

Rule-Based Equivalent Fuel Consumption Minimization Strategies for Hybrid Vehicles^{*}

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Abstract: The highest control layer of a (hybrid) vehicular drive train is termed the Energy Management Strategy (EMS). In this paper an overview of different control methods is given and a new rule-based EMS is introduced based on the combination of Rule-Based and Equivalent Consumption Minimization Strategies (RB-ECMS). The RB-ECMS uses only one main design parameter and requires no tuning of many threshold control values and parameters. This design parameter represents the maximum propulsion power of the secondary power source (i.e., electric machine/battery) during pure electric driving. The RB-ECMS is compared with the strategy based on Dynamic Programming (DP), which is inherently optimal for a given cycle. The RB-ECMS proposed in this paper requires significantly less computation time with the similar result as DP (within $\pm 1\%$ accuracy).

Keywords: Automobile powertrains, Hybrid and alternative drive vehicles, Nonlinear and optimal automotive control, Energy management

1. INTRODUCTION

Hybridization in vehicles implies adding a Secondary power source with reversal energy buffer (S) (i.e., an electric machine/battery) to a Primary power source with irreversible energy buffer (P) (i.e., an engine/filled fuel tank) in order to improve vehicle performance. The major desirable improvements are the vehicle's fuel economy, emissions, comfort, safety, and driveability. The fuel consumption of a vehicle can be reduced by down-sizing the engine, which results in less idle-fuel consumption, and a lower brake-specific fuel consumption. A second, though complementary method is recuperation of the brake energy, and re-using this stored energy when momentary fuel costs are high avoiding idle-fuel consumption and engine operation points with high brake-specific fuel consumption. The Energy Management Strategy (EMS) plays an important role in an effective usage of the drive train components, see, e.g., Delprat et al. [2004], Paganelli et al. [2002], Sciarretta et al. [2004], Rizonni et al. [2004], Koot et al. [2005]. Control strategies may be classified into non-causal and causal controllers respectively. Furthermore, a second classification can be made among heuristic, optimal and sub-optimal controllers Guzzella and Sciarretta [2005]. In the sections below some of these methods will be discussed in more detail.

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1.1 Optimal Control Strategy – Dynamic Programming

A commonly used technique for determining the globally optimal EMS is Dynamic Programming (DP), see, e.g., Koot et al. [2005]. Using DP the finite horizon optimization problem is translated into a finite computation problem Bellman [1962]. Note that although the DP solution may appear as an unstructured result, in principle the technique results in an optimal solution for the EMS. Using DP it is rather straightforward to handle non-linear constraints. However, a disadvantage of this technique is the relatively long computation time due to the relatively large required grid density. The grid density should be taken high, because it influences the accuracy of the result. Furthermore, it is inherently non-causal, and therefore not real-time implementable.

1.2 Sub-Optimal Control Strategy – Heuristic Control Strategy

Most of the described Rule-Based (RB) control strategies in literature Wipke et al. [1999], Lin et al. [2003] are based on 'if-then' type of control rules, which determine for example when to shut down the engine or the amount of electric (dis-)charging powers. The electric (machine) output power is usually prescribed by a non-linear parametric function. Each driving mode uses different parametric functions which are strongly dependent on the application (drive train topology, vehicle and drive cycle), and needs to be calibrated for different driving conditions. In Lin et al. [2003] the threshold values for mode switching and pa-

parameters are calibrated by using DP. Thereby, the power-split ratio between the secondary source S and the vehicle wheels for each driving mode is optimized. To overcome the difficulty of calibrating a large number of threshold values and parameters, control strategies are developed based on optimal control theory, which will be discussed in the following section.

1.3 Sub-optimal Control Strategy – Equivalent Consumption Minimization Strategy

In literature Equivalent Consumption Minimization Strategies (ECMS) are presented, see, e.g., Paganelli et al. [2002], Sciarretta et al. [2004], Musardo et al. [2005], Guzzella and Sciarretta [2005], which are based on an equivalent fuel mass-flow $\dot{m}_{f,eq}(t)$ (g/s). The equivalent fuel mass-flow uses an electric-energy-to-fuel-conversion-weight-factor, or equivalence (weight) factor $\lambda(t)$ (g/J) in order to weight the electrical power $P_s(t)$ (W) within the same domain at a certain time instant t . Basically, the $\lambda(t)$ is used to assign future fuel savings and costs to the actual use of electric power $P_s(t)$. Moreover, a well determined $\lambda(t)$ assures that discrepancy between the buffer energy at the beginning and at the end of the drive cycle with time length t_f is sufficiently small. The $\dot{m}_{f,eq}(t)$ is defined as,

$$\dot{m}_{f,eq}(t) = \dot{m}_f(P_s(t)) - \lambda(t) P_s(t), \quad \lambda(t) > 0 \quad \forall t \in \{0, t_f\}, \quad (1)$$

where $\dot{m}_f(t)$ is the instantaneous (actual) fuel mass-flow. Although, for example, during discharging $P_s(t) < 0$ the actual fuel mass-flow $\dot{m}_f(t)$ is reduced, Eq. (1) shows that the fuel equivalent of the electrical energy $-\lambda(t) P_s(t)$ is momentarily increased and vice-versa. The optimal momentary power set-point $P_s^o(t)$ for the secondary power source is the power, which minimizes Eq. (1) given a certain $\lambda(t)$:

$$P_s^o(t) = \arg \min_{P_s(t)} (\dot{m}_{f,eq}(t) | \lambda(t)). \quad (2)$$

The $\lambda(t)$ depends on assumptions concerning the component efficiencies and chosen penalty functions on deviation from the target battery state-of-charge. For an overview on various approaches to this optimization problem seen in literature is given in Hofman et al. [2007].

1.4 Sub-Optimal Control Strategy – RB-ECMS

In order to tackle the drawbacks of DP, RB and ECMS, which is the aim of this paper, a new and relative simple solution for the EMS control problem is introduced having the following main features:

- the proposed method consists of a combination of methods, i.e., RB and ECMS (RB-ECMS),
- the maximum propulsion power of the secondary power source (i.e., electric machine / battery) during pure electric driving is used as the main design parameter, and
- the predefined hybrid modes and rules are independent on the type of drive train topology.

Since a drive train topology defines the paths and the efficiencies of the energy flow between P, S and the vehicle wheels. However, a topology choice influences the optimization of the design parameter.

1.5 Outline of the Paper

The remainder of this paper is structured as follows: first, the general control optimization problem of a hybrid drive train is discussed in Section 2. Then, the derived hybrid driving modes and the RB-ECMS are discussed in the Sections 3 and 4 respectively. Furthermore, a physical background for not using all potentially available motoring power during pure electric driving is given. The relationship between $\lambda(t)$ as used in ECMS and the design parameter as used in the proposed RB-ECMS is discussed. In Section 5, results of the proposed RB-ECMS will be compared for a specific application (Toyota Prius, model 1998) with results from DP and the vehicle simulation platform ADVISOR Wipke et al. [1999]. Finally, the conclusions are given in Section 6.

2. PROBLEM DEFINITION

The optimization problem is finding the control power-flow $P_s(t)$, given a certain power demand at the wheels $P_v(t)$ minimizing the cumulative fuel consumption, denoted by the variable Φ_f , over a certain drive cycle with time length t_f , subject to several constraints, i.e.,

$$\Phi_f = \min_{P_s(t)} \int_0^{t_f} \dot{m}_f(E_s(t), P_s(t), t | P_v(t)) dt, \quad (3)$$

subject to $\mathbf{h} = 0, \mathbf{g} \leq 0,$

where \dot{m}_f is the fuel mass-flow in g/s. The state is equal to the stored energy E_s in the secondary reversal energy buffer in J, and the control input is equal to the secondary power-flow P_s in W (see, also Fig. 1). The energy level in the battery is a simple integration of the power and is calculated as follows,

$$E_s(t) = E_s(0) + \int_0^t P_s(\tau) d\tau. \quad (4)$$

The main constraints on the secondary power source S are energy balance conservation of E_s over the drive cycle, constraints on the power P_s , and the energy E_s :

$$\begin{aligned} h_1 &:= E_s(t_f) - E_s(0) = 0, \\ g_{1,2} &:= P_{s,min} \leq P_s(t) \leq P_{s,max}, \\ g_{3,4} &:= E_{s,min} \leq E_s(t) \leq E_{s,max}. \end{aligned} \quad (5)$$

The optimal solution is denoted $P_s^o(t)$. In this paper the

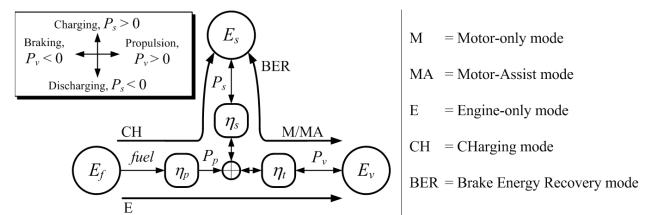


Fig. 1. Power-flows for the different hybrid driving modes. S connected at the engine-side of the transmission.

value for the energy level instead of the charge level in the battery has been used. Note that, if the open-circuit voltage of a battery is assumed constant, then the relative state-of-charge ξ is equal to the relative state-of-energy, i.e., $\xi(t) = E_s(t)/E_{cap}$. The energy capacity of the battery E_{cap} is assumed to be constant. However, for battery systems the open-circuit voltage typically changes slightly as a function of ξ . This is not considered in this paper.

3. HYBRID DRIVING MODES

A hybrid drive train can be operated in certain distinct driving modes. In Fig. 1, a block diagram is shown for the power distribution between the different energy sources, i.e., fuel tank with stored energy E_f , S with stored energy E_s , and the vehicle driving over a drive cycle represented by a required energy E_v . The efficiencies of the fuel combustion in the engine, the storage and electric motor S, and the Transmission (T) are described by the variables η_p , η_s , and η_t respectively. The energy exchange between the fuel tank, source S and the vehicle can be performed by different driving modes (depicted by the thick lines). The engine power at the crank shaft is represented by P_p . The power demand at the wheels (P_v) and the power-flow to and from S (P_s) determine which driving mode is active. The following operation modes are defined:

M: Motor-only mode, the vehicle is propelled only by the electric motor and the battery storage supply (S) up to a fixed propulsion power (design parameter), denoted as P_M , for the whole drive cycle, which is not necessarily equal to the maximum available propulsion power of the electric machine. The engine is off, and has no drag and idle losses.

BER: Brake Energy Recovery mode, the brake energy is recuperated up to the maximum generative power limitation and stored into the accumulator of S. The engine is off, and has no drag and idle losses.

CH: Charging mode, the instantaneous engine power is higher than the power needed for driving. The redundant energy is stored into the accumulator of S.

MA: Motor-Assisting mode, the engine power is lower than the power needed for driving. The engine power is augmented by power from S.

E: Engine-only mode, only the engine power is used for propulsion of the vehicle. S is off and generates no losses.

During the M and BER mode the engine is off, and as a consequence uses no fuel. This is also referred to as the Start-Stop mode.

4. THE RB-ECMS

The operation points for P and S given certain driving conditions (drive cycle and vehicle parameters) can be found in certain distinct driving states, or modes. For the ease of understanding, the modes are represented as operation areas in a static-efficiency engine map separated by two iso-power curves as are shown in Fig. 2. The solid iso-power curve separates the M mode from the CH mode, and the E mode. The dotted iso-power curve separates the operation points of the engine during the CH and the MA mode. The vehicle drive power values for which the secondary source during the M mode is sufficient (i.e., below the solid line in Fig. 2) is given by,

$$P_v(t) \leq -\max(\min(0, P_s(t)), P_M(t)) \eta_s(t) \eta_t(t), \quad (6)$$

with $P_{s,min} \leq P_M(t) < 0$ the largest possible motor-only power. The minimum discharging power is denoted as $P_{s,min}$. So we also have that in M mode:

$$P_v(t) = -P_M(t) \eta_s(t) \eta_t(t), \quad (7)$$

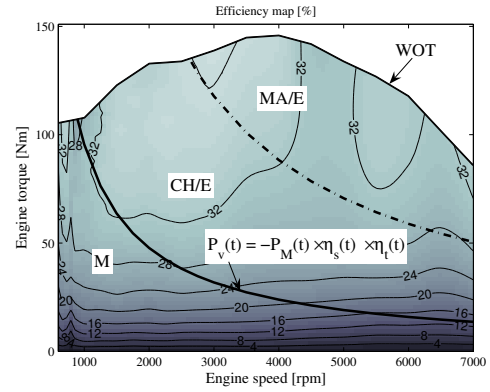


Fig. 2. Contour plot of the engine efficiency in % as a function of the engine torque and speed. WOT = Wide-Open Throttle torque

which is shown as solid line in Fig. 2. Following from the EMS calculated with DP (see, also Section 1.1), the decision variable $P_M(t)$ determining when to switch between the M mode and the other modes, appeared to be approximately constant with the vehicle power demand $P_v(t)$, i.e., $P_M(t) \approx P_M \forall t = [0, t_f]$. Whereas the (dis-)charging power and the mode switch between MA and CH mode varies with the vehicle power demand (dotted iso-power curve).

4.1 Power-Flow during the BER and the M Mode

Observed from the EMS from DP, the optimal power set-point $P_s^o(t) = P_{s,I}^o(t)$ during the M and the BER mode is respectively,

$$P_{s,I}^o(t) = -\max\left(\underbrace{P_v(t)/(\eta_s(t) \eta_t(t))}_{\text{M mode}}, \underbrace{P_v(t) \eta_s(t) \eta_t(t)}_{\text{BER mode}}\right). \quad (8)$$

The subscript I indicates the power-flow during the BER and M mode. The minus sign in Eq. (8) indicates that the source S is discharging during propulsion and charging during braking. Notice that if the source S is coupled at the wheel-side of the transmission then $\eta_t(t)$ in Eq. (8) is left out. The power set-point is limited between the following constraints,

$$P_{s,min} \leq P_M^o \leq 0 \leq P_{s,I}^o(t) \leq P_{s,max}. \quad (9)$$

Braking powers larger than the maximum charging power $P_{s,max}$ are assumed to be dissipated by the wheel brake discs. If only the M and/or the BER mode are utilized, then the energy difference $\Delta E_{s,I}$ at the end of the drive cycle becomes,

$$\Delta E_{s,I} = \int_0^{t_f} P_{s,I}^o(t) dt, \quad \Delta E_{s,I} \in \mathbb{R} \quad (10)$$

In order to fulfill the equality constraint h_1 of Eq. (5) this energy has to be counterbalanced with the relative energy $\Delta E_{s,II}$ at the end of the cycle during the MA and the CH mode as is shown in Fig. 3, whereby,

$$-\Delta E_{s,I} = \Delta E_{s,II}. \quad (11)$$

4.2 Power-Flow during the MA, the CH, and the E Mode

The fuel mass-flow during the BER/M mode is $\dot{m}_f(P_{s,I}^o(t)) = 0$. Therefore, the total fuel mass-flow $\dot{m}_f(t)$

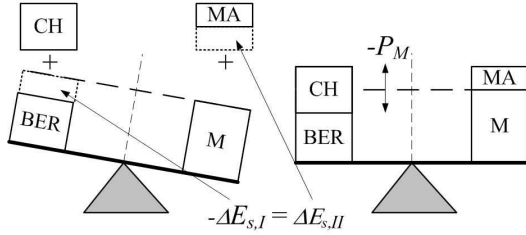


Fig. 3. Energy balance during the BER/M and the CH/MA modes.

can be written as the sum of the fuel mass-flow only depending on the drive power demand $P_v(t)$ (engine-only, E mode) and some additional fuel mass-flow $\Delta\dot{m}_f(t)$ depending on the (dis-)charging power $P_{s,II}(t)$ during the MA and the CH mode,

$$\dot{m}_f(t) = \begin{cases} 0, & \text{if } -P_v(t)/(\eta_s(t)\eta_t(t)) \geq P_M^o, \\ \underbrace{\dot{m}_f(P_v(t))}_{\text{E mode}} + \underbrace{\Delta\dot{m}_f(P_{s,II}(t))}_{\text{CH/MA mode}}, & \text{elsewhere.} \end{cases} \quad (12)$$

If $P_{s,II}(t) = 0$, then the vehicle is propelled by the engine-only (E mode). During the MA and the CH mode the engine is on and the optimal motor-assisting or charging power $P_{s,II}(t) \neq 0$ depends on the drive power demand $P_v(t)$, the component efficiencies and the amount of energy $\Delta E_{s,II}$ that needs to be counterbalanced with the energy used during the BER/M mode $\Delta E_{s,I}$. The optimization problem becomes finding the optimal power-flow $P_{s,II}^o(t)$ during the CH and the MA mode given a certain power demand $P_v(t)$ while the cumulative fuel consumption denoted by the variable Φ_f over a certain drive cycle with time length t_f is minimized subjected to the energy constraint of Eq. (11):

$$\Phi_f = \min_{P_{s,II}(t)} \int_0^{t_f} \dot{m}_f(P_{s,II}(t), t | P_v(t)) dt, \text{ subject to} \\ \int_0^{t_f} P_{s,II}(t) dt = \Delta E_{s,II}. \quad (13)$$

Finding a solution to this problem can be solved via an unconstrained minimization of the Lagrangian function Φ'_f using a Lagrange multiplier $\lambda(t)$.

$$\Phi'_f = \min_{P_{s,II}(t)} \int_0^{t_f} (\dot{m}_f((P_{s,II}(t), t) | P_v(t)) - \lambda(t) P_{s,II}(t)) dt \\ + \lambda(t) \Delta E_{s,II}. \quad (14)$$

The optimal solution can be calculated by solving,

$$\frac{\partial \Phi'_f}{\partial P_{s,II}(t)} = 0, \text{ and } \frac{\partial \Phi'_f}{\partial \lambda(t)} = 0. \quad (15)$$

The solution is given by,

$$\frac{\partial(\dot{m}_f(P_{s,II}(t), t) | P_v(t))}{\partial P_{s,II}(t)} - \lambda(t) = 0, \text{ and} \\ \int_0^{t_f} P_{s,II}(t) dt = \Delta E_{s,II}. \quad (16)$$

From classical optimal control theory, it follows that the solution for $\lambda(t)$ is a constant (see, e.g., Guzzella and Sciarretta [2005]). This under the assumption that the storage power-flow is not affected by the state-of-energy of the accumulator. This holds if the change in, e.g., the

internal battery parameters (open circuit voltage, internal resistance) is neglected, which is assumed in this paper. The constant λ_0 is also referred to the average equivalence weight factor. The optimizing solution λ_0 requires the a priori information of the complete drive cycle. If λ_0 is known, then the optimal accumulator power $P_{s,II}^o(t)$ can be calculated by solving at the current time instant t :

$$P_{s,II}^o(t) = \arg \min_{P_{s,II}(t)} (\dot{m}_f((P_{s,II}(t), t) | P_v(t)) - \lambda_0 P_{s,II}(t)), \quad (17)$$

whereby the power set-point is limited between the following constraints,

$$P_{s,min} \leq 0 \leq P_{s,II}^o(t) \leq P_{s,max}. \quad (18)$$

Then $\Delta E_{s,II}$ is discharged (charged) at vehicle power demands where the fuel savings (costs), i.e., $\Delta\dot{m}_f$ are maximum (minimum). In addition, the energy quantities during the MA and the CH mode are in balance with the BER and M mode over the whole drive cycle.

4.3 Optimization Routine (Offline) for calculating P_M^o

Summarized, the optimal power set-point for the secondary power source S as discussed in the previous two sections during the BER/M and the CH/MA mode becomes respectively:

$$P_s^o(t) = \begin{cases} P_{s,I}^o(t) \text{ (see, Eq. (8)), if} \\ -P_v(t)/(\eta_s(t)\eta_t(t)) \geq P_M^o, \\ P_{s,II}^o(t) \text{ (see, Eq. (17)), elsewhere.} \end{cases} \quad (19)$$

In the Fig. 4, a block diagram is shown of the offline optimization routine suggested in this paper. The routine consist of two iteration loops. In iteration loop 1, the value for λ using a chosen fixed mode switch value of $P_M = [P_{s,min}, 0]$ is determined, which assures that for the whole drive cycle the energy during the BER/M modes is in balance with the energy during the CH/MA modes. The corresponding λ is denoted as λ_0 :

$$\lambda_0 \in \{\Delta E_s = \Delta E_s(\lambda) \mid \Delta E_s(\lambda_0) = 0 \wedge \\ \Delta E_s = \Delta E_{s,I} + \Delta E_{s,II}\}. \quad (20)$$

In iteration loop 2, the optimal value for P_M is determined, which minimizes the total fuel consumption Φ_f :

$$P_M^o = \arg \min_{P_M} \Phi_f(P_M). \quad (21)$$

Then, simultaneously the corresponding value for λ_0 , denoted as λ_0^o , is stored. In the following section based on the results with DP and the RB-ECMS, the relationship between P_M^o and λ_0^o will be discussed in more detail.

5. SIMULATION RESULTS

5.1 Component Models

Simulations were done for a series-parallel hybrid transmission type (Toyota Prius, 1998). For the relevant component data of the Toyota Prius (model 1998) is referred to NREL [2002] and Hofman et al. [2007]. The inertias of the electric machines, engine and auxiliary loads are, for simplicity, assumed to be zero. All simulations performed presented in this paper have been done for the JP10-15 mode cycle. Furthermore, the engine is assumed to be operated at its maximum efficiency operation points.

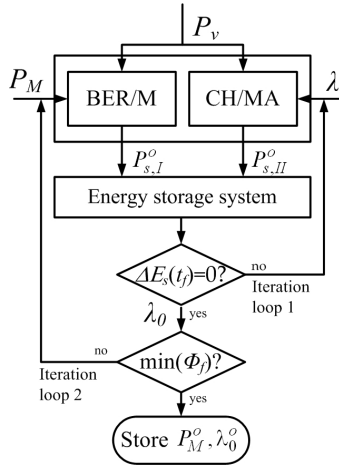


Fig. 4. Numerical optimization scheme for calculation of P_M^o (offline).

5.2 Control Models

For comparison the control strategy based on measurement data as is implemented in ADVISOR Wipke et al. [1999] is compared with the results from the RB-ECMS and DP (Hofman et al. [2007]). The control strategies, which will be compared are listed in Table 1.

Table 1. Simulated strategies for comparison

RB1	Default ADVISOR control strategy
RB2	Optimized ADVISOR control strategy
RB-ECMS	RB-ECMS control strategy
DP	The strategy based on the outcome of the DP algorithm.

Reference Heuristic Control Model – ADVISOR In the Table 2 the rule-based conditions that define which hybrid mode is active are given. If the wheel torque demand is negative, i.e., $T_v(t) < 0$, then the BER mode is active. The control parameters $f_M = P_p(t)/P_{p,max}$ (engine-power-ratio threshold value) and v_M (vehicle-electric-launch-speed threshold value) determine if the M mode is active. The battery is allowed to operate within a certain defined state-of-charge window, i.e., $\xi(t) = [\xi_{min}, \xi_{max}]$. If the state-of-charge $\xi(t)$ gets too low, then the battery is charged during driving (CH mode) with a certain charging power, which is the output of a proportional controller of which the input is the difference between ξ_{ref} and $\xi(t)$. Motor-assisting (MA mode) is only performed if the engine torque demand is larger than the maximum available engine torque $T_{p,max}$, which is a function of the engine speed $\omega_p(t)$. The default control parameters f_M and v_M as implemented in ADVISOR (RB1) were optimized (RB2) to achieve the highest fuel economy, while the final $\xi(t_f)$ is maintained within a certain tolerance band $\pm 0.5\%$ from its reference value ξ_{ref} .

5.3 Results

In Table 3 the fuel economy results for the different strategies are listed. Note that the measured fuel economy reported by Toyota is 3.57 l/100km (28 km/l). In Fig. 5 the energy distribution over the different hybrid driving

Table 2. Rule-based control model as is implemented in ADVISOR

Mode	Rule-based condition:
BER	$\xi(t) < \xi_{max} \wedge T_v(t) < 0$
M	$\xi(t) \geq \xi_{min} \wedge P_p(t) < f_M P_{p,max} \vee v(t) < v_M$
CH	$\xi(t) < \xi_{min} \vee \xi(t) < \xi_{ref} \wedge P_p(t) \geq f_M P_{p,max}$
E	$\xi(t) = \xi_{ref} \wedge P_p(t) \geq f_M P_{p,max}$
MA	$\xi(t) \geq \xi_{min} \wedge T_p(t) > T_{p,max}(\omega_p(t))$

modes for each strategy is shown. With the default control parameters as implemented in RB1 ($f_M = 0.20$ which is equivalent to $P_M \eta_s(t) = -6$ kW, and $v_M = 12.5$ m/s), it was found, that during propulsion at relative low $P_v(t)$ and braking the engine was not always allowed to shut off. This resulted in less idle stop and less effective regenerative braking power due to additional engine drag torque losses respectively. The optimized control parameters for the RB2 are $f_M = 0.116$, which is equivalent to $P_M^o \eta_s(t) = -5$ kW, and $v_M = 20$ m/s. The optimal value for f_M is lower than the default value, which decreases the energy used during the M mode and the required additional charging cost during the CH mode (see, Fig. 5). Furthermore, if the threshold value v_M is set to a larger value than the maximum cycle speed, then effectively more energy is charged during the BER mode, which reduces the required additional charging cost during the CH mode further. Although, electric machine 2 is specified at 30-kW only

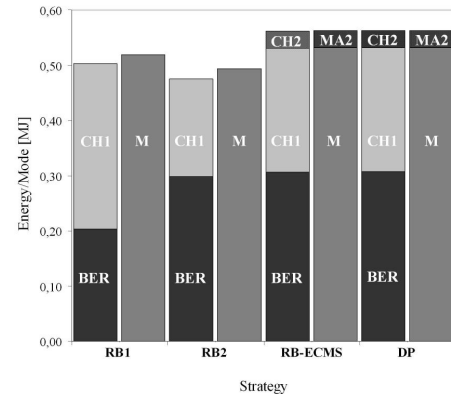


Fig. 5. Energy balances for the different strategies.

approximately 4.9 kW is effectively used for propulsion during pure electric driving (see, RB-ECMS in Table 3). The redundant machine power is mainly used for vehicle performance requirements. The discrepancy between the fuel economy results and the energy difference over time calculated with the RB-ECMS and DP is small ($\pm 1\%$). It can be concluded, that the fuel economy with the RB-ECMS can be calculated very quickly and with sufficient accuracy.

5.4 Evaluation of the Motor-Only Mode

The fuel mass-flow of the engine can be approximated by the affine relationship,

$$\dot{m}_f(t) \approx \dot{m}_{f,0} + \lambda_1 P_p(t), \quad (22)$$

$\dot{m}_{f,0} \triangleq \dot{m}_f(P_p(t) = 0)$ (idle fuel mass flow).

The idle fuel mass-flow at zero mechanical power is represented by $\dot{m}_{f,0}$. The slope of Eq. (22) λ_1 is approxi-

Table 3. Fuel economy results

REFERENCES

Strategy	$P_M^o \eta_s$ (kW)	f_M (-)	v_M (m/s)	Fuel economy (l/100km) Combined	$\Delta E_s(t_f)$ (kJ)	Comp. time* (s)
RB1	-6.0	0.20	12.5	3.34	-22.4	8.0
RB2	-5.0	0.12	20.0	2.99	-23.8	8.0
RB-ECMS	-4.9	-	-	2.98	0.9	7.8
DP	-4.9	-	-	2.96	0	462.0

* Pentium IV, 2.6-GHz, with 512-MB of RAM

mately constant and expresses the additional fuel mass-flow over demanded engine power. If the optimal threshold power for the engine to switch on corresponds to $P_p^o(t) = -P_M^o(t) \eta_s(t)/\eta_t(t)$, then the maximum fuel saving in the M mode is given by,

$$\Delta \dot{m}_f(t) = \dot{m}_{f,0} + \lambda_1 \cdot -P_M^o(t) \eta_s(t)/\eta_t(t). \quad (23)$$

It is found with results from RB-ECMS and DP, that the engine switches on at the motoring power, where the equivalent fuel cost for charging described by λ_0^o is equal to the maximum fuel saving in the M mode:

$$\lambda_0^o \cdot -P_M^o(t) = \dot{m}_{f,0} + \lambda_1 \cdot -P_M^o(t) \eta_s(t)/\eta_t(t) \quad (24)$$

$$\Leftrightarrow P_M^o(t) = -\frac{\dot{m}_{f,0}}{\lambda_1 \cdot \eta_s(t)/\eta_t(t) - \lambda_0^o}, \quad (25)$$

describing the relationship between the optimal motoring threshold power $P_M^o(t)$ and λ_0^o . The optimal motoring threshold power is approximately constant given that the secondary source and transmission efficiency are approximately constant for values around P_M^o , i.e.,

$$P_M^o(t) \approx (P_M^o | \eta_s(t) \approx \eta_s \wedge \eta_t(t) \approx \eta_t), \quad (26)$$

which is sufficiently accurate to be used with the RB-ECMS as shown in the previous section. For motoring threshold powers larger than $-P_M^o$ the fuel cost for recharging become larger than the fuel saving, which is schematically depicted in Fig. 6.

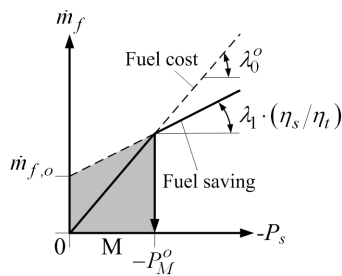


Fig. 6. Mode switch design parameter P_M^o .

6. CONCLUSION

In this paper, an overview of different control methods is given and a new rule-based EMS is introduced based on the combination of Rule-Based and Equivalent Consumption Minimization Strategies (RB-ECMS). The RB-ECMS consists of a collection of driving modes selected through various states and conditions. The RB-ECMS uses only one main design parameter and requires no tuning of many threshold control values and parameters. The discussed RB-ECMS is optimized offline very quickly, which can be used as part of a hybrid drive train topology selection and component specification tool, which is currently under development by the authors.

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