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Review

Haul Truck Body Payload Placement Modeling

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ABSTRACT

Ultra-class surface mining haul trucks are commonly used to transport ore and waste material. They account for a significant portion of a total equipment fleet and maintenance budget. The payloads they carry are important when considering truck reliability, as balance and magnitude contribute to performance. Unbalanced payloads cause increased rack (twist), pitch and roll (bias) events, resulting in increased maintenance and lost production through loss of availability. Excavator operators often report a restricted visibility of the truck body during loading, with limited aids to assist in balancing placed loads. In order to provide payload placement assistance, payload modeling has been developed based on the work of Chamanara and Joseph. Haul truck strut pressures were used to estimate and display the location and shape of a payload within the truck body. To verify the model, data from an operating Caterpillar 785C haul truck and lab tests using a scale Caterpillar 797B model were analyzed. Although the model accuracy will decrease for materials that clump and do not flow freely, the results were found to be useful for field implementation.

Keywords*:* Haul truck, Payload, Mining, Model, Ridder's method

INTRODUCTION

Shovel operators must visually identify the appropriate location for successive load passes to achieve a best estimate balanced final payload in a truck body. It is entirely up to the operators' judgement whether a truck will receive a balanced load.

The mining industry strives to increase productivity at lower operating costs; a major component of this being the maintenance of tools and assets. In order to lower such maintenance costs, there is an increase in the focus on the reliability of equipment to reduce the likelihood of failures. With haul trucks representing a significant portion of a surface mining equipment fleet, they also represent a major contributor to maintenance costs.

Understanding truck payload balance plays an important role in haul truck reliability. Unbalanced loading leads to excessive fatigue of structure, components and tires. For example, ultra-class tires in the 59/80R03 range cost well over $100,000 per tire. In addition to damage to assets, unbalanced loading can cause rapid deterioration of haul roads, which in turn causes further impacts on truck maintenance via, in particular, rack events known to be directly proportional to structural fatigue.

Rack, pitch and roll events due to unbalanced loading can also generate negative impacts on a truck operator's health, manifest as whole body vibrations. So, reducing the frequency and severity of such events will ensure a healthier work force, particularly in reducing long-term exposure impacts such as spinal injury.

Payload measurement distribution information currently available to shovel operators is limited to the total weight of the load, visible inspection of the load by the shovel operator, and post load scanning and weighting; all of which are post-placement and not an assistance during placement. As shovel operator visibility is often limited, it would be beneficial to provide operators with an improved view of the payload, permitting operators to better distribute material within the truck body.

Haul trucks are designed to run optimally when their loaded vehicle weight is evenly distributed between all six tires. Since there are two tires on the front axle and four on the rear, this equates to a loaded weight distribution of 33.3% on the front axle and 66.7% on the rear. In order to achieve this distribution, trucks are designed such that the empty weight is split so that the front axle supports 47.2%

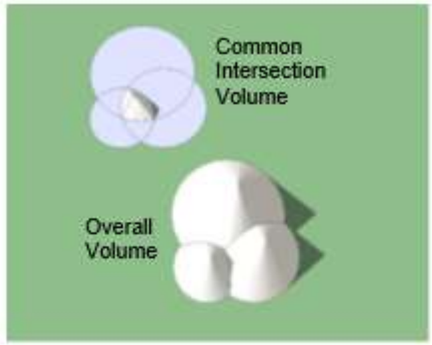


Figure 1. Intersecting cones (After Joseph and Chamanara, 2012)

and the rear axle supports 52.8%. A CAT 797F payload is then 58.3% of the GVW (Caterpillar, 2015a).

Original Equipment Manufacturers, (OEMs), have onboard information systems that record and interpret vehicle sensors to provide valuable information to mine personnel, such as the four suspension pressures, payload estimates (based on 2nd gear payload re-weigh) and truck ground speed.

While most mine payload reporting systems rely on truck sensors to determine payload, such data can also be estimated by determining the payload of individual excavator bucket loads. Lipsett suggested that there are two methods to determining shovel bucket payload, “instrument the bucket and assume that motion errors are small, or instrument the machine and calibrate its measurements for standard motions” (Lipsett, 2009).

Weigh Scale studies are a common industry practice for analyzing truck payload trends and verifying the accuracy of on board equipment weighing sensors. Scales are frequently used to verify accuracy of onboard systems by OEMs.

Modular Mining’s patent on a “Load Distribution System for Haulage Trucks” describes the use of haul truck strut pressure sensors to determine the relative position of the center of gravity of a payload (Baker. 2000). This center of gravity would then be displayed showing the current center of gravity’s position relative to an ideal center of gravity. The intent of this display would be to give excavator operators an indicator to aid in balancing payloads.

Chamanara and Joseph (2012) expanded on this concept, defining the shape of a progressively increasing payload, estimated as a series of sub-volumes placed per load at a defined center of gravity. The work of Chamanara and Joseph was based on the idea that granular materials tend to form conical shapes at an angle of repose for the material. Here, the center of gravity was re-measured by bucket load pass placement and the incrementing load generated. This method is expanded in this paper, with a focus on creating a visual model for the shovel operator.

Overall, Joseph and Chamanara suggested that, since trucks are loaded in multiple passes, the shape of a payload is actually the combination of a series of intersecting cones, Figure 1 (Joseph and Chamanara, 2012).

Joseph and Chamanara developed a mathematical model to determine a payload composite cone shape. The shape of the first load pass was defined using an assumed loose material density and angle of repose, as well as a known load location and weight derived from the proportional contributions of the four truck suspension responses, permitting the volume and centroid of the load pass to be determined. The locations of subsequent cones were then determined “by moving the combined first and second pass cones’ center of gravity to a common center of gravity location, while honouring the overall load distribution” reflected by the increased suspension pressure responses (Joseph and Chamanara, 2012).

This distribution was then used to evaluate the incrementally increasing payload distribution.

In thinking ahead to the advent of autonomous excavators; it is critical for an automated excavator to receive an accurate representation of a truck body incremental payload, as no operator is available to make visual choices. Rowe and Stentz proposed a system for planning and executing the motions of a hydraulic excavator, where their work focused on the motions that take place after the dig cycle, since: “Most of the research on autonomous excavation has focused on digging without much attention given to the completion of the rest of the task” (Rowe and Stentz, 1997). They described what information would be required to make such a system functional, where the ability to determine how the truck is loaded, including deciding where to place a load.

MODELING PAYLOADS

Based on strut pressure data, known truck dimensions and material properties, the location of a payload centroid and its expected volume may be determined. However, the shape of a payload is not necessarily a true cone, where

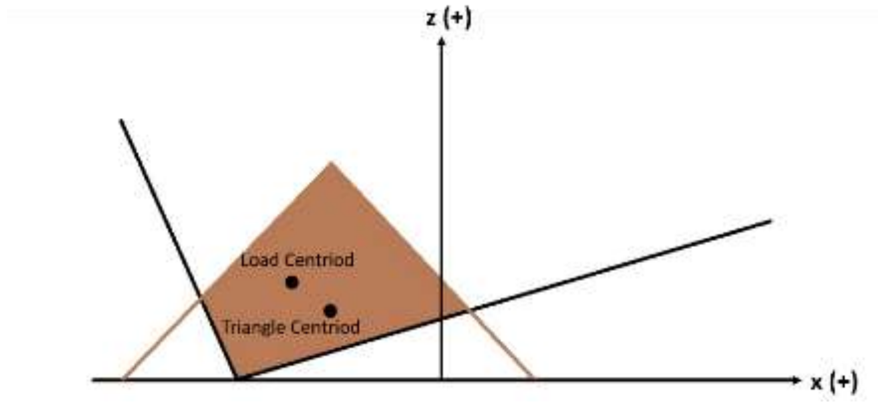


Figure 2. Centroid Deviation

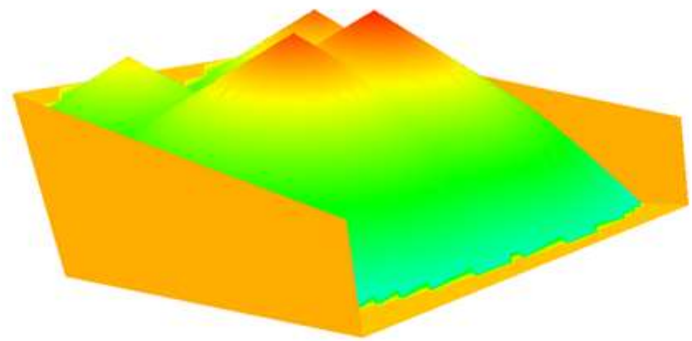


Figure 3. Example 3D Model

It's centroid is not located below the peak, as would be expected for a simple cone. This is due to the shape of haul truck body floors, which are not simply a flat plane but generally the combination of two inclined planes. For this reason a search algorithm was developed to determine the location of a payload's peak such that its centroid was as close as possible to a measured load centroid. An example of this deviation is shown in Figure 2.

The programming language used to develop the model here was C#; chosen for ease of programming. WPF (Windows Presentation Foundation) was then used to create a user interface, chosen as pre-set interface tools that could be employed. Payloads were modeled by creating a mesh network over a grid surface area representing the truck body. An example model is shown in Figure 3.

The following material properties were designated as required inputs to model the payload:

ρ = average material density, (kg/m^3)

θ = angle of repose, (degrees)

For the purposes of simplifying an initial model, the density was assumed to be constant throughout the material; although this assumption is invalid for most geological materials. Here, density was used by the model only to estimate the volume placed; however, it was recognized that problems might occur if the pre-set density was lower than the actual density of the material which would then cause the volume estimate to be too large, exceeding the capacity of the target truck body. Overestimated densities may cause a load shape to be too small.

The angle of repose was defined as the angle between the horizontal and the surface slope of a pile of granular blasted or crushed dry material. Variance from an assumed angle of repose could also cause a generated payload shape to be inaccurate. An overestimation would cause the shape to be too steep and compact, while an underestimation would cause the slope to be too small and the load to appear flattened and spread-out.

The following truck dimensions were required as inputs to model the payload:

d = Body Depth, (mm)

l = Body Length, (mm)

w = Body Width, (mm)

β = Angle from horizontal to front body slope, (degrees)

α = Angle from horizontal to rear body slope, (degrees)

x_f = x direction distance from edge of body to front strut, (mm)

y_f = y direction distance from edge of body to front strut, (mm)

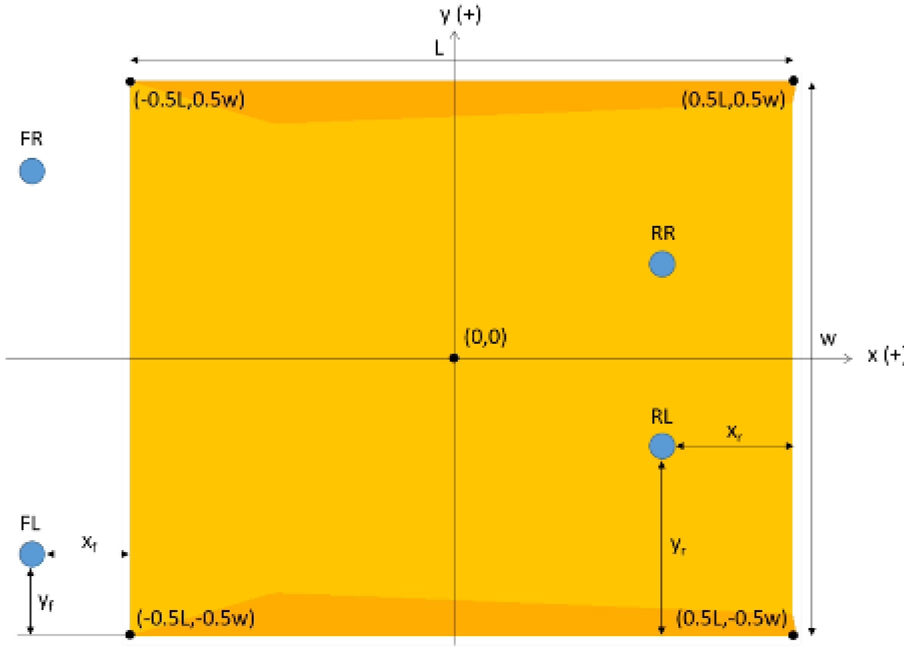


Figure 4. Approximate Strut Locations

x_r = x direction distance from edge of body to rear strut, (mm)
y_r = y direction distance from edge of body to rear strut, (mm)
All of the listed dimensions were available from manufacturer specification sheets.

Determining the Centroid

Figure 4 shows a top down diagram of a truck body and suspension strut locations (being the points of load recognition on the truck) where the struts were abbreviated as:

FL = Front Left
FR = Front Right
RL = Rear Left
RR = Rear Right

To determine an incrementing payload, the weights measured at each of the four struts were summed with each load pass. The percent load carried by an individual strut was defined as Equation 1:

$$\%Loading = \frac{Strut\ Loading}{Total\ Target\ Payload} * 100\% \tag{1}$$

In addition, the balance, reflected as the difference between front-to-rear or left-to-right suspensions, was determined via Equations 2 and 3, respectively:

$$\%Front\ Loading = \frac{FL\ Load + FR\ Load}{Total\ Target\ Payload} * 100\% \tag{2}$$

$$\%Left\ Loading = \frac{FL\ Load + RL\ Load}{Total\ Target\ Payload} * 100\% \tag{3}$$

From these calculations the centroid of a payload, using the coordinate system shown in Figure 4, was determined as:

$$x_{centroid} = \frac{-(0.5L + x_f) * (FL\ Load + FR\ Load) + (0.5L - x_r) * (RL\ Load + RR\ Load)}{Total\ Payload} \tag{4}$$

$$y_{centroid} = \frac{-(0.5w - y_f) * FL\ Load - (0.5w - y_r) * RL\ Load + (0.5w - y_f) * FR\ Load + (0.5w - y_r) * RR\ Load}{Total\ Payload} \tag{5}$$

This centroid provided a target for the model to seek when identifying the most likely suggested incremental payload location.

The shape of a payload within a truck body was estimated by a series of intersecting cones. The volume of a cone intersected with a flat plane is defined simply as:

$$Volume = \frac{\pi r^2 h}{3} \quad (m^3) \tag{6}$$

Where: r is the radius of the cone and h the height. Radius can also be determined based on a relationship between the height and the angle between the slope of the cone and the horizontal (angle of repose), such that:

$$r = \frac{h}{tan\theta} \quad (m) \tag{7}$$

Where: θ is the angle of repose, such that combining these two formulae results in a volume function based only on height and the angle of repose:

$$V = \frac{\pi h^3}{3tan^2\theta} \quad (m^3) \tag{8}$$

However, when the plane of cone base intersection is inclined or made of multiple components, such as the case of a haul truck body, as shown in Figure 2, the volume may be estimated by summing incremental volumes, with a grid spacing of s, described as:

$$V = s^2 * \sum_{i=1}^{n} h_i \quad (m^3) \tag{9}$$

Where n is the total number of grid points and h_i is the height of any cone increment, i, above the truck body. The height above the truck body can be determined by subtracting the z coordinate of the body from the z coordinate of any cone for all points where the cone is above the body. A value of 0 was then assigned to any point that would otherwise define a negative value, thereby locating below the truck body.

When estimating a payload shape based on strut pressures, the only known values are the location of the target centroid and the expected volume. The height of the cone's peak relative to the truck body is unknown. At any given location on the truck body there is only one height at which the volume of a cone will result in the expected volume reflected by the indication of the strut pressures. The base shape height was determined using a root finding algorithm, such as Newton, Bisection or Ridder's Methods.

Load shapes were generated as cones of heights determined by the root finding algorithm and at a given point centered under a cone peak. The cone being intersected at its base by the truck body enabled elimination of all parts of the cone that effectively were located below the body.

Bisection Method

The bisection method requires a target result for a given function to be set as well as a pre-determined initial estimate, and upper and lower bounds for the target variable. For the purposes of the model here, the target was set such that the difference between the volume of the modelled load and the expected volume was within 10 mm^3. The target function was then defined as:

$$\Delta V(h) = s * \sum_{i=1}^{n} (h_i) - V_{Expected} = 0 \pm 10\, mm^3 \tag{10}$$

Where h is the height of a simple cone measured from the base of the truck body. The height at which the above condition was met was considered to be the solution.

The initial cone height estimate was calculated by determining the height of a cone on a flat plane at the height of the truck body defining the x and y coordinates of the cone peak. The lower boundary (h_2) was then set to the height of a cone on a flat plane located at the bottom of the truck body. The upper boundary was set to be 5 times the height of the lower boundary. The results of this test are shown in Table 1 below.

The results showed that $5h_2$ was the best option, as a solution was always generated in the fewest iterations.

Once an estimated height had been tested and the volume determined to be above or below an expected volume, a new upper or lower boundary was set as the last tested height. The next estimate was then the midpoint between the new upper and lower bounds. This process was repeated until the difference between the two volumes was less than or equal to 10 mm^3. Figure 5 shows an example of how the search bracket was defined after each iteration.

Ridder's Method

Like the bisection method, Ridder's method requires a definition of a target and an upper and lower bound. The target, the lower bound and the upper bound were set to the same values as for the bisection method. The results of the various upper boundaries are shown in Table 2.

Again, $5h_2$ was shown as the best option as it always found a solution in the fewest iterations.

Once an estimated height had been tested and the volume determined to be above or below expected, a new upper or lower boundary was set. Ridder's method checked the signs of the last estimate, next estimate, and upper and lower bounds to determine how to set the next search bracket. If the sign of the last tested value and the next estimate were opposite, then the new bracket was set between the two. The method then checked if the next estimate and the lower boundary were opposing in sign. If so, then the new bracket was set between the old upper boundary and the next estimate. If not, then the new

Table 1. Average Iterations for Varying Upper Bounds Using the Bisection Method

Comparison of Iterations Required to Find a Solution for 21, 060 Loads					
Upper Boundary	**20h2**	**10h2**	**5h2**	**2.5h2**	**1.25h2**
Average Number of Iterations Required	36	35	27	42*	92*
Number of Indeterminate Shapes	0	0	0	3, 079	18, 444
**indeterminate shapes are given a value of 100 iterations*					

Table 2. Average Iterations for Varying Upper Bounds Using Ridder's Method

Comparison of Iterations Required to Find a Solution for 21,060 Loads					
Upper Boundary	**20h2**	**10h2**	**5h2**	**2.5h2**	**1.25h2**
Average Number of Iterations Required	8	7	6	5*	29*
Number of Indeterminate Shapes	0	0	0	1	5, 016
**indeterminate shapes are given a value of 100 iterations*					

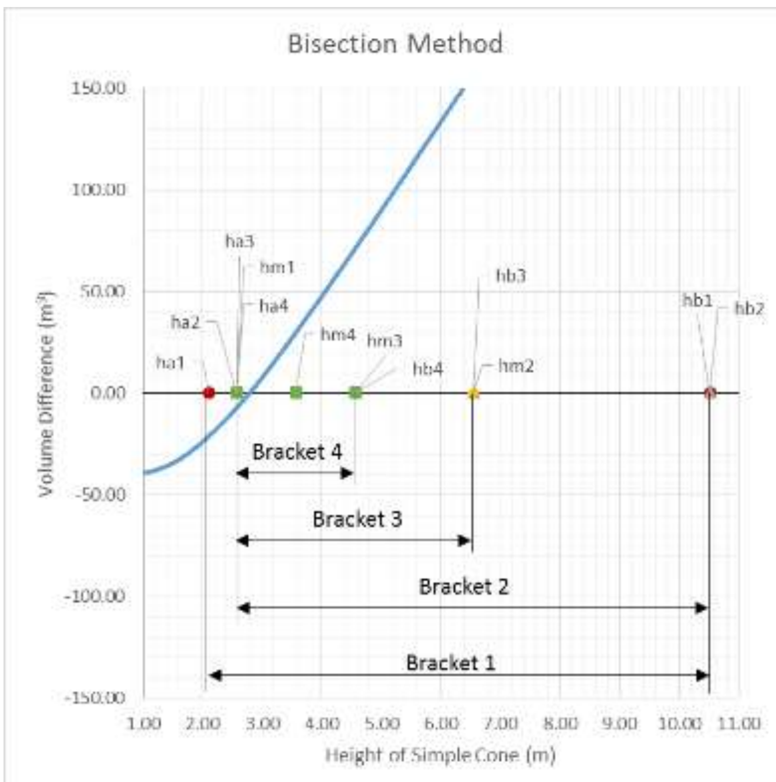


Figure 5. Example of Bisection Method

bracket was set between the old lower boundary and the new estimate. Figure 6 shows an example of how the search bracket was defined after each iteration.

While the centroid for a cone on a flat plane will be located at the same x and y coordinate of a peak, this no longer holds true for a cone on a more complex surface. As such, a search algorithm was designed in order to determine the correct location to place the cone peak in order to minimize the distance between the calculated and measured centroids; thus generating an acceptable payload.

An acceptable payload was defined as one that was found to meet the following conditions:

- The calculated volume was equal to the expected volume within 10 mm^3.
- The estimated payload shape must fit within the truck body geometry. No cone surface points making contact on the surface of the body may be above the body sides.
- The calculated centroid of the payload is based on an acceptable cone shape (within the angle of repose and

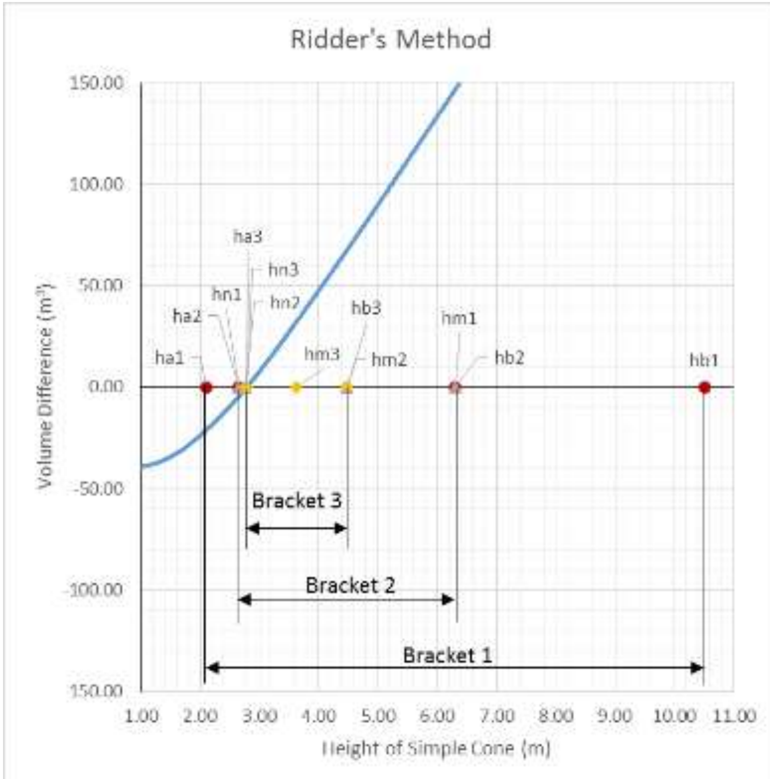


Figure 6. Example of Ridder's Method

density restrictions) with lowest error (horizontal (x, y) distance) from a measured centroid.

This algorithm generates an initial array of potential loads. A payload is generated with its peak located at each point on the grid. The centroid of this shape and its height from the base of the truck body were then calculated and saved in a co-ordinate array.

Simultaneously, as the centroid was calculated, the validity of the potential load shape was also evaluated, checking that all points within the load were at or below the sides of the truck body along the edges of the grid. If a point was detected to be above the allowable geometry, the centroid was seen to be set to be well outside the limits of the grid such that its distance from the measured centroid would be much higher than that of any valid shapes.

Once an array of potential load shapes had been generated, the algorithm then searched through every potential load shape and determined which had the minimum distance from the centroid indicated by the suspension pressures then indicating the load distribution within the truck body. Initially, an arbitrarily large distance was set as the minimum distance; large enough that invalid shapes would be ignored while still evaluating valid ones. As the algorithm searched through the points it then would replace, the minimum distance to the centroid with any value that was less than the previous minimum, thereby setting a new minimum. This process was repeated until all points were evaluated, at which point the key values required to recreate the best fit load were output to the visual model portion of the program. These key values included the height of the cone relative to the base of the truck body, as well as the x and y coordinates of the peak. This process is shown in Figure 7 below.

While the described search algorithm was very effective at finding the best possible location of the cone to meet the predefined constraints, it took a long time to do so. In order for the model to be useful as a real-time tool, it must be able to generate results between when a shovel operator places a load and before the next load is approaching the truck body for placement (approximately 25 seconds).

An appropriate algorithm to increase the speed of the model was to begin with a rough search of the truck body. The results of the search were checked to determine which was closest to the measured centroid. A second rough search was performed over the reduced area of the truck body narrowed by the first result. The result of this second search was evaluated in the same way as the first rough search to select a final search zone. A full search was then performed over this much narrowed area to determine the best solution.

This method was implemented in three phases:

- Phase 1 – Calculate 12 points spaced evenly through the truck body and determine the closest point.

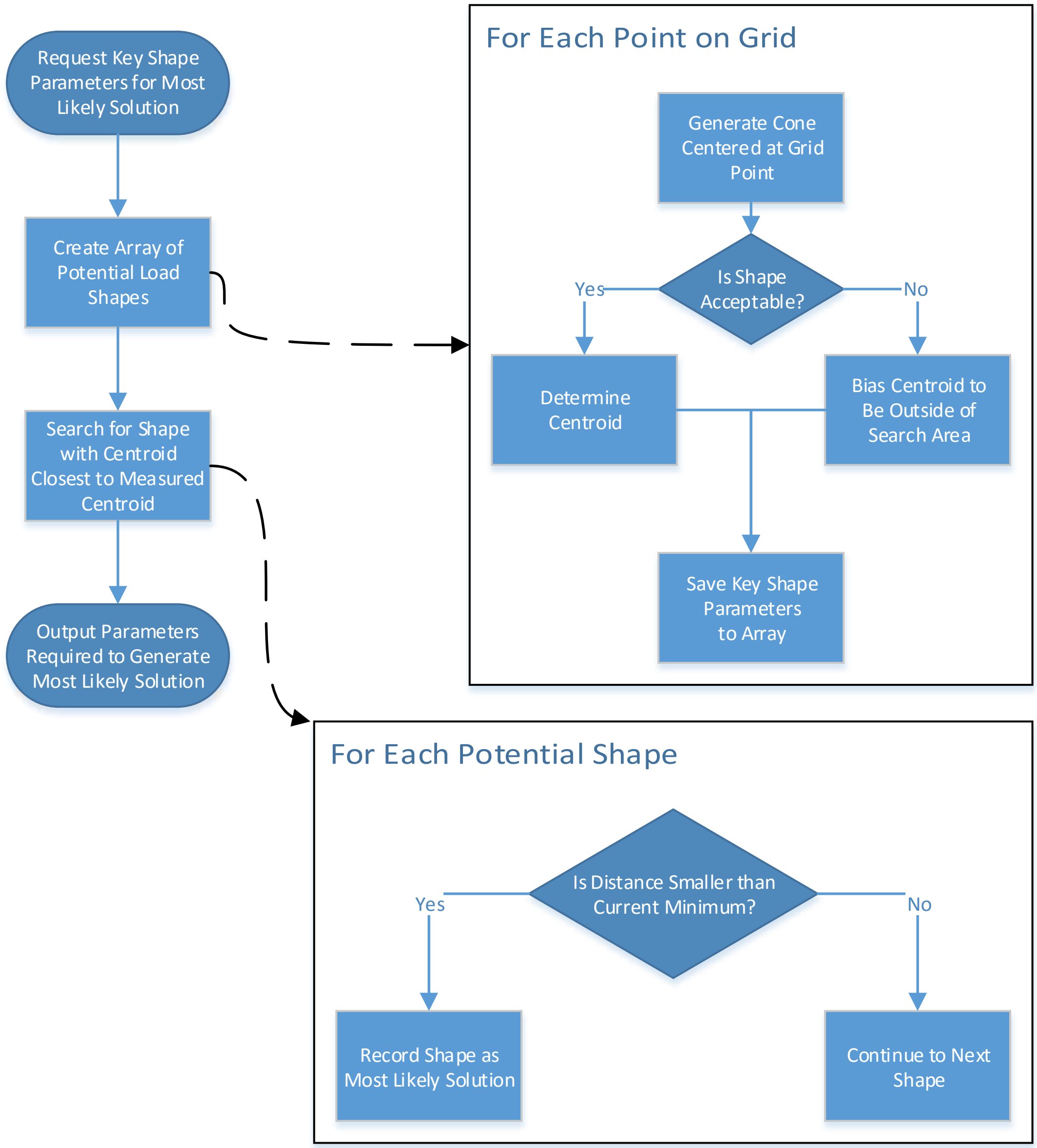


Figure 7. Search Algorithm

- Phase 2 – Calculate four points spaced evenly through the section represented by the previously narrowed area from Phase 1 and determine the new closest point and zone.
- Phase 3 – Perform a full search of the zone selected in Phase 2 and determine the closest payload shape.

This process is shown visually in Figure 8.

This system allowed the whole body to be scanned at a much faster rate than a simple full search.

The progressive narrowing search method was tested on sample data, with results shown in Table 3 below.

It was clear that using the Progressively Narrowing Search and Ridder's Method contribution provided the fastest model results. The payload shapes generated were also compared, based on the assumption that the full search provided the best possible result. These shapes are shown in Figure 9.

Based on these generated shapes it is clear that while the other search methods are significantly faster, they do not always generate the same result as the full search. The narrowing search appears to have gotten closer to the full search results but with significant visible loss of resolution.

LAB TESTS

The purpose of the lab tests were to create data sets based on scaled to actual loads that could be used to verify the model. Images of the loads were taken in order to allow visual comparison between the software model and the test results.

A 1:25 scale of a 797B haul truck body was constructed previously by Chamanara (2013). Linear dimensions were determined by scaling directly. Volume

Table 3. Processing Speed Comparison

Search Method		Processing Time (s) Full Search	Narrowing Search
Load Pass 1	Bisection Method	704	21
	Ridder's Method	502	15
Load Pass 2	Bisection Method	790	21
	Ridder's Method	475	14
Load Pass 3	Bisection Method	792	21
	Ridder's Method	454	13
Load Pass 4	Bisection Method	710	20
	Ridder's Method	378	12
Average	Bisection Method	749	21
	Ridder's Method	452	14

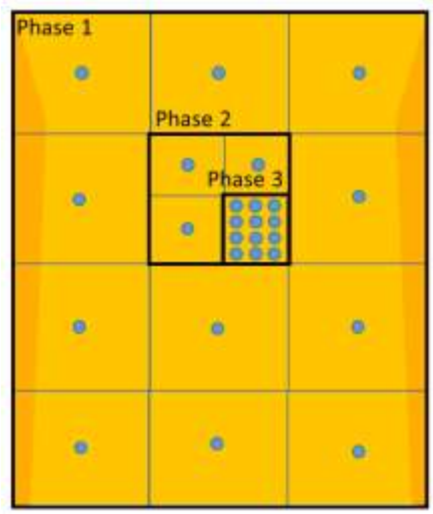


Figure 8. Progressively Narrowing Search

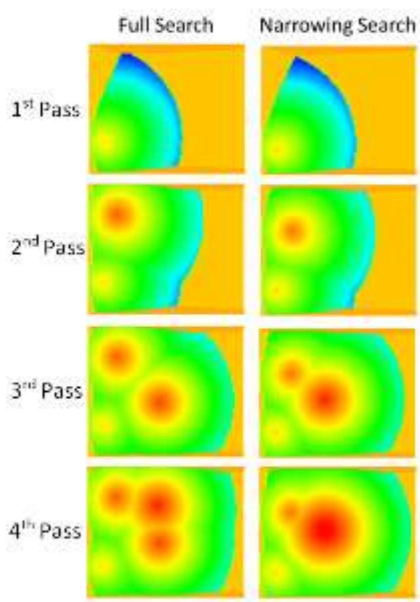
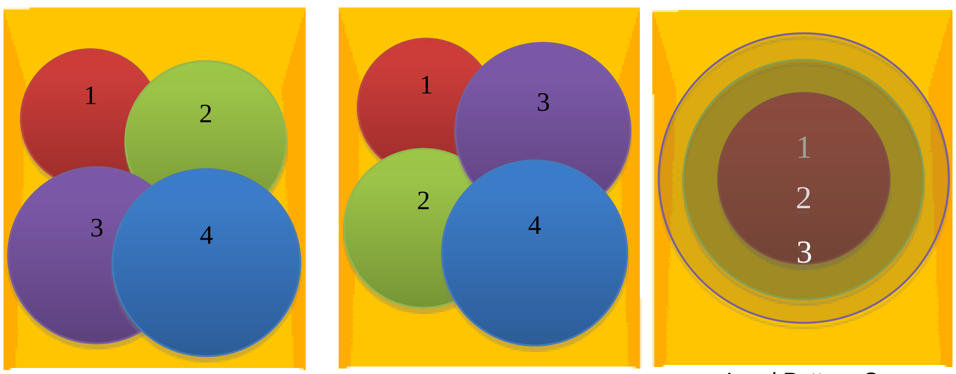


Figure 9. Payload Shape using Different Search Methods

Figure 10. Scale Model



Load Pattern A

Load Pattern B

Load Pattern C

Figure 11. Three Different Loading Patterns

and weight capacities were scaled down using a cube root approach based on the reported capacity of a Caterpillar 797B spec sheet (Caterpillar, 2015b).

The box has a theoretical volumetric heaped capacity of 14, 080 cm^3, scaled from the equivalent 797B capacity of 220 m^3. Given this capacity, loading in four passes would require a scoop of 3, 520 cm^3 per load, scaled from the equivalent loading matched shovel capacity of 55 m^3. The scaled weight was calculated as 23.04 kg from the equivalent 360 metric tonnes. The scale model is shown in Figure 10.

At each of the four suspension strut locations**,** Artech 20210- 50lb S-Shaped load cells were used to output load data as a voltage (Artech, 2015). A 3, 480 cm^3 pail was used to represent the shovel bucket, a size that would approximately load the box in four passes. A HBM MGCPlus data acquisition system was used to record the load cells at a frequency of 2 Hz, providing a reasonable number of data samples, while keeping the processing speed for the model high (HBM, 2015).

Two different materials were used for the lab tests, sand and crushed limestone. The sand was found to have an average loose density of 1, 647 kg/m^3 and an angle of repose of 32.2^{o}. The crushed limestone, representing scaled blasted rock, was found to have an average loose density of 1, 519 kg/m^3 and an angle of repose of 37.4^{o}. The angle of repose was calculated by dumping a load of material in a pile on a flat surface.

Three different loading patterns were used in order to provide a variety of payload distributions. Load Patterns A, B and C are illustrated in Figure 11. Pattern A involved placing loads subsequently into the Front Left, Front Right, Rear Left and then Rear Right quadrants; chosen to generate payloads that were biased towards the rear of the truck body. Pattern B required loads to be placed to generate payloads biased to the right of the truck body. Load Pattern C was performed by placing three loads in the center of the box. Only three loads were placed in this pattern as any further loads would have overflowed the box. Pattern C was chosen in order to verify that the model functioned correctly when subsequent load peaks were placed in the same location, causing increments to progressively overlap.

Test runs with sand were applied to all three patterns, but only Patterns A and B were used with a crushed limestone. Tests were labelled by combining a letter to

Table 4. Test Labels

Test	Material	Pattern
L-A	Limestone	A
L-B	Limestone	B
S-A	Sand	A
S-B	Sand	B
S-C	Sand	C

Table 5. Lab Test Payload Volumes

Test	Depth in Bucket (cm)	Mass (kg)	V Measured (cm^3)	V Estimated (cm^3)	% Error
L-A	21.27	18.05	11, 277	11, 887	5.13
L-B	22.86	18.10	12, 186	11, 919	-2.24
S-A	22.23	18.27	11, 821	11, 093	-6.56
S-B	22.86	18.63	12, 186	11, 315	-7.70
S-C	19.05	16.11	10, 019	9, 779	-2.45

Table 6. Payload Distribution

Test	FL	FR	RL	RR	Left	Right	Front	Rear
L-A	20.4%	15.5%	32.2%	31.9%	52.7%	47.3%	35.9%	64.1%
L-B	**18.3%**	**19.7%**	**31.2%**	**30.8%**	**49.5%**	**50.5%**	**37.9%**	**62.1%**
S-A	17.3%	22.0%	27.8%	32.9%	45.2%	54.8%	39.3%	60.7%
S-B	18.6%	21.6%	19.4%	40.4%	38.0%	62.0%	40.2%	59.8%
S-C	21.5%	19.9%	32.1%	26.4%	53.6%	46.4%	41.4%	58.6%

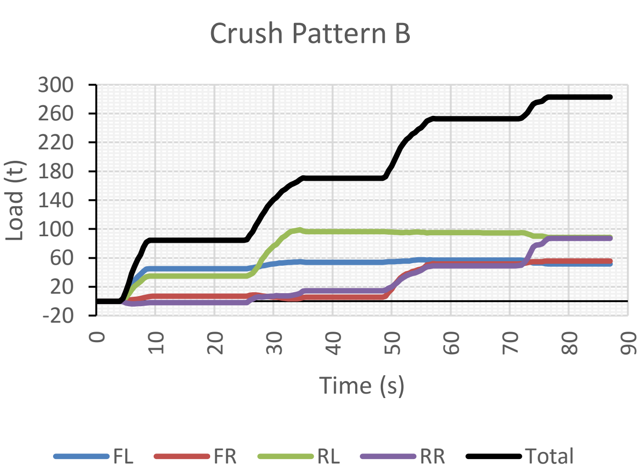


Figure 12. Limestone Pattern B Results and Payload

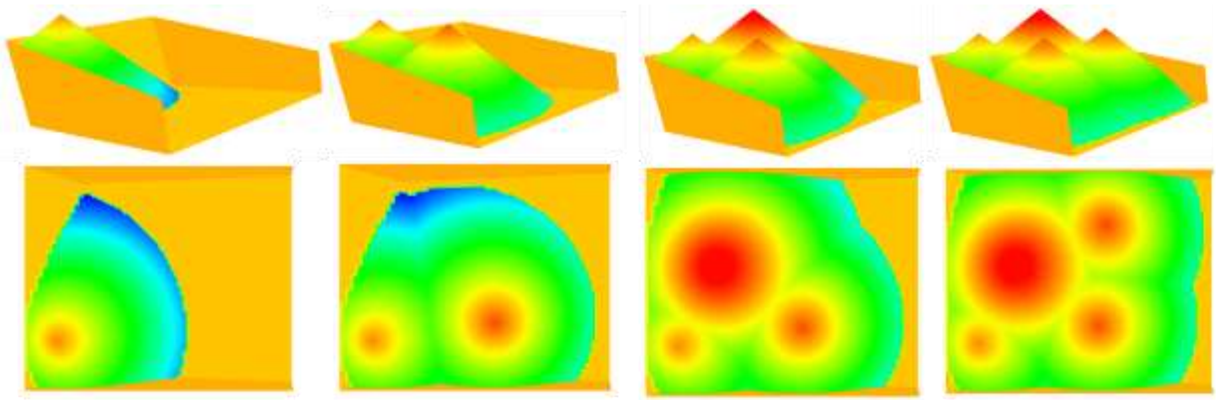


Figure 13. Pass by Pass of Modeled Shape for Limestone

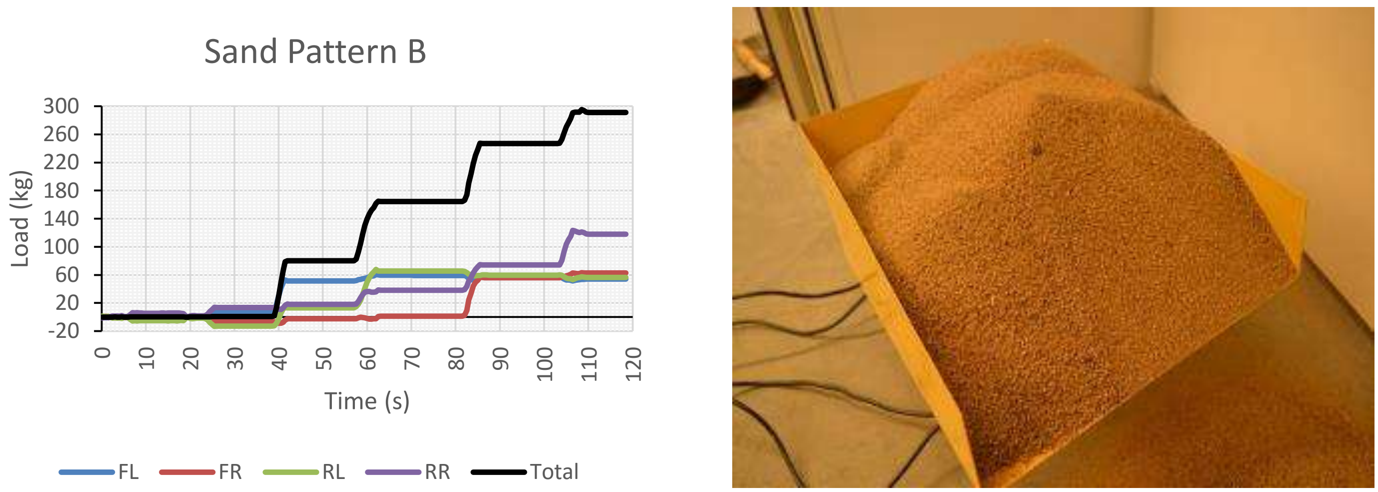


Figure 14. Sand Pattern B Results and Payload

indicate the material used and the pattern letter (Table 4 above). For example, "L-A" corresponds to a test using the limestone with Pattern A.

These measured volumes per load pass were compared with the volumes estimated using only the load cell readings, assumed material density and angle of repose (Table 5).

Table 6 shows a summary of the final payload distribution for each of the five tests. These results were calculated based on the load cell readings after the final load pass, subtracting the tare weight.

A detailed summary of the results of Pattern B loading for both the limestone and sand material are presented below.

The test results were scaled-up to a field equivalent load of 282 metric tonnes. As shown in Table 6 above, the payload was reasonably balanced between left and right, with only a 0.5% overload on the right. The front portion of the box held 37.9% of the load, while the rear held 62.1%. A graph of the strut loading and an image of the final payload can be seen in Figure 12; while Figure 13 shows the model representation of limestone Pattern B.

The test results for sand Pattern B scaled-up to a field load of 291 metric tonnes, as shown in Figure 14. The payload was overloaded on the right side, with 62% of the load held by the right struts. The front portion of the box held 40.2% of the load, while the rear held 59.8%. It can be seen that the RR strut was already overloaded after the third load pass was placed. Figure 15 below shows a visual comparison for the sand between the actual lab test payloads and the payloads from the model, which provided a reasonable estimation of the actual payload distribution.

FIELD DATA APPLICATION

Suspension strut pressure data for one loading cycle of a CAT 785C haul truck was converted to weight in tonnes by multiplying the pressure by the area of each respective

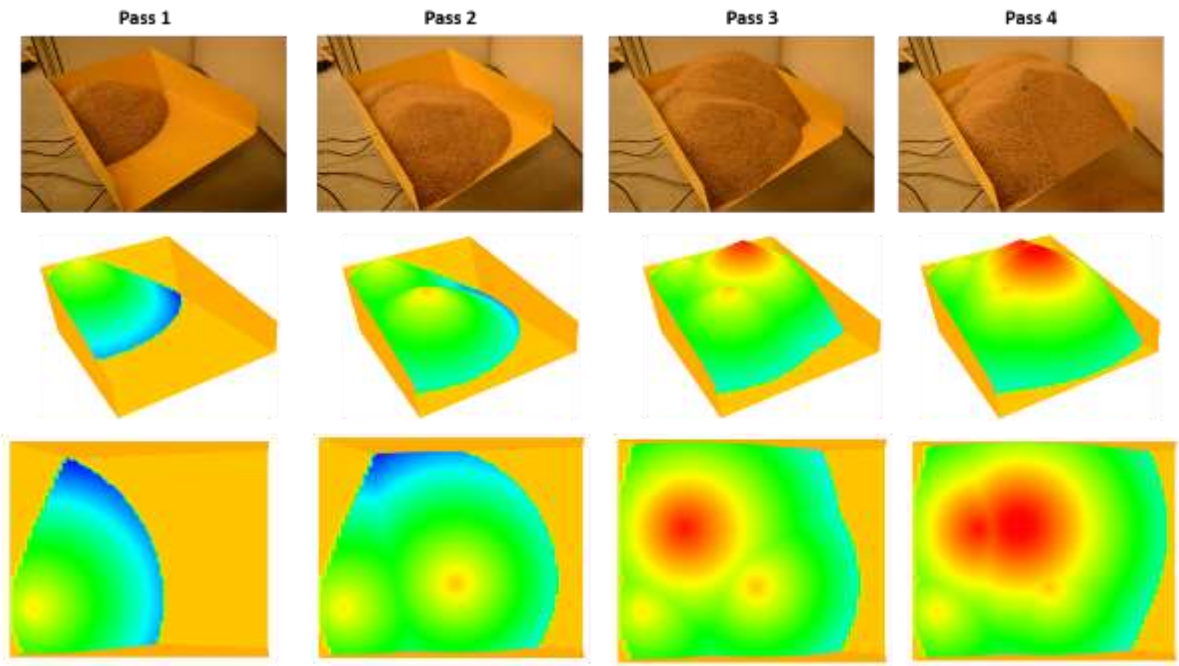


Figure 15. Pass by Pass Comparison of Modeled to Actual Payload Shape

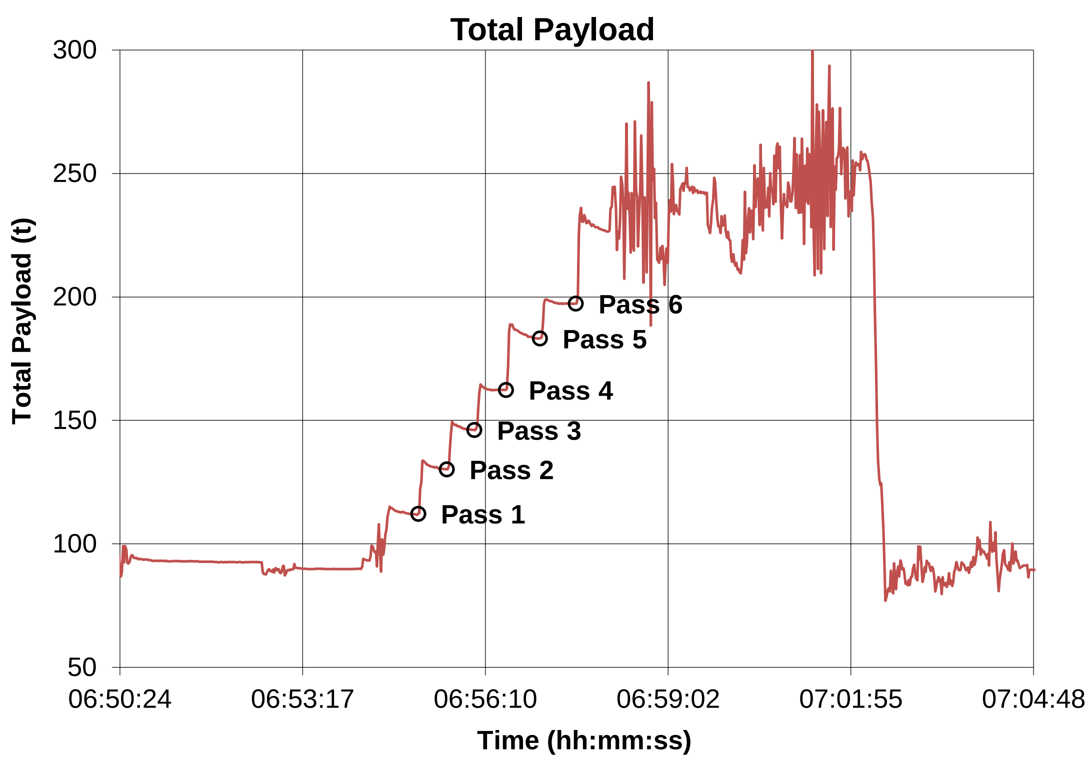


Figure 16. Payload for a CAT 785C hauler size cycle sample

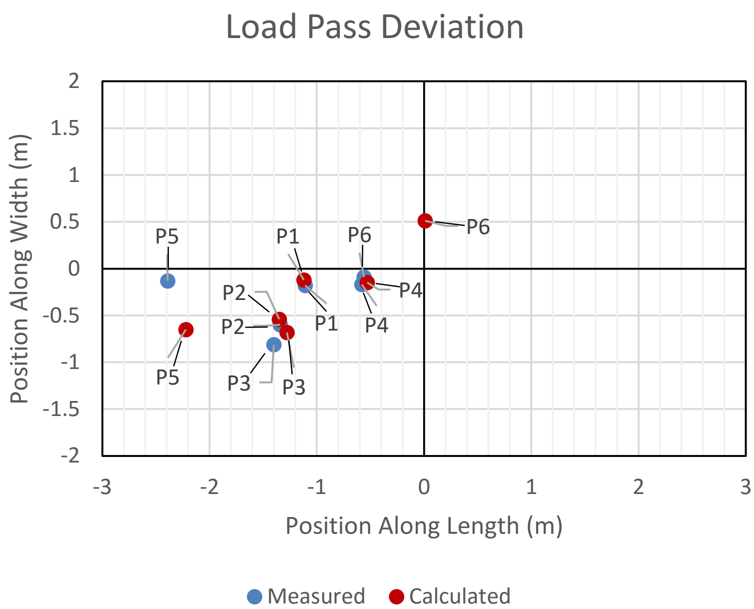


Figure 17. S1324 Load Pass Centroid Deviation

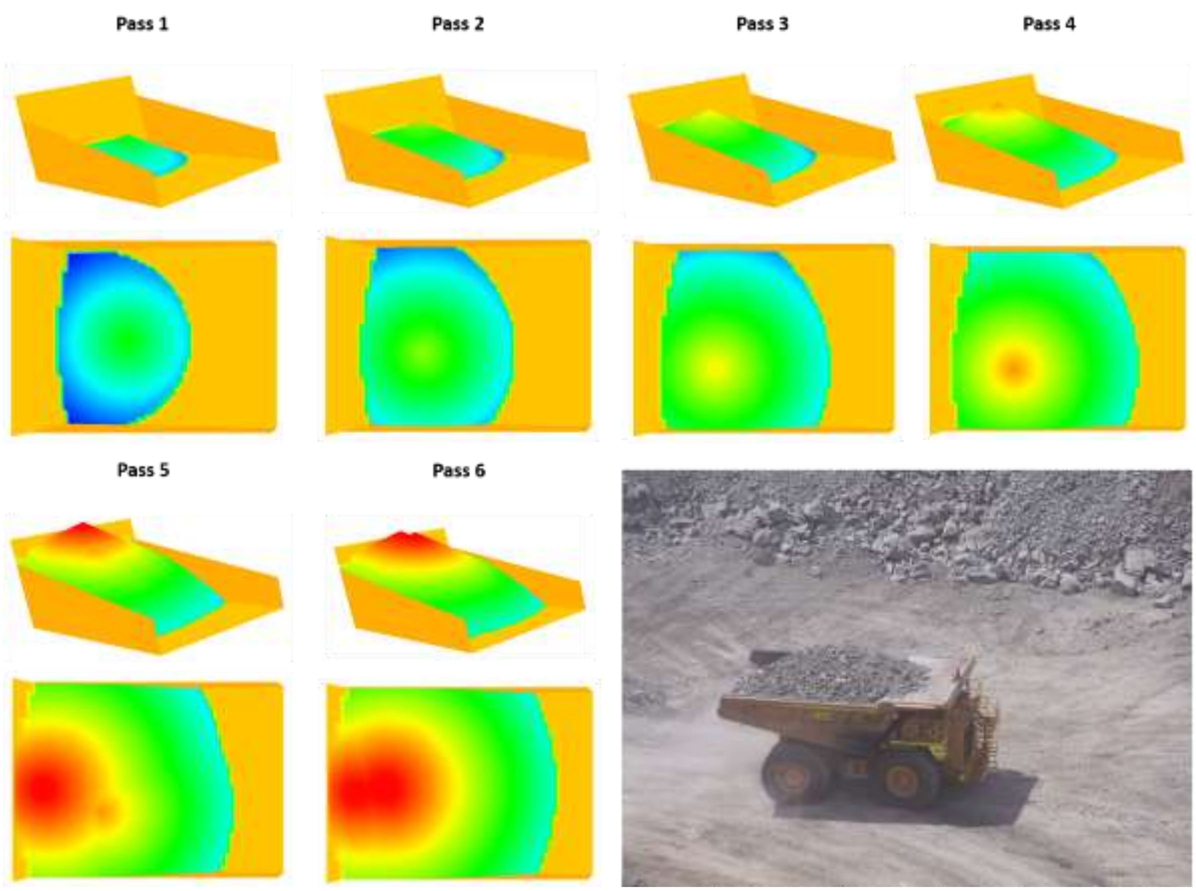


Figure 18. Pass by Pass Model of Payload

suspension cylinder. The data was then analyzed for each of six of a total seven load passes. Figure 16 shows the points at which readings were taken for six of the passes.

Readings were selected at points which best represented the payload, after the truck had ceased any motion resulting from load placement. A material density was 1, 972 kg/m3 and angle of repose of 26.25o was used based on field observations by Joseph (2003). Using these parameters and the CAT 785C reported dimensions, the following results were obtained.

The model successfully predicted the payload shape for all six load passes. Centroid locations for both measured and calculated load pass centroids were plotted in Figure 17.

Figure 18 indicates that while the model followed the shape of the payload shown in the photo, it did not fill the truck body as completely, as visible in the field.

CONCLUSIONS

Unbalanced haul truck payloads can cause increased frequency and intensity of rack, pitch and roll events. These events, in turn, can cause an excess in equipment maintenance, running surface deterioration and operator health issues. Excavator operators play a key role in balancing truck payloads. These operators have minimal aids to determine if a payload is balanced, instead relying on visual inspection alone. It is important that these operators be given additional aids so that they can better judge the balance of payloads. Such information must be reasonably accurate and provided within one cycle of the excavator to pass a load from a working face to truck body.

In order to provide excavator operators with additional information on truck payload balance, a model was developed using truck strut pressures, which determined the location of the load centroid and estimated the volume of the load. It assumed that granular material forms a conical shape at a constant angle of repose and the loose material density remains constant throughout the payload. Ridder's method of root finding was used to determine the shape of the load, where a search algorithm was used to generate a potential load for all points on a grid to calculate their deviation from the measured centroid. The minimum deviation was then determined and the corresponding load generated as a visual model.

A progressively narrowing search algorithm was able to meet the speed requirements within a one pass excavator cycle. Strut data was then collected from lab tests, where the corresponding modeled payload appeared to be similar to the actual payload for most tests. Field data was also modelled with the software for a sample loading cycle, successfully mimicking six consecutive passes with what visibly appeared to be reasonable accuracy.

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