCEV

V. Simulation Results and Potentials

A. Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP)

All vehicle variants were initially simulated in the WLTP. For the ECMS, the parameterizations of the equivalence factors are determined and used for further investigations in the customer cycle. The speed profile of the WLTP is shown in Fig. 9.

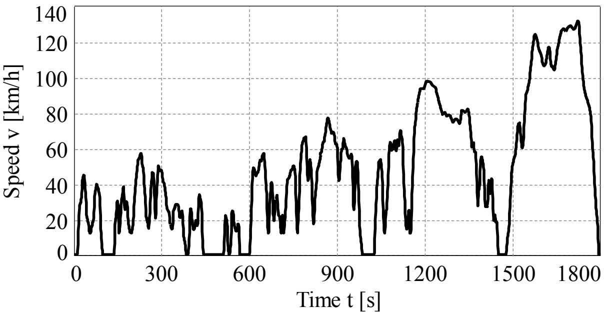

Fig. 9. Speed profile of the WLTP

TABLE II. shows the simulation results for the different vehicles in hybrid operation (charge sustaining mode) for the GOCS as well as the ECMS including the equivalence factors. It can be seen that the ECMS with equivalence factors adapted to a known cycle achieves results that differ only slightly from the global optimum. This was also shown in [2], [4] and [6]. A reason for this is that the ECMS has a predictive function in this case since the cycle profile is fully known and the weightings are adapted to it. The k_{E1} factors were assumed to be constant for all powertrains, whereby different battery capacities are taken into account. The equivalence factor k_{E0} is determined iteratively until the SOC is balanced. At least with regard to the WLTP, the ECMS represents a very efficient operating strategy, which is approximately on the same level as the global optimum.

TABLE II. SIMULATION RESULTS WLTP

Vehicle	Control strategy comparison				
	$B_{s,ECMS}$ [1/100 km]	k_{E0}	k_{E1} [kWh^{-1}]	$B_{s,GOCS}$ [1/100 km]	ΔB_s
HEV	4.28 l	2.65	1	4.27 l	-0.3 %
PHEV	4.44 l	2.70	1	4.43 l	-0.2 %
FCEV	0.806 kg	1.82	1	0.802 kg	-0.5 %
PFCEV	0.826 kg	1.82	1	0.823 kg	-0.4 %

The results for the HEV are shown in Fig. 10 and Fig. 11. On the basis of the SOC curves it can be seen that the GOCS uses a larger SOC window of the battery. At the beginning, the GOCS drives a little less electric, whereby the differences are rather small. In the rural part of the cycle, the GOCS often drives electrically in phases with low power demand. Since the battery is already discharged at this point, the ECMS tends to recharge the battery more quickly. This is due to the SOC dependence of the strategy. Despite the differences between the two curves, it can also be seen that they are parallel in a lot of situations. Thus, the two control strategies behave similarly. With regard to the ICE operation points in Fig. 11, it can be seen that the two control strategies use very similar engine operation ranges. The average ICE efficiencies are roughly the same, whereby the difference of approximately 0.3 % corresponds to the consumption difference.

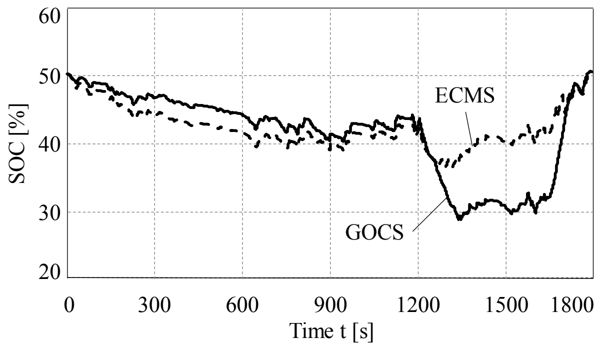

Fig. 10. SOC curves for GOCS (solid line) and ECMS (dashed line) for the HEV in the WLTP for charge sustaining operation

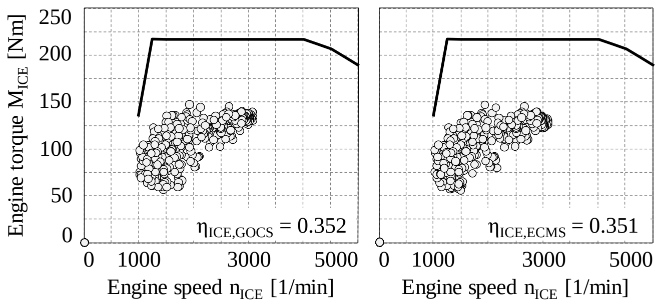

Fig. 11. ICE operation points in WLTP with GOCS (left) and ECMS (right) for the HEV. The average ICE efficiency for GOCS is $\eta_{ICE,GOCS} = 0.352$. For ECMS it is $\eta_{ICE,ECMS} = 0.351$

Similar to the HEV, the FCEV also shows differences for both control strategies. Fig. 13 shows the different SOC curves when using GOCS and ECMS. The GOCS charges the battery at the beginning of the WLTP, so that the load can be decreased at higher load requirements (from approx. 1500 s). This is advantageous as shown in Fig. 6. It can be seen that the behavior of a FC differs significantly from an ICE. The load decrease is also recognizable with ECMS, but less pronounced. Here again, the SOC dependent equivalence factor limits the SOC window of the battery as a constraint of the local optimization. The difference in operation of the FC can also be seen in Fig. 13. The electrical power output of the FC is shown as a function of the driving resistance. While the FC is operated very evenly between 15 kW and 20 kW by the GOCS in the range of its best efficiency, the ECMS also requires higher power from the FC where the efficiency is worse. As a result, the average efficiency drops by 0.6 % with ECMS compared to GOCS.

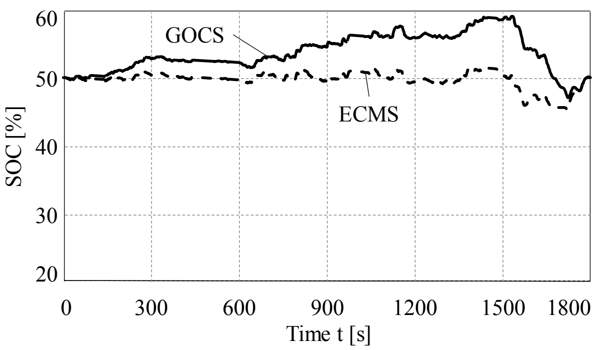

Fig. 12. SOC curves for GOCS (solid line) and ECMS (dashed line) for the FCEV in the WLTP for charge sustaining operation

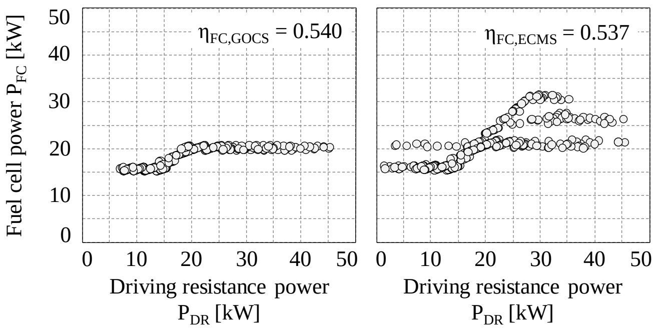

Fig. 13. FC power with GOCS (left) and ECMS (right) for FCEV in the WLTP depending on driving resistance power. The average FC efficiency with GOCS is $\eta_{FC,GOCS}$ = 0.540 and $\eta_{FC,ECMS}$ = 0.537 with ECMS

However, for both the HEV and the FCEV the results show that the ECMS can achieve consumption values on a similar level as the GOCS. Nevertheless, the advantages of the global optimum are recognizable. On the basis of these results, simulations are carried out for customer operation. A customer cycle was generated using the 3D method (Driver, Driven vehicle, Driving environs), as described, for example, in [8] and [9].

B. 3D customer cycle

An average driver was used as the basis for the customer cycle and a constant weight to power ratio of 13 kg/kW was assumed for the vehicle. A combination of city, rural and highway was chosen as driving environment. The total distance is about 85 km, so the PHEV and the PFCEV cannot cope with the cycle purely electric. The customer cycle is shown in Fig. 14. On the basis of cycle-related parameters, the customer cycle can be compared to the WLTP (TABLE III.).

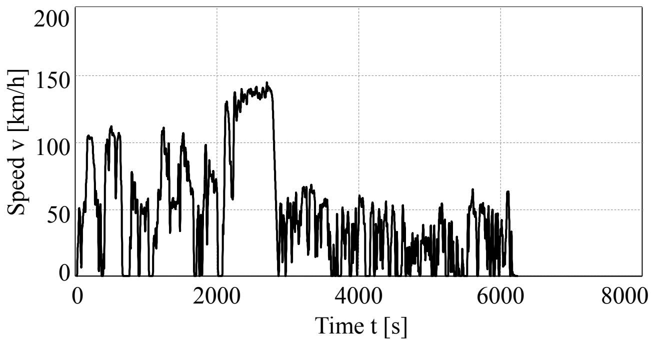

Fig. 14. Speed profile of the 3D customer cycle. It consists of a mix of rural, motorway and city environs. An average driver and a weight to power ratio of 13 kg/kW are assumed.

TABLE III. CYCLE-RELATED PARAMETERS FOR 3D CYCLE AND WLTP

Parameter	**Unit**	***3D cycle***		***WLTP***	
		traction	***thrust***	***traction***	***thrust***
Time	s	3930	1607	1125	449
Distance	km	67.5	17.4	18.5	4,7
Distance share	%	79.5	20.5	79.6	20.4
Average acc.	m/s²	0.15	-0.60	0.16	-0.62
Average speed	m/s	17.2	10.8	16.4	10.5
Effective speed	m/s	27.4	17.7	23.9	17.0

TABLE IV. shows the simulation results when using the ECMS with fixed equivalence factors from the WLTP as well as the GOCS. HEV and FCEV are operated in the charge sustaining mode, while charge depleting operation is carried out for PHEV and PFCEV. The consumption advantages of the GOCS result from the optimal use of the drive units depending on the speed profile. Higher potentials may be achieved if the considered scenario is designed in such a way that a prediction contributes to an increase of the practical recuperation potential. This may be the case, for example, if, as a result of the slope profile, the battery reaches its maximum SOC and therefore the vehicle has to be decelerated mechanically in the event of a gradient. In the presented paper, however, there is at no time a reduction for the recuperation due to an SOC limitation of the battery.

It can be seen in TABLE IV. that for vehicles without a plug-in capability (HEV and FCEV) the advantages of the GOCS are approx. 0.5 % to 1.0 %. Thus, the potential in the 3D customer cycle is only slightly higher than in the WLTP. A reason for this is the fact that the cycle parameters of the 3D customer cycle are similar to the WLTP. Thus, the parameterization of the ECMS also achieves good results in the 3D customer cycle. Above all, the results show that a prediction can only have small advantages for a HEV or FCEV, in case of an applied control strategy which can flexibly select the most efficient operation modes corresponding to the driving situation. As already mentioned, special scenarios which would reduce the recuperation potential without a predictive function represent an exception.

If the vehicle has a plug-in option, the potential increases significantly. It can be seen that the GOCS compared to the ECMS can achieve significant advantages both for the PHEV and the PFCEV. For the HEV or the FCEV, fuel and electrical energy can only be optimally balanced between the two energy storage devices. As a consequence, the efficiency of the ICE or the FC always limits the consumption potential. In the case of the PHEV or the PFCEV, the electrical energy is considered to be "free of charge", so that the energy consumption is not limited by the efficiency of ICE or FC.

Since electrical energy can be supplied by an external energy source, additional potential results from the prediction by exploiting the SOC reserves in hybrid operation. While the minimum SOC at the end of the ECMS is reached at most at random, an optimal prediction can minimize the SOC before the charging process. Both cases were investigated using the GOCS. GOCS-SOC_{ECMS} describes the result when ECMS and GOCS have the same end SOC. GOCS-SOC_{min} describes the case when the GOCS reaches the lowest SOC of the ECMS at the end of the cycle and fully utilizes the SOC reserve of the ECMS as a result. The simulation results are also shown in TABLE IV. Even with an identical end SOC, efficiency advantages of approx. 3 % for PHEV and PFCEV can be identified. By utilizing the minimum SOC, the potentials increase to approx. 4 % (PHEV) and 9 % (PFCEV). However, the potential depends strongly on the application of the basic strategy with regard to the design of the SOC reserve.

TABLE IV. SIMULATION RESULTS 3D CYCLE

Vehicle	Fuel consumption [l/100km or kg/100km]				
	ECMS **(*k_E = const.*)**	***GOCS SOC_{ECMS}***	***ΔB_s SOC_{ECMS}***	***GOCS SOC_{min}***	***ΔB_s SOC_{min}***
HEV	4.81	4.79	-0.5 %	-	-
PHEV	2.90	2.81	-3.2 %	2.78	-4.1 %
FCEV	0.905	0.896	-1.0 %	-	-
PFCEV	0.483	0.469	-2.9 %	0.441	-8.7 %

Fig. 15 shows the SOC curves for the PHEV with ECMS as well as GOCS with the different target SOC (GOCS-SOC_{ECMS} and GOCS-SOC_{min}) as explained above. Since the ECMS drives the vehicle in battery-powered mode for approx. 2200 s, the SOC drops considerably. At about 20 % SOC, the ECMS automatically changes to the charge sustaining mode. The lowest SOC that occurs during operation with ECMS is defined as SOC_{min}. The GOCS shows a continuous discharge of the battery over the cycle. The optimal use of the electrical energy means that the ICE is operated during the entire cycle.

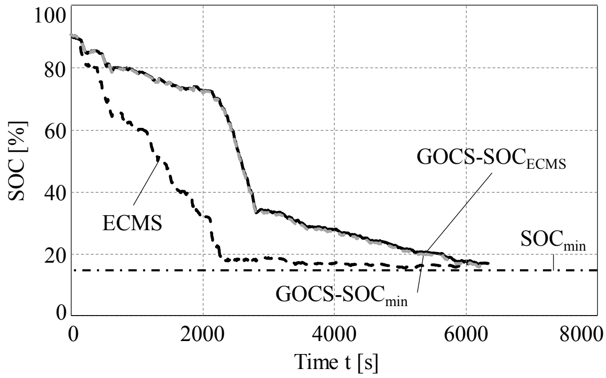

Fig. 15. SOC curves for the PHEV with ECMS (black dashed line) and GOCS (black solid and gray dashed lines). SOC_{min} is the minimal SOC which occurs with ECMS. GOCS-SOC_{min} uses SOC_{min} as the target SOC and GOCS-SOC_{ECMS} the same end SOC as the ECMS.

Fig. 16 shows the operation points of the ICE for operation with GOCS and ECMS. The ICE is used with different load profiles through both control strategies. With GOCS, an average efficiency of 35 % is achieved, while the ECMS only achieved 34.4%. This results in a difference of 1.7 % in engine efficiency. However, the consumption difference is even higher with 3.2 %. This is because the ECMS increases the ICE efficiency with load increase in charge sustaining operation. However, as explained in [1], this leads to additional losses which partly compensate or overcompensate the increases in engine efficiency. The GOCS does not operate the ICE under load increase at any time during the cycle.

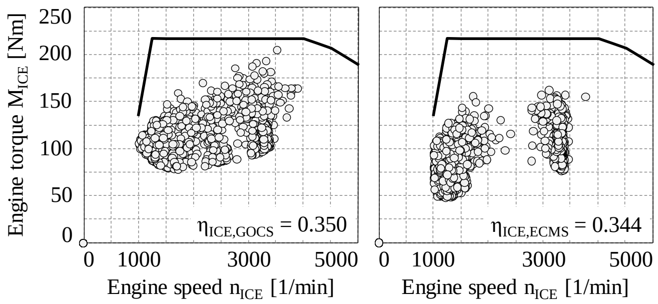

Fig. 16. ICE operation points in the 3D customer cycle with GOCS (left) and ECMS (right) for the PHEV. The average ICE efficiency for GOCS is $\eta_{ICE,GOCS} = 0.350$. For ECMS it is $\eta_{ICE,ECMS} = 0.344$.

Analogous to the PHEV, the results can be interpreted for the PFCEV. The difference between SOC_{min} and end SOC is greater for the ECMS. During highway operation, load decrease of the FC is particularly worthwhile, so that SOC_{min} is achieved here. In the following, the battery is recharged by the FC. Since a FC has a slower transient behavior compared to an ICE, the battery plays an even more important role for a FC powered vehicle especially in dynamic driving situations. Thus, this has to be reflected in a higher SOC reserve and therefore a higher potential for a predictive control strategy to exploit this reserve.

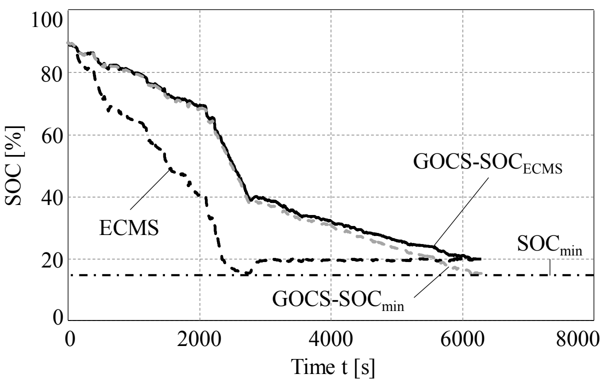

Fig. 17. SOC curves for the PFCEV with ECMS (black dashed line) and GOCS (black solid and gray dashed lines). SOC_{min} is the minimal SOC which occurs with ECMS. GOCS-SOC_{min} uses SOC_{min} as the target SOC and GOCS-SOC_{ECMS} the same end SOC as the ECMS.

Fig. 18 shows the FC power P_{FC} as a function of the driving resistance power P_{DR}. It can be seen that the GOCS operates the FC in phases where high wheel power has to be generated. However, this is done with a strong load decrease since the power of the FC always remains between 15 kW and 20 kW. An average FC efficiency of 54 % is achieved with the GOCS. With the ECMS, it is noticeable that the FC remains deactivated during phases of high wheel power. This shows the missing prediction, since these phases are performed electrically. Due to the non-optimal use of the electrical energy, the FC has to be operated temporarily at higher power where the efficiency drops. As a result, the average FC efficiency of 53.1 % with ECMS is approx. 1.7 % lower compared to the GOCS. Again, the difference in fuel consumption is even higher (approx. 3 % with equal end SOC).

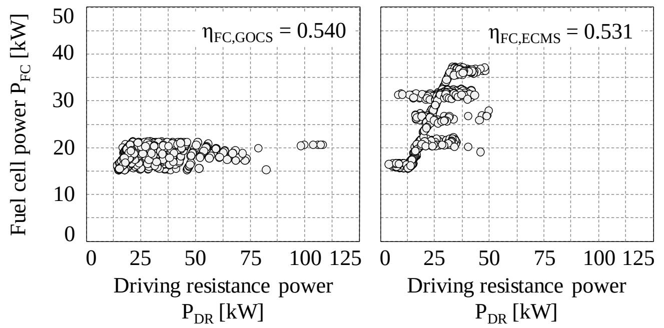

Fig. 18. FC power with GOCS (left) and ECMS (right) for FCEV in the 3D customer cycle depending on driving resistance power. The average FC efficiency with GOCS is $\eta_{FC,GOCS}$ = 0.540 and $\eta_{FC,ECMS}$ = 0.531 with ECMS.

C. *Influence of zero emission zones (ZEZ) in cities*

In order to improve air quality in the cities, legislators worldwide are increasingly opting for zero emission zones (ZEZ) in cities. This means that the vehicle must have sufficient electrical energy in the battery in order to drive electrically in the ZEZ. At the same time, this means a constraint for the powertrain control which can deviate from the energetic optimum. The influence of a ZEZ on fuel consumption and therefore on global CO_2 emissions is quantified below. A ZEZ between 3743 s and 5227 s with a length of 10.4 km is defined for the 3D customer cycle described before. It is indicated in Fig. 19.

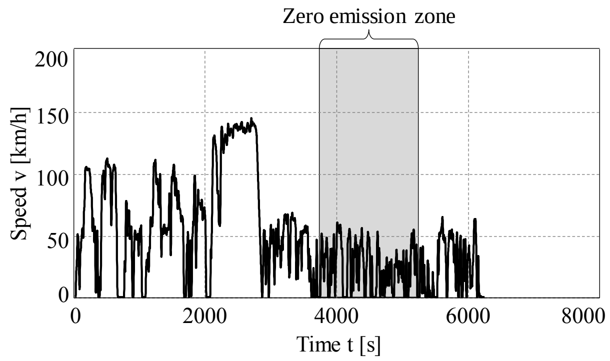

Fig. 19. Speed profile of the 3D customer cycle with zero emission zone

In this case, two cases are distinguished: In charge depleting operation, the externally recharged electrical energy is used for electric driving in the ZEZ. In charge sustaining operation, the effects of consumption are determined when the electrical energy is generated completely by the ICE. The results are shown in TABLE V. It turns out that the fuel consumption increases slightly in both charge depleting and the charge sustaining operation, while the effects in charge sustaining operation are greater. However, the results also have to be assessed regarding the overall cycle. The major part of the fuel consumption is generated in the rural and motorway part, since the ZEZ is only a small part of the whole driving cycle (10.4 km of 85 km). In addition, the ZEZ is usually characterized by a speed profile in which a high electrical driving share is present anyway.

TABLE V. SIMULATION RESULTS 3D CYCLE WITH ZERO EMISSION ZONE

Vehicle	**Fuel consumption [l/100km]**		
	$B_{s,ZEZ}$	B_s	ΔB_s
PHEV (CD)	2.785	2.780	+0.2%
PHEV (CS)	4.978	4.958	+0.4%

The following figures show the SOC curves for charge depleting (Fig. 20) and charge sustaining operation (Fig. 21). In the case of charge depleting operation, the forced electric driving is energetically compensated by the fact that the battery is previously discharged less strongly. An additional load increase is not performed. In contrast, this is not possible with charge sustaining operation since the electrical energy has to be generated completely by the ICE. This can be seen between 2500 s and 3000 s (Fig. 21). However, the GOCS also carries out a recharge of the battery without ZEZ in order to be able to drive more electrically subsequently.

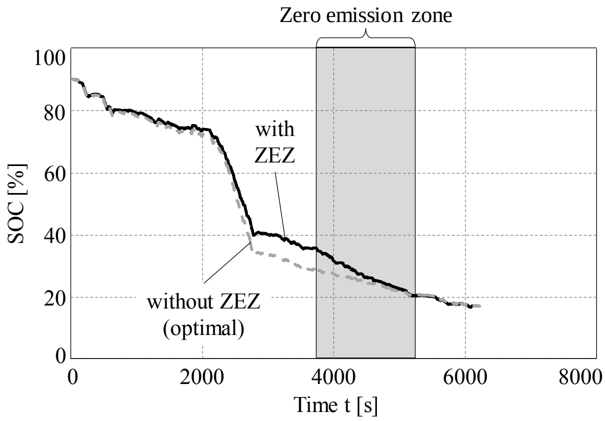

Fig. 20. SOC curve for the PHEV for charge depleting operation with ZEZ (black solid line) and without ZEZ (gray dashed line)

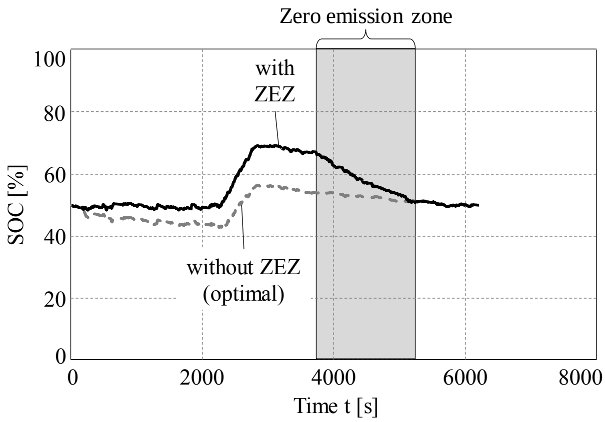

Fig. 21. SOC curve for the PHEV for charge sustaining operation with ZEZ (black solid line) and without ZEZ (gray dashed line)

VI. Summary and Outlook

In this article, the potential of a predictive control strategy regarding the energy consumption of hybrid and plug-in hybrid vehicles was considered. Both powertrain concepts with ICE as well as with FC were evaluated (HEV, PHEV, FCEV and PFCEV). Firstly, a method for the determination of the global energetic optimum was presented. The global optimal control strategy (GOCS) is based on a systematic sequence of different phases, whereby an energetic partial optimization is carried out in each phase. The global optimum represents the potential for a control strategy that has an optimal prediction. The GOCS was compared with the ECMS as a local optimal control strategy, whereby a fixed parameterization of the equivalence factors was determined using the WLTP and kept constant for all further investigations. This represents the reference case of an applied operating strategy which has been optimized for the WLTP and has no adaptation to another cycle. In the WLTP, therefore, only slight differences between approx. 0.2 % to 0.5 % between the ECMS and the GOCS can be recognized since both strategies behave similarly. To assess the prediction, a customer cycle was generated using the 3D method of the IAE. For the HEV and the FCEV, consumption advantages of 0.5 % to 1.0 % were achieved by the GOCS. The plug-in vehicles (PHEV and PFCEV) yielded advantages of 2.9 % to 8.7 %, depending on the size of the SOC reserve of a basis control strategy. Finally, the influence of zero emission zones (ZEZ) on fuel consumption was evaluated on the basis of GOCS. Electric driving within these zones is a constraint for the optimization, which is why deviations from the global optimum without ZEZ can occur. The investigations were carried out using the PHEV in charge-charging and charge-holding operation. Consumption increases of 0.2 % to 0.4 % were observed. This applies to a 10.4 km long ZEZ in a total driving cycle of 85 km. If the share of the ZEZ length is higher, the consumption will be higher or vice versa if the share is smaller.

References

[1] A. Lange and F. Küçükay, “A new, systematic approach to determine the global energy optimum of a hybrid vehicle”, Automotive and Engine Technology, The International Journal of WKM, ISSN 2365-5127, Springer International Publishing Switzerland 2016

[2] Serrao, L., "A comparative analysis of energy management strategies for hybrid electric vehicles”, Center for Automotive Research, The Ohio State University, J. Dyn. Syst. Meas. Control. 133, 031012-1–031012-9 (2011)

[3] M. Back, „Prädiktive Antriebsregelung zum energieoptimalen Betrieb von Hybridfahrzeugen“, Dissertation, Universität Karlsruhe (TH), 2005

[4] A. Sciarretta, M. Black and L. Guzzella, "Optimal control of parallel hybrid electric vehicles". IEEE Trans. Control Syst. Technol. 12, 3, 2004

[5] O. Sundström, “OPTIMAL CONTROL AND DESIGN OF HYBRID-ELECTRIC VEHICLES”, Dissertation, ETH Zürich, 2009

[6] C. Musardo, G. Rizzoni and B. Staccia, “A-ECMS: An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management”, Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005, Seville, Spain, December 12-15, 2005

[7] M. Khodabakhshian, L. Feng and J. Wikander, “Improving Fuel Economy and Robustness of an Improved ECMS Method”, 10th IEEE International Conference on Control and Automation (ICCA), Hangzhou, China, June 12-14, 2013

[8] M. Eghtessad, "Optimale Antriebsstrangkonfigurationen für Elektrofahrzeuge", Dissertation, TU Braunschweig, Institut für Fahrzeugtechnik, Shaker Verlag, 2014

[9] J. P. Müller-Kose, "Repräsentative Lastkollektive für Fahrzeuggetriebe", Dissertation, TU Braunschweig, Institut für Fahrzeugtechnik, Shaker Verlag, 2002