Green Wheel Loader – improving fuel economy through energy efficient drive and control concepts

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Abstract

The drive train components and the machine control system significantly influence the fuel consumption of mobile machinery. The demonstrator vehicle “Green Wheel Loader” developed within the joint research project “TEAM” combines the most promising drive concepts currently available for mobile machines with an innovative operating strategy. The developed drive and control system proved its functionality and performance under realistic operation conditions in a gravel pit. Reference test showed 10 – 15 % fuel savings of the prototype vehicle compared to a state-of-the-art series machine.

KEYWORDS: mobile machines, energy efficient drive trains, operating strategy

1. Introduction

Mobile equipment manufacturers are currently focusing their engineering activities on the increase of productivity, operator comfort and energy efficiency as well as the compliance to exhaust emission regulations (TIER 4 final, EU stage 4). Against this background, the use of new, energy efficient drive technologies is becoming more and more attractive. Agricultural machinery and construction equipment still offer significant fuel saving potential, which can be exploited through efficient drive train components and optimised control of their interaction. In recent years, new innovative solutions have been developed besides the continuous improvement of conventional drive technology. Concepts like power split travel drives /1 - 3/, displacement controlled implement drives /4 -6/ and hybrid solutions /7 - 9/ already showed their potential in practical applications. Previous research activities focused on the substitution of individual subsystems of the machines. A consequent implementation of new drive technology and the holistic operating strategies has not been done so far.

Within the joint research initiative “TEAM – Development of technologies for energy-saving drives of mobile machines”, the most promising technologies currently available are combined for the first time in a wheel loader with an operating weight of 24 t and

200 kW installed engine power. Besides efficiency advantages compared to conventional solutions, the subsystems regenerative capabilities and the possibility to improve the machine systems adjustment are expected to result in fuel savings.

2. Drive train and control system

2.1. Drive train

Figure 1 shows the "Green Wheel Loader's'" drive train layout /10/. A turbo-charged diesel engine optimized for low speed and high torque operation serves as primary energy source. It was also developed within the "TEAM" research project /11/, offers an output power of 200 kW at 7,8 l displacement and fulfils the emission standards of US TIER 4 final and EU stage 4. The travel drive's power split transmission is driven via the pump transfer gear and a cardan shaft. It features three drive ranges, of which the first is purely hydrostatic and the second and third are of input coupled power split structure.

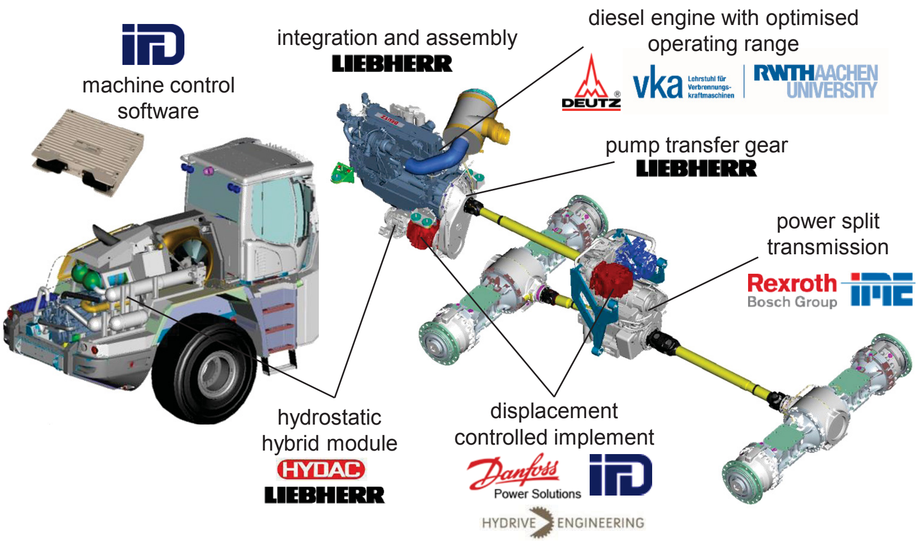


Figure 1: Drive train layout of the "Green Wheel Loader"

The implement's lift and tilt function are operated displacement-controlled by separate closed hydrostatic circuits. In order to use identical displacement units despite the functions' different flow demands, the pumps run at different speeds. Both, travel and implement drive enable energy recirculation in case of aiding loads or deceleration of the vehicle. This energy can be either directly reused by other subsystems or stored in a hydrostatic parallel hybrid. This consists of a closed-circuit 4-quadrant displacement unit for torque metering and a double piston accumulator /12/ to store the energy.

The displayed drive train is integrated into the chassis of a 24 t Liebherr L576 loader. Safety relevant systems such as brake or steering circuit are adopted with minor changes from the series machine. The central machine controller manages the complex interaction of the different subsystems and forms the link to the operator.

2.2. Control system architecture

The "Green Wheel Loaders'" drive system consists of various complex subsystems, which are engineered by multiple partners. To ensure time and resource-efficient development of the control strategies and software, machine functionality is modularized and distributed among the drive train subsystems. **Figure 2** shows the structure of the control system.

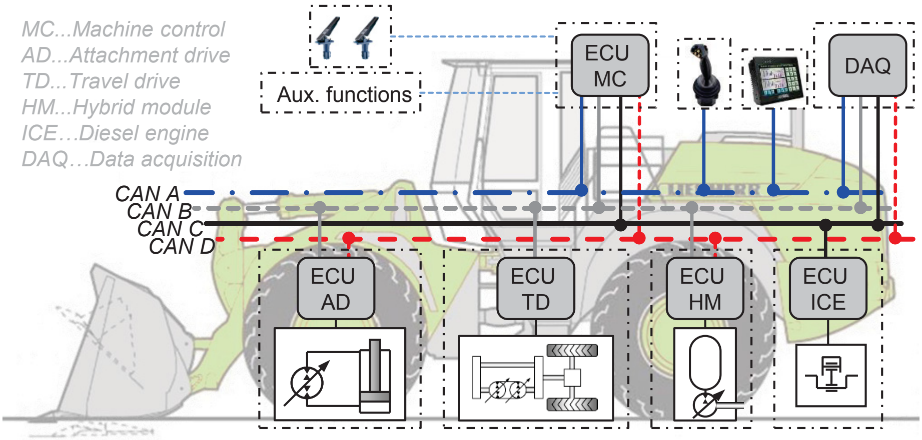


Figure 2: Control system architecture of the "Green Wheel Loader"

A central machine controller (ECU MC) interprets the operator inputs and generates the subsystems' set values according to the implemented operating strategy. Additionally, functions such as control of peripheral systems, monitoring and calibration routines are handled. Each subsystem comprises a separate controller for realising the machine controller's demands by controlling the subsystem's integrated actors. Furthermore, subsystem-specific data acquisition and monitoring functions are implemented. Data is only exchanged between the subsystems and the machine controller, a mutual control interference between subsystems is not permitted. Thus, the individual self-contained subsystems can be developed independently. The CAN-Bus "CAN A" forms the link between the machine controller and the HMI devices such as joysticks and display. CAN Buses "B and C" are used exclusively for the data exchange between subsystems and machine controller. This offered the possibility to specify the communications interfaces during an early stage of the development process but also to modify them in later phases. For acquisition of not control-relevant data, a separate CAN-Bus “CAN D” is used. Thus, the busload on CAN buses necessary for machine operation is reduced and disturbance of the machine functions by incorrect communication can be avoided.

3. Operating strategy and machine control software

3.1. Operating strategy

The „Green Wheel Loader's“ drive and control architecture enables new approaches for the subsystems' interaction. **Figure 3** shows the operating strategy's basic structure.

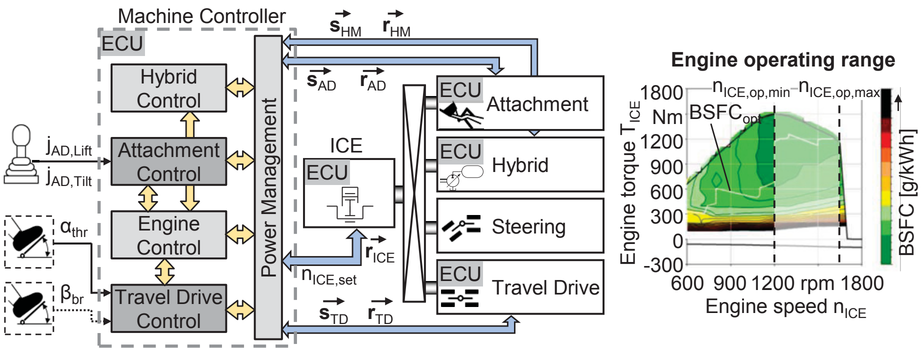


Figure 3: Basic structure of the “Green Wheel Loader's” operating strategy

In contrast to conventional vehicle control systems, the operator does not directly influence the diesel engine speed using the throttle pedal. Instead, the machine controller interprets the input signals from joystick and pedal as speed demands for implement functions and travel drive. Based on that, the software determines the minimum engine speed necessary to fulfil these demands. By comparison and prioritization of the different engine speed demands, the set value $n_{ICE,set}$ is calculated so that all operator demands can be satisfied. Thus, the machine can operate at the minimum engine speed technically possible. Besides lower drag losses in the driveline, this leads to higher torque and thus higher efficiency of the diesel engine. For reasons of engine dynamics and load response characteristics, the permissible engine speed range is limited. During loading operation, the engine operates in a set speed range of 1200 to 1600 rpm. Depending on the machine's actual operating conditions, the superordinated power management meters the hybrid module's torque to support the engine dynamically. Furthermore, it protects the engine from stalling or over speed conditions by influencing the subsystems' set values.

The machine controller determines the subsystems' set values based on the operator inputs and the nominal engine speed $n_{ICE,set}$ instead of using the actual value $n_{ICE,act}$. Thus, closed-loop control structures prone to oscillation can be avoided to a large extend. Due to the engine lugging under load, this also leads to a certain load sensitivity of the drive train, which serves as feedback for the machine operator. A detailed description of the individual subsystems' control algorithms is given in /13/.

3.2. Machine control software development

The functionality and effectiveness of the developed operating strategy and the subsystems' control algorithms were tested using detailed simulation models. However, these algorithms only represent a fraction of the functionality necessary to control the demonstrator machine. Additionally, functions such as control of peripheral systems, error detection and handling as well as monitoring and calibration routines have to be provided. For reasons of robustness, a commercially available electronic control unit (ECU) suitable for mobile applications is used as implementation target. This increases the software's complexity significantly. To ensure an efficient software development process and to detect coding errors as early as possible, a Hardware-in-the-Loop (HiL) test bench is used, see **figure 4**.

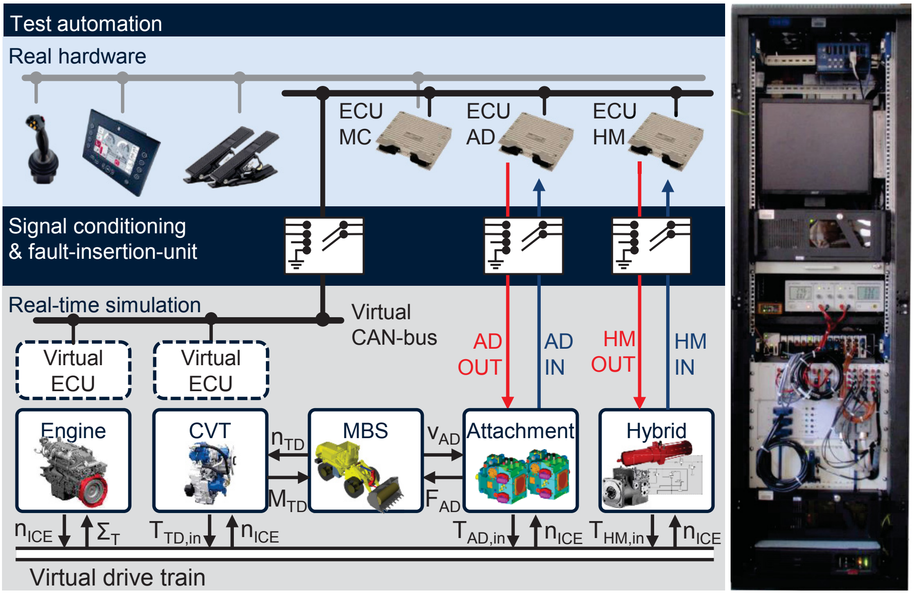


Figure 4: Basic structure of the used Hardware-in-the-Loop (HiL) test bench

Simulation models used before for algorithm development are modified to calculate in real-time /14/. They emulate the machine behaviour while signal condition modules integrate real hardware components such as ECUs, HMI and peripheral devices into the simulation. Thus, the developed machine control software can be easily tested on the real controller independently of the actual prototype machine.

By using test automation software the HiL test bench's benefit can be further increased. Once the test cases and the respective expected machine reactions are defined, new versions of the machine control software can be tested automatically for errors and changes in machine behaviour. Thus, a high level of maturity is ensured during the whole software development process and the effort for error detection and correction during commissioning of the prototype is reduced significantly.

4. Commissioning and testing

The aforementioned subsystems and the developed operating strategy were integrated into a demonstrator vehicle. After commissioning of the individual subsystems and first functional tests the machine was transferred to a gravel pit for testing and adjustment under realistic conditions, **figure 5**.

Figure 5: Integration, commissioning and testing of the „Green Wheel Loader"

The proof of the operating strategy's functionality and its parameterisation under realistic operating conditions are the basis for a sound evaluation of the developed drive and control system. Therefore, professional machine operators regularly evaluated the machines' behaviour and controllability in order to ensure a practice-orientated machine development. The adjustment activities focused on:

- Tuning of acceleration, deceleration and reversing characteristics
- Tuning of traction force metering characteristics at low speeds
- Tuning of the drive train's behaviour during static and dynamic loading situations

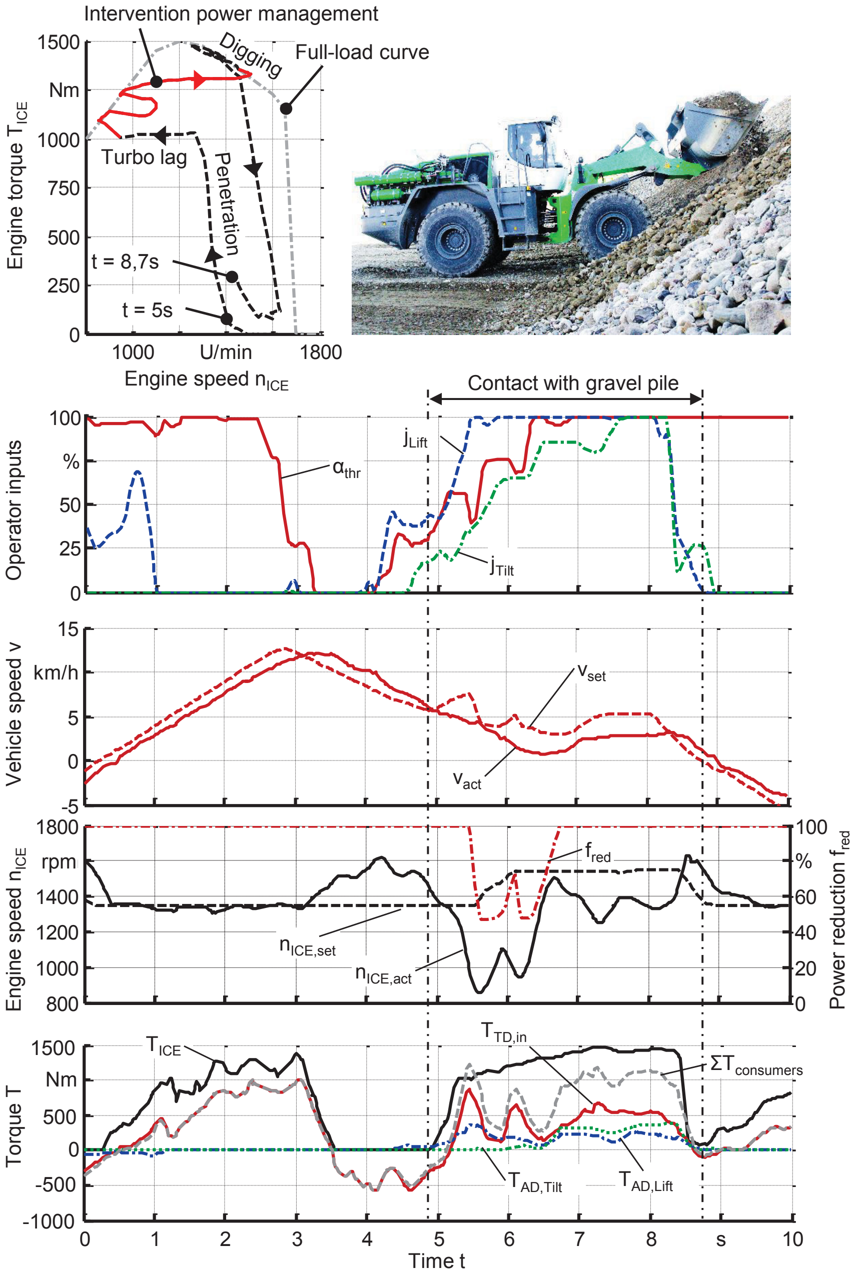


Figure 6: Measured load scenario "pile penetration"

Tuning the machine's acceleration and reversing characteristics as well as the system's behaviour during dynamic load situations posed the biggest challenges. **Figure 6** shows an exemplary measurement of a "pile penetration" load scenario. The operator accelerates the wheel loader with full throttle at maximum acceleration towards the gravel pile. Just before arriving at the obstacle's base, he decelerates the machine before penetrating the pile at a vehicle speed of 6 km/h. While filling the bucket, the operator actuates all input devices to 100 %, despite the fact that the machine is already working at its power limit. This happens subconsciously as the operator instinctively demands for more power than there is available. The machine's power management protects the diesel engine from stalling, despite the operator input signals. This is especially crucial at the moment of pile penetration. During the approach's last phase the vehicle decelerates, so the transmission capable of 4-quadrant operation recirculates energy. As no other consumers have significant power demands at that point this excess energy is dissipated by drag operation of the engine. The motor's speed regulator reacts by reducing the amount of fuel injected, which leads to lower exhaust output rate and therefore lower charge-air pressure generated by the turbocharger. When hitting the pile, the engine load increases instantaneously due to simultaneous actuation of all main consumers. As charge-air pressure is low, the engine can only provide a fraction of its nominal torque. The result is a drastic reduction of the engine speed. The power management counteracts by reducing the subsystems set values by means of the signal f_{red} . The resulting load relief leads to a recovery of the engine speed, until the motor is capable of bearing the whole load torque. During the filling process of the bucket, no intervention of the power management is necessary; the engine operates at maximum torque. Thus, reliable and speedy loading operation of the wheel loader can be ensured. During testing operation, the challenge was to tune the power management for effective engine stall protection in case of dynamic load situations. On the other hand, smaller load peaks during non-critical situations should must not negatively influence the vehicle's operating behaviour.

5. Energetic analysis

5.1. Reference testing

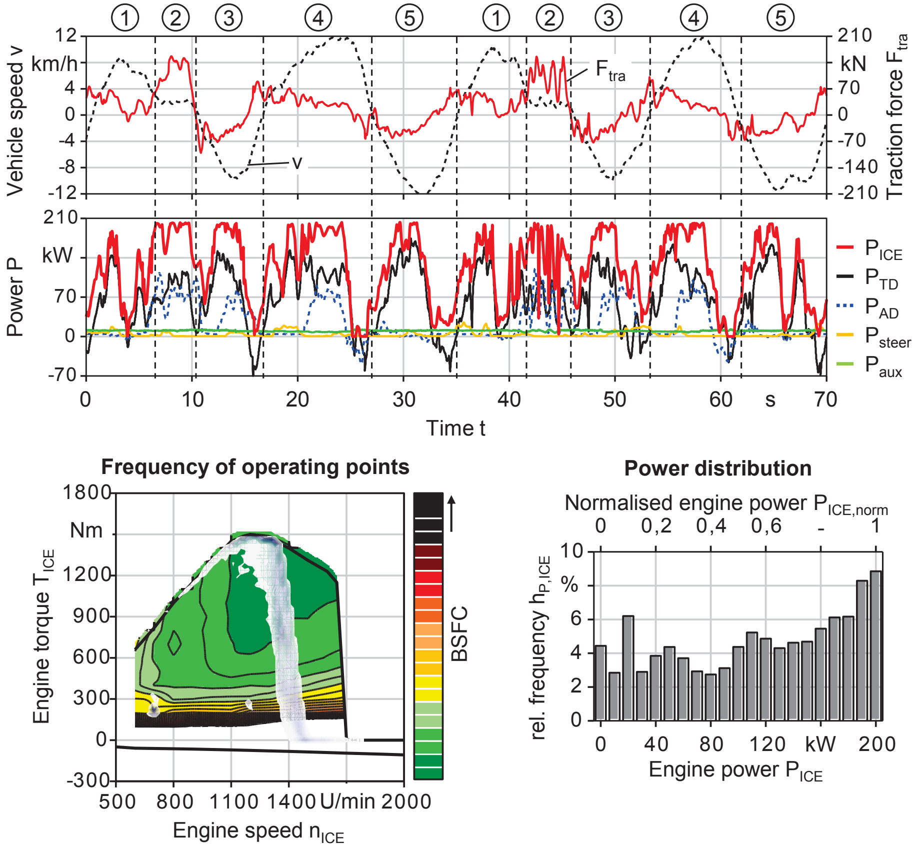
To evaluate the energy saving potential of the developed drive and control system, reference testing was done against a state-of-the-art machine (year of manufacture 2014) which already has an elaborate control strategy. Like the "Green Wheel Loader", the machine with an operating weight of 24 tons features a 220 kW engine that fulfils the exhaust emission regulations of EU Stage 4 and US TIER 4 final. The travel drive consists of a hydrodynamic torque converter with lock-up clutch and a 4-speed power shift transmission. By using the operating brakes for reversing instead of the torque converter its fuel consumption is already reduced compared to other machines. For implement actuation, two load-sensing pumps are used of which one also feeds the steering circuit via a common priority valve.

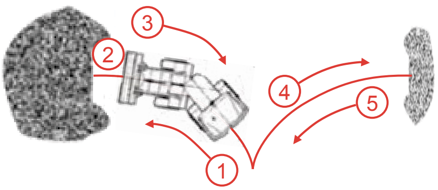
For reference testing, both machines performed a short loading cycle under comparable operating conditions, driven by experienced operators. **Figure 7** shows the reference test's setup. Both machines transfer material from a pile of loose, homogenous material to a location in a distance of 20 m. For each test, the cycle is repeated 30 times. The ground is flat and consists of compacted raw gravel, which leads to relatively high driving resistances and therefore high power demand of the travel drive.

Figure 7: Setup for reference testing

Figure 8 shows the subsystems' power demand and the vehicle speed and traction force for two exemplary consecutive working cycles. The hybrid module was deactivated during this test. Vehicle speed and traction force are calculated based on transmission output speed and transmission-internal sensor signals, as direct measurement of these values is not possible. The subsystems' power demand is also calculated based on subsystem-internal measurands and loss maps used before for system simulation, as it was not possible to use torque measurement equipment.

Both operating cycles last for about 35 s, the average duration of all 30 cycles was 34,6 s. This is comparable to conventional machines. The plot of the engine power P_{ICE} shows that the machine operates at its power limit very frequently. During penetration of the pile (phase 2), power consumption of travel and attachment drive is about equally high. The power management manipulates the subsystems' set values so the engine is kept operating at maximum output power. Also during the machine's acceleration (phase 1, 3, 4 and 5) the engine load rises to its maximum. Transmission-internal protection mechanisms and the superordinated power management intervene to protect the drive train from overloading. This is especially crucial during phase 4, when the machine accelerates to the unloading site and the implement with fully loaded bucket is lifted simultaneously.





	E_{norm}
Absorbed Energy	100,0%
Recirulated Energy	4,1%
Thereof	
Regenerated Energy	2,8%
Rekuperable Energy	1,3%

Figure 8: Measurement results of the reference testing

The distribution of the engine's output power shows an accumulation between 160 and 200 kW, which emphasizes the high loading of the diesel engine. The time average over all 30 load cycles is 120 kW or 60 % of maximum output power. The engine's main operating range is between 1000 to 1450 rpm at high torque, so energy is converted in the range of motor's highest efficiency.

Both travel and implement drive feed power back to the drive train. During deceleration of the vehicle, the negative power input of the travel drive rises up to 60 kW. However, this phase only lasts for 1 – 2 s, so the transferred amount of energy is low. The implement drive mainly recirculates power during unloading of the bucket. Over all 30 load cycles, 4 % of the engine's output energy are recirculated to the drive shaft. The majority is directly reused to power other subsystems, thus relieving the engine and reducing fuel consumption. Only 1 % cannot be used otherwise and is available for recuperation in the hybrid module. This operating condition only occurs during emptying of the bucket over the unloading site, when travel and implement drive both recirculate power and only auxiliary consumers absorb the excess torque. The engine is relieved completely and the surplus power dissipates in drag losses.

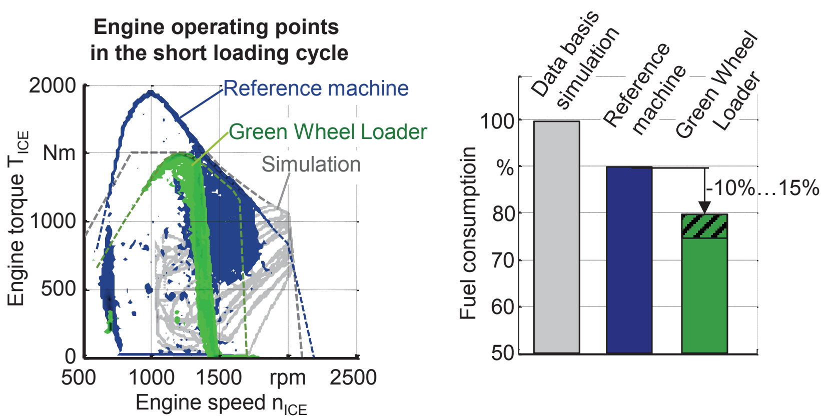


Figure 9: Comparison of engine operating points

The fuel consumption of both wheel loaders, reference and demonstrator vehicle, was measured by weighting of external fuel reservoirs. In repeated measurements, the "Green Wheel Loader" consumed 10 – 15 % less fuel than the reference machine with regard to the moved mass of gravel. **Figure 9** shows the engine operating points of both machines was well as simulation results obtained in an early stage of the research project /10/, /13/. Compared to the simulations the measurement results show deviations, which are mainly due to the data basis used for system simulation. The reference machine is considerably advanced compared to the configuration modelled in simulation. Especially the different diesel engine with lower idle speed and higher torque as well as the optimised torque converter configuration lead to an already significantly increased fuel efficiency. Under consideration of these effects, the simulation results supplement the experiments. The simulations show engine operations points at high engine speeds and medium to high torques. The reference machine converts the majority of energy at significantly lower engine speeds, which already reduces fuel consumption significantly. The “Green Wheel Loader’s” engine speed range is even lower. Together with the recirculated energy used to relieve the engine this results in the measured fuel savings.

5.2. Impact of the hybrid system

Due to the wheel loader’s operating characteristics and the used efficient subsystems capable of energy recirculation, the majority of the recirculated energy in the “Green Wheel Loader’s” drive train is regenerated and directly absorbed by other consumers. Only a small fraction of the engine output energy is available for recuperation in the hybrid module. Due to the small amount of energy and the lossy conversion processes, practically no energy is stored in the hybrid accumulator. Therefore, no additional power is available to support the engine during phases of high loads. In order to provide boost functionality increased machine performance, the necessary energy has to be supplied by the diesel engine by actively loading the hybrid’s accumulator. Measurements showed an increased machine performance due to the additional torque available. Especially during phases of dynamic power demand, engine speed undershoots could be reduced and more power was available for digging operation. The influence on the loading cycles’ duration is low, as acceleration and deceleration characteristics mainly depend on the machine control’s tuning and transmission-internal boundaries. Therefore, a significant increase of machine productivity is not to be expected. The increased machine performance leads to a surplus in fuel consumption of 7 % compared to measurements with deactivated hybrid, as besides the additionally necessary energy for filling the hybrid’s accumulator significant losses occur during the multiple conversion processes. Furthermore, the hybrid’s displacement unit causes drag and leakage losses, which additionally strain the “Green Wheel Loader’s” drive train.

By opening the engine’s operating speed range to lower values, further fuel consumption reduction is possible despite the hybrid’s additional losses. Lower engine speeds allow for decreased fuel consumption, but dynamic load capacity and available torques also deteriorate significantly. The hybrid module can compensate these functional deficits by dynamically supporting the engine. Thus, the machine’s functionality and performance are maintained while lowering fuel consumption. This approach was not part of the current research project and has to be addressed in future activities.

6. Conclusion and outlook

The joint research project “TEAM Green Wheel Loader” combines for the first time the most promising drive concepts currently available for mobile machinery in an innovative and energy efficient drive system. The drive system’s main consumers offer additional degrees of freedom in control compared to conventional solutions and the capability of energy recirculation. The developed operating strategy decouples the machine operator from directly governing the engine and rather controls it based on the individual subsystems’ demands.

Extensive testing of the demonstrator vehicle under realistic operating conditions in a gravel pit proved the developed drive and control system’s functionality. Professional machine operators regularly evaluated machines’ behaviour and controllability in order to ensure a practice-orientated machine development. Compared to a state-of-the-art series machine the “Green Wheel Loader” showed fuel savings of 10 – 15 % at the first attempt in a short loading cycle. Due to the low amounts of recuperable energy available in the load cycle, the parallel hybrid system could not contribute to the fuel savings.

With the “Green Wheel Loader, a functioning test vehicle is available for the evaluation of innovative drive and control concepts for mobile machinery. The testing under realistic operating conditions revealed continuative optimisation potential. Regarding the subsystems’ hardware configuration, potential lies in the improvement of load stiffness and dynamic behaviour. The operating strategy can be further enhances regarding engine speed control and machine operability. By further improving the machine control structure, the engine speed can be lowered while improving the load response characteristic at the same time, thus enabling additional fuel savings.

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BETREUT VOM
PTKA
Projektträger Karlsruhe
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8. Nomenclature

Variables

$BSFC$	Brake specific fuel consumption	g/kWh
E	Energy	kJ
j	Joystick signal	-
n	Rotational speed	rpm
P	Power	kW
$\vec{\boldsymbol{r}}$	Return values from subsystem controller	-
$\vec{\boldsymbol{s}}$	Set values for subsystem controller	-
T	Torque	Nm
α_{thr}	Throttle / drive pedal signal	-
β_{br}	Brake pedal signal	-

Indices

act	Actual value
AD	Attachment drive
HM	Hybrid module
ICE	Diesel engine (internal combustion engine)
$Lift$	Attachment lift function
set	Set value
TD	Travel drive
$Tilt$	Attachment tilt function