2^{nd} VegOil

Demonstration of 2^{nd} Generation Vegetable Oil Fuels in Advanced Engines

Workpackage WP2

Engine development

Deliverable N° 2.11:

Exposition of hybrid functions

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1 Introduction

As part of the EU-funded "**Demonstration of 2nd Generation Vegetable Oil Fuels in Advanced Engines**" project, the Chair of internal combustion engines (Lehrstuhl für Verbrennungskraftmaschinen, LVK) of the Technische Universität München (Technical University of Munich) works on the engine development work package (WP2). The objective of this workpackage is to develop engines able to comply with the EU Stage 4 (for non-road vehicles) emission norms if fuelled with the 2nd generation vegetable oil fuel developed in workpackage WP3. WP2 consists of development work regarding, in particular, exhaust gas after-treatment systems (responsible: John Deere) in the first steps of the project. The project also aims to develop a hybrid engine system to comply with future emission limits.

The development work at the engine laboratory of the LVK is done on a hybrid test stand. This test stand was built in project months 1 to 9 (please see Deliverable D2.7 for further information). During this time, testing and first measurements were executed, which are briefly described in Deliverable D2.8. To develop a hybrid engine operation strategy for the hybrid engine test stand, explicit differentiated operation profiles (e.g. typical for tractor engines) and operation cycles, which are specified by the EU for emission certification of non-road diesel engines, had to be selected and captured/noted (Deliverable D2.9).

Deliverable D2.10 describes the test results regarding the operation behaviour of the John Deere engine with fuelling by vegetable oil (rapeseed oil).

This Deliverable, D2.11, illustrates the exposition of the hybrid functions, focusing on the hybrid simulation model, which was developed during the reporting period. The workpackage goal is to develop a hybrid operating strategy, which affects the combustion engine operating profile and therefore the combustion engine emissions. For this reason, the hybrid simulation model has a central position in the entire development process.

The reason for the investigations concerning the hybrid technologies within the project "2nd VegOil" is that in case of the tractor application typical load / operation profiles are comparably transient. Even in high load operation (e.g. field work) the torque profile for the combustion engine varies (please see Deliverable D2.9 for details). Therefore it is reasonable to analyze the potential of hybrid technologies for the reduction of emissions within tractor applications. The strategies are mainly focussed on the functionalities "load point shifting", "dynamic reduction for the combustion engine" and "start-stop-operation", e.g. in long idle phases.

2 Reference to project planning: key partners, scope of the key partner, timetable and milestone

The key partner in the engine development WP2 is John Deere, who delivered the combustion engine for the test stand. The adaptation to the use of vegetable oil was executed by VWP (in case of the hybrid test stand this is rapeseed oil, delivered by Öl- und Bioenergie).

The scheduled time for Task 2.11, hybrid simulation, is nine months (month 12 to 20). It ends with the milestone M2.5H (“Hybrid functions for avoiding disadvantageous operation modes are identified), which are achieved within the foreseen time. This document summarises the results of Task 2.11.

3 Evaluation of hybrid technologies for the 2nd VegOil project

According to the EU directive 2007/46/EG [1], a hybrid vehicle is a vehicle with at least two energy transformers and two energy accumulators in the vehicle for driving / operating purposes. Concerning the 2ndVegOilproject, one energy transformer is the John Deere combustion engine CD6068HL481 fuelled with rapeseed oil (for detailed information please see Deliverable D2.7 – D2.10). The second part of the hybrid system is an electric system consisting of one or more electric motors and an electric energy accumulator (battery).Gear boxes and hydraulic components do not fall within the scope of this project: the John Deere combustion engine is preselected; only engine software modifications are possible in future project steps. There are no pre-settings for the electric part, so a literature analysis of applications is made. The findings of the analysis are evaluated for the 2ndVegOil project. Target specifications and the level of abstraction for the hybrid simulation model are deduced from the findings.

3.1 Hybrid system assembly

Series hybrid drive

In this configuration, the two energy transformers are formed in series – there is no direct connection between the wheel-drive and the combustion engine, whose operation strategy can be selected from a comparatively wide field. This offers significant potential for improvement of fuel consumption and emission behaviour.

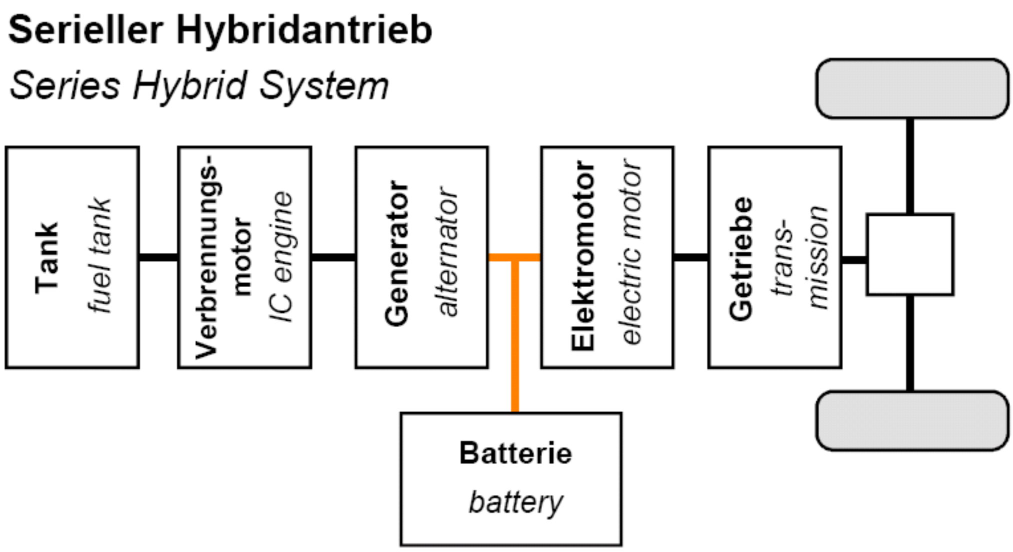

Fig. 1: Structure series hybrid system [2]

Depending on the choice of battery, purely electric drive is possible. Its main disadvantages are the efficiency losses of each energy transformation:

1) Chemical energy within the fuel is transformed into mechanical energy (combustion engine)
2) Mechanical energy is transformed into electrical energy (generator)
3) Electrical energy is transformed into mechanical energy (electric motor)
   And/or (depending on application)
4) Electrical energy is transformed into chemical energy (battery charging)
5) Chemical energy is transformed into electrical energy (battery discharging)
6) Electrical energy is transformed into mechanical energy (electric motor)

Where a conventional driveline is replaced with a series hybrid system, the electric part has to cover the complete performance range / demand. In the case of the JD6068HL481 combustion engine, this means a 142kW effective maximum power output. Taking into account the above mentioned efficiency losses (step 2) and 3)) and with a degree of efficiency of, for this example, 92%, this implies:

$$P_{eletric} = \frac{P_{effective}}{\eta_{electric}^{\ 2}} = \frac{142kW}{0.92^2} = 167{,}77kW \qquad (1)$$

Electric motors with comparable power specifications are usually heavy, large and expensive.

<u>Parallel hybrid drive</u>

In contrast to the series system, the parallel hybrid drive is equipped with only one electric motor, usually with continuous power dimensions. Both energy transformers (combustion engine and electric motor) are connected with a fixed speed or torque ratio. Free selection of the operation point is therefore not possible, although there are advantages regarding costs and packaging. The electric part is also able to support the combustion engine, such as in phases with very high but short load demands.

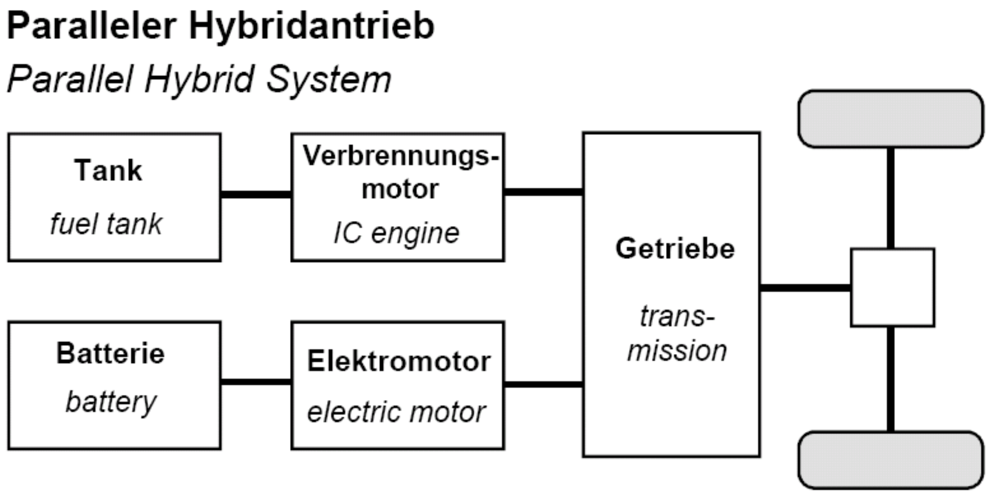

Fig. 2: Structure parallel hybrid system [2]

The efficiency chain in case of the parallel hybrid system:

1) Chemical energy within the fuel is transformed into mechanical energy (combustion engine) directly to the wheel-drive
   And/or
2) Mechanical energy is transformed into chemical energy (battery charging)
3) Chemical energy is transformed into electrical energy (battery discharging)
4) Electrical energy is transformed into mechanical energy (electric motor: boosting / electric driving depending on electric system application)

Where a conventional driveline is replaced by a parallel hybrid system, the electric part supports the combustion engine in various operation modes. Including as it does the possibility to connect the combustion engine to the wheel-drive, the parallel structure has clear efficiency advantages.

3.2 Realized concepts in the field of non-road applications

In the field of non-road applications, few prototypes have been developed with a focus on the reduction of fuel consumption. Considered economically, such systems are reasonable, if the lower fuel consumption over the product's lifetime is enough to balance the higher acquisition costs. One of the most promising concepts in this field is the downsizing concept: a smaller combustion engine is combined with an electric motor, and the system power output remains the same. A further step in this direction would be a more simply equipped combustion engine (for example, having no common rail system, no VTG turbocharger etc., for such a concept in passenger cars please see [3]) in combination with a high level electric part, which would handle transient demands. Such a system could be more cost effective, or at least would probably not be more expensive, than a standard driveline.

The most decisive criterion for the hybrid idea, however, is the typical operating profile of the various non-road application.

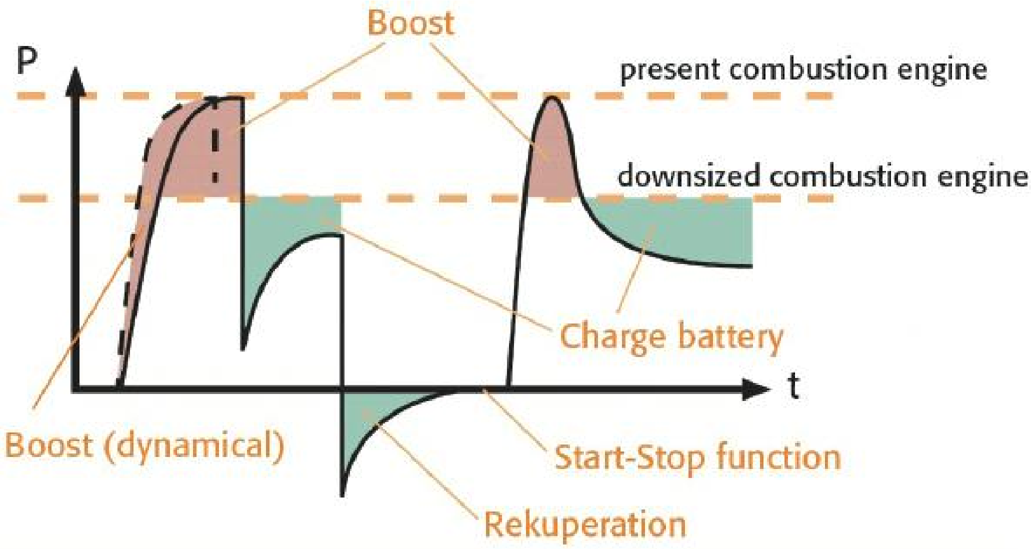

Fig. 3: Ideal operating profile for a hybrid application [4]

Fig. 3 shows an idealised operating profile which would be optimal for the downsizing concept. The range of high load areas is not too distinctive, even recuperation is possible. In this case the combustion engine assumes only the mean power demands; load peaks are covered by electric motor boosting.

A wheel loader is a possible example of such an application. The company Atlas developed an electric hybrid wheel loader in conjunction with the company Deutz AG [5]. In this application the electric motor design is a crankshaft generator, which replaces the combustion engine's flywheel and was developed by the company Heinzmann. Fig. 4 provides some technical data:

Combustion engine	
type	4 cylinder Diesel engine
power output	36.9kW @ 2100rpm
Electric motor	
type	Permanent solenoid synchronous machine
nominal power output	10kW
maximum power output	30kW
efficiency	<90%

Fig. 4: Power specs Atlas hybrid wheel loader [6]

Another example is the hybrid drive for a forklift truck developed by the companies Linde and Heinzmann, Fig. 5.

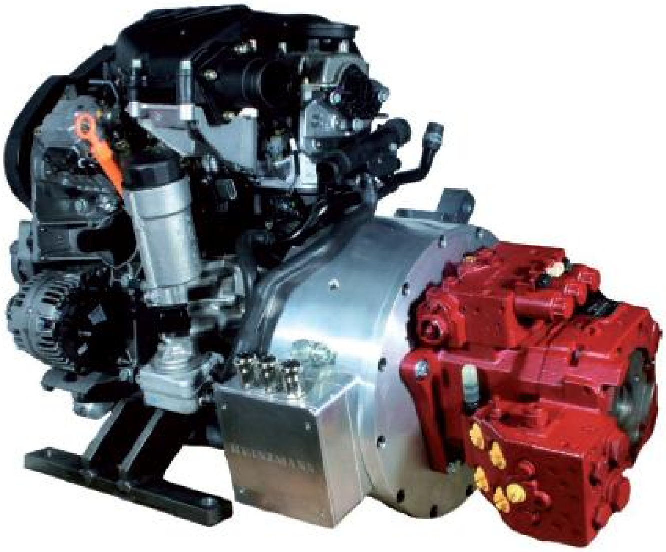

Fig. 5: Hybrid drive for a forklift truck [3]

Both applications have in common a mean power demand in the typical operating profile that differs clearly from the maximum power demand. Additionally, a typical “stop and go” operating profile recuperation of energy is possible for these applications. A “start-stop” function is also feasible due to the crankshaft generator’s contribution to the reduction of fuel consumption.

3.3 Evaluation of existing applications for the 2nd VegOil project

The goal, within the scope of the project in engine development WP2, is to develop a hybrid operation strategy for a simulated hybrid driveline (with a preselected combustion engine, the John Deere CD6068HL481). There are no restrictions concerning the electric part of the hybrid driveline, and so a reasonable proposal for the present application may be as follows.
The hybrid driveline affords possibilities for reducing emissions. The electric part of the hybrid system is able to function alone in various operation points without producing emissions. Although the energy required for purely electric driving has to be converted by the combustion engine before or after the electric-only driving phase, a process in which the fuel energy is transformed into mechanical energy, which again is transformed back into chemical energy in the battery.
The biggest advantage for emissions reduction may lie in the possibility of scrolling the combustion engine operation point to another engine map point (e.g. to a higher load point for charging the battery system, which in some cases brings advantages in terms of better specific emission values as a result of the much higher power output compared to the smaller increase in emission output [specific emission unit in g/kWh]).Significant advancement can also be expected with the reduction of the dynamic operating part of the combustion engine in high transient cycles such as the non-road transient cycle (NRTC), especially concerning particulate matter (and/or soot) output. Soot emission, in the case of a high dynamic operating profile, is high due to the turbo charger not yet having reached the speed required to

boost the requisite amount of air into the cylinders for the requested load. The fuel for the requested load point has however already been injected, and this leads to a fat-fuel mixture and consequently high soot emission, until the turbo charger reaches the necessary speed.
In principle, both of the introduced hybrid systems (series, parallel) come into consideration. This greater chance of feasibility has yet to be confirmed for the parallel assembly, due to the comparatively little adaption work required on the existing system. The electric motor could be designed as a crankshaft generator: a continuous electric power output of only 15-30kW would then be sufficient [5]. For these reasons, we now focus on a parallel hybrid system.

Series system:

- Free selection of the combustion engine operating point
- Combustion engine = energy transformer (η!)
- Large electric components necessary: electric motors have to adduce complete power requirements
- Investigation of „downsizing" is not in the scope of the project: JD engine will not be modified (hardware)

Parallel system:

- Easier installation/package (e.g. crankshaft generator)
- Combustion engine assistance $\Rightarrow$ dynamic reduction
- Undocking of the combustion engine imaginable: pure electric driving
- Smaller electric components: already electric motor power outputs up from 15kW can be reasonable (depending on application) [5]

Focus on parallel hybrid system

Fig. 6: Selection of the hybrid system structure

<u>Electric components</u>

One major challenge facing future series productions is the question of the energy accumulator. Existing systems differ in numerous aspects and so, depending on the scope of the application, several parameters (cyclic lifetime, energetic efficiency, self discharging, environmental compatibility and costs) have to be considered. Above all stands the main challenge of electric accumulators: availability is given either with high power density or high energy density. Even so, the energy density of, for example, a lithium ionic accumulator is small (<0.5MJ/kg) compared to that of rapeseed oil (37MJ/kg) or Diesel fuel (43MJ/kg) at present.
Regarding the selection of an electric motor, efficiency advantages mean that selection favours a three-phase machine. Three-phase machines are available as synchronous and asynchronous machines. The latter features a less advantageous torque curve, which can be

compensated by the adaptation of the machine`s layout; not, however, without consequences for the efficiency of the machine [7], Fig. 7.

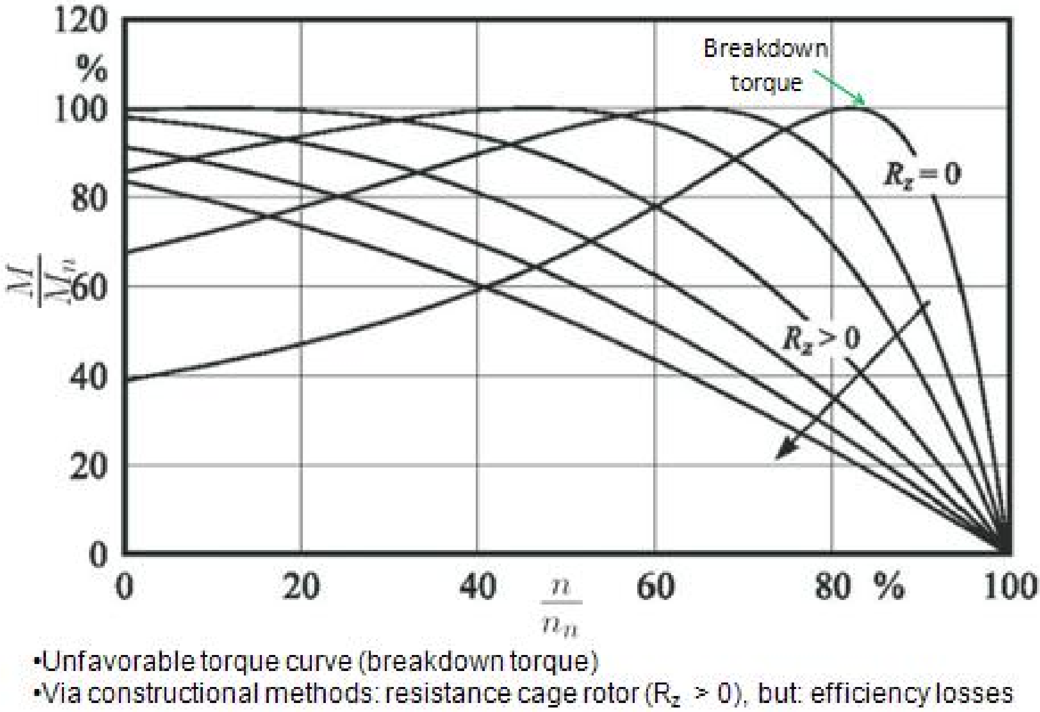

Fig. 7: Torque curve of the asynchronous machine [7]

The typical torque curve of a synchronous machine, by contrast, is clearly suitable, Fig. 8.

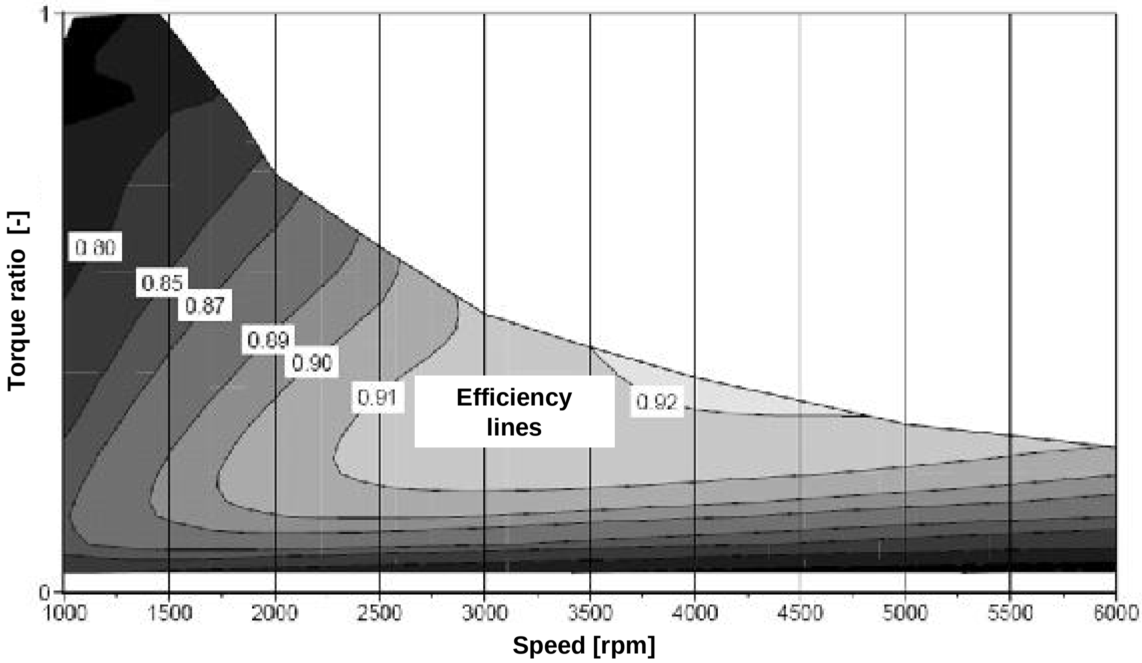

Fig. 8: Exemplary efficiency map of a synchronous machine [8]

The torque curve closely follows the traction hyperbole. This high torque supply at very low speeds allows high dynamics in the complete system.

For these reasons, the synchronous machine is used as a basis for the later modelling of the electric motor (chapter 4).

3.4 Target specifications of the hybrid model and level of abstraction

The goal of these target specifications is to build a model which is able to reduce development time. To this end, many different operation strategies, model applications and hybrid system controller settings will be tested. The most promising concepts are then validated at the test bench. Because of the possibility of using the test bench for to provide hard results, the model does not claim to display every single detail. In fact, the model must represent the system behaviour qualitatively very exactly; the quantitative behaviour performed in a reproducible and reasonable way.

The characteristics and the functionalities of the hybrid model are:

- Demonstration of various hybrid configurations and their effects on combustion engine emission behaviour (goal: reducing combustion engine emissions caused by high transient operating demands)
- Efficient pre-calculation of the combustion engine's emission behaviour resulting from differences in controller adjustment (validation of selected simulation results by the test bench)
- Simple transformation of the operating profile for the combustion engine at the test bench, for validation of the simulation results and detection of the measured cycle results

The model structure with its components (as 3.3 focuses on a parallel system) is listed below (Fig.9):

Hybrid simulation model components:

- **Driveline (parallel system)**
    - John Deere CD6068HL481 combustion engine (fuelled with rapeseed oil)
    - Electric motor (e.g. as crankshaft generator, synchronous machine), overload compatible
- **System controller**
- **Accumulator model**
- **Power take-off**

Input parameters

- Driveline speed and torque (subject to the speed and torque demand of the John Deere CD6068HL481 combustion engine at the test bench, given with the cycles NRTC and NRSC, see Deliverable D2.9 for details)

Output parameters

- Torque curves of the combustion engine and the electric motor
- Combustion engine behavior (focus: emission output)

Fig. 9: Model components, input/output parameters

Level of abstraction

Due to the availability of a real combustion engine (John Deere CD6068HL481) within the project, the simulation of the combustion engine will be effected firstly by the implementation of engine maps (measured at the test bench). The second step constitutes the modelling of the combustion engine's transient behaviour. This transient behaviour modelling requires several transient measurements at the test bench, and the successive adjustment of the combustion engine model within the hybrid model. As a result, the transient behaviour will be available during the next task, 2.12 (hybrid measurements).

The electric part of the hybrid system is represented with a reasonable degree of abstraction: due to the absence of constrictions, the selection is oriented on the literature findings in chapter 3.2. Details regarding the technical specifications within the model are listed in chapter 4.

4 Hybrid model

4.1 Implementation and modelling with DYMOLA

“Dymola”Software

Dymola exhibits a simulation environment which is able to transfer and to solve physically described problems in efficient mathematical formula systems using a range of algorithms. The simulation models are programmed in Modelica, an equations-based, object-oriented computer language developed to describe physical models, although abstract or logical models can also be described.

One major advantage of using Dymola is the physical approach of its modelling procedure. The individual elements of the model are simply described with the required basic equations. The necessary conversions and adaptions are conducted by Dymola’s algorithms: no manipulation by the user is usually required. The physical approach allows various components to be linked within one simulation environment. For example, multi-body systems can be linked with complex regulators and electrical drivelines, which can be modelled in great detail including single resistors, switches or capacitors.

Modelling and methods

In Dymola, a model is assembled either by using the graphical user interface or directly by programming in the Modelica code. In modelling the single submodels (e.g. the driveline), a hierarchical structure is reasonable. Here, Dymola offers pre-assembled simulation components: for example, whole component libraries are on offer for hydraulic components.

For modelling, several classes are available: the package and model classes are of particular relevance. Multiple other classes can be combined with that of packages: this class includes a collector directory. The model class can consist of source code, inputs and outputs, or of more subclasses (type: model). This class constitutes the basis of Dymola.

Each class has several display layers. The icon layer, which shows the interfaces and a free designable graphic for rapid identification of the simulation object, is at the top.

The diagram layer shows the internal relations of the simulation object. In the documentation layer, the user can give explanations and make annotations concerning the simulation object. The deepest layer is the Modelica text layer with the Modelica code, which defines the particular class and its content. All other layers are essentially a graphical display of a part of the Modelica code.

The possibility of heredity is an important characteristic of Modelica. New model components arise out of existing components with all their characteristics and content. Changes made later in the model development process in the parent component are acquired from the child components. This allows an efficient, logically-structured, modeling.

With the methods and target specifications described (chapter 3.4), a model, intended to provide information concerning the emission behaviour of the combustion engine in case of a number of hybrid operation strategy situations, is assembled. The model does not claim to display the thermodynamic and mechanical processes and circumstances very exactly. It is intended as a tool for the potential analysis of simulated hybrid operation strategy solutions without using the test bench.

4.2 Model structure

The components of the simulation model are examined in detail. All shortcuts within the figures are listed below:

n	Engine speed
J	Inertia
olf	Overload factor
SOC	State of charge
t_{csd}	time for reaching „constant speed mode“
T	Torque
$T_{delta, selected}$	max. allowed torque difference
P	Power
INDEX	
Acc	Accumulator
BT	Border torque
BTM	Border torque map
CE	Combustion engine
CSD	Constant speed detection
DBT	Dynamic border torque
E	Electric motor
HE	Hybrid engine
Max	Maximum
Nenn	Nominal
opt	Optimum
PT	Power take-off
SSD	Start-stop detection
target	Target value
theo	Theoretical
TO	Torque optimum

4.2.1 Cycle component

The cycle component contains a *Modelica* library source block (Combi Time Table), which extracts time-dependent parameters from tables and imports them from Matlab files or text files. This component is used to import the cycle parameters (speed and torque demand over time: NRTC and NRSC cycle).

4.2.2 Accumulator component

The accumulator, with an energy capacity of 7.5kWh (value proposed by John Deere) is simulated by an abstract model: it consists of a gateway for the power output and a calculation of the state of charge (SOC), see Fig. 10. The model calculates the current SOC based on the electric power demand or electric power input. Specifics concerning chemical, thermodynamic processes or ageing are not considered (yet). This step is not feasible before the constitution of the precise accumulator type.
To achieve realistic efficiency behaviour, an efficiency map for (dis-)charging in connection to the SOC is deposited.
Typical SOC initial values are around 70±15%. The necessity of reaching the start level at the end of the cycle for a balanced SOC is considered within a tolerance range of ±2%. The balanced SOC is managed with the hybrid controller component.

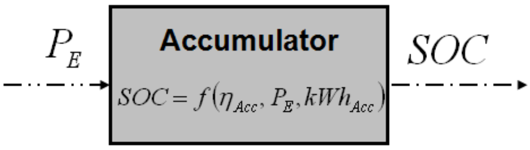

Fig. 10: accumulator model

4.2.3 Driveline component

The cycle torque demand is provided to the driveline model block, which includes the combustion engine and the electric motor in parallel alignment. Here, the division of the torque demand for the combustion engine / electric motor takes place, which again is transmitted to the power take-off flange.
Parallel alignment is characterised by the connection of both the combustion engine and the electric motor to one shaft, which rotates with cycle speed demand. The blocks “starter” and “starter logic” are explained later in 4.2.3. Fig. 11 displays the driveline component:

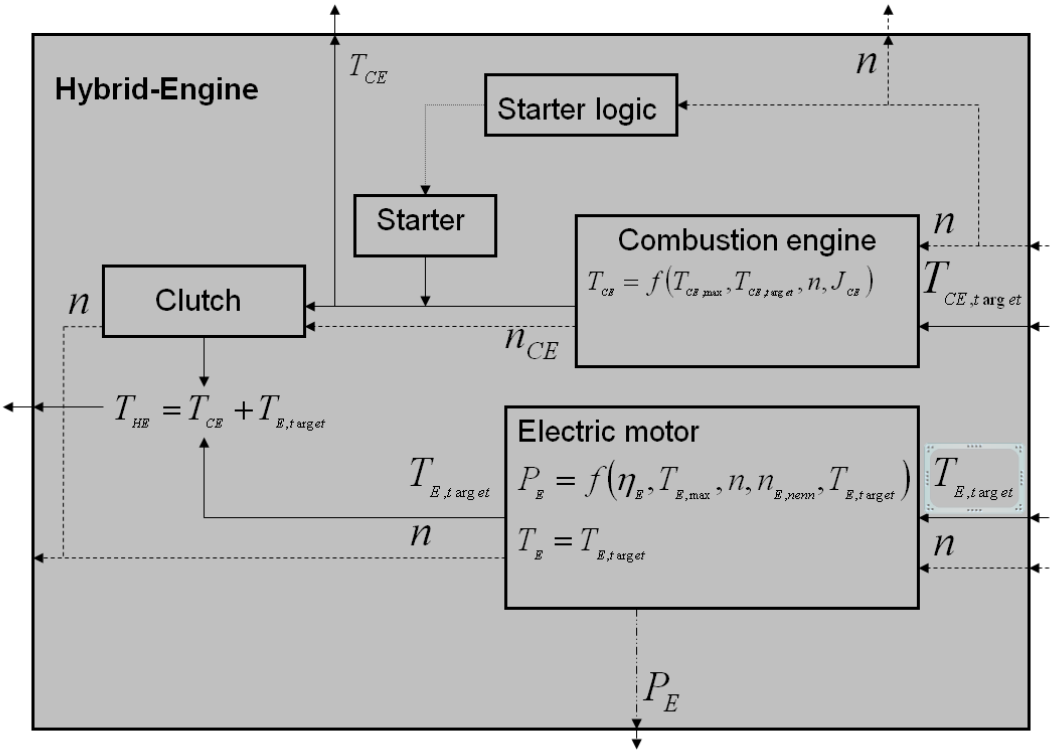

Fig. 11: diagram view model component: parallel driveline

<u>Combustion engine (CE)</u>

Current combustion engine modelling consists of the implementation of measured engine maps (compliant with stationary combustion engine behaviour). To represent mechanical losses in towed operation mode (electric driving with closed clutch), bearing friction and inertia are implemented.

The simulation of transient combustion engine behaviour is an important step for a more precise modelling: this step requires several transient measurements at the test bench, as well as the successive adjustment of the combustion engine model. As a result, the transient behaviour is available during the next task 2.12: hybrid measurements.

However, the stationary model of the combustion engine already delivers promising first results, which will be presented and discussed in chapter 4.4.

<u>Electric motor</u>

The electric motor is modelled by the implementation of a synchronous machine efficiency map (a typical map is shown in Fig. 8, chapter 3.3) and the definition of the torque and power data (examples in Fig. 12).

This facilitates the investigation of varying electric motor configurations (power range 20 to 35kW, overload ability factor 2 to 4).

The acceptable overload of the electric motor is controlled by monitoring average power demand. Overloading is allowed, as long as the average power demand during a monitored time interval does not exceed a defined value. If the value is exceeded, the overload functionality is blocked until the average power demand returns to below the defined value.

$P_{continuous}$	$Torque_{max}$	Peak overload factor	Monitoring time	Max. average power	Average power for overload reactivation
35kW	720Nm@460rpm 160Nm@2100rpm	4	300s	$P_{continuous}$	0.8 x $P_{continuous}$
25kW	450Nm@530rpm 115Nm@2100rpm	2	300s	$P_{continuous}$	0.8 x $P_{continuous}$

Fig. 12: Table: exemplary data for electric motors

<u>Clutch</u>

For electric-only driving, a clutch is implemented in the driveline component. This clutch is modelled as a coulomb-friction clutch.

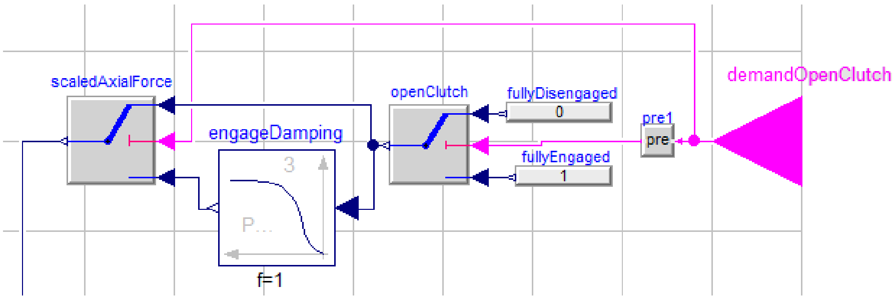

Fig. 13: Driveline module in DYMOLA: clutch action

The shutdown and start-up of the combustion engine are controlled by the hybrid controller component described in chapter 4.3.

4.2.4 Emission calculation component

The real emission output is composed of stationary and transient parts. Dependent on current project status, simulation of the combustion engine is based on maps of the stationary measurements (please see Deliverable D2.8 and D2.10): time variable processes have not yet been implemented (to follow with Deliverable D2.12). The maps show the emission values [in g/h] documented subject to the engine speed and load (and where appropriate, torque). Depending on the current combustion engine operation point, these values are readout, converted into an adjustable time unit and integrated. Finally, the absolute values [e.g. g/h] are calculated in terms of specific values [g/kWh].

The fuel consumption is also deposited as map and is determined within a submodel.

Due to the current direct stationary calculation of the emission output, the emissions measured will differ from the calculated ones. In terms of NO_x emission, only a moderate difference is expected (due to the **e**xhaust **g**as **r**ecirculation (egr) system and its influences, e.g. hysteresis of the egr-valve). The difference in particulate matter (soot emission where appropriate), should be higher, due to the turbo charger run-up with very high load / torque steps.

Ultimately, the current stationary implementation of the combustion engines emission behaviour is acceptable for definite qualitative comparisons between different hybrid operation strategies.

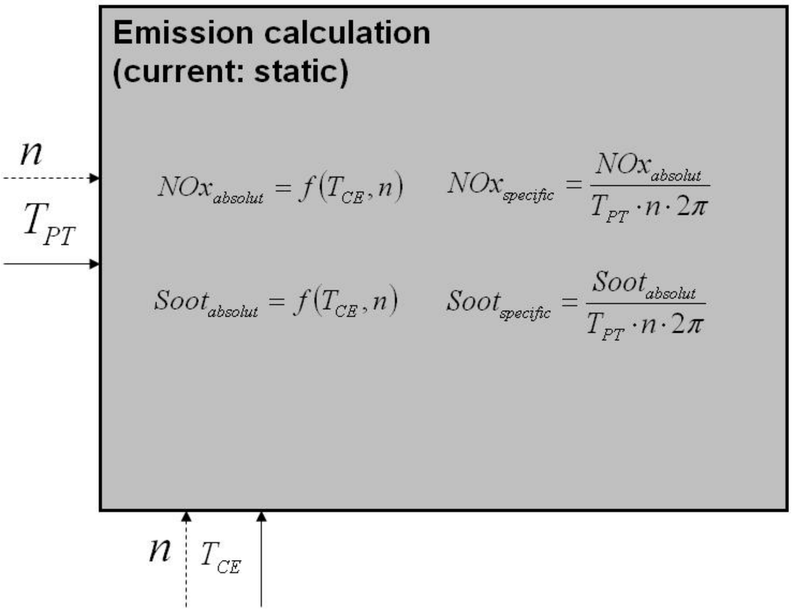

Fig. 14: Diagram view model component emission calculation

4.2.5 Assembler component

The model has an assembler component, which combines any unprocessed sensor signals. This component serves as an assortative structure without influencing the hybrid operation strategy.

4.2.6 Power take-off component

The power take-off component displays the virtual pendant of the test bench brake, which controls the speed while the driveline component provides the combustion engine / electric motor torque (depending on the hybrid controller adjustment).

4.2.7 Hybrid controller component

The controller component is one of the most important submodels of the complete hybrid model. The interface of this component has inputs for cycle demands and SOC, and outputs for the torque demands for the driveline component (combustion engine and electric motor) and driveline speed. With this interface various hybrid controllers are developed (chapter 4.3).

4.2.8 Complete hybrid model

A template, with all the submodels / components presented, is generated for experimentation with the hybrid driveline. All component interfaces are included and connected accordingly within this template. The individual submodels are replaceable, for example, various hybrid controller solutions are easily adjustable. Fig. 15 illustrates the complete hybrid model.

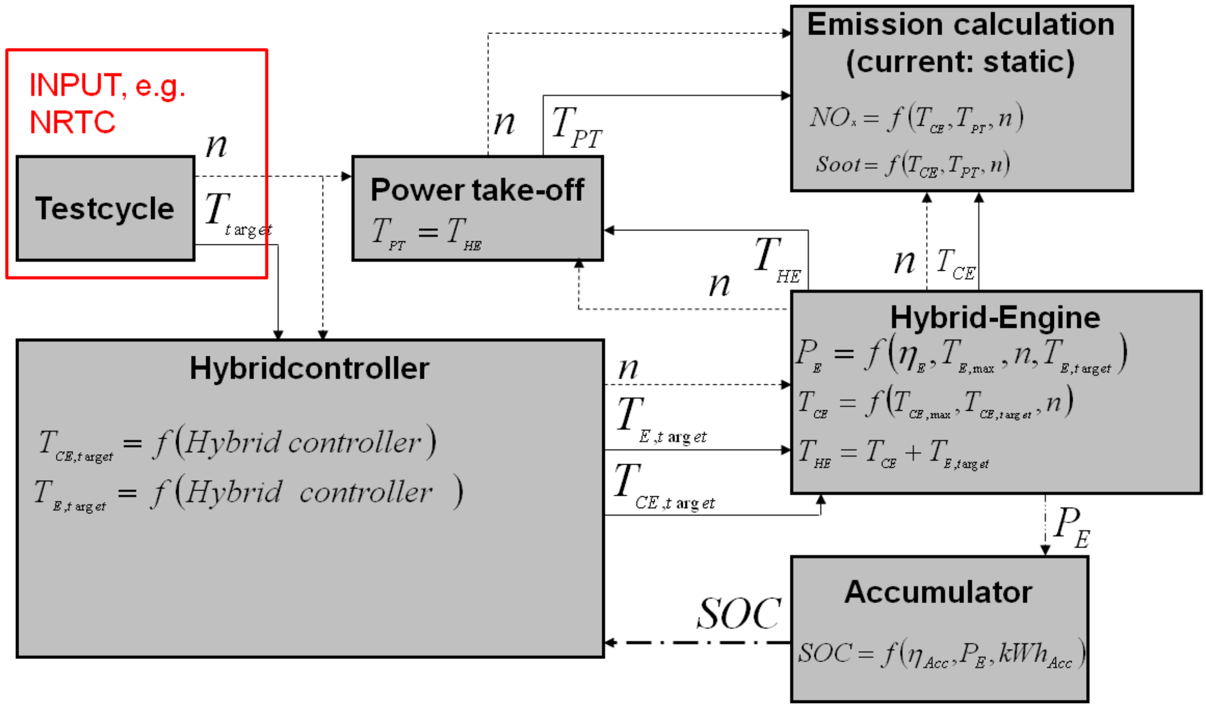

Fig. 15: hybrid model

4.3 Hybrid controller strategies

There are several appendages for the reduction of the John Deere CD6068HL481 combustion engines' emission output through the development of hybrid operation strategies.
The hybrid controller component has the main influence on the operation strategy. The accumulator and its SOC also have considerable impact on the strategy. According to [9], the recommended discharge depth for lithium ionic batteries enables conduction at 5-10%. During a measurement of the Toyota Prius hybrid passenger car, according to the SAEJ1711 (guidelines for the emission measurement of hybrid vehicles) in 1999, the operating range of the NIMH battery SOC lay between 54% and 69% [10]. SOC strongly influences use of the electric motor with the hybrid model.
The hybridization concept in the 2ndVegOil project sets its priorities on the reduction of emission output, in particular nitrogen oxide emission and particulate matter/soot emission (especially the latter due to the high transient NRTC). With the stock combustion engine application, the possibility of fulfilling the upcoming emission limit EU Stages 3B/4 is theoretical, because of the few operation points already reaching the limits. The hybridization is also not able to compensate for this: the best emission point of the combustion engine is the best possible emission point of the whole hybrid driveline. This means that the advantage of hybridization for reducing emissions lies within the reduction of the dynamic demand for the combustion engine. It is therefore necessary to make a proposal for the adaptation of the stock engine application, as far as possible within this project, to lift the combustion engine into an area of lower emissions. This development is achieved in Deliverable D2.12 and affects the controller strategies, meaning that continuous adaptation will be necessary during

development work. The strategies described here are therefore based on a stock combustion engine application, and display the potential of the hybridization for the current project status.

4.3.1 Influences of the parallel hybrid structure and of the John Deere CD6068HL481 combustion engine

The parallel hybrid structure couples the speed of the combustion engine and that of the electric motor: the torque demand for the two machines is the adjustable parameter. The speed and the driveline torque demand are given with the particular operation cycle (such as the NRTC). With the current project status, controller strategies are based on the stationary emission behaviour of the combustion engine (see also chapter 4.2.3).

The emission maps of the John Deere CD6068HL481 combustion engine show the characteristics of the stock application for fulfilling emission stage 3A with several techniques (cooled exhaust gas recirculation system, common-rail injection system, variable turbine geometry turbocharger). To fulfil the targets set by 3A, the optimization of the combustion engine by the manufacturer was carried out on the eight NRSC points (please see Deliverable D2.8 for further information), which is reflected in the emission maps (for example, the NO_x emission map shown in Fig. 16).

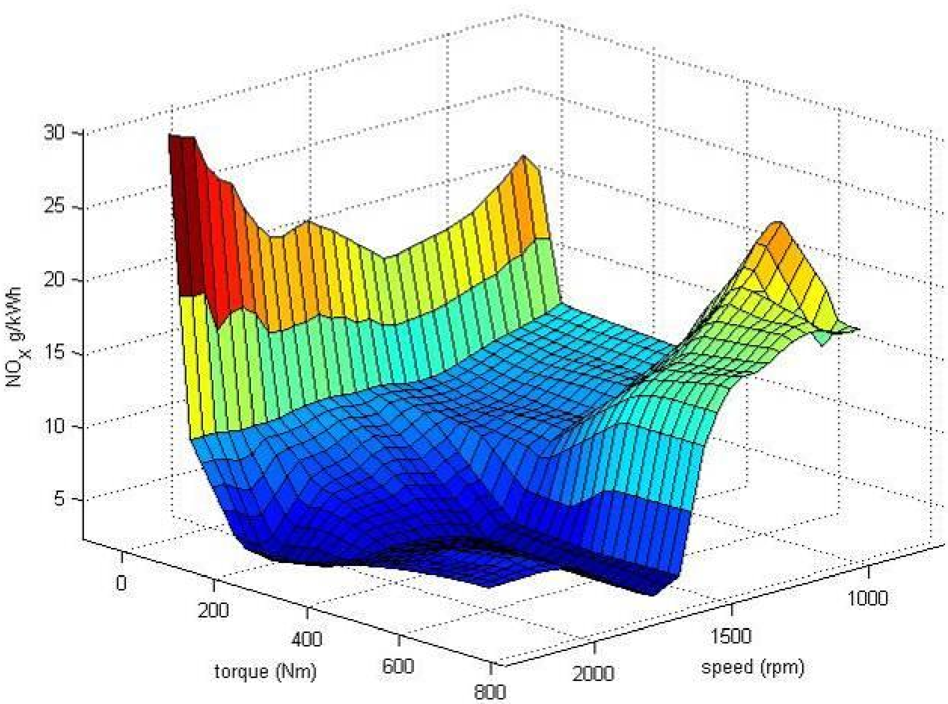

*Fig. 16: measured specific NO_x emission map (**stock application**) with rapeseed oil*

By operating the simulated hybrid engine with the NRTC and its permanently changing speed demand, any possibility for a combustion engine's optimal torque corridor for minimal emissions is eliminated. Even at neighbouring speeds, the emission outputs for identical torque values can be very different.

4.3.2 Hybrid controller model components

For easier application and development work, the controller parts are implemented in submodels. These submodels are described below.

<u>Checking of the electric section</u>

With this part of the controller model the reasonable physical limits are checked (depending on the electric motor simulated). The input parameters (Fig. 17) are the SOC, the target cycle speed and the suggested torque ($T_{E,\,In}$) given by the different controllers described later.

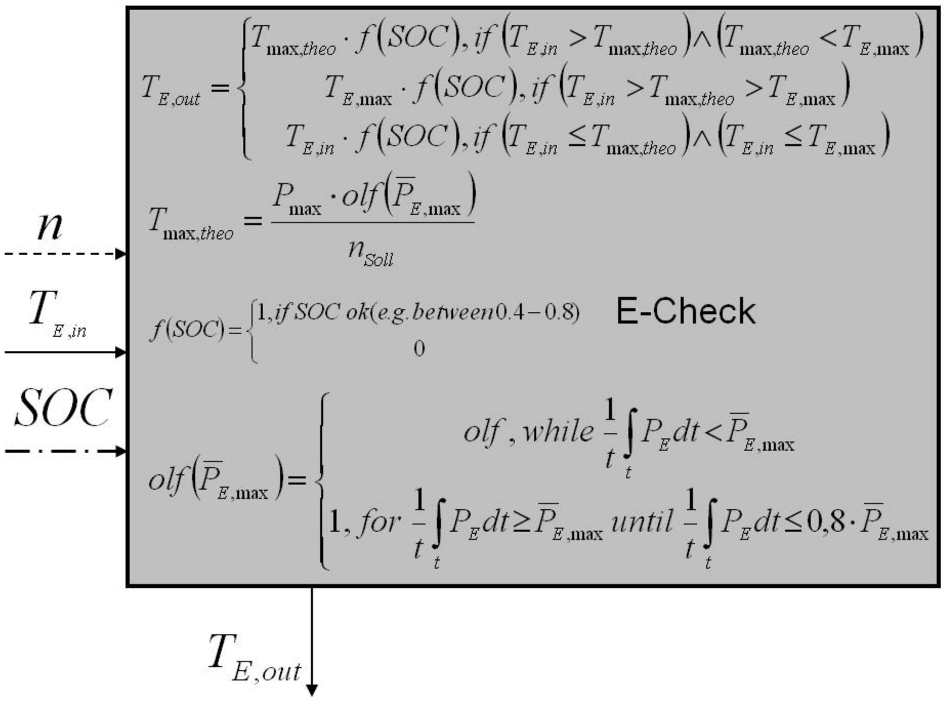

Fig. 17: e-check component

The overload function is monitored within the e-check component by integrating P_E over a defined time period and comparing it with the mean maximum electric power output of the e-motor. *Olf* (overload factor) is set to 1, if $\frac{1}{t}\int_t P_E\, dt \ge \overline{P}_{E,max}$. The overload function is available again, if $\frac{1}{t}\int_t P_E\, dt \le 0.8\ \overline{P}_{E,max}$.

Another important part of the e-check is the monitoring of the *SOC*, which has to lie in a defined interval (e.g. between 40% - 80%).

The next step is the calculation of the theoretical maximum torque, $T_{max,\,theo}$ in dependency on the overload factor. Finally the output of the component ($T_{E,out}$) is selected in reference to $T_{E,in}$, $T_{max,theo}$ and $T_{E,max}$.

Optimum controller

The optimum controller and its strategy, constantly forces the combustion engine into the best possible emission operation point at the given cycle speed. Depending on the SOC, these points are either at the absolute best point (emission output in g/h means low loads for the combustion engine) or at the specific best point (emission output in g/kWh means higher loads for the combustion engine). The optimum controller model is shown in Fig. 18:

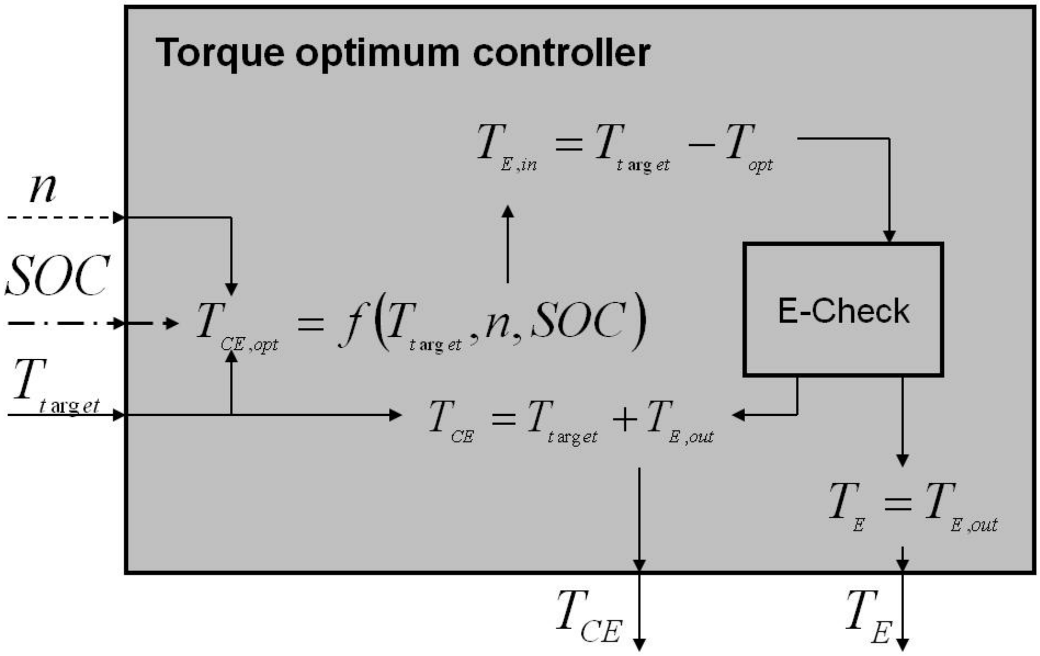

Fig. 18: optimum controller component

A hysteresis switch takes care of shifting between the absolute-and specific best emission output modes. Next the torque value to be delivered by the combustion engine is set. This calculation affects the electric motor value, which is dependent on current cycle torque demand. The electric motor torque value is checked against the e-part check component submodel. The result of the e-part check is again compared with cycle torque demand. Finally, the torque value for the combustion engine is set.

First simulation results using the optimum controller (cycle: NRTC) show more, and higher, load steps for the combustion engine than are already in the cycle. Fig. 19 displays the difference in the torque gradients between the simulated combustion engines when optimum controller driven and when stand-alone driven:

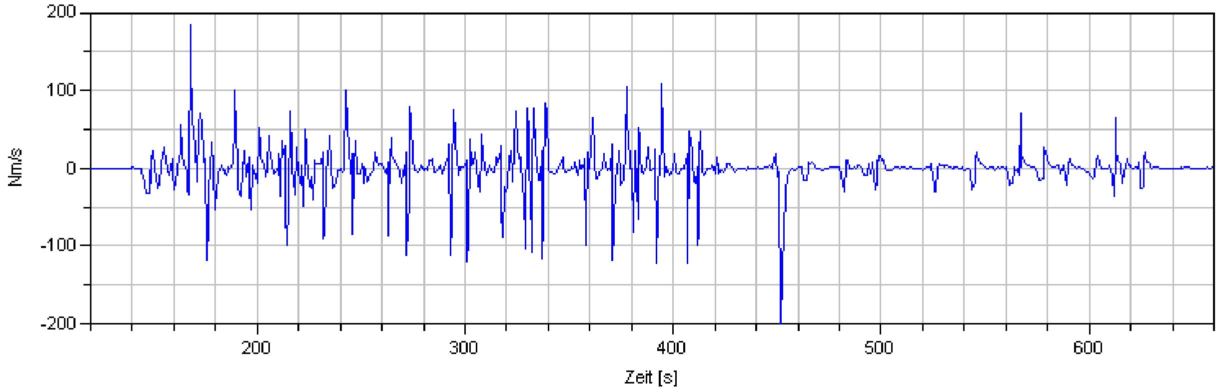

Fig. 19: Difference in torque gradients optimum controller / stand-alone combustion engine (cycle: NRTC)

Negative effects on the transient emission behaviour of the combustion engine have to be expected when using the optimum controller. Another controller strategy is therefore necessary when using the stock engine application.

<u>Border-torque controller</u>

To avoid higher load steps for the combustion engine, the strategy of the border-torque controller forces the *JD CD6068HL481* into the closest local emission minimum, rather than the global minimum. For every combustion engine operation point there is a local emission minimum operation point available, searched by derivation of the emission curve in subject to torque at the given cycle speed. With consideration of the demanded torque gradient, the direction of the border-torque load point shifting is fixed: depending on the gradient, the next local minimum is selected.

The located emission minima for every combustion engine operation point are deposited in a map ("border torque map"). This target operation point is the border-torque point, at which the controller is allowed to drive the combustion engine. For the operation of this controller, two of these maps are compiled: one for the best specific emission [g/kWh] and one for the best absolute emission output [g/h]. These functions are embedded in the border-torque controller with a subcomponent that shifts between these maps depending on the SOC.

Cycle speed and torque demands and the current SOC are given as input parameters for the model. The output of this component complies with the suggested torque for the combustion engine.

Fig. 20 shows an extract of the simulated NRTC with the border-torque controller working. The red curve displays the suggested combustion engine torque, the blue curve the cycle torque demand. The load point shift in a local emission minimum point as a function of the SOC is also illustrated.

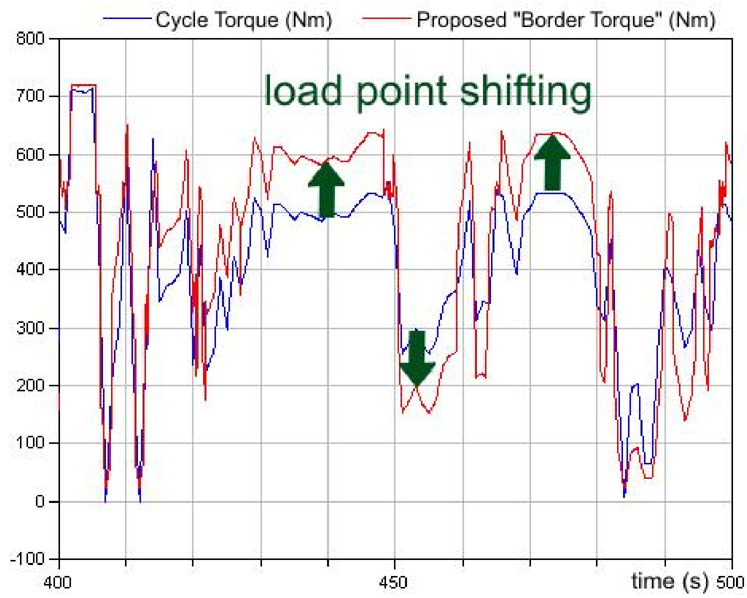

Fig. 20: Engine load shifting by border-torque controller

Dynamic controller

Due to high transient NRTC with large load steps in a short time, a high transient emission output is expected, especially of particulate matter and soot. For this reason, a controller has been developed which activates the electric motor as soon as the torque demand on the combustion engine crosses a certain threshold. For this kind of application, the overload availability of the electric motor has to be taken into account: here, the ability to overload up to four times the continuous torque output in case of a synchronous machine [4] brings advantages for the reduction of dynamic demand on the combustion engine.

For such an implementation, only the suggested torque for the combustion engine is needed. A DT1 element affects the torque gradient in [Nm/s]. When a pre-defined value (e.g. 100 Nm/s) is exceeded, the difference between the suggested value and the torque gradient limit is forwarded to an interface: the electric motor torque is then corrected by this difference. The second output (new engine torque) exports the torque value for the combustion engine (Fig. 21):

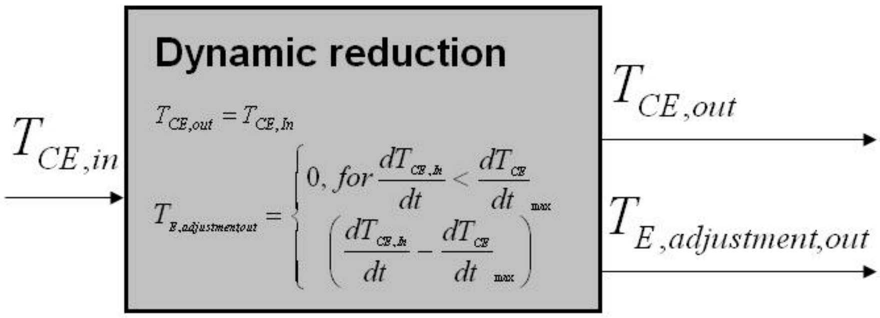

Fig. 21: dynamic controller

Combination of border-torque and dynamic controller

The combination of the border-torque and the dynamic controller generates a new component: the dynamic border-torque controller. The suggested electric motor torque value delivered by the border-torque block is added to the correction from the dynamic controller component, before the e- check component becomes active.

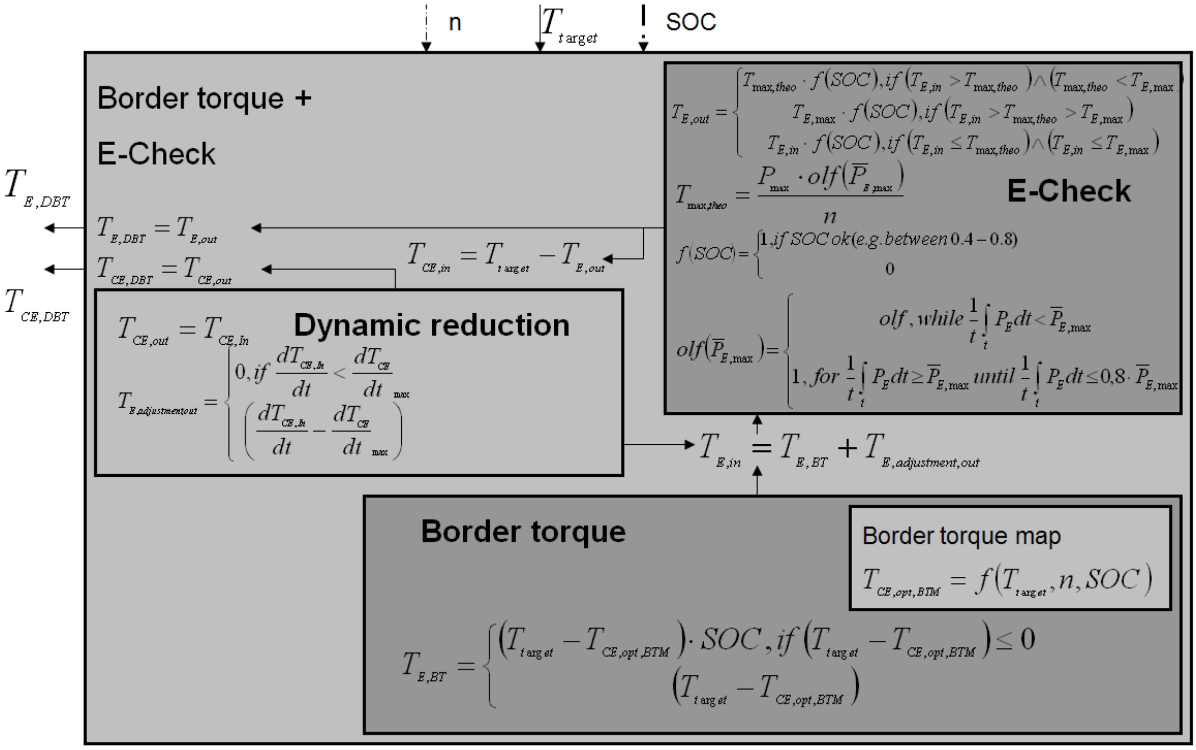

Fig. 22: Combination of border-torque and dynamic controller

Fig. 23 shows a comparison between the cycle torque demand (blue), the border-torque controller (red) and the dynamic border-torque controller (green): the damping of high load steps, which has great impact on soot emission and particulate matter, is evident.

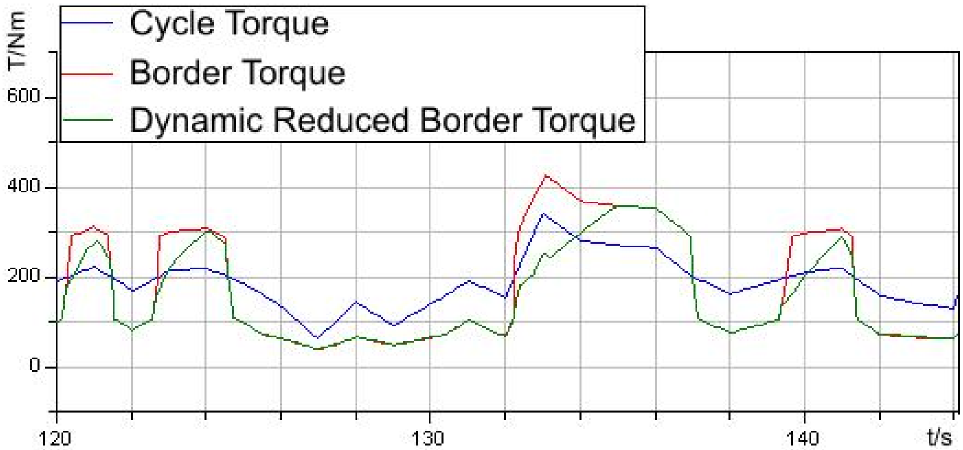

Fig. 23: Comparison of border-torque controller with/without additional dynamic reduction, torque curve of the simulation combustion engine

Start-stop-controller

It could be reasonable at some points, especially in idle, to stop the combustion engine, causing no emissions for as long as the stop phase lasts. An idle mode detector and a start-stop controller have been developed for this purpose.

With the given cycle demand, idle conditions are identified (n=850 1/min, T = 0Nm). After five seconds in idle conditions, a Boolean output variable is set as false. When idle conditions end, the variable is set as true again.

This idle detection is used for the start-stop-controller, which sends a speed demand to the driveline: n=0 for combustion engine shut-off, n=850 for engine run-up. The opening/closing of the clutch (within the driveline component) is also controlled by the start-stop functionality.

Constant speed mode + two mode controller

In cycle operation areas in which the speed of the driveline is relatively constant (typical for some tractor applications, therefore also present in the NRTC), use of the optimum controller can be advantageous. For this reason, a constant speed detection module is implemented (Fig. 24):

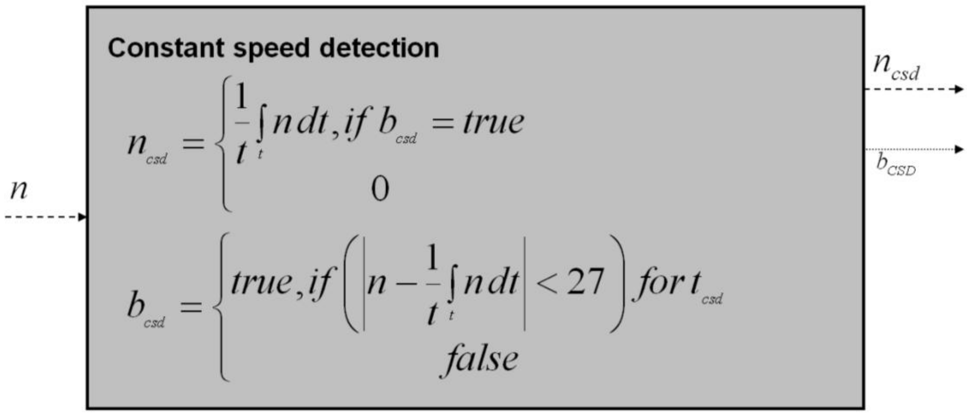

Fig. 24: Constant speed detection module

From the input *n*, a running average is built by integrating the signal, calculating the difference of the integral and its value at a defined past time and dividing the result by the same time value. The resulting average is compared again to the current exact speed value. Whenever the difference falls below a defined accepted speed variance (here: 27rpm), a timer is started. If the timer reaches a defined value (e.g. 8s), indicating that speed has not varied excessively in the given time interval, a Boolean output value is set as true. At the moment of the activation, the average speed is taken by a trigger and transported via a real output for use in the hybrid controller as current constant speed.

With the constant speed driven combustion engine, the torque optimal controller (described above) can be used, which could bring advantages with shifting the combustion engine in the global emission minimum point. The torque optimal controller only works when constant speed is detected.

Because of this, the two-mode controller takes care of shifting between the currently implemented controller and the optimal torque controller. However, the optimal torque lines for specific best emissions have to be reduced by about 10-20Nm to enable the engine to hold the torque reliably when short speed peaks occur within the tolerance and speed is not within the torque plateau.

Fig. 25 shows the effect of this shifting strategy with an example of a hybrid configuration with 35kW electric power, overload factor 4. In this case, the long constant speed phases in the last third of the NRTC can be used to load the accumulator, while the dynamic reduction elements can be used during the rest of the cycle.

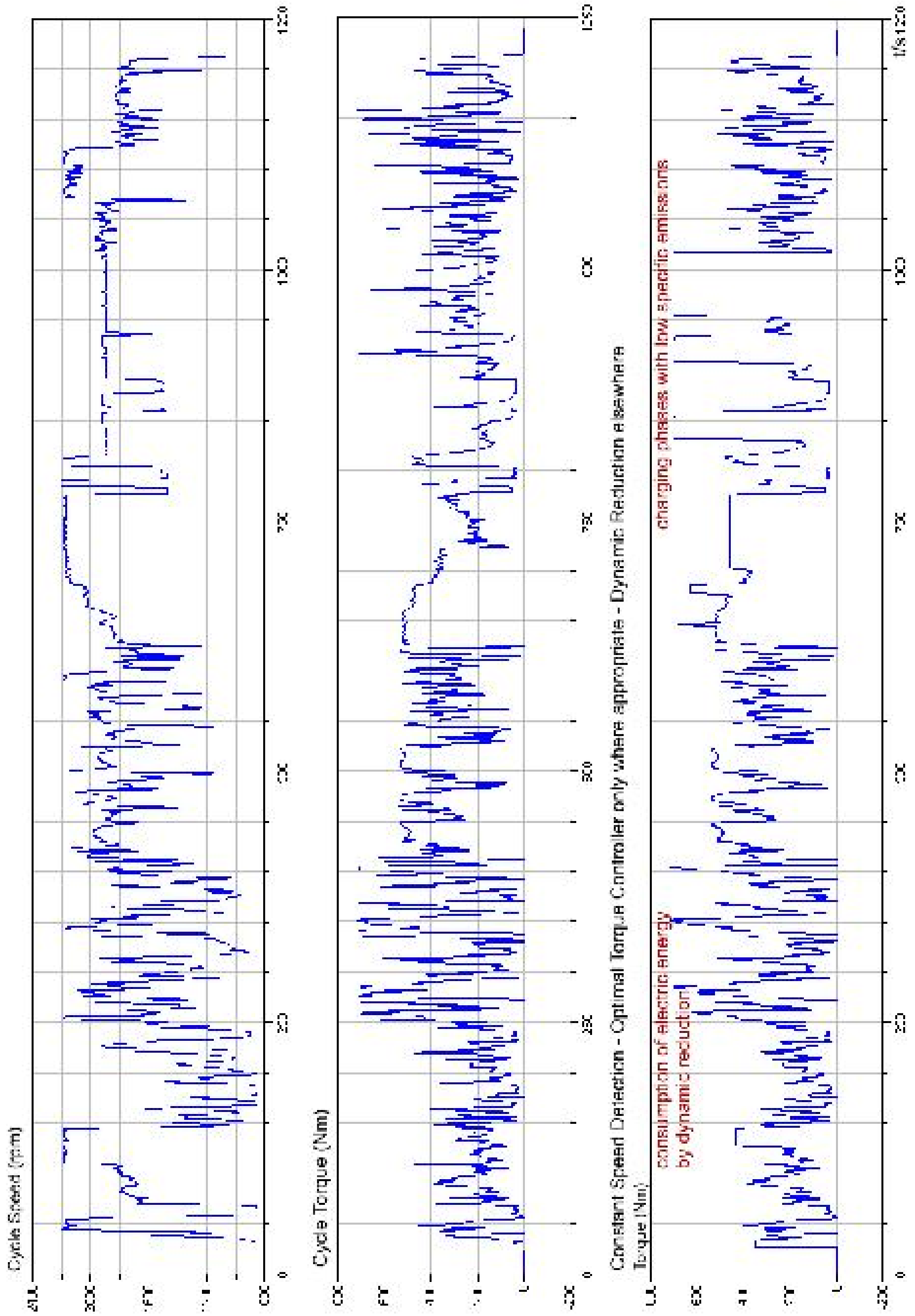

Fig. 25: Two-mode controller with torque-optimal operation in constant speed phases

Finally, all controller elements are integrated into one component, which combines all functionalities described, such as constant speed mode detection and start-stop functionality, Fig. 26:

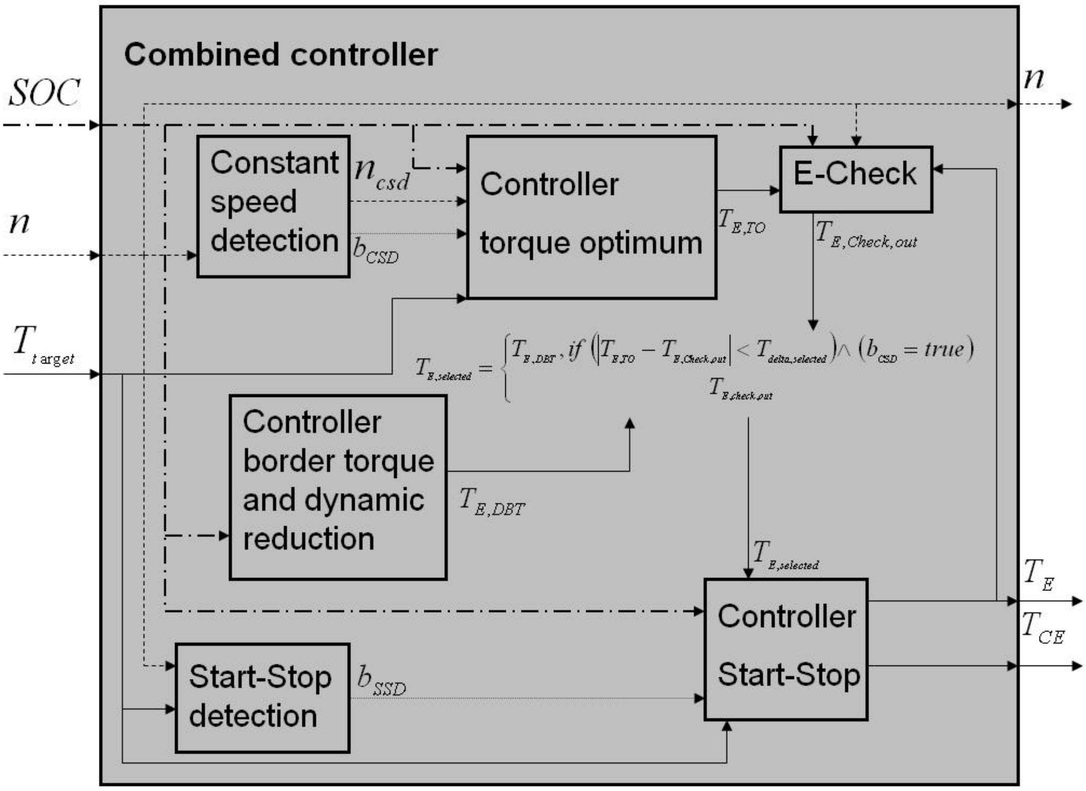

Fig. 26: Combined controller

Switching between the torque optimum and border torque / dynamic reduction controller is not only dependent on the constant speed detection, but also on the e-check component: if $T_{E,TO}$ and $T_{E,Check,out}$ differ too much, $T_{E,DBT}$ is used to avoid larger load steps for the combustion engine.

4.4 Simulation results concerning the emission output

In the following table (Fig. 27) the simulation results of the single hybrid operation strategies (for the stock ECU application without regarding the transient emission behaviour) are listed (soot optimal strategies for the NRTC). The electric motor configuration is:

- 25kW continuous power output
- 2 times overloading capability
- Accumulator capacity: 7.5kWh

Hybrid controller type:	NO_X	CO	HC	Soot	Cons.	ΔSoot	$ΔNO_X$	ΔCons.
	g/kWh					%		
Combustion engine simulated	5.3	1.5	0.048	0.0098	261	ref.	ref.	ref.
Combustion engine test bench	6.0	1.8	0.050	0.0234	267	139%	13%	2%
Torque optimal	6.3	1.4	0.047	0.0092	292	-6%	19%	12%
*Border torque dynamic reduced	6.8	1.5	0.052	0.0073	285	-26%	28%	9%
*+ Torque optimal in constant speed	6.7	1.6	0.053	0.0072	288	-27%	27%	10%
*+ Start-stop in idle	6.6	1.7	0.052	0.0096	285	-2%	25%	9%
*+ Optimized run-up	6.6	1.5	0.052	0.0072	286	-27%	25%	10%

Fig. 27: Table of simulation results concerning the emission output (NRTC), soot-optimal strategies

The table shows individual results for the various emission outputs and for fuel consumption (unit: g/kWh). The differences between the reference values (simulated combustion engine without electric support) and the various hybrid controllers are also listed. In addition, the results of the NRTC-driven combustion engine from the test bench are displayed, for comparison of the single simulated combustion engine. As expected (and explained above), the soot emission of the transient driven combustion engine differs significantly from that of the stationary driven (simulated) combustion engine (0.0098 g/kWh compared to 0.0234 g/kWh). NO_x emission also varies, but not as greatly as the soot emission. Finally, development work for modelling the combustion engine's transient emission behaviour is necessary (to follow in D2.12).

Discussion of the various hybrid controller results

The target for every individual simulation with electric support (hybrid simulation), in terms of the NRTC, is a soot-optimal strategy. For example, the torque optimal controller forces the combustion engine into every single global soot optimal operation point possible (dependent on the SOC). This means that the global minimum at the speed demanded is the target. It is therefore necessary for the electric motor to support the combustion engine in reaching the target point, because in some cases the torque step is so high that the combustion engine is not able to reach the best point in the short time available. All in all, this strategy leads to high overloading of the electric motor even in early phases of the NRTC, which results in a limitation on overloading in the rest of the cycle and, step-by-step to a relatively small decrease in specific soot emission (-6%).
The simulation with the dynamic border torque controller, which offers great advantages concerning soot emission output (-26% in comparison to the simulated combustion engine) is executed next. The NO_x emission output increases due to the soot-optimal strategy (typical NO_x-soot trade off for diesel engines). The higher fuel consumption points to efficiency losses (especially due to the charging/discharging of the accumulator and the additional losses of the electric motor). Combustion engine efficiency should be higher, because of more complete combustion resulting from the soot-optimal strategy (its higher NO_x emission is an indicator for this theory).

Additionally, using constant speed detection (and subsequently the torque optimal controller at stationary operation points), results in soot emissions only a little better than those achieved with the dynamic border torque controller, although a decreasing NO_x emission brings a slight improvement.
The soot emission result produced using the start-stop functionality is not greatly improved on that produced using the simulated combustion engine alone. The reason for this is the very high soot emission during the combustion engine's start phase (in warm conditions) with the stock starter. Due to this, an optimized run-up is implemented, which then leads to a soot result comparable with the result produced using the dynamic border torque and torque optimal in constant speed controller. Obviously, the start-stop functionality (entirely electric drive) is not appropriate for improving the soot emission output of the combustion engine with driving the NRTC. Concerning PM emission, the start-stop function in conjunction with an optimized run-up could be advantageous and will be in the focus within the next task.
The simulation results have to be validated by test bench results, which will follow during the next task and will be reported in Deliverable D2.12.

Using the NRSC as cycle for the certification of the gaseous emissions, the hybrid operation strategy is switched to a NO_x-optimal strategy.

Note: It is important that the results of the emission outputs are calculated with raw data and not with converted data (humidity, temperatures are considered here). This is the reason why the emission values for the simulated combustion engine are higher than the measured converted values released with Deliverable D2.10.

For that stationary cycle, only one controller is reasonable: here, constant speed detection is necessary, which is compared with the simulated combustion engine, Fig. 28:

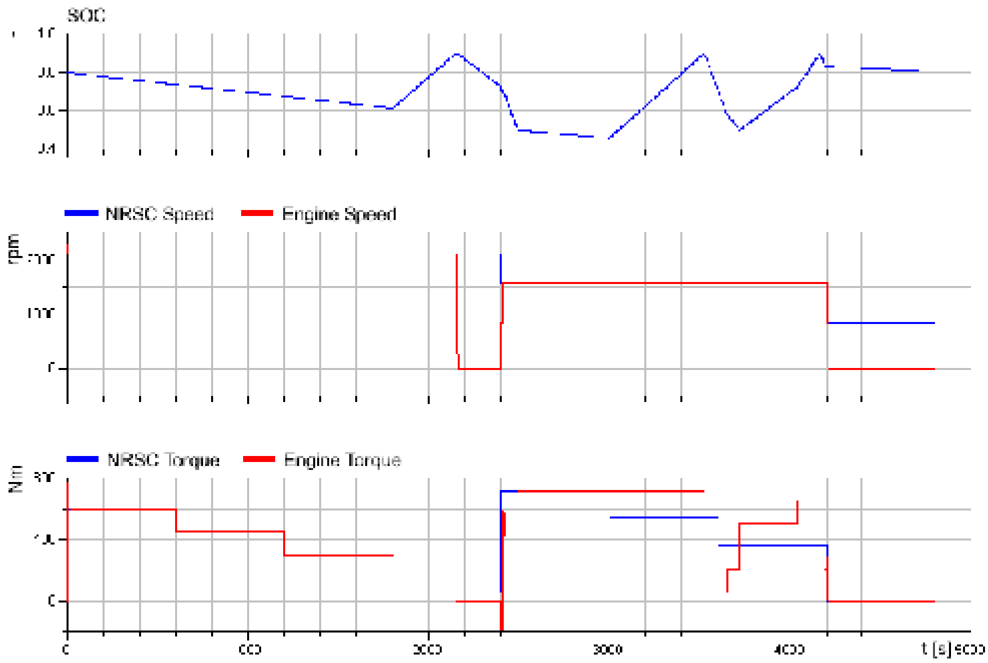

Fig. 28: State of charge, speed and torque in NRSC Simulation

The SOC starts at a level of 80%. The demand for a balanced SOC is fulfilled as the start value is reached at the end of the cycle. As the load point shifts in the fourth NRSC point (demand: n=2100rpm, 10% load) from 62Nm to 200Nm (Fig. 28 lower diagram), electric-only driving is possible (time index approximately 2150s, combustion engine torque (red curve) is zero). Also in the last operation point (idle) in the NRSC cycle, the combustion engine is off. The table in Fig. 29 shows the results of this strategy:

Hybrid controller type:	NO_X	CO	HC	Soot	Cons.	ΔSoot	$ΔNO_X$	ΔCons
	g/kWh					%		
Combustion engine simulated	4.3	0.8	0.033	0.0077	253	ref.	ref.	ref.
Torque optimal (NO_X) in constant speed	4.2	0.6	0.027	0.0081	261	5%	-2%	3%

Fig. 29: NRSC simulation results, NO_X-optimal strategy

The hybridization is obviously not very effective for a purely stationary cycle such as the NRSC, at least for stock ECU mapping and for reducing NO_x emission output. The specific NO_x improvement is only 0.1 g/kWh (-2%), whereas the soot emission and the fuel consumption increase (+5% respectively +3%). The impact on the particulate matter however has yet to be considered: there may be advantages, particularly in very low load rapeseed oil operation points such as in idle.
In respect of NO_x emission output, the adaption of the combustion engine's injection strategy and subsystems (charge air cooling, egr cooling) appear to be more effective (not considering exhaust gas aftertreatment systems).

5 Conclusion and summary

The exposition of the hybrid function by implementation of a hybrid model demonstrated the various possibilities of hybridization. A verified strategy (NO_x / soot-optimal controller strategy for the NRSC/NRTC) with stock combustion engine ECU rapeseed oil mapping for the reduction of emissions was developed. NRTC offers great advantages in soot reduction potential (up to 27% lower soot emission) in comparison to the single simulated combustion engine. These results have yet to be validated by the test bench in subsequent project steps, particularly with the real particulate matter emission output. Furthermore, development work on the modelling of the combustion engine's transient behaviour remains to be done, in order to minimize test bench measurements.

Regarding the hybridization in conjunction with the NRSC and stock ECU mapping, it should be noted that its effectiveness is not conclusive. The improvement in NO_x emission output is small.

All in all, it is necessary to adapt the combustion engine's ECU mapping and its subsystems (such as charge air cooling or egr cooling system) to develop an operation point corridor for the hybrid combustion engine.

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