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Operator effect on the performance of a wheeled excavator

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Abstract.

This paper investigates how human operators influence the performance of a wheeled excavator. A 16t wheeled excavator with a load-sensing hydraulic system was instrumented with sensors enabling kinematic and hydraulic measurements. Two professional and five non-professional operators executed a standardized 90° dig-and-dump-operation under controlled operating conditions. From the recorded data, three indicators were derived: mean cycle time, simultaneity level of actuator operation and mean hydraulic pump power. The correlation between these indicators was analysed across multiple repetitions performed by each operator. The results highlight the influence of operator behaviour on machine performance.

Keywords. Excavator, mobile machines, mobile hydraulics, operator, duty cycle

1. INTRODUCTION

Improving the energy efficiency of off-highway mobile machinery is a key lever for reducing fuel consumption, operating costs, and emissions in construction and mining. Hydraulic excavators are among the most energy-intensive machine types. While extensive research is conducted on improving component and system efficiency (optimized hydraulic architectures, energy recovery, advanced control strategies etc.), the influence of the human operator on the energetic performance of the machine has received comparatively less attention. Modern excavators offer increasing degrees of automation and assistance, making it important to understand which aspects of operator behaviour most strongly affect performance, and how they interact with the hydraulic system.

This gap is addressed by experimentally studying the influence of different operators on the performance of a wheeled excavator during a standardized load cycle. However, the scope of this work is limited to a 90° dig-and-dump-operation.

2. STATE OF THE ART

While many authors agree that the operator is one of the largest influences on machine performance, rigorous quantitative studies are still relatively scarce, especially for excavators. This section briefly summarizes a selection of existing research on this topic.

Kunze et al. [1] analysed 153 measurements of 7 different operators, ranging from novice to expert level, performing trenching operations with a 20t wheeled excavator. From the gathered data and video analysis they computed the mean cycle time and simultaneity level ("[…] the number of hydraulic cylinders being manipulated through the joystick axes at the same time, averaged over a closed working cycle." [1]). The exact signal-processing steps are not described in detail. They found that cycle time correlates negatively with simultaneity level and used k-means clustering to separate operators into groups (Figure 2.1), that correspond well to their skill level.

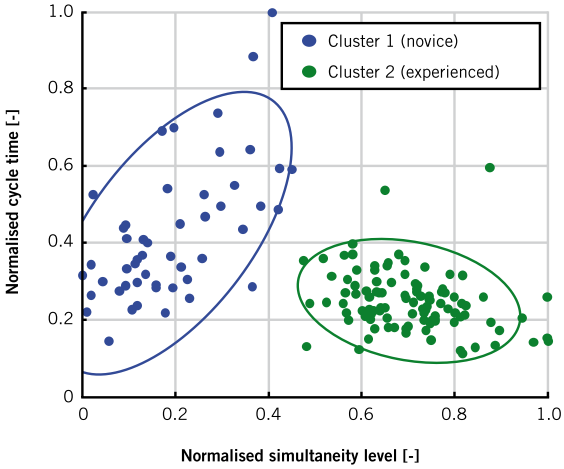

Figure 2.1. Clustering excavator operators by skill level [1]

Mieth et al. [2] extended this approach to 285 trenching cycles and included mean cycle power as an additional feature. Their results indicate that more skilled operators not only achieve higher simultaneity and shorter cycle times, but also higher hydraulic power usage.

Extensive research by *Filla et al.* [3–7] and *Frank et al.* [8, 9] addressed operator interaction with wheel loaders, ranging from development of operator models [3–5], to studies on machine operability (i.e. the ease with which the operator can perform the task) by using psychophysiological measurements (heart rate, finger temperature etc.) [5–7] and operator influence on machine performance [8, 9]. *Frank et al.* [8, 9] performed different loading cycles with 73 operators and measured productivity (moved material per time , t/h), and efficiency (moved material per fuel consumption, t/l). Their results show that for predefined duty cycles, productivity can increase by up to eight times, and fuel efficiency by up to three times for highly skilled operators. One interesting finding from machine operability research is that design changes in components or control logic can unintentionally increase operator workload, worsen bucket handling and reduce fuel efficiency if they conflict with established operator strategies [5].

Sturm [10] used measurements from three excavator operators to validate a developed operator model, but did not systematically analyse the operator influence itself.

Inderelst et al. [11] studied various influences on a 21t crawler excavator, including hydraulic system principle (LS vs. NFC), engine speed, operator (four different operators), and ground conditions. They found that the spread in fuel consumption and digging performance caused by different operators is comparable in magnitude to changes achieved by hardware or parameter modifications.

Fecke [12] used fleet management telemetry data from nearly 12000 machines (excavators and wheel loaders). His work focusses on deriving standardized duty cycles and reducing operator variability in efficiency measurements.

3. METHODOLOGY

The objective of this study is to quantify the influence of the human operator on the performance of a wheeled excavator. The used methodology is similar to *Kunze et all* [1] and *Mieth et al.* [2].

To this end, a Volvo EW160D wheeled excavator was instrumented with an extensive sensor array and operated by drivers with different experience levels under controlled test conditions.

In detail, the methodology comprises four main elements:

- Test machine and instrumentation: description of the excavator and the additional measurement equipment installed on the hydraulic and mechanical subsystems.
- Test operation and operators: definition of the task and the participating operators.
- Derivation of performance indicators: computation of used hydraulic pump power, simultaneity level of actuator operation, and mean cycle time from the recorded data.
- Assessment of limitations: discussion of constraints and uncertainties of the experimental design and data evaluation.

The following sections describe each element in detail.

3.1. Test Machine

The experiments were conducted using a Volvo EW160D, a 16t wheeled excavator equipped with a load-sensing hydraulic system. The machine remained in its original configuration; no major modifications were made to the drivetrain or the control system. Only measurement equipment was added to enable data acquisition.

3.2. Data Gathering

The excavator was equipped with a range of sensors to capture the relevant hydraulic and kinematic quantities during operation. There is additional measurement equipment installed (for example, optical sensors), these were used for research outside the scope of this work and therefore aren’t described here.

3.2.1. Kinematic Measurements

Figure 3.1 schematically depicts the placement of the wire-based linear position sensors on the boom, stick, bucket, and auxiliary boom cylinders. These sensors (S1–S4) measure the extension and retraction of the respective cylinders, enabling the calculation of the linear actuator velocities via numerical differentiation.

In addition, Inertial Measurement Units (IMUs) were mounted on the upper carriage and on the individual components of the excavator arm. These IMUs provide the rotational motion of the upper carriage and the arm links as well as the inclination, allowing reconstruction of the excavator arm kinematics.

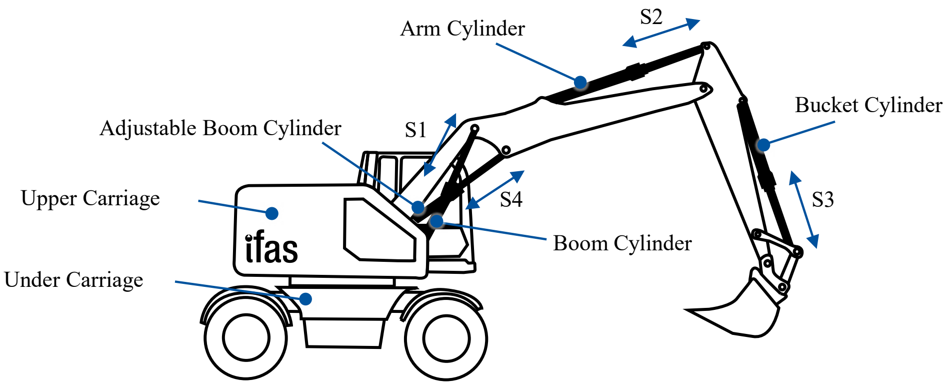

Figure 3.1. Measuring technology mounted on the test machine to record movement

3.2.2. Hydraulic Measurements

Figure 3.2 presents a simplified hydraulic circuit schematic, showing the locations of the sensors integrated into the hydraulic system. Numerous pressure sensors were installed at different points in the hydraulic circuit to measure:

- Actuator chamber pressures (excluding dozer shield and outrigger cylinders)
- Pressures at the main control valve (for the linear actuators)
- Load-sensing pressure p_{LS}
- Supply: Pressure of the main (p_{pump}) and secondary pumps (supply pilot pressure, braking and steering)
- Tank pressure
- Actuator pilot pressures

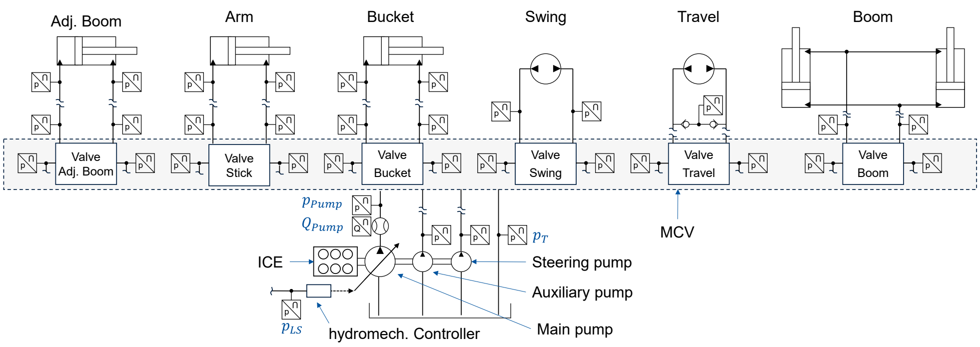

Figure 3.2. Measuring technology mounted to the hydraulic drivetrain

A turbine-type volume flow sensor was installed in the main pump outlet line to measure the pump flow. Note, that this introduces an additional pressure loss in the supply line, that is not present in series machines.

3.3. Performed Operation

Wheeled excavators are versatile machines typically used for digging, trenching, and grading operations [13]. Several defined operations were performed with the test machine during the measurement campaign; however, this paper focuses exclusively on an elevated 90° dig-and-dump-operation.

Figure 3.3 depicts the executed 90° dig-and-dump-operation. Each cycle consists, in simplified form, of:

1. Positioning the bucket at the excavation area
2. Filling the bucket with material
3. Swinging the upper carriage by approximately 90°
4. Dumping the material at the designated dump location
5. Returning to the initial position to start the next cycle

For this operation, the machine was positioned on top of a hill, approximately three meters above ground level. The material was loaded at ground level and dumped at excavator level. All operators performed repeated cycles under comparable conditions.

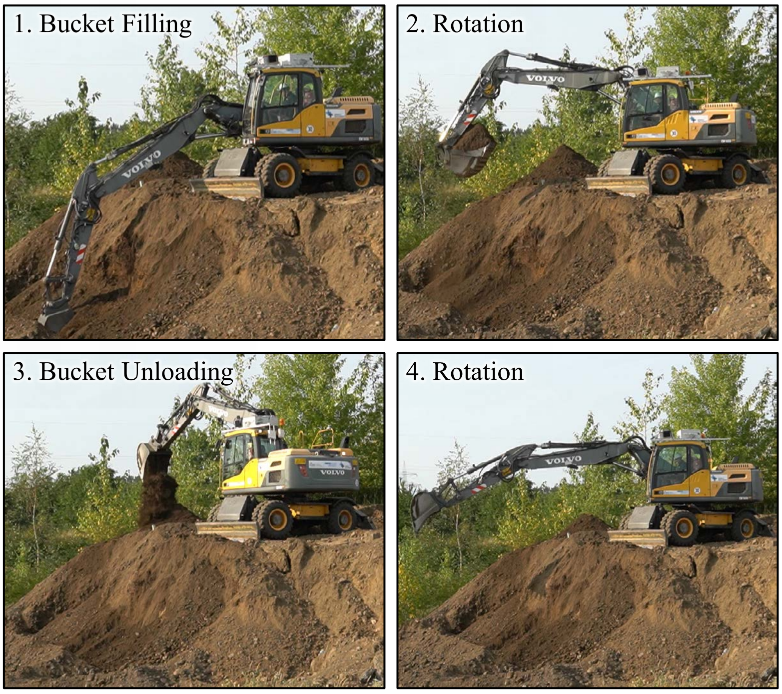

Figure 3.3. Example of performed 90° dig-and-dump-operation

The test series included two operator groups:

- Two professional operators (P1, P2), with substantial prior experience in operating excavators in daily construction work

- Five non-professional operators (NP1–NP5), with varying amounts of experience, ranging from intermediate to novice level

All operators executed the same predefined dig-and-dump-operation using the same machine and test setup (for example positioning), so that differences in performance can be attributed primarily to operator behaviour.

3.4. Calculated System Variables

From the recorded sensor data, several indicators were derived to quantify operator performance:

- Mean Pump power (compare *Mieth et al.* [2])
- Simultaneity level of actuator operation (compare *Kunze et al.* [1])
- Mean cycle time of the 90° dig-and-dump-operation (compare *Kunze et al.* [1])

The following subsections describe each indicator in detail.

3.4.1. Pump Power

Figure 3.5 shows the load-sensing pressure, pump pressure, flow and power for an excerpt of one of the measurements.

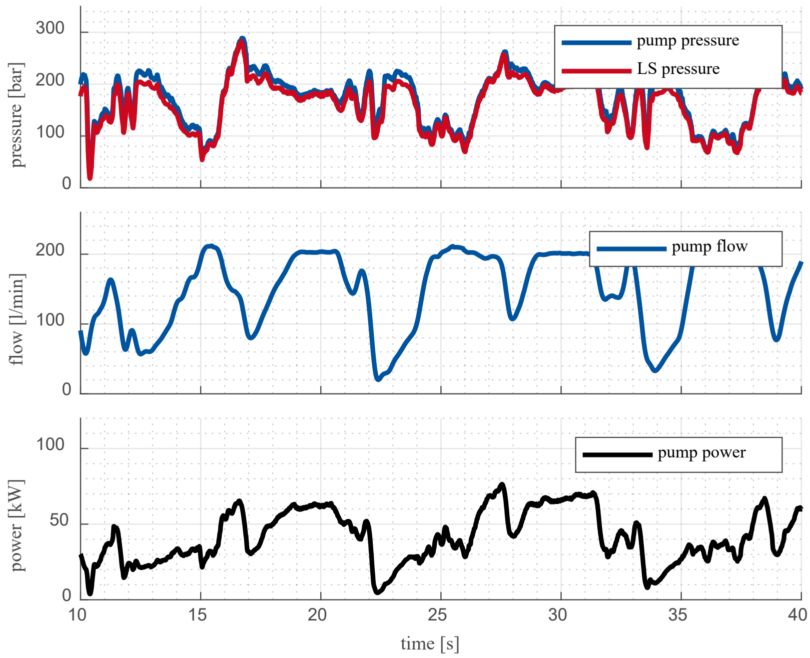

Figure 3.5. LS pressure, pump pressure, flow and power

The pump flow Q_{Pump} can be calculated from recorded impulses of the turbine-type volume flow sensor using a corresponding calibration curve. The instantaneous hydraulic power of the Pump P_{Pump} is calculated from the pump flow Q_{Pump} and pressure p_{pump} (equation 3.1).

$$P_{Pump} = Q_{Pump} \cdot p_{pump} \qquad (3.1)$$

During the measurement campaign, the pump pressure sensor proved to be unreliable, meaning that for some of the performed measurement the pump pressure value was not available. Instead, the pump pressure is calculated according to equation (3.2),

$$p_{Pump} = p_{LS} + \Delta p_{lS} \qquad (3.2)$$

where p_{LS} is the load-sensing pressure (maximum supply pressure of all active actuators) and Δp_{lS} is the load-sensing pressure difference. In equation (3.2) it is assumed, that Δp_{lS} is a constant offset, however in reality this is not true, as figure 3.6 shows (measurement with intact pump pressure sensor)

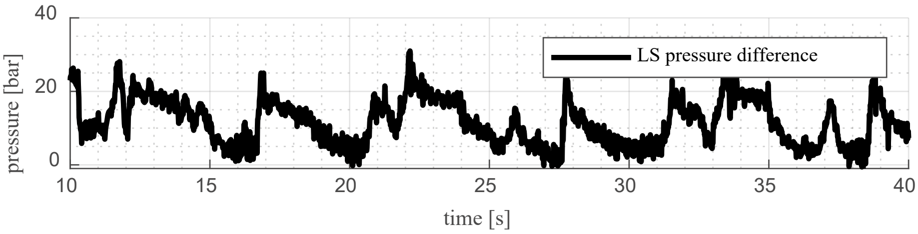

Figure 3.6. LS pressure difference

For the pump pressure calculation, a constant value derived from averaging was used. This introduces a small error in the pump power calculation. A more sophisticated approach would be evaluating the dependency of Δp_{lS} on pump pressure and flow, fit a function to the data und use this as the pump pressure estimation for the affected measurements, but this is outside the scope of this work.

With this approach focussing on pump power, potential operator influences on the total machine energy consumption or fuel consumption that arise from different engine operating points cannot be identified. The analysis is limited to the hydraulic subsystem. Specifically, the operator influence on the hydraulic power demand is captured, while effects related to engine and drivetrain efficiency lie outside the scope of this work.

The mean pump power $P_{Pump,mean}$ can be calculated by averaging P_{Pump} across operation duration.

3.4.2. Simultaneity Level

The simultaneity level, described by *Kunze et al.* [1] quantifies the mean number of actuators that are active in parallel during operation. Since operating several actuators simultaneously requires more coordination, a higher simultaneity level is typically associated with higher operator skill [1]. Within this work, the simultaneity is calculated as follows:

First a binary logic signal (filter) is generated for each actuator i, indicating whether this actuator is actively commanded at time t_n.

Figure 3.7. shows the measured stroke and pilot pressures for the bucket cylinder and the calculated cylinder velocity and activity filter signal for an excerpt of one of the measurements.

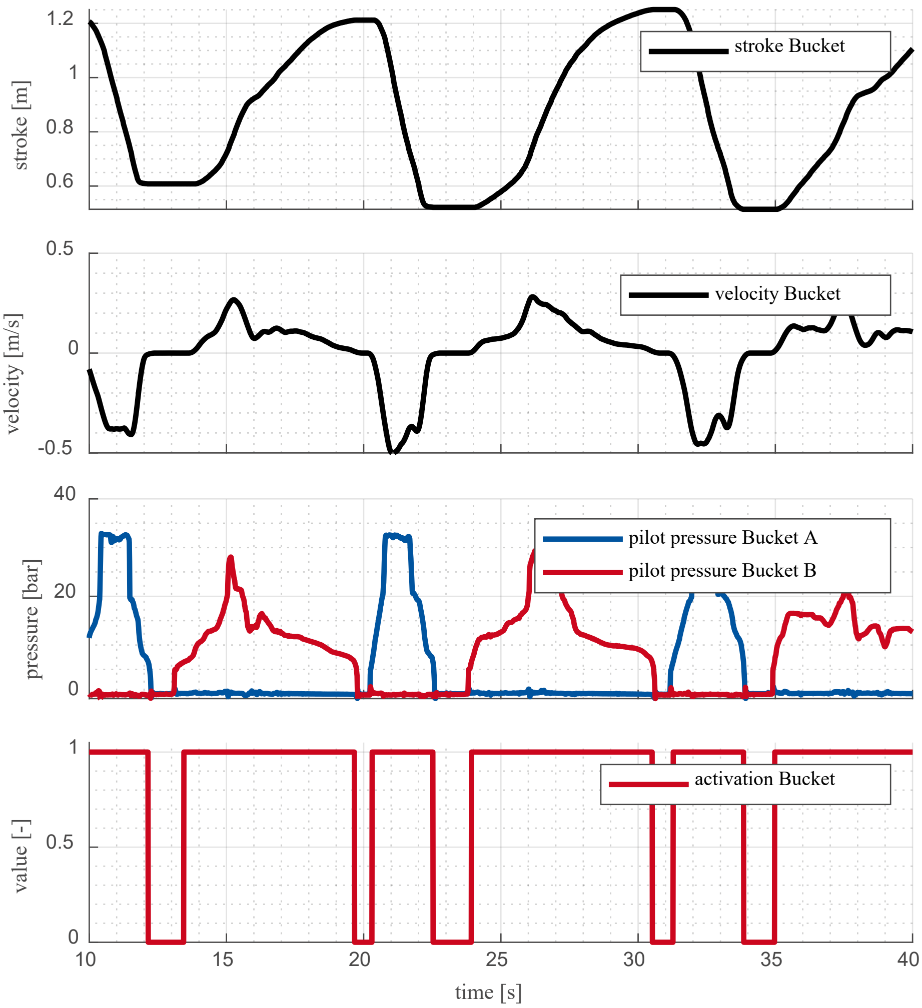

Figure 3.7. Bucket stroke, velocity, pilot pressure and activity filter signal

A straightforward approach would be to decide based on non-zero actuator (angular) velocity. However, numerical differentiation of the measured cylinder strokes introduces noise into the velocity signals. Filtering these velocities can in turn introduce phase delays, which complicates accurate detection of the onset and end of actuator movement.

To avoid this issue, the method used here relies on the pilot pressures of the hydraulic joysticks. The machine is equipped with hydraulic joysticks which pilot pressures actuate the spools of the main control valves. Thus, the pilot pressures $p_{\mathrm{pilotA},i}$ and $p_{\mathrm{pilotB},i}$ for each actuator i can be used as an indicator of operator command.

For each actuator i, the logic filter $\mathrm{filter}_i[t_n]$is defined by equation 3.3 as

$$filter_i[t_n] = \begin{cases} 1\,, if\ p_{pilotA,i}[t_n] \geq p_{tresh}\ or\ p_{pilotB,i}[t_n] \geq p_{tresh} \\ 0\,, otherwise \end{cases} \quad (3.3)$$

where $p_{\mathrm{thresh}}$is a pressure threshold determined experimentally. Note that only the main actuators were considered: Boom, Adjustable Boom, Arm, Bucket, Swing, Travel (not used during the evaluated operation). Auxiliary functions like the dozer blade and outriggers were not considered.

The simultaneity level is then obtained from the individual filters of all considered actuators by addition at each time step and then averaging over the entire observation period:

$$\text{simultaneity level} = \text{mean}(\textstyle\sum_i filter_i) \quad (3.4)$$

This yields the average number of actuators that are commanded simultaneously during the task.

3.4.3. Cycle Time

Cycle time is used in this study as a proxy for operator productivity. A more precise metric would be measuring the productivity directly in t/h, obtained by weighing the moved material and relating it to the working time. However, such measurements are beyond the scope and resources of this work.

All test operations were recorded on video. The number of completed buckets (i.e., cycles) was determined manually by reviewing the footage. For each operator and test run, the mean cycle time $t_{cycle,mean}$ was calculated with equation (3.5) as

$$t_{cycle,mean} = \frac{t_{eff}}{N_{buckets}} \quad (3.5)$$

where t_{eff} is the total effective working time and N_{buckets} is the number of counted buckets. Only successful cycles with a clearly full bucket were counted. This choice intentionally penalizes poor bucket filling, as cycles with low bucket fill would reduce the achievable t/h productivity and are therefore not treated as equivalent to full cycles. Non-productive pauses within were excluded from the total effective working time by cutting these intervals during the timing evaluation. In this way, the resulting mean cycle time reflects the net time required by each operator to perform one productive dig-and-dump-operation under the given test conditions.

3.5. Limitations

The methodology employed in this study is subject to several limitations and potential sources of uncertainty that must be considered when interpreting the results. First, the influence of operator fatigue and the sequencing of the different tests was not systematically controlled or analysed. Possible learning effects, warm-up effects, or performance degradation over time may therefore affect the measured performance, but investigating these effects in detail would require a substantially more extensive experimental design and is beyond the scope of this work.

Second, the characteristics of the excavated material were not captured. Neither the mass of the excavated material nor other properties like its moisture content was measured. The material was not uniform; it consisted mostly of soil with varying amounts of rubble.

Variations in density, cohesion, and moisture may influence digging resistance and thus the required hydraulic power and achievable productivity. Consequently, some portion of the variability in the results may be attributable to changing material conditions rather than purely to operator behaviour.

Third, the number of repetitions per operator and the total number of participating operators is relatively low. This limited sample size restricts the statistical robustness of the findings and makes it difficult to fully average out day-to-day performance fluctuations of individual operators. The results should therefore be interpreted as indicative trends rather than as statistically rigorous population estimates.

In addition, the determination of cycle times and bucket counting was carried out manually by reviewing video recordings. This process is inherently prone to human error. Although care was taken to ensure a consistent procedure, small inaccuracies cannot be ruled out.

Moreover, the chosen performance indicators simultaneity level and cycle time primarily describe the operator's handling of the machine during the active working phases. As previous work by the authors has shown [14]–[16], the machines spent a substantial proportion of the shift on typical road construction sites in idle, and the time share of different operations may fluctuate heavily from day to day. Consequently, depending on the type of construction site, the derived indicators may have limited explanatory power with respect to the operator's overall daily productivity. The results are likely more representative for quarry-like sites or other applications with relatively constant, repetitive operations than for urban road construction sites with highly variable tasks.

The dig-and-dump-operation used in the tests represents a simplified, standardized duty cycle that does not fully reflect the variability and irregularity of real-world operation. Instead, the focus and strength of the present methodology lies in comparing relative differences between operators under controlled, reproducible conditions, with particular emphasis on the hydraulic subsystem.

4. RESULTS

This chapter presents the results for the 90° dig-and-dump-operation. For each operator, the three calculated indicators mean cycle time, simultaneity level and mean pump power were evaluated. Pairwise relationships between these indicators are analysed using scatter plots (Figures 4.1–4.3) and the Pearson correlation coefficient r, which measures the linear association between two variables [17].

Figure 4.1 shows the mean cycle time and simultaneity level. A strong, negative correlation is observed ($r = -0.86$), measurements performed by operators with higher simultaneity levels achieve shorter cycle times. The two professional operators (P1, P2) lie close together, combining the lowest cycle times with the highest simultaneity levels. The non-professional operators (NP1–NP5) are more widely scattered, with generally lower simultaneity and longer cycles. NP1, who has the most experience among the non-professionals, approaches the region occupied by P1 and P2. This supports the interpretation of simultaneity level as an indicator of operator skill. It also confirms, that this effect found during trenching operation in [1, 2] appear to apply to 90° dig-and-dump-operation as well.

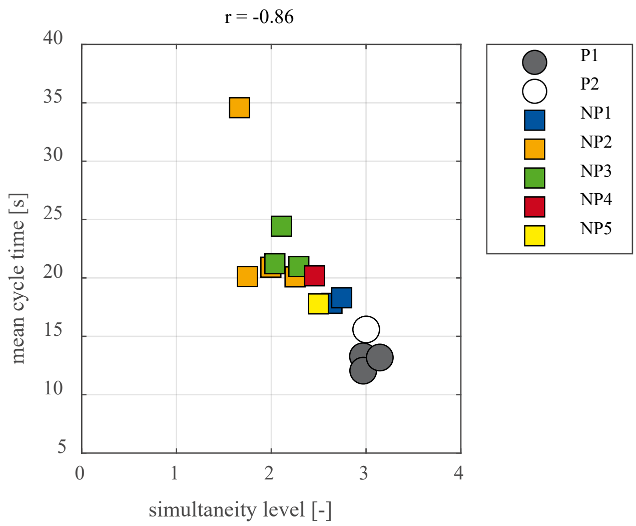

Figure 4.1. mean Cycle time and simultaneity level

Figure 4.2 plots mean cycle time against mean pump power. Here, a moderate negative correlation is found ($r = -0.49$). Overall, faster operation comes with a higher mean pump power, but the relationship is not strong. Further analysis can be conducted. This result aligns with results found during from trenching operations reported in [2]. An approach could be to analyse the net used power and system efficiency to find how effective the machines power is used by differently skilled operators.

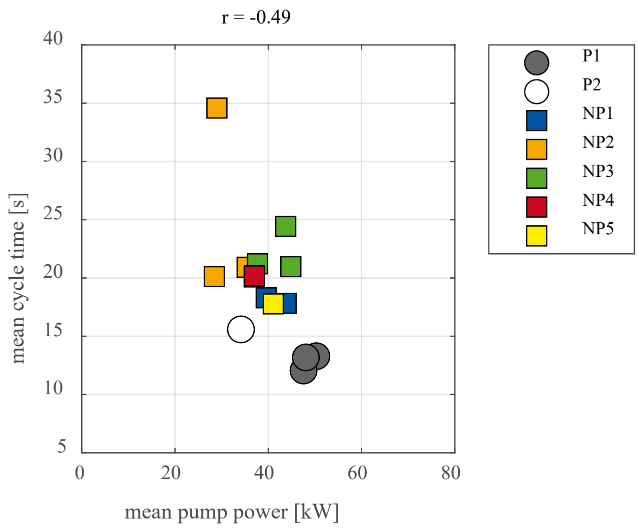

Figure 4.2. mean Cycle time and mean Pump Power

Figure 4.3 shows simultaneity level as a function of mean pump power. In this case, a moderate positive correlation is obtained ($r = 0.7$). Operators with higher simultaneity levels tend to exhibit higher mean pump power, which is consistent with the expectation that more frequent parallel actuator operation increases hydraulic power demand. This result corresponds to a similar trend found during trenching operation in [2].

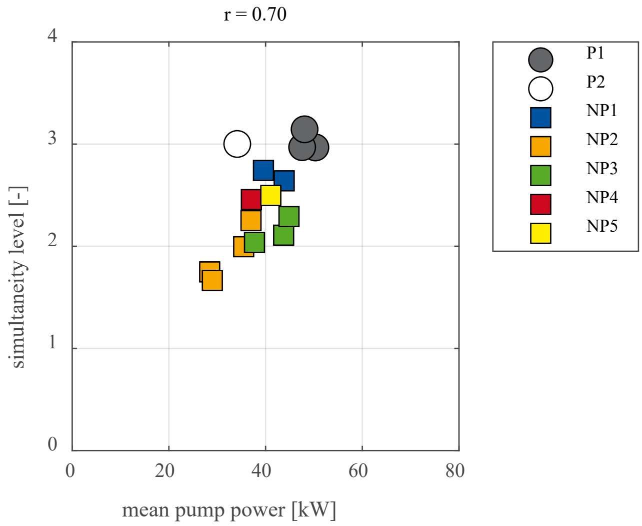

Figure 4.3. Simultaneity level and mean pump power

In summary, simultaneity level correlates strongly with cycle time and with mean pump power, whereas mean pump power and cycle time are only moderately related in this task.

5. Conclusion and Outlook

This work showed that operator behaviour has a clear and measurable influence on the performance of a wheeled excavator during a standardized 90° dig-and-dump-operation. Using an instrumented Volvo EW160D and a mixed group of professional and non-professional operators, it was possible to relate objective indicators such as cycle time, pump power and a pilot-pressure-based simultaneity level to differences in how the machine is handled. In particular, the simultaneity level proved to be a useful proxy for operator skill, capturing how effectively actuators are coordinated.

Building on these findings, future work should move from power-based to energy-based evaluation by relating input energy at the pump to useful work at the actuators, enabling a more direct assessment of hydraulic efficiency under different operators and load cycles. It is also promising to extend the analysis to the additional recorded operations to understand how robust the identified relationships are across varying tasks. In the longer term, the indicators could be used in operator training or assistance systems and help improve both productivity and energy efficiency of mobile hydraulic machines in real-world applications.

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Prof. Katharina Schmitz studied mechanical and chemical engineering at RWTH Aachen University and Carnegie Mellon University, Pittsburgh (USA) and graduated 2015 as Dr.-Ing. at RWTH Aachen University. Since 2018, she is full professor at RWTH Aachen University and director of the Institute for Fluid Power Drives and Systems (ifas). In addition, she is Vice Dean of the Faculty for Mechanical Engineering at RWTH Aachen, a position she holds since 2020. Prof. Schmitz's awards and honors include several best paper awards and 2023 IMechE Joseph Bramah Medal award.