Comparison of energy saving methods for loader

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Abstract

There is still a potential for significant improvement on fuel efficiency of mobile machines. This study concentrates on two methods, which are known but still not widely utilized: independent metering and/or hybridization. The goal is to determine their effect on fuel consumption and give answers to question, what is the most (of the studied solutions) economical way to reduce fuel consumption.

The study is made using a 6-ton municipal loader as research platform. As a baseline for study, experimental data from the loader with load-sensing (LS) hydraulics has been gathered during a y-pattern cycle. Then numerical study is done to compare the fuel economy of four different system configurations. The studied systems are 1) System with standard LS valve as baseline, 2) System with independent metering valves, 3) Hybridized system with standard LS valve and 4) Hybridized system with independent metering valves.

The study shows that the fuel consumption of the machine can be decreased around 15 % by using one method, either independent metering valves or hybridization. Fuel savings up to 28 % can be achieved in such load cycle utilizing both methods.

Keywords: Wheel loader, Hydraulic hybrid, Independent metering
1 Introduction

There are numerous potential ways to decrease fuel consumption in wheel loaders. Hybridization is one option and both, electric and hydraulic alternatives are possible. Another option is to use conventional power source without hybridization and reduce the energy losses in system level and components.

Diesel-hydraulic hybrids are an attractive option in wheel loaders as there is no need for electric to hydraulic energy conversion and expensive electric motors. Achten proposes a diesel-hydraulic hybrid drive train for off-road vehicles in 2008. The system is in essence a series hybrid where the engine supplies its power to charge a common pressure rail (CPR). The linear actuators and the hydrostatic drive motors take their energy from the CPR through hydraulic transformers. [1]

Pettersson et al. presents a diesel-hydraulic hybrid consisting of constant pressure rail and secondary controlled working hydraulic actuators. The linear actuators are multi-chamber cylinders enabling considerably decreased power losses when compared to standard two-chamber asymmetric cylinders. The drive line is based on a hydromechanical power-split transmission. [2]

An example of a diesel-hydraulic parallel hybrid system in a wheel loader application is presented in [3]. The hybrid system consists of variable displacement pump operated in a closed hydrostatic circuit and a double piston hydraulic accumulator.

Diesel-electric hybrid is also a widely studied concept for wheel loaders. Filla presents a multitude of different diesel-electric hybrid solutions for a wheel loader in [4]. The presented system concepts are combinations of parallel and series hybrid solutions applied in working functions and drive train of a wheel loader.

Nokka studies the energy saving capabilities of electric hybrid system in an underground mining loader through simulation and virtual prototyping. The simulations show a 50 % reduction in fuel consumption when compared to standard non-hybrid version of the loader. Nokka reminds that the energy density of diesel fuel, when turned into electric or mechanical energy in diesel engine is roughly 40 times higher than the electrical energy density of present-day batteries [5]. Volvo reports similar fuel saving results at their website. The result presented is from an experimental test carried out with their diesel-electric hybrid wheel loader prototype [6].
Martinovski et al. studies different type of diesel-electric hybrid system for mining loaders in [7]. The working functions of the loader are directly powered by constant displacement pumps driven by variable speed electric motors.

Energy efficiency of wheel loaders can be improved also without hybridization by reducing the power losses of the system. Independent metering valve is a concept capable of considerable energy savings when compared to standard (load sensing) proportional directional control valve. Independent metering valve concept for wheel loader application is studied for example in [8]. However, the energy efficiency is not the main subject of the paper, but the paper concentrates on HIL simulation for control design. Huova et al. presented a digital hydraulic version of the independent metering valve concept for a wheel loader application in [9].

The throttling losses can be avoided completely by introducing direct pump control, which, on the other hand, typically increases the amount of installed displacement and idle losses. Schneider et al. utilizes displacement control in working actions of a wheel loader in [3]. Displacement control can also be applied to steering function of a wheel loader [10].

This paper compares the energy saving potential of different system types through numerical analysis. Three energy saving systems in addition to the baseline wheel loader are studied. The work functions of the baseline system are controlled using load sensing proportional directional control valves. The drive train of the baseline system as well as the energy saving systems is realized as hydrostatic transmission. In the first energy saving system, the standard valves of the work functions are replaced by independent metering valves. The two other energy saving systems are hydraulic hybrids: one is based on the standard proportional valve while the other is based on independent metering valves.

Different hydraulic hybrid circuits for wheel loaders are analyzed in [11] and [12]. The hybrid circuit selected for this study is very simple consisting of just 2/2 proportional control valve and an accumulator. Nevertheless, the fuel saving potential is significant in such application. The studied system is, in essence, a municipal loader, which is used in a wheel loader application. The hydraulic diagram of the system is given in figure 1.1. The goal of the paper is to compare the fuel economy of the concepts and discuss which system provides the best fuel saving when compared to added cost and system complexity.
2 Method

The comparison of the different energy saving methods is done using steady-state models of the systems. The input data is gathered from an experimental test where a gravel pile is moved in short Y-cycle. During the seven minute long work cycle, the consumed power of the hydrostatic transmission is recorded as well as the chamber pressures and piston positions of the two working functions. The chamber pressures are used to estimate the actuator load forces and piston velocities are calculated from the position measurements. These are the inputs of the calculation model.

The output of the model is the fuel consumption of the diesel engine. Energy losses of the diesel engine, pumps and valves are taken into account. The diesel engine rotational speed is set to a constant value in this analysis, which simplifies the control logic of the hybridized systems. Furthermore, the diesel engine is not downsized in order to avoid decreased performance in load cycles requiring continuous full power. Such load cycles could emerge e.g. from long and steep climbs with heavy load. Details of the calculation model are given in [11].

Small excerpt of the work cycle data is presented in figure 2.1. The data presented includes two Y-cycles. However, the energy saving potential of the systems is evaluated using the full work cycle data. The measured operation points of the
Two work functions are presented in Figure 2.2. Majority of the positive movement of the lift actuator is driven against load force around 120 kN. The lowering of the boom is performed with empty bucket, thus the overrunning load force is only approximately 25 kN.

The bucket is emptied by driving the tilt actuator into negative direction. The load force is positive thus indicating overrunning loading. After the bucket is emptied, it is levelled up for next filling. This is seen as slow positive movement against slightly restricting loading of approximately 20 kN. The filling of the bucket results in varying load force seen at higher positive velocities.
3 Energy saving concepts studied

There are three different energy saving methods studied in this paper. First method relies on independent metering valves. The configuration used in the numerical study is shown in figure 3.1. The energy saving potential of such valve configuration is the ability to remove undesired outflow side pressure difference, thus lowering load sensing supply pressure. Another benefit is the ability to use different control modes such as inflow-outflow and differential connection. While using optimal control modes, the supply flow rate can be decreased in many situations especially in multi-actuator systems.

![Figure 3.1: Independent metering valve](image)

The second energy saving system is a hydraulic hybrid circuit presented in figure 3.2. The hybridization is realized in a very simple way. A hydraulic accumulator is connected to the supply line of the work functions using a 2/2 bidirectional proportional control valve. The principle idea of this particular hybridization is to assist the supply pump of the work functions, when the desired power level of the diesel engine is exceeded. Furthermore, the sum flow from the accumulator and the supply pump is used, when the flow demand of the work functions exceeds the capacity of the pump. The accumulator is charged, when the diesel engine load is light and the charging does not induce significant power losses in the work functions. This is true, when the work functions are in standstill or the load sensing supply pressure is close to the accumulator pressure level.

The last of the energy saving systems studied is a hybridized version of the independent metering valve based machine. The system is achieved by replacing the proportional directional control valves of figure 3.2 with the independent metering valves.
4 Results

The results of the analysis are given in figures 4.1...4.4. Figure 4.1 presents the calculated power of the baseline system. The output power of the work functions is given in black color. The dark grey presents the hydraulic input power of the control valves. The difference between these curves is thus the power loss induced by pressure loss in the control valve. The light grey curve represents the mechanical input power of the work pump. The mechanical power produced by the engine is given as white color. In addition to the work pump, the engine drives also the hydrostatic transmission and the auxiliary pump.

In figures 4.2...4.3, the engine power of the baseline system is given as dotted line to assist the comparison. In the results of the hybrid systems (figures 4.3 and 4.4), the accumulator pressure is given in the lower diagram.
Figure 4.2: Calculated power of the independent metering valve system

Figure 4.3: Calculated power of the hybridized system with load sensing proportional directional valves

Figure 4.4: Calculated power of the hybridized system with independent metering valves

Figure 4.5 presents an overview of the fuel consumption of the different systems. The figures given are relative compared to the fuel consumption of the baseline system.
In figure 4.5, the white bar indicates how large portion of the chemical energy of the fuel is lost in diesel engine while generating the required mechanical energy. The lightest grey bar indicates the energy consumed by the hydrostatic transmission. This is equal for all systems as the HST is not altered between the systems. Aux pumps includes the input power of the auxiliary pump and the HST boost pump. Work pump losses is calculated as the difference between input power of the pump and the control valves of the actuator. In hybrid systems, this bar includes also the energy loss of the throttling valve in series with the accumulator. Valve losses includes the throttling losses occurring in the actuator control valves. Finally, the actuator output is the work done by the work functions.

5 Discussion

In addition to the comparison of the fuel efficiency of the systems, it is interesting to analyze, what is the reason for the efficiency improvement in each system. The independent metering valve is controlled such that the pressure differences over the active control edges are 1.5 MPa whenever possible. This reduces the load sensing supply pressure considerably at certain operation points when compared to the load sensing proportional directional control valve, which, in this case, generates considerable outflow-side pressure drop. Such spool configuration improves the controllability of heavily overrunning loadings, but increases power consumption. Another benefit of the independent metering valve is the use of...
different control modes. Finally, the diesel rotational speed is modelled as 1600 RPM, when the baseline system is modelled with 1650 RPMs. The rotational speeds are selected such that the RPM is as low as possible, but still providing sufficient output power. The small reduction in RPM reduces the power consumption of the auxiliary pump and boost pump of the HST slightly.

The main benefit of the hybridized proportional directional control valve based system is the possibility to drive the diesel engine at lower RPM. Instead of 1650 RPM, 1100 RPM is enough to deliver the average output energy needed. This reduces the power consumption of the boost pump and the auxiliary pump. Furthermore, even if slightly bigger supply pump of work functions is required, the pump losses are smaller due to lower rotational speed. The losses generated by the diesel engine get significantly smaller due to improved efficiency and smaller output energy required. The energy lost in the throttle valve of the accumulator does not ruin the overall efficiency, as the accumulator is used only to assist the engine during highest power peaks. The benefits of better diesel operation point and decreased input power of the pumps overcome the additional throttling losses in this load cycle. The improved diesel operation point and the decreased input power of the pumps result in roughly equal fuel saving in this case.

The best fuel efficiency of the studied systems is provided by the hybridized independent metering valves. The main benefit comes from the 25 % smaller output energy required from the engine, when compared to the baseline. This results from lower diesel (and therefore auxiliary and boost pump) RPM and from significantly smaller valve losses. The efficiency of the diesel engine is improved slightly due to decreased engine rotational speed: 1100 RPM. This results in the rest of the improvement in the fuel efficiency.

This study was performed using constant diesel engine RPM. Another degree of freedom is achieved by actively controlling the diesel engine RPM [12], but it was left outside the scope of this paper. It is worth to note that the original test system has a hydro-mechanical controller for setting the angle of the HST pump/motors. In order reach the energy saving results presented, the control of the HST pump/motors should be converted to electrical to decouple the control of engine RPM and HST.

Of the concepts studied, the most complex system with independent metering valves together with hydraulic hybridization is the best option in terms of fuel efficiency. The second best option is the hybridized version of the standard valve
circuit. However, the fuel efficiency is only slightly better than the efficiency of the non-hybrid independent metering valve system. When considering the simplicity of the hybrid suggested, the hybridized version of the standard valve circuit seems more attractive option of these two systems in terms of cost and complexity. Furthermore, the control of this hybrid circuit is simpler than energy optimal control of independent metering valves.

6 Conclusions

The results show a fuel consumption reduction of 28 %, when independent metering valves are utilized in a hydraulic hybrid wheel loader. Without the hybridization, the independent metering valves bring a reduction of 14 %, when compared to a standard 4/3 proportional control valve.

The hybridization principle studied in this paper is simple. There are no additional hydraulic pumps or motors, just a 2/2 proportional valve and a hydraulic accumulator. If the control valves of the system are not changed, but the simple hydraulic hybrid is introduced, the fuel consumption is reduced roughly 16 %. In terms of cost and complexity, the introduction of the simple hydraulic hybrid seems more beneficial than the independent metering valve concept.

The study was made using a single application in a single work cycle. Therefore, the results cannot directly be applied to other machines or work cycles.

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8 References


