Alternative System Solutions
for Wheel Loaders
and other Construction Equipment

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Abstract

− Holistic approach to wheel loaders as complex energy conversion systems
− Possible Reduction of fuel consumption by 50% through use of hybrid technology
− Considerations of customer segment and business case

Keywords: alternative drive trains, hybrid power systems, construction machinery
Brilliance is simply the art of planning ahead.

(from the tv series “Lexx”, episode “Brizon”)

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1 Background

Within the Volvo Group [1] there exist long-ranging experiences regarding hybrid propulsion systems for heavy commercial vehicles of the brands Volvo Trucks, Renault Trucks, Mack Trucks, Nissan Diesel and Volvo Bus [2]. For commercial vehicles like these, hybrid technology is to be regarded seriously and a business case is often given.

The search for energy efficient solutions goes on also for construction equipment, and hybrids are everyone’s topic. Within Volvo Construction Equipment [3] there is a tradition of researching and developing energy efficient solutions, an example of which was the presentation of a first prototype of a hybrid wheel loader [4] in the beginning of 2008.

In this paper, the wheel loader will be used as an example for other types of construction machinery. Using a systematic design approach, several more principle design solutions can be found. Reducing fuel consumption by a large percentage while keeping the performance and productivity at the same level is only possible by considering the complete machine as one system using a holistic approach.

Computer simulation of complete vehicles and machines can today be considered to be the state of the art of conceptual design. Especially in the on-road sector, be it on the consumer side (cars) or on the commercial side (trucks and buses), the trend has progressed from simulation of sub-systems to the simulation of complete systems, among other things to evaluate handling, comfort, and durability. Particularly challenging for the off-road equipment industry is that its products, working machines, are complex in architecture: sub-systems of various domains and their interconnections cause a non-trivial behaviour of the total system [5].

1.1 Wheel Loaders

In this paper, a wheel loader is chosen as a perfect example of a working machine. Other examples can be found among agricultural equipment and in the forestry sector.

Wheel loaders are highly versatile machines and are built in vastly varying sizes. The smallest have an operating weight of just 2 tons while the world’s largest wheel loader weighs more than 262 tons. Naturally, not only are there technical differences between these extremes, but also differences in their application. Smaller wheel loaders are often built with a hydrostatic drive train and are used for all kinds of service jobs at smaller construction sites, farms etc. A large number of attachments exist, for example buckets, grapples, forks, material handling arms, cutting aggregates... Machines of this size are purchased for their immense versatility. The opposite is true for larger wheel loaders, which are often bought for one single application in e.g. a quarry or a mine.

The work presented in this paper focuses on medium to large-sized wheel loaders. Figure 1 shows a Volvo L180E with a nominal operating weight of 26 to 29 tons. Such wheel loaders are usually assigned to one specific application, but not limited to mining.
or work in a quarry. Several special attachments exist; there even is a machine variant with a high-lift loading unit for timber loading.

![Wheel Loader](image1.png)

**Figure 1.** Wheel Loader

Due to their versatility, wheel loaders need to fulfil a great many requirements, which are often interconnected and sometimes contradictory. Leaving aspects such as total cost of ownership, market availability, reliability etc. aside, the most important machine properties are productivity, energy efficiency, and operability. Paper [6] gives a more detailed break-down of performance-related aspects and points out that while some of the items are clearly determined by more than just one sub-system (e.g. lift force, which is determined by hydraulics and load unit), others seem to be possible to attribute to one single sub-system (e.g. traction force). One might thus, wrongly, be tempted to leave such aspects out of the optimisation loop when it comes to trading-off product targets against each other when choosing technical solutions. A modern wheel loader, however, consists of tightly coupled, non-linear sub-systems that interact even in seemingly simple cases (Figure 2).

![Simplified power transfer scheme](image2.png)

**Figure 2.** Simplified power transfer scheme of a wheel loader

The power transfer scheme in Figure 2 visualises how the diesel engine’s power is split up between hydraulic and drive train, which are two parallel sub-systems. Medium
to large wheel loaders are usually equipped with a conventional drive train that includes a hydro-dynamic torque converter and an automatic power-shift transmission. Modern wheel loaders feature load-sensing hydraulics with variable displacement pumps. The linkage of the loading unit acts as a non-linear transmission between hydraulic cylinders and attachment.

The next sections will show that the human operator in fact plays an essential role in controlling the total system, a fact that needs to be taken into account when designing a new wheel loader. Electronics can render useful assistance. Essentially all wheel loaders today are equipped with several electronic control units (ECUs), each dedicated to one specific component or sub-system, and all ECUs connected to a data bus. “X by wire” is a trend also in the off-road equipment industry, which implies that operators communicate their wishes to the machine via electronics, rather than controlling it directly.

1.2 The Harmonic Wheel Loader

The challenge in designing a wheel loader, from a manufacturer’s point of view, is to find an appropriate, robust, and maintainable balance between productivity (material loaded per time), energy efficiency (fuel consumed per loaded unit), and operability over the complete area of use.

At Volvo, engineers have begun to use the terms Machine harmony and the Harmonic wheel loader as the ultimate goal: A machine that is intuitively controllable and that can be used in a straightforward manner. Everything works smoothly and the work task can be performed without much conscious thought or strategy.

1.3 Short Loading Cycle

Because wheel loaders are highly versatile machines, it is difficult to define a standard test cycle that covers every possible aspect of the various tasks and workplaces. However, a so-called short loading cycle, sometimes also dubbed V-cycle or Y-cycle for its characteristic driving pattern, is highly representative of the majority of applications. Typical for this cycle is the loading of some kind of granular material (e.g. gravel) on an adjacent load receiver (e.g. a dump truck). As can be seen in Figure 3, several phases can be identified in such a loading cycle [6].

The short loading cycle has been established as the main test cycle during development of wheel loaders. Several other cycles exist and are of interest, too, but a short loading cycle reveals any flaw in the following three critical balances:

- **Force balance**: Critical during phase 1, Bucket filling
- **Motion balance**: Critical for the cycle time (and thus productivity). In a proper short cycle revealed by the start of phase 4, Reversing
- **Power balance**: Especially critical during phases 1 and 4.
In the following sections, each balance will be described and the reasons for their importance to wheel loader design will be given. It will also be shown that each balance is affected by the way the human operator uses the machine to perform work.

1.4 Force Balance

Figure 4 displays the forces and moments of interest during the bucket filling phase of a short loading cycle.

For loading granular material like gravel, the bucket first has to penetrate the pile. This requires traction force, which is achieved by transferring torque from the engine via a torque converter, transmission, axles, and wheels to the ground (Figure 2). In accordance with Newton’s Third Law of Motion, the Law of Reciprocal Actions, the gravel pile exerts an equal and opposite force upon the loader bucket. A typical sequence for actually filling the bucket is then to break material by tilting backwards a little (i.e. rotation around the lower bucket hinge), lifting a little, and penetrating even further. The lift and tilt functions require engine torque to be transferred via hydraulic pumps (converting torque to hydraulic pressure), cylinders (converting hydraulic pressure to longitudinal force), and loading unit (Figure 2).

Figure 4 reveals how these two efforts work against each other: in order to achieve a lifting force, the cylinders have to create a counter-clockwise moment around the loading unit’s main bearing in the front frame. At the same time, the reaction force from the traction effort creates a clockwise moment that counteracts the lifting effort.
Because of this, the gravel pile can be seen as a hard coupling between drive train and hydraulics, forcing them to interact with each other, and to experience each other’s effort as an external load. Furthermore, Figure 2 has already shown that hydraulics and drive train are parallel systems, each competing for the limited engine torque. When these two paths are brought together in the gravel pile, the coupling works like a short circuit, where all loads are transferred back to the origin – the engine. Figure 5 shows this interesting situation, in which engine torque is transferred to the wheels to accomplish traction, but at the same time counteracts that part of the engine torque that has been transferred through hydraulics to accomplish lifting and tilting – in turn requiring even more torque to be transferred.
speed and lifting time. In addition to this, loading unit geometry, and bucket design are of great importance for a smooth bucket filling. Ultimately though, it is the machine operator’s task to achieve a favourable balance by using the available controls. As already pointed out, implementing sophisticated electronic control strategies can be of great help, but each work place is different, and different bucket filling strategies are required for the various materials that exist.

1.5 Motion Balance

An experienced operator chooses the point of reversing so that the bucket will have the necessary height approximately when the loader reaches the load receiver. Figure 6 shows a diagram displaying bucket height over integrated machine speed (i.e. the machine’s travelling distance) in a short loading cycle.

![Figure 6. Machine harmony diagram with phases of a short loading cycle](image)

The ratio of lift speed to machine speed, which is crucial to how long the loader needs to be driven backwards until reversing, can here be seen as the graph’s slope. The graph is fairly straight from the beginning of phase 2 (where the loader leaves the bank) to the end of phase 5 (where the loader arrives at the load receiver). This indicates that the operator judged well when to reverse. Otherwise, the slope would become steeper at the end of phase 5, indicating that the operator needed to slow down or even stop in order for the bucket to reach sufficient height for emptying.

The distance between the point of reversing and the bank (or load receiver) is an indication of how good a balance has been achieved between the two motions of lifting and driving. Engineers at Volvo CE have begun to call this a Machine harmony diagram, because it visualises aspects that are important for a machine’s operability. Such
Alternative system solutions...

Together with time plots, such Machine harmony diagrams are a useful tool for evaluation of how good a motion balance has been achieved. Additionally, they reveal to a certain degree the operating technique of the human operator.

1.6 Power Balance

Phase 1, *Bucket filling* and phase 4, *Reversing* are the most challenging phases from an engine’s point of view. Both drive train and hydraulics have high power demands. High traction, lifting, and break-out force are needed during bucket filling, while during reversing, the engine is run at a lower speed and needs to simultaneously cope with increased load from the torque converter and with hydraulic power demand due to continued lifting. The operator’s impression of the wheel loader as a powerful machine depends on either the engine’s ability to satisfy all power demands, the overall machine control system’s ability to govern each sub-system, or a combination of these abilities.

![Power distribution to hydraulics and drive train in a short loading cycle](image)

**Figure 7.** Power distribution to hydraulics and drive train in a short loading cycle (total engine power = top of the black area)

The diagram in Figure 7 displays data recorded during a short loading cycle. The distribution of engine power to hydraulics and drive train seems on average to be approximately equal, however with large momentary deviations from that rule. Most engine power is required during bucket filling. The oscillations in power and in distribution
ratio are a reflection of the operator’s bucket filling technique and the work place conditions.

Mapping these data on power requirements to the power available at the current engine speed gives an indication of the wheel loader’s performance margins. The engine’s response but also its fuel consumption can vary dramatically depending on the specific combination of torque and speed that accomplished power. It is therefore important to analyze the engine’s load duty (Figure 8):

![Figure 8. Engine load duty in a short loading cycle [7]](image)

### 1.7 Summary

The human operator plays an active role in simultaneously maintaining all three of the critical balances described above in order to perform the assigned working task. Each of the balances is not only crucial for the wheel loader’s total productivity and energy efficiency during a loading cycle, but also for its perceived operability.

At the beginning of this chapter, the complexity of working machines was mentioned. In light of all the background information presented, we can conclude that the main challenge with regard to the topic of this paper is that working machines are complex systems whose main properties productivity, energy efficiency, and operability are not solely defined by the machine itself, but to a large degree also by how its operator uses it. To a lesser extent this claim can also be made for vehicles (e.g. fuel consumption as a function of acceleration profile or gear shifting strategy), but in the case of working machines the human operator plays a far more significant role.
2 Hybridization

2.1 Introduction

A lot of different definitions and descriptions are used when it comes to hybrids. In general, a hybrid uses energy/power from two different sources, whereof at least one is reversible, i.e. can also store energy. In this paper, only electric hybrids are considered. However, the principles are the same, irrespective if electric, hydraulic or pneumatic machines are used.

2.2 Classification

Different ways of dividing hybrids into classes are used:

- Classification by technology (electric, hydraulic, …)
- Classification by characteristic component (fuel cell, plug-in, ISG, …)
- Classification by functionality/power level (micro, mild, basic/strong, full)
- Classification by topology (parallel, series, complex/power-split)

The first two, classification by technology and characteristic component, are generally quite fuzzy due to their brevity. A clearer description can be given by a combination of the latter two, classification by functionality/power level and topology.

Usually all definitions of hybrids consider the driveline, but not the other major power consumer in a wheel loader – hydraulics. In the following, examples are given for the equivalent hybrid system in the hydraulics domain, compared to the better-known driveline setups:

- Conventional system
  A conventional drive train in a wheel loader is mechanically connected to the engine, possibly via a clutch or torque converter.
  A conventional hydraulic system is also mechanically connected to the engine, possibly via a set of gears in a power take-out (PTO).

![Figure 9. Conventional systems (drive train and hydraulics)]
• **Parallel hybrid**
  The driveline is enhanced by one electric machine which is mechanically connected to the engine crankshaft and which can either supply torque in parallel to the engine or act as a generator.
  The same electric machine can also support in driving the hydraulic pumps.

![Figure 10. Parallel hybrid systems (driveline and hydraulics)](image)

• **Series hybrid**
  In its simplest form, a series hybrid driveline features one electric machine mechanically connected to the engine crankshaft ("generator") and another electric machine mechanically connected to the driveline ("motor"). There is no mechanical connection between driveline and engine, the power flow from engine is passing the electric machines where it is converted to electrical power and then back to driveline as mechanical power.
  The naïve series hybrid hydraulic system simply consists of electrical driven pumps.

![Figure 11. Series hybrid systems (driveline and hydraulics)](image)

However, using electric machines to drive these systems usually opens up for radical new possibilities in system design, as well as system size (downsizing) and system control. For a driveline, this could be integration of the electric machines directly into the wheel hubs [9]; and for hydraulics, one natural path of evolution could be towards pump-controlled “valveless” systems [10].

• **Complex hybrid (power-split)**
  A power-split hybrid driveline can be seen as a combination of parallel and series hybrid. There exists both a mechanical connection between engine and driveline, realised by means of a transmission and an electrical connection via
two electric machines. The amount of power to be transferred either way can be chosen according to the current situation. This offers the possibility to combine the advantages and to avoid the disadvantages of above mentioned topologies.

Power-split hydraulics can in principle be seen as conventional hydraulics with electrically driven boost pump. But it might also be designed so that both the engine-driven pump and the electrically driven pump share the generation of hydraulic power in a larger time frame.

![Figure 12. Complex hybrid systems / power-split (driveline and hydraulics)](image)

Also here, much more sophisticated designs than above displayed naive sketches are possible. The common ground is some sort of summation device, be it a transmission, valve system, or the implement to be affected (e.g. the road for a driveline or the loading unit for wheel loader hydraulics).

Combining all the variants, we find a matrix of hybrid system possibilities (Figure 13). Some combinations are not drawn because they are not logically possible: if e.g. a series hybrid driveline is installed, then naturally any installed conventional hydraulics is automatically a parallel hybrid because the electric machine connected to the engine is at the same time also connected to the hydraulic pumps.

### 2.3 Holistic approach

The challenge is to find the right hybrid topology that offers reduced fuel consumption to a reasonable cost. Wheel loaders are versatile machines and used in various applications. Thus, one hybrid topology might show significant energy savings in one application but not so in another. The chosen hybrid loaders should also have a high degree of commonality with its conventional counterparts and preferably within AB Volvo – thus using effects of scale to keep the cost increase to a minimum.

However, the first steps in the conceptual design phase consist of exploring the total design space without limitations on cost, performance etc. Here, the task is to establish technical boundaries, rather than commercial or strategic ones.
Figure 13. Combination matrix of hybrid topologies
For conceptual design of a hybrid wheel loader, this means to evaluate each combination shown in Figure 13 against available background knowledge (as briefly presented earlier). From this we gather that diesel engine, hydraulics and driveline are rigidly coupled which means that neither can work efficiently, independent of the others. An analysis of how much power is consumed over a short loading cycle, and when and by what system, leads to the conclusion that a lot of unnecessary losses in both driveline and hydraulics occur due to this coupling.

These losses are mostly not inherent to either driveline or hydraulics; they are not caused by these systems alone, but occur because the systems have been chosen to get coupled in this rigid way.

Looking at the total amount of engine power consumed in a short loading cycle, one also sees that on average only a little bit more than just half of installed peak engine power is consumed. This means that in this situation, a much too large engine is installed. This, of course, is due to the requirement of satisfying the sum of driveline’s and hydraulics’ momentary power demand at all times, which is approximately twice the average power demand.

If a large energy storage was available, then the engine could be run at only the average power. For smaller energy storage capacities, the engine could at least be run more phlegmatic, meaning that it does not have to follow the power demand right away but can use the energy storage as a buffer instead, so that the high-frequent transients will be satisfied via the energy storage, while the lower-frequent load waves will be met by the engine itself.

Such reasoning, as e.g. in done [11], would lead to the recommendation of a series hybrid topology. In short loading cycles, extreme fuel savings of up to 50% could theoretically be achieved.

However, considering other working cycles with a larger amount of transport (e.g. so-called Load & Carry cycles), the series hybrid’s higher efficiency in transient situations might no longer compensate for its lower efficiency in steady-state operation. Then, a parallel hybrid solution might be better.

Considering only technical possibilities and neglecting commercial issues, the undecided might even opt for a complex or power-split hybrid, which would make a certain adaptation possible.

And finally, taking into account that up to 40% of a wheel loader’s time can be spent with the engine idling, the particular choice of hybrid topology may become a minor issue as long as the engine can be shut off during idling and a quick restart can be provided.

For almost each combination in Figure 13 a favourable wheel loader application and a corresponding working cycle can be found. The different hybrid variants of course show different potential in various situations, but almost no combination can be ruled out by looking at the technical boundaries alone. This is where the commercial and strategic aspects come in, ranging amongst others from cost and reliability to serviceability and safety.
For a customer of construction machinery, the most important aspect is total cost of ownership (TCO), of which fuel cost amounts to approximately one third. Obviously, lower fuel consumption has a direct positive impact on TCO. However, the machine is always part of a production chain, which means that every time the machine is not available, the customer’s TCO is affected in a negative way – sometimes drastically e.g. if one is a sub-contractor and contract fines have been negotiated. For certain customers, the benefit of potentially lower TCO due to lower fuel consumption might not outweigh the risk of potentially higher TCO due to reliability issues, even though such issues might only be perceived and will never occur.

3 The L220F Hybrid wheel loader

To find a satisfying solution to the considerations above, Volvo has chosen to base its first hybrid wheel loader as close as possible on its conventional counterpart L220F with a proven reliability. The selection of a parallel hybrid topology not only lends a certain redundancy to the total system, but made it also possible to use components from AB Volvo’s common hybrid platform (Figure 14).

![Volvo L220F Hybrid](image)

Figure 14. Volvo L220F Hybrid

Depending on operator and working cycle, fuel consumption can be reduced by ~10%. This is achieved by three measures:

Firstly, the electric machine can boost the drive train with up to 700Nm from standstill, or with up to 50kW above the electric machine’s base speed. Volvo CE has always designed its engines with high torque at low engine speeds, but with the additional in-
stantaneous torque from an electric motor, operators can get even better engine response which enables and encourages driving in a lower speed range. This in turn leads to lower losses in the driveline, and thus lower fuel consumption.

Secondly, the engine can be shut off when idling. The electric machine allows a rapid restart of the engine as soon as needed.

And thirdly, the AC compressor is driven electrically, which not only enables better control independent of engine speed (and thus saves energy), but it is also a necessity in order to get customer acceptance for engine shut-off during idling.

Naturally, development of hybrid construction machinery will continue at Volvo and will lead to more future improvements, both evolutionary and possibly also revolutionary by employing other system topologies. But for wheel loaders, the first step is taken with a concept that allows for higher efficiency and economy, without a reduction in reliability.

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http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-15588


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