ON INCREASING FUEL EFFICIENCY BY OPERATOR ASSISTANT SYSTEMS IN A WHEEL LOADER.

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Abstract: The main focus of this paper is to estimate the potential increase in fuel efficiency and productivity by means of an operator assistant system, in a wheel loader working in a bucket application in a production chain. This is done based on an empirical study. A line of argument is presented on how to go from the empirical study to theoretical optimal control of a wheel loader. A suggestion of the human-machine-interaction is also presented. Fuel efficiency (ton/l) increases of 20-40% and productivity (ton/h) increases of 40-80 % are expected.

Key words: Wheel loader, fuel efficiency, operator assistant system, construction machines, operator feedback, HMI.

I. BACKGROUND

A couple of hundred thousand wheel loaders are sold all over the world each year. Due to the fact that the wheel loader is a quite versatile machine many of them are sold as multi-purpose machines but more than half of them are so called production machines. These production machines are specialized in one particular task, often some sort of bucket application, and part of a larger production chain, in for example an open pit mine or quarry. This means that uptime, productivity, fuel efficiency and operability are key features [1] to be able to solve the specific work assignment as quick as possible to the lowest possible cost per ton loaded material.

The fuel cost, for a wheel loader working in a production chain, represents roughly 30-60 percent of the total cost of ownership, in $/ton loaded material, depending on market. This implies that fuel efficiency is an important aspect when purchasing a wheel loader. However, often productivity is equally, or more, important. This is because if the production rate can’t be held the whole production on the site slows down, resulting in expensive loss of income. This is why the productivity always has to be accounted for, even when the main focus is on fuel efficiency.

The fuel efficiency and productivity of a production machine wheel loader in a bucket application mainly depends on three major aspects; the machine specification, the working environment and the operator behaviour.

• The fuel efficiency and productivity due to the machine specification can be affected in three main ways;
  I. Using a correctly sized machine, not too small to solve the work assignment but not too big with unnecessary overcapacity [2].
  II. Using appropriate attachment, especially bucket and tires is important.
  III. Increase the base machine efficiency, meaning the efficiency of the wheel loader itself, which is not only the sum of all the components in the wheel loader but also the system efficiency. This cannot be affected by the customer and is something the OEM’s are working hard to increase [3,4]. Simply because it is a major competitive advantage to have a wheel loader with high fuel efficiency and productivity.

• The working environment, the site layout and the planning of the site are also important to ensure maximum fuel efficiency and productivity. The site planning is mostly done by the customer but sometimes the dealer [5] or an external company either give education [6] or help planning the site.

• Last, but not least, [7,12] is the operator behaviour. During the working life of a wheel loader the operator, together with the assigned work task, affects the fuel efficiency and productivity the most after the machine has been chosen and the site is planned. The traditional way to address the fuel efficiency and productivity difference due to operator behavior is operator training such as the Eco Operator® training, or equivalent, [8,9]. Here a trainer coaches the operator during a number of days, providing tips and tricks to increase the fuel efficiency and, if necessary, the productivity. A simpler alternative is to distribute manuals [10] from where the operators can get some tips of operating the wheel loader in a more efficient way.

This means that the machine specification and the working environment are more subjects for optimization in the
beginning, when planning a site, while optimizing the operator behavior is a continuous undertaking.

It can be considered established within the construction industry that the operator plays a vital part regarding fuel efficiency and productivity [7,12]. Presumably, once the work assignment is set and the machine and the working environment has been configured, the operator affects the fuel efficiency and productivity of a wheel loader the most [11]. The fact that the operator have a high impact on the fuel efficiency and productivity becomes very clear when looking at Figure 2, realizing that the operator is in the middle of the control loop while trying to solve the specified work assignment [12,13]. Hence this is why the focus in this paper is on finding ways to help the operator to be as fuel efficient and productive as possible.

Figure 2. A schematic picture of the power balance and the control loop in a wheel loader during bucket fill [12,13]. ECU is an on-board computer.

II. INTRODUCTION

The main objective in this paper is to increase the fuel efficiency and productivity for wheel loaders, working in production chain, bucket application.

Referring to previous research regarding wheel loader fuel efficiency difference due to operator behavior distribution it is known that the operator plays a vital part when it comes to fuel efficiency and productivity. Differences between individual operators are as much as 200% regarding fuel efficiency and 700% regarding productivity [11]. Therefore a large potential should be in developing an operator assist system that helps all operators to be as fuel efficient and productive as the best operator. This means that instead of estimating the potential of predictive control, and other advanced control strategies, to around 10%, in a wheel loader, based on related research on on-road applications [14] the results of a more comprehensive empirical study, of a wheel loader, are reported in this paper.

Based on the differences in fuel efficiency and productivity due to operator behavior concluded in previous research [11] the results of an empirical study translates to a theoretical potential of an operator assist system based on optimal control, when it comes to know what to recommend to the operator via an operator assist system or performing automated functions in an optimal way, and pattern recognition [15], when it comes to predicting the future or adapting to the past. The line of argument is that if one operator is able to reach certain fuel efficiency and productivity it should be possible for all other operators to achieve the same.

This means that within the near future the operator training can quite possibly come to be complemented by more advanced algorithms in the wheel loader which helps the operator, in real time, to solve the work assignment as fuel efficient as possible with as high productivity as possible. This can be done in different steps, see Figure 3.

![Figure 3. Conventional to fully autonomous according to the HAVEit-project[16].](Image)

If the nomenclature in Figure 3, which originates from on-road applications, should be applied to a wheel loader it would mean that the machine functionality goes from a conventional to fully autonomous wheel loader according to;

1) A conventional wheel loader, where the operator does all the work; thinking, planning and controlling.

2) A conventional wheel loader with operator assist, meaning advanced algorithms help the operator to operate the wheel loader as fuel efficient as possible, for the production rate given by the operator. Through human-machine-interaction devices, such as head-up displays and haptic pedals/levers, the recommendations from the algorithms can be communicated to the operator.

3) A wheel loader with semi-automatic functions, such as cruise control and automated bucket fill where parts of the work cycle is done completely by the wheel loader itself at optimum fuel efficiency and productivity. Then the operator takes over and operates the wheel loader with operator assist systems, as in 2), in the rest of the work cycle.

4) A semiautonomous wheel loader, where no operator is involved in the work, once the work assignment is defined by the “system operator”, which handles several machines on remote control from an office.

However before deciding upon any automation level between “driver only” and “fully autonomous”, it has to be carefully considered which functions shall be performed by the machine and which shall be performed by the human operator.

In order to create trust in an automatic function, i.e. establishing the belief that by using the automation e.g. workload will be decreased or fuel efficiency will increase, it needs to be transparent to the operator. Ideally, the operator understands exactly the algorithm, scope and limitations of any automatic routine. However, due to the complexity of such functions, an understanding at this depth will hardly ever be the case but the OEM’s can make sure that the assistant system is intuitive in a way that the operator feels like the understanding is there.

According to [17], trust in automation guides people to rely on it in uncertain situations, even when the complexity of the automation makes a complete understanding impractical. But there is the risk that the operator either overtrusts the automation and therefore misuses it, or the operator
undertrusts the automation and therefore disuses it, as discussed in [17,18,19,20]. Both misuse and disuse are examples of inappropriate reliance on automation. Misuse refers to failures that occur when people inadvertently violate critical assumptions made by the developer of the automation used, while disuse refers to failures that occur when people reject the capabilities of automation [17,18,19]. An appropriate use of a system is facilitated by calibrated trust, i.e., trust that matches the system capabilities. As [17] argues, this could actually require an automatic function to be made more simple, rather than more complex. Hence this is why somewhere between 2) and 3) in Figure 3 is a good way of starting introducing these advanced operator assistant systems.

Making any automatic function adaptive to the situation at hand, for example activation of a certain level of assistance only when there is a need for it, has to be valued against confusion due to reduced predictability. This requires a consistent behavior, which seems to contradict the idea of supporting the human operator depending on the current need. A solution might be to offer aid at a few, distinct levels and inform the operator clearly on which level is enabled and what type of support will be given at that level. Once a certain support level has been activated, it should not be deactivated for a foreseeable period of time. It also seems appropriate to let the operator explicitly accept or deny this assistance, rather than just activating or deactivating it automatically.

III. METHODOLOGY

To be able to do an estimation of the potential fuel efficiency and productivity increase the results from an empirical study of operator behavior distribution is used [11]. The operators in the study are seen as a representative sample of the wheel loader operators worldwide. This is of course not true, however the impact on the results will be that the estimation will be rather conservative due to the fact that the probability that the best operator in the world has been part of this study is rather low.

To get the empirical study as representative as possible 80 operators joined the study, working for 20 minutes each. Four groups of operators, covering the complete range of experience, were included in the study: (1) novice operators that had operated a wheel loader for 2-10 hours, (2) average operators that know how a wheel loader works but do not operate wheel loaders as a profession, (3) internal professional operators who are evaluating wheel loader and/or working as test operators and/or demonstration operators and/or trainers at Volvo Construction Equipment, (4) external professional operators who are working every day operating wheel loaders in bucket applications as a profession.

To increase reliability and robustness in the results, and to investigate different degrees of difficulties in the bucket fill phase, three different bucket applications, see Figure 4, were investigated for every operator;

1. Short loading cycle, loading gravel onto a load receiver. This would be a typical re-handling application where processed material is loaded on out-going trucks from the site.

2. Load and carry uphill, loading gravel to a pocket. This is a longer cycle than the short loading cycle where the travel distance is not 10-15 m as in the short loading cycle but rather 100-150 m and the load receiver is exchanged to a hopper that is connected to a conveyer belt. This would also be a typical re-handling application where pre-crushed material is loaded into a hopper that, for example, via a conveyer belt feeds another crusher or sorting machine.

3. Short loading cycle, loading rock onto a load receiver. This would correspond to a face application where the wheel loader is loading blasted rock from face, similar to Figure 1. This corresponds to an application where the bucket is a lot harder to fill, meant to differentiate the operators a bit more than just loading gravel in which it is quite easy to fill the bucket.

![Figure 4. The three different applications measured. From the left; short loading cycle gravel, load and carry gravel and short loading cycle rock.](image)

During the measurements the most important task was to isolate the operator behavior as the sole source of deviations. This was done by using the same machine with the same equipment and same bucket and same tires in each application for all operators to minimize the machine specification dependence. The same calibrated gravel pile and simulated work site, and assignment, layout where used to minimize the working environment dependence. The same gravel was reused for all operators, in the hope that this would minimize the deviation in bucket fill easiness, hence also differences in fuel efficiency and productivity due to material and environment deviation. The material was worn a bit more than expected resulting in finer material than expected towards the end of the measurements for the gravel applications, however analysis showed that this had small impact on the fuel efficiency and productivity.

The reason why the isolation of the operator behavior is important is because the line of argument is that the estimation of the potential increase in fuel efficiency and productivity in an operator assist system can be based on the difference between operators. An operator assist system should be able to help all operators to be as good as the most fuel efficient operator.

The aim in this paper is set at 2) and 3) in Figure 3, meaning an assist system that recommend the operator with some operator overriding to partly automated functions. The reason why aiming at this level is due to the fact that the wheel loader is a versatile machine, doing a lot of different jobs on a worksite, resulting in that very few wheel loader can be replaced by fully autonomous machines, completely without operator.

IV. RESULTS

All the results are based on that the fuel efficiency and productivity are most important. The machine specification and the working environment are considered to be fixed for each and one of the three applications investigated. Hence
things like operability and work assignment are implicitly also fixed.

The results from “short loading cycle gravel” are shown as an example, however similar result could be seen in all three applications and the same reasoning is valid.

The main result with respect to fuel efficiency and productivity is that the difference between operators is very large. One operator can have five to eight times higher productivity than another, depending on application, while the difference between two other operators can be two to three times higher fuel efficiency, depending on application. The fuel efficiency and productivity distribution for all the operators in “short loading cycle gravel” are shown as an example in Figure 5. The other two applications had similar appearance.

![Figure 5. The fuel efficiency and productivity for all the operators in “short loading cycle gravel”. EP is the external professional, IP is the internal professional, IA is the average and IR is the novice operators.](image)

Interesting is that both fuel efficiency and productivity seem to have a more or less linear dependence of the experience, or skill level, of the operators, meaning that a straight line could be drawn in Figure 5. The closer an operator is to the up right corner, the more experienced operator. One exception is however the intensity measurement, the blue square at the far right in Figure 5, where the test operator was asked to stress the machine to an abnormally fast pace.

To be able to do an estimation of the fuel efficiency and productivity increase potential for the complete fleet of operators a trade-off curve is created, meaning the highest possible fuel efficiency the wheel loader can have at every specific production rate. This enables the possibility to do a comparison of any operator and the optimal point, given a specific productivity demand.

To get the trade-off curve, two approaches can be considered. Either the convex hull of all the operators’ averages in Figure 5 that will represent a Pareto front that is called the trade-off curve, or each and one of the operator’s individual cycles is plotted in the same plot and the convex hull from this is taken as the trade-off curve. Both are plotted in Figure 6. Due to some inaccuracy in the cycle detection algorithm a couple of outliers are excluded, however every outlier have a corresponding inlier meaning that the average results are valid. The outliers could however be avoided with better measurement equipment.

![Figure 6. All the operator’s individual cycles with the trade-off curves from the average cycles, “Mean”, and from the individual cycles, “Max”.](image)

The reasoning is that the “Max” trade-off curve, which is the modified convex hull for all the individual cycles, is the real trade-off curve per cycle for this specific wheel loader in this specific work assignment. Short loading cycle in gravel is shown as an example in Figure 6 but similar can be seen in the other two applications. These both approaches are under the assumption that the measurements has been done on infinite number of operators. Considering that this is not the case, the method still works and, as mentioned before, the only difference is that the estimations can be seen as a bit on the conservative side due to the fact that the probability that the best operator in world attended this study is very small. However important to mention here is that the fuel saving between these two curves that one might think is realistic for all the operators in this study is not really a reality since there are some difference between 1st, 2nd and 3rd bucket when loading onto a load receiver due to the positioning of the load when unloading the 3rd bucket. This means that the real trade-off curve on an average cycle is somewhere halfway between the two curves.

If the entire fleet of operators would operate the wheel loader at the point where the operator that had the highest fuel efficiency operated, the average fleet fuel efficiency would increase by 20-40%, depending on application. In addition to that the average fleet productivity would also increase 40-80%, depending on application.

From now on the operator with the highest average fuel efficiency is considered the best operator and called the “shadow operator”. The shadow operator can of course be chosen by other means, for example highest productivity, all depending on the work site demand. However in this paper the main focus is fuel efficiency hence the shadow operator is chosen accordingly.

Analyzing an example from the study mentioned in [11] where a total of 80 operators are compared against the shadow operator in 15 short loading cycles. The 80 operators consist of the complete range from professionals to beginners. For the complete cycle the results are shown in Figure 7.
Dividing the analysis in fuel efficiency and productivity to find out how to increase each and one of them a line of argument is presented for each of them below.

Regarding the fuel efficiency, most operators spend the majority of the extra fuel consumed compared to the shadow operator in the bucket fill phase, see Figure 8. This implies that to increase the fuel efficiency the bucket fill is where it is the most important to help the operator to be able to solve the work assignment in an as optimum way as possible. Luckily the bucket fill phase is a quite isolated incident that is rather suitable to do automatically; the operator gives the command and the wheel loader fills the bucket at the optimum fuel efficiency and productivity.

Figure 8. The difference in fuel used in a complete cycle and in the bucket fill phase for all the operators, comparing to the shadow operator.

To make a more detailed study one operator is selected, operator #47. The detailed results for this operator are reported in [21]. The accumulated fuel consumed during an average cycle is 13% higher, the bucket fill is 5% lower, and cycle time is 13% longer compared to the shadow operator. This means that fuel efficiency is 17% lower and productivity is 18% lower.

As in the general trend almost all of the extra fuel consumed by operator #47 is within the bucket fill phase. Also the bucket fill factor is lower. Looking into the data from the study presented in [11, 21] the main differences can be found. For this particular case it is mostly due to the fact the amateur operator pushes the bucket harder into the pile and fills it at lower bucket height. Looking at engine operation it is clear that more power is used and that the machine is closer to stalling. This gives higher fuel consumption, i.e. lower fuel efficiency, while the bucket fill is lower than that of the shadow operator. Here the operator would need help to not penetrate the pile too much and instead fill the bucket over a longer motion upwards in the pile. This could be achieved by an active control of engine speed, that over-rides the operator demand, and does not allow high engine speed. This is especially important simultaneously as bucket lift is commanded. This means that an automated bucket fill function is suitable to implement. If an automated function is not implemented an operator assist system can inform the operator, via for example a head-up display and haptic pedals/levers, to adjust the behavior to achieve higher fuel efficiency.
Regarding the productivity the general trend seen in Figure 7 is that the reason for lower productivity mostly depends on longer cycle times. The bucket fill are actually higher for some operators, compared to the shadow operator. A probable cause of longer cycle times in general is that it takes a lot of experience to simultaneously control all machine functions. Therefore an operator assistance system that reduces the number of functions needed to be controlled by the operator are also deemed as a suitable aid for the general operator who needs to improve time in all cycle phases. The measurements in [11] show that for the 80 operators the time loss compared to the shadow operator is in general evenly distributed between the phases in the cycle.

For the studied operator #47 however, the major part of the loss of time is during the bucket emptying phase. A probable cause for longer cycle times is the lower skill in maneuvering the machine simultaneously as positioning the bucket. This could be improved by introducing semi-autonomous functions that help the driver. Looking at for example operator #47, who mostly loose time in bucket emptying, a system that help emptying bucket as fast as possible would improve the productivity a lot.

Important is to cater all existing types of operators. Any assistance system needs to be gentle, consistent, predictable, and – most of all – possible to disengage completely. If done right, expert operators will not feel being negatively affected from having such an assistance system enabled, while inexperienced operators will rapidly boost their performance and confidence.

The gentle, trust-increasing way of assistance would be to indirectly guide the operator towards a more fuel-efficient operating style by the means of increased signal feedback, context-dependent information and operating suggestions similar to what is taught in the Eco Operator® training [8], perhaps even subtly altering the shape or magnitude of the operator’s control commands, rather than a brutal override.

The first step, increased signal feedback, covers both visualization efforts by means of head-up displays and the usage of other sensory channels of the human being, for example auditory feedback by means of sound generators and haptic feedback in pedals and levers. The latter even gives the possibility to subtly guiding the operator towards a certain control input for example by controlling the force feedback of a pedal, or lever, in a certain way.

Augmented Reality technology in connection with head-up displays can be used to provide context-dependent assistance in navigation and positioning of both machine and attachment. This enables not only optimal control of a certain route but also route optimization.

V. CONCLUSION

When analyzing the potential increase in fuel efficiency and productivity by operator assistant system in a wheel loader, working in a bucket application in a production chain, it is convenient to divide the problem into two parts. First, on individual basis fuel efficiency increases with up to two to three times, or 100-200%, and productivity increases with up to five to eight times, or 400-700%, between novice and professional operators can be seen. If the novice operators are excluded fuel efficiency increases with up to one and a half to two and a half times, or 50-150%, and productivity increases with up to two to four times, or 100-300% is visible, all depending on the application. Second, on fleet basis, that means the average of all operators, fuel efficiency increases up to 20-40%, and productivity increases up to 40-80% are possible, all depending on the application. This is if all the operators reach the average of the most fuel efficient operator, if everybody also would reach halfway up the “Max” trade-off curve in Figure 6 additionally 10-20% fuel efficiency increase could be expected, depending on the application.

For most operators an assistive bucket fill system could have a significant impact on fuel efficiency. This could be solved by for example automated bucket fill, where the wheel loader fills the bucket by its own in the most efficient way. To improve the productivity more studies have to be done but in general it can be stated that an assistive system should aim at helping the operator to operate the wheel loader faster to get through the work cycle in a shorter amount of time. One way of doing this is by decreasing the number of control inputs that the operator has to worry about, for example an extended bucket emptying algorithm that takes care of the complete emptying of the bucket for the operator.

Furthermore, if a site manager knows the trade-off curve for the specific application and the specific wheel loader on the site, then the operators on that site can be trained towards the optimal point on the trade-off curve, depending on the site boundary conditions. Also if the trade-off curve is known the site can be planned after that, optimizing the complete site fuel efficiency, and if all the trade-off curves for all the equipment on the site were known, complete site optimization would be possible. The optimization could be done either by maximizing production of minimizing energy consumption for a given production rate or a weight between the two, everything to maximize profit.

VI. FUTURE WORK

This empirical investigation and estimation of the potential increase in fuel efficiency and productivity by an operator assistant system in a wheel loader can also be seen as a pilot study in estimating the potential if more advanced control strategies in a wheel loader. This can, for example, be optimal control such as dynamic programming or equivalent consumption minimization strategy (ECMS). Using optimal control strategies result in that the most fuel efficient operator is calculated, instead of measured, as in this study. This result in that instant feedback can be given to the operator, making the operator assistant system even better. However the same methods as the ones presented in this paper should be applicable.

However when using optimal control it is of great advantage to have some sort of prediction of the future or adaption to the past, this could be, for example, pattern recognition.

Still left to develop is the virtual “optimal operator” and implementing an on-line strategy where the real operator can adjust the behavior by the help of the operator assist system to be as fuel efficient and productive as possible.
REFERENCES

Internet links verified 2012-02-12.

[16] http://haveit.lighthouse.gr/LH2Uploads/ItemsContent/26/PPT_3.3.3-HAVEit.pdf