

Quantification of Energy Saving Influencers in a 21t Excavator Hydraulic System – A Holistic Investigation?

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The paper is about to show a comprehensive evaluation of energy efficiency in the field of excavating machinery. The results detected with 21t excavator platforms over years deal as a basis to determine the major energy efficiency influencers in and outside the machine. Cycles are given for a state of the art hydraulic system in Asian markets. The measurement data collected and results provided finally lead into an ABC-analysis to show the urgent need for new approaches to really save energy in future construction processes.

Keywords: Hydraulic systems, energy efficiency, loss analysis, ABC-analysis, excavators

Target audience: Mobile Hydraulics, Mining Industry, Machine and process design

1 Introduction

The XCMG European Research Center GmbH was founded in Krefeld/Germany in 2013. XCMG ERC is responsible for all research and development activities in Europe and owns test rigs and test grounds for detailed investigations with XCMG's mobile machines. The goal is to optimize and develop innovative technologies for our construction machinery in the fields of hydraulic, drive and control systems that finally result in especially efficient, environmentally friendly, multifunctional and ergonomic construction equipment products for the global market.

Through the last five years our team in excavator-related development projects investigated and optimized various systems, components and test conditions. All investigations covered different hydraulic system approaches like negative flow control and load-sensing systems. We optimized these systems with regard to costs, higher dynamics and controllability as well as to fuel consumption and digging performance. The optimizations realized were implemented by adaptations of own hydraulic components like valve spools and main control valve manifolds, new control principles in the sub-circuits for pilot oil supply and joystick actuation or through the selection of new pumps and drives of new suppliers.

The following chapters deal with the energy efficiency influencers in excavating machinery. For this purpose, test machines and conditions will be specified before discussing the results. All data provided and dealing as the basis has been conducted on 21t excavators using fully hydraulic drive systems and controls.

2 Demonstrator and hydraulic systems

Along with the projects on excavator machinery in XCMG ERC in Krefeld several tests have been realized to finally improve controllability and digging performance but also fuel consumption. For this purpose, series machines from China were sent to Krefeld for detailed testing, analysis and several optimizations in the hydraulic system of the machines. The two test machines are equal 21t crawler excavator platforms with same diesel engines, cooling systems, electrics, steel structure parts and hydraulic drives like the differential cylinders for boom, arm, bucket and the hydraulic motors for the swing and the track drives.

Corresponding data that deals as the basis for all tests discussed later can be taken from *Figure 1*. The differences within the hydraulic system layout and pumps (NFC vs. LS) are described later in more detail.



Total weight	21t		
Diesel Engine	Stage II	128 kW	
Cooling Power	10kW		
	Boom	Arm	Bucket
Piston-Ø [mm]	120	135	115
Rod-Ø [mm]	85	95	80
Stroke [mm]	1221	1475	1060
Mass [t]	1.65	0.83	0.8
Length [m]	5.8	2.9	1.2
Capacity [m³]	0.9		
Displacement [ccm]	129.2		
Gear box ratio [-]	121.6		
LS-Pump [ccm]	210		
NFC-Pump [ccm]	2x106		

Figure 1: Variety of digging results for excavator efficiency and performance testing

Both machines have been equipped with powerful measurement systems of the same structure. Each measurement system consists of a local PLC with EtherCAT connection to a large number of data acquisition components and more than 100 sensors to detect all state variables within time steps of 5 ms. The most important signals collected by the data acquisition system are listed as follows and refer to the setup used in the investigations by /1/:

- Diesel engine: set and actual speed values, fuel consumption
- Hydraulic system: Oil temperature, position and speeds of all cylinders and rotary drives, pressure sensors (joystick outputs and valve spool actuation, pump pressures and pump control signals, internal piloting signals for special functions, load ports at MCV and at the drives, local pressures close to valves, tank line backpressure etc.)
- Electrics: Boost function, travel mode, pilot oil switch and pump power solenoid current

The test machines vary in the hydraulic system like mentioned above. One machine is still equipped with a series level Negative Flow-Control system. The other test excavator is based on a single-pump circuit load-sensing system. As both system principles vary significantly, they are schematically introduced by *Figure 2*. The diagrams only feature connections and components to distribute power in the hydraulic systems. All valve piloting and logic circuits to activate any special functions are neglected.

The load-sensing system of the first test machine is based on a single-pump circuit. All valves to control the consumers are connected to a common pump. Pilot oil is provided by an additional gear pump. All closed-centre valves regulate the flow by primary pressure compensators, if pump pressure is higher than the individual load pressure resulting from higher loads operated in another sections. The load-sensing signal limited through a pressure relief valve in a way that the pump pressure cannot exceed the opening pressure for the main pressure relief valve, so that this component has mainly a safety function. For the arm and boom sections locking valves

are integrated to avoid undesired movements of the cylinder function in the non-actuated direction. Regeneration features to regenerate flow from the rod to the piston side (arm section) and in the other direction (boom section) are used to share more flow in the arm section for the levelling task or to save energy for lowering the boom during digging. Parallel function speed ratios are to be set by various parameters like the valve curve setups, the compensator spring, the ratio of saturation and the effective pressure to actuate the valve spools. For power control, the pump is equipped with an electric pressure control valve to manipulate the offset of the LS-pressure. In this way the pump's displacement can be reduced to finally limit the torque on the engine shaft and therefore, engine droop together with an electric controller.

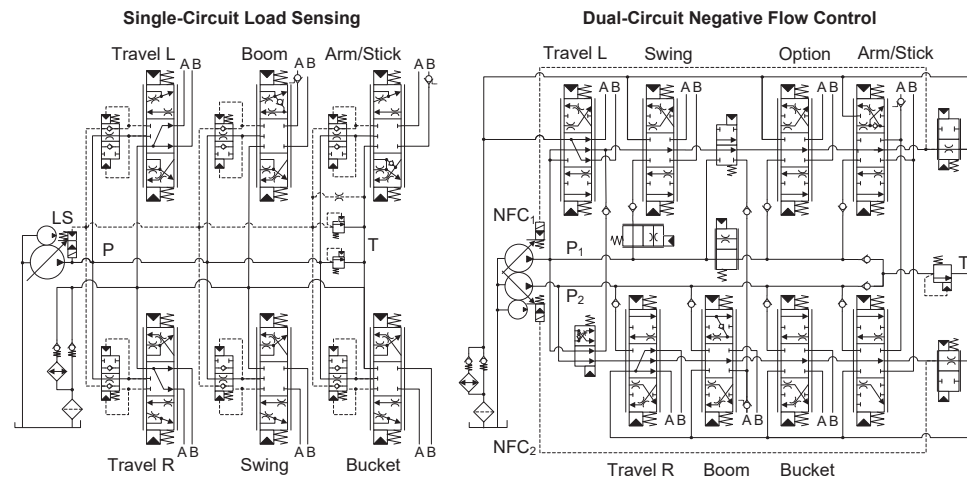


Figure 2: LS and NFC system architecture for 21t excavators (only power circuits; logics and signals neglected)

The negative flow system is a dual-pump circuit system using two rows of open-centre valves. They relieve idle pump flow through NFC orifices to tank or, when activated, distribute the pump flow among parallel functions while manipulating the pump-controlling NFC signal by reducing the open-centre flow. Critical over-pressure is relieved through a common pressure relief valve whenever flow provided by the pumps cannot be totally consumed by the hydraulic drives activated. The sections are arranged to one of each pump pressure lines and in special order along the open centre line to set their priority. Whenever these measures are not enough to distribute flow in the desired ratio, priority valves will be activated to limit or block flows. Only arm and boom function have valves arranged on both pumps as these consumers require total flow of both pumps for some tasks. A confluence valve is integrated between both pump circuits to manage straight travelling while additional functions located in the upper frame or of the attachment are activated. In this situation, this valve distributes the flow in a way that travel track drives are supplied together out of one pump while the other pump supplies all the working functions of the upper frame. Like in the load-sensing system, regeneration features and locking valves are available for both arm and boom. The double pump is equipped with an internal power limitation and can vary hydraulic power set value through a solenoid valve.

In contradiction to the excavator test machines known from other investigations on hydraulic systems /1/, /2/, /3/, /4/, XCMG reference and test machines already feature state of technology solutions in terms of boom and arm regeneration that have been used over years in excavator machinery. In consequence, many later publications in the hydraulic community may lack accuracy when talking about efficiency improvements achieved by new system approaches, as those have been referenced to outdated or simplified valve system technology without these standard regeneration circuits.

However, both hydraulic systems presented are based on the throttle principle which is conventionally used in today's 21t excavator machinery. In addition, both machines share the principle of full hydraulic joystick actuation. A comparison about the major difference between both systems is roughly given by Table 1. The

evaluation is based on the experience gained through all projects executed with excavators and other construction machinery inside XCMG in the last years.

The comparison shows, that the LS-system features higher load-forces and load-compensation by its principle. The driver feedback is that LS-system cannot feature a so-called pseudo-coupling of joysticks and the attachment drives that he can feel in the flow-controlled systems. A possible explanation can be given by the fact, that the LS-pump regulates the pressure that must be adapted to the right pressure drops through the metering edges by pressure compensators to finally provide the demanded speed along. It is obvious that load-sensing systems prior the force and not the speed. In addition it benefits better part-load energy conditions whenever the drives cannot consume the pump flow available.

Criteria	Full Hydraulic LS-System		Full Hydraulic Flow-Control-System (NFC)
Main PRV Opening	Only for safety reasons to protect hydraulic components from over-pressure	+	- Safety reasons, bypass function when pump flow higher than consumed by active drives
Force/Power	Controlled by pump in 1 st priority	+	- Result of power available and flow distributed
Load compensation	Precisely realized through primary pressure compensators	+	o Roughly implemented using priority valves
Speed handling	Depends on compensator and pump dynamics	o	+
Oscillation potential	By pump controller, pressure compensator setup and load pressure changes	-	+
Controllability	Force always available, missing pseudo-coupling of joystick to the attachment	o	+
Energy Consumption	Low: flow only provided when consumed in closed-centre (CC) systems	+	o Medium, as flow is bypassed through main relief valve during acceleration of the functions

Table 1: Differences between full hydraulically operated LS and NFC systems

In contradiction, flow-controlled systems feature a much better connection between the joysticks and the attachment drives that can be explained by the direct use of the pump flow. But, as the pump flow is not limited to the real flow consumption of the drives and the pressure-relief valve will open under this conditions, especially during acceleration of the rotary drives and when the cylinders reached the end stop positions, full hydraulic flow-control system have worse part-load energy condition than the LS-systems.

To sum up, hydraulic systems in excavators vary in terms of controllability, comfort, available forces and the energy consumption. The operating comfort is to be realized by avoiding harsh impacts of the functions under each condition which can occur by pressure peaks in the system. Controllability varies with characteristics like dynamics, response, resolution, hysteresis and the speed ratios for multi-operations. Digging forces and energy consumption are finally the result of the system principle, the special circuits implemented and the setup of all hydraulic components. When also taking regulations for exhaust gas emissions and the CE declaration into account it becomes obvious, that hydraulic system development for 21 t excavators is a challenging tasks.

3 Tests and boundary conditions

Over years of pump load-sensing system investigations and development various test data has been recorded. Digging tests have been realized under same conditions, so that today comparison and analysis of the data is possible. Because of the long-time passing, boundary conditions and changes of the machine have been noted carefully. However, data is maybe not documented perfectly, but was selected in a way to determine the key performance indicators of energy efficiency in mobile hydraulic systems, especially for 21 t crawler excavators. General influencers on the fuel consumption and digging performance are expected in various sub-systems. Some of them are known from different publications. These influencers are roughly described as follows.

1. Machine structure and design with regard to the kinematics, sizes and weights of the steel parts (boom, arm, bucket/tools and counterweight), etc.
2. Engine-related influencers covered by the combustion principle, engine type and sizes, speed settings, load conditions, cooling system, etc.
3. Hydraulic system configurations defined by the circuit type (open / closed), number and sizes of pumps, valves and drives, settings of different backpressure levels for tank line, load-sensing offset pressure, spring and orifices settings, leakage values, oil cooling power, filtering, pipe/hose diameters, etc.
4. Task description: type (digging, levelling, travelling, etc.), precision, truck and obstacle positions, etc.
5. Material: density, compaction, humidity, homogeneity, ice, corn size, etc.
6. Driver: experience level, job strategy (digging direction, filling level) /5/, daily feeling, talent, motivation, concentration, fitness, simultaneous functions, etc.
7. Weather conditions: day/night, wind, temperature, rain, snow, fog, etc.
8. Service state: lubrication, wear, filtering, etc.
9. Air condition: temperature, humidity, density, oxygen, pollution, etc.

It is obvious that some of those parameters cannot be set as constant values but will vary with the testing. The boundary conditions changed along with the investigations will be discussed by the chapters below.

3.1 Standard duty cycle and task description / definition

Regarding duty cycles and energy consumption detection, there is no clear standard available. Some standards like the JCMAS H020 /6/ already regulate how to test excavators, but test description only contains part load conditions for air digging tests with empty buckets. For detecting full load digging fuel consumption test conditions have still not been fixed and agreed upon by the construction machinery companies. In consequence, fuel consumption data cannot be found in the data sheets for excavators like it is familiar for passenger cars that are regulated via NECD and NFD cycles. For excavators, the most typical test to evaluate the digging and fuel consumption performance is the 90° digging cycle for a fixed time period while the truck is standing next to and in the same altitude than the excavator. Data detected on both machines for such boundary conditions is shown in Figure 3. This data is similar to the data provided by other studies on similar excavators /1/, /2/.

The diagram shows all movements of cylinders and the swing drive as well as corresponding forces or torque in the same time frame. In addition to this load cycle data for an average load cycle in 1 m depth and an unloading height of roughly 3 m, pressures are given for the pump outputs, the system-related signals for LS or NFC and the joystick signals. Such the cycles were detected for both systems with a number of different drivers, so that the different operating habits can be also derived from these diagrams.

As mentioned before, the working task is not furthermore specified and it is not clear that the driver will always perform same cycle conditions. For reasons to more specify and to finally better analysis and compare the test data, the working task has been defined in another way. Old and new task descriptions are given as follows:

- Old task: “Dig as fast as possible until fuel tank (10 litres) is empty” – time and cycles to be recorded
- New task: “Dig a hole with the dimensions of 5x4x3 buckets” – time, cycles and fuel to be recorded

In contradiction to the old cycle that only aims for digging and fuel performance values, the new task now allows also covering controllability aspects being remarkable whenever engine power is not consumed totally caused by higher positioning efforts. The task is defined by the hole dimensions that finally lead to a total volume of approximated 70 m³ and a mass to be moved of about 126 t. It is the basis for all investigations being discussed in the following sections.

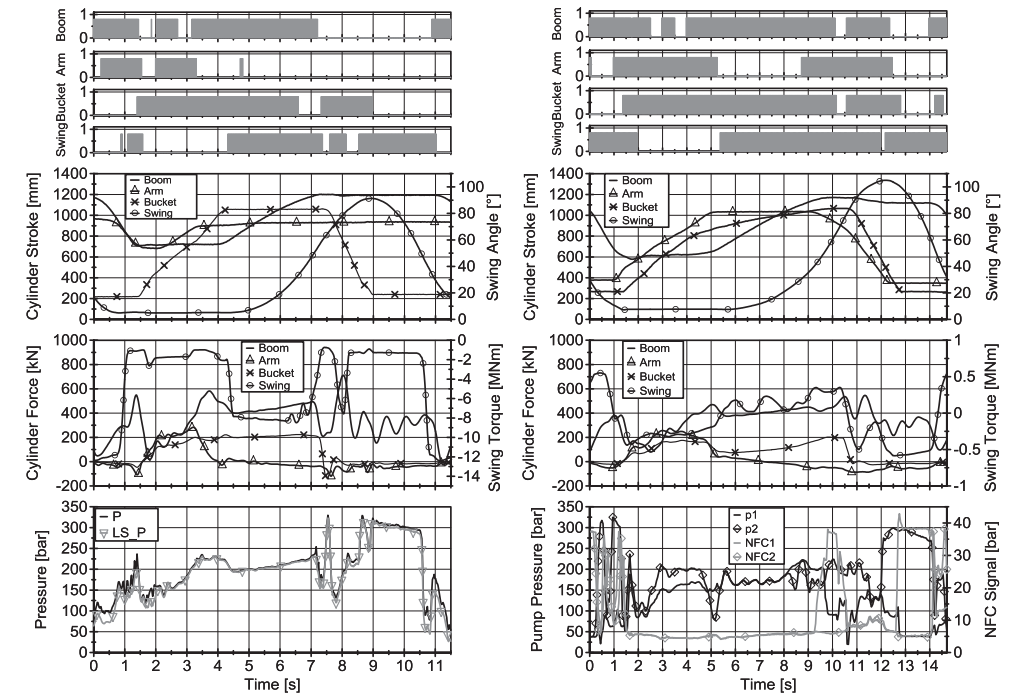


Figure 3: LS and NFC 90°-digging cycle data

3.2 Test setup / matrix

The idea of the investigation is to not only focus on the hydraulic system or drive train and the primary energy source, e.g. the diesel engine, like it has been done in several other studies /3/, /4/, /7/, /8/. These studies provide so-called holistic investigations that are limited to a hydraulic system boundary that is fixed between the engine and the mechanical power take-offs of the hydraulic drives. For hydraulic component and system suppliers this system boundary can be accepted.

As a developer and producer of the entire excavator application, measures to benefit fuel consumption and the performance of the machine need to be balanced with other criteria like controllability, additional costs and so on. For more detailed understanding and a more comprehensive investigation, the system boundary needs to cover the full machine design, the environment, the driver and the process as well. For this purpose, the investigation was extended to consider more influences on the performance and fuel consumption of the machine. Figure 4 shows the parameters changed over all tests being executed with both test machines in Krefeld in the last years.

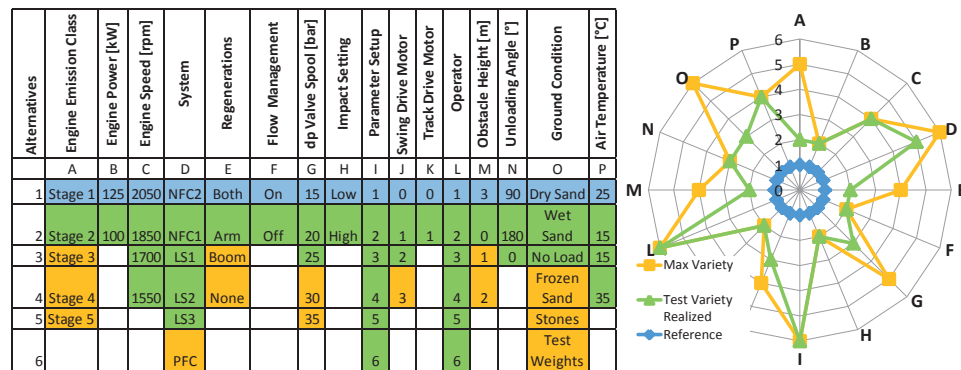


Figure 4: Modifications in test conditions among the investigation range

The table shows the different criteria varied from test to test in columns, the lines represent the options available in each criterion. The first blue line shows the definition of the reference machine which was the series product configuration of 2014. The green coloured fields have been covered with the test being executed whereas the orange fields are intended to be tested soon, but are not taken into consideration for the results being presented in this article. For easier demonstration of all changes in the test setup or the machines, modifications to the reference will be given in the spider grid diagram. In here, reference is always set to option “1” and illustrated by a blue line whereas the green line shows the variety realized by the tests.

For sure, data collected by this procedure is not standardized and gives no statistically evidence to exactly quantify the real influences on efficiency of the different influencers. However, it will provide new more comprehensive impressions.

4 Results

4.1 Overall Results

For a better overview all tests executed are summarized in the diagrams provided in Figure 5. The digging performance diagram on the left-hand side shows the fuel consumption per hour on the y-axis versus the digging performance in tons per hour on the x-axis. It deals as a diagram to illustrate overall digging performance for excavating machinery by the ratio of output work which is represented by the material moved to fuel energy, see eq. (1). The ratio can be also understood as an efficiency value.

$$\eta_{tot} = \frac{W_{out}}{E_{in}} \sim \frac{m_L}{V_{Fuel}} \quad (1)$$

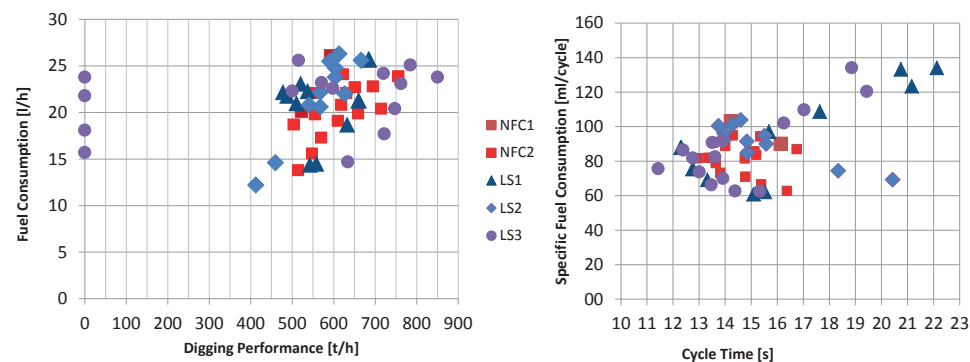


Figure 5: Variety of digging results for excavator efficiency and performance testing

Data is marked for five different hydraulic systems. It becomes obvious that even with same machine platforms and a same task, fuel consumption and digging performance values can vary significantly. This is the root cause that makes the determination of precise fuel consumption or digging performance values so difficult and therefore has not lead to data provided in data sheets until today. Furthermore, data discussed in many research projects all over the globe must be rated carefully if based on a low number of tests.

The second diagram on the right-hand side shows the specific fuel consumption per cycle versus the cycle time. The results look different compared to the first diagram, because the amount of soil moved varies with the tests and therefore the load in the bucket changes. The question to be answered is how to reduce confusion about the results and give a more clear understanding. For this purpose, data in the diagrams will be deeper analysed in the following subchapters.

4.2 Changing Conditions

In the following subsections, results we be provided to figure out the influences of all modifications covered by the different tests executed. The results will be finally used to determine most significant influencers of energy efficiency in the crawler excavator machinery by an ABC-analysis, see more in section 4.3.

4.2.1 Engine

During the investigations with both test machines, different engine speeds have been set and tested, see Figure 6. Specific fuel consumption was detected for different engine speeds and operators on the same machine. The data strongly varies with Diesel engine speed as for all drivers the ratio between fuel consumption and digging performance decreases. In general, efficiency is better for lower engine speeds.

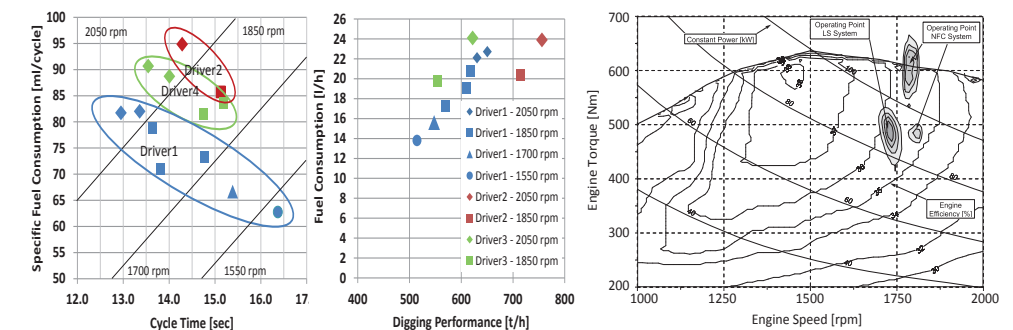


Figure 6: Diesel engine operation points and digging values versus engine speed

The right diagram shows an engine efficiency map that considers the shaft torque on the y-axis and the engine speed on the x-axis. In addition, lines of equal power are provided. Both of the systems, the load-sensing and the negative flow control, are plotted to the map whereas engine operation points are high-lighted for 90 % energy performed for the digging tasks. Both systems are exemplarily compared by considering the best digging performance values in the economic mode with an engine set speed value of 1850 rpm. Average engine efficiency varies for both of the system between 35 – 36 %. Best engine operation points provide energy by roughly 40 % efficiency whereas minimum efficiency in idle mode can perform close to 25 % /1/, /3/.

It turned out that the fuel efficiency is better for lower diesel engine speed along with lower digging performance values. This means, a compromise has to be found in the balance of fuel consumption and digging performance. Assuming the diesel fuel price won't increase significantly, fuel saving costs by lower diesel engine speed cannot compensate higher costs for operator capacities needed to move the same amount of material. In the future, fully autonomous excavators could move more slowly but not being time-limited and therefore can work in better operation points. As the machine can work more than 8 - 10 hours a day, digging performance can also be increased when productivity is rated per day.

4.2.2 Hydraulic Components

To quantify losses in the hydraulic components, the bubble plot diagrams in *Figure 7* show pump operation points for the load-sensing and the NFC system for different speed settings. Other parameters were not changed during the tests. As engine speed varies with the bubble groups, pump pressure is drawn against the relative pump displacement.

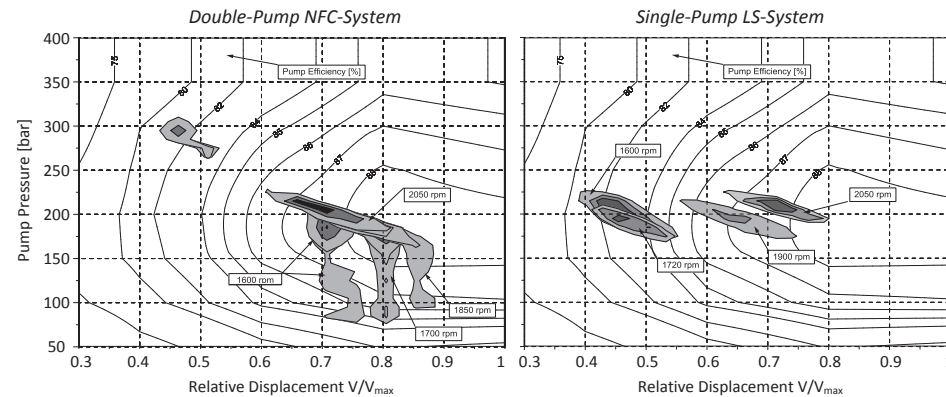


Figure 7: Pump operating points of both test machines

The diagram shows, that the operation points shift to lower pump displacements with the reduction of the engine speed set value. This is caused by the fact that lower engine power available at lower speeds limits the pump power and hence the pump displacements when load pressure conditions are nearly the same. The operation points of the both the systems LS and NFC vary in an overall pump efficiency range between 80 % and 89 %. In consequence, this strong relationship between pump efficiency and engine speed settings needs to be considered during the development process and the selection of suitable pump hardware when designing for energy efficiency. The pump size selection is a compromise between efficiency under full load conditions of the diesel engine whereas pump displacement will be limited due to the maximum speed available for the tasks operated in part load conditions of the diesel engine.

Regarding the other components like cylinders, motors and valves, *Figure 8* illustrates corresponding diagrams by drawing the load pressure on the y-axis versus other state variables on the x-axis like the velocity (cylinders, left-hand side), and the relative rotational speed (swing drive, right-hand side). The bubbles plotted in the diagrams consider all drives for arm, boom, bucket and swing.

The efficiency values of the cylinder operating map already show that these components indicate less losses compared to components like valves and motors. The efficiency values of the cylinders vary between 96 % and 98 %. For boom and arm cylinders operational points consider the regeneration function during fast feed operations and whenever potential energy drives these functions.

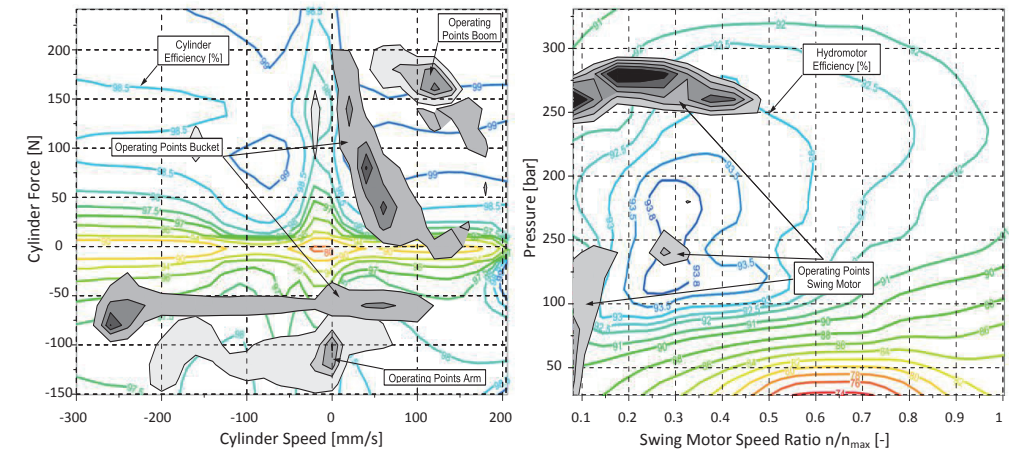


Figure 8: Operational points of the cylinders, valves and the swing drive motor

For the exemplary digging cycle plotted, major swing drive energy is consumed in ranges of 90% efficiency and higher. It can be seen that maximum swing speed cannot be achieved over the 90°-digging cycle. In general, swing drive motor efficiency is quite high for the operating points covered through digging.

As a conclusion it can be pointed out that hydraulic components already feature quite good efficiency values in wide ranges of the digging cycle for the 21t excavator applications. It can be advisable to check if further efficiency improvements are necessary or if the development focus of such components should be adjusted on finding reasonable balance between efficiency, endurance and costs by maybe also decreasing efficiency again. If costs can be reduced this way, the cost savings can maybe compensate additional costs necessary for improvements in non-hydraulic excavator sub-systems with higher influences on energy efficiency of excavating machinery. In general, customers will accept higher costs for the machine for a better product, but those additional costs should be compensated by the fuel savings within the first year.

4.2.3 Systems

To roughly rate influences of the hydraulic system configuration and parameter setups for LS and NFC, both machines were tested with varying configurations, see *Figure 9*. The LS setups therefore feature different valve spool geometries as well as diverse parameter sets balancing driving comfort versus fuel efficiency. The two NFC system states tested represent two generations of development, mostly valve spool sizing differs. In addition on the right-hand side, results from [7] are illustrated in a way the energy consumption and losses of different new hydraulic system approaches applied to excavator machinery can be estimated.

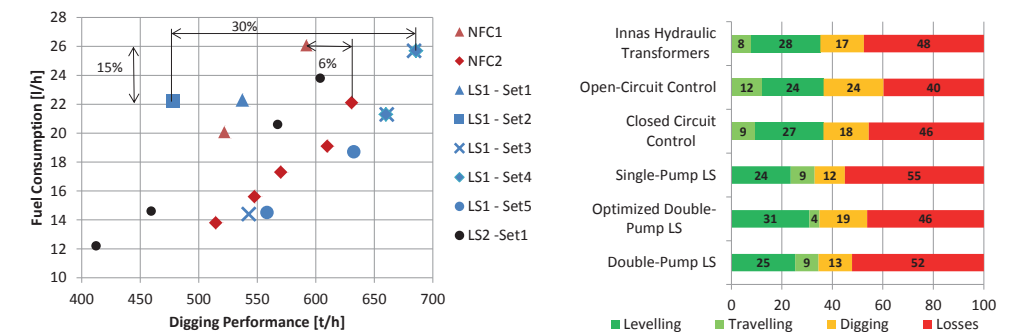


Figure 9: Variety of digging results for excavator efficiency and performance testing

The results show that the system efficiency for valve systems varies very much with the parameter setups that are a compromise between driving comfort, energy savings and controllability in other tasks. In the LS-system the digging performance varies in a range of 30% along with fuel differences of 15%. Fuel savings of 15% can be achieved by the second generation NFC-system machine. For the single-pump LS-system with a series level parameter setup, fuel and digging performance is located between the first and second generation NFC systems.

The second diagram shows the overall hydraulic system efficiency for the different tasks digging (full load conditions, orange), travelling and levelling (part load conditions, green). The red colour represents permanent losses of each the systems that cannot be avoided. Net efficiency of all systems including pump and drives is between 45-60%. The results show the known fact that full load conditions in the digging cycle have much higher effective energy share than part load conditions for levelling or travelling. Valve-based or throttle type system architectures in excavators have quite low efficiencies for the levelling tasks that can be significantly reduced by any displacement control-based approach. But, for the displacement control-based system principles, travelling becomes less energy efficient by the drag torques of all inactive pumps.

The results collected by the investigations are compared with the results known from public research in the field of excavator hydraulic system improvements [1], [3], [4], [7], [9]. To better understand the results of the digging process analysis, total efficiency is in the following defined as the ratio between the work performed at the output and the total Diesel fuel energy invested at the input, see eq. (1).

$$\eta_{tot} = \frac{W_{out}}{E_{in}} = \frac{n \cdot (m_L \cdot g \cdot h_{av} + 0.5 \cdot m_L \cdot (\omega \cdot r_L)^2)}{E_{Fuel}} \quad (1)$$

The work at the output of the excavator is in here understood as the mass of ground material moved. Work is separated into potential energy and kinetic energy. The average height is defined as the sum of average digging depth and unloading height. The speed of the load is considered by the rotational speed of the upper structure during the turn-lifting phase times the bucket distance to the vertical axis. The corresponding data can be seen in Figure 10. The results show that the new system approaches that control the hydraulic drives directly by the pump improve the efficiency but also feature a higher digging performance. The single-pump LS-system seems to be competitive to replace a double-pump NFC system without influencing digging performance and fuel consumption. Furthermore, the results obviously point out, that overall machine efficiency is rising with the machine size from less than 1% up to 13% for excavators between 4 t and 30 tons.

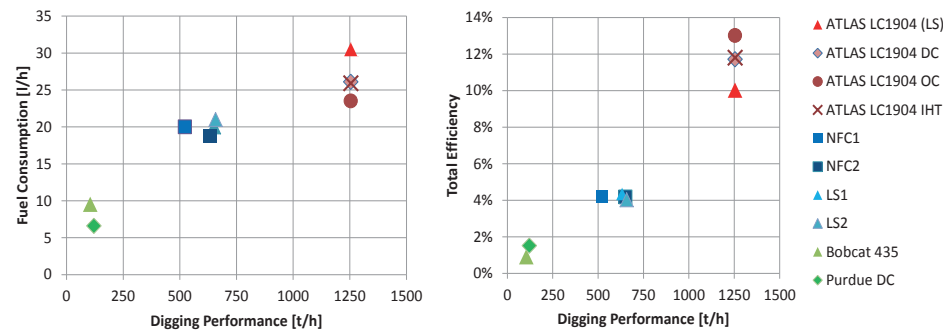


Figure 10: Variety of digging results for excavator efficiency and performance testing

The right diagram shows also that the excavator machine is generally not suitable for energy efficient digging, if digging is understood as the pure movement of material. The energy consumed to cut through the ground and to crush or mix the material is considered as a loss here. Which parts of these losses may be useful work or not is to be considered when thinking of future machine concepts.

4.2.4 Structure and Machine Design

In this section, results have been selected to determine losses impacted by the machine design. For this purpose, Figure 11 provides data and diagrams for the digging performance, the specific fuel consumption per cycle vs. the cycle time as well as an energy distribution for the attachment during the 90°-digging cycle.

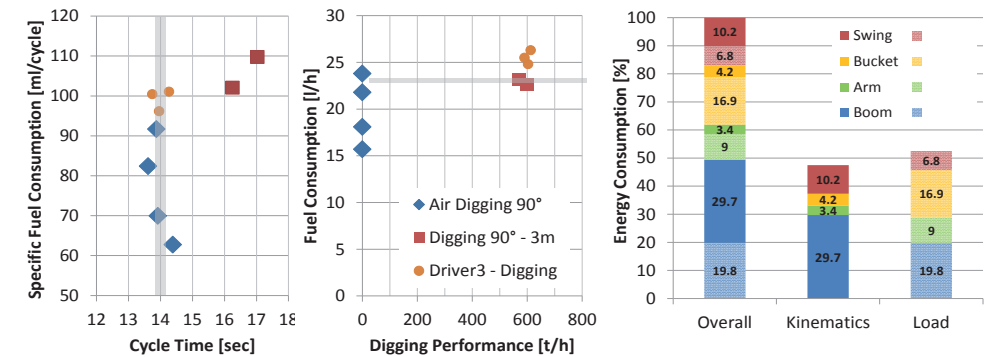


Figure 11: Energy consumption of the attachment

The energy consumption for the unloaded bucket situation which is in following called *air-digging* is quite high compared to the loads operated. As the cycle time varies too much, it is hard to precisely determine the real impact of the structure with the results available. For a better understanding results of another driver are used too directly compare in the same time frame. Along with Diesel engine speed reduction, the fuel consumption varies between 10% and 38% along with the investigations. The big fuel consumption differences during the air-digging test can be explained by the part load operations of the diesel engine, but also of the pump especially when pump flow is not totally demanded by the driver for the higher engine speed settings.

Multi-body simulations allow a more detailed determination of the energy consumed by only the steel structure parts along the digging cycle. It turned out that the energy consumption strongly depends to the load in the bucket. With higher loads in the bucket, relative energy share of the attachment becomes less. During conventional digging tests providing the data illustrated in Figure 11 the load in the bucket only consumes 54% of total energy invested in the movement of the attachment and the swing drive, so that the machine's steel structure or kinematic maximum efficiency is roughly rated to 46%. When watching the results provided in terms of digging performance, it becomes obvious that air digging efficiency of the machine must be set to zero as air digging has no effective work realized at the output.

4.2.5 Operators

The investigations with different hydraulic system configurations installed in the same crawler excavator platform have been executed by different drivers from EU and Asian countries on both systems. The results can be seen in Figure 12. All results for specific fuel consumption, the moved material per hour or the cycle time are drawn against the average amount of simultaneous functions, like presented by [10]. For the values determined in the diagrams, the driver was the only change among the test conditions that means that the points selected share same engine speed settings. The diagrams demonstrate that operators generally keep their individual simultaneously level for the 90°-digging cycle when operating machines with difference hydraulic systems like here the LS and the NFC. The results also show that all drivers nearly achieve the same cycle time on the NFC system along with comparable specific fuel consumptions for this system. For the LS system the results of all operators are more varying in which driver 1 had the highest experience level on the load-sensing system.

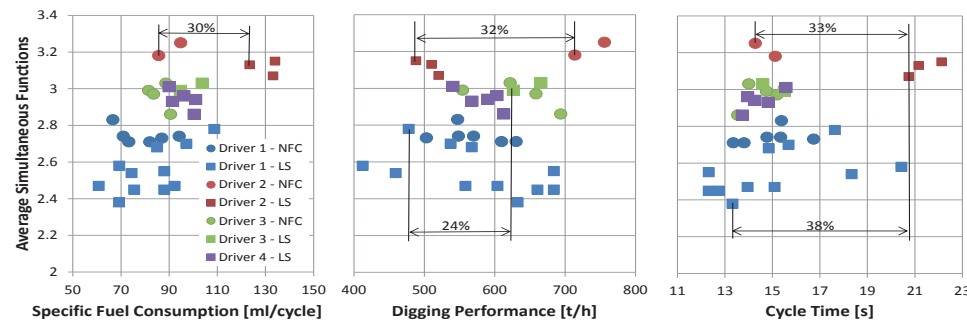


Figure 12: Digging results influenced by the operator

In terms of the specific fuel consumptions, the highest deviation between the LS and NFC system are about 30% for the same operator. The deviation between different drivers on the same system is up to 44%. Regarding digging performance results vary 24% for different drivers on the same machine whereas the same operator on different systems deviates up to 32%. The cycle varies under the same conditions between 32% and 38%.

4.2.6 Cycle and Ground Conditions

Regarding the energy influences of the cycle conditions, tests have been executed with the same driver and same machine, but cycle conditions were changed. Changes were realized by changing the truck position for unloading while the unloading height was about 3 m. This is normal boundary conditions when the truck and the machine are standing in the same height level. Results can be taken from the diagrams in Figure 13.

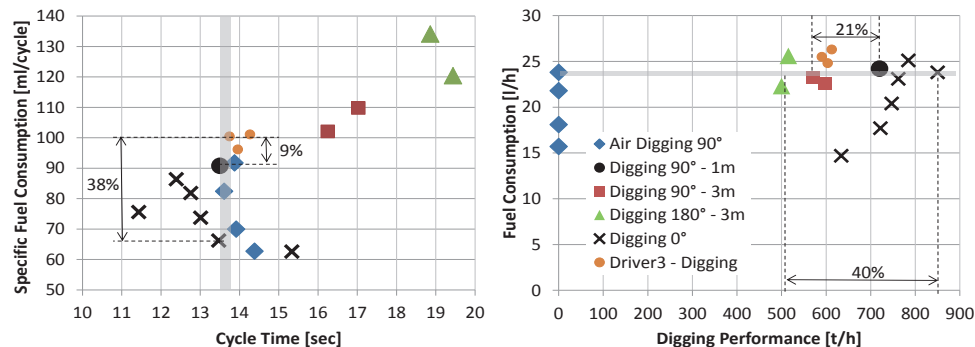


Figure 13: Digging energy consumption varying with the cycle conditions

The difference in digging performance realized by a 180°-digging cycle are about 14 %. For digging and unloading in the same angle range results vary about 30 % to the reference 90°-digging cycle. In addition, the machine was standing higher than the truck, so that effective digging height was only 1 m. The results show that just with the digging height reduction the excavator performs roughly 25 % more material movement with the same fuel investment. Air-digging results discussed above but referenced also in the diagrams indicate that load changed by the ground conditions like stones, gravel, etc. might also change digging performance with comparable fuel consumptions.

When looking at values for specific fuel consumption per cycle versus the cycle time, energy savings can be easier derived from results operated in the same time periods. To rate against the 90°-digging cycle with loaded bucket, results of another driver with a comparable cycle time are added to the diagram. Load changes can be quantified in a range of higher fuel investment between 9 and 30% depending to the engine speed set points. Regarding the digging angle influencing the results as swing drive was not operated for the 0°-digging cycle,

fuel savings of about 38% seem to be possible. To sum up task efficiency it becomes obvious that the digging task itself has high potential to reduce fuel efficiency by 38% or to increase the digging performance by 40%.

4.3 ABC-Analysis

All efficiency values determined and discussed in the chapters above are fed into an ABC-analysis that contains the whole digging process from fuel energy input through all parts and sections of the excavator machine and process influencers like the driver, the tasks and so on, see Figure 14. The upper red bars show permanent losses of each the influencers which are always given and cannot be avoided. The variable range in orange colour depends on different boundary conditions whereas energy that is always consumed effectively is coloured in green.

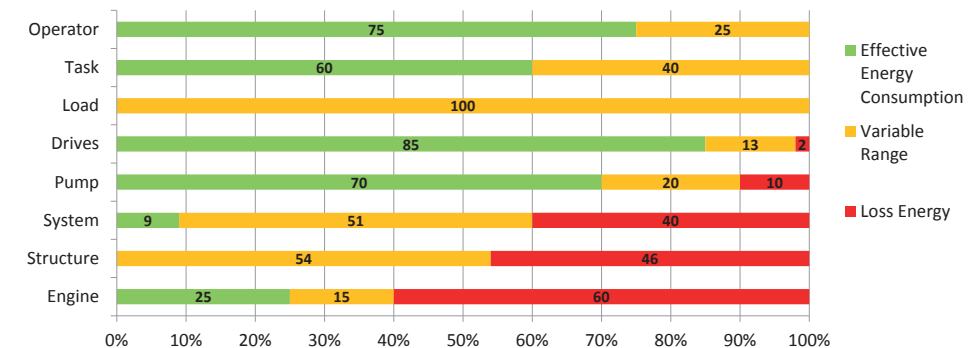


Figure 14: ABC-Analysis over full digging process

It turned out that not only the diesel engine efficiency impacts the fuel consumption dramatically, also the steel structure parts or in general kinematics of the excavator that build the basic machine principle as well as the hydraulic system are major energy dissipaters and therefore of class A. These energy dissipaters should be reduced by new principles which means, a new machine to realize the digging task both with high digging productivity but also efficient fuel consumption. But, to define new digging processes and machines along with changing laws cannot be realized by the construction machinery companies only, so that there is a need for public research.

Comparably low losses occur in the hydraulic components like cylinders, motors and pumps which are categorized into class B. Pumps and motors have higher potential for further efficiency improvements than cylinders, but the question is if corresponding efforts in costs will be finally accepted by the producers or the customer, like it was discussed in 4.2.2.

The influencers like the task, the load in the bucket and the operator are of class C and can influence the energy consumption during digging, but is hard to rate with regard to permanent losses. In consequence, this class does not share any permanent losses, but a huge range exists that impacts the fuel consumption of an excavator machine. Measures to manage the digging task will become more and more important in the future and training of the operators for more efficient digging using machine data seems to be reasonable /11/.

5 Summary and Conclusions

Along with several development and research projects at XCMG European Research Center GmbH various digging performance test data has been collected for 21t excavators. The analysis of the data enables a comprehensive view on the influencers of energy efficiency of such machines. An ABC-analysis of the influencing factors on energy consumption covering the full digging process discovered the diesel engine, the steel structure as well as the hydraulic system as the major energy dissipating factors. It turned out that excavator machinery has been designed for ergonomic benefits and the digging performance but not for efficient operation of the digging tasks itself. Also the task and the truck position impacts the digging results significantly. As there are very high losses in the total machine significant improvements could be only achieved by new digging principles and machine designs in the future.

The results also show that bad machine efficiency is not caused by the hydraulic components. Here, cost savings through allowing less efficiency realized by higher volumetric losses in hydraulic pump and motor units can provide the investment cost for bigger changes in the hydraulic system but also can improve the cooling and wear behaviour of these components. Valve-controlled systems have in general higher losses especially in part load conditions than displacement-controlled system approaches presented by /4/, /7/. Lower engine speeds result in lower digging performance along with higher fuel savings. As less comfortable system setups can also save fuel it becomes obvious, that an automatization of excavators will end-up in huge efficiency improvements. As these machines will be able to work the entire day in contradiction to human operators, also higher digging performance can be expected by the customers for tasks and conditions that allow automated work.

It becomes obvious by the data presented that the energy efficiency for excavators is hard to evaluate and to understand as there are so many different factors that can significantly influence the tests and final results. The excavator machine efficiency finally rises with the bucket and hence the excavator size.



Figure 15: Will excavating change in the future?

The final question is how excavating will develop in the future and how to develop new competitive hydraulic systems in future. The need for higher productivity and more energy savings along with higher intelligent systems justify starting machine development on blank papers again. For this purpose, public research at universities and other institution could play an important role for future excavating system and processes.

Nomenclature

Variable	Description	Unit
E_{Fuel}	Diesel fuel energy amount	[kJ]
E_{In}	Input energy	[kJ]
g	Gravitational constant	[m/s ²]
h_{av}	Average digging height	[m]
m_L	Mass of the load or material in the bucket	[kg]
n	Number of cycles	[-]
r_L	Distance of bucket to the rotating axis during turn-lifting	[m/s]
V_{Fuel}	Diesel fuel amount	[l]
W_{out}	Total work performed	[kJ]
η_{tot}	Discharge Coefficient	[-]
ω	Angle	[°]

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