ABSTRACT
A study is undertaken to determine the most significant sources of variation in the operation of a large hydraulic shovel, and to quantify the effects on productivity. Data, including cycle times, bucket payloads and signals from various mounted sensors were collected from a Liebherr 996 hydraulic face shovel over four weeks. During this time variations were seen in operators, digability conditions and bench heights. Hypothesis on the sources of variation in the data have been generated and tested using ANOVA and t-test techniques. “The operator” is discovered to have the most significant effect on productivity and can be contributed to a 20% variation in bucket payload and a 25% variation in cycle time.

1.0 INTRODUCTION
The paper presents findings from a field study undertaken at WMC’s Mt Keith Nickel Operations in Western Australia. The aim of the study was understand the issues impacting on the performance of Liebherr 996 hydraulic face shovel with the focus on identifying and attributing sources of operational variation.

Figure 1 shows the typical month-to-month variation in production seen by the fleet of Liebherr 996 shovels operating at Mt Keith. Over the year, the difference between best and worst months is approximately 500 bulk cubic meters (BCM) per hour. This equates to approximately 35 percent of average hourly production. Understanding the source of this production variance is pre-emptive to implementing strategies to improve the overall productivity of the shovels.

The methodology used for this study was to conduct a comprehensive data collection field trial on Shovel 1066 at Mt Keith and to systematically analyse the data for sources of variation. The field trial was based on a similar study undertaken by Hall (2003) on an O&K hydraulic shovel, and involved recording machine signals, machine operation data and
geological data over a four week period. The analysis presented in this paper primarily uses the machine operation and geological data collected from these trials. Productivity indicators such as bucket load, instantaneous productivity and cycle times are tested, using Analysis of Variance (ANOVA) techniques, against variation factors including operators, material digability and bench height.

The paper has the following structure. Section 2 gives an overview of the field trials, detailing the shovel operational and geological data collected. Section 3 describes the statistical analysis tools used in analysing data to understand how the factors affect the productivity indicators. Section 4 gives the results and discussions from the statistical tests on the effect of operators on productivity indicators. Similarly, Section 5 details the effect of digability and Section 6 the effect of bench height. Conclusions are drawn in Section 7.

2.0 FIELD TRIALS
Operational data was recorded from Shovel 1066 at Mt. Keith over a period of 4 weeks during which the shovel was subjected to various operators, digging conditions and bench heights. Three categories of shovel data were collected: machine signals, machine operation data and geological data. These are detailed in the subsections below.

2.1 Machine Signals Measured
The following machine signals was measured by installed sensors. The sensor outputs were low pass filtered to avoid aliasing and sampled at 50Hz using a purpose built data logger mounted onboard the shovel.

- **Stick, boom, and bucket roll cylinder extensions**: Measurements were made using three Celesco PT9420 cable transducers. These were fitted to the right-side boom, stick and bucket roll hydraulic cylinders, using purpose mounted brackets. They returned a current signal proportional to the extension of the cylinders.
- **Stick, boom and bucket-roll cylinder pressures**: Measurements were made using six Druck PTX 1400 pressure sensors. Two sensors were connected to each right-side cylinder, measuring pressures either side of the pistons. Each sensor returned a current signal proportional to the hydraulic pressure.
- **Machine house vibration**: Measurements were made using two Crossbow CXL04LP1 accelerometers. These were mounted on the left and right of the rear counterweight, and were oriented to measure the acceleration in the vertical direction.
- **Machine house slew rate**: One Crossbow IMU 300 rate gyroscope was fitted to the machine-house to measure slew-rate (swing velocity).
- **Shovel position**: A Global Position System (GPS) was build into the data logger. The antenna was mounted on the back of the machine house. Position and altitude information was logged each second.
- **Joystick references**: The joystick and pedal voltage signals were recorded.

2.2 Machine Operation (Annotation)
The machine signal data stream was manually augmented by an additional channel indicating the shovel state, i.e. dig, swing, dump, return, wait on truck, propelling and idle. This was done for 4 hours per day while viewing the operating shovel. This annotated data stream is used to determine the following:
• **Dig time**: the time from which the bucket teeth engage the muck pile until the bucket exits the muck pile.

• **Swing time**: the time taken to swing the loaded bucket from the end of dig to the waiting truck.

• **Dump time**: the time taken to dump the material in the bucket into the truck’s tray, i.e. from the point the bucket clam is opened until the bucket is empty.

• **Return time**: The time taken from the end of the dump to the beginning of the next dig.

• **Cycle time**: the total time taken to complete the four above.

In addition to the state annotation, truck payload was recorded as the trucks pulled away from the shovel. This was done using the trucks’ onboard payload monitoring system. Individual bucket loads were recorded by averaging the truck payloads over the number on passes required for the load. Instantaneous production rates were calculated, in tonnes/hour, for each cycle by taking the truck averaged bucket loads and dividing them by each cycle time recorded.

### 2.3 Geology

A history of the digging conditions was recorded through a number of variables relating to the geology of the dig material. The variables used to characterize the material are detailed below:

• **Bench Height**: Bench height was assigned into one of three groups: 10 meters, 15 meters and 20 meters. The height of the bench was gauged using the shovel height as a reference, and was confirmed with the operator. Occasionally, the bench conditions were not ideal. These situations included digging in the Edge Protection Zone (EPZ), digging out a haul route that had been covered by a blast rill, and the initial stages of digging a freshly blasted free-face shot. Under these non-ideal conditions, the bench height was either highly variable or the face angle to horizontal was small. These non-ideal situations have not been included in the analysis.

• **Digability Index**: A digability index was assigned for each shot number dug during the trials by the sites continuous improvement engineer, Tim Riley. This index is based on a 1 to 5 scale: 1 – very easy, 2 – easy, 3 – normal, 4 – difficult, and 5 – very difficult. Assignment of the digability index was a qualitatively analysis that took into account a number of factors including the geology of the block, its structural trend, the powder factor used for the blast, the number of blast holes, the blast hole pattern, blast drill penetration and the blast initiation. A summary of the digability index for each block dug during the trials is given in Table 1.

• **Rilling Index**: A rilling index, describing how well material rilled from the face was assigned and recorded during each annotation session. This index is based on a 1 to 4 scale, where a rilling index of 1 indicates a free rilling face not requiring any operator actions to bring material down. A rilling index of 4 is a very rocky face that tended to

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3 Mt Keith runs a fleet of Caterpillar 793C off-highway dump trucks. The payload monitoring system on these trucks was re-calibrated using in-ground scales one month after the field trails. The payloads readings used in this paper have been adjusted according to this calibration.

4 Tim Riley has 8 years experienced at Mt Keith and is very familiar with the geology and the digging conditions experienced in the pit.
stand-up, requiring the operators to use the teeth to dislodge material. The rilling index was found to be very closely correlated with Tim Riley’s Digability Index.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Digability Index</th>
<th>Geology Summary</th>
<th>Blast Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-424-45</td>
<td>4</td>
<td>Hard end of normal with a soft patch in SW and a hard patch SE.</td>
<td>Sub-optimal blast for looseness.</td>
</tr>
<tr>
<td>F-394-20</td>
<td>3</td>
<td>U/M softer rock to west, normal to east.</td>
<td>Generally loose tightening into NE corner.</td>
</tr>
<tr>
<td>F-469-67</td>
<td>1</td>
<td>Soft clay dirt, easy digging, ramp giving deepening face 8 - 15m.</td>
<td>On Oxide / Fresh interface - danger of harder toe at base of shot.</td>
</tr>
<tr>
<td>F-379-07</td>
<td>2</td>
<td>Nice soft rock.</td>
<td>Good blast but center lift not as loose as a trim shot.</td>
</tr>
<tr>
<td>F-379-08</td>
<td>3</td>
<td>U/M in west, normal to east.</td>
<td>Loose but may tighten into both northern corners.</td>
</tr>
<tr>
<td>F-379-12</td>
<td>3</td>
<td>Normal with local hard area in south.</td>
<td>Loose, but may tighten up in SE Corner iCT.</td>
</tr>
<tr>
<td>F-379-13</td>
<td>3</td>
<td>Normal with hard area in North.</td>
<td>Loose, but may tighten up in NE Corner iCT.</td>
</tr>
<tr>
<td>F-409-37</td>
<td>5*</td>
<td>Very variable, very hard east &amp; centre, normal to west.</td>
<td>Could be tight and blocky.</td>
</tr>
<tr>
<td>F-424-44</td>
<td>3*</td>
<td>Very variable, very hard SW, soft central band, normal to west.</td>
<td>Could be blocky on SE corner, with soft central zone.</td>
</tr>
<tr>
<td>F-424-47</td>
<td>3*</td>
<td>Very variable, hard in east, soft in north, normal to west.</td>
<td>Highly variable geologically, but should be normal overall.</td>
</tr>
<tr>
<td>F-424-52</td>
<td>4</td>
<td>Likely to be blocky / hard.</td>
<td>Loose but blocky, tightening to West.</td>
</tr>
<tr>
<td>F-424-53</td>
<td>3</td>
<td>Consistent, normal.</td>
<td>Should be loose, well fragmented.</td>
</tr>
<tr>
<td>F-379-15</td>
<td>3</td>
<td>Consistent, normal.</td>
<td>Should be loose, well fragmented.</td>
</tr>
<tr>
<td>F-379-16</td>
<td>3</td>
<td>Consistent, normal.</td>
<td>Should be loose, well fragmented.</td>
</tr>
</tbody>
</table>

Table 1. Summary of Digability Indices

3.0 MULTIPLE COMPARISONS ANOVA TESTING

Multiple comparison ANOVA (Analysis of Variance) testing is used to analyse the shovel operational data for sources of variation. ANOVA is a statistical technique used to test whether the difference between groups of data are caused by random variations, or by the factor used to group the data.

The ANOVA method works by partitioning the total variance of a set of data groups into two components: a between-groups component, and a within-groups component (see Vardeman, 1994 and Montgomery, 1976). The ratio of these two components (between-groups component over within-groups component) is the test statistic $F$. An $F$ value close to 1 indicates that there is insufficient evidence, in the data, to reject the hypothesis that the variation between group means is cause by randomness. Under this condition, the means for each group can be assumed the same and the grouping variable independent of the data. If the value of $F$ is much greater than one, there is sufficient evidence in the data to accept that there is more variation between groups than within groups. It can then be inferred that the factor used to group the data does affect the group means.

In this paper we visualize the output from the multiple comparison ANOVA by plots similar to that shown in Figure 2. The plot shows the output from a multiple comparison ANOVA test on 5 groups of data. The data groups are indexed, 1 to 5, on the y-axis. The mean for each group is found by projecting the center point of the circular icon onto the x-axis. The
wings either side of the circular icon represent the 95% confidence interval\(^5\) for that group’s mean. If the mean confidence interval for one group overlaps the mean confidence interval for another group, there is insufficient evidence in the data to assume, to 95% confidence, that the two means are statistically significantly different (i.e. there is insufficient evidence in the data to assume that the grouping factor influences the groups). For any two groups in which the confident intervals do not overlap, there is sufficient evidence to assume the two means are statistically significantly different and that the grouping factor has influence. In Figure 2, Group 1 is significantly different from Groups 2, 3, and 4, and Group 4 is significantly different from group 5. The other possible combinations of groups are not significantly different. The term ‘significant’ should be read as meaning ‘significant in a statistical sense to a 95% confidence’.

Figure 2. Example of a multiple comparison ANOVA output.

### 4.0 THE EFFECT OF OPERATOR SKILL ON PRODUCTION INDICATORS

Eleven operators used the shovel over the period of the trials. Their backgrounds ranged from trainee and beginner to expert operators. In this section we look at the effect operators have on bucket payloads, cycle-time, dig-time and instantaneous production rate.

Data from the field trials has been divided into three groups, each with a constant digability index and a constant bench height but containing operators with varying degrees of experience. The grouping is done to marginalize the effect of digability and bench height so that operator traits become more apparent. The three groups are summarized in Table 2. Note that only Operators F and G appear in more than one group.

<table>
<thead>
<tr>
<th>Operators</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digability Index</td>
<td>1 (Very Easy)</td>
<td>3 (Normal)</td>
<td>4 (Difficult)</td>
</tr>
<tr>
<td>Bench Height</td>
<td>15 meters</td>
<td>15 meters</td>
<td>20 meters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Op. G (expert operator)</td>
</tr>
</tbody>
</table>

Table 2. Operator Groups

\(^{5}\) It is customary to use a 95% confidence or 5% significance level in hypothesis testing.
In the following subsections we discuss the results from the multiple comparison ANOVA for each group.

### 4.1 Operator Group 1

![Figure 3](image)

Figure 3. ANOVA results for Operator Group 1 ((a) the effect on bucket load, (b) the effect on cycle time, (c) the effect on instantaneous productivity rate, (d) the effect on dig time).

Figure 3 shows the ANOVA results for Group 1 against, bucket load, cycle time, dig time and instantaneous productivity. The four operators in this group range in experience. Operator A is a beginner while Operator C is an expert operator and the site trainer. Operators B and D are both considered moderately experienced and experienced respectively.

The plots reveal that the operators do have a significant effect on productivity. The following observations are made from Figure 3:

- The more experienced operators have larger mean bucket-loads. The data shows a significant difference of 10 tonnes per bucket, approximately 15% of the bucket’s capacity, between Operators C and D and Operators A and B.
- The analysis indicates that Operator C, the most experienced of the operators, has a mean cycle time (at 38.45 seconds) that is significantly longer than all the other operators. The difference in mean cycle time across all the operators is approximately 6 seconds (approximately 20 percent). The two most experienced operators, C and D, share the slowest and second fastest mean cycle times, these are separated by 4.5 seconds.
The analysis on instantaneous productivity rate reveals that the two most experienced operators have the highest productivity. The difference over the 4 operators is 1500 tonnes/hour, approximately 26 percent. Despite having the slowest cycle time, Operator C holds a high productivity by having higher bucket loads. Operator C matches the productivity achieved by Operator D by having a slightly lower bucket load but faster cycle time.

The analysis indicates that the more experienced operators spend more time digging. The ANOVA reveals that Operators C and D have mean dig times significantly larger than Operators A and B. Operator D takes approximately 1.6s longer than Operators A and B, while Operator C takes approximately 3.1s longer. The data reveals that the differences between Operator C and D, and between operators A and B are not significant. When compared with bucket loads, it appears that operators who spend more time digging get better bucket fills.

In further analysis the cycle times have been broken into their other components revealing the following observations:

- There are two significantly different groups of mean return times, operators D and B have the fastest return times while Operators C and A have the slowest. The two groups are separated by approximately 2.3 seconds, approximately 25 percent. It is an interesting observation that Operator C, the most experienced has the slowest mean return time.
- Operator B gives the fastest swing time mean at approximately 6.2 seconds, 1.2 seconds faster (approximately 16 percent) than Operator C who gives the slowest. The analysis cannot differentiate between the swing time means of Operators A and D. It is again observed that the differences do not correlate with operator experience.

4.2 Operator Group 2

Figure 4 shows the ANOVA results for Group 2 against, bucket load, cycle time, dig time and instantaneous productivity. This group has less diversity in operator experience than Group 1, both Operators E and F are considered experienced operators and Operator G is an expert operator. The ANOVA shows the operators still have an effect on productivity although the significance of the effect is less than observed in Operator Group 1.

The following observations are made from Figure 4:

- There is no evidence to suggest that operators influence the bucket load.
- Operator G consistently produces faster cycle times then Operators E and F. Operator G’s cycle times are approximately 5 seconds faster (approximately 14 percent).
- Operator G’s mean dig time is the fastest at 11.3 seconds. This approximately 25 percent faster than Operators F and E, which have mean dig-times at 14.3 and 15.9 seconds respectively.
- Operator G’s faster cycle time results in a higher productivity rate than the other operators. The difference is approximately 300 tonnes/hour, approximately 6 percent.
Further analysis reveals that return time distributions are not dependent on the operators. Operators G and E, however, have mean swing times that are significantly lower than Operator F, with the difference being approximately 1.2 seconds or 15 percent. Operator G also has the fastest dump time with a mean of 3.35 seconds, 25 percent faster than Operator F with a mean time of 4.3 seconds.

4.3 Operator Group 3

Figure 5 shows the ANOVA results for Operator Group 3 against bucket load, cycle time, dig time and instantaneous productivity. The six operators in this group have a broad range of experience. Operator J is a trainee (and is being trained by Operator I), Operator H is moderately experienced, Operators I, K and F are experienced and Operator G is considered an expert.

Group 3 data again suggests that operators have a statistically significant influence on the production indicators. The following observations are made from Figure 5:

- Operator G’s cycle times are significantly lower than those of the other operators. The difference among experienced operators is approximately 4 seconds (13 percent), and if operator J, the trainee, is included the difference becomes 11 seconds (33 percent).
- In contrast to the cycle times, the bucket-load analysis shows that Operator G, the most experienced, has the lowest mean bucket-load. The variation in mean bucket loads across all operators is approximately 12 tonnes, 20% of the buckets capacity. No bucket-load data was collected for Op. H.
• Operator J’s mean dig time is significantly larger than the mean dig time of all the other operators. Operators F, G, and K have the lowest mean dig times while Operators H and I have intermediate dig times. The difference between the fastest and the slowest of the experienced operators is 5.5 seconds. If the trainee is included the difference is 10 seconds.

• The analysis on productivity rate reveals a variation 600 tonnes per hour among the experienced operators, an approximate 12 percent variation.

Further analysis also reveals that mean return times vary by 3.5 seconds with operators H and G the fastest and operators J, K, and F equally slow. Mean swing times vary by 1.75 seconds with Operator F the slowest at just over 8 seconds and Operators H and G the fastest. Operator G has the fastest mean dump time, 0.8 seconds faster than the other experienced operators.

5.0 THE EFFECT OF DIGABILITY ON PRODUCTION INDICATORS
The annotated field data was split up into three groups according to digability Index. The three groups correspond to a digability index of 1 (very easy digging), 3 (normal digging) and 4 (difficult digging). Each of the three groups contains various operators and bench heights but the data does not completely overlap, meaning not all operators and bench heights are experienced in each group. Other Digability Indices experienced during the field trials were not included in this analysis because data was only collected for a single operator.
Figure 5 shows the ANOVA results for testing the effect of Digability Index on: bucket-load, cycle-time, instantaneous productivity and dig time. The analysis reveals that Digability Index does effect productivity although the variation is less significant than that attributed to the operator. The following observations are made from Figure 5:

- Higher bucket-loads are obtained in easier digging. The mean bucket load for a digability index of 1 is approximately 4.0 tonnes higher than for a digability index of 4, approximately 7 percent of the buckets capacity. The ANOVA reveals that the mean bucket-load for a digability of one (46.6 tonnes) is statistically significantly larger then the mean bucket-loads for the other two digability groups. However, the analysis indicates that mean bucket-loads for the groups with digability indices 3 (43.0 tonnes) and 4 (42.8 tonnes) do not differ significantly.
- The highest Digability Index results in longest cycle time, with the difference between the three digability conditions being approximately 1.5 seconds, an approximate 5 percent variation. The 35.9 second mean cycle time for the digability index of 4 is significantly larger then those for digability indices 1 and 3. There is no significant difference between the mean cycle times of digability condition 1 and 3.
- A Digability Index of 1 produces the highest productivity at 4870 tonnes/hour. This is significantly larger then the productivity rate at Digability Index 3 at 4570 tonnes/hour which is significantly higher than the productivity rate at digability index 4, 4420 tonnes/hour. The overall difference between the three digability groups is 450 tonnes/hour, approximately 9.5 percent.
- The difference in dig time between the three conditions is approximately 1.0 second. The data indicates that the mean dig time for the digability condition 3 (14.75 seconds) is significantly lower than those for digability conditions 4 and 1. The cause of digability index 1 producing to longer dig times maybe a result of the softer material and deeper penetration obtained by the bucket teeth.

Analysis on return times, dump times and swing times reveals the following:

- A digability index of 1 gives the lowest mean return time (8 seconds), followed by a digability of 3 (9.25 seconds) and 4 (9.8 seconds). The cause of this difference is due to spotting time at the end of the return. In easy digging situations the operator doesn’t have to be so selective in positioning the bucket in preparation for the next dig.
- The mean dump time for a Digability Index of 3 is less than that for a digability index of 1 and 4, although the difference is small, about 0.35 of one second. The ANOVA cannot differentiate between the mean dump times for digability Indices 1 and 4. The longer dump times for a Digability Index of 1 is result of the larger bucket loads, that is, it takes longer to empty a fuller bucket. The longer dump times for a digability of 4 maybe a result of larger fragmentation, requiring more care while dumping into the truck’s tray.
- Analysis on swing time reveals that a Digability Index of 1 has the fastest swing time but only by 0.3 of a second.
6.0 THE EFFECT OF BENCH HEIGHT ON PRODUCTION INDICATORS

The data has been divided into three bench height groups, 10m, 15m and 20m. Data was omitted from these groups when the bench height for that data was highly variable, or, if the digging conditions were exceptional. Examples of exceptional digging conditions included working in the EPZ (Edge Projection Zone), or digging out haul routes that had been covered by blast rill. Each of the three bench height sets contains a number of operators, with no operator overlap amongst the sets. Digging conditions are also not consistent across groups. Digability is hardest for the 20m bench height, while the 10m and 15m bench height groups have both moderate and easy digability indices.

Figure 7 shows the ANOVA results for testing the effect of bench height on: bucket-load, cycle-time, instantaneous productivity. The following observations are made:

- The data appears to show that overall, a 15m bench height does produce higher bucket-loads. However, we must note that the significant difference between 20 and 15 meters may be because the majority of the data collect under a 20 meter bench height was for a harder digging condition. The mean bucket load for the 15m bench height (45.4 tonnes) is higher than that for the 20m bench height (41.7tonnes). The mean bucket-load for the 10m bench height (43.2 tonnes) is higher than the 20m bench, and lower than the 15m bench, but the ANOVA does not indicate that these differences are significant.
• The 15 meter bench gives the fastest mean cycle time (33.9 seconds), approximately 1.25 seconds faster than in the 20 meter bench, and 2.25 seconds faster than in the 10 meter bench.

• The overall productivity rate difference between the three bench height groups is 500 tonnes/hour, approximately 10.0 percent. A bench height of 15m produces the highest productivity at approximately 4900 tonnes/hour. This is significantly larger then the productivity rate at bench heights 20 and 10 meters.

• The 15 and 20 meter bench gives the fastest mean dig times, approximately 1.5 seconds faster than the 10 meter bench. Mean dig time for the 10m bench is, significantly slower than the mean dig times for 15m and 20m benches. The 10m bench gives the highest mean dig time, of approximately 16.2 seconds. The mean dig times for the 15 meter bench is the lowest at 14.6 seconds, although, according to the ANOVA, there is not a strong indication that this mean is statistically different from that of the 20 m bench which has a mean of 14.9 seconds.

In the analysis not shown in Figure 7, the 15 and 10 meter bench offer the fastest mean return times, approximately 1 second faster than the 20 meter bench. There was no indication the bench height affected swing time or dump time.

The analysis indicates bench height does affect the production indicators to some degree, although the variation seen is small when compared to the affect of operators and digability. It appears from the data that, overall, a 15 meter high bench produces better production then a 10 meter or 20 meter bench height.

6.1 The effect of bench height on shovel position

Leading into this study, there was the suggestion that bench height might affect how the operators position themselves with respect to the face. There is anecdotal evidence that suggests when the bench height is high, operators, have the anti-productive behaviour of standing the shovel further from the face fearing that the face might collapse on them. In this section we use the data collected to test this theory.

From the machine signals data set, the hydraulic cylinder extension measurements were coupled with a kinematic model of the shovel’s arm to obtain the position of the bucket teeth. We use the maximum horizontal extension of the bucket teeth from the machine house during digging as an indicator of how far the operator is standing from the face.

Figure 8 gives the result for 95% confidence ANOVA on the effect of the three bench height groups on the maximum horizontal extension of the bucket teeth. The analysis indicates that the mean maximum bucket extension for the 20m bench (14.165m) is significantly lower than that for the 15m bench (14.25m), although the difference in the means is only approximately 10mm. The mean maximum bucket extension for the 10m bench (14.235m) lies between those for the 20 the 15 meter bench heights, but the ANOVA indicates that the mean dig reach for the 10m bench is not significantly different to either of the other bench heights.

From this analysis we can conclude that there is no evidence in the data that the operators stand further back from the face when the bench is higher.
7.0 CONCLUSIONS

This paper has aimed at understanding the main sources of variation affecting productivity in hydraulic shovel operation. The following conclusions are made:

- Operators are found to have the largest influence on machine productivity. In similar digging conditions, more experienced operators produced bucket fills that are as much as 20 percent (of total bucket capacity) higher than inexperienced operators. More experienced operators are generally found to cycle faster than inexperienced operators. In similar digging conditions, average cycle times among operators varied...
by up to 5 seconds. The variation in production rate across operators was found to lie in the range of 300 to 1500 tonnes/hour.

- Material digability is an important factor affecting production, but the variation is less significant than that attributed to the operator. A 1.5 second increase in average cycle times is observed in moving from the easiest to hardest digging conditions. Most of this occurs as an increase in return time. Return times for the easiest digging condition are, on average, 1.8 seconds faster than those for the hardest digging condition. A 7% decrease in payload is observed in moving from the easiest to the hardest digging conditions. Productivity rate was seen to increase by 450 tonnes/hour moving from the easiest to the hardest digging conditions.

- Bench height appears to affect productivity. Because it was not possible to collect data for bench heights in all digging conditions, this conclusion is suggestive rather than definitive. The data appears to show that a 15 meter bench is more productive than a 10 or 20 meter bench. The 15 meter bench produced, on average, bucket loads 3.5 tonnes higher than the 10 or 20 meter benches. Cycle times were 1.25 to 2.25 seconds faster for the 15 meter bench. The majority of this difference is due to faster dig and return times.

- Bench height does not have a significant effect on how operators position the shovel with respect to the face. There was no evidence in the data that: Operators stand back further from the face when digging higher benches.

ACKNOWLEDGEMENTS

The authors acknowledge WMC Resources and in particular Charles McHugh for his enthusiastic involvement in the study, and for providing the funding and access to the site and the Liebherr 996.

REFERENCES

