Proceedings of the World Congress on Engineering 2010 Vol II
WCE 2010, June 30 - July 2, 2010, London, U.K.

Scaling To Full Size Dipper Design Via Geometric and Performance Field Data

Tim G. Joseph, Member IAENG, Ning Shi

***Abstract*—Data from 1/20th by volume small scale field trials for conventional and concept dipper designs is evaluated and compared with ½ by volume mid sized and full sized ultra class conventional dipper designs. Digging effort through hoist motor current draw or strain gauging data was used as the performance indicator for comparison. Crowd effort, although available was not used as it represents a minor proportion of the total effort expended. The results of the comparison showed that there are linear relationships between dipper capacity and suspended load and peak hoist load. These relationships were used to establish normalizing factors in the units of original data measurement, allowing a common plot of all shovel sizes for the conventional dipper design. Given all evaluations are common, the conventional and concept dipper small scale field trial performance data suspended and peak load reference relationships were evaluated to allow prediction of the ultra class concept design performance from an independent ultra class shovel data set. The outcome yielded a peak hoist requirement of 15.5% less to achieve the same capacity production, representing good evidence to investigate the concept design further.**

***Index Terms*—dipper design, scaling approach, performance and geometric analysis, field tested**

I. Introduction

Example test results from a scaled concept shape dipper field test compared to a conventional model of similar size were collected and tentatively showed that the proposed dipper design performance indicated an improvement over the original design. To show that similar performance advantages would be manifest for the full size concept design without performing an expensive full ultra class concept field test at more than $1M, it is necessary to show that scaling through intermediate to larger sizes will hold. In this paper only ultra class box dippers pre 2001 models were considered, [1], [6] and [7], as too many new variables are introduced with the post 2001 models of Bucyrus and P&H, representing the largest cable shovel manufacturers, and little data is available for post 2001 dipper models.

Manuscript received March 14, 2010. This work was supported in part by JPi geo-industry engineering consultants, Edmonton, Alberta, Canada. Full names of authors are preferred in the author field, but are not required. Put a space between authors' initials.
Tim G. Joseph is Associate Professor and Director, Alberta Equipment - Ground Interactions Syndicate at the University of Alberta, Edmonton, AB, Canada. T6G 2W2; (phone: 780-492-3810; fax: 780-492-0249; e-mail: tim.joseph@ualberta.ca)
Ning Shi, was with AEGIS at University of Alberta, Edmonton, AB T6G 2W2. He is now an independent mining engineering consultant in Beijing, China.

If a relationship between dipper performance and dipper size from the available data can be established, this would allow greater confidence in scaling to a new concept ultra class sized dipper based on the performance and comparison of smaller and intermediate versions of similar design. Figure 1 illustrates an approach to make use of available shovel performance data collected or in the literature.

A literature and industry search for performance data representative of power draw from shovel monitoring systems or via hoist and crowd forces through strain gauging was made yielding table 1, which provides a summary of the available data that could be used.

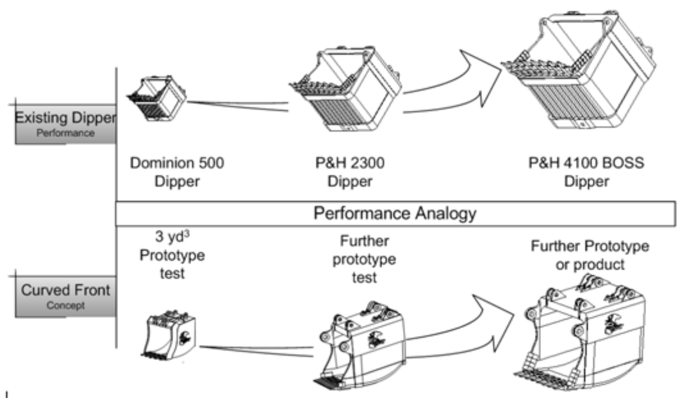

Figure 1: Scaling process

Table 1: Summary of available shovel performance data

	Hoist force?	Power draw	Source
2 yd^3 conventional	Yes	No	field test
3 yd^3 curved	Yes	No	field test
30 yd^3 conventional	No	Yes	lit. source
58 yd^3 conventional	No	Yes	field test

II. Shovel Analogy

If minor geometric differences are ignored, the first criteria that allows a relationship to be found between performance and size of dippers is that cable shovels must share the same structure, geometry, and mechanical configuration. Fortunately, over the past 50 years, the cable shovel has

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

changed little either in geometry or mode of operation. The only obvious difference is the two different crowding mechanisms: a rope drive from Bucyrus and a gear drive from P&H. As for the accompanying dippers from the two manufacturers, the only important improvement (or revision) is the side to side curvature. This is suggested to reduce the initial ground impact by engaging the teeth in sequence from the center to side.

Data for these newer model dippers was not available and only the more traditional dipper shapes have data reported and available here. All performance data used in this section came from P&H medium to ultra-sized shovels. The performance data from the field test for the small size range were based on the use of a Dominion 500 shovel, [2]. Therefore, an analysis is needed to show that the Dominion shovel has either the same or an acceptably similar configuration to the P&H shovel.

Figure 2 illustrates the comparison of the geometry configurations. The top right and bottom left projection of the Dominion 500 is scaled by 2.85 times to match the P&H4100. The projection lines show that the Dominion shovel has a very similar configuration to that of the current P&H shovel, although the Dominion 500 is over 50 years old. The crowd mechanism, double stick and gear drive are also the same. The only mechanical difference is that the P&H shovel crowd gear is located on the bottom of the handle while the Dominion shovel crowd gear is located on the top of the handle. The only significant geometrical difference is that the Dominion shovel handle is proportionally longer than the P&H shovel handle. From the Dominion 500 field test, it was found that the handle was seldom fully extended during digging cycles. Therefore, the above difference was not expected to appreciably affect the comparison between the two shovel models.

The P&H 4100 and 2300 model shovels are direct geometric and operational scales of each other.

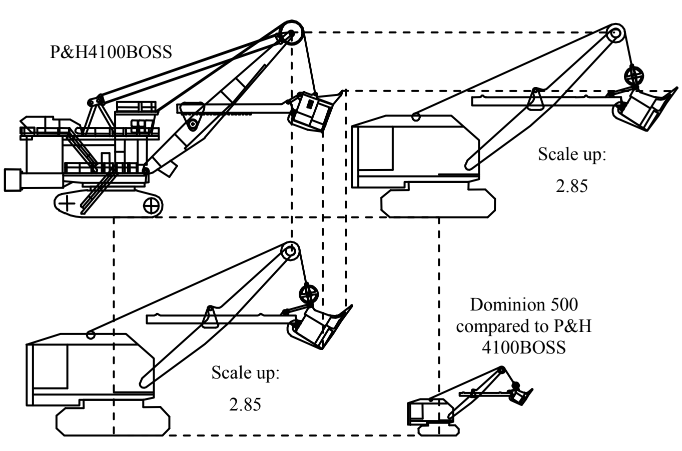

Figure 2: Geometry of P&H 4100 vs. Dominion 500.

III. Hoist Performance Analogy

Figure 3 shows a segment of the shovel hoist force plot for the Dominion 500 shovel with the original dipper, figure 4 shows a segment of hoist motor current plot for a P&H 2800 shovel, [3] and figure 5 shows a segment of hoist motor current plot of the P&H 4100 shovel, [5].

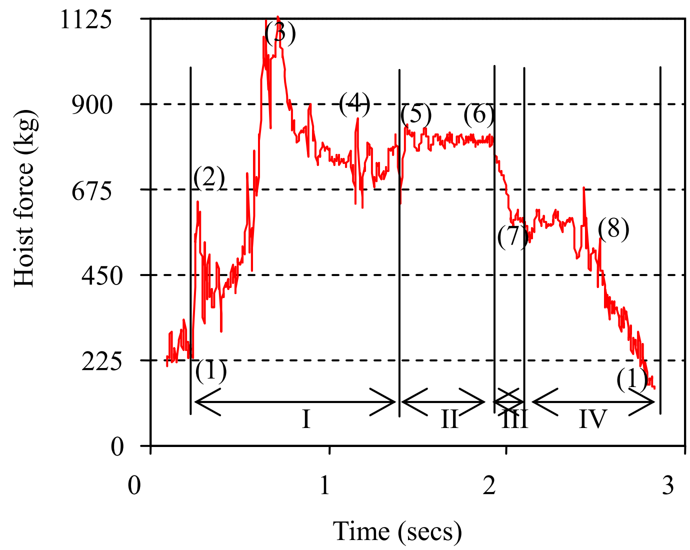

Figure 3: Sample cycle for Dominion 500 with 2 yd^3 dipper

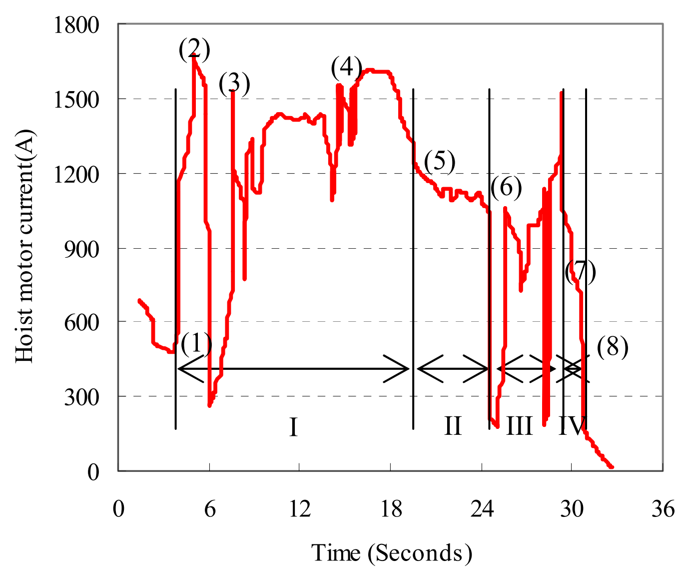

Figure 4: Sample for P&H 2300 with 30 yd^3 dipper [3].

Hendricks et al, [3] and [4], carried out an analysis of shovel performance monitoring. In this work, the electric motor power draw for the P&H 2300 mining shovel were recorded and analyzed. They concluded that the armature current of the motor is proportional to the output torque or force. For all three performance plots, figures 3 through 5, four phases and eight key points were identified and are marked as such on each.

I Digging in the face
II Dipper and handle held with swing to dump spot
III Dump into waiting truck
IV Dipper and handle held with swing to the mining face and lowering the dipper to the tuck position.

(1) Tuck start position prior to face digging activity
(2) Peak force due to dipper, handle, hoist drum inertia.
(3) Peak force due to maximum digging resistance
(2, 3) Digging
(4) Dipper release from face and swing to dump
(6) Before dumping in truck
(7) After dumping in truck
(8, 1) Returning to the tuck position.

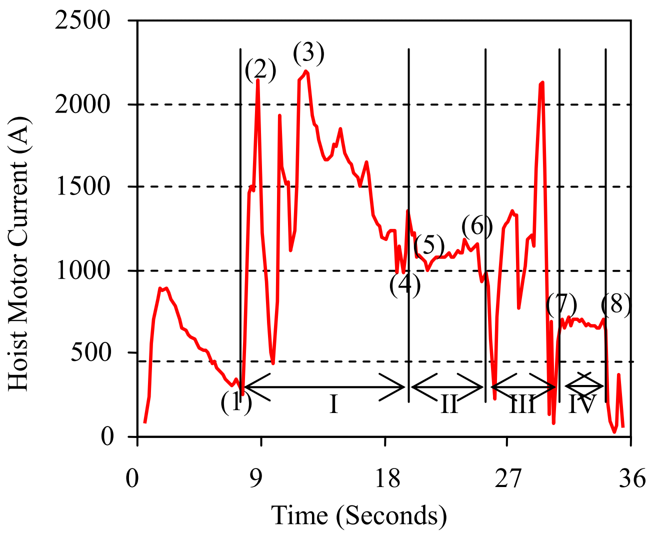

Figure 5: Sample for P&H 4100 with 57.5 yd^3 dipper [5].

The significant difference between the hoist force plot and the hoist motor current plots are the current plot has higher magnitude surges when the dipper and handle change motion direction. For example, when the dipper has been lowered to the tuck position to commence a cycle, there is a surge on both types of plot. However, the current surge has a much higher magnitude in contrast to the force surge monitored on the bail. This is because the hoist motor has to resist the inertia of its own motor, the transmission, the drive drum, the bail and the dipper while the hoist force monitored at the bail was influenced only by the inertia of the dipper and the handle.

From the plot for the P&H 4100 shovel combined with a video record, it was identified that the operator consistently lowered the dipper slightly after the dipper was pulled out of the face. As a result a clear flat segment that is evident is not so in other plots for the loaded swing phase.

In a summary, although the hoist current and the hoist force monitored on the bail exhibit slightly different features, these plots show very similar patterns.

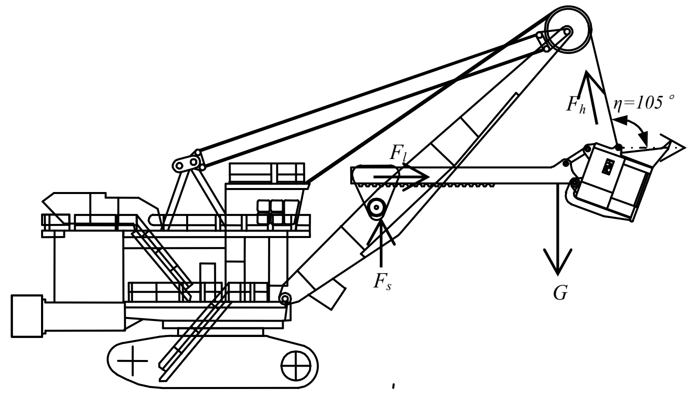

Figure 6: Dipper handle force equilibrium during payload suspension from face to dump

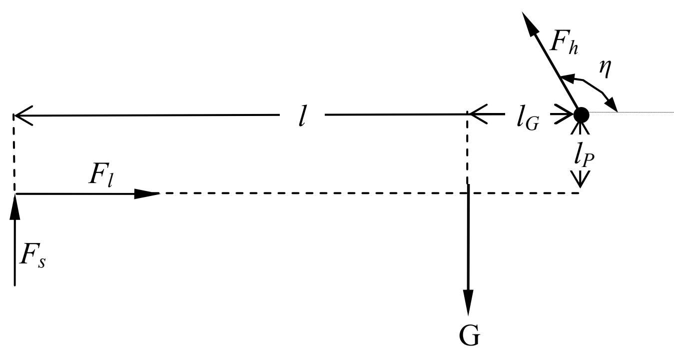

Figure 7: Free body diagram of the free suspended load condition from face to dump

To compare these hoist performance plots it would be more convenient to transform the motor currents to a force. An approach used to calibrate strain gauges for field tests was adopted to transform the current to the force. Figures 5 and 6 illustrate the force, angle and moment arm considerations, where F_s, F_l and F_h are the support reaction, crowd and hoist forces respectively, η is the hoist rope angle with the horizontal, G is the composite gravity load of dipper, handle and payload and l, l_G and l_P are the respective moment arms for the gravity load and hoist forces about the shipper shaft reaction point. By summing forces and taking moments, equation 1 is established for the free suspended system.

In figures 4 and 5, the free suspended load condition, phase II, during which the dipper was fully loaded and the handle was held steadily at the horizontal, was identified as the common reference point. Via equation 1, the ratio of F_h over G with respect to the cable angle η was evaluated and reported in table 2.

$$F_h = G\frac{(l - l_G)}{(l\sin\eta - l_p\cos\eta)} \quad (1)$$

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Table 2: Hoist force (F_h):suspended weight (G) ratio

Cable angle (η)	P&H 2300: F_h/G	P&H 4100: F_h/G
90°	0.85	0.83
95°	0.85	0.83
100°	0.85	0.84
105°	0.87	0.85
110°	0.89	0.87
115°	0.92	0.90

When the handle of the P&H 2300 and 4100 are held at the horizontal, fully extended and ready to dump, figure 6, the cable direction is about 105°. Over a number of the duty cycles, an average hoist motor current for free suspension and peak hoist motor current is obtained. By using the ratios shown in table 2, the suspended load (hoist force) is obtained, allowing the peak hoist force to be determined via scaling, table 3. A summary of the three shovels' specifications and hoist performance are also given in table 3. The dipper capacity and weights of the dipper and handle were taken from the manufacturers' specification sheets, [6] and [7]. It is assumed that the dippers were loaded at the nominal capacity, for a loose material density of 1700kg/m^3.

Table 3: Shovel specifications and performance, [2], [6], [7]

Model / Parameter	Dominion 500	P&H 2300	P&H 4100
Dipper capacity (m^3)	1.53 (2yd^3)	23 (30yd^3)	44 (58yd^3)
Dipper width (m)	1.2	2.9	3.6
Payload (kg)	2,600	39,000	75,000
Dipper handle (kg)	5,400	51,480	90,325
Suspended load (kg)	8,000	90,480	165,325
Peak hoist dig force (kg)	14000	125,280	285,560

Using the data from table 3, the relationships between dipper capacity, suspended load and peak force were plotted in figure 8. The two traces show that the hoist force is proportional to the dipper capacity. In other words, for a given digging material, the hoist performance to shovel capacity relationship is linear.

Figure 9 illustrates the peak hoist force increment compared to the free suspended load (hoist force) for the three shovels. The definition of the increment in figure 9 is given by equation 2:

$$IR = \{(Hp - Hs) / Hs\} \, 100\% \qquad (2)$$

Where IR is the increment and H_P and H_S are the peak hoist force and suspended load respectively.

The P&H 2300 shovel exhibited a lower rate of increment. This can be explained as the P&H 2300 shovel data used in the study were from a different mine site where the ground material was relatively easier to break.

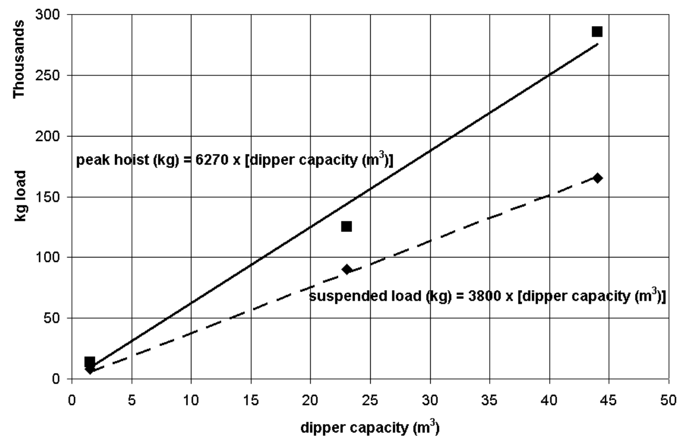

Figure 8: Dipper capacity versus the suspended load and the peak force

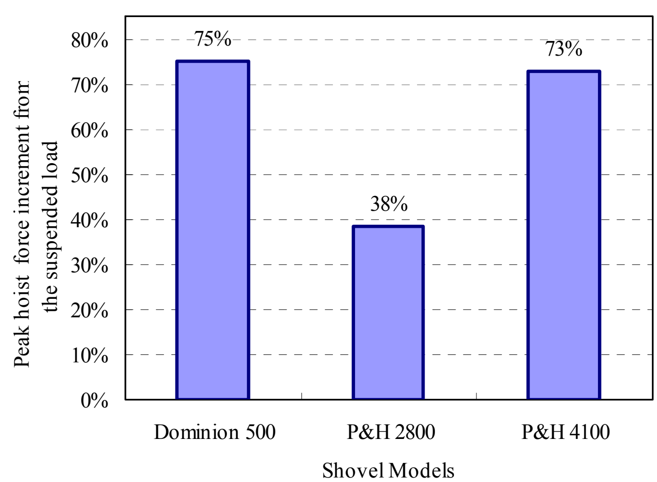

Figure 9: Peak hoist force over suspended load by shovel

IV. Crowd Performance Analogy

During the digging cycle, most of the energy was consumed in hoisting; only a small portion of the energy was consumed in crowding. The crowding performance of the Dominion 500 and P&H 2300 shovels is briefly reviewed, but will not be used in the subsequent scaling analysis

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Figure 10 illustrates a segment of the crowd force for the Dominion 500 shovel. Here the tensile forces are positive and the compressive forces negative. Figure 11 illustrates a segment of the hoist motor current plot for the P&H 2300 shovel. In general, the two shovels operate very similarly, with the crowd force and the crowd motor current plots exhibiting similar patterns. Like the hoist motor current plot for the P&H 2300, due to the inertia effect of the motor and transmission, the crowd motor current plot shows higher frequency and magnitude of fluctuation.

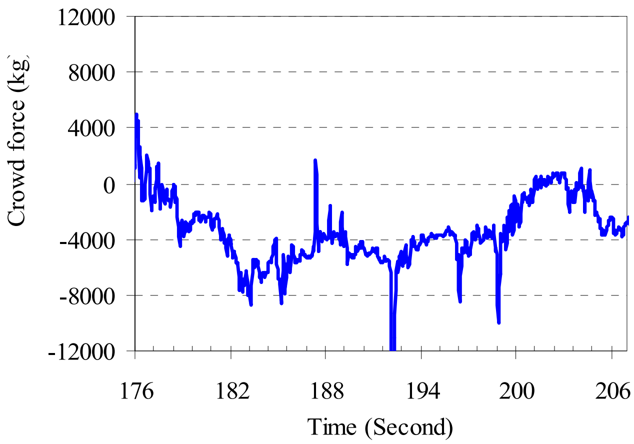

Figure 10: Sample crowd force plot for the Dominion 500

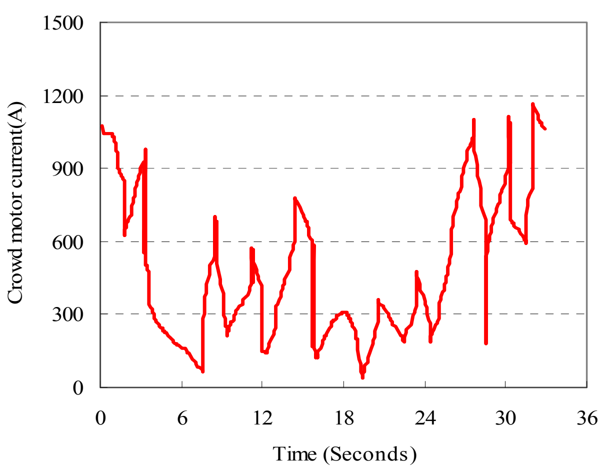

Figure 11: Sample crowd current for the P&H2300 after [3].

V. Normalized Hoist Performance to Permit Scaling

Figures 12 through 14 illustrate three hoist performance plots for the three different shovels, the hoist force plot for the Dominion 500 shovel and the hoist motor current plots for the P&H 2300 and 4100 shovels. Although some shape similarity can be seen in the three separate plots, it is hard to identify common characteristics due to different units and scales.

In this evaluation, the three sets of hoist performance data that are of varying shovel size data source were normalized by using a normalizing factor that is the free suspended load expressed as an equivalent hoist force or motor current. The average free suspended force or motor current for the different shovels are summarized in table 4.

The resulting normalized performance data obtained were plotted in figure 15, enabling the three sets of data to be compared on the same chart.

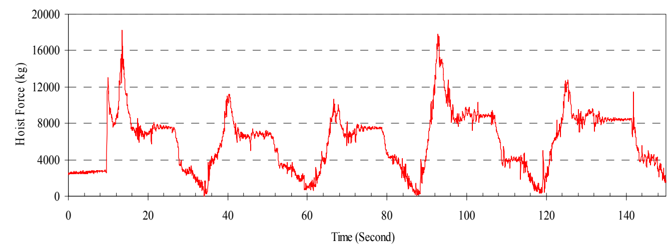

Figure 12: Dominion 500 shovel hoist force plot

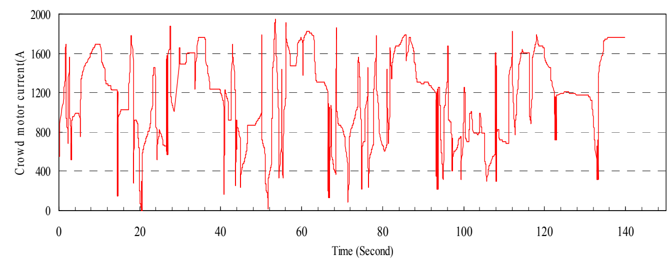

Figure 13: P&H 2300 shovel hoist motor current plot

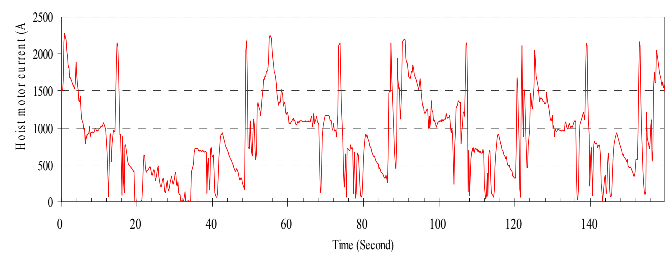

Figure 14: P&H 4100 shovel hoist motor current plot

Table 4: Shovel performance data normalizing factors

Shovel performance data	Normalizing factor	Units
Dominion 500 hoist force	8000	kg
P&H 2300 hoist motor current	1300	A
P&H 4100 hoist motor current	1100	A

From figure 15 it is obvious that the Dominion 500 and P&H 4100 shovels have similar digging cycle shapes. Some cycles are almost identical. The P&H 2300 has smaller peak values than the other two shovels. This is due to the different working geology and operating conditions of the source data. This enhances the relationship between the P&H4100 and Dominion 500 which worked in similar oil sand conditions.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Figure 15 indicates that the performance of the traditional flat front dippers on both the Dominion 500 and the P&H 4100 can be directly correlated through the capacity – suspended load relation established in figure 8, the similar suspended to peak load increment illustrated in figure 9 and the normalization factors established in table 4.

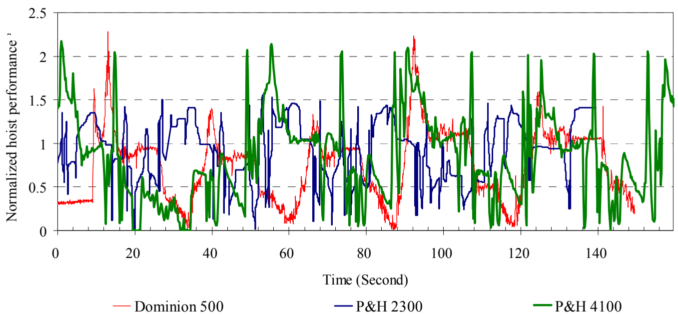

Figure 15: Dominion 500, P&H 2300 and 4100 shovel normalized hoist performance index plots

It can thus be concluded that by correlating the hoist performance data between the traditional and concept dippers tested using the same Dominion 500 test shovel, and using the scaling relationships established above between small and ultra class traditional dippers, ultra class concept dipper performance can be predicted.

VI. SCALE FIELD TRADITIONAL VERSUS CONCEPT DIPPERS

The hoist force plots representing the traditional 2yd^3 AMSCO dipper to the 50% by capacity concept 3yd^3 dipper but with the same tare weight in figures 16 and 17 were compared. From this comparison it can be observed that:

(1) The concept dipper took a 50% greater payload without a significant increase in generating face resistance forces. The average stabilized suspended mass (dashed lines) increased from 8,000kg to 9,100kg. The concept dipper has 0.76m^3 (1 yd^3) more capacity. If the extra capacity is filled with loose oil sand, the extra weight is 0.76m^{3}x2000kg/m^3/1.3=1176kg, where 2000kg/m^3 is the bank density and 1.3 is the swell factor. The difference of 1,100kg measured is about equal to the extra expected oil sand weight in the new dipper.

(2) The concept dipper yields a lower overall peak hoist force, which was the sum of the weight and the maximum digging resistance in the face.

(3) The hoist force during the digging period did not vary between the two designs; however, the concept dipper, being somewhat wider than the original dipper, seemed to yield qualitatively a smoother hoist force trace.

Other parts of the plots corresponding to dumping, swinging and tucking are almost identical between the two dippers, which should be expected as the two dipper weights and modes of attachment were matched.

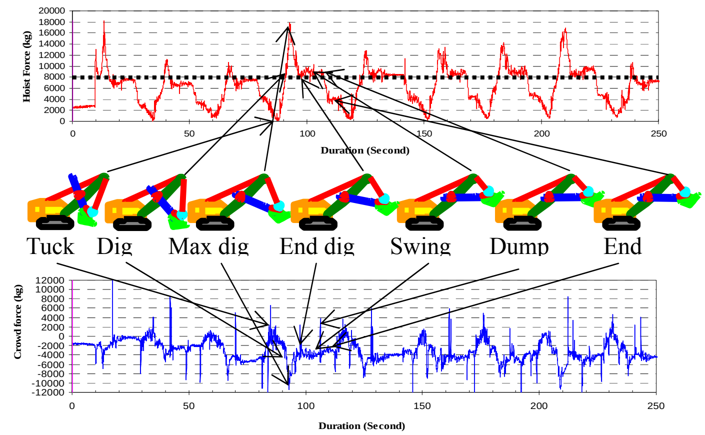

Figure 16: Hoist and crowd force plots for the original AMSCO 2yd^3 dipper

Table 5: Dipper test results summary

Performance	Original Dipper (2 yd^3)	Concept dipper (3 yd^3)	Ratio
Average stabilized suspended mass (empty dipper)	4,200kg	4,200kg	1.0
Average stabilized suspended mass (full payload)	8,000kg	9,100kg	1.14 *0.93* *(2 yd^3 eq)*
Average peak hoist equivalent mass	14,000kg	13,400kg	0.96 *0.84* *(2 yd^3 eq)*
Average payload	3,800kg	4,900kg	1.29 *0.86* *(2 yd^3 eq)*
Average cycle time	29 s	28 s	0.97

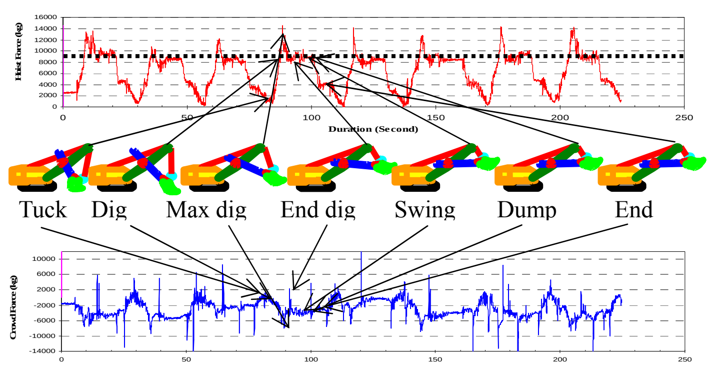

Figure 17: Hoist and crowd forces for 3 yd^3 dipper concept.

VII. SCALING FROM PROTOTYPE TO ULTRA CLASS DIPPER

Table 5 summarized the key data from figures 16 and 17 for the scale tested conventional and concept dippers respectively. Using the concept to original dipper ratios, the capacity –

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

force relationships from figure 7 and the normalizing factors from table 4 for the Dominion and P&H 4100, table 6 is generated showing the predicted key performance parameters for ultra class dippers compared to the conventional ultra class actual data.

Table 6: Predicted key performance for conventional versus concept ultra class dippers

Dipper model / Performance	Predicted ultra class concept design	Predicted ultra class P&H 4100 current design	Actual ultra class P&H 4100 current design
Dipper capacity m^3 (yd^3)	44 (58yd^3)	44 (58yd^3)	44 (58yd^3)
Payload (kg)	76,875 (+2.5%)	76,875 (+2.5%)	75,000
Suspended dipper handle tare weight (kg)	90,325 (unchanged)	90,325 (unchanged)	90,325
Suspended load (kg)	167,200 (+1.1%)	167,200 (+1.1%)	165,325
Peak hoist force (kg)	231,739 **(-18.8%)**	275,880 **(-3.4%)**	285,560

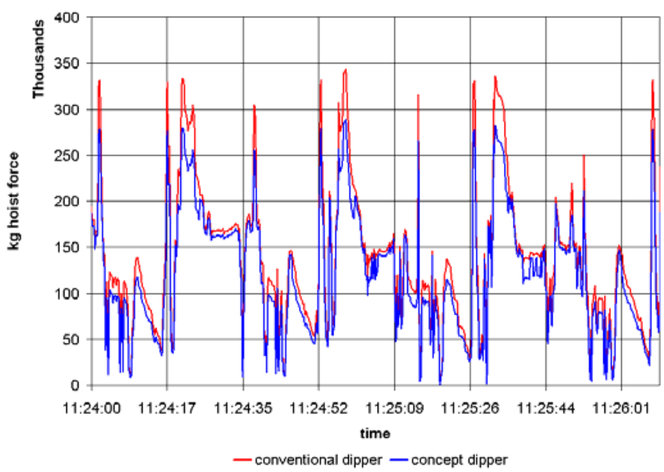

Figure 18: Predicted ultra class concept and conventional dipper performance comparison

The suspended and peak predicted values generated in table 6 were applied to manipulate a raw hoist motor current data set from a P&H 4100 BOSS machine operating in an oil sands face. This allowed the raw conventional dipper data to be converted into an equivalent predicted concept ultra class dipper data set and referenced to the original data. What is most noticeable is an average 15.4% reduction (18.8 – 3.4%) in required peak hoist force to excavated the same volume of material. Figure 18 provides the outcome, showing that during peak events the required force to excavate an average 15.4% less for the concept dipper compared to the conventional model, but the suspended load is essentially maintained, ensuring that payload or suspended load are not compromised.

VIII. Conclusions

A scaling approach using correlations between similar dipper shape but different sized units' performance hoist current or force traces; and correlations between different dipper shapes but of similar sizes were outlined, evaluated using available data and shown to allow prediction of full size prototype dipper concept designs from small scale field trials. The geometry and operating range for a small Dominion 500 and ultra class P&H 4100 BOSS operating shovels was shown to be similar by a linear scale increase of 2.85. The orientations of both the small and ultra class conventional dippers and the small concept dipper were shown to be similar with respect to teeth and heel locations in the free suspended load condition.

Normalized hoist effort through hoist motor current draw or strain gauging for the two model shovels with the conventional small and ultra class dippers were shown to be virtually identical in face reaction and free suspended magnitude. This allowed the small scale conventional and concept dipper hoist force differences from field trials to be used to proportionally to scale up to the ultra class size with an overall peak force reduction of 15.4% between the two designs.

An independent set of data from an ultra class P&H 4100 BOSS cable shovel operating in an oil sands face was used to predict the ultra class performance of the concept dipper design on the same machine and compare to the conventional dipper with reference to the scaling relationships established for operating in oil sand.

References

[1] Bucyrus, 2003, Bucyrus 495 BII HF cable shovel specifications sheets, Bucyrus International Inc.
[2] Dominion, 1957, Dominion 500 Shovel Manual, Dominion Inc, Montreal.
[3] Hendricks C. and Scoble MJ, 1990, Post-blast evaluation through shovel performance monitoring, Proc. of the Conf. on Explosive and Blasting Techniques, , Orlando, Florida, 227-243.
[4] Hendricks, C., Scoble, M.J., and Peck, J., 1989, Performance Monitoring of Electric Mining Shovels. Trans. Inst. Mining Metall. Section A: Mining Ind. 98, pp.151-159.
[5] Joseph T.G. and Hansen G.W. 2002, Oil sand reaction to cable shovel motion, CIM bulletin, Vol 95 pp62-64
[6] P&H MinePro Services, 1990, P&H2300XP electrical shovel specification sheet, Harnischfeger.
[7] P&H MinePro Services, 2001, P&H4100BOSS electrical shovel specification sheet, Harnischfeger.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)