Reducing Whole-Body Vibration Exposure in Backhoe Loaders by Education of Operators

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Abstract

Whole-body vibration is a health hazard for operators of construction machinery. The level of whole-body vibration exposure on the operator is governed by three different factors; performance of the suspension system of the machine, planning of the work and the skills of the operator.

In this research work it is investigated whether there is a potential in bringing down the level of whole-body vibration exposure by educating operators of backhoe loaders. This is carried out by an experimental setup. Six experienced operators participated in the experiments carried out on two different sizes of backhoe loaders. Each operator had to complete three different tasks without any kind of instructions. Subsequently they got a short education on eco-driving and vibration avoidance and carried out the tasks once more. Time duration, whole-body vibration exposure and fuel consumption was registered before and after education.

The result of the short education was an average reduction in the whole-body vibration exposure of 22.5%. And for all completed tasks expect one a considerably fuel saving was obtained too - up to 38%. This experiment

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demonstrates that education of the operator will improve the occupational health and save fuel. The results also indicate that these improvements can be obtained without reduction in productivity as the instructions become a habit for the operators. Thus it is profitable for the employer to educate the employees operating construction machinery.
The findings of this work is highly relevant to the construction industry. It shows a great potential in reducing damaging vibration and at the same time reduce fuel consumption. It also emphasizes the need for better education of machine operators.

Keywords: Whole-body Vibration, Construction Machinery, Operator Education, Fuel Saving

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1. Introduction

The risk associated with awkward posture has been a known issue and a topic of research for some years now. As an example, original work on the effect of mirrors and cameras on the postural stress in agricultural tractors was done in the 1980's by [1].
Whole-body vibration (WBV) has later been recognized as a health hazard for operators of off-highway mobile machinery and thorough investigations have been carried out. In [2] it is concluded that exposure to whole-body vibrations predicts subsequent disability pension retirement.
In July 2002 a European Directive was introduced [3]. This European Directive establishes minimum requirements for the protection and safety of workers exposed to WBV.

[4] have made an extended review of papers concerning health hazards. One of the findings is that WBV together with awkward posture is considered as some of the major health hazards for operators of construction machinery and may result in excessive risk of musculoskeletal injury and disorder to the lower back. Further [5, 6] has shown that there is a good correlation between objective methods for determining ride comfort and subjective comments from crew driving in vehicles. Thus reducing the WBV exposure on the operator will not only reduce the health hazards but also affect his subjective experience of the working environment in a positive way.

In an overview [7] looks at strategies to reduce WBV of drivers of vehicles in general and divide the strategies into two categories. The first is design considerations of the manufacturer and the second is the skills and behavior of the operator. Considering construction machinery especially also maintenance in the construction site, changes in environment and planning of the work is of great importance [8, 9].

The awareness of the influence of the operators on the dynamics are treated in several studies; [10] and for construction machinery particularly: [11, 12, 13, 14, 15] have realized the importance of the ability to model the operator when developing wheel loaders. The operator has great influence on the dynamic response and hence the WBV exposure. It has been established that operator input influences the vibration exposure [16].

That operator instruction is of great importance concerning vibration exposure is emphasized in [9]. For cars, trucks and busses it is a well known fact that education of the drivers can decrease the fuel consumption [17, 18, 19]. In the forestry industry it has been shown that education of operators with the purpose of reducing fuel consumption has a positive affect on the exposure of vibrations [20, 21]. Here this research is taken further and the impact of operator instructions on the overall performance of a backhoe loader is considered. Specifically, it is investigated whether it is possible to reduce whole-body vibration exposure and fuel consumption when operating a backhoe loader in different operation modes. The duration of each task is also measured in order to evaluate whether any improvement is noticeable on the productivity.

According to [7, 22, 23, 24] the WBV exposure for an off-highway vehicle is linear proportional with the speed. Experiences from the forestry industry show that an operator typically will drive up to a level of $0.8m \cdot s^{-2}$ if the vehicle speed is the limiting factor of operation mode [23].
This implies that the input from the operator also is important concerning the WBV exposure.

2. Method

A number of tasks that reflect on-site duty cycles for backhoe loaders are designed. The tasks are specified by the instructors at Ulfborg Kjærgård who daily educate operators of backhoe loaders and other types of construction machines. For each task duration, fuel consumption and WBV exposure are measured and registered.

Figure 1: Experiment procedure

The procedure of the experiment is shown in Fig. 1 and explained here First the operator completes the tasks. For each task fuel usage, WBV exposure and duration of the task are registered. The operator is asked to complete the task as he would do it in an ordinary workday on a construction site.
Then the operator gets a short education in fuel saving and vibration reducing operating techniques and some insight into machine capacity.
At last the tasks are carried out again. This time the operator has to adopt the techniques and the knowledge provided to him and mostly important focus on the goal to save fuel and reduce the vibrations emitted to his own body and the machine. Duration, fuel usage and WBV exposure are registered.

Two different size of backhoe loaders are used for the experiment. Both machines are slightly used machines but in very good condition, see Tab. 1.

Table 1: Machine Data for #1 and #2.

	Machine #1	**Machine #2**
Hours of use	3350	1650
Weight [kg]	8,200	9,400
Loader shovel capacity [m^3]	1.3	1.6
Seat configuration	Mechanical	Air
Tire specification	500/70 R24	650/55 R30.5

Six different experienced operators all male were used for the experiment, designated O#1, O#2 and so on, listed in Tab. 2. The experiment was carried out with two operators a day on the two machines in three different days. Thus the didn't partipate the same class but got the same information.

Table 2: Operator data.

Operator	Years of experience	Type of employment
O#1	> 25	Municipal
O#2	> 25	Municipal
O#3	7	In a corporation
O#4	16	Private entrepreneur
O#5	14	Private entrepreneur
O#6	9	In a corporation

All experiments are carried out in agreement with the directions put forward in [25], which prescribe how vibration exposure values shall be determined on mobile machinery. The machines are both in good condition. The tires are in good condition, tire inflation pressure is checked to be in accordance with the operator's manual and filters (fuel and air inlet) have been renewed.

2.1. Measuring Equipment

Each task is observed by an instructor with a stopwatch determining the elapsed time and visually observed the operator input and performance. The tasks were video recorded.

Figure 2: Extra fuel tank mounted.

For measuring the fuel consumption an extra small fuel tank of $25L$ is mounted to the backhoe loader, Fig. 2. The tank is easy to detach and thus makes it possible to weight out the fuel left in the tank. The fuel tank is linked up to the existing fuel supply system by hoses connected at the outlet and inlet of the original fuel tank, Fig. 3. The fuel pump uses some fuel for cooling the electronics and thus an amount of fuel is let back to tank. Therefore both the suction hose and return hose are connected to the extra tank. It is possible to connect and disconnect the extra tank so only the exact amount of fuel used for the given task is taken from the extra tank.

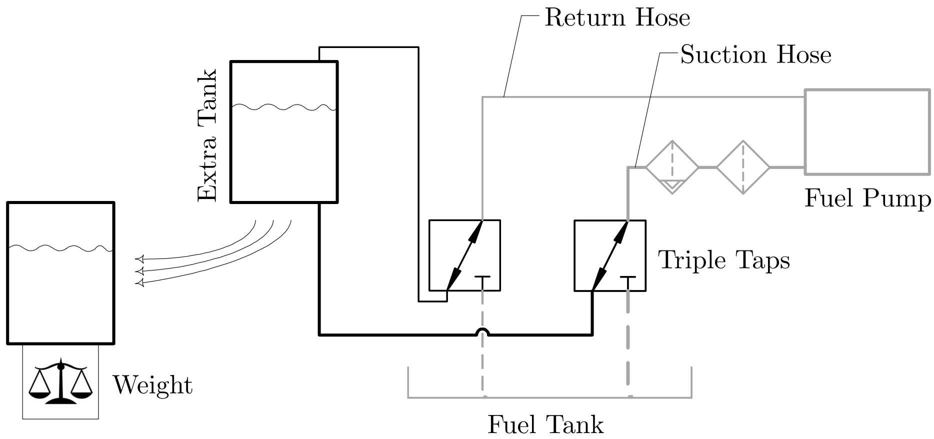

Figure 3: Fuel measuring system.

For measuring the WBV exposure a SVAN 958 Vibration Analyzer with a SV 39A Whole-Body Seat Accelerometer from Svantek is used. This dosimeter measures the acceleration, filters the signal and calculates the frequency weighted root-mean-square acceleration for each of the three axis. Eq. 1 according to [26] and fulfill the requirements in [27].

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}} \tag{1}$$

To compare the vibration level before and after education a vector sum a_V of the three vibrations are calculated by Eq. 2.

$$a_V = \sqrt{a_{w,x}^2 + a_{w,y}^2 + a_{w,z}^2} \tag{2}$$

The health weighting factors to each axis for health are not applied for this comparison. The SVAN is placed as a pillow on the seat, Fig. 4.

Figure 4: SV 39A Whole-Body Seat Accelerometer placed on seat.

2.2. *Task Description*

According to [11] four different operation modes exist for a wheeled backhoe loader; load and carry motion, V-shaped motion, excavating and transfer movement. Based on [11] and experience of the instructors the following three tasks have been chosen to be proper for investigating the effect of education:

1. V-shaped motion
2. Trenching
3. Removal of overburden

Transit mode is not considered as only speed and steering wheel input governs the WBV exposure and thus does not reflect machine operator skills in general [8, 9, 22]. The site of the experiment is the test area of Ulfborg Kjærgård. The gravel has the same structure and the area is leveled off with a bulldozer equipped with a laser control system to ensure same elevation of the surface. The area has reposed for three months thus the structure is firm and hard. The pile used for the V-shaped motion is surplus gravel from the leveling.

V-shaped motion is the designation of loading a dump truck from a pile of gravel, Fig. 5. The dumper body is filled up 5 times which approximately is 100 metric ton of gravel totally. The average elapsed time was approximately 22 minutes.

With a bucket the operator has to trench a 30.0m long and 1.4m deep straight ditch, left in Fig. 6. This gives 25.2m^3 of gravel that has to be removed. An instructor assists the operator by means of a laser surveying

Figure 5: V-shaped motion loading a dump truck.

system so that the depth of the ditch becomes exactly $1.4m$. The average elapsed time was approximately 30 minutes.

With a wide incline leveling bucket the operator has to remove overburden in a depth of $0.4m$ from an area of $60m^2$ ($6m$ wide and $10m$ long), right in Fig. 6. This gives $24m^3$ of gravel that has to be removed. As for the trenching an instructor assists with a laser surveying system to ensure exact depth of the area. The average elapsed time was approximately 30 minutes.

2.3. Education

In a half hour lesson after the first tasks was accomplished the instructors from Ulfborg Kjærgård gave input to the operators. The input was taken from a theoretical course in eco-driving and from the observations of the completed tasks. Measurements from [16] regarding WBV and a more detailed explanation of the machine capacity were presented by Hydrema. The lesson was accomplished through a dialog with the participating operators how to reduce fuel consumption and vibrations. After the tasks was completed again the results was discussed with the operators and they were interviewed by a journalist.

There are several important tips to notice concerning fuel consumption. The most important content of the eco-driving section of the education are mentioned here.

Figure 6: Trenching with 600mm bucket (left) and removal of overburden with an incline leveling bucket (right).

It is important to ensure proper maintenance of the machine. Especially clean radiator, clean and renew fuel and air filter. The air condition shall only be used with closed doors and windows to ensure efficiency of the system. Avoid cooling down the cabin more than necessary to also save energy. The shovel and bucket shall never be lifted unnecessarily. The object for an optimal work cycle is minimizing local minima of the tool point curve of the shovel or bucket. Besides the shovel or bucket shall never be lifted higher than necessary.

The tool point (bucket or shovel) shall always follow the shortest possible track from loading to unloading point. This track has been the objective of optimization in several studies. Among these [28] has tried to optimize the tool point track for the backhoe to save energy.

The way of trenching is also of great importance. The cutting edge should always attack perpendicular to the direction of motion. It is important not to break and lift at the same time. The correct way of doing energy efficient excavating is shown to the left in Fig. 7. Here energy is only used for breaking and filling up the bucket. Excavating the wrong way as shown to right in Fig. 7 greatly increases the risk of pressing the bucket against the underlying

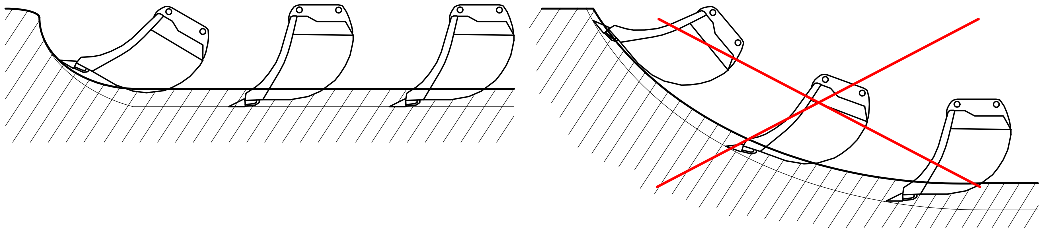

Figure 7: Right and wrong way of excavating.

gravel. This will make the hydraulic supply use more energy without doing extra work. Besides, when a bucket of gravel has been removed no gravel must remain over ground level. If so, the bucket has dozed gravel instead of excavating which is a waste of energy.
When excavating, the rotational speed of the engine is chosen by the operator from experience. This speed will typically give higher output power than required by the hydraulic system. An energy analysis of the excavating process of a backhoe loader similar to machine #2 has been performed by [29]. According to this work the flow and power requirement for trenching has been determined, Fig. 8. From here it is observed that an engine speed of $1260 - 1270rpm$ would be sufficient in order for the system to deliver enough power and flow. This plot is presented to the operators in the lesson.
When driving and especially when doing V-shape motion unnecessary slip of the tires shall be avoided. Some slip will always be required to obtain reaction forces between tires and ground [30]. All slip is loss of energy thus wheel spin shall be avoided.

There are different techniques to avoid vibrations and jolts. The most important is mentioned here and introduced to the operators in the education session.
It is very important to adjust the seat properly so it will never hit the mechanical end stops neither on the top or bottom [31].
Doing V-shaped motion the x-axis acceleration (longitudinal) is the critical acceleration. The speed of the vehicle when the front shovel enters the pile of gravel is crucial for the WBV exposure. Figure 9 shows the longitudinal acceleration on the seat doing V-shaped motion. Two cycles are presented by the figure. The two peak acceleration areas are when the shovel enters the pile and the vehicle is stopped by the resistance of the gravel. Entering the pile with very low speed will reduce the amplitudes of the longitudinal

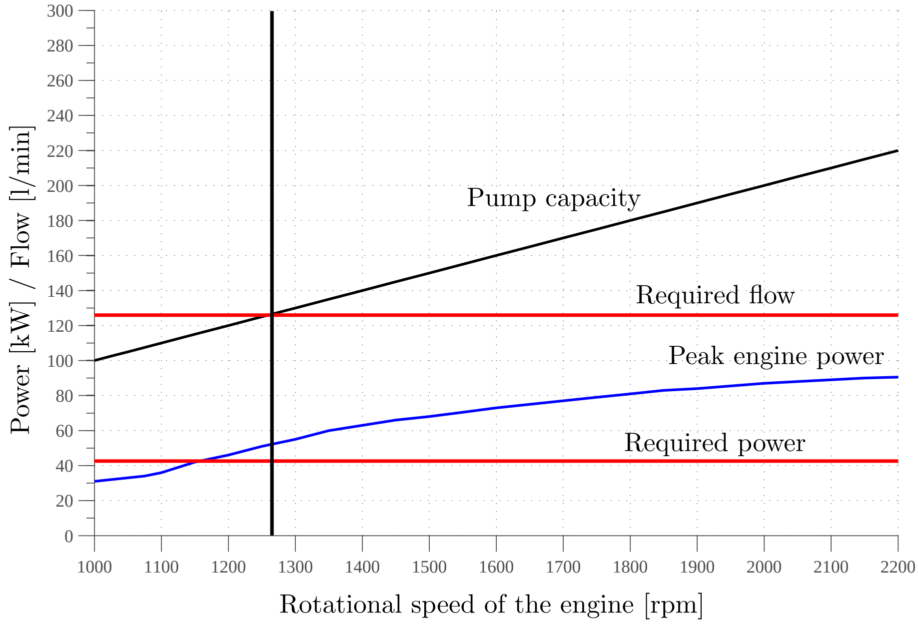

Figure 8: Power and flow requirement for trenching [29].

accelerations. From Fig. 9 two peaks are observed for each time the shovel enters the pile. This is due to the automatic transmission that increases the gearing when the resistance is increased. On the second session the operators are asked to use a different approach when they enter the pile. Firstly, they should use a lower velocity and not use the impulse from the vehicle to fill the shovel. Secondly, the automatic transmission should be disengaged (done via a button on the loader joystick) effectively locking the gearing.

Doing any kind of excavating it is a common procedure to use the two sta-

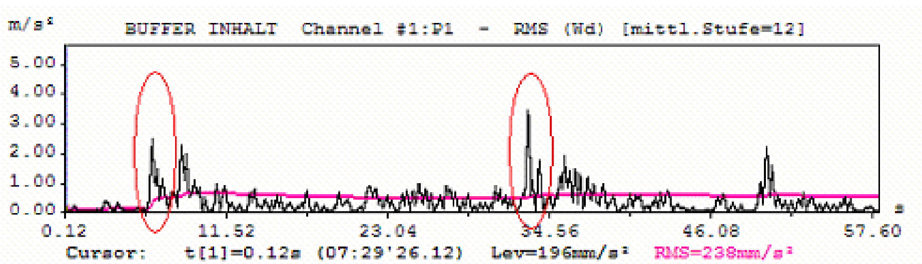

Figure 9: Longitudinal acceleration of two V-shaped motion cycles [16].

bilizers on the back of the machine. Also the front shovel is pushed against the soil. The purpose is to stabilize the machine and leveling the machine to a horizontal orientation. A gyroscope in the cabin enables the operator to ensure horizontal orientation of the vehicle. In [16] it is experienced that excavating without stabilizers and lowered front shovel increases the vibration exposure on the operator by a factor of approximately two as shown in Fig. 10. When trenching the operator often has to move the vehicle backwards

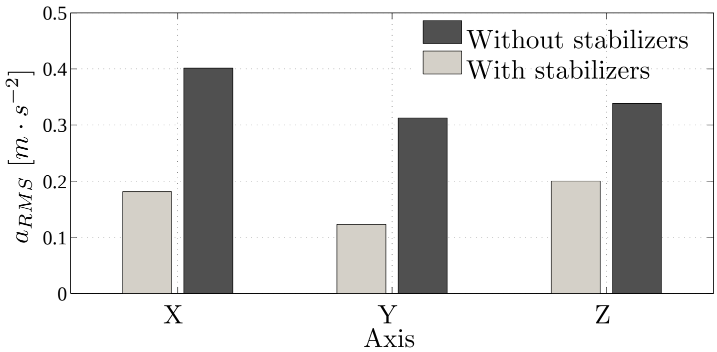

Figure 10: Difference in vibration exposure depending on use of stabilizers. The vibrations are measured as an RMS value of the acceleration of the seat.

several times. It is recommended to reduce engine rotation speed when lifting the front shovel and stabilizers, moving the machine and lowering the shovel and stabilizers again to avoid unnecessary jolts.

Lowering the engine speed reduces the potential risk to introduce undesired jolts and vibration to the machine caused by undesirable gain of the joystick input and reduces the sensitivity of the hydraulic system to operator input. The goal is to obtain a more smooth operation of the machine.

As mentioned in Sec. 1 the planning of the work is also of great importance to avoid undesired vibrations. Choose the right machine size for the job, and plan the job to minimize transfer motion of the machine. The fewer times the vehicle should be moved and the shorter distance the gravel has to be moved a better productivity is obtained. The advice about moving the vehicle is applied in this experiment. The operators should excavate as much as possible from the same vehicle position.

3. Results

Only the changes for each operator are considered in this work. No comparison of the two machines is made. The percentage reduction in vibration values are provided without the health weighting factor from [26]. In Tab. 3 the percentage reduction in vibration level, fuel consumption and elapsed time after education are shown for each operator together and the average result of all six operators with the standard deviation (SD). The measured parameters consists of the three vibration level for each axis $a_{w,x}$, $a_{w,y}$ and $a_{w,z}$ together with the vector sum from Eq. 2, the fuel consumption in liters and the elapsed time.

From Tab. 3 it is observed that the average vibration level for all axis were reduced in the range of 16.5-26.8%, which is a quite significant improvement of the work environment. Also the average fuel consumption for each task decreased. The main fuel saving is observed for the excavating tasks though 9.4% was saved on the V-shaped motion task. There is quite a big difference in the fuel savings. Especially operator #2 saved a lot of fuel on the excavating tasks. When trenching the operator reduced the fuel consumption from 5.63 liters to 3.4 liters which is a saving of nearly 40%. The same operator also improved the fuel efficiency when removing overburden with approximately 35% and completed the job 4% faster, though most of the task for all the operators took more time. Observing Tab. 3 there seems to be a connection between the fuel reduction and the increased elapsed time. Removal of overburden by operator #4 took nearly 50% more time. By interview afterwoods the operator told, that he tried to do a more precise job avoiding manual trimming afterwards.

For the V-shaped motion the front-back acceleration axis $a_{w,x}$ was the dominating axis. The same axis also obtained the highest decreasment with above 20%. Nearly 10% fuel was saved and the average elapsed time increased by approximately 3% only.
During trenching the dominating axis were also front-back $a_{w,x}$ and vertikal acceleration $a_{w,z}$ (also after applying the health weighting factors of 1.4 on $a_{w,x}$ and $a_{w,y}$). Both axis obtained an average reduction in vibration level off more than 22%.
For the removal of overburden task the sideway acceleration level $a_{w,y}$ was reduced by 26.8%.

Thus overall for all tasks the average dominant axis obtained the highest improvements in terms of reduced vibration level.

Table 3: Percentage reduction in vibration level in $m \cdot s^{-2}$, fuel consumption in liters and elapsed time in minutes after education.

	O#1	O#2	O#3	O#4	O#5	O#6	SD	Average
V-shaped motion								
$a_{w,x}$	12.25	22.68	22.10	30.08	22.41	11.11	6.558	20.10
$a_{w,y}$	-2.66	19.12	23.24	24.20	13.64	18.75	9.042	16.05
$a_{w,z}$	8.10	37.42	14.54	36.10	5.66	20.93	12.511	20.46
a_V	8.07	25.99	19.84	29.59	14.20	16.06	7.222	18.96
Fuel	12.83	-4.19	1.45	16.74	7.73	19.95	8.437	9.09
Time	6.09	-12.08	-6.16	-2.49	-3.25	-1.54	5.432	-3.24
Trenching								
$a_{w,x}$	15.33	29.65	15.00	34.78	13.64	26.32	8.193	22.45
$a_{w,y}$	8.24	33.16	6.57	26.90	16.67	13.04	9.655	17.43
$a_{w,z}$	28.51	34.36	15.31	18.67	17.07	22.22	6.739	22.69
a_V	20.29	32.58	13.15	27.14	16.34	19.97	6.514	21.58
Fuel	7.16	39.61	17.36	13.43	19.48	22.10	10.033	19.86
Time	-31.26	-21.94	-9.09	-4.96	-3.94	-9.64	9.878	-13.47
Removal of overburden								
$a_{w,x}$	26.25	-1.90	21.23	41.99	10.53	37.50	15.051	22.60
$a_{w,y}$	24.03	5.43	19.27	40.54	25.00	35.48	11.314	24.96
$a_{w,z}$	25.33	32.38	18.17	28.81	20.69	16.00	5.816	23.56
a_V	25.25	13.86	19.36	37.73	19.86	29.78	7.795	24.31
Fuel	7.91	36.43	17.15	4.76	7.46	10.63	10.721	14.06
Time	-7.58	3.61	-24.05	-46.87	-3.40	-5.42	16.926	-13.95

4. Discussion

The objective of this work is to investigate whether whole-body vibrations can be reduced in backhoe loaders by education of skilled operators. The results shows that the vibration level decreased more than 20% in average and there is a positive relation between fuel consumption and whole-body vibration exposure. This was also the finding in [20] and [21].

Based on the average reduction in Tab. 3 and the typically exposure values in [32] and assuming an operator should spend all day on doing V-shape operation without education, then according to [3] the operator was

only allowed to do this for 3 hours and 8 minutes in order to not exceed the daily exposure action value on $0.5m \cdot s^{-2}$. After the education and with the decreased vibration level the permitted work time for V-shaped motion is 5 hours and 2 minutes instead. This is a significant improvement.
Regarding the two excavating tasks the vibration exposure is typically low enough without any specific education that the operator could spend all day doing these task without exceeding the daily exposure action value [32].
Assuming a workday divided equal into the three tasks based on the typically exposure values in [32] the permitted work time is increased from 7 hours to above 11 hours as a result of the education without exceeding the daily exposure *action* value. Though the daily exposure *limit* value allows much longer operation times. In reality the workday of a backhoe loader will include a number of different tasks with some idle time also. Thus there seems to be no risk for the operators of modern backhoe loader operators to exceed the daily exposure *limit* value in any way.

Observing the percentage vibration reduction underpin that all of the six operators picked up the knowledge presented in the lesson. Except for one single task performed by operator #2 fuel was saved for every task. This implies a positive connection between the low vibration exposure and fuel consumption though the fuel savings differs a lot depending on the operator. By interview it was observed that some operators especially from one man companies care a lot more about the fuel consumptions.

Concerning the elapsed time of the tasks it is clear that most tasks demanded more time although two tasks were done faster while still managing to save fuel and decrease the vibration level.
The extra time consumption corresponds to a reduction in productivity. Clearly, the increased time is due to the new operator input. This is not surprising since the operator action changes from habit based to a more mindful operation [33]. It is reasonable to expect an increase in productivity when the new types of operations become habits [33].
A side effect of the increased time was the precision of the work. In several cases the tasks were performed more precisely the second time as a result of the smoother operation of the machine. A more precise job will decrease the demand of subsequent manual trimming afterwards. Smoother operation resulting in fewer vibrations in the machine also decrease the wear on bushings and joints as well as the fatigue on structural parts. This will probably

contribute to fewer service expenses on long term.

Subjectively, the operators found the lower engine rotational speed especially annoying in the sense that they felt the available power and hydraulic volume flow were too small for the excavating task.
All of the operators felt an improvement of the work environment. Thus WBV is a measure for the experience of the ride comfort as claimed by [5] and [6]. Smoother operation gained fewer vibrations and lower noise level. Also they felt less stress carrying out the tasks.
The most important finding in the experiment is that the cognitive process by the operators during this experiment is the key to obtain good results. This is underpined by [34] who has studied learning mechanisms of operators.

Based on the results it is expected that the operators can catch up with the decreased productivity in terms of elapsed time and still gain better work environment and save fuel savings. It will take time before the new way of operating becomes a habit [35]. The participating companies do believe that the benefits from lower machine wear, lower fuel consumption, fewer sick days and decrease the demand of subsequent manual trimming will compensate for increased elapsed time.

Experiments with eco-driving courses on passenger cars [17] and busses [18], [19] have investigated the long term effect of the courses. The common conclusion is the one that the operator tends to fall back into their original driving habits. Reinforcement learning by reward could be a way of maintaining the effect [36].

5. Conclusion

It is demonstrated that education via instructions can reduce the WBV level in backhoe loaders considerably. The experiments carried out in the reported work also suggest that there is a positive relation between fuel efficient operation and the WBV level. Thus fuel can be saved and the work environment of the operator can be improved at the same time.

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