On wheel loader fuel efficiency difference due to operator behaviour distribution.

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Summary. The focus in this paper is on how the operator behaviour affects the fuel efficiency and productivity of wheel loaders working in bucket applications in production chains. The methods are implemented on an empirical study on real wheel loaders but are also valid for simulator exercises. A theoretical fuel efficiency increase potential of up to 200% and productivity increase potential of up to 700% is concluded. An initial suggestion of a training tool that teach the operators to be as fuel efficient as possible for the production rate given by the site is also presented.

1 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 is 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.

Figure 1, a production machine wheel loader in a bucket application, loading blasted shot rock from face.

As can be seen in **Figure 2**, the fuel cost represents roughly 30-60 percent of the total cost of ownership, in $/ton loaded material, depending on market.

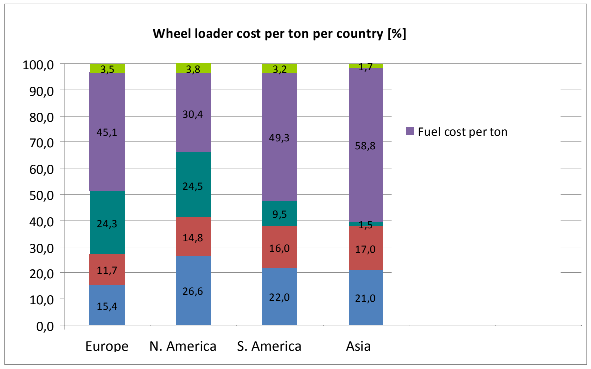

Figure 2, estimated fuel cost per ton for a wheel loader in a production chain, bucket application. One country per region serves as an example and all other costs are crossed out due to intellectual properties.

This implies that fuel efficiency *(ton/l)* is an important aspect when purchasing a wheel loader. However, not shown in this chart is that productivity *(ton/h)* is equally, or more, important because if the production rate can't be held then the whole production site slows down, resulting in expensive loss of income.

The fuel efficiency and productivity of a production machine wheel loader in a bucket application can be said to mainly depend on three major areas; 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;
  - Using the correct wheel loader size [2]. This is chosen by the customer, however the dealer can help, using advanced software to simulate the customer site [3]. It is vital to have a machine big enough to be able to keep the productivity and to solve the specified work assignment. For instance a too small machine is not suitable for loading shot rock from face. It is however also important to not have a too big machine, if over-sized the fuel efficiency will decrease since the wheel loader will go on part load and not be fully utilized.
  - The equipment and attachment of the wheel loader; such as tyres and type of bucket. This is usually specified by the customer, but the dealer can help in the same way as in machine sizing, depending on the application and primary work assignment of the wheel loader [2,3].
  - The base machine efficiency, meaning the efficiency of the wheel loader itself, which is the sum of all the component of the wheel loader, everything from the engine to the transmission to the hydraulic system and, of course, also the complete machine control system. The machine efficiency is something the OEM are working really hard to increase [4,5] simply because it is a major competitive advantage to have a wheel loader with high fuel efficiency and productivity. This is due to the fact that uptime, productivity and fuel efficiency is some of the most important aspects when customers are choosing which machine they are going to purchase.
- The *working environment*, the site layout and the planning of the site is also important to ensure maximum fuel efficiency and productivity. For example; not to

carry around material and stock-pile unnecessarily is a key to avoid loss in fuel cost and productivity. The properties of the loaded material, such as excavation severity and density, is also included here as an important parameter. The site planning is mostly done by the customer but sometimes the dealer [3] or an external company either give education [6] or helps planning the site.

- Last, but not least, [7] is the *operator behaviour*. This is the single most important parameter after the machine is chosen and the site is planned. This means that during the working life of a wheel loader the operator is the main parameter, together with the assigned work task, that affects the fuel efficiency and productivity the most. The traditional way to address the fuel efficiency and productivity difference due to operator behaviour distribution is operator training such as the Eco Operator® training, or equivalent, [8,9] where a trainer coach 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.

2 Introduction

With the three major areas that affect the fuel efficiency and productivity; *machine specification*, *working environment* and *operator behaviour* in mind then if analysing a specific work assignment;

- The *machine specification* is, from a customer perspective, costly to affect once a machine, with a certain equipment and attachment, is bought and chosen to do the work assignment.
- Once the work site has been set up and made ready the *working environment* is hard to affect since a chosen material is to be transported a decided distance according to the specified work assignment.
- The *operator behaviour* however can be affected.

This means that the *machine specification* and the *working environment* is more in the beginning when planning a site while the *operator behaviour* is a continuous occurrence. To cite a few voices within the construction industry;

"The biggest factors in fuel efficiency are properly trained operators and machine maintenance," Chad Ellis, product and governmental sales manager, Doosan Infracore. [7]

"Both the machine design and operator play important roles in fuel economy," "Poorly trained operators will cause even a good machine design to suffer poor fuel economy, and poor machine design will limit the fuel efficiency well-trained operators can attain. Operators who ride the brakes on wheel loaders cause excessive fuel burn and maintenance to the machine, for example." Jahmy Hindman, product marketing manager for wheel loaders, Deere & Company. [7]

"The design of the loader is great, but all the design efforts are wasted if the operator does not utilize the features. I feel the operator will play the most important role." Nick Tullo, articulated haulers and wheel loaders, Volvo Construction Equipment. [7]

While it can be considered an established opinion that the operator plays a vital part when considering fuel efficiency and productivity one might wonder why that is. Well, focusing on a production machine wheel loader in a bucket application, it is important to understand the position of the operator in the control loop when a wheel loader and its operator solve a specific work assignment.

To be able to explain the operator position in the control system a typical short loading cycle, see **Figure 3**, is explained first.

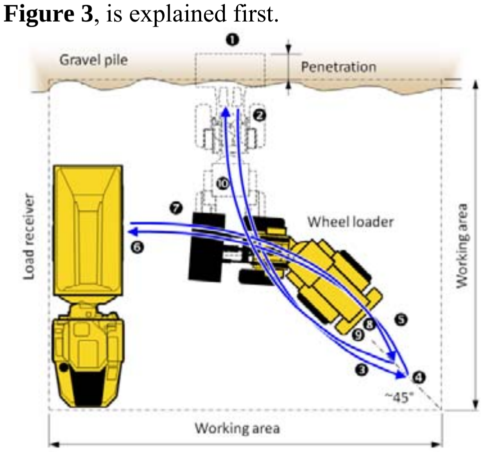

Figure 3, typical short loading cycle of a wheel loader onto a load receiver, also called Y-cycle or V-cycle [12].

Assume that the wheel loader start at the reversing point, 4, driving forward towards the pile and accelerating after just putting the machine into forward and decelerating just before the pile. Then entering the pile, at 2, where the operator has to put pressure on the front wheels to achieve friction enough to get the traction enough to penetrate the pile. All this while lifting and tilting bucket while driving forward and completing the bucket fill. After bucket fill is completed the operator put the machine into reverse and accelerating backwards, decelerating just before the turning point 4. Then the operator put the machine into forward, accelerating to later on decelerate again just before the load receiver while during the complete traveling phase the operator has lifted the bucket to ensure the precise height so that the emptying phase can begin. In the emptying phase the operator is lifting and tilting to put the material in the correct place onto the load receiver. Transporting and lowering the bucket towards the pile is done in the same way as towards the load receiver but the other way around [12].

Supported by **Figure 4**, the control effort of the operator during the typical short loading cycle in **Figure 3** can be described as; when approaching the pile from the revering point the operator has to not only transport the machine to the front of the pile but also position the machine in a way that the machine goes into the pile at a good entry point, both in regards to lateral and vertical position, depending on how the pile looks like but also position the bucket in a way that the ground, i.e. worksite, is not disturbed. Once in the bucket fill phase the operator has to start with enough penetration to be able to lift enough material to ensure sufficient ground pressure to guarantee enough traction to secure the capability to penetrate the gravel pile even more to be able to fill the bucket while lifting and using the tilt to ensure to not get stuck and tilt back the bucket at the correct time to minimize the time in the gravel pile while at the same time maximizing the load in the bucket. The operator is all the time during bucket fill balancing traction, which is non-linear due to the converter characteristics, and the working hydraulic that also depends on the speed of the engine. The tilt often also gets priority over the lift due to the lower pressure demand, resulting in that when using the tilt the lift speed get lower. To further complicate the steering has always priority, meaning that the speed of the lift and tilt depends on how fast the operator steer. The working hydraulics has also priority over the propulsion. This means that the accelerator pedal not only controlling the traveling but also some nonlinear traction and also the speed of the hydraulic pumps resulting in a dependence of the lift and tilt speed at a given position of the lift and tilt lever. The lift lever controls the lift speed of the bucket but also the longitudinal position of the bucket because of the linkage layout. The tilt lever controls the angle speed of the bucket but also indirectly the lift speed due to the priority. And the only input the operator has is the viewing of the gravel pile and the speed of the different actuators, propulsion, lift and tilt, see **Figure 4**. Then while reversing from the gravel pile, changing to forward gear and then approaching the load receiver the operator has to ensure that the bucket have reached the correct height to be able to get over the edge of the load receiver and dump the material in the bucket. Everything under the same restrictions as during bucket fill, the lift speed is dependent on the engine speed that is controlled by the accelerator pedal that also control the machine speed. This results in a delicate choice of reversing point, 4, in **Figure 3**, depending on machine layout. When returning to the gravel pile the bucket has to be positioned once again [11].

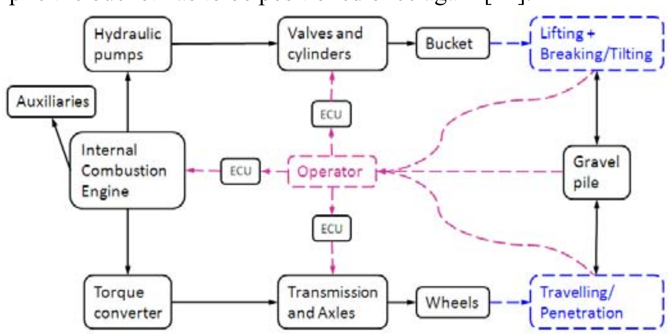

Figure 4, schematic picture of the power balance and the control loop in a wheel loader during bucket fill [11,12]. ECU is a board computer.

This line of argument results in, not totally surprising, that the operator is very much in the centre of the control loop, having a lot more input/outputs then driver of an on-road vehicle, e.g. a long-haul truck, see **Figure 4**. This, in turn, leads to that the operator in a wheel loader, performing a specific work assignment, affect the fuel efficiency and productivity more than the on-road driver. In addition the performance indicators of a wheel loader operator is two dimensional, fuel efficiency *(ton/l)* and productivity *(ton/h)*, comparing to the driver that only have to concern about the fuel consumption *(l/10km)*. An even more important aspect is that when an operator can't hold a certain given production rate a lot more depend on this. A complete production chain can slow down if the wheel loader does not perform.

3 Method

With the main goal in mind, investigating the fuel efficiency and productivity difference of a wheel loader in a bucket application in a production chain caused by differences in operator behaviour, the most important was to try to eliminate all other parameters not affected by the operator but still have a as close to realistic condition as possible. The decision was made to do the measurements in real world operations, not in a simulator where it would be easier to control the machine and environmental conditions. This was due to two main reasons; the simulator is just a model that does not correspond to the real world, in respect to fuel consumption and loaded material in the bucket, to the needed extent. Hence the fuel efficiency and productivity is hard to get correct. The skill transfer is also not necessarily linearly from real world operation to simulator [13], or vice versa, where some more inexperienced operator get a more “video-game feeling”, not corresponding to how they would operate a wheel loader in the reality, primarily with regards to risk-taking and safe operating.

To avoid cycle-beating, and to investigate different degrees of difficulties when it comes to bucket fill, three different bucket applications was investigated;

1. Short loading cycle onto a load receiver, see **Figure 3**, loading gravel. This would be a typical re-handling application where processed material has been stock-piled and then a wheel loader loads out-going trucks from the site from these stock-piles. See **Figure 5**.
2. Load and carry uphill to a pocket, loading gravel. This is a longer cycle than the short loading cycle in **Figure 3** where the distance between point 4 and 6 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 goes to a conveyer belt. This would also be a typical re-handling application where pre-crushed material is stock-piled and then a wheel loader put this material into a hopper that goes to another crusher or sorting machine, with settings depending on the customer demand. Another typical application this could correspond to is the stock-piling itself. See **Figure 5**.
3. Short loading cycle onto a load receiver, see **Figure 3**, loading rock. This would correspond to a face application where the wheel loader is loading blasted shot rock from face similar to **Figure 1**. This corresponds to the harder bucket fill application, meant to differentiate the operators a bit more than just loading gravel which is quite easy to fill the bucket with. See **Figure 5**.

Figure 5, the three different applications measured. From the right; short loading cycle gravel, load and carry gravel and short loading cycle rock.

3.1 Measurements

As mentioned above, the most important was to isolate the *operator behaviour* as the sole source of deviations. This was done by, in all three applications, using the same machine with the same equipment and same bucket and same tyres in each application for all operators to minimize the *machine specification* dependence and using the same calibrated gravel pile 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, dependence due to material and environment deviation.

240 measurements á 20 min, 80 in each application, were done with 73 operators. Four groups of operators was included in the study; 1) novice operators that has operated a wheel loader for 2-10 hours, 2) average operators that know how a wheel loader works but do not operate wheel loader as a profession, 3) internal professional operators that are evaluating wheel loader and/or working as test operators and/or show operators and/or trainers at Volvo, 4) external professional operators that are working every day operating wheel loaders in bucket applications in production chains as a profession.

The initial idea was to have 16 operators in each group, simply because this was the highest reasonable number to measure in this large extent and still be able to freeze the surrounding parameters *machine specification* and *working environment*. However the measurements ended up with a few extra operators due to the fact that when searching for external professional operators more than 16 customers showed interest. And so it was decided by Volvo that all customers inquired should be allowed to attend the event. Also some extra average was added because the personnel that performed the measurements wanted to join the investigation.

Three of the most experienced internal test operators was asked to do so called intensity measurements, meaning that they were supposed to operate the wheel loader in three different intensities; 1) slow driving and low bucket fill factor, corresponding to "Sunday driving", 2) medium driving pace and medium bucket fill factor, corresponding to what to expect when operating the wheel loader in 8 hour shifts, 3) as fast possible driving and as full bucket as possible, corresponding to a pace that only could be held by an operator for less than one hour due to the high mental and physical workload on the operator. The reason for these intensity measurements was to map the complete wheel loader working area in respect to productivity versus fuel efficiency. All other operators was asked to operate the wheel loader in a pace corresponding to how they would work in if they were supposed to do an eight hour shift with the specified work assignment.

Some factors was not possible to freeze during the complete measurement such as the weather, so unfortunately the applications "load and carry uphill" and "short loading cycle rock" that were made outside were affected by the weather conditions in a way that the material is heavier when it is wet, hence it is easier to get higher productivity and fuel efficiency. The weather during the measurements were typical Swedish late summer/early autumn which is very changing, meaning that the piles were pretty moist all the measurement but in various level. In the "short loading cycle gravel" the measurements were conducted inside so this measurement was unaffected by the weather conditions.

During the measurements some more unexpected issues rose as well. The material was worn a bit more than expected resulting in more fine material than expected resulting in a higher density in the end of the measurements for the gravel applications, especially the "load and carry" measurement. This results in that it was easier to get a heavier load in the bucket in the end of the measurement, hence also easier to get higher productivity and fuel efficiency. Also the wheel loader in the "short loading cycle rock" had a minor problem with a hydraulic regulator, resulting in that for a handful of operators that machine was a little harder to operate. There were also a problem due to a faulty cable resulting in that the measurement system did not work properly resulting in loss of data for a one external operator in the "load and carry uphill" and five external operators in the "short loading cycle rock" resulting in an odd number of operators.

Last, the rock application is not really representative to a real shot rock application. This was done on purpose for two reasons; for once, if letting novice operator operate in a shot rock application would be stupid due to safety risks due to risk of slicing the tyres and second, the rock-like application that was used during the measurement was more repeatable than shot rock could ever be arranged to be resulting in that the pile can be seen as almost calibrated and same for all operators which wouldn't be possible using real blasted shot rock.

3.2 Analysis

As the main objective with this investigation was to identify the relation between operator behaviour and fuel efficiency, and implicit also productivity, the main focus when processing the data from the measurements was to measure the time and bucket load as correct as possible because these parameters is the base for the fuel efficiency and productivity calculations. The analysis was done in four levels;

The first level is on average for the complete run. On this level the most important was to only count the wheel loader cycle. This means that when the articulated hauler was away emptying in the "short loading cycles gravel or rock" or if there was any problems with the conveyer belt in the "load and carry gravel" the fuel and time in the wheel loader cycle should not be accounted for. This was done by instructing the operators to stand still in neutral gear and then the data was recalculated so that the dataset was shrunk to only include the time when the wheel loader was working. The only source of fault in this level was that the weighing system sometimes misses a load. The maximum allowed percentage of missed loads were set to twenty percent, if the number of missed loads were higher than that the measurement was seen as corrupt and not used. A correcting algorithm for this was constructed, adding an average bucket load for every missed load. The confidence that the mean values are correct at this level is very high.

The first level is used for evaluating operators comparing to each other in regards to fuel efficiency and productivity. The reason why the evaluation is on average values is due to the fact that these are the values shown in the daily work.

The second level is on cycle basis. Here the fuel efficiency and productivity per cycle is calculated. This is done by identifying a point in the working cycle that is easy to detect and occur at the same time every cycle. Due to some problems with the weighing system and unexpected operating behaviour, especially by the novice operators, the only point that were feasible to detect was the positioning point of the bucket just before entering the pile. However this point can move a bit in the cycle depending on whether or not the operator decides to scrape off and clean the ground on the way into the pile. This results in that the cycle times is a bit more shaky, even though the average is correct, the cycle time in the analysis can differ some seconds from the real value if using a stopwatch. This will affect the fuel efficiency and productivity for isolated cycles.

The second level is used to see a pattern, regarding to 1st, 2nd and 3rd bucket onto the load receiver and also for the operators to see what cycle is the best and how that differ from the others, more or less learn from your own goods and bads. The cycle values of fuel efficiency and productivity are also used to establish a trade-off curve for that specific wheel loader in that specific work assignment. The trade-off curve shows the highest possible fuel efficiency for a given productivity within the wheel loader working area. Hence these trade-off curves can then be used to evaluate how much better an operator can become in that application in that wheel loader. This curve will of course depend on the number and skill level of the operators in the study and is not an absolute truth but rather a way to show the method and how a tool could look like if a larger base of operators could be reached. This is important to realize when going from an empirical study like this to an estimation of fuel consumption savings. This is a conservative way too look at the savings due to the fact that the probability that the best operator in the world was in the study is small. Another important thing is that the highest fuel efficiency does not have to be the best for the customer, if a higher productivity is demanded it is often fine to go down in fuel efficiency. That is why it is important to get the trade-off curve for the complete working area of the wheel loader and application in mind rather than just an optimal operating point. Reasoning in the same way, it is only possible to increase productivity, allowing higher fuel efficiency if the site conditions allow intermittent operation.

The third level is on phase [14,15,11,12] basis. Here the cycles are divided into three phases; “Bucket Fill”, “Bucket Empty” and “Transport”. These phases are distinguished by a number of conditions resulting in that the “Bucket Fill” is everything from when the bucket get close enough to the ground until the operator set the gear shift lever in reverse and leaving the pile, “Bucket Empty” is more or less from when the operator rises the bucket to a certain height and then until the bucket comes down to a lower height again after moving towards the load receiver and then emptying and then started to reverse from the load receiver. “Transport” is the rest, loaded and unloaded, forward and reverse. The difficulties in the second level applies in this level too, resulting in that the exact time for the phase division is not achieved but rather an approximate point in time.

The third level is used to see what did go right or wrong in closer detail than on complete cycle level and also how each phase correlate to each other and to the complete cycle performance value. From this it can be concluded which phase is the most important for a specific operator to adjust to increase the fuel efficiency and productivity and what in the phase that has to be adjusted.

The forth level is not actually another level but rather a way to break down and show the operator what happened during a specific cycle, or phase, showing individual signals. Here individual signals show what the operator feels, hears or sees, for example engine torque, engine speed or actuator (lift, tilt, propulsion) speed on one hand and then the signals the levers and pedals the operator uses, such as lift, tilt lever and accelerator and brake pedal. In that way the operator can recognize the system, and really analyse the operator behaviour, when getting the feedback from the proposed training tool, see chapter 4.2. It is also on this level each operator can compare with the “Shadow operator” which is the “optimal” operator. In this study that is the best operator in the study but it could also be a virtual operator calculated by a computer, especially if the training is done in a simulator environment.

After investigating and comparing between the three different applications the conclusion was that the weather, worn of material and hydraulic controller malfunction addressed in chapter 3.1 was not affecting the analysis to any larger extent hence the results are valid but one can still have these factors in mind.

4 Results

All the results is 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.

4.1 Fuel efficiency and productivity distribution due to operator behaviour

The main result in regards to fuel efficiency and productivity is that the difference between different operators is huge! One operator can have five to eight times higher productivity than another, depending on application, whiles the difference between two other operators can be two to three times higher fuel efficiency for one comparing to the other, see **Figure 6**.

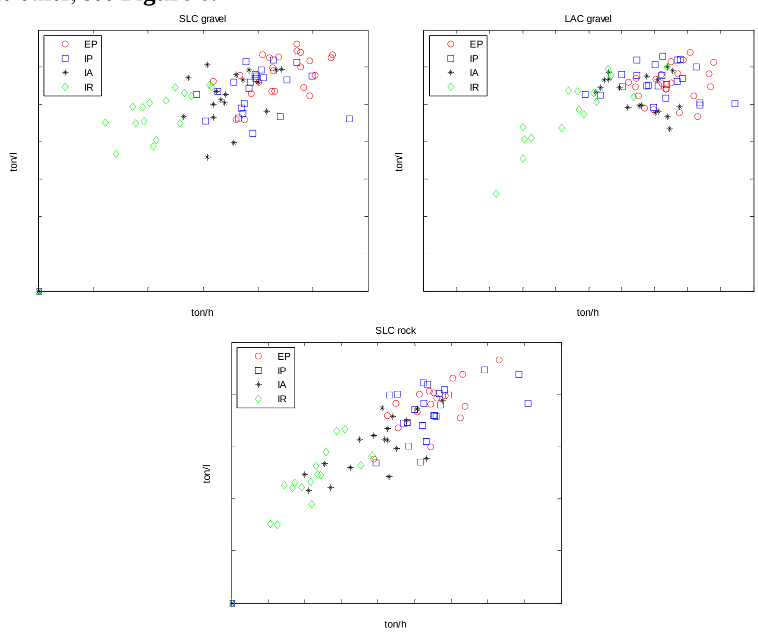

Figure 6, the fuel efficiency and productivity for the different operators. EP is the external professional, IP is the internal professional, IA is the average and IR is the novice operators. SLC is short loading cycle and LAC is load and carry. *(Note that the ticks is not the same in the different applications)*

It is however a bit unfair to compare the extremes since an operator is not that novice for a long period of time. However even if the novice operators are excluded the productivity is two to four times higher and the fuel efficiency is 1.5 to 2.5 times higher, as can be seen in **Figure 6**. The exception is of course day-to-day workers, many with no experience, but this is rather unusual looking at the world market.

Another interesting thing is that both the fuel efficiency and the productivity seems to have a more or less linear dependence regards to the experience, or skill level, of the operators, meaning that a $y=kx+m$ line could be drawn in **Figure 6**. The closer an operator is to the up right corner, the more experienced operator. One exception is however some of the intensity measurements where the test operators were asked to stress the machine to an abnormal behaviour.

Another interesting result that can be seen in **Figure 6** is the dependence on application, in the short loading cycle gravel the operator is somewhat closer to each other than in the other applications. In the load and carry gravel this is resulting from that the bucket fill factor is much more important in this application due to the fact that the load are going to be transported such a distance using a larger amount of fuel in the "Transport" phase only a small difference in the bucket fill factor results in large differences in fuel efficiency and productivity. In the rock application the larger difference is mostly because it is much more difficult to fill the bucket with the material in the rock application but also what kind of material that ends up in the bucket, large rocks or a lot of fine material, resulting in a much larger deviation between the operators and individual cycles.

As mentioned in chapter 3.2 each cycle fuel efficiency and productivity was also calculated. Interesting here is that every operator in itself has a quite large deviation from the mean fuel efficiency/productivity. In **Figure 7** the cycle distribution of operator IA1 is shown, with the average value marked with a larger marker, together with all the other operator average. The results from this implies that if operator IA1 operate the wheel loader at the best point achieved then the mean fuel efficiency would increase with about 10-15 percent and the productivity by roughly 10 percent. Alternatively the operator could increase the productivity by about 20 percent and the fuel efficiency by a few percent, all depending on the current site boundary conditions.

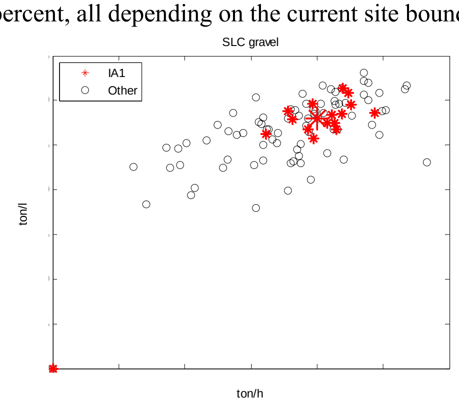

Figure 7, the fuel efficiency and productivity distribution of one operators cycles comparing to the other operators average. The larger IA1 marker corresponds to the mean IA1 cycle and the smaller are each individual IA1 cycles.

To be completely fair the assumption is not 100% correct since some deviation between the buckets when loading a load receiver is inevitable since the 3rd bucket onto the load receiver has to be positioned more carefully to not spill material off the load receiver. However similar behaviour is apparent in all three applications, short loading cycle in gravel is shown as an example in **Figure 7**.

To get the trade-off curve, mentioned in chapter 3.2, two approaches can be considered. Either the convex hull of all the operators average cycles in **Figure 6** that will represent a Pareto front that is called the trade-off curve or each and one of operators individual cycles, as IA1's example in **Figure 7**, is plotted in the same plot and the convex hull from this is taken as the trade-off curve. However due to the concerns regarding the cycle time raised in chapter 3.2 the convex hull has to be slightly modified to take away unreasonable points. This could however be avoided with better measurement equipment. In **Figure 8** the two different trade-off curves are plotted using the two different methods mentioned above.

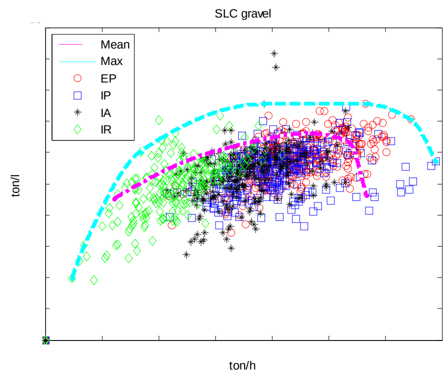

Figure 8, all the operator's individual cycles with the trade-off curves from the average, "Mean", cycles and from the individual cycles, "Max".

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 for this specific wheel loader in this specific work assignment. Short loading cycle in gravel is shown as an example in **Figure 8** 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 work and 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 all the best operators 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 has to be accounted for. But for the "fleet" of operators in this study the "Mean" curve should be able to be raised to around half of the distance between the two curves, meaning around 10 percent fuel efficiency increase, depending on the productivity demand. If the conditions on the site allow part engine-off time then a lot more could be saved of course, then only operating the wheel loader at the optimal productivity resulting in up to around 20 percent fuel efficiency increase. This also means that if the site manager knows the trade-off curve for the specific application and the specific wheel loader on the site, then the site can be planned after that, optimizing the complete site fuel efficiency.

The reason why the trade-off curve looks like it does can be explained by just setting up the equations for the different system in a wheel loader. The reason why both fuel efficiency and productivity goes towards zero is not that surprising. If just standing still, or just driving around then fuel and time will be wasted and no material moved, hence zero productivity and zero fuel efficiency. The reason why the trade-off curve then flattens and finally goes down a bit is due to the fact that there are components with speed related losses that increase in square and also components that is trimmed to have their maximum efficiency at lower speeds than the ones that are necessary when the wheel loader is stressed to its maximum capacity.

Fuel efficiency and productivity for each phase was also calculated but was decided not to be shown here simply because these parameters was no good indicator of how well each phase were performed. The conclusion was that an operator can cheat in one phase, for example in the bucket fill, by only filling the bucket very little and very quick, by using only the machine inertia. In that case an operator can get very high fuel efficiency and productivity in the bucket filling phase, but losing a lot in the other two phases, transport and bucket empty. This due to that there are very little load in the bucket resulting in very low fuel efficiency and productivity in the complete cycle due to the much lower payload percentage. However, as indicated in the text above there was a clear connection of a well performed bucket fill phase, meaning a lot of load in the bucket to a low amount of fuel, and a well performed cycle, meaning high fuel efficiency and productivity. This indicates that the “Bucket Fill” phase is important for the complete cycle performance.

4.2 Training tool

The proposed training tool works just as well in a simulator as in a real wheel loader and there are of course benefits and drawbacks with both of them. In the real wheel loader the difficulties to measure, to have a calibrated gravel pile and to take the weather into account, the travelling for the operators and so on have already been touched upon in previous chapters. In the simulator the problem is more of the “playing a video-game feeling” [13] and that it is still not the same as a real wheel loader has already been touched upon in previous chapter and there are also barriers for using simulators in operator training of construction equipment [16].

The proposed training tool is built in a way that; the tool chooses what is considered the optimal operator given the circumstances. This means that for a given base of operators the tool chooses the one that has the highest fuel efficiency, if that is the criteria, the criteria can for example just as well be productivity. In the example in this paper the optimal operator is chosen to the one with the highest average fuel efficiency but the optimal operator could just as well be chosen to be the operator with the cycle with the highest fuel efficiency. Or it could be a virtually composed operator from three different operators, each and one best in the three phases, bucket fill, transport and bucket empty. In a future edition the optimal operator can be a computer computed operator, especially in a simulator edition.

The training tool takes this optimal operator and set this to be the “Shadow operator” and this is what the operator compares themselves to. The idea is that the operators that joined the training should be able to understand what the “optimal” operator did that the operator did not do. For that sake the training tool is built up in the three levels discussed in chapter 3.2. The idea is that the operator identifies where the operator is, in regards to fuel efficiency and productivity, compared to the “Shadow operator”. This is done in a plot like the one in **Figure 6**. Once that has been done the operators own potential in analysed in a plot like **Figure 7** coming to the conclusion that if the operator should have operated the wheel loader as efficient as at the best cycle how close would the operator be comparing to the “optimal operator” be then? Then the operator goes one level deeper and start to look at individual parameters, such as cycle time and load in the bucket, in individual cycles that has a direct correlation with the fuel efficiency and productivity, this can look like **Figure 9**. The operator also gets the fuel efficiency and productivity in histogram shape so that the correlation between a well performed cycle and how the operator controlled the wheel loader in that particular cycle can be done.

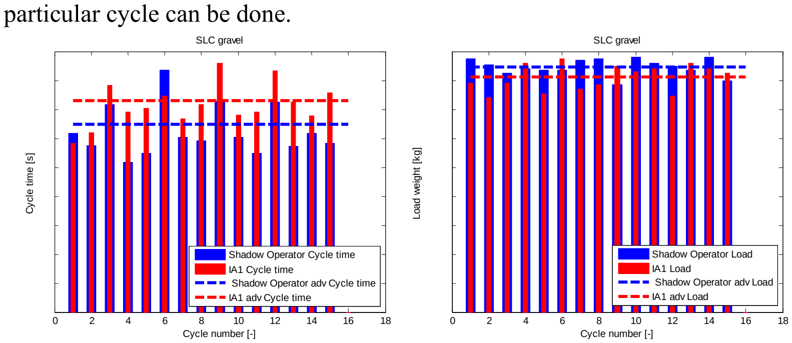

Figure 9, the cycle time and load in the bucket per cycle is shown as example histogram from the training tool highest level.

Already at this level, reasons can be seen why the operator A1 gets lower fuel efficiency and productivity than the “Shadow operator”. This is because the cycle times are too long and the bucket loads is too low, both resulting in lower fuel efficiency and productivity.

To understand why these high level parameters, for example the cycle time and bucket load, ended up as they did the operator can go one level deeper and analyse all the parameters in **Table 1** and how the operator’s histograms differ from the “Shadow operator”. The idea here is that the operator should be able to imagine how it was in the wheel loader when operating, so all the impressions from the wheel loader should be represented in the histograms, everything from hearing and feeling the speed and torque of the engine to seeing the velocity of the machine and on the lift and tilt to how the operator actually actuates the three different actuators; propulsion, lifting and tilting. An example of how this level can look like is shown in **Figure 10**.

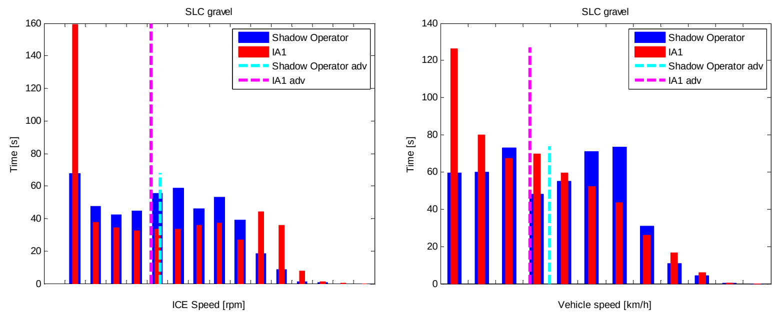

Figure 10, examples of histogram from the training tool mid-level showing how much time per cycle in average the operator has spent in each engine speed and machine velocity bin.

At this level the operator A1 can start to get the understanding of why the cycle time is higher than for the “Shadow operator”. The operator A1 has much more standing still time per cycle, in this case in the “Bucket Empty”, also the speed of the machine is lower indicating that the transport phase takes longer time, both visible in the next, lower level. It also shows is that the operator A1 does not utilize the engine as much as the “Shadow operator”, to know how this affect the load the “Bucket Fill” can be analysed at the next level where the cycles has been broken up in the three phases “Bucket Fill”, “Transport” and “Bucket Empty”, an example of how that can look like, when looking on how the actuators are controlled is visible in **Figure 11**.

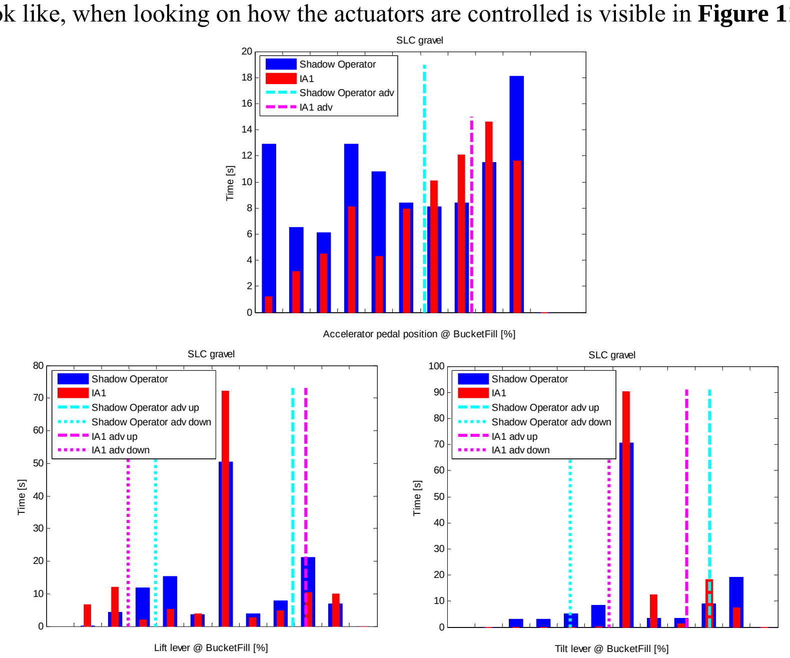

Figure 11, examples of histogram from the training tool lowest level showing how much time in the bucket filling phase in average the operator has spent in each actuator controller bin.

And once again it is visible for the operator A1 what could be improved the next time, in this case it is simply, for all actuators that the operator A1 is too gentle and cannot control the wheel loader as fast as the “Shadow operator”. This means that to get the same fuel efficiency and productivity as the “Shadow operator” the operator IA1 has to utilize more of the wheel loader capacity to a larger extent. To be able to do that the IA1 operator has to learn how to control the wheel loader faster.

In this paper all the axes has been crossed out due to intellectual properties. However in the real training tool this will of course be visible. The method is however the same.

Table 1, Content of the training tool in regards to the different levels mentioned in chapter 3.2.

Parameter	Unit	Average	Per cycle	Per phase
Fuel efficiency	[ton/l]	✓	✓	✗
Productivity	[ton/h]	✓	✓	✗
Load weight	[kg]	✗	✓	✗
Cycle time	[s]	✗	✓	✗
Phase time	[s]	✗	✗	✓
Accumulated fuel	[l]	✗	✓	✓
Fuel consumption	[l/h]	✗	✓	✓
Distance	[m]	✗	✓	✓
Speed	[km/h]	✗	✓	✓
Accelerator pedal position	[%]	✗	✓	✓
Load sensing pressure	[MPa]	✗	✓	✓
Engine torque	[Nm]	✗	✓	✓
Brake pressure	[kPa]	✗	✓	✓
Brake pressure @>0.5km/h	[kPa]	✗	✓	✓
Engine speed	[rpm]	✗	✓	✓
Engine power	[kW]	✗	✓	✓
Gear	[-]	✗	✓	✓
Lift angle speed	[mRad/s]	✗	✓	✓
Tilt angle speed	[mRad/s]	✗	✓	✓
Lift lever	[%]	✗	✓	✓
Tilt lever	[%]	✗	✓	✓
Lift angle	[mRad]	✗	✓	✓
Tilt angle	[mRad]	✗	✓	✓
Lift angle @ F→R	[mRad]	✗	✓	✗

5 Conclusion

The most important conclusion that can be drawn from this study is the vital part for fuel efficiency and productivity the operator plays. Fuel efficiency increases of up to three times, or 200%, and productivity increases of up to eight times, or 700%, between novice and professional operators can be seen and if the novice operators are excluded fuel efficiency increases of up to two and a half times, or 150%, and productivity increases of up to four times, or 300% is visible. This means really big potentials in cost savings! This means that this should be a key area for continued research within the construction industry.

An interesting conclusion is as well that the fuel efficiency and productivity level seems to be linear to the experience, or skill level, resulting in that a site manager can quite easy calculate the payback time of a training fee.

Interesting is also that the application seems to play an important role, meaning that even if a site manager employ an experienced operator it could be useful to train the operator on that specific application if that differ a lot from what the operator is used to.

Interesting is also the deviation from the average for a single operator in one specific application. That one operator could deviate from the mean by ±10-20 percent both regarding fuel efficiency and productivity shows the potential in letting the operator know the importance of these things and maybe even have a bonus system, encouraging the operators to do their best in regards to fuel efficiency and productivity as well as solving the work assignment.

An interesting result regarding the trade-off curves is that, if a site manager knows the trade-off curves, the manager can control the choice of wheel loader size, set the pace of the production and optimize the overall efficiency of the complete site. This requires of course that the trade-off curves for all the machinery in the site is known and a total site optimization is done based on all the trade-off curves.

The main conclusion regarding the training tool is that it is possible to just record a number of operators and then let a computer do an automated analysis and then present the results to the operators in different levels. Then the operator can analyse the behaviour and realize what to do better the next time. And due to the fact that not even the best operator will reach the "max" curve in **Figure 8**, with the mean cycle values all operators have something to learn in this training tool. The really nice thing with this training tool is that until the virtual, or computer calculated "optimal" operator is done in a robust way it can just as well be used with only real operators, in simulator or real world. Especially if a really good specialist trainer comes along and operate the wheel loader in the same pile.

The training tool is, of course, most powerful in the hands of a competent trainer who can interpret the results in a way so that the operator understands the feedback the best.

All the conclusions, and many of the algorithms, can be applied to developing of an advanced operator assist system [17].

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