Efficiency definitions of hydraulic transformers and first test results of the FCT80

INNAS

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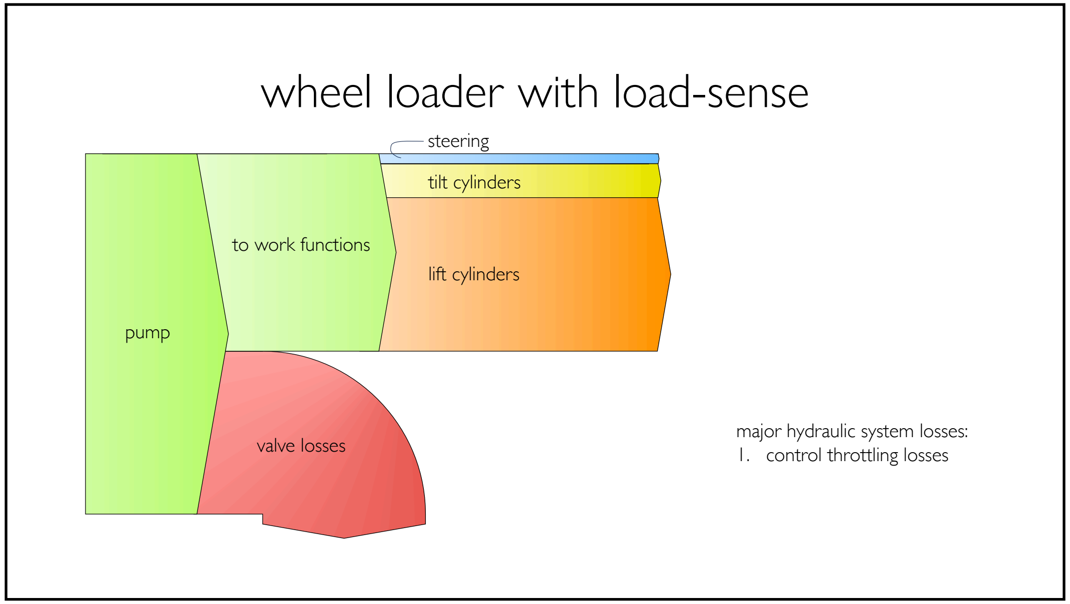
Welcome everyone, and thank you for joining me this morning. Today, I want to talk about the efficiency of hydraulic transformers. More specifically, about the efficiency of a prototype transformer that we made, called the FCT80.

However, this transformer is just a single component in a much bigger hydraulic system. So before we dive into the performance of that single component, I want to start by explaining to you why we built this prototype in the first place, and what kind of implications it has on the complete system.

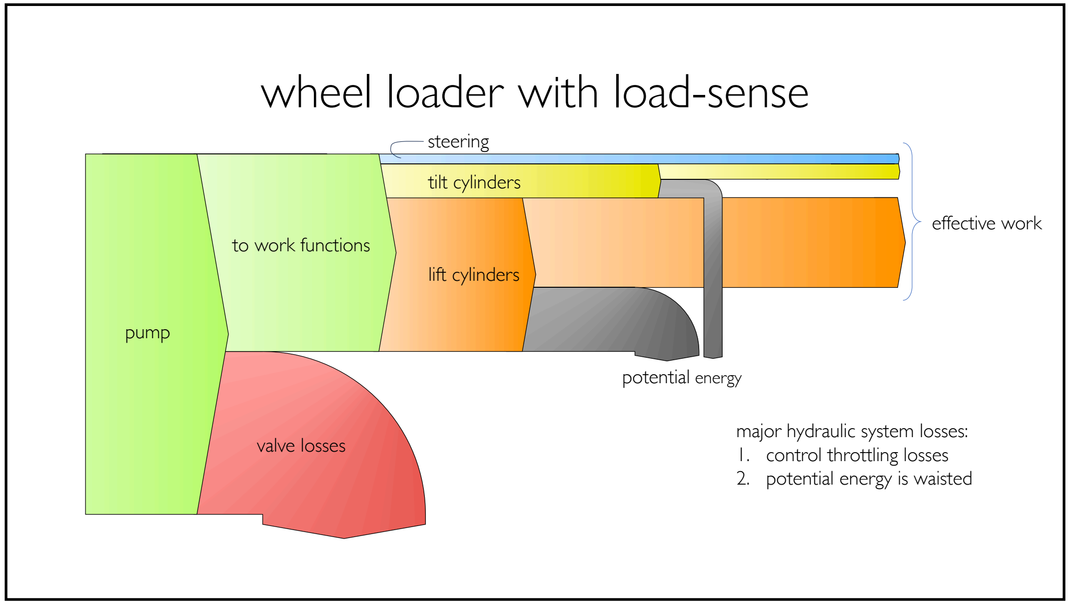
hydraulic system loss

of a conventional wheel loader

To do so, we are going to look at the energy losses in a typical hydraulic system. In this case, I am going to show you loss calculations of an actual wheel loader with a conventional load-sense system.

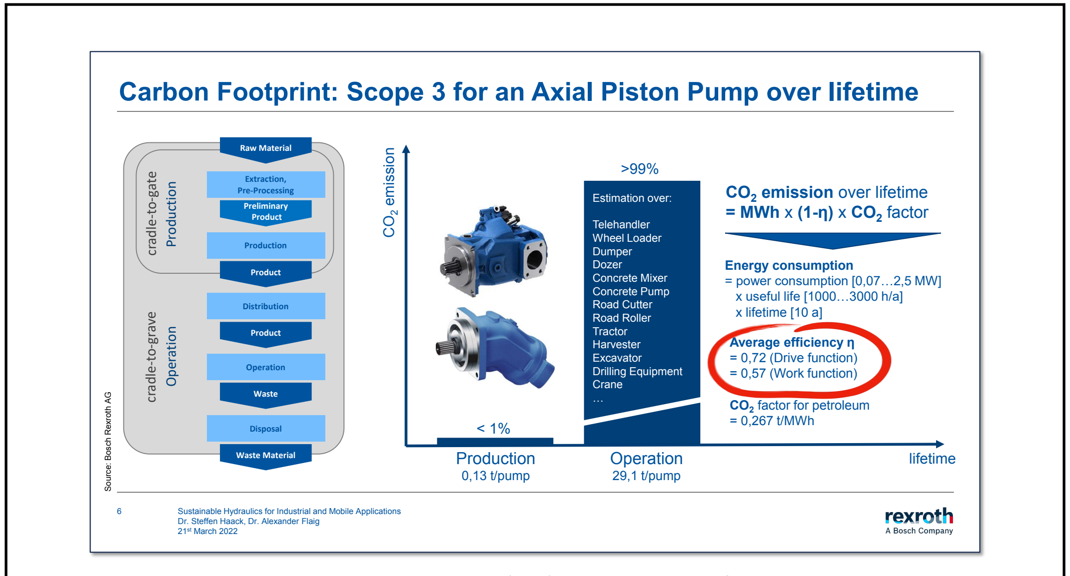


If we ignore the drive function for now, this wheel loader has three work functions: steering, tilt and lift. The relative amount of energy that is used at each of these functions is illustrated by the size of the arrows in this diagram. On the left side, you can see that the pump needs to supply significantly more power than is actually needed at the cylinders. This is because a large amount of hydraulic power is throttled as a result of the load-sense architecture of this system, which uses proportional valves and pressure compensators to control the cylinder movement.



Something that might be less obvious, is that the power that is being sent to the work functions is only partially used to effectively do work. In a wheel loader for example, whenever you are lifting and lowering your load, you are also lifting and lowering the bucket and the arm. These components have some significant weight to them, and that means that you are moving potential energy around. Unfortunately, in a conventional system like this, there is no way to re-use or recuperate this potential energy. The loss of this potential energy is a significant part of the energy losses in a system like this.

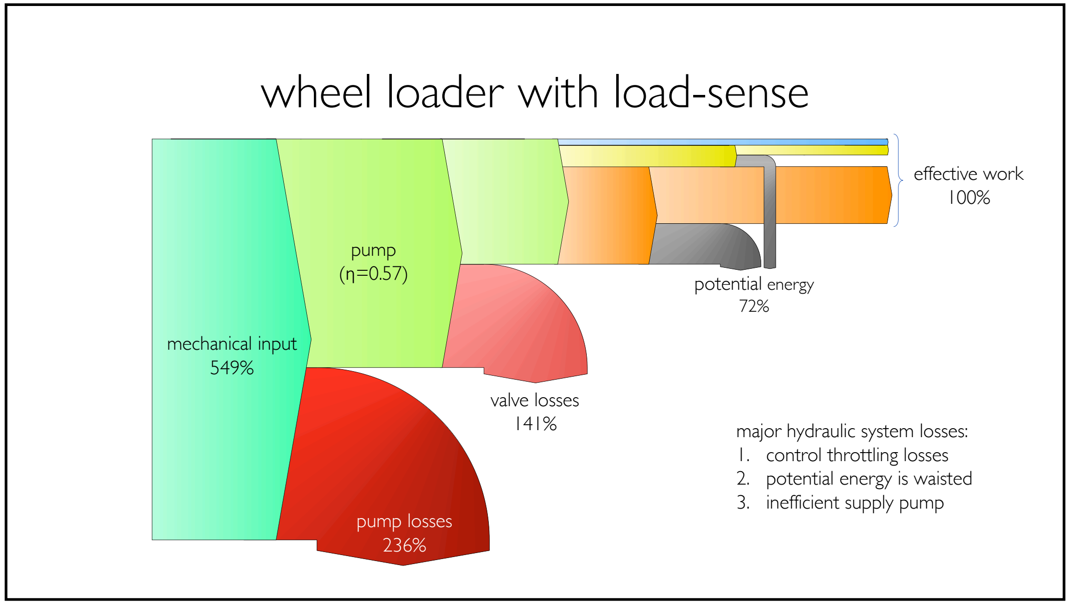
Next to these two major hydraulic system losses, there is a third big source for loss and it can be found on the left side of this diagram.



S. Haack, A. Flaig (2022) *Sustainable Hydraulics for Industrial and Mobile Applications*, IFK2022

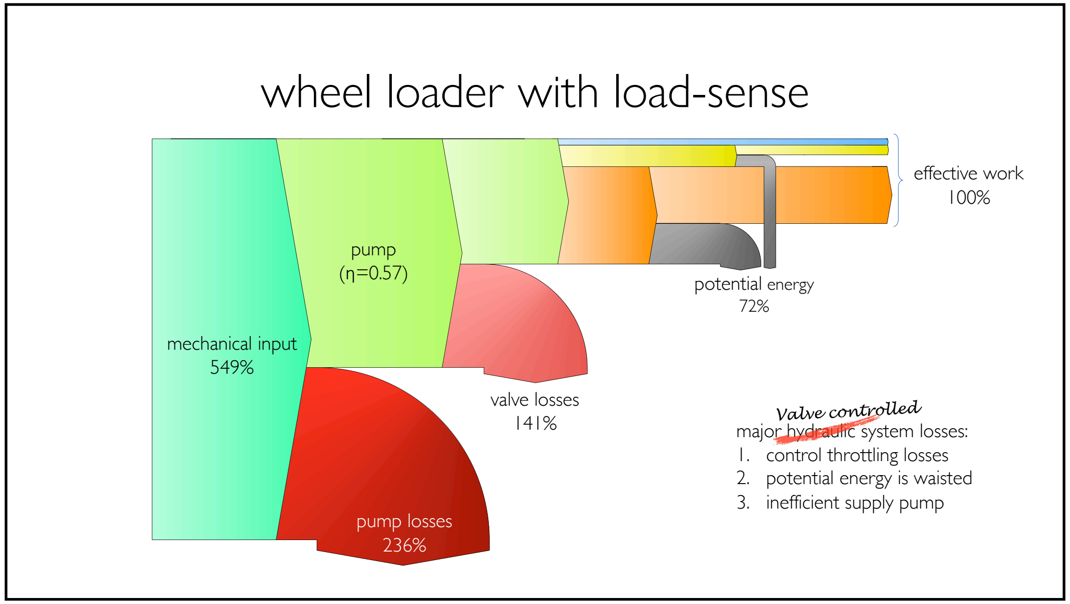
You need to get hydraulic power from a pump, but unfortunately this pump is operated at very inefficient conditions.

At the previous IFK, which was held in 2022 in Aachen, Dr. Steffen Haack and Dr. Alexander Flaig from Bosch Rexroth showed this slide. They describe that most CO_2 emissions of their pumps are emitted during operation. From an investigation among their clients, they found that the average efficiency of a pump that is being used to operate work functions (like lift and tilt cylinders) is only 57%. This number is so low, because this needs to be a variable displacement pump that is being operated at partial conditions, basically all of the time.



When we include this efficiency into our loss calculation, we find that we would need to supply this system with an enormous amount of energy in order to get it to work. In fact, if you look at the numbers, you can see that for every unit of effective work, you would need to supply more than 5 times the amount in order to account for all of these losses.

This is actually one of the reasons why you cannot simply replace the combustion engine with an electric motor in a machine like this. You end up with either a machine with a very large, very expensive battery, or with a machine that needs to recharge after a few hours of work. The customer will not accept such a machine.

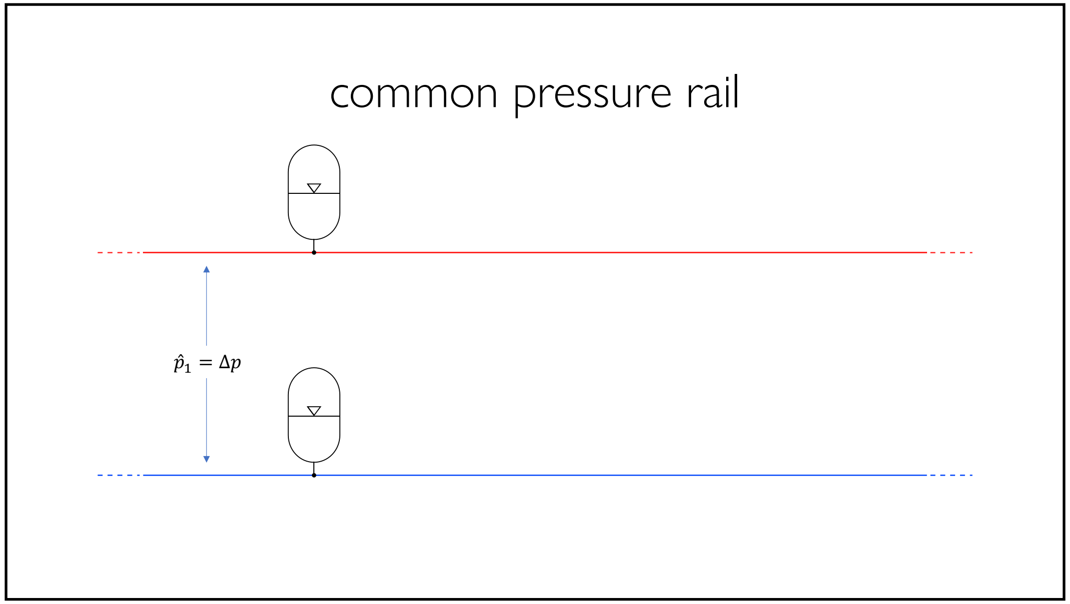


However, there is some good news: the losses described here are not inherent to hydraulic systems. They are just inherent to the way we have traditionally designed the control architecture for these machines, in a time when we did not have to bother about fuel cost or CO_2 emissions. There actually are alternative ways to control this machine using hydraulics.

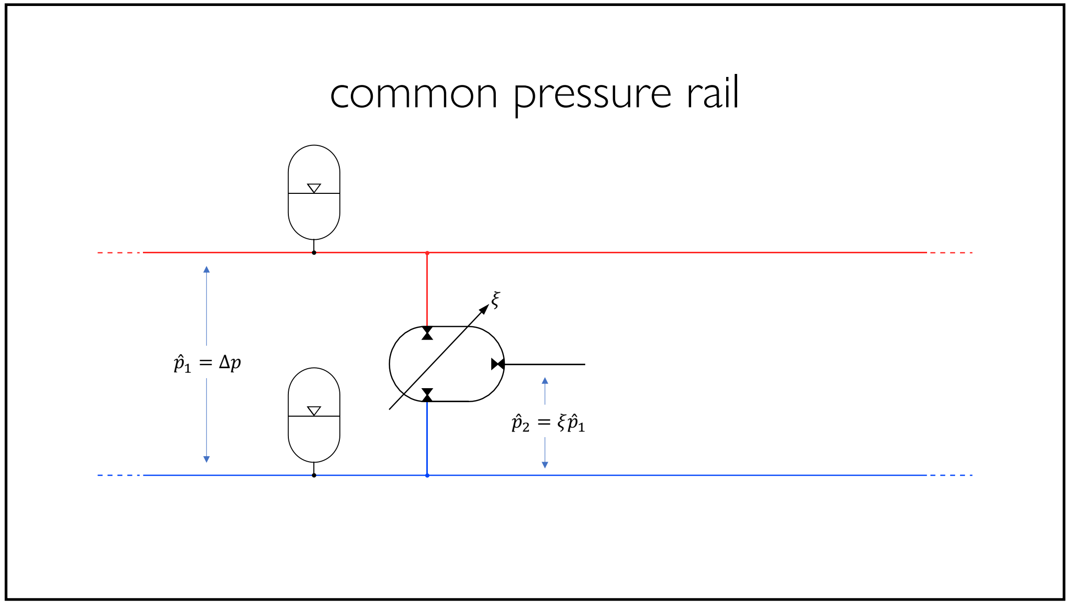
the alternative

common pressure rail and hydraulic transformers

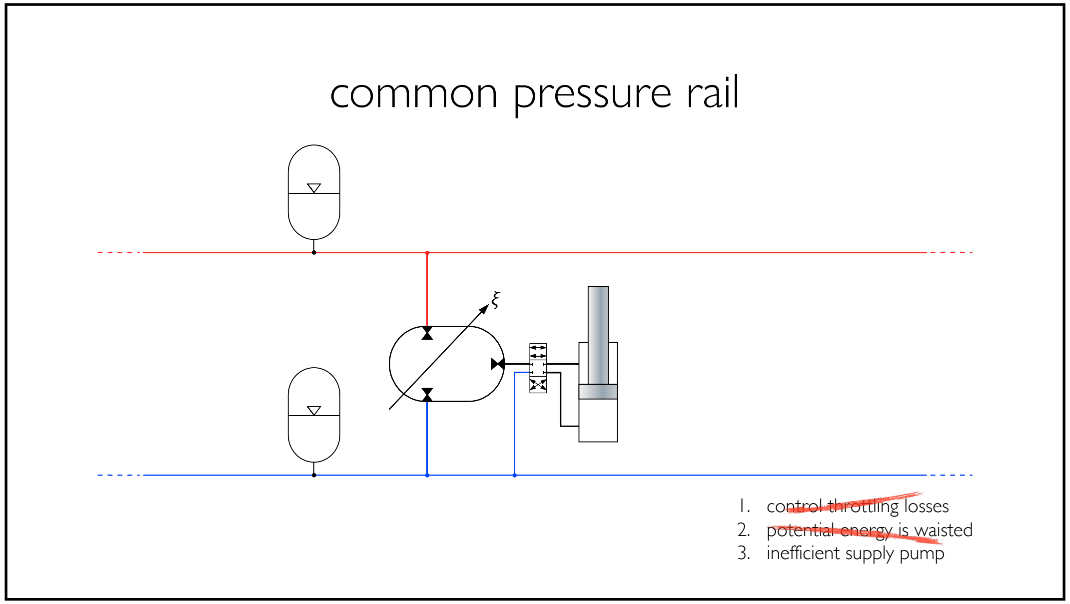
One of these alternative system architectures, is an alternative that INNAS has been working on for the last few decades. The backbone of this system is called the “common pressure rail” or CPR.



Such a CPR system relies on multiple pressure rails, usually there is one high pressure rail and one low pressure rail. A pressure rail itself is basically nothing more than an accumulator that can be shared by the different loads in your system. At any given moment, there is a pressure difference between these two rails, a Δp, which means that you have potential energy available at all times.

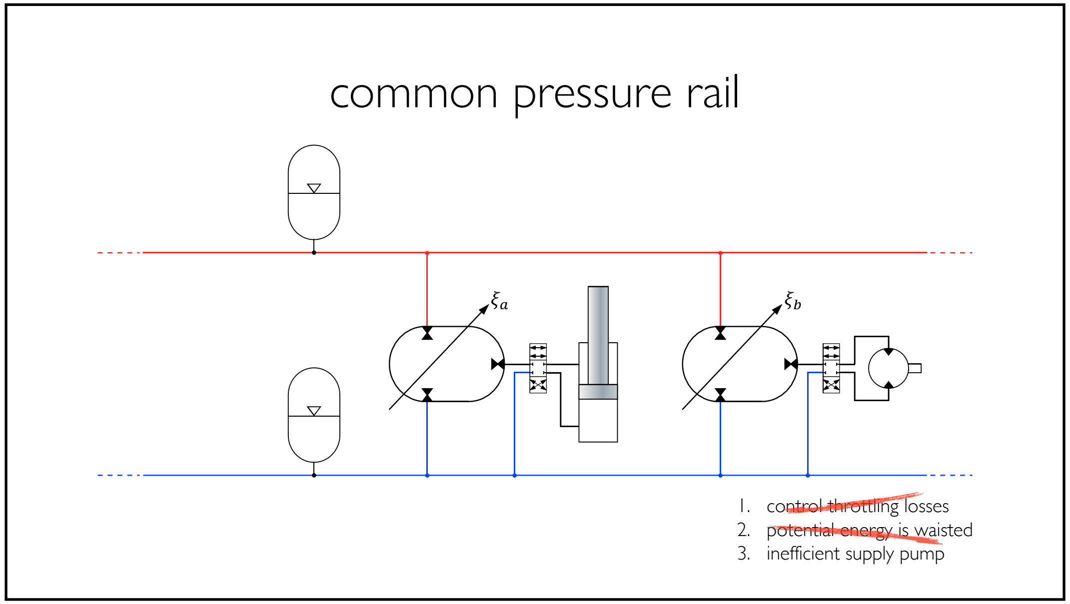


The component that is added here, represents a hydraulic transformer. It is supplied with pressure from both common pressure rails. The transformer can use the supplied pressure difference to create a third pressure level, using an internal control parameter. Because you have full dynamic control of this parameter and thus the output pressure, you can use that pressure to control a load function.



So we can attach a cylinder to the work port of the transformer. When we take power from the accumulator at a certain pressure level, this pressure level is transformed to a level that is needed to operate the cylinder. Since this way of control relies on power transformation instead of dissipation, the hydraulic power is no longer throttled.

An additional benefit of this system is that the process of transformation also works the other way around. Potential energy that has been used to raise an arm for example, can therefore be used by the transformer to recharge the accumulator of the pressure rail.

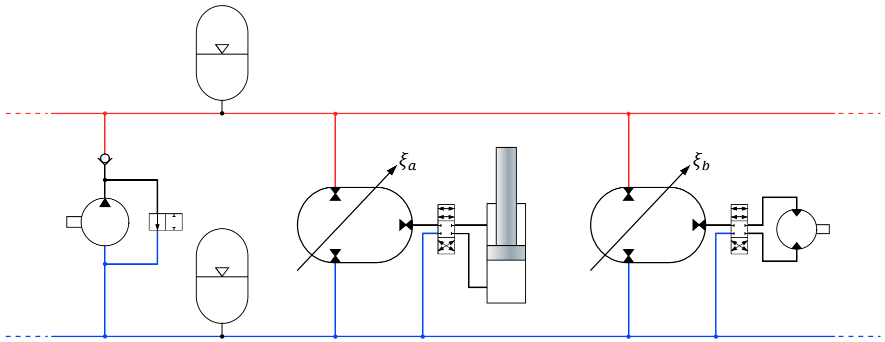


So using a hydraulic transformer has already solved two of the major system losses that we had before: work functions can be controlled without throttling losses and we can recuperate potential energy.

If you have multiple work functions, you can just add them by connecting another transformer to the shared pressure rails. Each transformer can use the current charge in the accumulator and can be operated independent of the other transformers.

At some point in time, the accumulator will run low on charge. So in order to supply this system with energy, you will need a charge pump to charge the accumulator.

common pressure rail

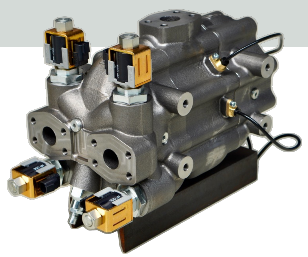


1. ~~control throttling losses~~
2. ~~potential energy is waisted~~
3. ~~inefficient supply pump~~

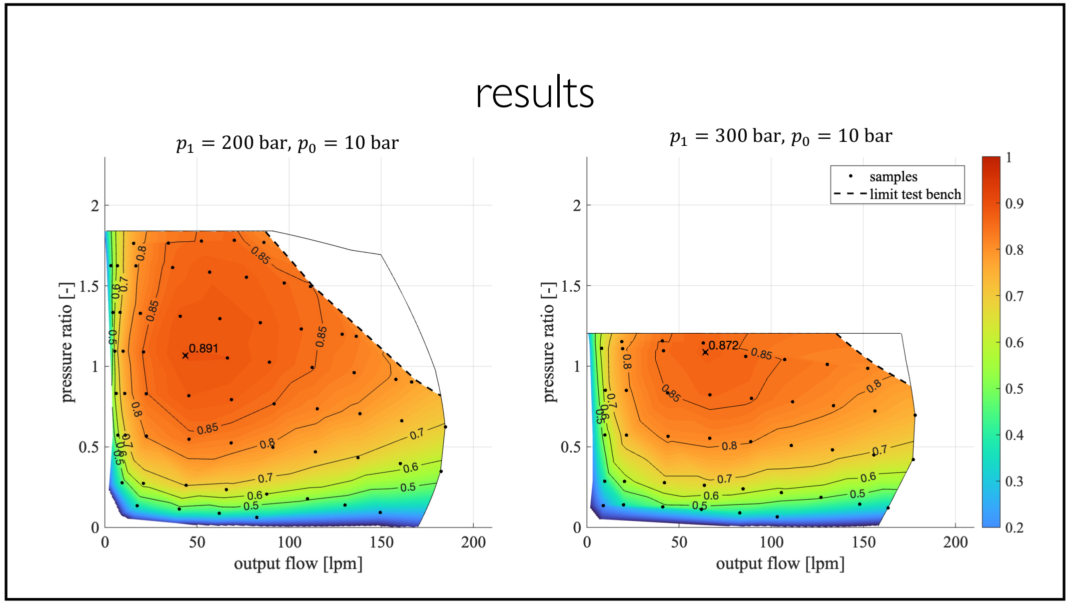
Due to the use of accumulators, the energy consumers (transformer+work function) are decoupled from the energy supply (charge pump). This means that you can use a constant displacement pump that can run near its optimum efficiency operating point whenever the system needs to charge, while it can run idle or be shut off in the meantime. This way, the third major system loss is also avoided.

As you can see, this different control architecture has an enormous potential for energy saving. However, there is one big problem: this system relies on an efficient and dynamic hydraulic transformer. At the moment, there is no hydraulic transformer commercially available on the market.

efficiency of the FCT80



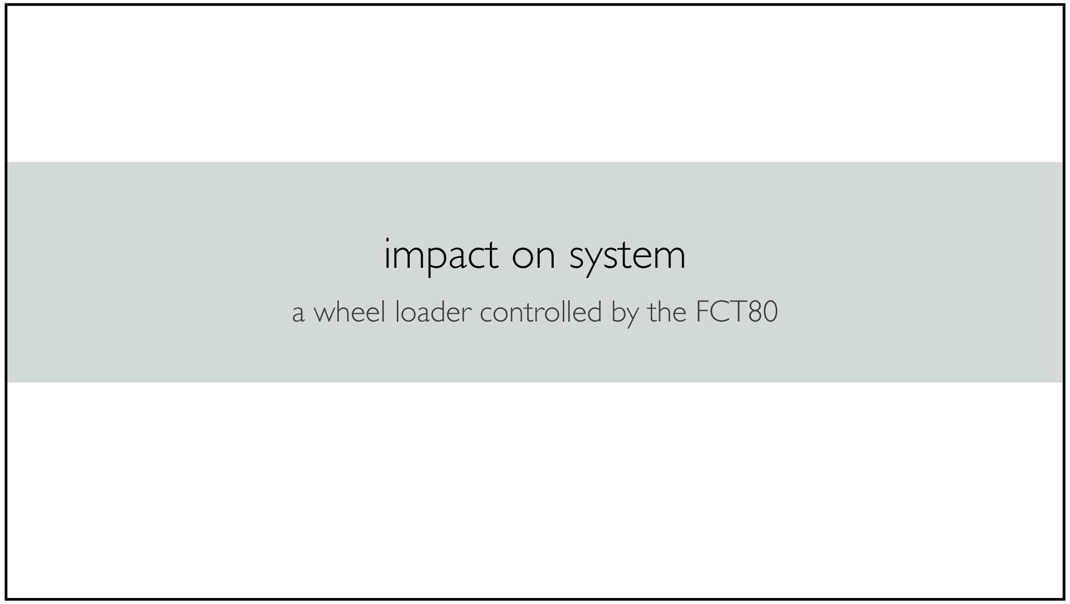
And that is precisely the reason why we have developed a prototype hydraulic transformer. Here you see a picture of the actual machine that we made. It is called the Floating Cup Transformer 80, or FCT80. The design of this machine has already been shown and discussed at the SICFP in 2023 in Tampere, so I won't go into detail about the internals of this machine. For this conference, we focussed on measuring the performance of our new prototype.



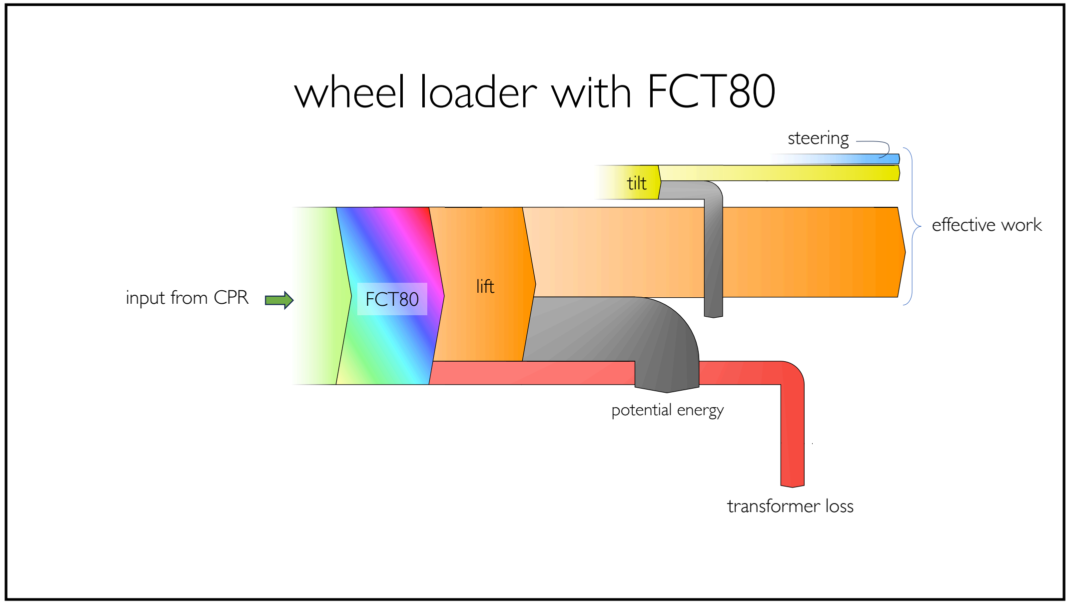
This slide shows two efficiency contours. The left figure shows the efficiency at a supply pressure of 200 bar, while the right figure shows it at 300 bar. The horizontal axis shows the amount of oil flow at the work port. You can see that this machine has a maximum flow rate of roughly 180 l/min which can be delivered to a work function. The vertical axis shows the pressure ratio, which is defined as the work pressure divided by the supply pressure. As you can see, the FCT80 is also able to amplify the supply pressure (ratio > 1). In our measurements we used a maximum work pressure of 350 bar, which explains the difference in maximum pressure ratio between the two figures.

The results show a maximum efficiency of just under 90%. When you look at the higher output powers, so high flow and high pressure, the efficiency is pretty good. Near the edges of the field of operation, especially at lower pressure ratios, the transformer performed significantly worse. This is definitely something that will need to be improved in future prototypes.

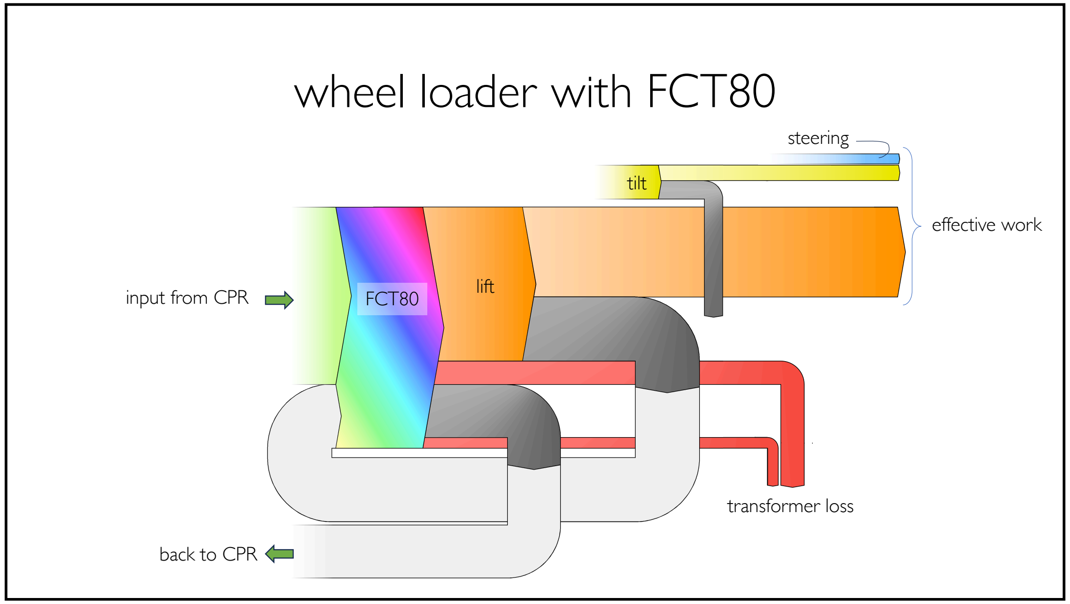
One thing to note is that the FCT80 has a built-in hydraulic actuator to control the machine. This actuator therefore draws some power from the accumulator as well. In the figures shown here, these control losses are included as input power. So the numbers you see are the efficiency of the transformer including the losses associated with control.



So what does it mean that a transformer has an efficiency of 80% or 90%? In order to answer that question, let's have a look at the same wheel loader we saw before, but now we are going to operate it using two FCT80's.

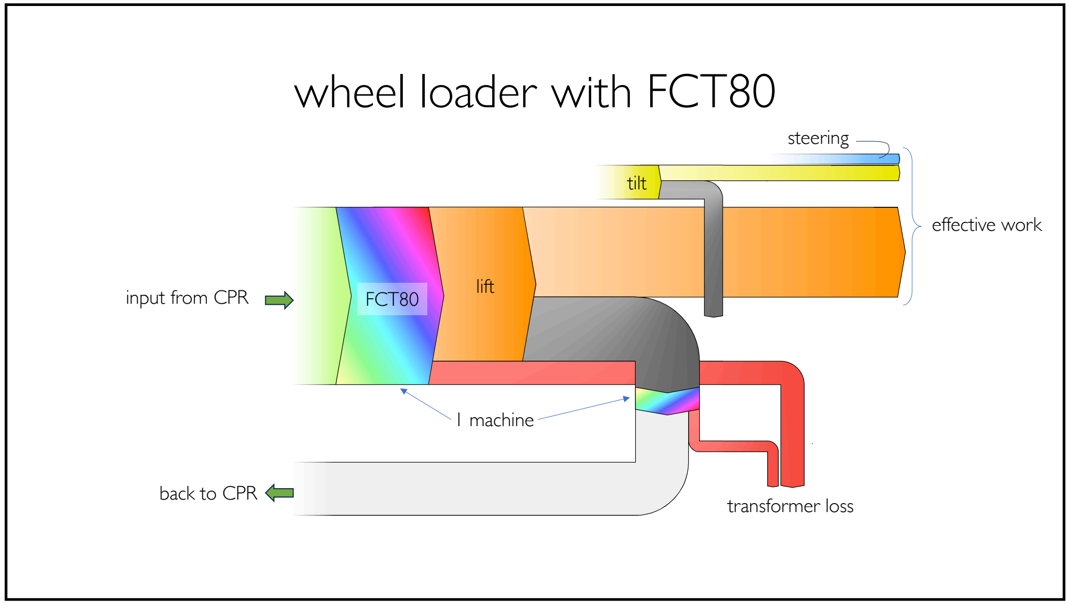


On the right side, we assume that the machine needs to perform the same effective work. However, we are now going to use our transformer to supply the lift cylinders with the amount of power required to operate this work function. Since we saw that the FCT80 does not have an efficiency of 100%, there will still be some losses here. These transformer losses are shown with the red arrow.

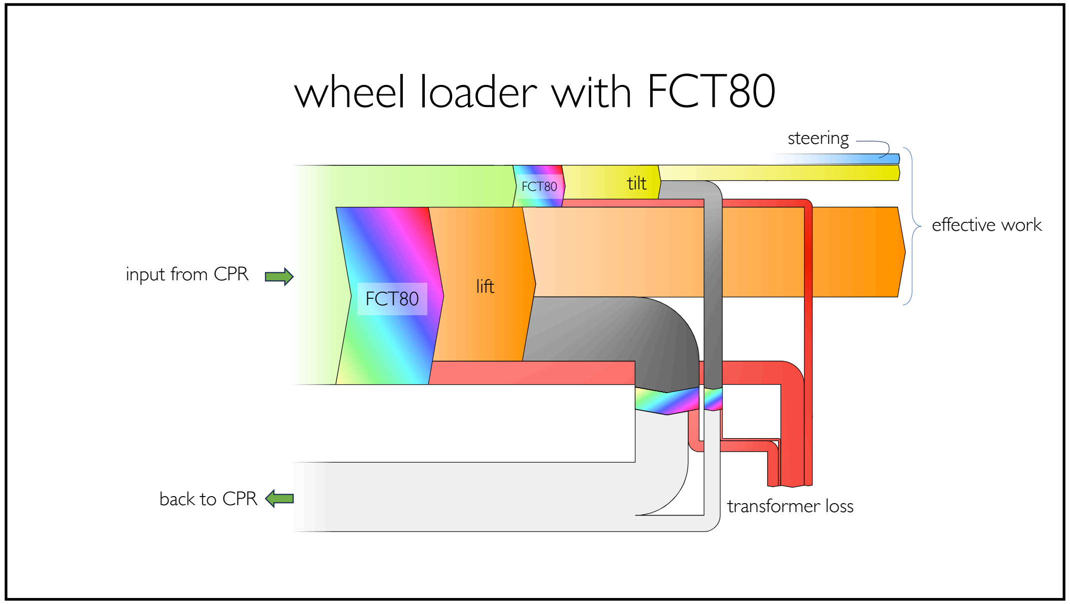


As mentioned, the transformer can re-use the potential energy in the cylinders to charge the CPR accumulator again. Since this is also a process of transformation, there will result in some losses.

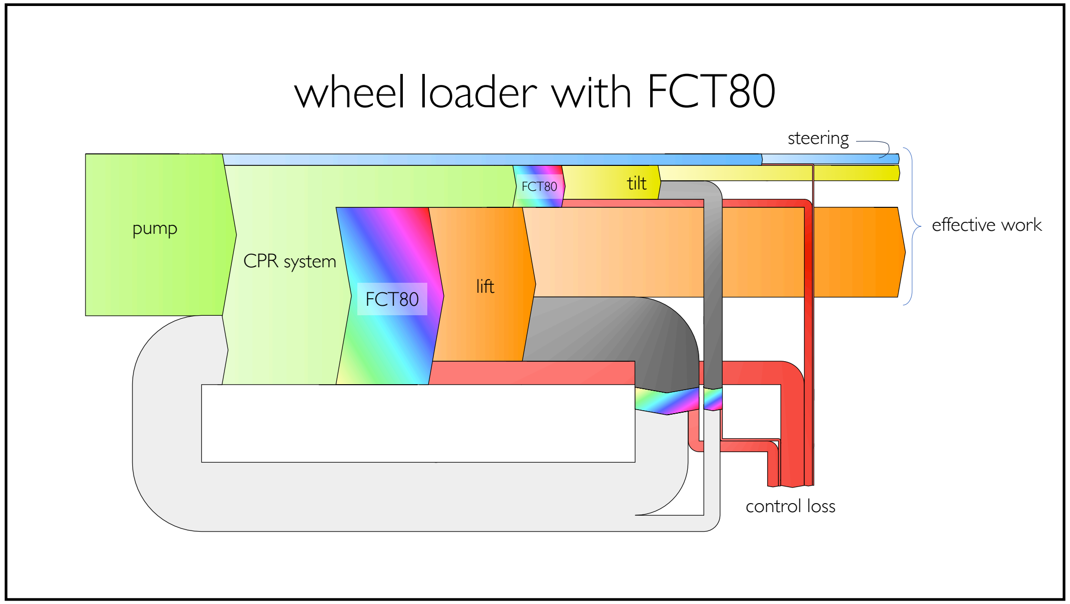
As you can see, these energy flows can become quite messy, so let's simplify this diagram a bit for clarity.



This shows the same recuperation proces, but compressed into a single loop back to the CPR. The two rainbow blocks still represent a single transformer thought.

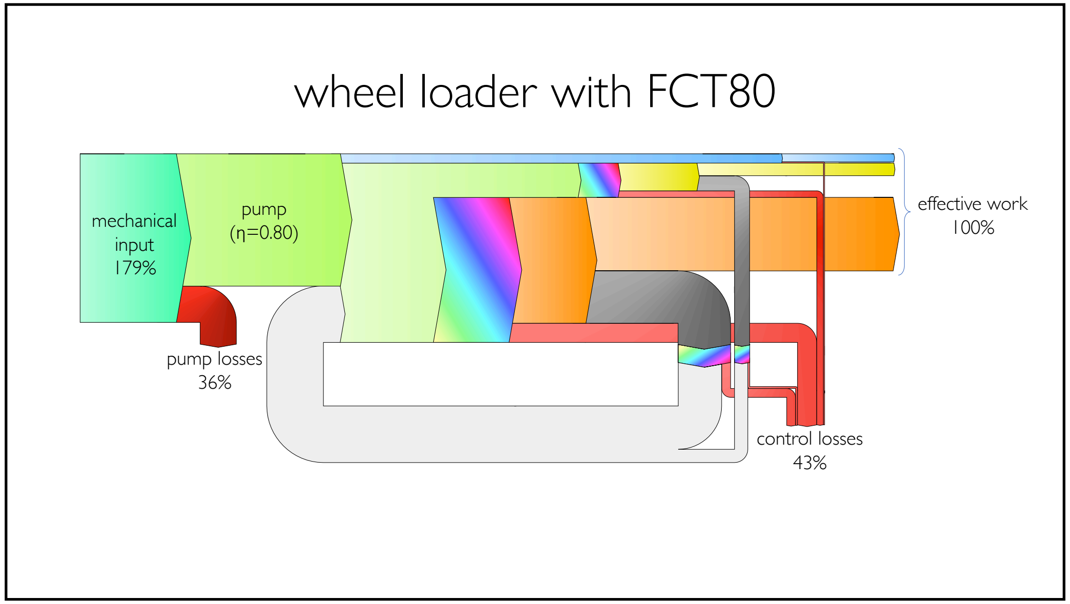


If we assume to use a FCT80 for the tilt cylinders as well, you can see that the results are very similar. We lose some more energy, and we can also send some energy back to the CPR system.



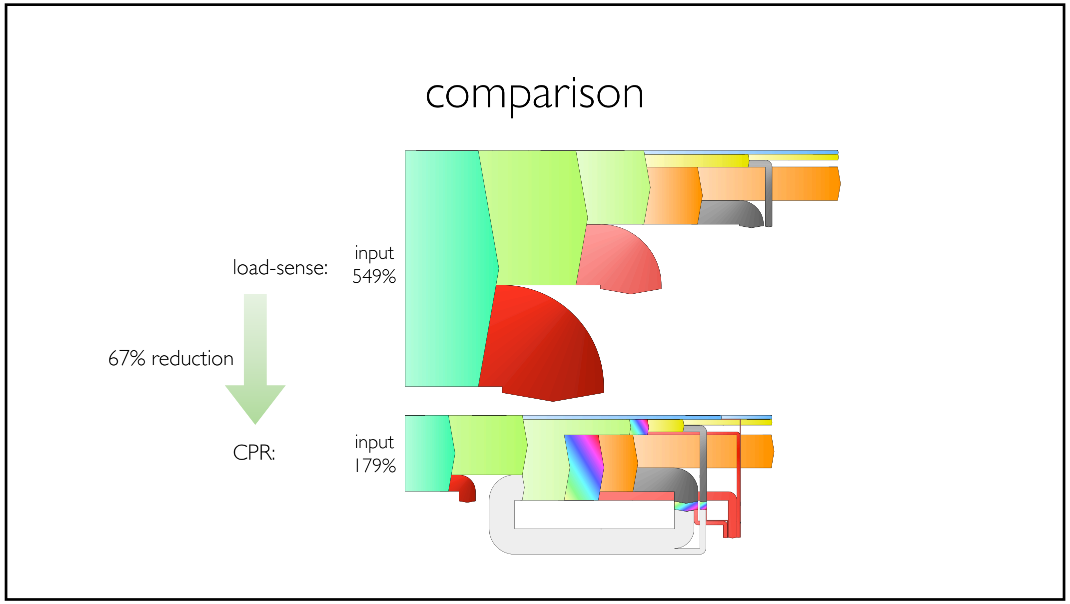
For steering, the situation is slightly different. First of all, the output power of this work function is relatively low. Secondly, the steering cylinders work in the horizontal plane, which means that there is not much potential energy to be regained during this work proces. Therefore, we opted to keep the control of the steering function as is.

To complete the system, we need to supply the CPR system with hydraulic energy from a pump.



As mentioned, the pump in this system can be a constant displacement unit, running near its optimum operation conditions. While there are definitely more efficient pumps available on the market, let's take a rather conservative estimate of 80% efficiency for this pump.

Looking at the numbers, this diagram shows that you would need to supply this system with less than 2 times the amount of effective output power.



If we compare these findings to the original system, we can see that using transformers can lead to a reduction of two-third in terms of energy usage. Of course, these are just calculations and estimations, based on assumptions. But as you can see, there is a huge potential for saving energy.

We want to know how well these transformers perform in a real use case. That is why we are currently working together with an OEM that is building these prototype transformers in an actual machine. And we are looking very much forward to finding out if we can come anywhere near these kinds of energy savings.

Thank you for your attention!