Estimation of the potential in predictive control in a hybrid wheel loader

Bobbie Frank[+*], Jochen Pohl[+] and Jan-Ove Palmberg[+]

[+]Department of Management and Engineering, Linköping University, S-58183 Linköping
[*]Volvo Construction Equipment, Eskilstuna, Sweden
bobbie.frank@volvo.com

ABSTRACT

In this paper the potential of predictive control in a hybrid wheel loader is estimated using related research results as a basis. The application of hybrid technology to a wheel loader application is discussed and differences between on-road vehicles and wheel loaders are clarified. The main part of the related research has its focus on on-road vehicles where the usage patterns are more coherent to a greater extent than for a wheel loader. The challenge with the design of hybrid technology for a wheel loader lies in the large variety of applications, ranging from more or less standardized loading cycles to material handling and transportation of goods. It is stated that a wheel loader during transportation is close to a typical on-road application. A line of arguments is presented which conclude that it should be possible to reach up to around 10% fuel savings using predictive control in a real wheel loader in a real application. However, much work remains to be done, for example on cycle definitions, high-level and low-level predictive controllers, and signal analysis before this point is reached.

1 INTRODUCTION

Increasing fuel prices, decreasing oil reserves and the desire of many western governments to reduce dependency on oil have led to accelerated development of fuel-efficient vehicles. Greater fuel efficiency can be achieved through a number of technologies, of which hybridization is one.

The introduction of hybrid drivetrains began with small cars in the mid-1990s, continued with larger SUVs in the early 2000s, and buses and distribution trucks are now being launched by several large manufactures. An obvious follow-up is of course to also implement this hybrid technology in off-road vehicles such as construction machinery.

Many control engineers have been tempted to develop optimal control strategies for different hybrid vehicles with different hybrid configurations due to the greater degrees of freedom offered by a hybrid vehicle in comparison with conventional vehicles. However, most of the work that has been done is limited to on-road vehicles, which are discussed in section 2. Traces of this can be seen all over the world in research findings.

The major contributions in this paper are to establish whether the work done and the methods developed for on-road vehicles such as cars, trucks and buses can be used in a construction machinery application and to estimate the potential of predictive control in a hybrid wheel loader compared to on-road applications.

The focus in this paper is on wheel loaders but the line of argument can also be extended to other construction machinery such as articulated haulers and excavators. The reason for choosing the wheel loader was that in a normal wheel loader application both the hydraulic system and the drivetrain are used extensively. However, in an excavator almost all the work is done by the hydraulic system and in an articulated hauler by the drivetrain. It should therefore be possible, in the area of predictive control, to consider the excavator and articulated hauler as special cases of a wheel loader operating in extreme applications that consume little energy from the drivetrain or hydraulic system respectively.

The outline of the paper is as follows: section 2 discusses related research; section 3 describes the wheel loader application; section 4 discusses an estimation of the potential of predictive control in a wheel loader, and section 5 concludes the paper.

2 RELATED RESEARCH

The potential of predictive control in on-road applications is commonly assessed by first carrying out an optimal control study [1], [3] and then, from this, drawing the conclusion that this is as good as it can be, and with the help of predictive control only a part of this potential can be realized. Work done on the application of optimal control is therefore also discussed in some extent in this chapter.

The presence of many degrees of freedom in fuel consumption optimization for hybrid drivetrain makes optimal control methods an interesting choice for drivetrain energy management. Much effort has therefore been put into optimal control, such as dynamic programming and cost-function minimization, but also in predictive control, which is a natural continuation of optimal control. This is due to the fact that in many optimal control investigations the future is assumed to be known.

The most comprehensive and interesting work that has been found is presented in [2], [3], [4], [5], [6], [7] and [8]. In this chapter, the most relevant parts of these research papers, regarding predictive control in a hybrid wheel loader, are discussed. Section 4 presents a more extensive discussion of whether the methods presented in this section are applicable in the wheel loader application and what fuel savings should be expected in the wheel loader application compared to the work done in the research papers presented in this section. All the research papers except one, [8], focus on on-road applications such as cars, trucks, and buses.

In [8] Thuring investigates the possibility to implement model predictive control in a hybrid excavator where the swing function is driven by an electric machine. The model predictive control tool used is a Matlab toolbox called MPCtools, developed at Lund Institute of Technology. This is freeware that is primarily intended for research and teaching but is free to use for any purpose [9]. The conclusion in [8] seems to be that model predictive control ought to be a good approach in a hybrid excavator and should give positive results regarding fuel savings, but due to the complexity of the system in a hybrid excavator and the fact that the Matlab toolbox used was not designed for such large and complex systems, the prediction horizon was not large enough to make a really serious evaluation of the fuel saving potential using model predictive control.

In [1] and [2] Johannesson investigates the fuel saving potential using predictive control in a parallel hybrid city taxi. The controller, that minimizes fuel consumption, is derived using stochastic dynamic programming and the future operation is modeled as a Markov process using recorded data from real life recordings in Gothenburg, see Figure 1.

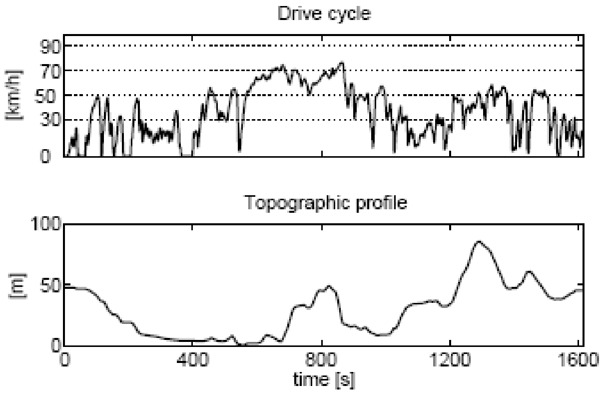


Figure 1, The drive cycle and the topographic profile used in the simulations.[1]

Robustness studies of the controller are also made in respect of driving cycles by cutting up and randomly connecting the real life recording and then simulating. Johannesson compares a "standard" controller with the predictive controller and also the differences between when the predictive controller knows the whole route and when it is only partially known. The main focus is on how to use GPS and navigational information to plan the buffer usage. Here, the conclusion was that only "average" information about the route was needed; however, the topology profile of the route was essential. The size of the buffer also had an effect: a significantly smaller electrical energy storage system resulted in the prediction becoming more important. A concluding remark was also that due to the curse of dimensionality in dynamic programming, many simplifications had to be made which may have resulted in a suboptimal controller. When simulating, the fuel consumption reduction potential using predictive control in a parallel hybrid city taxi seems, however, to be around 5% according to Johannesson.

In [3] Ottosson investigates the fuel consumption reduction potential between an optimal controller compared to a heuristic controller in a parallel hybrid car with a rear wheel drive unit. The line of argument is that the optimal controller achieves the lowest possible fuel consumption and thereby constitutes the lower limit for fuel consumption regardless of the type of controller, including a predictive one. The optimal controller is based on dynamic programming which uses power demand as input to the optimization of the power split between the internal combustion engine and the electric machine. When simulating the NEDC and US06 driving cycles, Ottosson seems to come to the conclusion that the fuel consumption reduction potential for the optimal controller compared to the heuristic controller is round 7-9% for a parallel hybrid car with a rear wheel drive unit.

In [4] Hellström investigates the potential fuel savings using look-ahead control in a heavy truck. Look-ahead control is a predictive strategy using dynamic programming, GPS, and altitude maps. The boundary conditions in the study are that the heavy truck using predictive control should drive the same distance in the same time as an ordinary heavy truck. Hellström has tried his algorithm in a real life demonstrator and the fuel consumption for the heavy truck using predictive control appears to be approximately 3.5% lower than for the ordinary heavy truck while driving the same distance in the same time. Another positive side effect is that the number of gear shifts is reduced by around 42%. Hellström also shows good conformity between simulated results and real life measurements.

In [5] Persson and Lundberg investigate the fuel consumption reduction potential between an optimal controller compared to a heuristic controller in a parallel hybrid city bus. An attempt is also made to get the heuristic controller to mimic the optimal controller. When simulating CBR85, the optimal controller seems to show a potential fuel saving of roughly 3.5% without an optimizing gear shift strategy and up to 12% when a gear shift strategy is implemented. When simulating the heuristic controller that mimics the optimal controller the approximate reduction in fuel consumption of 3.5% falls to about 2%.

In [6] Beck, Bolling and Abel show two different optimal control strategies when using predictive control in a parallel hybrid car. The most important results from this paper are that even between two optimal strategies the fuel consumption can differ up to approximately 3.5%. This figure of course also varies with the prediction horizon.

In [7] Kim, Manzie and Watson investigate potential fuel savings by means of look-ahead control in a mild parallel hybrid car using telematics. This system includes vehicle-to-vehicle communication and modifies the driver’s demands such as demanded velocity in order to create an intelligent vehicle. When simulating the mild parallel hybrid car on the Australian urban cycle with a prediction horizon of 150 meters, the conclusion seems to be that this look-ahead intelligent vehicle system can reduce fuel consumption by around 9% compared to an ordinary mild parallel hybrid car.

The research papers outlined above were chosen to represent a much larger population of the research work done on predictive control in general and in the automotive sector in particular. They were chosen for their relevance, novelty and coverage. It seems that most of the work done in the area of predictive control in the automotive sector focuses on solving the prediction, or optimization, problem using external signals such as GPS, 3D maps, vehicle-to-vehicle communication, or other navigational information that more or less reveals the route ahead. A controller can thus be designed on knowing the route ahead, with the exception of some stochastic “deviations” such as, for example, traffic lights, congestion, road works, weather conditions, etc.

3 THE WHEEL LOADER APPLICATION

The wheel loader is a construction machine with the primary task of load handling and the secondary task of transporting loads, see Figure 2. This is in contrast to on-road vehicles whose primary task is restricted to the latter, viz. the transportation of goods or passengers. The sooner one can reconcile with the notion that the wheel loader is more like a tool than a vehicle the easier it is to see how complex this working machine really is.

Figure 2, a wheel loader loading an articulated hauler.

In this section the focus is on showing in broad outline what a wheel loader is, how it is used, and how the subsystems in a complete wheel loader interact.

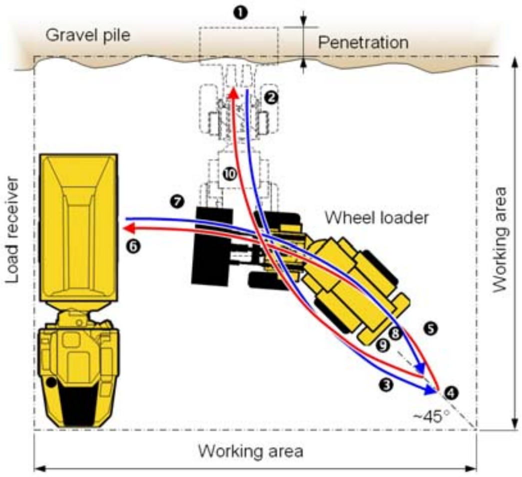
As mentioned above the wheel loader is a working machine. What is special in the wheel loader application in comparison to other construction equipment, is that the wheel loader has tremendous adaptability due to the versatility of the attachment bracket, and is therefore used in a large number of applications. The work carried out by wheel loaders ranges from loading different materials into or onto load receivers, pallet and block handling, and log handling to various support and cleanup functions, see Figure 3.

Figure 3, various wheel loader applications.

It is easy to assume that a machine as versatile as a wheel loader would be almost impossible to predict since in addition to the many different applications and materials handled, which affect the load on the hydraulic system, it is also an off-road vehicle, which means that the machine works on different ground conditions which affect the traction ability of the driveline. However, this is a false assumption because most wheel loaders, at least the larger models, have a fairly uniform working behavior due to the fact that they are often part of a production chain. Take, for example, loading a load carrier in a mining application; the wheel loader can then be part of a production chain where granular material is transported up from the mine on a conveyer belt and the wheel loader loads it onto a transport carrier which then transports the material to a processing plant, see Figure 2. In this example it should be fairly easy to identify some kind of cyclic behavior because the granular material comes from a belt and ends up in the same place all the time, the transportation stops, more or less, in the same place every time, and it is usually the same kind of transportation, which means that it takes the same number of buckets to fill the transporter each time. The example does not take into account things like cleaning up the yard and breaks for the operator, but except for this there are applications that are just as predictable. There are of course also applications, especially among the smaller wheel loaders, that exhibit no cyclic behavior whatsoever, for example support functions at a building site or a farm.

The belief is that by far the great potential of predictive control lies in the very repetitiveness of cycles, and identifying the cycles thus becomes an integral part of predictive control.

Going back to the example from the mining industry, when looking at a single load cycle from gravel pile to load receiver it is highly likely that it will be a so-called short loading cycle, see Figure 4. If so, it can be divided into ten different phases [10] as shown in Figure 4 and a more detailed analysis of the cyclic behavior can be made.



❶ Bucket filling
❷ Leaving bank
❸ Retardation
❹ Reversing
❺ Towards load receiver
❻ Bucket emptying
❼ Leaving load receiver
❽ Retardation and reversing
❾ Towards bank
❿ Retardation at bank

Figure 4, schematic short loading cycle [10].

The distances and loads can of course also be adjusted in each phase which means that even if two different full cycles appear to be completely different, they can both be described using the phases in Figure 4 even if some phases are not present in some applications. Most of the applications, at least the ones with cyclic behavior, can therefore be described using this method. This opens up for prediction on two levels: a cycle-dependent prediction which controls cyclic behavior and a phase-dependent prediction with a very short prediction horizon that controls what happens in that particular phase.

To be able to make some kind of analysis of a working wheel loader, one must know what is really going on in and between the different subsystems when the machine is working.

The illustration to the left in Figure 5 shows a schematic picture of the main subsystems in a wheel loader, that is, the drivetrain and the hydraulic system. The definition of drivetrain here is from the torque converter to the wheels, through the transmission and axles. The definition of the hydraulic system is from the hydraulic pumps to the loading unit, for example a bucket, through valves and cylinders that move the lift and tilt. The hydraulic system also provides power to the steering and the cooling fan but these loads are often small in comparison to lift and tilt and are therefore not included here.

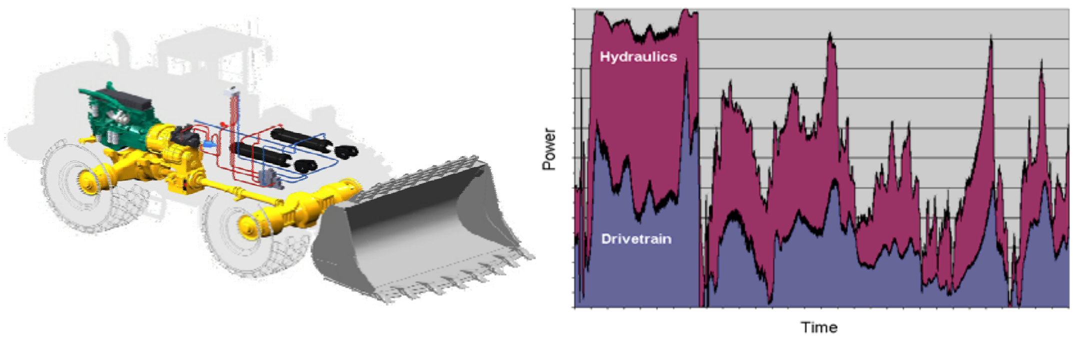


Figure 5, a schematic picture over the subsystems in a wheel loader and the power outtake for each of them in a short loading cycle [10].

What is interesting to notice in the illustration to the right in Figure 5 is, first, of all the very transient behavior of the power outtake from the internal combustion engine, this is the upper curve in the graph and the x-axis is in seconds; second, the fact that that in the bucket filling phase more or less all the power that the internal combustion engine can provide is consumed; and, third, the complex interaction between the drivetrain and the hydraulic system. Another interesting hint that may be considered is that even if the output power of the internal combustion engine appears to be too low in certain areas the average power outtake is around sixty percent of the maximum. Using predictive control in a hybrid wheel loader, it seems that it would be possible to assist during the power intense phases and simultaneously downsize the internal combustion engine, thus saving fuel.

The reason why the power outtake is so transient is that the operator often has to balance the power outtake between the hydraulic system and the drivetrain [10], where the bucket filling phase constitutes the most challenging part [11]. Figure 6 shows how the driver does this. The whole problem originates from the fact that there is a hard coupling between the internal combustion engine and the drivetrain and the hydraulic pumps via gears, and then when penetrating the gravel pile a hard coupling occurs via the gravel pile as shown in the right-hand sketch in Figure 6. This results in the operator having to perform a balancing act every bucket filling phase, otherwise the internal combustion engine will overload itself resulting in engine stall and shutdown. This could be avoided with a good predictive control.

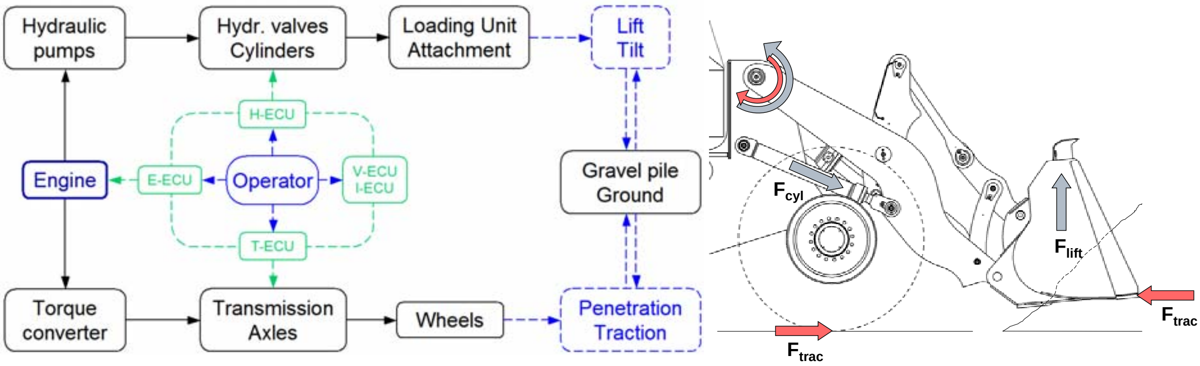


Figure 6, (left) a schematic scheme over the power balance in a wheel loader and (right) how the drivetrain and hydraulic system forces counteract each other in the bucket filling phase [10].

An interesting observation in this context is that even if this balancing phenomenon only appears to occur in the bucket filling phase, it can also be observed in other phases. For example, the reversing from bank phase is very demanding on the wheel loader due to the fact that the internal combustion engine is running at low revolutions because the operator does not want to reverse at high speed, but the hydraulic system is at the same time loaded by lifting a full bucket of gravel, which will easily kill the internal combustion engine if the operator is not careful [10].

In summary, it should be clear that a wheel loader is a complex system to control in an optimal way but there are interesting areas to look at when evaluating predictive control.

4 PREDICTIVE CONTROL IN A WHEEL LOADER

To be able to estimate the potential of predictive control in a wheel loader with the starting point in the related research in section 2, it is important to know the differences between an on-road vehicle such as a bus, truck or car, that most of the research has been done on, and an off-road machine such as an excavator, articulated hauler or wheel loader. The wheel loader was chosen to represent the off-road machines due to its complexity, which means that some of the reasoning in this section may be specific to wheel loaders but much of it should also be applicable to other construction equipment.

Whilst the differences are many, the similarities between an on-road vehicle and a wheel loader are surprisingly few, often being merely that both have wheels and, at least conventionally, an internal combustion engine as the primary energy converter. While there are many obvious differences regarding size, weight, wheel radius, maximum speed, load capacity, and so on, the focus in this chapter will be on comparing the use, that is the load/drive cycle, of the on-road vehicle and a wheel loader. This because the load/drive cycle pattern is the most important aspect to analyze when estimating the potential of predictive control.

The obvious differences in load/drive cycle can be seen merely by comparing an ordinary driving cycle in an on-road vehicle, for example the city taxi driving cycle in Figure 1 that Johannesson used when assessing the potential of predictive control in a city taxi, with a regular short cycle such as the one mentioned in chapter 3 and illustrated in Figure 5. Bear in mind that every tick in the short loading cycle in Figure 5 is one second, making a total of about 30 seconds, while the city taxi driving cycle in Figure 1 totals around 1,600 seconds. When analyzing these two load/drive cycles there are some important things to realize:

The first is the much more transient behavior in the short loading cycle. This means that the internal combustion engine in a wheel loader lives a much more nervous life than one in an on-road vehicle. The on-road vehicle often travels greater distances at more or less the same speed and when transients occur, in the form of slopes or changes in traffic conditions, the time between each transient is far longer than in the wheel loader, which works more or less transiently all the time. Also, when comparing load cycle on the internal combustion engine, a typical car spends much of its time at medium load while in the wheel loader application much of the time is spent at high load and maximum power outtake, see Figure 7.

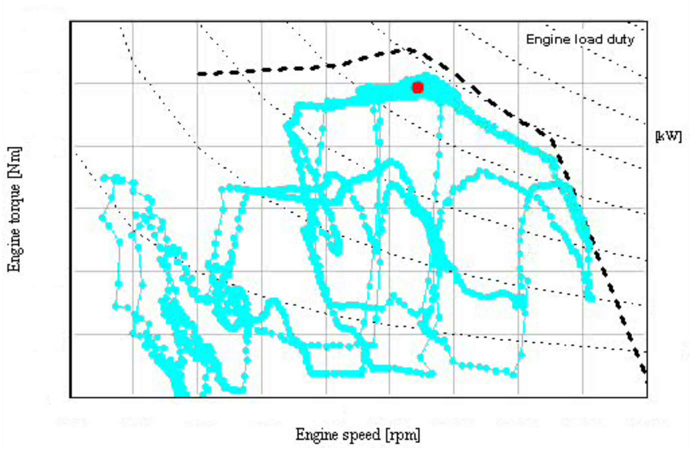


Figure 7, typical load cycle of the internal combustion engine in a short loading cycle.

This means that in some situations in a hybrid wheel loader where torque assist is available, it could be advantageous to allow the driver a higher power outtake than the internal combustion engine alone can provide. However, to do this and still have a repetitive machine the energy needed in the torque assist needs to be known and for knowing this prediction is essential. Much of the reason why the internal combustion engine has such a completely different load cycle in a wheel loader compared to an on-road vehicle, both as regards transients and the high load, is that a wheel loader has two consumers, the drivetrain and the hydraulic system, as explained in chapter 3, while the on-road vehicle only has one, the drivetrain.

The second is the cycle time and what the following load/drive cycle looks like. In most on-road vehicles such as cars and most trucks the next “cycle” is unknown and in most cases completely different from the previous ones regardless of the length of the cycle. However, there are exceptions in the on-road vehicles such as buses and distribution trucks which drive the same route over and over again. These vehicles often have similar cycles, with the exception of traffic situations, following each other. However, the main issue in these vehicles, if they are hybrids, is that the long cycle times make it difficult to optimize over a complete cycle when, for example, sizing energy storage systems or establishing a prediction horizon. Parts of the cycle are therefore sub-optimized instead. In the wheel loader, however, the cycle length is short enough to both perform component sizing and make a prediction over the complete cycle. This means that in addition to the sub-optimization done in on-road vehicles, a complete cycle optimization can also be done in a wheel loader. Many of the larger wheel loaders are also a part of a production chain, as described in section 3, which means that the following cycle often looks much the same as the previous one, with the exception that the gravel has to be picked up in a slightly different position each cycle and the load in the bucket may vary somewhat from cycle to cycle. If only working time is taken into account, which means that for example idling is not accounted for but only the time the machine actually works, typically around three-quarters of the time, depending on the application of course, can be repetitive. The complete cycle optimization can then often be more or less spot-on, which means that a prediction of the cycle and an optimization of the control algorithm should be much more valuable in the wheel loader application than in an on-road vehicle.

A more practical difference between an on-road vehicle and a wheel loader is that whilst on-road vehicles can use external signals such as GPS, 3D maps, vehicle-to-vehicle communication, and other navigational information, a wheel loader must rely on internal signals from the vehicle/machine itself, which makes the prediction task more of a challenge.

So what is the essence of predictive control in the case of a wheel loader and where are the major energy savings to be expected?

As opposed to on-road vehicles, the name of the game in a wheel loader is complete cycle optimization which also includes complete vehicle/machine optimization and of course component optimization specific to the wheel loader application. This means that while it is acceptable to sub-optimize, for example, electrical energy storage usage in the case of regenerative braking, because this is by far the most important source of fuel savings in an on-road vehicle such as a car, bus or truck, the primary source of fuel savings is much harder to detect in the wheel loader application, which results in a need for a complete vehicle/machine optimization and the complete cycle optimization is then merely a result of the need to perform a complete vehicle/machine optimization.

The benefit of predictive control is closely related to the type of machine/vehicle, the exact drivetrain configuration and sizing in combination with the operating/driving cycle. While some drivetrains do not require predictive control in order to achieve maximum fuel efficiency, others do. The main reason for this is the energy storage size. One example is if the energy storage is too small or too large; if the energy storage is too small it is very likely that it will be empty when regenerative energy, such as braking and lowering loads, is available, and if the energy storage is too large there will probably be storage capacity left. In both cases predictive control does not have that much to contribute when focusing on fuel consumption reduction. The design and sizing of the hybrid system must therefore be taken into consideration in order to understand how predictive control can be utilized.

In answer to the question of whether the methods developed for on-road vehicles can be used in the wheel loader application, some should be applicable but would only give some kind of sub-optimization if used alone and would probably give less fuel savings than if complete vehicle/machine optimization could be done. To be able to do this it will probably be necessary to implement a “high-level” and a “low-level” in the predictive controller. The “high-level” predictive controller will take care of the cycle-to-cycle predictions, that is, identify some kind of cyclic behavior with a specific spread; this will be the equivalent of the complete vehicle/machine optimization. A “low-level” predictive controller will take care of all situations in which cyclic behavior is could not be identified; this will be the equivalent of the sub-optimization found in on-road vehicles.

The high-level controller thus becomes machine type dependent, i.e. wheel loader, articulated hauler or excavator, while the low-level controller becomes hybrid concept dependent. The high-level controller thus changes the detailed optimization criteria of the low-level controller. The machine operates according to the nominal optimization criteria if cyclic behavior cannot be established by the high level controller. This modular controller structure has a number of advantages when it comes to large numbers of product variants. Controller modularization into separate levels enables reuse of function components and test and verification activities are kept to a minimum.

Now that the differences between an on-road vehicle and a wheel loader have been established and what has to be done in a different way as regards predictive control in a wheel loader compared to an on-road vehicle has been determined, at least through reasoning, it is also easy to say that it is not obvious how the results from on-road vehicles should be related to potential results in the wheel loader application. However, the fact is that a large wheel loader often has a cyclic behavior and that it is also possible, due to the often short cycle times, to perform complete cycle optimizations and these two facts together mean that full day optimizations are possible in a more extensive way in the wheel loader application then in the on-road vehicles. For this reason alone the fuel saving potential in a wheel loader application should be greater than in the on-road vehicles, alongside that, actions that are much more difficult to determine such as easier bucket fill etc. should also contribute to lower fuel consumption. Taking only the “high-level” / “low-level” reasoning into account where, more or less, complete day predictions/optimizations should be possible it not unlikely that a reduction of approximately 10% could be achieved in a real application, or almost the double the figures presented in section 2. The main reason for this is the ability to fully predict the future, with a spread of course, which means that the figure is only valid for a wheel loader that is a part of a production chain or similar. If the future is known, from prediction made possibly by cyclic behavior, it should be possible to implement more or less optimal control in the wheel loader. The reason why the fuel consumption savings in a wheel loader with an optimally controlled hybrid drivetrain should be greater than in a on-road vehicle is due to the hard couplings and high load cycles mentioned in section 3. This is because the known future should be able to involve different power outtake limitations and internal combustion engine and other components being able to be optimized to a greater extent than in a much less complex on-road vehicle. In addition to the fuel savings, there should also be a significant possibility to save on the initial cost of the hybrid drivetrain since the electrical energy storage system can be sized rather than oversized. This means that the payback for the customer is attacked from two directions using predictive control, making hybrid wheel loaders a more viable production solution.

5 CONCLUSION

The main conclusion is that due to the large differences between on-road vehicles and wheel loaders it is very difficult to make a complete evaluation of the potential in predictive control in a wheel loader. However, after some reasoning the conclusion is that it should be possible to achieve savings up to approximately 10% in a real application. This is because it should be possible to perform full day optimizations in some wheel loader applications whilst in an on-road application a sub-optimization is necessary because most on-road vehicles do not have cyclic behavior and the few that do have a very long cycle time. However, much work remains to be done before this potential can be realized, mainly because much more work is needed on the predictive controller for the wheel loader application. More about this can be found in section 4.

6 FUTURE WORK

As this is the very beginning of a research project there is of course a lot of work that needs to be done. Some of the things already encountered that seem crucial for the continuation of the work on predictive control in hybrid wheel loaders are:

- Cycle identification, that is, determine a certain number of typical cycles, define a spread, and adapt data so that a predictive controller can use it as a base when predicting the future to be able to control the hybrid drivetrain to achieve optimal fuel consumption and component wear.

- Define, create, and implement the “high-level” and “low-level” predictive controllers so that they co-operate well and that the “high-level” can control as much as possible because this is the one that has the knowledge of the future.

- Determine what signals that are suitable to use in a predictive controller and make those signals work.

- Test the predictive controller in a real wheel loader in real applications at customer sites.

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