

Next-Generation Low-Voltage Power Nets Impacts of Advanced Stop/Start and Sailing Functionalities

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ABSTRACT

The range of tasks in automotive electrical system development has clearly grown and now includes goals such as achieving efficiency requirements and complying with continuously reducing CO₂ limits. Improvements in the vehicle electrical system, hereinafter referred to as the power net, are mandatory to face the challenges of increasing electrical energy consumption, new comfort and assistance functions, and further electrification. Novel power net topologies with dual batteries and dual voltages promise a significant increase in efficiency with moderate technological and financial effort. Depending on the vehicle segment, either an extension of established 12 V micro-hybrid technologies or 48 V mild hybridization is possible.

Both technologies have the potential to reduce fuel consumption by implementing advanced stop/start and sailing functionalities. Additional engine-stop phases and even reduced driving resistance have positive impacts on the fuel consumption but lead to higher load on the electrical system and an energy deficit by reducing the recuperation and charging phases. Therefore, power net architecture and electrical energy management play an essential role with regard to safety and efficiency issues.

The first step of this study is an examination of stop/start and sailing functionalities by analyzing extensive real-world driving measurements of a C-segment vehicle. The sailing function decouples the engine in situations without driver torque request with the engine remaining idle. Fuel and electrical energy consumption are analyzed in detail on defined test routes with varying electrical load.

Secondly, simulations are carried out to evaluate the impacts of advanced sailing functionalities. A vehicle simulation is coupled to a dedicated power net simulation and calibrated to the real-world driving measurements. An engine off sailing algorithm is implemented, and the effects on fuel consumption and electrical energy balance are evaluated under varying boundary conditions. These analyses are conducted in several dual-battery and dual-voltage architectures. Starting from those results, the requirements for prospective automotive power nets can be derived to give an outlook for further opportunities and optimization potential.

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INTRODUCTION

Faced with challenging fleet consumption targets, the automotive industry has developed several strategies within recent years. Among the currently still expensive alternative and high-voltage electrified propulsion systems, many automotive manufacturers are trying to guide their established conventional powertrains to their maximum potentials.

An essential aspect is state-of-the-art micro-hybrid technologies, which combine engine stop/start systems (SS; see the attached abbreviation summarization list) with intelligent alternator control. Preceding studies have already shown that the implementation of such technology results in fuel savings of approximately 5 % in the NEDC [1, 2, 3]. This potential basically consists of the avoidance of idling during standstill and can be realized by improved cycle-resistant starter

batteries and battery monitoring features at low additional system cost. Dhand et al. detected the system constraints, which are mostly affected by the electrical system and environmental conditions. Thus, under real-world driving conditions, 80 to 90 % of the engine stop potential is usable, depending on the location and degree of comfort [1].

Further studies focus on engine losses in driving situations [2, 3, 4, 5, 6]. State-of-the-art engines cut off fuel injection during deceleration, and engine drag torque is overcome by the vehicle as soon as the driver releases the accelerator pedal. Instead of fuel cut-off, the engine can be decoupled from the powertrain to retain the kinetic energy. The distance covered during coasting depends on the vehicle mass, inertia and longitudinal dynamics, and it can be easily doubled from 100 to 50 km/h with sailing, i.e., with the decoupled powertrain [2]. Additionally,

the engine can remain idle or be turned off, hereinafter referred to as sailing idle (SI) and sailing engine off (SEO), respectively. Engine off sailing at low speed before vehicle standstill is also referred to as advanced stop/start (ASS). Mueller et al. mentioned that the fuel savings potential strongly depends on the driving cycle, its tolerances and the driving style [2, 3]. Thus, sailing time-share amounts to 20 % in the FTP-75 and up to 50 % under real-world driving conditions, with a fuel benefit of 2 to 3 % for sailing idle and 6 to 12 % for sailing engine off. Similar fuel savings potentials and saw-tooth operation at average speed were presented in other investigations [4, 5, 6].

Overall, the impressive potential of advanced stop/start and sailing functionalities was confirmed, but at the same time, system complexity, especially with regard to the power net during sailing engine off, was seen as critical and not analyzed in detail. Additional engine starts, less charging, and recuperation phases despite increasing electrical energy demand lead to critical operation. Therefore, this study connects reasonable sailing behavior and electrical load scenarios from extensive real-world driving measurements with a power net simulation to identify challenges and determine the potential of novel power net architectures. Firstly, the test setup and functionalities are introduced, followed by detailed evaluation of the real-world driving measurements. Secondly, development of the simulation approach and model is described. After model validation, conventional and novel power net architectures are compared via simulation analysis.

SAILING POTENTIAL UNDER REAL-WORLD DRIVING CONDITIONS

Test Vehicle and Procedure

Considering realistic sailing conditions, vehicle measurements on a state-of-the-art micro-hybrid vehicle with sailing idle are conducted in a real-world drive cycle. The vehicle topology is shown in Figure 1.

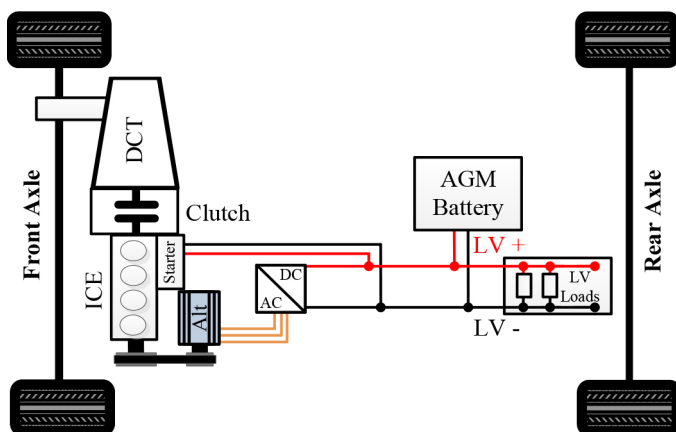


Figure 1. Topology of the micro-hybrid vehicle under investigation

It is a C-segment vehicle with a 4-cylinder in-line turbocharged diesel engine, 6-speed dual clutch transmission (DCT), and front-wheel drive. The conventional single-battery power net is supplied by a 12 V lead-acid AGM battery and a belt-driven alternator, which is integrated in opposition to the engine output side (P0-position). The technical details are summarized in Table 1.

Table 1. Test vehicle technical details

Vehicle mass	1400 kg
Engine displacement	1968 cc
Cylinder	4
Compression ratio	16.5:1
Maximum torque	380 Nm
Maximum power	135 kW
Transmission	6-speed DCT
Maximum alternator current	180 A
Battery	80 Ah AGM

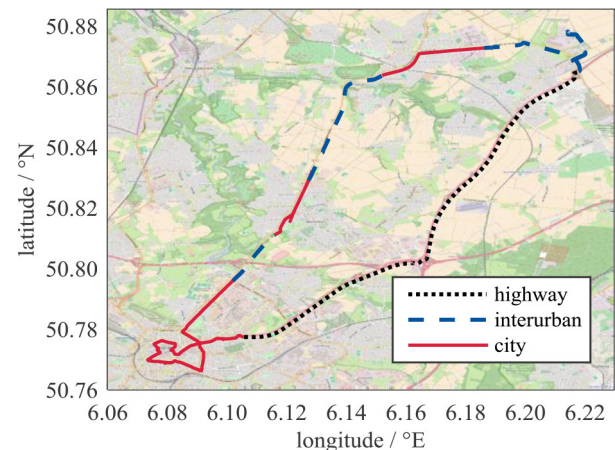


Figure 2. Route of the real drive cycle in the area of Aachen, Germany

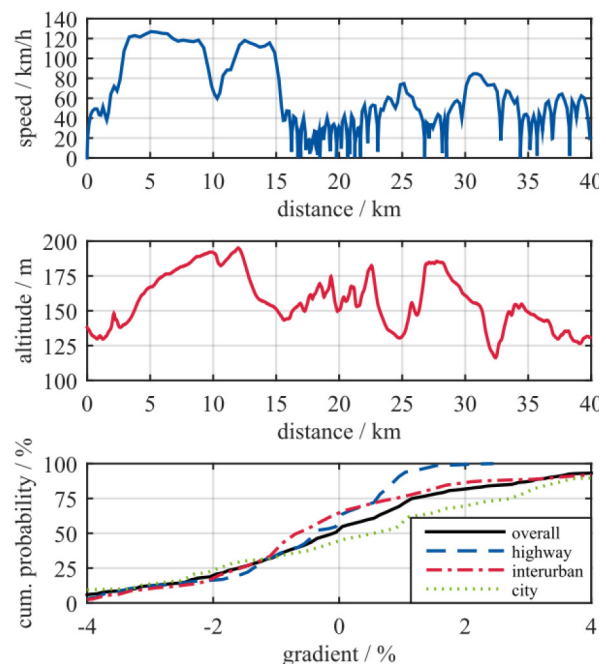


Figure 3. Exemplary profile of the Aachen Cycle

The real-world drive cycle around Aachen is shown in Figure 2. It has a distance applied distribution of 35 % city, 32 % interurban, and 33 % highway. The overall distance is 40 km, and the travel time is approximately one hour. A total of 57 traffic lights are encountered in the drive cycle, and the vehicle stops 32 times on average. An exemplary

distance-based speed and altitude profile is visualized in Figure 3. The lower graph contains the cumulative road gradient of the cycle and its sections. The cycle has a balanced gradient, i.e., the positive and negative gradients are compensating each other over the complete cycle. Thus, the black line of the third subplot in Figure 3 crosses the origin of ordinates. The highway is also almost balanced, and the additional interurban downhill part is compensated in the city. Essentially, the absolute gradient is below 4 % the majority of the time.

The measurements are performed by day under moderate climate conditions of approximately 15 to 20 °C and outside of rush hours to reduce traffic impact. This study contains ten cycles in total. An overview of the conducted cycle measurements is given in Table 2. The vehicle offers two driving modes: an eco mode with sailing idle and a normal mode without. The stop/start system is available in both modes and can be selected manually. Additional measurements in normal mode without sailing idle allow a comparison of the time-shares of usual engine operation modes, which are described in the following section. Varying electrical load scenarios during sailing idle measurements consider the realistic impact on the vehicle power net. It is varied by the activation of different selectable electrical consumers.

Table 2. Overview of Aachen Cycle measurements

Cycle No.	Mode	Functions	Avg. speed km/h	Avg. load A
1	Normal	-	39.4	29.8
2		SS	39.3	35.5
3			39.2	33.0
4	Eco	SS + SI	30.0	34.5
5			34.3	57.3
6			36.4	51.0
7			32.6	61.8
8		SI	36.7	44.5
9			35.6	46.3
10			37.1	29.9

Sailing Idle Function

The sailing idle function is analyzed separately to identify necessary boundary conditions for entering it. Transitions of the vehicle states are shown in Figure 4. Sailing idle is only available from the driving state. If eco mode is activated and the driver releases the accelerator pedal, entering sailing idle depends on vehicle speed, transmission gear, engine temperature and battery state of charge. There are indeed further safety inhibitors, e.g., extreme lateral acceleration or slopes, but they can be neglected due to moderate driving and rare occurrences during the performed cycle measurements (cf. Figure 3). However, these entrance conditions are less restrictive compared to other vehicles, especially regarding vehicle speed, where an upper limit cannot be observed while testing up to 220 km/h.

Figure 5 illustrates a typical sailing idle event. At a vehicle speed of 98 km/h, the driver releases the accelerator pedal. After 1 s, the engine is decoupled and reaches an idle speed of 850 rpm. During the sailing event, the idle speed is slightly increased up to 900 rpm, and

the vehicle decelerates without engine drag torque. At 834 s, the driver exits sailing by pushing the brake, and the engine is coupled within 1 s into 5th gear with fuel cut-off.

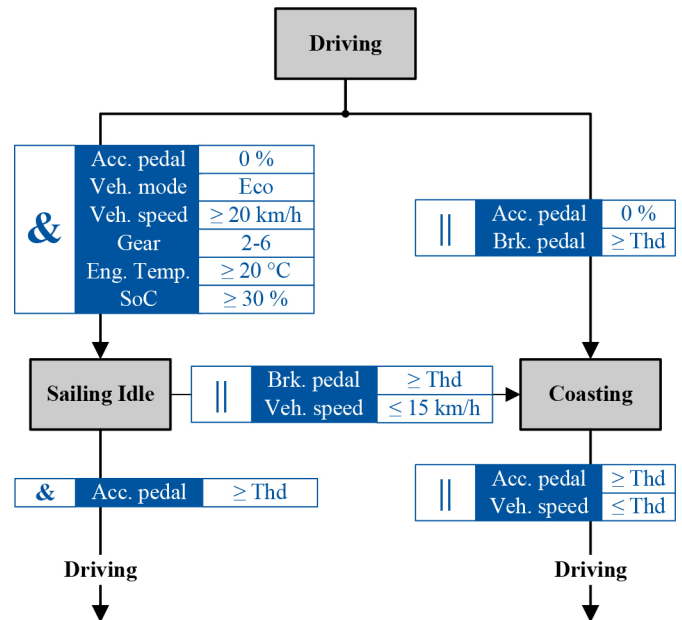


Figure 4. Vehicle state flow chart

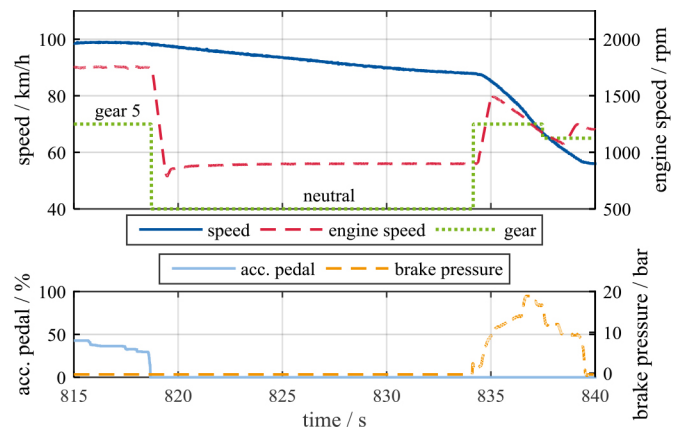


Figure 5. Typical sailing idle event

Engine Operation Analysis

The engine of the vehicle basically has four modes of operation: engine off, engine idle, fuel cut-off and running. The availability depends on the vehicle state and selected functionalities. The stop/start system is preselected; thus, during standstill, the engine is usually turned off automatically. If the stop/start system is deactivated, the engine remains in idle, and injection is active to overcome the engine friction and auxiliaries, such as the alternator, climate compressor, engine coolant, and oil pump. Depending on the torque demand, idle fuel consumption is approximately 0.6 to 1.0 l/h. While coasting, the engine operates in fuel cut-off as long as the engine temperature and rotational speed are above certain thresholds. Otherwise, the engine runs according to the driver torque request. If eco mode is selected, the vehicle enters sailing idle mode if possible instead of fuel cut-off. Consequently, an essential amount of operation time is spent in fuel cut-off to idle operation, as shown in Figure 6.

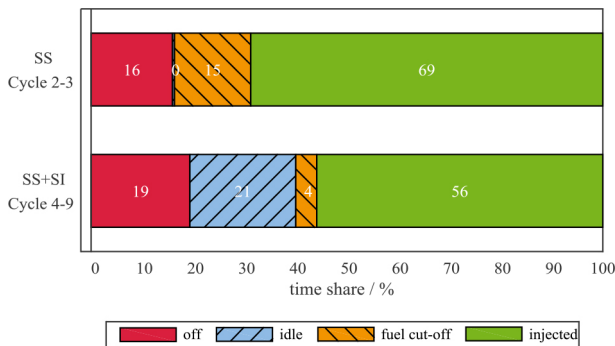


Figure 6. Time-shares of engine operation modes during the Aachen Cycle

The bar plot contains average time-shares of each engine mode. The first bar is derived from the non-sailing cycles 2 and 3. The second bar indicates the sailing idle cycles with stop/start (see Table 2). The engine off share of the non-sailing cycles is slightly lower and simply caused by less time of vehicle standstill. The 21 % idle share of the sailing cycles basically arises from the fuel cut-off and running operation. As a result, 11 % of fuel cut-off is shifted to idle operation with active injection. In the end, operation with deactivated injection, consisting of engine off and fuel cut-off, is reduced by 8 % in total. In addition, a situation where conditions for fuel cut-off are fulfilled usually brake energy recovery by the intelligent controlled alternator is also possible. Thus, the electrical energy balance is influenced at the same time. Therefore, this issue is analyzed in detail in a following chapter.

To summarize, the fuel savings potential of sailing idle is debatable because the distance benefit has to outbalance the minimized fuel cut-off. At least the potential is strongly limited for this reason. However, sailing engine off can, in fact, reduce fuel consumption if all other system requirements are satisfied because the engine operation time with active injection is shortened.

Sailing Analysis

This analysis evaluates all cycle measurements with sailing idle (see Table 2). Figure 7 contains all sailing events of the Aachen Cycle (blue) and another real drive cycle for comparability reasons. The FEV Cycle (red) is not explained in detail in this study. Nevertheless, it offers almost a third of the distribution of the city, the interurban and the highway with a slightly more dominant and hillier interurban part. The cycle distance is approximately 260 km and takes approximately four and a half hours.

Data are plotted over sailing entry speed. The upper graphs show the absolute sailing time of each event, and the lower one depicts the cumulative sailing time-share related to the overall travel time. The lower limit of 20 km/h for the entry speed is clearly exposed. Basically, almost all sailing events of the Aachen and FEV Cycles are below 20 s. A major part of the Aachen Cycle is concentrated at lower entry speeds with shorter sailing events, whereas data of the FEV cycle is distributed more evenly over the entry speed. On the one hand, the lower graph reveals that the overall sailing share is impressively high, with 18 % in the Aachen and 22 % in the FEV Cycle. On the other hand, the sailing impact regarding time is

comparatively small for higher speeds (more precisely, above 80 km/h for the Aachen Cycle and 100 km/h for the FEV Cycle); the remaining time-share related to the overall sailing time is approximately 10 %.

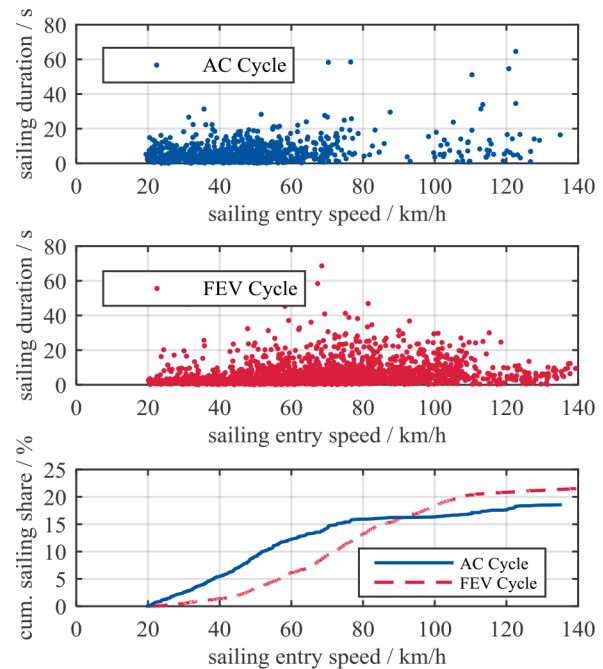


Figure 7. Absolute sailing time and cumulative sailing time-share over the sailing entry speed including all sailing events during the entire measurements in the Aachen Cycle (blue) and FEV Cycle (red)

Figure 8 contains the sailing time and distance share of each cycle with respect to the cycle average speed (cf. Table 2). The average time-share is 19 %, whereas the distance share is approximately one third. In all, the cycles exhibit good comparability regarding the time and distance share. The outlier is caused by heavy traffic. As a result, the average speed and sailing occurrence are reduced. A linear correlation between the cycle average speed and sailing time-share as described in [6], where similar sailing analysis was published for Indian real-world driving conditions, is implied. However, due to the short data range, it is not valid.

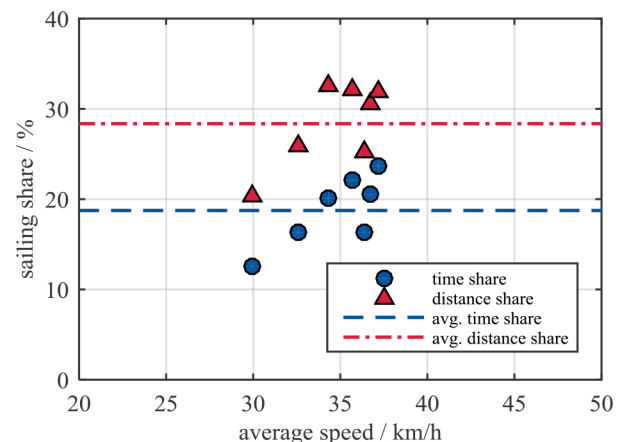


Figure 8. Sailing time (blue) and distance (red) share of each cycle over its corresponding average speed in the Aachen Cycle

The probability of sailing events over vehicle entry speed in Figure 9 also leads to similar results, except for higher speeds, which were not taken into account in [6]. This, at least, is an indication that sailing occurs more often at lower vehicle speeds in city and interurban areas.

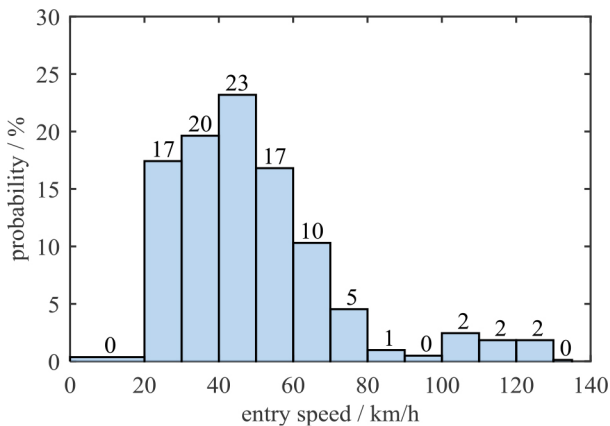


Figure 9. Probability of sailing events over the sailing entry speed

Figure 10 exemplifies the statistical occurrence of sailing events and the corresponding sailing time related to the distance in the particular cycle sections. As stated above, sailing appears particularly in city and interurban areas. With an average of approximately five sailing events per km, the city section dominates the others by far. Together with the cumulative sailing time-share (see Figure 7), it can be concluded that a sailing function is very sensitive to the lower entry speed limit in general. This boundary condition affects the sailing occurrence and time-share to a special degree. It can influence the overall system in two directions - either towards the maximum potential by an extreme low limit or towards increased safety with higher restrictions.

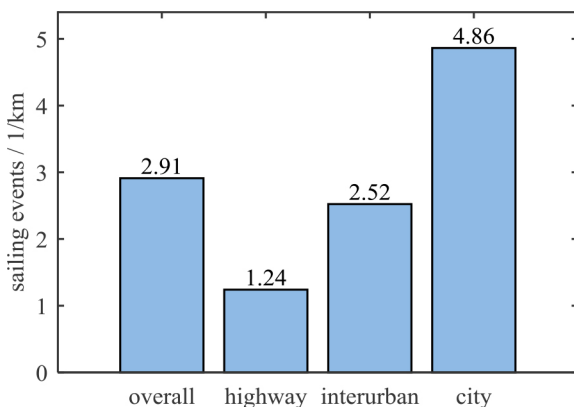


Figure 10. Distance-related sailing events divided in the cycle sections

Sailing Engine Off Potential

In principle, every sailing idle event described in the previous chapter is suitable for turning off the engine. Additionally, there is even more potential if sailing is extended without a lower speed limit towards 0 km/h. This type of implementation would combine sailing engine off with advanced stop/start. On the one hand, the potential for fuel savings increases due to the decreased engine operation, and on the other hand, restarts caused by a lower speed limit are avoided. Nevertheless, there are inevitably various important safety, drivability, and comfort issues that have to be taken into account:

- Due to the typically reduced noise, slight deceleration and driving resistance at low vehicle speeds, the driver is more sensitive to automatic vehicle actions, such as restart and decoupling.
- Change of mind situations, e.g., in front of traffic lights where the vehicle just decelerates shortly, require fast and comfortable restart capabilities.
- Auxiliaries are not driven during the engine off period, so they must be either electrified or activated in a timely manner by an engine restart.
- Electrical energy supply for the vehicle power net must be provided by electrical energy storages at all times.
- At the same time, extended engine off periods lead to shorter generation and recuperation phases and can cause an electrical energy deficit.

Because this study focuses on sailing with regard to the vehicle power net as the main impact factor, only the engine off potential is subsequently analyzed. Therefore, the following sailing states are introduced in Table 3 and exemplified in a time-based plot in Figure 11.

Table 3. Definition of sailing states

State	Description
SI	The sailing idle state corresponds to the vehicle strategy, implemented on the test vehicle and recorded during road measurements (cf. Figure 5)
SEO	The sailing engine off state is equal to SI
SEO potential	The sailing engine off potential state extends SI/SEO until a driver torque request or vehicle standstill
SS	The stop/start state is calculated via the measured engine speed
SS potential	The stop/start potential extends SS to a complete standstill period, where the measured vehicle speed is zero

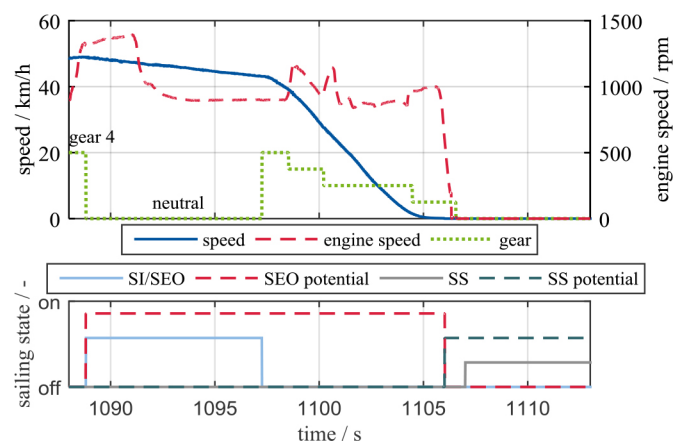


Figure 11. Typical sailing event and corresponding sailing states

Figure 12 illustrates how these different types of sailing implementations affect the total number of engine starts. The boxplots summarize all sailing events during the Aachen Cycle and show average engine starts per km of each cycle, as well as the overall average (dark red), overall standard deviation (light blue) and standard error (light red). SS contains the actually measured engine restarts. SEO adds an engine restart for every transient from sailing to driving or coasting and leads to an increase by a factor of five. The SEO potential connects sailing with stop/start and reduces

engine starts to a remaining factor of 4 compared to SS. Thus, sailing inhibitors also positively affect the drivability and component durability.

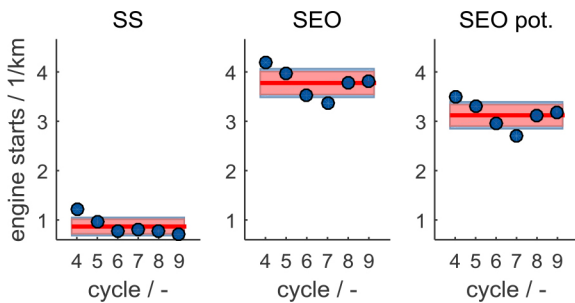


Figure 12. Engine starts with a stop/start system, sailing engine off and sailing engine off potential

In addition, the SEO potential shifts the sailing duration towards longer periods and reduces the probability of short sailing events. Thus, the center of the sailing duration probability distribution, which is depicted in Figure 13, moves to the right.

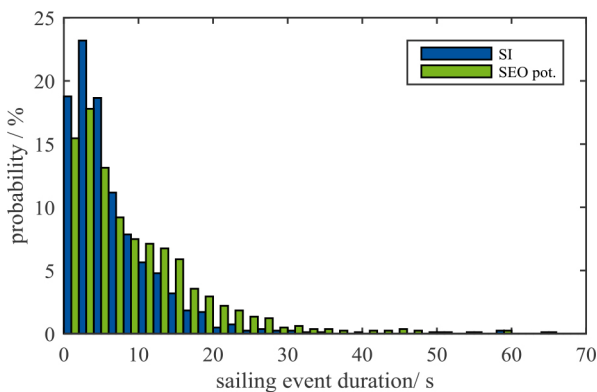


Figure 13. Probability of the sailing duration for sailing idle (blue) and post-processed sailing engine off potential (green)

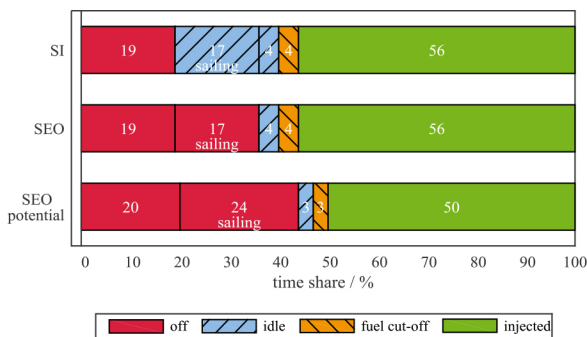


Figure 14. Engine off potential of the different sailing types: sailing idle, sailing engine off and sailing engine off potential

A concluding comparison of the sailing engine off potential is represented in Figure 14. It shows the average time-shares of engine operation modes for the different types of sailing implementations over all cycles with SS and SI. The engine off time-share is 19 % on average, and by implementing SEO, it is extended to as high as 36 % in total. Considering a non-restrictive functionality of as low as 0 km/h with the SEO potential, an engine off time-share of 44 % is realistic. The additional part basically consists of a running engine operation and

only slightly reduces fuel cut-off. To summarize, high engine off time-shares are reasonable and offer great potential for reducing the fuel consumption, simultaneously leading to less recuperation phases.

SIMULATIVE ANALYSIS OF THE IMPACTS OF ADVANCED STOP/START AND SAILING FUNCTIONALITIES

In the following section, impacts on fuel consumption and the vehicle power net are evaluated by simulative analyses for the different sailing types. The simulation approach is based on the real-world drive cycle data.

Data-Driven Open-Loop Forward Simulation

Table 4. Input data for open-loop forward simulation

Inherited data from Aachen Cycle measurements		
Engine speed	$n_{\text{eng}}(t)$	rpm
Transmission gear	$g_{\text{tra}}(t)$	-
Sailing state (SI/SEO, SEO pot.)	$b_{\text{sail}}(t)$	-
Electrical consumption	$I_{\text{cns},12V}(t)$	A
Engine oil and coolant temperature	$T_{\text{eng,oil}}(t), T_{\text{eng,cool}}(t)$	°C
Transmission oil temperature	$T_{\text{tra}}(t)$	°C
Battery temperature	$T_{\text{bat}}(t)$	°C
Control input data from Aachen Cycle measurements		
Vehicle speed	$v_{\text{veh}}(t)$	km/h
Road gradient	$m_{\text{grd}}(t)$	-

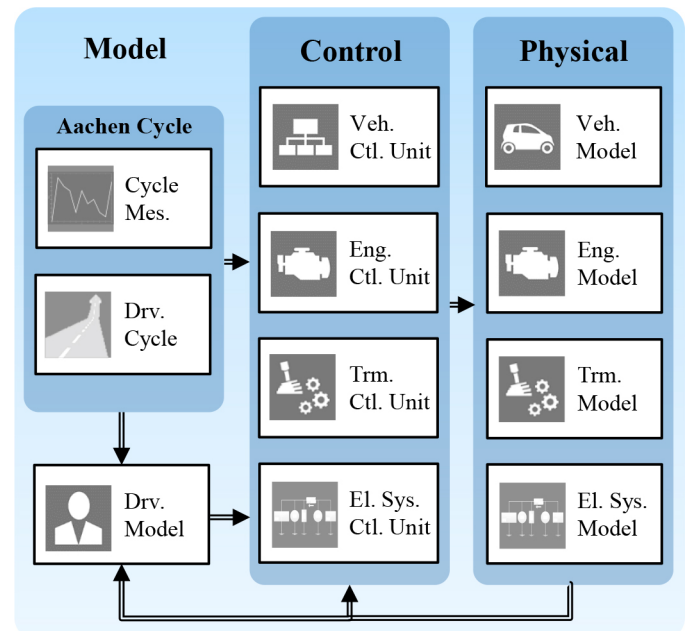


Figure 15. Data-driven open-loop forward simulation

The data-driven open-loop forward simulation connects the real drive cycle data to a dedicated combined vehicle-power-net simulation. The structure is derived from a closed-loop forward simulation outlined in Figure 15. Basically, the model has control and physical