Optimization and Comparison of Heuristic Control Strategies for Parallel Hybrid-Electric Vehicles

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Abstract

Due to the structure of a parallel hybrid, different operating states and degrees of freedom for the torque of the combustion engine arise. To manage the transition between the different operating states as well as to provide the setpoint for the torque of the combustion engine, a control strategy is required. The transition between the different operating states can be initiated depending on various vehicular variables like vehicle speed or required drive torque. For the torque setpoint of the combustion engine different approaches are known [1]. The vehicular variables which initiate the transition between the operating states and the approaches for the setting of the torque of the combustion engine can be combined to different heuristic control strategies by basic IF-THEN-rules. The determination of the design parameters of the different control strategies can be regarded as an optimization problem with the objective to "minimize fuel consumption". As a constraint for the optimization, the state of charge (SOC) of the electrical energy storage has to be sustained. From the optimization results it becomes apparent that for nearly all developed control strategies in all driving cycles and for all vehicle masses a charge sustainability and a reduction of fuel consumption are possible compared to a conventional reference vehicle. The optimal parameters of the strategies depend more or less on the driving cycle and the vehicle mass, but some parameters and approaches for setting the torque of the combustion engine turn out to be comparatively independent. Thus, these control strategies are predestinated for the use in a real vehicle.

Keywords: Hybrid-electric vehicle (HEV), control strategies, optimization.

1. Introduction

Due to the structure of hybrid-electric vehicles, degrees of freedom in the power flow arise, which require a control strategy. For hybrid-electric vehicles a multiplicity of different control strategies are well-known, which can be classified into optimal, sub-optimal and heuristic control strategies [2]. Heuristic strategies are based on boolean or fuzzy rules incorporating different vehicular variables (e. g. torque of the combustion engine or vehicle speed) [3],[4]. These strategies are characterized by an intuitive and easy implementation and do not depend on the knowledge of future power demands. One drawback of heuristic strategies is that their results (e.g. fuel saving) are more or less depending on the driving conditions, in particular on the drive cycle [2]. In this contribution, different heuristic control strategies are developed, optimized and compared. The intention is to examine how far the savings of a control strategy depend on the particular driving conditions. The design and analysis of the control strategies are exemplified by a parallel hybrid, whose structure and operating states are presented in short in Section 2. Based thereupon, different approaches for heuristic control strategies are presented in Section 3. The various strategies are examined and optimized on the basis of a simulation model. The simulation model will be described in Section 4, the optimization in Section 5. The results are presented in Section 6.

2. Parallel Hybrid

Hybrid-electric vehicles are composed of a combination of a combustion engine, one ore more electrical drives and an electrical energy storage. Depending on the arrangement of these components in the power train, different hybrid structures as serial hybrid, parallel hybrid, power split hybrid etc. can be distinguished. The structure of the parallel hybrid power train investigated in this contribution is depicted in Fig. 1. From this structure, the operating states displayed in Table 1 arise.

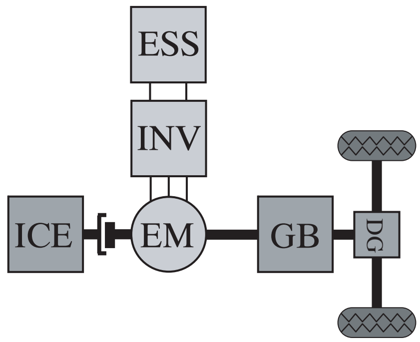

Figure 1: Structure of the parallel hybrid power train (ICE: combustion engine, EM: electrical motor, INV: motor inverter, ESS: electrical energy storage, GB: gearbox, DG: differential gear)

Table 1: Parallel hybrid operating states

	State	**Description**
1	E-drive	Driving power is provided by the electrical drive.
2	ICE-drive	Driving power is provided by the combustion engine.
3	Combined	Both combustion engine and electrical drive provide power. This state can be divided into: - Boost: Driving power is provided by both the combustion engine and the electrical drive. - Recharge: The combustion engine provides driving power as well as extra power to charge the energy storage by the electrical drive.
4	Regenerative braking	Braking power is (partially) provided by the electrical drive.
5	Conventional braking	Braking power is provided by the conventional way (friction brakes).

3. Heuristic control strategies

To manage the transition between the different operating states as well as to provide the operating points of the combustion engine and the electrical drive a control strategy is required, which can pursue different objectives. The control strategies presented here follow the objective to minimize fuel consumption. Simultaneously, the state of charge (SOC) of the electrical energy storage has to be sustained without external recharge.

3.1 State transition

The transition between the different operating states can be initiated depending on various vehicular variables. In this contribution the following variables are regarded:

- vehicle speed v
- required drive torque T_{a}
- rotational speed of the power train n
- required driving power P_{a}
- state of charge of the electrical energy storage SOC

3.2 Setpoint of the engine torque

Speed of the combustion engine and speed of the electrical drive are coupled with each other as well as with the driving speed by the structure depicted in Fig. 1. Thus, the only degrees of freedom for setting the operating points are the torque of the combustion engine and the selection of a gear. As this survey follows a fixed strategy for gear selection, only the torque of the combustion engine has to be given by the control strategy. This can be realized by different approaches which will be presented in the following. These approaches are based on [1].

Constant Engine Torque (CET)

The idea of this approach is to keep the torque of the combustion engine constant. Thus the combustion engine provides a base torque, while the electrical drive covers the varying torque demanded by the drive cycle. Magnitude of the base torque is selected in a way that the combustion engine has a good efficiency across a large speed range.

Constant Torque Sections (CTS)

This approach extends the former one by subdividing the speed range of the engine in multiple sections, in this examination into three sections. Depending on the speed section, different constant base torques are provided by the combustion engine.

Maximum Engine Torque (MET)

In this approach, the combustion engine always provides the maximal possible torque for each speed instead of a constant base torque. The underlying idea is that combustion engines often feature a high efficiency when operated at maximum torque.

Maximization of Engine Efficiency (MoEE)

Expecting the combustion engine to produce the highest losses of the power train, this approach sets the torque of the combustion engine depending on its speed according to the objective to maximize its efficiency.

3.3 Control strategy

The several vehicular variables which initiate the transition between the operating states and the approaches for the setting of the torque of the combustion engine can be combined to a control strategy by basic IF-THEN-rules. This will be explained with the example of the vehicle speed and the approach of a constant engine torque (CET):

- INITIAL STATE: Start driving solely electrically (E-Drive).
- IF the upper threshold of the vehicle speed is reached or exceeded ($v \geq v_{max}$), THEN the combustion engine will be started (Combined). The torque of the combustion engine will be regulated to a constant value. The difference to the driving torque is covered by the electrical drive. Depending on the required driving torque, the electrical drive is operated in motoric (Boost) or regenerative mode (Recharge).
- IF the vehicle speed falls below the lower threshold ($v < v_{min}$), THEN the combustion engine will be stopped and the vehicle is operated solely electrically again (E-drive).

Similarly, further control strategies can be implemented by using the other vehicular variables and approaches for setting the engine torque. A summary of the possible combinations is depicted in Table 2.

Table 2: Combination of vehicular variables and approaches for setting the engine torque

	CET	CTS	MET	MoEE
v	x[1)]	x	x	x
T_a	x	x	x	x
n_a	x	x	x	x
P_a	x	x	x	x
SOC[2)]			x	

[1)] The combinations marked by an 'x' have been examined.
[2)] The SOC is implicitly included also with all other combinations.

If the drive power is negative ($P_a < 0$), for all combinations of strategies considered in Table 2 it is intended to recuperate as much braking power as possible. In order to increase the lifespan of the electrical energy storage, only a part of its energy content is used. Typical values for batteries are about 10-20% of the maximum energy content. In this survey, the electrical energy storage is operated in a range of 62.5-77.5% of the SOC. To meet this restriction, further state transitions may arise. Besides, the electrical drive has to provide the difference between the torque of the combustion engine and the required drive torque for all approaches. Thereby the operating limits of the different components have to be regarded. Thus it is possible that there are further deviations from the desired torque of the combustion engine under some driving conditions.

4. Simulation model

To evaluate the qualities of the different control strategies, two simulation models were developed in Matlab/Simulink for the parallel hybrid depicted in Fig. 1 and a conventional reference vehicle. The structure of the models is based on the principle of backward-facing simulation. In this backward-facing simulation the operation modes of each component are determined in dependence of the drive cycle [5].

The simulation models contain the following components:

- a model of the drive cycle, providing the vehicle speed,
- a model of the vehicle including the various components of the power train,
- the different control strategies.

4.1 Drive cycle

To consider a broadly diversified range of vehicle applications, different drive cycles including city, interurban and highway cycles were examined. An overview of the considered drive cycles is listed in Table 3, visualized in Figures 2, 3 and 4.

Table 3: Examined drive cycles

Drive cycle	**Duration**	**Maximum speed**	**Average speed**	**Distance**
New European Driving Cycle (NEDC)	1180 s	120 km/h	33.6 km/h	11.0 km
City Cycle (UDDS)	1372 s	91 km/h	31.4 km/h	12.0 km
Highway Cycle (USA)	765 s	96 km/h	77.4 km/h	16.5 km

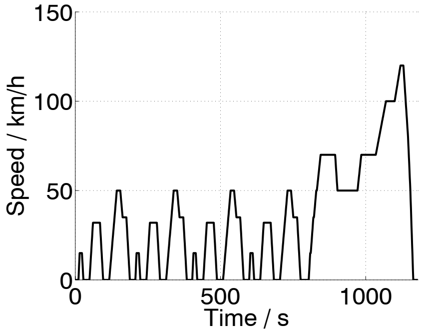

Figure 2: New European Driving Cycle

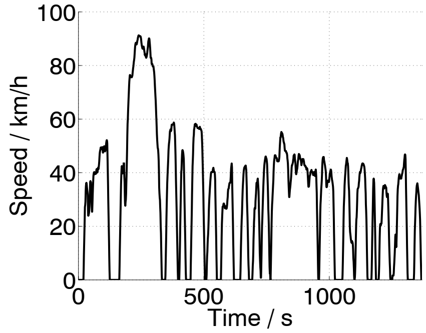

Figure 3: City Cycle (UDDS)

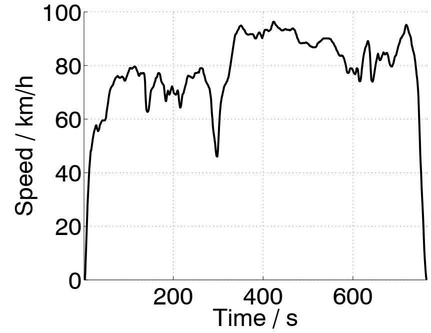

Figure 4: Highway Cycle (USA)

4.2 Vehicle

The vehicles are modeled based on the technical data outlined in Table 4. When designing the parallel hybrid, a smaller rated combustion engine was used (downsizing). Concurrently, the electrical drive and the electrical energy storage have been dimensioned according to the principle that the hybrid has to be comparable to the reference vehicle concerning its driving characteristics, especially the acceleration from 0–100 km/h. For the parallel hybrid vehicle, an extra weight of 56 kg arises from the additional components. The combustion engine, the electrical drive and the electrical energy storage are modeled by look-up tables taken from the simulation tool *ADVISOR2004*. Losses and inertia of the gear and differential gear are neglected.

Table 4: Technical data of the reference vehicle and the parallel hybrid

	Reference vehicle	**Parallel hybrid**
Combustion engine	95 kW@6,000 rpm 165.36 Nm@4,500 rpm 4 cylinder, 1.9 l displacement, gas	63 kW@5,500 rpm 145.17 Nm@2,000 rpm 4 cylinder, 1.9 l displacement, gas
Electrical drive		(PMSM), 49 kW, 275 Nm, 60 kg
Energy storage		NiMH, 360 V, 43.2 kC (12 Ah), 100 kg
Weight (tare/payload)	1,340 kg / 415 kg	1,396 kg / 359 kg
Frontal area	2.00 m^2	
Air drag coefficient	0.28	
Tires	195/65R15	
Gears (gear ratios)	5 (3.55, 1.90, 1.31, 1.03, 0.82)	
Differential gear ratio	3.94	

5. Optimization

To design the various control strategies, different parameters can be considered. An overview is given in Table 5.

Table 5: Design parameters of the various control strategies

	$v_{\min}$	$v_{\max}$	$T_{\mathrm{a,min}}$	$T_{\mathrm{a,max}}$	$n_{\min}$	$n_{\max}$	$P_{\mathrm{a,min}}$	$P_{\mathrm{a,max}}$	$SOC_{\min}$	$SOC_{\max}$	T_{const}
$\mathrm{CET}_v^{1)}$	x	x									x
CET_T			x	x							x
CET_n					x	x					x
CET_P							x	x			x
CTS_v	x	x									$\mathrm{x}^{2)}$
CTS_T			x	x							$\mathrm{x}^{2)}$
CTS_n					x	x					$\mathrm{x}^{2)}$
CTS_P							x	x			$\mathrm{x}^{2)}$
MET_v	x	x									
MET_T			x	x							
MET_n					x	x					
MET_P							x	x			
MET_{SOC}									x	x	
MoEE_v	x	x									
MoEE_T			x	x							
MoEE_n					x	x					
MoEE_P							x	x			

$^{1)}$ The abbreviation refers to the approach for setting the engine torque. The index refers to the vehicular variable which triggers the transition between the state E-drive and Combined.
$^{2)}$Three torque values, one for each speed section

To get a intuition for the dependence of the fuel consumption on the different design parameters, the fuel use is exemplarily plotted against the different parameters for the approach *Maximization of Engine Efficiency (MoEE)* using the *New European Driving Cycle (NEDC)* in Figures 5 to 8.

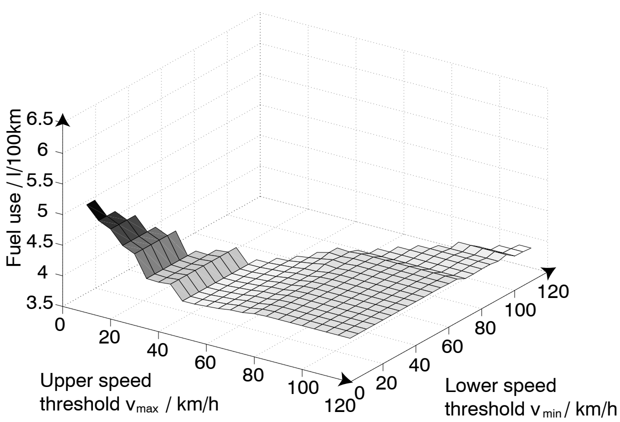

Figure 5: Fuel use over vehicle speed for MoEE_v in NEDC

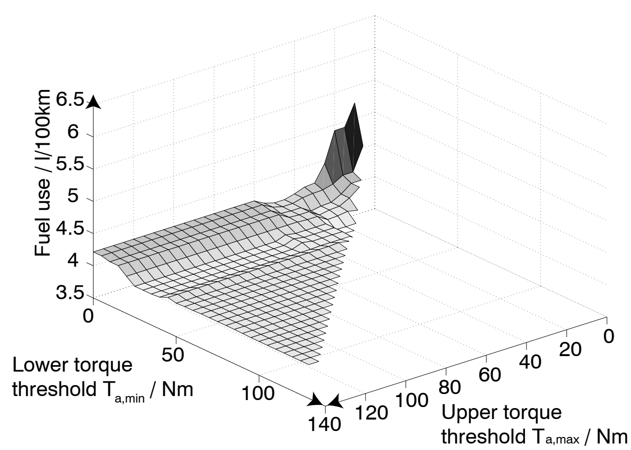

Figure 6: Fuel use over drive torque for MoEE_T in NEDC

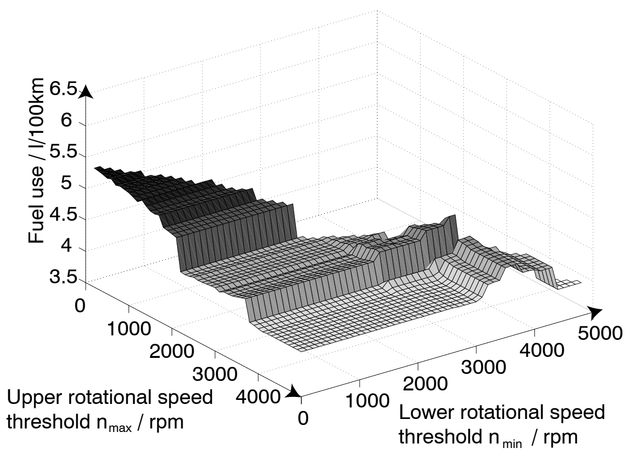

Figure 7: Fuel use over revolution speed of the power train for MoEE_n in NEDC

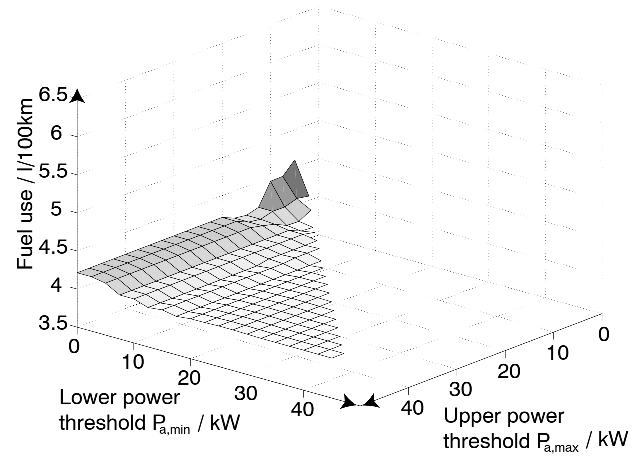

Figure 8: Fuel use over required driving power for MoEE_P in NEDC

From the Figures, the following issues become apparent:

- The fuel consumption depends on the selection of the design parameters on all accounts.
- The graph flattens for some areas of the vehicular variables, as the operating limits of the SOC of the energy storage or the electrical drive torque are reached, resulting in further transitions which are independent of the variables.

The determination of the design parameters of the different control strategies (see Table 5) can be regarded as an optimization problem with the following objective function to be minimized:

$$\text{Fuel consumption :} \qquad f = V_{\mathrm{ICE}} + V_{\mathrm{EM}}$$

It has to be considered that fuel consumption of hybrid vehicles consists of two parts: consumption of the combustion engine V_{ICE} and consumption of stored electrical energy. From the latter, an equivalent fuel consumption V_{EM} is calculated assuming average efficiencies [2]. As a constraint for the optimization the state of charge (SOC) of the electrical energy storage has to be sustained. Optimization is done using the simplex method “Nelder Mead” [6]. The optimization was performed for the various drive cycles (see Table 3) and two different vehicle loads (without/with payload), respectively. As becomes apparent from Figures 5 to 8, there are multiple different local minima. In order to be able to find a global minimum by the used simplex-algorithm, several optimization runs have been performed, using different starting points.

6. Results

The optimization results are evaluated regarding the following issues:

- Reduction of fuel use in comparison to the reference vehicle
- Sensitivity of the optimal parameters of a control strategy to the driving cycle and to the vehicle mass

6.1 Reduction of fuel use

The fuel consumption under the various control strategies and drive cycles is noted in Table 6 for two different vehicle masses. The displayed differences refer to the reference vehicle. It becomes clear that a distinct reduction in fuel consumption of about 35-50% can be achieved by nearly all control strategies. As expected, the reduction is more explicit during the city than during the highway cycle. With some control strategies, it is not possible to sustain the required SOC difference between beginning and end of the drive cycle. Irrespective of the approach for determining the torque of the combustion engine, the lowest fuel consumption can be achieved when triggering the state transitions by the required drive torque. Contrary to the first assumption, the Maximization of Engine Efficiency (MoEE) approach does not obtain the greatest fuel saving.

Table 6: Minimal fuel consumption with a maximal allowed difference of the SOC of 2.50% between beginning and end of the drive cycle

	without payload[1)]						with payload[1)]					
	NEDC[2)]		City[2)]		Hgwy[2)]		NEDC[3)]		City[3)]		Hgwy[3)]	
	l/100km	%	l/100km	%	l/100km	%	l/100km	%	l/100km	%	l/100km	%
CET_v	4.29	-39.30	4.23	-38.35	5.25	-2.07	4.61	-37.22	*)	*)	5.36	-3.51
CET_T	3.81	-46.01	3.49	-49.08	4.25	-20.67	4.23	-42.38	3.87	-46.29	4.65	-16.18
CET_n	4.28	-39.32	4.09	-40.41	4.72	-11.85	4.57	-37.78	4.56	-36.74	5.30	-4.48
CET_P	3.95	-44.09	3.60	-47.57	4.35	-18.77	4.42	-39.85	4.04	-43.93	4.77	-14.01
$MoEE_v$	*)	*)	4.25	-38.09	5.21	-2.72	*)	*)	*)	*)	5.26	-5.14
$MoEE_T$	3.87	-45.23	3.43	-49.99	4.46	-16.75	4.17	-43.23	3.81	-47.14	4.62	-16.75
$MoEE_n$	4.45	-37.04	4.35	-36.63	4.63	-13.64	4.80	-34.75	4.77	-33.90	5.22	-5.87
$MoEE_P$	3.98	-43.60	3.58	-47.88	4.33	-19.28	4.34	-40.92	3.97	-44.87	4.80	-13.55
MET_v	4.27	-39.46	4.20	-38.72	5.27	-1.77	*)	*)	4.62	-35.89	5.42	-2.41
MET_T	4.14	-41.38	3.88	-43.43	4.28	-20.14	4.48	-39.07	4.00	-44.53	4.57	-17.61
MET_n	4.30	-39.03	4.30	-37.28	4.72	-11.99	4.97	-32.39	4.78	-33.75	5.28	-4.88
MET_P	4.13	-41.54	3.67	-46.49	4.37	-18.54	4.52	-38.45	4.49	-37.76	4.74	-14.52
CTS_v	4.27	-39.56	4.19	-38.94	5.24	-2.25	4.61	-37.22	4.72	-34.49	5.33	-4.01
CTS_T	3.81	-46.01	3.40	-50.43	4.23	-21.06	4.18	-43.13	3.83	-46.88	4.62	-16.74
CTS_n	4.27	-39.54	4.04	-41.05	4.66	-13.04	4.57	-37.78	4.52	-37.26	5.29	-4.76
CTS_P	4.18	-40.77	3.57	-47.93	4.31	-19.56	4.36	-40.71	3.96	-45.11	4.69	-15.47
MET_{SOC}	4.29	-39.29	4.13	-39.81	4.75	-11.37	4.69	-36.17	4.61	-36.12	5.06	-8.85

[1)] Vehicle mass without payload 1415 kg, with payload 1645 kg
[2)] Fuel use reference vehicle NEDC: 7.06 l/100km, City: 6.86 l/100km, Hgwy: 5.36 l/100km
[3)] Fuel use reference vehicle NEDC: 7.35 l/100km, City: 7.21 l/100km, Hgwy: 5.55 l/100km
*) The maximal allowed difference of the SOC could not be achieved

6.2 Parameter sensitivity to driving cycle and vehicle mass

The fuel consumptions stated in Table 6 can be achieved if the parameters of the control strategies are optimized explicitly for the considered drive cycle and vehicle mass. In practice, both the drive cycle and the vehicle mass are variable. The question arises how much reduction in fuel consumption will result if, e. g., a fully loaded vehicle passes the *City Cycle* using a control strategy optimized for its tare weight and the *NEDC*. To get an impression of the dependencies of the optimal parameters on the drive cycle and the vehicle mass, the variance of the parameters is exemplarily depicted in Figures 9 to 12 for some of the control strategies and for different drive cycles and vehicle loads. The studies show that the parameter *required drive torque* T_{a} is comparatively independent from the examined drive cycles.

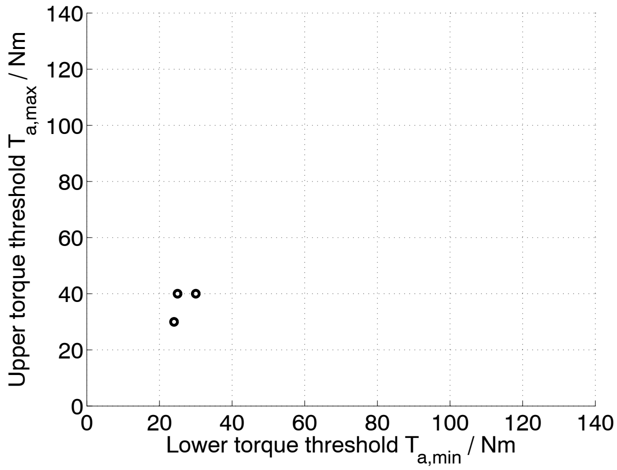

Figure 9: Variance of parameter *required drive torque* T_a with the various drive cycles for CTS_T (without payload)

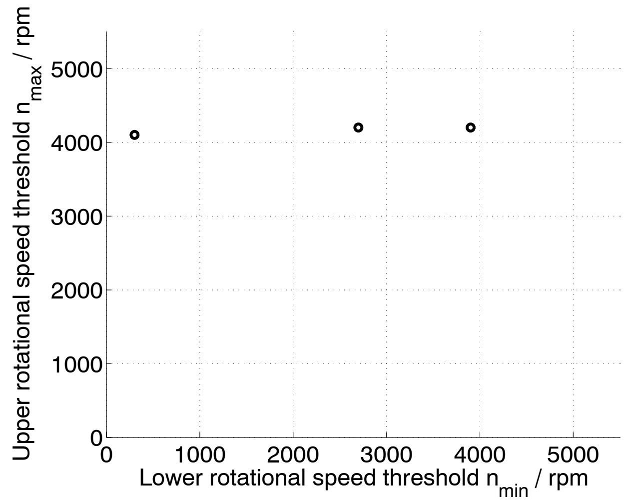

Figure 10: Variance of parameter *rotational speed of the power train* n with the various drive cycles for CTS_n (without payload)

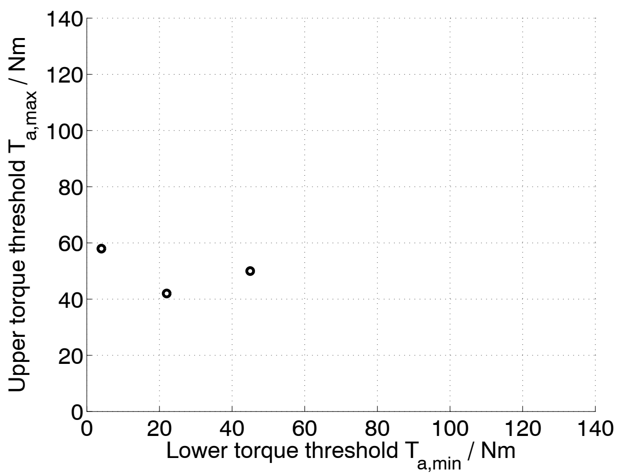

Figure 11: Variance of parameter *required drive torque* T_a with the various drive cycles for MET_T (without payload)

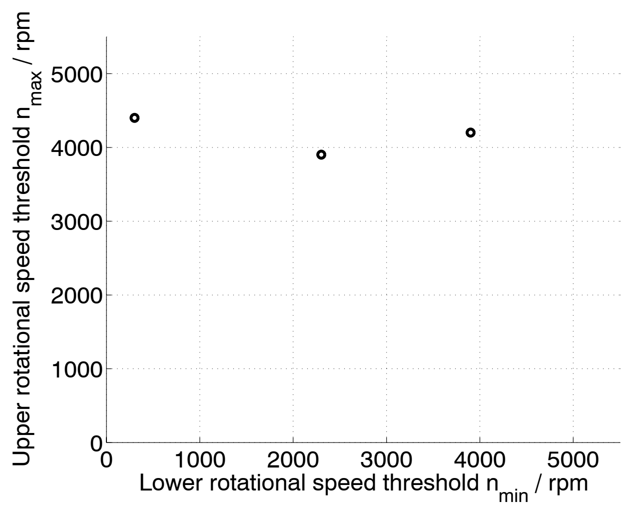

Figure 12: Variance of parameter *rotational speed of the power train* n with the various drive cycles for MET_n (without payload)

When considering all combinations examined, the following issues become apparent:

- The parameters vary in a greater range if the *drive cycle* is changed compared to the variation of the *vehicle mass*.
- The *MET* (Maximum Engine Torque) seems to be lesser applicable than the other approaches due to the strong dependence of the parameters on the vehicle mass as well as the drive cycle.
- For the other approaches, the transition variable *required drive torque* T_a produces the least variance of the parameters for the different drive cycles and vehicle mass.
- Considering only the variation of the parameters for the different drive cycles when keeping the vehicle mass constant, the approaches *MoEE* and *CTS* show the best results.

7. Conclusion

The results can be summarized as follows:

- ○ For nearly all developed control strategies in all driving cycles and for all vehicle masses a charge sustainability and a reduction of fuel consumption compared to the reference vehicle is possible.
- ○ The optimal parameters of the strategies depend more or less on the driving cycle and the vehicle mass. The parameter *required drive torque* T_{a} is comparatively independent from the examined drive cycles and the vehicle mass.
- ○ The *MoEE*$_T$ and *CTS*$_T$ control strategies are characterized by their optimal parameters being almost independent of the driving cycle as well as of the vehicle mass. Thus these control strategies are predestinated for the use in a real vehicle.

8. Acknowledgments

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