Journal Paper

Summary of results of ACARP project on cross-belt cutters

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Synopsis

A project was funded by the Australian coal industry to investigate the mechanisms that might lead to sample bias when using cross-belt cutters, in order to help coal industry personnel to make better decisions about the purchase, maintenance, and operation. It concentrated on DEM modelling of skew cutters. These are set at an angle to the belt with the intention of minimizing disturbance to the non-sampled material.

Two bias mechanisms are likely to cause bias for cross-belt cutters. Waves of material are bulldozed off the belt by the upstream side of the body of square cutters and material is thrown by the leading edges of cutter blades for all types of cross-belt cutters. These mechanisms cause some parts of the load of material on a belt to be over-represented.

The effects of these mechanisms cannot be made to be negligible, so cross-belt samplers cannot be trusted to produce unbiased samples, especially for segregated streams of material. However, it is possible to give a bound on the maximum likely bias. The grades of two portions of the stream can be estimated by stopping the belt and shovelling off 1/3 of the cross-section of the load on the belt into a container, concentrating on the final side of the belt and the top of the load. The remaining material should be put into another container and the difference in grade determined.

The maximum likely bias is typically about 10% of this difference.

For a cross-belt cutter, having an extraction ratio near to 100% is not a reliable indication that the cutter has little or no bias. Some bias mechanisms affecting cross-belt sample cutters make sample mass too high and some make it too low, so an extraction ratio near 100% can occur if two bias mechanisms are both active.

Keywords: sampling, DEM simulation, sample bias, accuracy, precision.

Introduction

Through the Australian Coal Association Research Program (ACARP), the Australian coal industry funded a project (C15072) to investigate the mechanisms that might lead to sample bias in order to help coal industry personnel to make better decisions about the purchase, maintenance and use of cross-belt cutters. We conducted this project and this paper is a summary of its main findings.

The primary technology used in this project was three-dimensional discrete element modelling (DEM) as described by Cleary (2004). This enables estimation of cutter bias and comparisons of different cutter designs to be performed more precisely than is possible using physical testing. It requires that particle properties be input on the basis of observations of real materials, but the estimates of bias are seldom sensitive to particle properties, so model calibration is not a major concern.

Types of cross-belt cutters

Cross-belt samplers are devices for taking samples of material while it is being transported on a conveyor belt. They are widely used in the coal industry, partly because they are easier to retrofit than falling-stream samplers. They have a cutter which is scraped across a conveyor belt as a way of taking a sample of the material being carried on the belt. The body of the cutter is rotated about an axle which is parallel to the belt. The body has a back plate which pushes material off the belt. The sides of the cutter body each have one curved edge which pushes against the belt. The leading edges of the sides of the cutter are the 'cutter lips'. For most types of cross-belt cutters, these leading edges are located such that they are displaced in the direction of motion of the belt from each other.

Two types of cross-belt samplers are common. 'Square cutters' or 'hammer samplers' have sides which are square to the belt. 'Skew cutters'' have sides set at an angle to the belt in order to reduce the amount of disturbance to the material on the belt, which is near to the cutter but is not intended to be sampled. Both types of cutter are rotated about an axis which is parallel to the belt. For both types of cutter the leading edges of the cutter blades are parallel and displaced in the direction of the motion of the belt from each other.

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In the Australian coal industry, skew cutters are more common than square cutters, so the DEM simulations in this project concentrated on skew cutters.

Delimitation and extraction of samples

In the terminology of Gy (1982), sample delimitation describes which particles are intended to be included in a sample. Sample extraction is the practical process of getting as many as possible of the delimited particles into a sample container with as little contamination as possible by nondelimited particles. As explained in Robinson, Sinnott and Cleary (2007), sample delimitation for cross-belt cutters is correct even if the cutter speed is not constant. This is because the length of the region defining the delimited sample is the same at all positions across the width of the belt. For DEM simulations, we often refer to the set of delimited particles as the 'reference sample'.

The main problems with cross-belt sample cutters are concerned with sample extraction. According to our DEM simulations, the proportions of delimited particles which become part of the sample are substantially different for the top and bottom of the load on the belt and for the two sides of the load on the belt.

Experiments conducted using discrete element modelling

Set-up of DEM runs

The DEM simulations for this project had the following features for the base case:

- There is a conveyor belt which moves at a constant speed of 4 m/s
- The conveyor belt is on an uphill slope. This was a 20% gradient (or 11.3 degrees)
- Particles are generated in a region over one end of the conveyor belt. They fall onto the belt where they settle to form a moving stream with a standard profile
- There is a sample cutter which is moved across the particle bed to take a sample. This movement occurs after the belt is fully laden
- The simulated region extends beyond the sample cutter sufficiently far that the flow of particles in the region of the cutter is not affected by particles being removed at the far end of the domain
- The belt was 1 200 mm wide. Its cross-section near the cutter has a 680 mm radius over an angle of 70° and is straight with a slope of 34° on both sides of that central region
- The belt loading was about 1 600 tonne/h. The cross-section of the load was realistic. The angle of surcharge (the angle between the material near the edge of the load and horizontal) was about 25°, the shape of the top surface was approximately circular, and the clearance at the edge of the belt (measured along the belt rather than horizontally) was about 90 mm.
- The full size distribution used is given in Table I, but all of the mass of particles smaller than 12 mm was modelled using 12 mm particles. Therefore the particles modelled ranged in size from 12 mm to 50 mm
- Particles were modelled with a super-quadric shape as illustrated in Figure 2. The super-quadric index which describes particle blockiness varied over the range 2.5 to 6. Its inverse was taken to be uniformly distributed over the range from 1/2.5 to 1/6. Particle aspect ratios were uniformly distributed over the range 0.7 to 1. This is a plausible representation of real shapes of coarse coal particles
- Coefficients of friction were: 0.8 between coal particles, 0.9 between coal particles and the belt, and 0.5 between coal particles and the cutter
- The coefficient of restitution of coal particles was taken to be 0.25
- The skew cutter was designed to operate at angle arctan(1/1.5) = 33.7° from square to the belt for a cutter speed that was 1.5 times the belt speed
- The external radius of the cutter fits was 680 mm. Its sides were 10 mm, reduced to 3 mm at the leading. The corners of the leading edges which touch the belt were bevelled with a radius of 70 mm
- The cutter volume was such that the angular size of the cutter is about the same as the width of the material on the belt. i.e. the leading edges reach one side of the load on the belt at about the same time as the back of the cutter reaches the other side of the load
- The cutter aperture was 150 mm.

Sample planes

Sample planes are two-dimensional regions, as described by Cleary and Robinson (2008). The characteristics of particles passing through those regions are accumulated and classified. Each sample plane has a defined direction, so a particle passing through a sample plane twice in the forwards direction and once in the reverse direction is counted only once.

Most of the DEM cases used for this project used four sample planes.

- The 'target sample plane' is just inside the jaws of the cutter. In Figure 1 this is the plane ABCD. It measures the material actually entering the sample cutter and is used in the determination of the reference sample.

Table I

Particle size distribution for some coal that we tried to match in DEM simulations

Size range (mm)	Percentage by mass
0–5	45.58
5–6	3.71
6–7	3.29
7–8	2.95
8–9	2.68
9–10	2.45
10–12	4.35
12–15	5.48
15–20	7.23
20–25	5.64
25–30	4.56
30–35	3.78
35–40	3.19
40–45	2.74
45–50	2.37

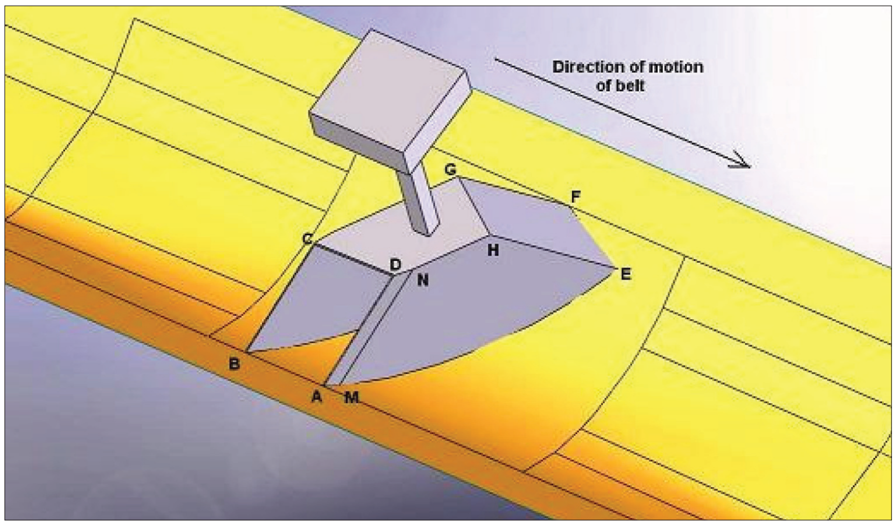

Figure 1—CAD diagram of the belt and a skew cutter

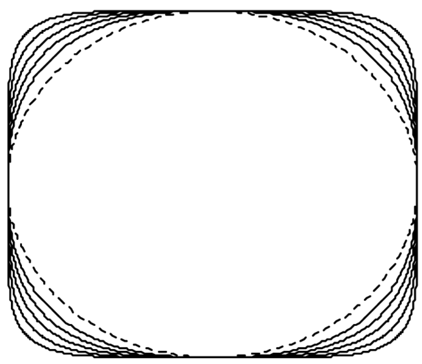

Figure 2—Two-dimensional projection of shapes of DEM particles with super-quadric indices 2.5, 2.93, 3.53, 4.44 and 6. A particle with super-quadric index 2 is elliptical and is shown as a dashed line

- The 'classifying sample plane' is just upstream of the cutter. It is rectangular with about the same width as the belt and high enough so that all particles on the belt pass through it. As particles pass through this plane they are classified according to their horizontal and vertical position, and also classified according to whether or not their centres are expected to pass between the jaws of the cutter. Particles which are expected to pass between the jaws of the cutter belong to the 'reference sample'.
- Another sample plane accumulates data about particles thrown off the belt. One edge of this is just inside the edge of the belt and the other edge is near the axis of rotation of the cutter.
- The 'chute sampling plane' is a subset of the previous sampling plane. It allows for the fact that cutters often have skirts or baffles so that material can be thrown off the belt within about only 100 mm of the region, which has to be open so that the cutter can rotate without hitting anything. The material passing through this sampling plane is referred to as the 'chute sample' and corresponds to the physical sample, which is actually taken by a physical cross-belt cutter.

The reference samples defined at the classifying sample plane report on the sample delimited by the cutter. These samples are unbiased like the reference samples used in stopped-belt physical bias testing. Because they are taken from the same section of the material stream as the chute samples, they allow more precise bias testing than is possible with physical bias testing.

Experiments conducted

The DEM simulations conducted can be regarded as a series of 16 experiments. The first experiment compared skew and square cutters for two different ratios of cutter speed to belt speed. This was reported in Robinson, Sinnott, and Cleary (2007). Several aspects of the DEM set-up were revised after this first experiment, so it is not directly comparable with later results. A total of 90 simulations are discussed in the final report (Robinson, Sinnott, and Cleary, 2009).

Factors investigated were cutter aperture, the size of the smallest particles explicitly modelled, the amount of segregation by particle size of the load on the belt, the range of particle densities (such as the difference between washed and unwashed coal), the distribution of particle shapes, material properties such as the coefficients of restitution and friction of particles, cutter volume, the size of the gap between the cutter and the belt, belt loading, cutter speed, belt slope, the shape of the edge of the belt, belt speed, and cutter design.

In the final, and perhaps most interesting, experiment the sample cutter was replaced by either a single rod, which was moved in a manner corresponding to the leading edge of a cutter blade, or a rod with a trailing plate which, was moved like the upstream leading edge and side plate of a square cutter.

Performance of different cross-belt samplers

A qualitative understanding of the most important results can be gained from Figures 3 to 5, which are all overhead views from the same position. Figure 3 shows a skew cutter for the base case. The cutter is moving from top to bottom and the belt is moving from left to right in this picture. Particles which belong to the reference sample have been coloured green (or light grey). We can see that the cutter has cleared a path across the belt. Most of the particles which are in the cutter are from the reference sample. Most of the particles from the reference sample, which did not enter the cutter, have been thrown by the cutter blades and can be seen in this figure at the bottom on the right-hand side of the cutter blades.

The average mass of reference samples was 20.81 kg. Of this material an average of 17.39 kg entered the body of the cutter and thereby became part of the sample, and 2.49 kg was thrown by the cutter blades into the sample chute without first entering the cutter body. An average of only 0.94 kg of the material in the reference samples missed becoming part of the sample.

Most of the particles not in the reference samples are little perturbed by the motion of the cutter. However, an average of 0.23 kg of such material entered the cutter body and 2.98 kg was thrown by the cutter blades into the sample chute. The non-reference particles thrown into the sample chute are primarily from the top of the load on the belt and from the final side of the belt (the bottom in Figure 3).

For the base case of a skew cutter moving at 1.5 times belt speed (shown in Figure 3), a more detailed breakdown of cutter performance is illustrated in Figure 7. There are nine regions which correspond to the regions shown in Figure 6. The widths of the plotted bars are proportional to the masses of the corresponding portions of the reference sample. The dotted lines are at a constant height, so the areas below the dotted lines are also proportional to the mass of the portions of the reference sample. The diagonally hatched regions have areas proportional to the masses of the corresponding amounts of reference material, which become part of the chute sample. The boxes with solid external lines and no hatching have areas proportional to the mass of material, which becomes part of the chute sample but which was not in the reference sample. The regions above these boxes, bounded at the bottom by solid lines and on the other three sides by dashed lines, have areas proportional to the masses

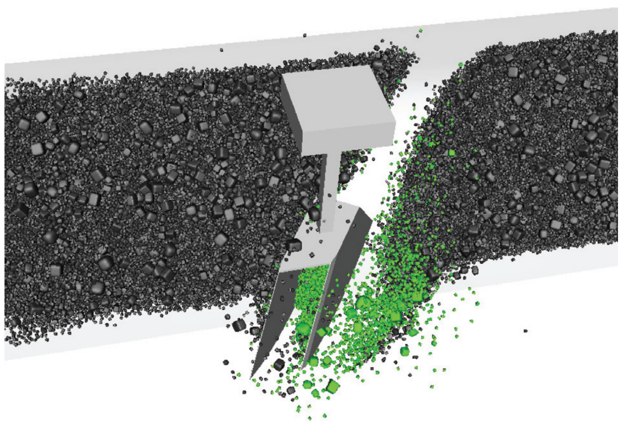

Figure 3—Overhead view of a skew cutter for the base case simulation

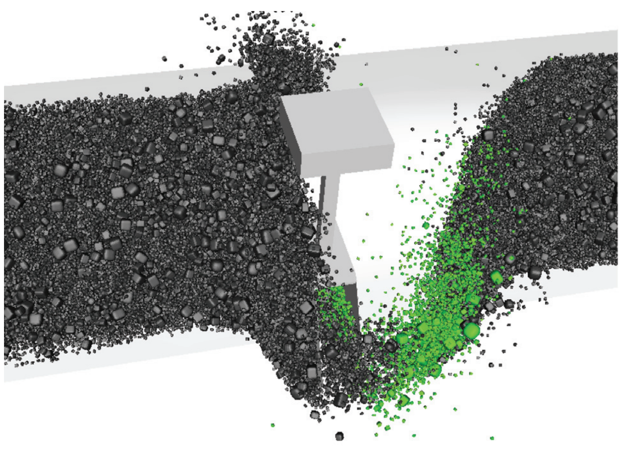

Figure 4—Overhead view of square cutter travelling at 1.5 times belt speed

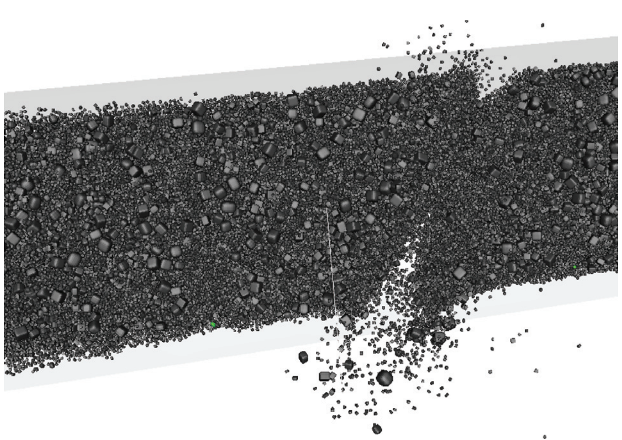

Figure 5—Overhead view of 3 mm diameter rod moving with a tip speed of 6 m/s

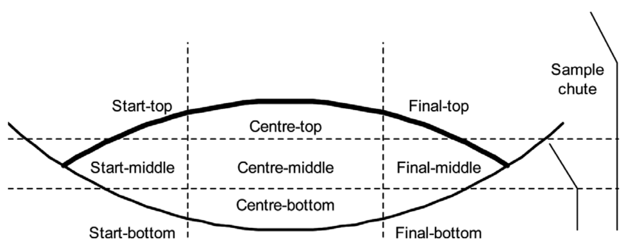

Figure 6—Classification of coal upstream of the cutter according to position across the belt and height

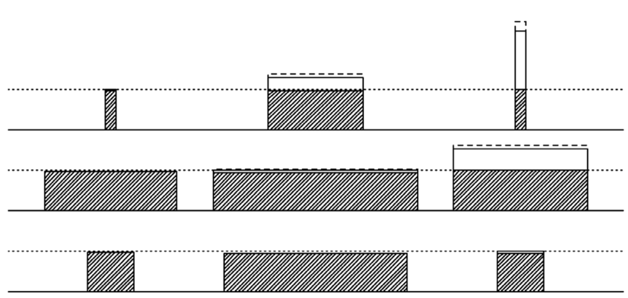

Figure 7—Average recovery for base case simulation of skew cutter

of material from each of the regions, which is bulldozed or thrown off the belt but does not go into the sample chute. The heights of the boxes can be interpreted as extraction ratios, with unity being shown as a dotted line. This figure shows that the material, which was initially towards the top of the load on the belt and towards the final side, tends to be over represented in samples taken by skew cutters.

Figure 8 shows the material entering the cutter rather than the material entering the sample chute in a manner similar to Figure 7. The nine regions in this graph again correspond to the nine regions illustrated in Figure 6. The widths of the diagonally hatched regions are proportional to the masses of the corresponding portions of the reference sample. The heights of the boxes show the proportions of the average amount of reference material which entered the cutter. This graph also shows the masses of material, which entered the cutter but which were not in the reference sample, using boxes with solid external lines and no hatching. In this case, the heights of these boxes are so small that the boxes are visible only as thicker-than-normal lines on the tops of the hatched regions.

Comparison of Figures 7 and 8 shows that on the side of the belt first reached by the cutter there is very good correspondence between being in the reference sample, entering the cutter and becoming part of the chute sample. This means that almost all particles which are in the reference sample enter the cutter and become part of the chute sample and that very few particles which are not in the reference sample enter the cutter or become part of the chute sample. For the material in the centre-bottom, final-bottom and centre-middle regions the correspondence between being in the reference sample, entering the cutter and becoming part of the chute sample is nearly as good as for the material on the 'start' side of the belt. The correspondence is much worse for the material in the centre-top, final-middle and final-top regions. Many particles, which were in the reference sample, do not enter the cutter and many particles, which were not in the reference sample, are thrown into the sample chute. The fact that the portions of the load on the belt are unequally represented in the sample can cause substantial sample bias if the load on the belt is segregated, perhaps due to passage over many sets of idlers, being loaded from more than one source or being loaded from one side.

Figure 4 shows a square cutter moving at 1.5 times belt speed. The cutter is moving from top to bottom, the belt is moving from left to right, and particles which belong to the reference sample have been coloured green (or light grey). The square cutter causes much more disturbance to the coal that should not sampled than does the skew cutter. There is a substantial gap on the belt downstream (to the right) of the cutter. Upstream (to the left) of the cutter there is substantial build up of particles against the side of the cutter. This pile acquires some momentum from the motion of the cutter and a substantial quantity of particles is bulldozed off the belt in what looks like a bow wave near the front of a ship moving through water. Some particles from this wave flow into the cutter body. Downstream (to the right) of the cutter we can see that some particles from the reference sample have been thrown by the cutter blades. The average mass of reference samples was 17.09 kg. Of this material an average of 11.19 kg entered the body of the cutter and thereby became part of the sample and 1.47 kg was thrown by the cutter blades into the sample chute without first entering the cutter body. An average of 4.43 kg of the material in the reference samples missed becoming part of the sample.

A substantial mass of material not in the reference samples is perturbed by the motion of the cutter. An average of 2.31 kg of such material entered the cutter body, 27.33 kg was bulldozed or thrown off the belt and 3.22 kg was bulldozed or thrown by the cutter blades into the sample chute. It was assumed that there were baffles with 10 mm clearance from the sides of the cutter so that most of the material thrown off the belt did not go into the sample chute.

Figure 5 shows a 3 mm diameter rod moving with a tip speed of 6 m/s, which is the same as the leading edge of one of the cutter blades for either of the cutters. The rod is moving from top to bottom and the belt is moving from left to right. In this case there is no reference sample. We can see that the moving rod knocks a substantial amount of coal off the belt. The average mass of material thrown off the belt by two rods was 6.07 kg. This is essentially the same at the average of 6.20 kg of material thrown off the belt by the skew cutter. The mass thrown into the sample chute by the skew cutter is smaller than this because it was assumed that there were baffles with 10 mm clearance from the sides of the cutter so some material thrown off the belt did not go into the sample chute.

Figure 9 shows the average recovery for the two simulations of a square cutter moving at 1.5 times belt speed. Comparing this to Figure 7, much more material is thrown off the belt than for the skew cutter. However, the amount of material sampled by the square cutter is slightly closer to the correct amount than for the skew cutter. Real square cutters always have baffles, so the amount of material thrown into sample chutes is more relevant to the performance of real

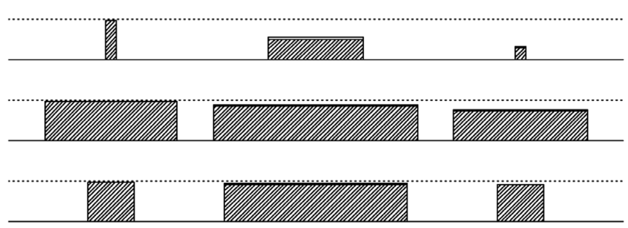

Figure 8—Average mass entering cutter for base case skew cutter

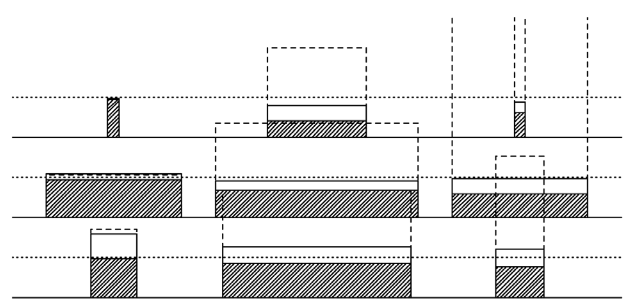

Figure 9—Average sample recovery for square cutter moving at 1.5 times belt speed

cross-belt cutters. This suggests that provided their baffles are well designed, square cutters will have extraction ratios slightly nearer to 100% than skew cutters. However, the difference in extraction ratio is not large and the amount of sample bias depends in different ways for the two types of cutter on the pattern of segregation of the material on the belt so we cannot conclude that square cutters have smaller bias than skew cutters.

Figure 10 shows the average amount of material entering the cutter for the two simulations of a square cutter moving at 1.5 times belt speed. Comparing this to Figure 8, we can see that the total amounts of material entering the cutter from the nine regions of the load on the belt are similar for the square cutter and for the skew cutter. For the skew cutter, nearly all of the material which entered the cutter was from the reference sample but for the square cutter a substantial proportion of the material which entered the cutter was not from the reference sample.

One other interesting result is shown in Table II. This gives the masses of material following various paths through the system. The feature to be highlighted is that the masses of reference material that misses entering the cutter, of reference material that misses the sample chute, of nonreference material that enters the sample cutter, and of nonreference material that enters the sample chute are all almost constant over the range of cutter apertures. This observation is not consistent with the idea that the mechanism which causes bias is congestion at the entrance to the cutter.

The crucial mechanisms

The most important conclusion to be drawn from this project is the identification of the two crucial mechanisms which are likely to cause sample bias for cross-belt cutters.

Waves of material bulldozed off the belt by the upstream side of the body of a square cutter

The motion of square cross-belt cutters causes waves in the material which does not enter the cutter body, as we saw in Figure 4. Momentum square to the belt is delivered to these waves by friction against the moving cutter, so some material flows off the belt in waves as if being bulldozed. This potential bias mechanism is very important for square cutters. Its reduction was a major driver in the development of skew sample cutters. This mechanism is not important for skew cutters.

This mechanism may be reduced by increasing cutter speed. Fewer particles will bank up against the upstream side of the cutter if the cutter speed is increased. A commonly used rule is that the cutter speed should be at least 1.5 times belt speed. The mechanism can also be reduced by having baffles which can prevent most of the material in these waves from leaving the belt and ending up in the sample chute.

Material thrown by leading edges of cutter blades

The leading edges of cutter blades tend to throw material off the belt. For skew cutters, most of this thrown material ends up in the sample chute. Some particles are hit directly by the cutter blades; some particles are thrown indirectly by other particles which have hit the cutter blades. The motion might best be described as waves of particles being thrown by the motion of the leading edges of the cutter blades. This mechanism occurs even when a cylindrical rod was moved in a manner like the leading edge of a cutter blade. Similarities in flow behaviour between cases using rods and ones using skew cutters provided clear evidence that this mechanism is a very important cause of bias for skew cutters.

This bias mechanism occurs with both square and skew cutters. It can be reduced by having baffles and the reduction is greater for square cutters than for skew cutters. For square cutters, the baffles can be made to have a gap only a small amount wider than the cutter aperture. For skew cutters, it is not possible to put a baffle near to the downstream cutter blade because the body of the cutter would collide with it. The mechanism can also be reduced by moving the cutter at a slower speed.

This bias mechanism would also occur with helical cutters (shaped like a portion of a screw), whether having leading edges displaced from one another in the direction of travel of the belt or having the more complex geometry proposed by Lyman, Hawthorne, and Osborne (2007).

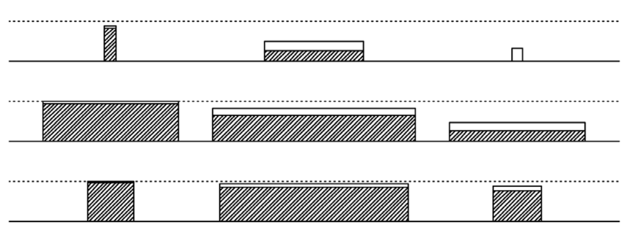

Figure 10—Average mass entering cutter for square cutter moving at 1.5 times belt speed

Table II

Masses for simulations of skew cutters with different cutter blade separations

Cutter aperture	100 mm	125 mm	150 mm	175 mm	200 mm
Reference sample mass (kg)	14.08	17.46	20.81	24.20	27.44
Mass into cutter (kg)	10.40	13.97	17.92	21.57	24.90
Missed into cutter (kg)	3.80	3.66	3.42	2.96	2.97
Extra into cutter (kg)	0.12	0.16	0.23	0.33	0.41
Mass into sample chute (kg)	16.34	19.60	23.08	26.44	29.70
Missed into chute (kg)	1.16	0.96	0.94	0.85	0.97
Extra into chute (kg)	3.41	3.09	3.21	3.10	3.22

Since the mechanisms that cause sample bias are different for skew and square cutters, we recommend that they be dealt with separately in standards. For square cutters, both mechanisms occur. The first mechanism decreases with cutter speed and the second mechanism increases with cutter speed, so for a given pattern of segregation of material on the belt there will be a speed that minimizes the total bias caused by the two mechanisms. We have not estimated this optimal speed. We consider that the commonly accepted rule that square cutters should be operated at 1.5 times belt speed or more should be interpreted as meaning that the extent of the first mechanism is unacceptable for cutter speeds lower than 1.5 times belt speed. It does not mean that 1.5 times belt speed is the best operating speed.

For skew cutters the first mechanism does not occur, so cutter design and operation should try to minimize the extent of the second mechanism. From our modelling we believe that skew cutters set at 45 degrees to the belt and moved at belt speed are better than skew cutters designed for 1.5 times belt speed in that less material will be thrown off the belt by the leading edges of cutter blades. It is likely that larger skew cutters which moved more slowly would further reduce the second bias mechanism

Robustness of the results

DEM models an idealized system and is not a perfect representation of reality (as is the case for all models). There is also substantial real variation in material properties between mines and within mines and all variants cannot be explicitly checked. However, the effects of the bias mechanisms identified were found to be robust to variations in the broad range of particle properties investigated. Therefore we believe that our main conclusions are robust across a broad range of materials and operating conditions.

Table III shows the average masses of material thrown for many different situations. These results are averages of two replicates, except that the mass given for the base case (a skew cutter with 150 mm aperture) is an average of six replicates. For cutters the mass thrown is computed as the mass of material leaving the belt minus the mass which entered the cutter. For the rods with face plates (which are like the upstream side of a square cutter) the mass thrown is measured directly. For the rods without face plates (which are like one leading edge of any type of cross-belt cutter) the mass thrown by a rod is doubled in order to make it comparable to the mass thrown by the two leading edges of a cutter.

We can see in Table III that the mass thrown off the belt by a skew cutter or a pair of rods moving with a tip speed of 6 m/s is approximately 6 kg. The mass is fairly consistent across a wide range of simulated particle properties and other simulation conditions. One change to simulation conditions that does affect this mass is that as the particle bottom size was changed from the base value of 12 mm to 10 mm and further to 8 mm, the mass thrown changed from 6.20 kg to 5.21 kg and 4.97 kg respectively. The trend in the results suggests that the mass of material thrown off the belt would

Table III

Masses of material thrown. For the rods without face plates the mass is doubled since a cutter has two leading edges

Description of DEM run	Tip speed (m/s)	Mass thrown (kg)
Square cutter moving at twice belt speed	8	27.83
Square cutter moving at 1.5 times belt speed	6	33.17
Rod and square face plate moving at 6 m/s	6	31.46
Rod and square face plate moving at 4 m/s	4	40.94
Skew cutter on belt moving at 6 m/s	9	7.92
Rod moved at 9 m/s	9	7.55
Skew cutter with 100 mm aperture	6	6.72
Skew cutter with 125 mm aperture	6	6.52
Skew cutter with 150 mm aperture (base)	6	6.20
Skew cutter with 175 mm aperture	6	5.63
Skew cutter with 200 mm aperture	6	5.36
Load on belt not segregated	6	6.93
Alternative particle shape distribution	6	5.75
Particle-particle friction 0.5 (usually 0.8)	6	5.27
Particle-cutter friction 0.9 (usually 0.5)	6	6.66
Coefficient of restitution 0.5 (usually 0.25)	6	5.71
Belt with perfectly circular cross-section	6	5.66
Slightly modified particle size distribution	6	5.75
Bottom size 10 mm (usually 12 mm)	6	5.21
Bottom size 8 mm (usually 12 mm)	6	4.97
Helical cutter	6	5.15
1.5 mm diameter rod moving at 6 m/s	6	5.56
3 mm diameter rod moving at 6 m/s	6	6.07
3 mm diameter rod moving at 4 m/s	4	5.30
Skew cutter on belt moving at 2 m/s	3	1.77
Skew cutter on belt moving at 1 m/s	1.5	0.83

be slightly smaller than 5 kg if finer particles were included in the DEM model rather than being modelled as 12 mm, 10 mm or 8 mm particles. The qualitative conclusion that a substantial mass of material is thrown off the belt by the leading edges of the cutter blades does seem to be robust.

How large a bias might a cross-belt cutter actually have?

We can conclude from our analysis of the DEM results that sample extraction for cross-belt sample cutters is not correct. But this does not necessarily mean that they should never be used. The extent of underrepresentation of some portions of the stream of material on a belt and overrepresentation of other portions may be acceptable in some circumstances.

A procedure for estimating the maximum likely sample bias is based on stopping a belt on a few occasions when the amount of segregation is thought likely to be greatest. Each time the belt is stopped, put down a frame like those often used for stopped-belt bias testing. Shovel off about 1/3 of the material on the belt, primarily from the top and from the final side, and put this coal into one container for sample preparation and assaying. Shovel off the remainder of the coal and put this coal into a second container for sample preparation and assaying. The maximum likely sample bias is then approximately 1/10 of the largest discrepancy between the pairs of assay results. For example, if coal were being sampled and assays of 10.7 and 10.1% ash were found, then the maximum likely bias would be estimated to be 0.06% ash.

The logic underlying this approximation is as follows. Suppose that the grades are A and B. The true average grade is $\frac{1}{3}A + \frac{2}{3}B$. The average sample grade if a skew cross-belt sampler overrepresents the A material by a factor of 1.5, as appears possible from Figure 7, is $(1.5 \times \frac{1}{3}A + \frac{2}{3}B)(1.5 \times \frac{1}{3} + \frac{2}{3}) = \frac{3}{7}A + \frac{4}{7}B$. The discrepancy between the estimated grade and the true grade would be $\frac{2}{21}(A - B)$. The average sample grade if a square cross-belt sampler underrepresents the A material by a factor of 0.9 and overrepresents the B material by a factor of 1.2, as appears to be possible from Figure 9, is $(0.9 \times \frac{1}{3}A + 1.2 \times \frac{2}{3}B)/(0.9 \times \frac{1}{3} + 1.2 \times \frac{2}{3}) = \frac{3}{11}A + \frac{8}{11}B$. The discrepancy between the estimated grade and the true grade in this case would be $\frac{2}{33}(B - A)$.

How useful is monitoring of the extraction ratio?

For falling-stream cutters, most of the potential causes of bias lead to the extraction ratio being less than unity. The only exceptions that come quickly to mind are when a sample container was parked in a position where it collected dust and a case where material from a hole in a chute went straight into a sample container. Both of these types of problem should have been detected by routine inspection. Apart from such situations, bias mechanisms tend to decrease the extraction ratio. Therefore nearness of the average extraction ratio to unity is generally a reliable indication that a falling-stream cutter has small bias.

In contrast with that logic for falling-stream cutters, the bias mechanisms relevant to cross-belt cutters whereby waves of material are bulldozed off the belt by the upstream side of the body of a square cutter and whereby material is thrown off the belt by the leading edges of cutter blades both tend to increase the mass of sample. There are many other possible causes of incorrect increment extraction that tend to decrease the mass of sample, such as poor contact between the cutter and the belt, particles being unable to enter overfull cutters, loss of sample through gaps near scrapers and material sitting in imperfections in the surface of belts. If we knew that a cross-belt sample cutter had an extraction ratio near to 100 per cent then we cannot be confident that none of the possible bias mechanisms are active. It might be that two bias mechanisms are active, one tending to increase the mass of sample and the other tending to decrease it. Therefore nearness of the average extraction ratio to unity is not reliable as an indication that a cross-belt cutter has small bias.

Conclusions

This study has identified two mechanisms as being crucial for cross-belt cutters. The first of these is waves of material being bulldozed off the belt by the upstream side of the body of square cutters. This mechanism is substantial only for square cutters. The second mechanism is particles being thrown off the belt by the leading edges of cutter blades. It affects all types of cross-belt cutters.

All cross-belt cutters will have some bias, with material from different positions across the width of the belt and from top to bottom of the load on the belt being unequally represented in samples. The extent of the bias depends on the amount of segregation of the material on the belt. A practical procedure is proposed for estimating the maximum likely bias so that users of cross-belt cutters can decide whether the likely amount of bias is acceptable.

Having an extraction ratio near to 100% is not as reliable an indicator that a cross-belt sample cutter is performing well as it is for falling-stream cutters. For cross-belt cutters there are some bias mechanisms that tend to increase the extraction ratio and other bias mechanisms that tend to decrease the extraction ratio, so many combinations of active bias mechanisms can be consistent with an observation that the extraction ratio is 100%.

References

Cleary, P.W. Large scale industrial DEM modelling, *Engineering Computations*, vol. 21, 2004. pp. 169–204.

Cleary, P.W. and Robinson, G.K. Evaluation of cross-stream sample cutters using three-dimensional discrete element modelling. *Chemical Engineering Science*, vol. 63, 2008. pp. 2980–2993.

Gy, P.M. *Sampling of Particulate Materials*. Revised edition. Elsevier. 1982.

Lyman, G, Hawthorne, C., and Osborne, D. An optimised hammer sampler design. *Third World Conference on Sampling and Blending*. 2007.

Robinson, G.K., Sinnott, M., and Cleary, P.W. Do Cross-Belt Sample Cutters Really Need To Travel At 1.5 Times Belt Speed? *World Conference on Sampling and Blending* 3, J. Felipe and J.C. Koppe, (eds.) 2007. pp. 112–125, Porto Alegre, Brazil, 23–25th October.

Robinson, G.K., Sinnott, M., and Cleary, P.W. Understanding bias for cross-belt cutter sampling of coal—ACARP Project C15072. CSIRO Report Number CMIS 2009/47. 2009. ◆