

# AN ANALYSIS OF CUTTER BAR SKEW

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## INTRODUCTION

The cutter bar of a mower, swather, or combine is said to be askew when the center line of the guards, in the plan view, is not in the direction of travel. For pull-type vehicles (mowers, swathers, and combines), the cutter bar is askew if its outer end lags behind the inner. The lag is what commonly occurs and is a function of the crop, the rolling resistance, and the ground slope. The cutter bar will be askew for self-propelled and pull-type vehicles on turning, if the turning center is not located on the axis of the cutter bar.

The lateral motion of the guard, due to the skew of the cutter bar, deflects the stalks out of the vertical prior to shearing, thus increasing the variation in the stubble height. If the deflection is large, the guards may be unable to penetrate the stalks satisfactorily. When this occurs, the crop will not be cut and the cutter bar may plug. For example, Harrison *et al.* (4) experienced plugging with some pull-type mowers due to skew if the crop density and the ground speed exceeded specific values. For a pull-type swather, Harrison and Reed (3) observed that the crop would be cut satisfactorily even when the skew was 15°. For a tractor-mounted swather, Harrison and Reed (2) concluded that the minimum turning radius that would permit the crop to enter the guards was 22 ft (6.7 m).

The objectives of this study were as follows: to determine the relation between the deflection of stalk by a guard and the cutter bar skew; to estimate the maximum skew and stalk deflection that would avoid plugging of the cutter bar; and to determine the effect of some design features of a mower, swather, or combine, such as wheel location on the cutter bar skew.

## MAXIMUM STALK ANGLES AND DEFLECTION

A stalk that is deflected by the lateral motion of one guard may interfere with the adjacent guard prior to being cut, if the skew is large. The maximum stalk angle for a mower guard should be less than 70° to avoid the stalk dragging on two guards simultaneously and, therefore, to avoid the risk of plugging (Figure 1). For a stalk angle of 80°, the stalk may pass below the guards and not be cut. For a swather or combine guard, the maximum stalk angle should be less than 75°.

The stalk angle,  $\tau$ , can be related to the nominal stubble height,  $H$ , and the deflection,  $D$ , (Figure 2a) by the elastic-curve equation indicated by Seely (7), which is

$$d^2y/dx^2 = \frac{(1 + (dy/dx)^2)^{3/2}}{EI/Px} \dots (1)$$

where  $P$  = concentrated load;  $I$  = area moment of inertia of the stalk; and  $E$  = modulus of elasticity of the stalk. Integrating<sup>a</sup> equation (1)

$$dy/dx = x^2 \sqrt{k} / \sqrt{1 - kx^4} \dots (2)$$

where  $k = (P/2EI)^2$ . If the nominal stubble height,  $H$ , is large in comparison with the depth of the guard, as it is for a swather or combine, then the difference between  $H$  and  $h$  can be ignored. Figure 2 shows that  $\tan \tau = \Delta D / \Delta h$  or  $dy/dx$ , equation (2) becomes

$$\tan \tau = H^2 \sqrt{k} / \sqrt{1 - kH^4} \dots (3)$$

Integrating equation (2) by first expanding the binomial into an infinite series, substituting  $D$  for  $y$ , and using zero and  $H$  for the integration limits, equation (2)

becomes

$$D = k \left[ \frac{H^3}{3} + 1/2 \cdot \frac{k \cdot H^7}{1! \cdot 7} + 1/2 \cdot 3/2 \cdot \frac{k^2 \cdot H^{11}}{2! \cdot 11} + \dots \right] \dots (4)$$

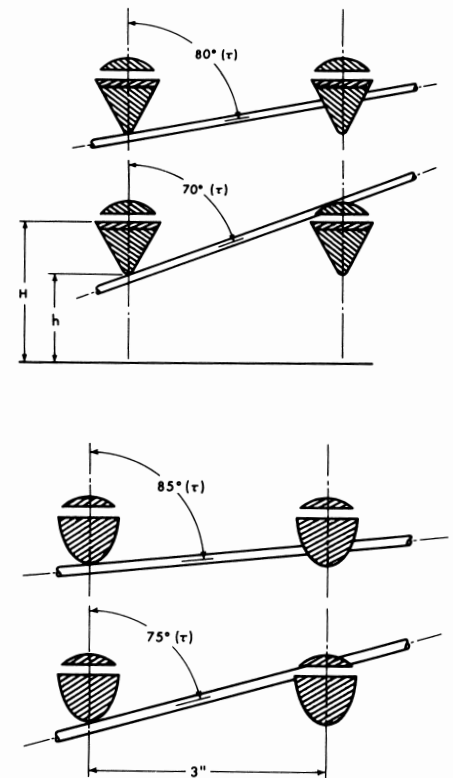


Figure 1. Cross section of mower guards (top group), swather/combine guards (bottom group), and stalk interference.

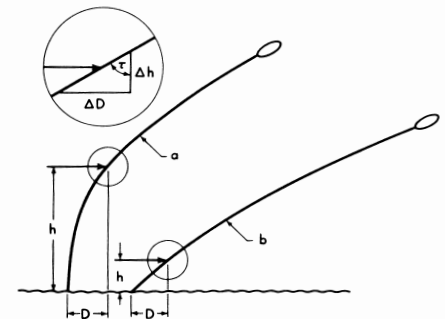


Figure 2. Stalk deflection without failure (a) and with failure (b).

<sup>a</sup> Equation (1) and the subsequent integrations are simplified for normal beam deflection because  $dy/dx$  is considered to be negligible.

TABLE I CUTTER BAR DATA

	Mower			Swather/Combine		
Stalk angle ( $\tau$ )		65°			70°	
Stubble height (inches)	1-1/2	2	2-1/2	6	8	10
Stalk deflection (inches)	1.3	2.4	3.5	2.1	2.9	3.6
Skew ( $\theta$ ) (degrees)	14	26	33	28	34	38

The deflection, D, was calculated for two ranges of nominal stubble heights by assuming that  $\tau$  was 65° for the mower and 70° for the swather and combine. The value of k was determined from equation (3) and subsequently used to determine D from equation (4). Though it was not necessary to determine P, nor estimate E or I, the values of k for the small stubble heights of a mower (1-1/2 - 2-1/2 inches or 38 - 63 mm) were such that the magnitude of P would cause the stalk to fail; that is, the slope of the stalk at the fixed end would not be zero and equations (3) and (4) would not apply. In view of this, the stalk deflections for the mowers were determined using a relation suggested by Figures 1 and 2, which is

$$D = h \tan \tau \dots \dots \dots (5)$$

where h = the difference between the nominal stubble height, H, and the depth of the guard. The depth of a mower guard is about 7/8 of an inch (22 mm). The stalk deflections for the mower and swather/combine are given in Table I.

MAXIMUM SKEW

The graphical relation between the cutter bar or guard skew and the deflection of the stalk is noted in Figure 3. The dimensions of the guards illustrated are typical values (1). If a stalk engages the guard at M, and if there is no friction, the stalk will be deflected at right angles to the surface of the guard along MO. Friction, however, will cause the stalk to be deflected along the line MN. The angle between MO and MN is the friction angle,  $\phi$ , where  $\tan \phi$  is equal to the coefficient of friction. If the maximum deflection of the stalk, D, is equal to MN, then the direction of travel of the guard must be parallel to the line PN for the stalk and the corner of the ledger plate, where the stalk can be sheared, to coincide. The relation between the stalk deflection and the skew,  $\theta$ , is

$$\frac{D}{MP} = \frac{\sin(\theta + \sigma)}{\sin(90 - \phi - \theta - \sigma)} \dots \dots (6)$$

According to Kepner (5), Bosoi suggests

that the friction angle,  $\phi$ , for smooth-edged knives, which approximates the guard surface, is 17°. The angle,  $\sigma$ , is approximately 10° (Figure 3) for either the mower or swather/combine. Though MP is equal to  $a/\cos \sigma$ , MP can be assumed to be equal to a because  $\sigma$  is small. Substituting in equation (6)

$$\frac{D}{a} = \frac{\sin(\theta + 10)}{\sin(63 - \theta)} \text{ or,}$$

$$\tan \theta = \frac{(D \sin 63^\circ - a \sin 10^\circ) / (a \cos 10^\circ + D \cos 63^\circ)}{\dots \dots \dots (7)}$$

Using this relation, the skews were calculated for the two ranges of stubble heights (mower and swather/combine) (Table I). As expected, the 15° skew observed by Harrison and Reed (3) for a pull-type swather is less than the smallest value obtained for the swather/combine. It is useful to note that raising the cutter bar should lessen the risk of plugging due to cutter bar skew.

PULL-TYPE VEHICLE SKEW

In the free-body diagram of a pull-type swather (Figure 4), P' is the cutter bar/crop reaction, which is a function of P in equations (1) to (3); F is a force that is a function of the weight of the swather and the ground slope (F may have a lateral component if the ground has a side slope); R<sub>l</sub> is the rolling resistance of the wheels in the plane of travel; R<sub>s</sub> is the lateral soil reaction of the wheels (at right angles to the plane of travel); and P<sub>l</sub> and P<sub>s</sub> are the tractor drawbar action forces.

The summation of the moments about the hitch point (x<sub>l</sub> is small and can be ignored) is

$$P'x_c + Fx_f + R_l x_r = R_s r_r + R_s l l \dots (8)$$

It is the lateral soil reactions of the wheels that minimize the skew. As these reactions are zero for zero skew, it follows that for P' or F greater than zero, or both, the swather must skew. P' can be significant even for the relatively small cutting width of a mower because P is large for small stubble heights. In a soft soil, the rolling resistance will be large and, for the right wheel, in the same direction as P' and F;

that is, the skew is also a function of the wheel sinkage. Also, if the guards experience some difficulty penetrating the crop, because of the cutter bar skew, the value of P' will be large, which will add to the skew, which in turn, will increase the difficulty of the guards penetrating the crop and plugging will occur.

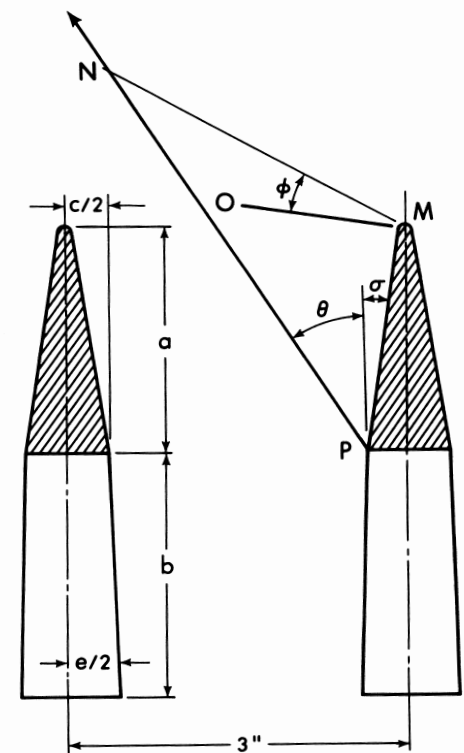
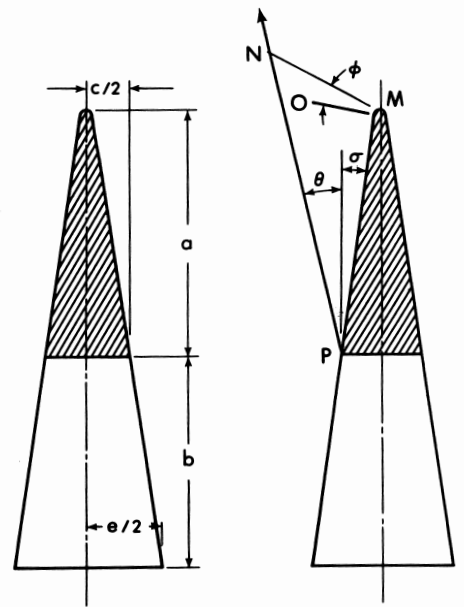


Figure 3. Cutter bar skew for mower guards (top pair) and swather/combine guards (bottom pair).

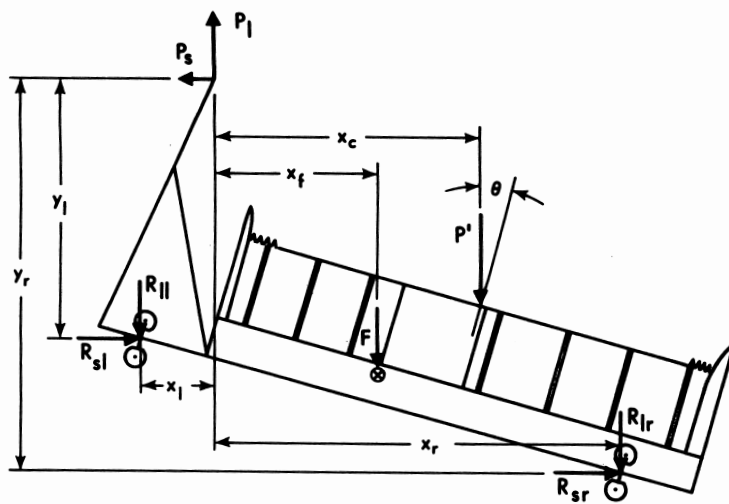


Figure 4. Cutter bar skew for pull-type swather.

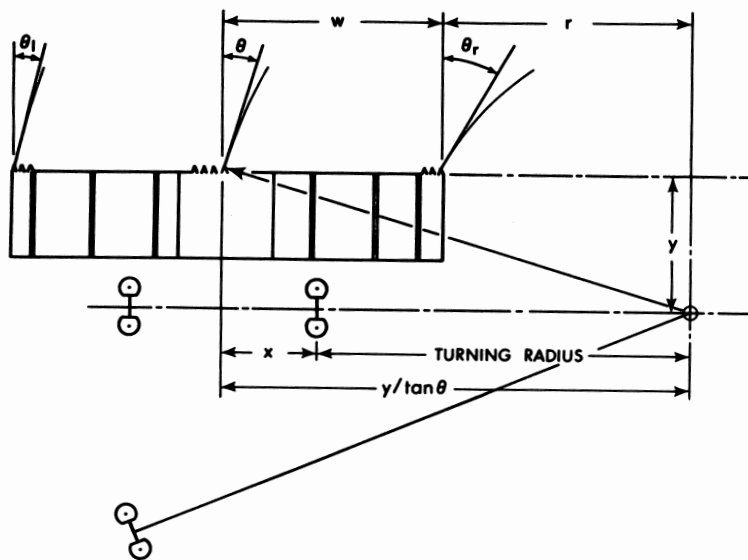


Figure 5. Cutter bar skew on turning for self-propelled swather.

remedy was used by Harrison *et al.* (4) for one make of a pull-type mower. It may be necessary to avoid loading the right tire in a soft soil as this increases the rolling resistance, which may increase the skew instead of reducing it.

### VEHICLE SKEW ON TURNING

Cutter bar skew can occur for a self-propelled swather while turning (Figure 5). In this instance, the skew is not uniform from one end of the cutter bar to the other. From Figure 5 the relation between the skew at the center of the table,  $\theta$ , and the turning radius is

$$\text{turning radius} = (y/\tan \theta) - x \quad \dots \quad (9)$$

where  $x$  = the distance between the center of the table and the wheel; and  $y$  = the displacement of the wheel axis from the cutter bar axis. If the skew of the right or left end of the table ( $\theta_r, \theta_l$ ) is to be used then the value of  $x$  would be different.

It is evident from equation (9) that if the turning center is not on the cutter bar axis ( $y > 0$ ) then the minimum turning radius, which can be negative, cannot be used (Figure 5). A negative turning radius occurs when the direction of rotation of one wheel is opposite to the other, and as a result, the turning center is located between the two wheels.

As noted previously, the minimum turning radius required to avoid guard and stalk interference for a tractor-mounted swather (2) was approximately 22 ft (6.7 m). This radius can be compared with the radii given in Table II, which were calculated using equation (9) and the skews in Table I. For the 8-inch (203-mm) stubble height, there is a reasonable agreement between the calculated values and that observed. It is not possible to be more explicit, as Harrison and Reed (2) did not specify the stubble height in their observation.

To circumvent obstacles in the field, the turning center must lie to the right or left of the table (or vehicle) on the wheel axis. If the skew is not to extend the values in Table II, then there is a maximum displacement of the wheel axis from the cutter bar axis, which in turn is dependent on the size of the obstacle. This can be seen from Figure 5 or by rearranging equation (9).

$$y = (\text{turning radius} + x) \tan \theta \text{ or,} \\ y = (w + r) \tan \theta \quad \dots \quad (10)$$

where  $w$  = the distance between the

The most effective ways to minimize the skew are not easy to implement. One of these is to "toe-out" the wheels (to the right in Figure 4) so that the wheel skew is larger than the cutter bar skew. According to Phillips (6), there is a maximum lateral soil/wheel reaction in the horizontal plane that occurs for a wheel skew much less than  $45^\circ$  and that the rolling resistance is also a function of the wheel skew; that is, a wheel skew beyond a specific angle will increase the cutter bar skew and not reduce it.

Another way to minimize the skew is to install a linkage between the tractor drawbar and vehicle, which would introduce a counter-clockwise moment. Such a linkage was available from one swather manufacture (3). A third way would be to lengthen the hitch frame of the swather to increase the dimensions of  $y_r$  and  $y_l$  (Figure 4). It is complicated by

the necessity of lengthening the PTO drive shaft as well. One manufacturer, who has recently introduced a very wide swather, has adopted still another way, which is to "power" the outside wheel. This provision is complicated by the difficulty of matching the peripheral speed of the wheel with the ground speed of the tractor. Minimizing the skew by the various mechanisms listed above are not practical modifications for the user. Some relief, however, may be obtained by increasing the weight of the implement if the skew is mainly due to the crop/cutter bar reaction.

Phillips (6) states that the soil/wheel reactions in the horizontal plane are a function of the vertical soil/wheel reaction as well as the skew. Filling the vehicle tires with a calcium chloride solution is one way of increasing the vertical soil/wheel reaction. Such a

**TABLE II MINIMUM TURNING RADII FOR A TRACTOR-MOUNTED SWATHER**

$y = 16$  ft,  $x(\text{left}) = 3$  ft, and  $x(\text{right}) = 1$  ft)

Stubble height (inches)	6	8	10
$\theta$ (degrees)	28	34	38
$y/\tan \theta$ (ft)	30	24	20
Left-turn radii (ft)	27	21	17
Right-turn radii (ft)	29	23	19

**TABLE III CUTTER BAR AND WHEEL AXES DISPLACEMENT**

Cutting circle radius (ft)	Cutting height (inches)	Axes displacement	
		12-ft table	16-ft table
2	6	4.2	5.3
	8	5.4	6.8
	10	6.2	7.8
6	6	6.4	7.4
	8	8.1	9.4
	10	9.4	10.9

table center and the outer limits of the vehicle and that is normally half the table width for a self-propelled vehicle;  $r$  = the radius of a cutting circle around the obstacle, which is the radius of the obstacle plus the clearance between the obstacle and vehicle or table. The maximum displacements of the axes for self-propelled vehicles are given in Table III for some combinations of table widths, cutting heights, and cutting circle radii ( $r$ ) using the skews in Table I. These displacements may be compared with the dimension  $y$ , which is the sum of the platform depth, the wheel radius, and the clearance between the wheel and the platform. This dimension is about 5 ft (1.5 m) for self-propelled swathers and about 6-1/2 ft (2.0 m) for combines. The required dis-

placements are less than the usual dimensions of  $y$ , where the table width, cutting circle, and cutting height are small.

It is necessary to make a distinction between turning of a vehicle to circumvent an obstacle, such as a tree, and the manoeuvre that is normally executed at a corner of the field. In the latter instance, the turning radius of the swather or mower for most of the manoeuvre is less than zero. The turning radius is partly dictated by the necessity of locating the swath or windrow for subsequent operations and that is not a restriction on the combine. The operator of a swather or mower can begin to execute the turning manoeuvre prior to the cutter bar emerging from the crop. Though cutting proceeds during the turn, it is limited to the outside end of the cutter bar where the skew is minimum ( $\theta_1 < \theta$ ). The operator of a self-propelled swather can choose to delay the execution of the manoeuvre until the cutter bar has emerged because he can reverse both or either traction wheel with relative ease. The skew has no significance in this instance as there is no crop to cut. A rigorous analysis would be complex, and because it is of limited value, has not been attempted. It is sufficient to note that the need to reverse both wheels is a function of the displacement of the cutter bar/wheel axes. For the tractor-mounted swather, noted previously (2), reversal was required and for a tractor with a standard transmission, time consuming. Reversal may also be required for a combine if an attempt is made to use it for a swather.

### SUMMARY AND CONCLUSIONS

The deflection of stalks by the guards of a mower, swather, and combine is a function of the cutter bar skew. The deflection and skew are determined by the inability of the stalks to penetrate the guards of the cutter bar. The skew,

in turn, is defined by the soil and crop reactions for pull-type mowers and swathers. The skew may be reduced by a number of design alternatives but the simplest is to increase the vertical soil/wheel reaction. For both self-propelled and pull-type vehicles, the skew is a function of the turning geometry. In this regard, tractor-mounted swathers are unsatisfactory, and to an extent the use of a combine as a swather as well, because the driving wheel axis cannot be located close enough to the cutter bar axis.

### REFERENCES

1. Cessford, R.G. 1967. A field study on parts standardization. Royal Commission on Farm Machinery Research Project No. 3-2-17A.
2. Harrison, H.P. and W.B. Reed. 1959. Dual windrower swather. Test rep. 859. Agricultural Machinery Administration, Government of Saskatchewan, Regina, Sask.
3. Harrison, H.P. and W.B. Reed. 1962. Oliver 67-A pull-type swather. Test rep. 1461. Agricultural Machinery Administration, Government of Saskatchewan, Regina, Sask.
4. Harrison, H.P., W.B. Reed, and E.O. Nyborg. 1961. Massey-Ferguson 51 and 52 pull-type mowers. Test rep. 960 and 1060. Agricultural Machinery Administration, Government of Saskatchewan, Regina, Sask.
5. Kepner, R.A. 1952. Analysis of the cutting action of a mower. Agr. Eng. 33(11): 693-697.
6. Phillips, J.R. 1959. Experimental determination of the forces on some towed drifting sheels. J. Agr. Eng. Res. Vol. 4, No. 4.
7. Seely, M.S. 1947. Resistance of materials. 3rd ed. John Wiley and Sons, Inc., New York, N.Y.