Effect of varied approach angle on high speed moldboard plow performance

by

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GLOSSARY

Draft: The horizontal component parallel to the direction of motion of the force required to pull an implement.

Moldboard plow bottom: A tillage tool consisting of a cutting edge and a warped surface for loosening and inverting the soil furrow slice.

a) Plow moldboard: The major warped surface of the plow bottom.

b) Plowshare: The part of the plow bottom which includes the bottom cutting edge.

c) Shin: A warped surface of the plow bottom adjacent to the furrow wall; vertical cutting edge when a coulter is not used.

d) Frog: The structure which supports the plowshare, plow moldboard, and shin.

Moldboard plow: A primary tillage implement consisting of one or several plow bottoms plus associated frame and accessories.

Specific plow resistance: The draft per unit of furrow cross sectional area.

Tillage, high speed: A tillage operation utilizing velocities considered to be higher than those velocities commonly used.

Tillage tool: An individual soil working element.

Tillage implement: The composite of the individual tillage tools, structural components, wheels, control, and shielding devices.

INTRODUCTION

Increased productivity is the constant goal of every modern day farmer. This increased productivity means for the farmer that he can obtain a higher standard of living and at the same time produce food and fiber for a hungry world. In tillage work this productivity is measured in acres per hour, although other units can be used. An equation (Hunt, 1973, p. 4) for the productivity or actual field capacity of a tillage implement can be written as:

$$\text{AFC} = \frac{S \times W \times E}{8.25} \tag{1}$$

where

AFC = Actual Field Capacity (acres per hour)

S = Speed (miles per hour)

W = Width (feet)

E = Field efficiency (decimal).

This equation for Actual Field Capacity or AFC defines the factors that determine the capacity of an implement. To increase productivity, one can 1) increase the field efficiency, 2) increase width, or 3) increase speed.

The efficiency of the operation can be improved to increase the actual field capacity. Time losses such as turning at the end of the field, equipment adjustment, and maintenance reduce the field efficiency. Reduction of time losses will increase the field capacity of any given operation.

The idea of increasing productivity by increasing the width of the machine is not new. Increasing the width of the machine has been natural with the shift from horses to massive higher horsepowered tractors. For a publicity stunt in about 1910, three International Harvester steam engines were used to pull 55 plow bottoms for a total width of 64 feet (McCormick, 1931). Each of the three tractors was individually pulling over 18, 14-inch plow bottoms. This is no small feat even today.

Increasing the speed of tillage is not a new concept. The walking speed of men, oxen, or horses can be used as a reference for tillage velocity. With the introduction of the steam engine in the early 1900's, the speed of tillage began to rise. This trend has been almost continual up to the present day.

Speed and width as means of increasing productivity are related to drawbar horsepower as given in equation 2 (Hunt, 1973, p. 27).

$$\text{DBHP} = \frac{FS}{375} \tag{2}$$

where

DBHP = Drawbar Horsepower required to pull the implement (HP)

S = Forward velocity of travel (miles per hour)

F = Draft or force required to pull the implement measured at the drawbar (lbs.)

375 = Conversion factor (miles-lb./hour-HP).

Doubling the width in order to double the actual field capacity essentially doubles F in equation 2. If F is doubled and speed held constant, the DBHP required for the tillage operation is increased by a factor of two. The tractor must have an engine which is capable of producing twice as much horsepower, but this tractor must also be capable of producing twice as much tractive force, F. Increasing the tractive ability may be accomplished by several methods but is usually realized by increasing tire size, tractor weight, and torque capabilities of the drive train.

Herein lies the advantage of high speed tillage. When the speed of operation is doubled and F held constant, the DBHP requirement is still twice as much; but the tractor does not have to be designed to produce twice the tractive effort. Thus, high speed tillage helps to alleviate soil compaction problems associated with massive tractors and drive train design problems associated with wide high draft tillage equipment.

A complete high speed tillage system will deal satisfactorily with four main areas:

1. Operator comfort and safety
2. Product reliability
3. Cost of manufacturing
4. Tillage implement performance.

Mental and physical stress affect the operator's comfort, fatigue him, and thus affect his safety while operating the implement system. At high speeds a greater degree of operator alertness is required. Decisions about machine monitoring and maneuvering must be made more quickly. A point is reached where the operator may feel he is no longer in control. Electronic monitoring systems help to extend this level.

The increased physical stress caused by vibrations also affects the comfort of the operator. Simply putting a spring on the seat is an answer for slower speeds, but active suspension systems described in the research reported by Roy E. Young and C. W. Suggs (1973) will be necessary to solve this problem.

Product reliability deals with the structural integrity of the implement. Stresses resulting from impact loading increase at higher speeds. The solution to this problem is either stronger or improved structural members in combination with adequate trip release mechanisms.

The complete high speed tillage system must be economically competitive with other comparative tillage methods. Simplicity of design is usually the best from the standpoint of product reliability and cost of manufacture. For example, modification to improve the performance of the moldboard plow must be very successful to justify changes to this simple rugged tillage tool. Slat bottom moldboards which increase scouring performance also increase unit cost and reduce reliability.

Performance is directly related to the design of the tillage tool. Without an acceptable implement design the first three problem areas do not exist because any high speed tillage attempted would not give acceptable results. For this reason the high speed tillage research undertaken in this investigation deals specifically with the necessary design parameters for a successful high speed plow bottom.

OBJECTIVES

The ultimate goal of tillage research is to increase man's understanding of the soil-tool interaction. This increased knowledge permits the design of tillage implements to better accomplish the desired end result. Within this broad goal, the objectives of this research are:

1. To determine the design parameters necessary for a high speed moldboard plow.
2. To evaluate the effect of different approach angles on two production moldboard plows.

LITERATURE REVIEW

Evaluation of Plow Performance

The evaluation of a particular plow bottom design is based on two main items:

1. The physical condition of the plowed land.
2. Forces on the plow bottom.

Physical condition of plowed land

The physical condition of the tilled land includes such items as soil bulk density changes due to pulverization, amount of necessary trash coverage, and wind and water erosion control considerations. This is possibly the most undefinable of the problem areas because the determination of soil physical condition is largely based on a value judgment by the farmer.

Tillage goals are not well defined quantitatively. The tool must improve tilth, but how is tilth evaluated? Pulverization or soil breakup can be estimated using rotary sieves (Gill and Vanden Berg, 1967). Various sized screens are used to separate the different sized soil particles. Rotary sieves may give erroneous readings due to additional soil breakup during the sieving process. This can be minimized by a gentle sieving action. The optimum breakup or pulverization of the soil is not easily specified.

The lack of quantitative soil physical parameters makes the design of tillage equipment less exact. Samuel A. Knox patented in 1852 a method of developing a moldboard based on mathematical principles.

According to Ellis and Rumely (1911, p. 150), "His plow was of light draft, but pulverized the furrow slice very little, hence did not meet with the approval of the Eastern plowmen". This identifies the problem of plow design. Farmers expect the plow not only to invert the soil but also the plow must pulverize the soil to some undefined correct extent.

Research such as Dan H. Luttrell's (1963), "The Effect of Tillage Operation on Bulk Density and Other Physical Properties of the Soil", helped to establish a basis for evaluation of soil physical condition. Soil bulk density changes and surface roughness for different tillage combinations of plowing, disking, and harrowing were evaluated. Luttrell concluded that plowing created the lowest bulk density of the tillage operations and that the method of evaluation used in his study could be effectively utilized in evaluating field physical conditions. He did not make any recommendations as to optimum bulk density or surface roughness.

When speed of plowing is increased with a given moldboard, the lateral movement of the soil is increased. Söhne (1959) stated that this affects the physical appearance of the soil and he plotted the furrow profile for different plowing velocities. He stated that this increase in soil movement is objectionable to the farmer and should be eliminated or minimized for a high speed moldboard.

Ashby (1931) evaluated plow performance by measuring draft and covering ability. The covering ability was expressed in a percentage of stalks left uncovered. An optimum or desirable percentage of covering is a subjective judgment and its value is affected by soil conservation considerations.

Increased tillage speed is also thought to increase pulverization. Research indicates that in some cases pulverization is not increased but rather the various size soil particles are simply redistributed differently in the furrow profile. Söhne (1960, p. 7) stated that "at high speeds there occurred a kind of separation, whereby coarse clods and also very fine crumbs got to the surface, while medium crumbs and clod sizes fall back". Thus, a general rule stating that increased tillage velocity increases pulverization is not absolutely true.

Forces on the plow bottom

The most quantitative method of evaluating plow performance is measurement of the forces on the tool. Interest in draft, which is the horizontal component of tool force in the direction of travel, has a long history. Ocock (1912) measured specific plow resistance versus depth of plowing using a team of three horses and a recording dynamometer.

Clyde (1936) refined the field test to a great degree by developing his tillage meter. The forces on a tillage tool to be investigated were isolated by attaching the tool to a triangular frame. The tillage meter employed hydraulic dynamometers. Strain gauges have largely replaced hydraulic dynamometers in force analysis due to ease in use and recording (Morling, 1963).

Clyde (1936) defined the forces on a given tool to be either useful or parasitic. Useful forces are those required to overcome cutting, breaking, and moving of the soil. Parasitic forces are the supporting forces such as the forces on the moldboard landside.

Mayauskas (1959) analyzed the useful forces normal to the plowshare during field operations using pressure transducers placed in and level with the plowshare surface. His results showed that the normal pressure was greater near the forward edge or point of the plowshare. These results are substantiated by the observation that the point of the plowshare experiences the most wear in field use.

A disadvantage of tests conducted in the field is soil variability from one part of the field to the next (Morling, 1963). This variability makes comparative tests of several tools difficult. This disadvantage can be minimized by using soil bins where soil conditions can be more closely regulated.

Rowe (1959), utilizing a soil bin, analyzed the effect of speed on draft of a simple tillage tool. The tool was an inclined plane 4 inches wide and 2 inches long mounted on sensing units to measure the three principal direction forces. He used a theoretical analysis to predict tool forces and compared these with his measured results. Rowe's results showed that the shear strength of soil did increase with loading rate. This increase was greater at higher clay and moisture contents.

Terzaghi (1943) explained variable soil strength for a saturated soil in terms of the load carried by the internal hydrostatic pressure. He stated that any stress applied to the soil will be accompanied by a change in water content. "If the stresses which ultimately lead to failure of the test specimen are applied more rapidly than the corresponding changes in water content of the specimen can occur, part of the applied normal stress σ will be carried, at the instant of failure, by the excess hydrostatic pressure which is required to maintain the flow of the excess water out of the voids of the soil" (Terzaghi, 1943, p. 7).

The greater increase of draft with increased clay content and moisture content of the soil observed by Rowe (1959) is explained by analyzing the coefficient of friction μ'. Nichols (1931) determined the coefficient of kinetic friction μ' by pulling a flat piece of metal over a smooth soil surface. A calibrated spring balance was used to measure the force required for plate movement. Nichols used a constant speed motor to pull the plate when the effect of velocity was investigated. Nichols defined four friction phases as: A Phase - Compression, B Phase - Friction, C Phase - Adhesion, and D Phase - Lubrication. On a light, loose sand - A Phase - the relationship of μ' to speed was expressed in the following equation (Nichols, 1931, p. 322):

$$\mu' = 0.010s + 0.33 \tag{3}$$

where

μ' = coefficient of sliding friction

s = speed in feet per minute.

The coefficient of friction (μ') varied with soil moisture content according to Figure 1. The coefficient of friction (μ') also varied with colloid content as shown in Table 1 (Nichols, 1931, p. 322).

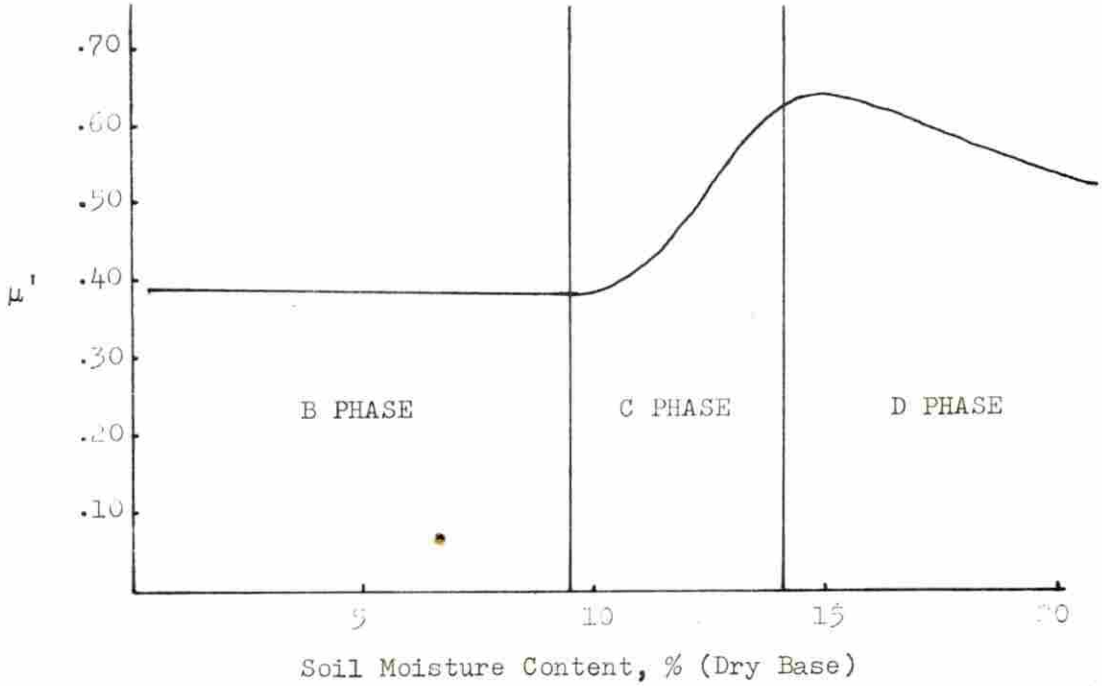


Figure 1. A typical curve showing the effect of soil moisture content on friction values. The B Phase is classified as the pure friction phase, the C Phase as the adhesion phase and the D Phase as the lubrication phase (Nichols, 1931, p. 321)

Table 1. The relation of colloid content to B Phase friction

Colloid Content %	Coefficient of Friction
0	0.26
8	0.36
16	0.40
24	0.47
32	0.51

Reduction of the friction force will reduce the draft. A teflon coating effectively reduced draft by reducing the coefficient of friction (Fox, 1962) but due to wear its use is limited to special applications where scouring is a problem.

Scouring, or the ability of a tool to shed soil, is an important aspect of plow performance. In an unscouring condition soil will stick to the moldboard changing the effective shape of the moldboard and the quality of plowing. This change in performance was pictured by Gill and Vanden Berg (1967). Two different plows were used in the same sticky soil where one scoured and the other did not.

Doner and Nichols (1934) studied the forces on the moldboard as they related to scouring. A mathematical analysis was used to determine the tangential forces necessary to maintain movement of the soil on the moldboard. An approximate formula for scouring was given.

Reducing draft by changing sliding friction to rolling friction is attempted in the rolling plow design. The roller plow which replaces the moldboard with a moving belt or cylindrical roller has been developed in Europe. Sharov (1962) compared Soviet and Hungarian roller plows of similar design in regard to soil inversion, pulverization, and draft. He concluded that both plows performed satisfactorily and draft reduction was possible with the roller moldboard.

Rowe (1959) concluded that the increase in shearing strength, not the increase in soil acceleration, was the major factor in the increase of draft with increased tillage speeds. He postulated that changes in tool geometry would have little effect on reducing the draft increase if the same degree of soil loosening was required.

Reed (1941) evaluated the effect of shape on the draft of 14-inch plow bottoms. Sixteen moldboard plows representative of the major classifications of sod, general purpose, and stubble were tested. His results indicated that draft increased with forward velocity and the shape of the plow bottom affected draft considerably.

The change in draft as a function of velocity is one of the better documented phenomena in tillage work. McKibben and Reed (1952) compiled much of this data between 1919 and 1949. The data included tests of 25 moldboard plows, 1 rolling coulter, and 1 subsoiler. The draft at 3 mph for all the tools was assigned a value of 100 percent. McKibben and Reed (1952) fitted the following equation to their plot of draft versus forward velocity:

$$Y = A (X - 3)^{1.5} \tag{4}$$

where

Y = Percent increase in draft over draft at 3 mph

A = 5, 10 or 15 depending on the data

X = Forward velocity (mph).

Draft increased with forward velocity for all the data analyzed except at the slow speeds where scouring, or lack of it, had a possible effect.

Many equations of plow draft as a function of forward velocity are available. Gorjatschkin's equation (Söhne, 1960, p. 4) expressed this relationship in a basic manner.

$$Z = Z_o + Ev^2 \tag{5}$$

where

Z = Specific plow resistance (F/LL)

Z_o = Static part of plow resistance (F/LL)

E = Coefficient pertaining to the dynamic portion of plowing resistance. Function of soil conditions and type, and moldboard type

v = Forward velocity (L/T).

The increase of draft with increased tillage speeds is one of the most severe restraints to high speed tillage. From equation 2 if speed is doubled to double field capacity and F remains constant, the DBHP is increased by a factor of two, but F increases with increased velocity. From this it can be seen that additional energy input is necessary to do a given amount of tillage at the higher speed.

The goal in the design of a high speed plow bottom is to reduce the draft increase with velocity while at the same time retaining the desired quality of work. Analysis of the design parameters of the plow bottom will aid in the realization of this goal.

Evaluation of Plow Design Parameters

The conventional moldboard plow body is defined by the following parameters, as diagrammed in Figure 2.

1. Orientation of tool
    a. share lift angle (α)
    b. share approach angle (ϕ)
    c. moldboard wing angle (γ)
2. Width of cut (Y')

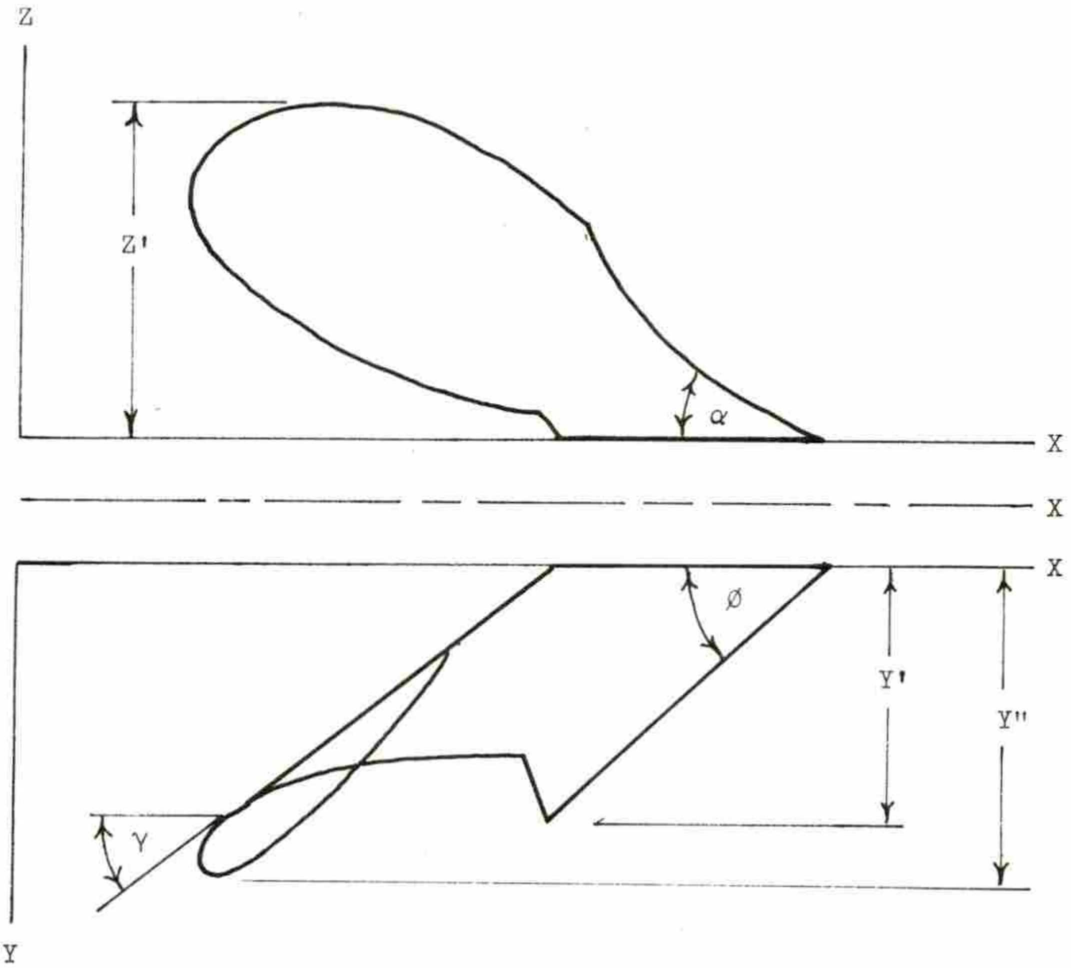


Figure 2. Coordinate system and parameters for moldboard plow description

3. Surface shape

4. Width and height of moldboard (Y",Z')

Research dealing with specific plow parameters has mainly utilized the simplest possible tool arrangements. Simple tools, as opposed to the complex shape of the moldboard plow, lend themselves to more exact control of the experiment due to fewer variables. Recommendations of optimum values gained from simple tools can be criticized. This criticism stems from the limited available knowledge of the interaction of the various processes, such as share cutting and moldboard inversion performed by the complex shape of the plow. The writer feels that while optimum plow parameters may be difficult to define from the results of simple tillage tools, desirable ranges for design may be identified.

Orientation of the tool

Payne and Tanner (1959) used rectangular plate tines 1 to 4 inches wide to evaluate the effect of rake (lift) angle on draft. Rake angles between 20° and 160° were used. From their results draft was minimum for the 20° tine and increased with larger rake angles. In the field tests draft increased very slightly for a change from 20° to the next larger tine rake angle of 48°.

Surikov (1968), studying inclined plates drawn through the soil, indicated that draft was relatively constant for lift angles between 10° and 30° but increased rapidly for angles larger than 30°.

To evaluate the effect of lift angle and approach angle on draft, Kaburaki and Kisu (1959) used inclined plates with a constant width and depth of cut in sand. Their results were consistent with other literature in that the draft increased only slightly with increased lift angles from 20° to 30° and increased more rapidly from 30° to 90°. The approach angle had little effect on cutting resistance between 30° and 90°. Cutting resistance increased slightly for cutting angles smaller than 30°.

Söhne (1956) evaluated lift angle effect on draft using inclined planes 10 cm wide and 5 cm high at a forward velocity of 1 meter per second. Minimum draft for both calculated and measured values of α was about 10°.

For a cylindrical moldboard the approach angle determines to a large extent the lateral velocity of the soil during plowing. Söhne (1959) stated that this lateral velocity component must not increase at higher operating speeds if the tool is expected to give acceptable performance. Performance may be unacceptable because the increased lateral soil acceleration at higher forward velocities causes an increase in draft and is evident in the increased lateral movement of the soil.

Width of cut

The parameter Y' describes the desired width of soil manipulated by the moldboard. Y' is usually a nominal figure specified by the designer although there is research to indicate that specific draft is a function of width of cut.

Gill and McCreery (1960) tested various width sections of a moldboard plow. They found that specific draft of the tillage tool as well as pulverization of the furrow slice decreased when size of cut (width) was increased.

Randolph and Reed (1938) measured the specific draft versus width of cut utilizing a 12-inch and 16-inch plow keeping the depth of cut constant. Their data indicated only a slight difference in specific draft as the cut was varied from 8 to 16 inches and 8 to 20 inches, respectively.

Surface shape

To evaluate the moldboard shape a method of description is necessary. The description can be either mathematical or graphical. The mathematical approach is limited in many cases because of the complex shape of the moldboard.

Thomas Jefferson (1799) developed one of the first accurate methods of describing a plow surface. Jefferson described his physical method of constructing the moldboard surface as combining enough theory to satisfy the intellectual with a method of construction intelligible to the most unlettered laborer. A mathematical equation of the surface was not determined.

Söhne (1959) used a slit light projector with a camera to photograph moldboard contours. These contours were used to investigate the shape of plow required for high speeds.

Nichols and Kummer (1932) developed an apparatus for measuring moldboard surfaces. They theorized that "the curvature of the moldboard which keeps the soil slipping on all shear planes simultaneously and uniformly must be constantly increasing at a rate which is proportional to the distance traveled up the curve" (p. 281). This theory led to the following equation (p. 281):

$$Z = ae^{bX} \tag{6}$$

where

Z,X = Coordinates of the curve

a,b = Constants of the curve

e = Base of natural logarithms.

They found that the major portions of the moldboards of all the plows in their study could be fitted using equation 6.

O'Callaghan and McCoy (1965) evaluated shape by coating a moldboard with nitrocellulose lacquer and obtaining scratch paths left by the soil flow over the moldboard. They calculated the acceleration of the soil and observed that the soil flow paths were different at different speeds. The soil tended to rise higher on the moldboard with increased velocity. The calculated acceleration of the furrow slice for one moldboard accounted for about 4 percent of the total draft at 2 mph and increased to about 27 percent at 8 mph.

Ashby (1931) compared 40 different production plow bottoms and the results of his tests showed that the shape of a plow bottom affects both covering ability and draft.

Width and height of moldboard

Determination of moldboard width and height describes the outer boundaries to the moldboard shape. These determinations are empirical, depending on the principle that the soil should not flow over the top of the moldboard in order that proper inversion will be achieved.

Söhne and Möller (1962) compared the parameters necessary for a high speed bottom with a conventional bottom (Table 2). The parameters for a high speed plow were based on the principle that the plowing resistance, furrow shape, soil breakup, and soil inversion should not differ greatly from the conventional bottom. Their observations that at higher plowing speeds the soil was moved farther laterally led to the following conclusion: The lateral component of velocity should

Table 2. Design parameters for a 3.3 mph and a 5 mph moldboard (Söhne and Möller, 1962)

Parameter	Shape for 3.3 mph	Shape for 5 mph
Working width (in)	12	12
Working depth, t (in)	8.7	8.7
Maximum height (in)	13.8	15.8
Share cutting angle	45°	37°
Cutting angle at the share point	22°	17°
Cutting angle at the end of the share	18°	13°
Parabola of vertical contour		
height (in)	10.2=1.18t	11.4=1.3t
depth (in)	7.9	10.6
Lateral directional angle of horizontal contour		
at moldboard land side	43°	37°
at moldboard end	40°	26°

be kept constant for a high speed plow design. Keeping the lateral velocity component constant helped to keep the furrow shape from changing and also reduced the increase in draft with higher speeds. Three plow designs for three different plowing velocities are shown in Figure 3.

The design parameters in Table 2 indicate large differences between the approach angle and moldboard wing angle for plows to be operated at 3.3 mph and 5 mph. The design of a 7 mph plow would require still smaller angles for ϕ and γ, in accordance with Figure 3.

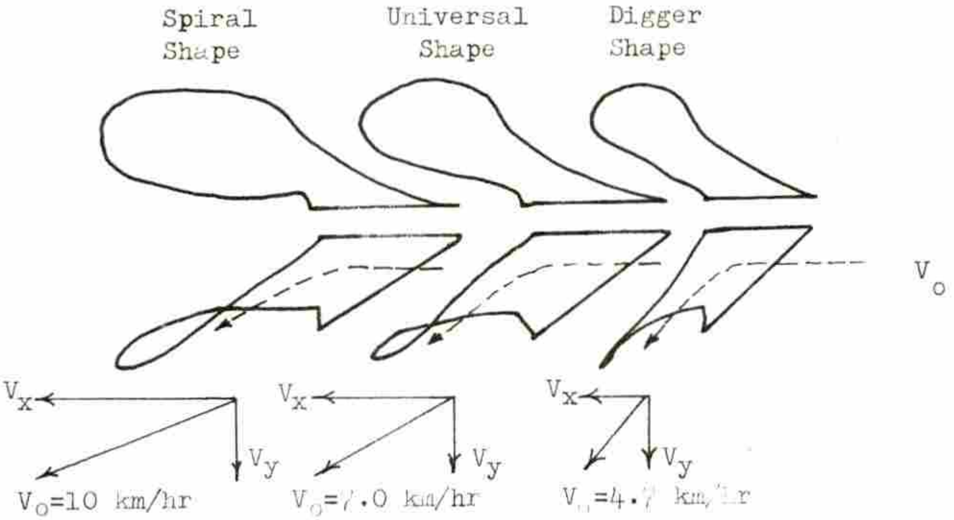


Figure 3. Plough body shapes for three different speeds of travel with the same lateral velocity components V_y of the soil leaving the moldboard (Söhne, 1960, p. 21)

A moldboard design for 7 mph operation will occasionally be operated at slower speeds. The high speed plow design may not give acceptable results with reduced speeds at the end of the fields and in cases where power is limited due to extra heavy plowing. Thus, it is desirable to design a plow that performs adequately at variable speeds. The experimental part of the research, presented in the next chapter, was to vary the approach angle in an attempt to satisfy the conditions necessary for a variable high speed plow.

EXPERIMENTAL WORK

Description and Preliminary Preparation of Equipment

Two Allis-Chalmers production moldboard plow bottoms were chosen for the testing procedure. The first was a high speed bottom, model 392; the second was a general purpose design, model 387 (Figures 4 and 5). The high speed bottom was selected because it was originally designed for higher plowing speeds with an approach angle of 35°. The general purpose bottom with an approach angle of 45° was chosen for the experiment to test the effect of shape and to give a base line comparison with the high speed design.

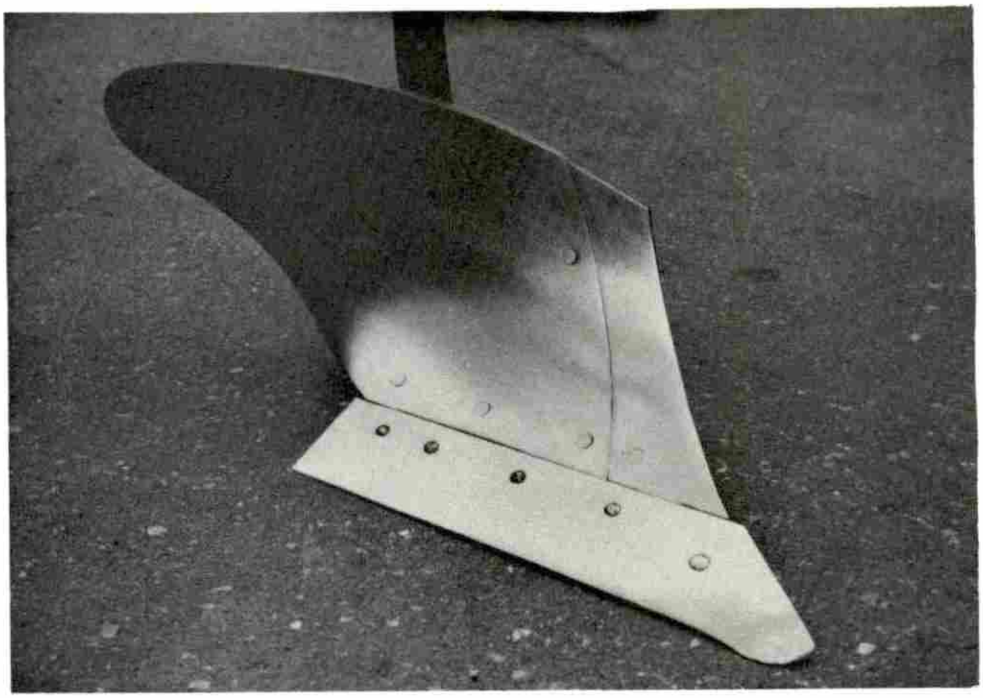
During factory production the plow bottoms are polished to remove surface scale and any large defects. After the final polishing they are painted to protect the steel surfaces from corrosion. To insure the proper operation of the plow bottoms during any experimental testing, it was decided to field plow until a field polish was attained. Before attempting to plow with the new bottoms, the protective paint was removed using paint solvent and fine sandpaper, grit No. 220.

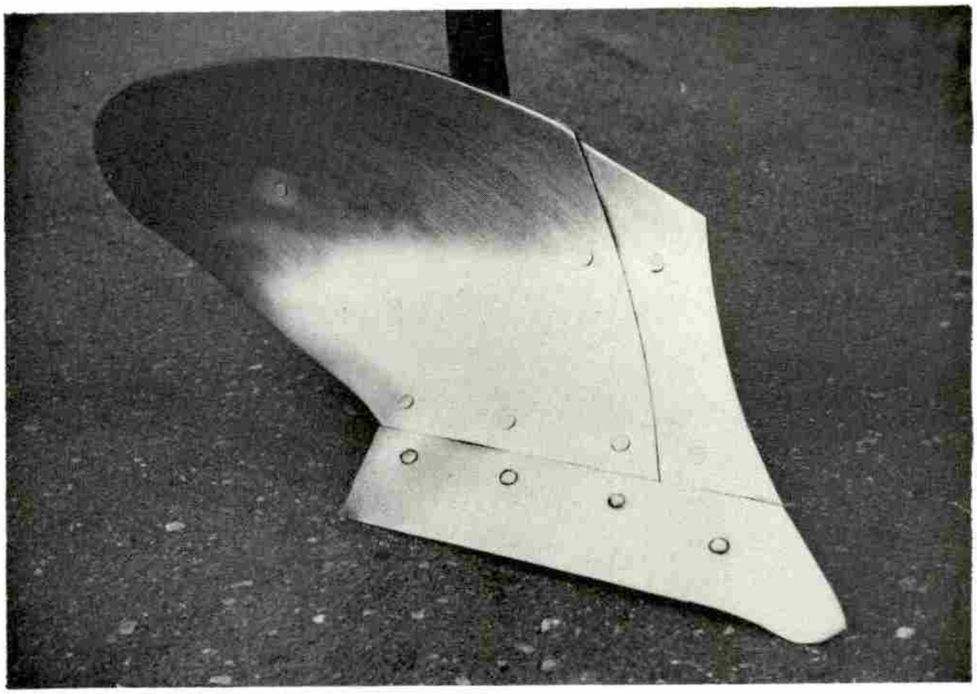
The field polish on the moldboards was attained after approximately 2 acres were plowed with each bottom. The plowing, which ranged between 3 and 5 mph, was conducted at the Agricultural Engineering-Agronomy Research Farm, Iowa State University.

The testing procedure required the ability to reduce the approach angle of the moldboards by 15° from its initial design position. When the moldboard was turned to reduce ϕ, the landside clearance changed.

Figure 4. Allis-Chalmers high speed moldboard plow bottom, model 392

Figure 5. Allis-Chalmers general purpose moldboard plow bottom, model 387





To obtain adequate clearance the frog or supporting structure of the moldboard plow bottom was modified.

The frog was repositioned on each bottom such that the approach angle was reduced 10°. Care was taken to insure that the design lift angle for each plow bottom was maintained as the frog was removed and rewelded. The frog on each bottom was modified after the field polish was attained and the initial field tests were completed.

It was thought that the clearance for the additional 5° approach angle change would be realized when the landside was removed. During initial testing at ϕ-15°, this was not correct. The bottom portion of the frog contacted the furrow wall and influenced the force measurements to a great extent. The necessary landside clearance was attained by removing approximately one inch of metal on the extreme lower furrow wall edge of the frog.

Test Procedure

The effect of varied approach angle on plow performance was tested in two separate procedures. The first was a study conducted in the field at the Agricultural Engineering-Agronomy Research Farm, Iowa State University. The second more extensive phase was conducted at the National Tillage Machinery Laboratory, Auburn, Alabama.

Field tests

The field tests were undertaken to determine qualitatively the performance of the moldboard plows. A rear wheel drive agricultural tractor was used to pull the 3-bottom mounted plow used in the field tests. The plow had a rear guide wheel which was set to regulate the depth of plowing at approximately 7 inches. The plow frame was adjustable for either 14-inch or 16-inch width of cut by each bottom. The width of cut for the investigation in the field was adjusted to 14 inches.

Of the several methods of evaluating performance it was decided to evaluate the plow bottoms by inspecting the furrow profile produced at different speeds. The speeds which were considered of interest were 4, 6, and 8 mph. The time was measured to complete a 200-foot test run to accurately determine the average speed of plowing for each test.

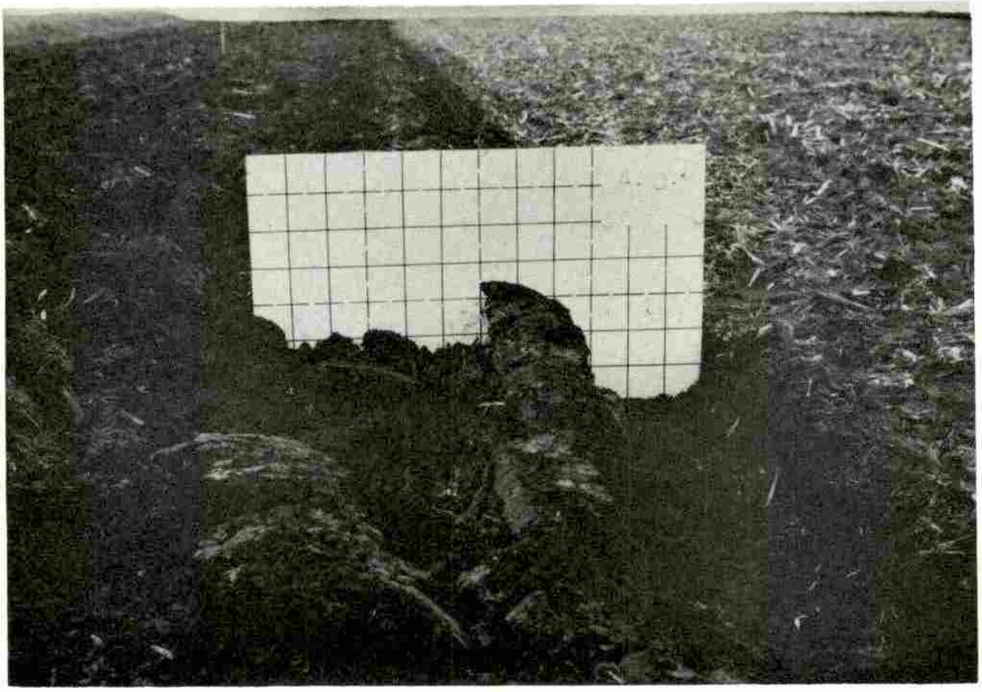
The shape of the furrow profile was established with the aid of a grid board inserted in the plow furrow. The 28-inch by 48-inch board was constructed of quarter-inch thick plywood. The plywood was first painted with white enamel. The lines to establish the grid system were 4 inches apart on center and painted with black enamel over the white background. The grid board as it was used in the test is shown in Figure 6.

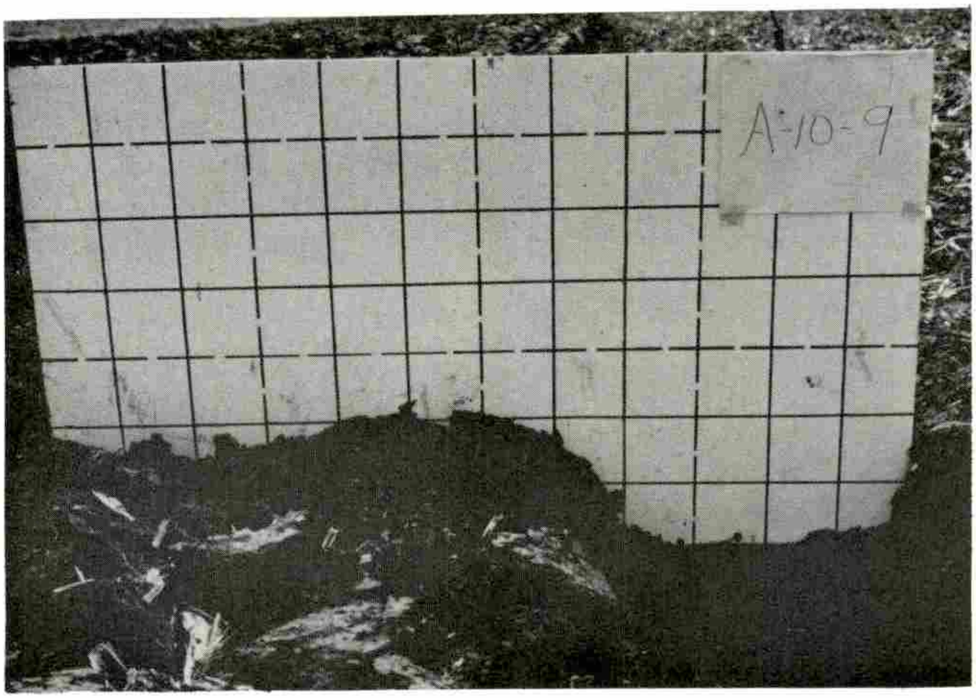
The original test procedure called for the plow bottom of interest to be mounted on the plow frame by itself with the other two bottoms removed. When this method of testing was attempted, it was found that the control of width of cut with the single plow bottom was not adequate. It was decided to mount two bottoms on the plow frame with the plow bottom of interest behind the first. This insured that the width of cut for the rear test plow bottom would be 14 inches.

The field tests were conducted on ground which had been cropped with corn the previous year. The field had been disked approximately

Figure 6. Grid board as positioned in furrow profile for tests (furrow profile is for model 392 at 4.0 mph with approach angle reduced 10°)

Figure 7. Furrow profile for model 392 at 8.0 mph with approach angle reduced 10°





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two months before the test which insured a relatively level surface with a light covering of corn stalks. After the 200-foot test run was completed two locations were chosen that typified the performance of the plow bottoms. In these two positions a trench was dug in the plowed ground at right angles to the furrow wall, into which the grid board was inserted. The right edge of the grid board was positioned against the furrow wall while the bottom edge of the board was placed even with the bottom of the plow furrow. A level was used on top of the grid board to insure that the grid board was always parallel with the furrow bottom. Photographs were taken of the grid board positioned in the furrow to record the profile.

The furrow profiles of both production plow bottoms were observed at their design approach angles; model 392 is shown in Figure 8. The profiles for the design approach angles were not recorded at the highest velocity (approximately 8 mph) due to inability to control depth of plowing and lack of constant speed for the 200-foot test run.

The two moldboard plows were again tested after the approach angle of the plows had been reduced 10° by repositioning the frogs as previously described. The furrow profiles of the same two plow bottoms were again recorded with the same width and depth of cut of 14 inches and 7 inches, respectively. The profile for model 392 is shown in Figure 9. With the reduced approach angle, it was possible to test the plow bottoms at the highest speed (approximately 8 mph).

The plow bottoms tended to throw the soil farther as the speed was increased. Reducing the approach angle of the plow bottoms 10°

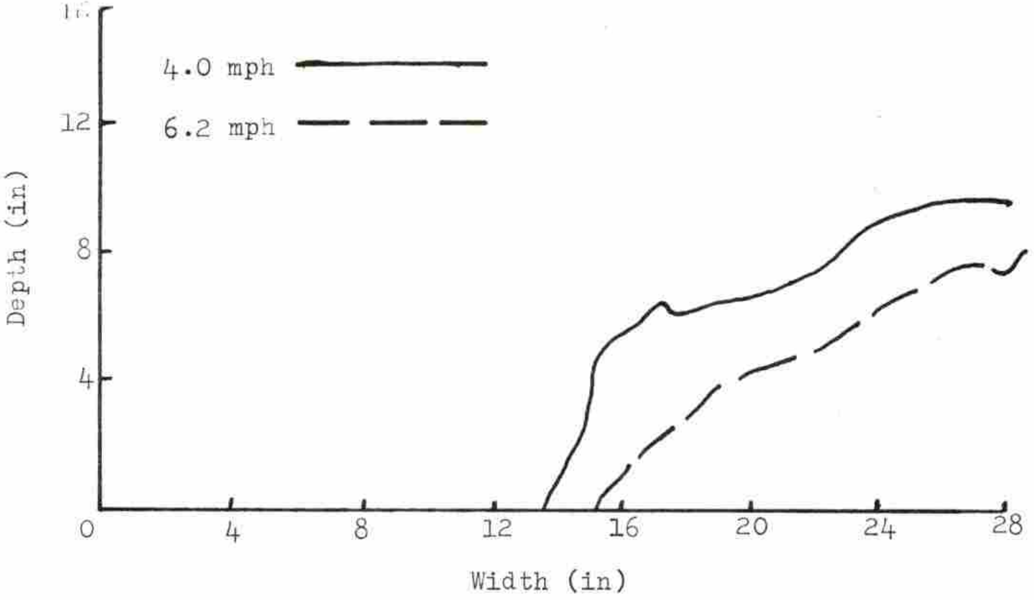


Figure 8. Furrow profile at two speeds for model 392 tested at its design approach angle

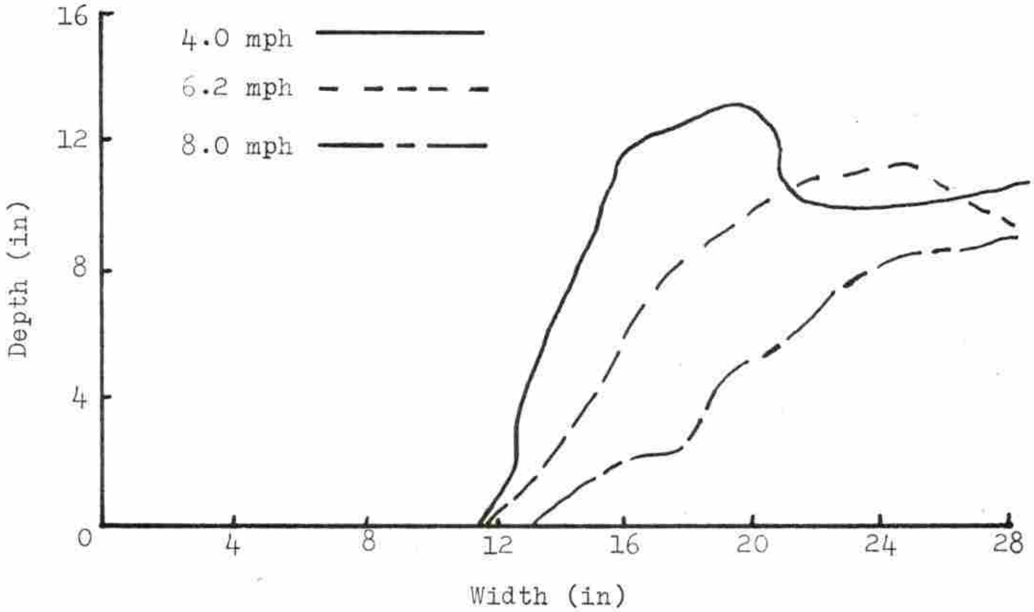


Figure 9. Furrow profile at three speeds for model 392 tested with design approach angle reduced 10°

changed the shape of the furrow profile markedly (Figure 9). The profile of the high speed production bottom at 4 mph was about the same as the profile at 8 mph of the same plow bottom with the approach angle reduced 10°. In other words, with the reduced approach angle model 392 performed about the same at 8 mph as it did at 4 mph with the design approach angle. This same trend was observed with the universal shape, although to a lesser degree.

Figures 6 and 7 are furrow profiles of model 392 with the approach angle reduced 10°. All test conditions were similar except forward velocity. The furrow profile of the modified plow bottom at 4.0 mph was very abrupt with the furrow standing almost on edge (Figure 6). It was noted that at speeds lower than approximately 4 mph proper inversion of the soil slice did not occur and at 4 mph inversion was marginal. Figure 7 is taken at 8.0 mph and shows a conventional furrow profile with complete inversion of the slice.

The additional throwing of the soil slice at high plowing speeds was reduced by reducing the approach angle of the moldboard plows. It was felt that a savings in draft at higher speeds would be possible by reducing the approach angle. To test this hypothesis the second more extensive testing of the plow bottoms was completed at the National Tillage Machinery Laboratory.

National Tillage Machinery Laboratory tests

Description of test facility   The testing of the plow bottoms was completed at the National Tillage Machinery Laboratory (NTML), Auburn, Alabama. The Laboratory has outdoor as well as indoor soil bins for model or full sized tests. For this investigation three different bins were used which contained Lakeland loamy sand, Norfolk sandy loam, and Decatur clay loam soil types. The outdoor bin containing sand was 250 feet long and 20 feet wide. The loam and clay types were contained in two different indoor bins, 190 feet long and 20 feet wide.

The individual plow bottom was supported on the implement carrier (Figure 10) which allowed for precise control of the depth, width of cut, and orientation of the plow bottom. Two separate cantilever beam strain gage dynamometers on the tool carrier were used as force transducers.

The coulter was mounted on the front dynamometer ahead of the plow bottom. Mounting the coulter separately allowed for segregation of the tool forces. The tool forces were recorded continuously in an instrument car pulled behind the tool carrier.

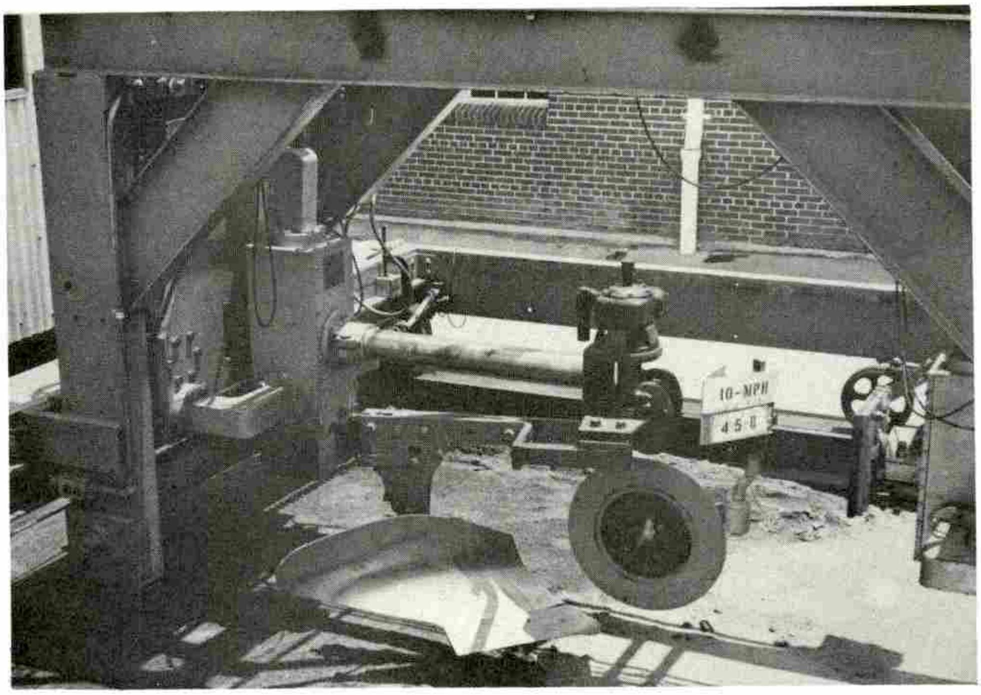
The forward velocity of the implement carrier could be varied from 0 mph to approximately 8 mph in the indoor bins and to approximately 10 mph in the longer outside bins. Tests could be run at a constant speed or at a gradually accelerating velocity. An overall view of the complete test apparatus including the power car, implement carrier, and instrument car is pictured in Figure 11.

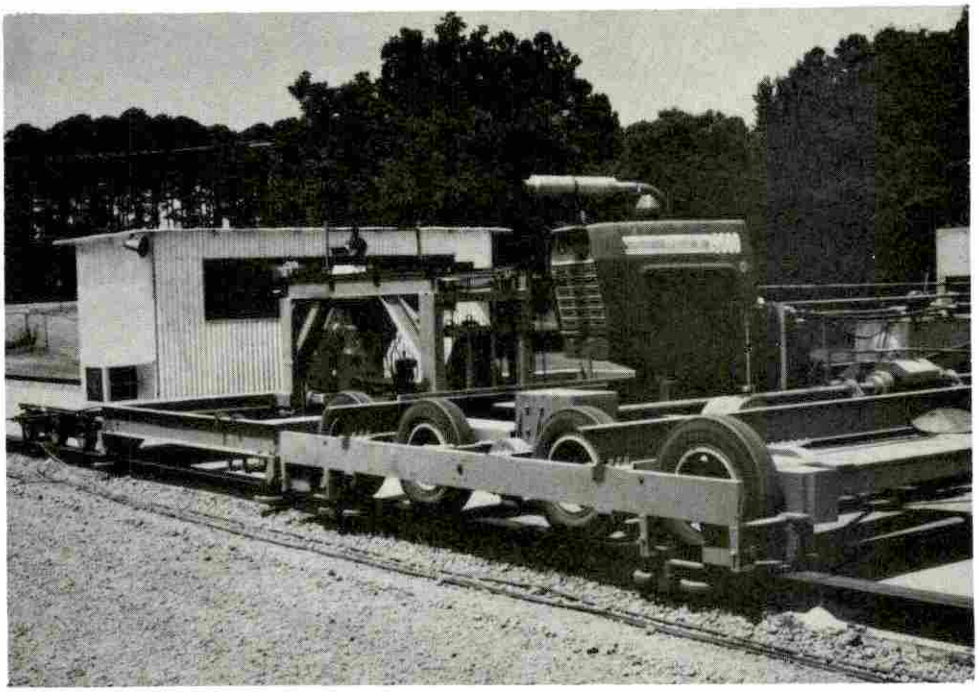
A complete description of the NTML is contained in USDA publication ARS 42-9-2 (1965).

<u>Soil bin preparation procedure</u> The guiding principle in the soil bin preparation was to obtain a soil that was of uniform consistency and uniform strength for a given depth. Soil consistency included moisture

Figure 10. Implement carrier showing position of plow bottom and coulter as mounted on separate cantilever beam strain gage dynamometers

Figure 11. Overall view of complete test apparatus including the power car, implement carrier, and instrument car


10-MPH
45-0



and bulk density. If these criteria were met it was possible to compare different treatments in the same soil bin and be confident that any trend or treatment difference was due to the treatment and not to variable soil strength or soil consistency. Thus, while the steps outlined below were used for this investigation they could be modified if necessary to obtain the desired end result in the soil bin.

A. Bin leveled: The soil in the bin was leveled to redistribute the soil evenly across the bin after any previous test.

B. Water added: Water was added to the soil to obtain a desired moisture content. The moisture content influences the degree of packing of the soil thereby influencing soil strength and bulk density. Water may be added at any time but was usually added in this step or as close to the beginning of the bin preparation as possible.

C. Roto tilled: The depth of tilling may be varied. The purpose of the rotary tiller was to create a homogeneous soil.

D. Bin leveled: Soil was again leveled to a uniform height across the bin.

E. Subsoil packed: V-shaped packing wheels were used to insure the packing of the subsoil. This step was necessary if a dense subsoil was desired as a surface packer will not adequately pack the lower levels of the soil.

F. Bin leveled: The soil was again leveled across and with the length of the bin. This insured a uniform soil height.

G. Final packing: Heavy rollers were used to pack the surface of the soil and helped to create a uniform soil strength.

After the final packing the soil parameters were measured. When the soil data were taken the bin was ready for the moldboard plow tests.

Soil data collection The soil properties of moisture content, bulk density, and soil strength were measured and recorded for each soil bin preparation prior to conducting the plow tests. The data were analyzed to assess any inconsistencies in soil bin preparation which could influence the results of the experiment.

A standard penetrometer was used to measure soil strength. The penetrometer was 1/2 square inch in cross sectional area at the top of the cone with a 30° included angle. Penetrometer readings were taken at 6 positions along the length of the soil bin and at 10 different positions 18 inches apart across the width of the bin for a total of 60 readings. The penetrometer readings versus depth were recorded continuously on a Hewlett-Packard Moseley 135 X-Y plotter, USDA 169170 ARS. The graphs of the penetrometer readings for each bin are an average of 60 recordings.

Undisturbed soil samples were collected at 5 random positions along the soil bin using 470 cc sample cans at each position. Samples were taken at three different depths for a total of 15 separate samples. The samples were taken at 0-$2\frac{1}{2}$ inches, $2\frac{1}{2}$-5 inches, and 5-$7\frac{1}{2}$ inches deep. These samples were used to determine bulk density and moisture content.

Moisture content was determined on a wet basis. The cans were weighed, then dried at 105°C to a constant weight. A Shadograph Scale, model 4112-MB and serial no. 416721, was used to weigh the samples.

The moisture content and bulk density were averaged over the three depths. The moisture content of the samples increased with depth and the bulk density decreased with depth. This accounted for a higher standard deviation than if they had been averaged over the same depth. The complete soil data are recorded in Appendix A.

Design of experiment The field tests indicated that the soil was thrown less when the approach angle was reduced. The tests at the NTML were conducted to see if the draft would be affected by reducing the approach angle.

Three soil types which ranged from a light sand to heavy clay were used in the experiment. This range of soils ensured that any results from the experiment would be attributed to the treatments and not to a specific soil type. The model 392 moldboard was used for most of the testing because it was originally designed for higher speeds. The universal shape, model 387, was tested in the loam along with the high speed bottom to compare the effect of the two different shapes. Four different treatments (approach angles) for each plow bottom were tested completely in a single soil bin preparation. The width of the soil bin allowed two replications of each treatment per bin, thus four replications of a treatment were possible with two soil bin preparations. Table 3 shows the number and type of soil bin preparations used in the experiment.

Table 3. Number and type of soil bin preparations used in the experiment

Plow Bottom Model Used	Soil Bin Type		
	Sand	Loam	Clay
392	Prep. 1	Prep. 1	Prep. 1
392	Prep. 2	Prep. 2	Prep. 2
387 & 392		Prep. 3	
387 & 392		Prep. 4	

The design approach angle was reduced by rotating the plow bottom about a vertical axis approximately through the point of the share. A total approach angle reduction of 15° was accomplished in 5° increments. As the plow bottom was rotated the effective width of the share was reduced. This reduction for model 387 at the maximun 15° change in approach angle is shown in Figure 12.

Both plow bottoms had an initial effective share width of 14 inches. The maximum effective share width reduction (measured from the point of the share) at Ø-15° was approximately 4 inches and 5 3/4 inches for model 387 and model 392, respectively. For the experiment the width of cut was set at 12 inches for all tests to reduce the effect of the share width reduction.

When the plow bottom was rotated the shin of the moldboard changed position with respect to the point of the share. This caused the furrow wall which is normally vertical to be sloped at an angle with respect to the bottom of the furrow. This variation in the furrow wall shape affected the effective share width reduction and the coulter setting of the plow bottom.

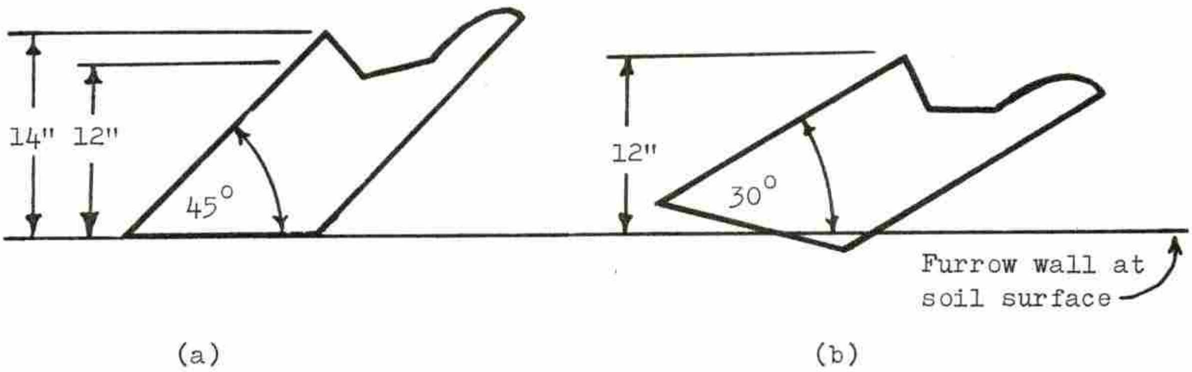


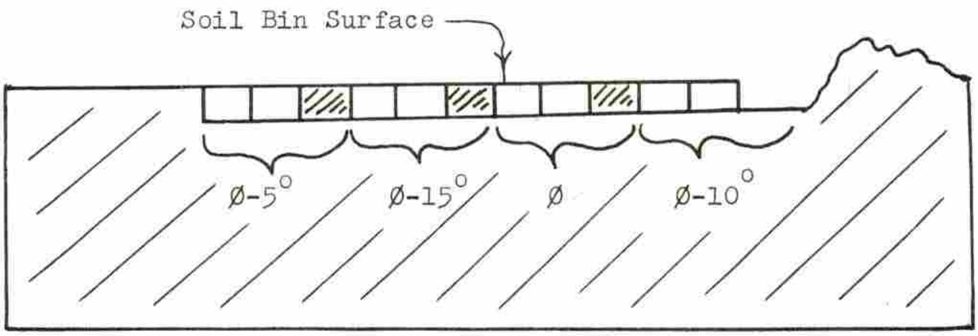
Figure 12. Top view of model 387 at a) design approach angle and b) maximum approach angle reduction of 15° showing effective width of share for a 12-inch furrow slice

The width of cut of a plow bottom was defined from the intersection of the moldboard shin with the soil surface, not from the point of the plowshare. In conventional operation the point of the plowshare is directly ahead of the shin so this distinction is unnecessary. As the shin changed position with respect to the point of the plowshare (Figure 12) the width of cut was not reduced as much as the reduction in effective share width would indicate. This tended to offset the reduced effective width of the share.

It was originally intended to set the coulter at one setting for all approach angles. This worked for ϕ, $\phi-5^{\circ}$, and $\phi-10^{\circ}$ but did not work for $\phi-15^{\circ}$. At $\phi-15^{\circ}$ the shin of the moldboard was cutting the furrow wall with no assistance from the coulter. The draft of the plow bottom was increased by the additional work being done by the moldboard shin. For this reason the coulter was repositioned for each approach angle tested. The guiding principle for the coulter setting was to obtain a clean furrow wall for the tests while keeping coulter depth constant at 4 inches. The side clearance of the coulter as measured from the intersection of the moldboard shin and the soil surface was approximately 3/4 inch for ϕ, 1/2 inch for $\phi-5^\circ$, 1/4 inch for $\phi-10^\circ$, and 1/8 inch for $\phi-15^\circ$.

To ensure that a constant cross sectional area of soil was plowed for each approach angle, the following method was used. The depth of the plow bottom was set nominally at 7 inches for all tests. The coulter was set to cut 4 inches deep and was adjusted in relation to the shin such that a clean furrow wall was produced. The plow bottom was then run the length of the soil bin with no draft data recorded. The plow bottom was returned to the beginning of the soil bin after this opening furrow. The implement carrier frame was then set over 12 inches. Thus the furrow cross section was 7 x 12 inches for all the tests. This procedure ensured that a valid comparison between different approach angles was possible.

Figure 13 shows a typical method of conducting the experiment in each soil bin. A random numbers table was used to assign the approach angles across the bin. In the combined tests where both moldboards were used in the same bin preparation, the model 387 was tested at four approach angles and the model 392 was tested at its design approach angle of 35°.



▨ Opening furrow, no data recorded

Figure 13. Soil bin cross sectional view showing an assignment of all treatments (approach angles)

<u>Data analysis and acquisition</u> Forces in the three mutually perpendicular directions were measured versus velocity for each plow bottom. Draft and vertical forces versus speed were recorded for the coulter. The forces were measured utilizing two separate dynamometers for the coulter and the plow bottom. The force and velocity signals from the instrument carrier transducers were recorded continuously in the instrument car on magnetic tape. An X-Y plotter in the instrument car was used to monitor the plow draft force as the experiment was being conducted.

A simplified block diagram of the data acquisition system is shown in Figure 14. A complete description of the NTML system is contained in ASAE paper No. 690583 (Prather, Schafer and Jarrell, 1969).

The force and velocity data as recorded from the transducers were in analog form. These analog data were converted to digital form in

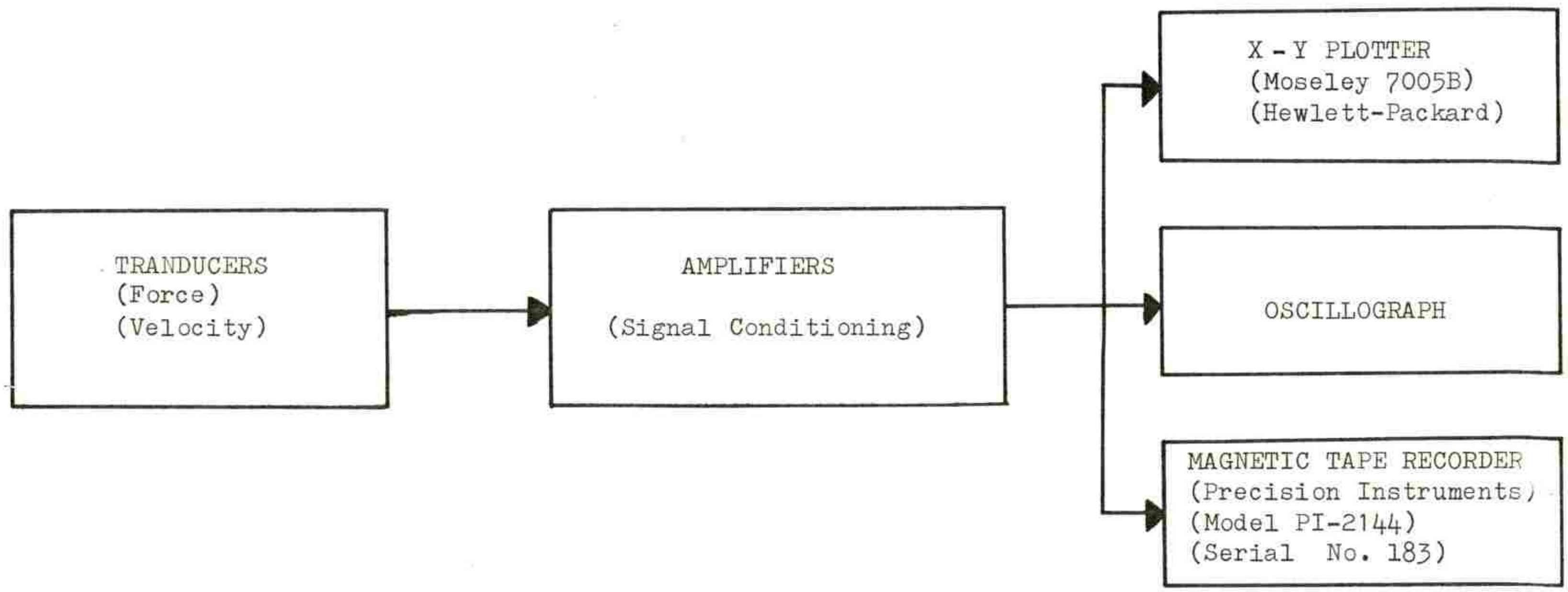


Figure 14. Block diagram of the NTML data acquisition system as used in the experiment

order to use a digital computer for the data analysis.

The four replications of a given approach angle were combined. A regression equation, in the form of a third degree polynomial, was fit to this combined data. An F value was calculated for each regression equation by dividing the regression mean squares by the residual mean squares. The forces, regression coefficients, F values, and total number of data points included in each regression are compiled in Tables 8 through 11, Appendix B. The computer program used for the above analysis is on file at the NTML under the identifying number, OP4ANA.

The coulter draft and vertical forces were not a function of the positioning (approach angle) of the plow bottom. Therefore composite curves of the coulter forces were plotted with the data combined for all four approach angles in a soil type. The coulter vertical forces are negative due to the sign convention used for measurements. These plots are included in Figures 28 and 29, Appendix B.

In summary, the test procedure at the NTML consisted of:

A. Preparation of soil bin to obtain uniform consistency of the soil.

B. Measurement of soil parameters:

    1. Bulk density

    2. Moisture content

    3. Penetrometer cone index.

C. Initial opening furrow run, no data recorded, correct coulter setting checked.

D. Test run conducted measuring the following forces versus velocity:

1. Plow draft (horizontal direction)
2. Plow vertical force
3. Plow side force
4. Coulter draft
5. Coulter vertical force.

E. Approach angle of plow changed to desired value and coulter set.

F. Steps C, D, and E repeated for remaining approach angles.

G. Acquired data analyzed.

The outlined procedure allowed for a systematic investigation of the effect of varied approach angle on performance. The main results are presented in the following chapter.

RESULTS AND DISCUSSION

The experiments at the NTML included both a quantitative measurement of forces and a qualitative measurement of performance utilizing photography. The measurement of forces acting on the two plow bottoms was of major importance although the pictures of the plow bottoms in motion were also helpful in evaluating performance and explaining some of the force versus speed measurements.

Both still and motion pictures were taken of the plow bottoms in operation. These pictures indicated, as did the field tests, that the lateral and vertical movement of the soil was reduced with a reduced approach angle. The series of photographs in Figure 15 are all at 8 mph with a constant 12-inch width and 7-inch depth of cut. The coulter setting was four inches deep in all cases. For each test the forces in three mutually perpendicular directions versus speed were recorded. The three forces were plow draft, plow side force, and plow vertical force. The draft force was that force parallel to the direction of travel and necessary to maintain forward motion of the plow bottom. The side and vertical forces were supporting forces perpendicular to the direction of travel and necessary to keep the vertical and side motion of the plow bottom equal to zero. In the field the side and vertical forces are carried by supporting members of the implement such as the landside of the plow bottom, implement wheels, and in the case of mounted equipment the rear wheels of the tractor.

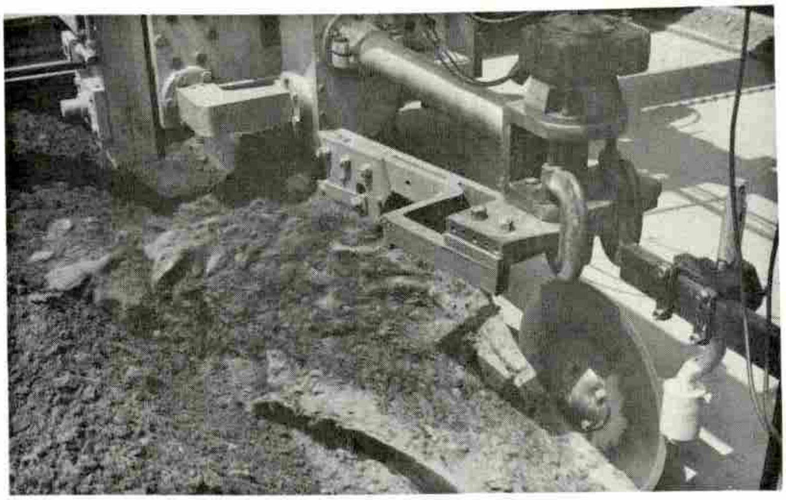
All results indicated that the plow side and plow vertical forces versus speed for reduced approach angles were equal to or less than

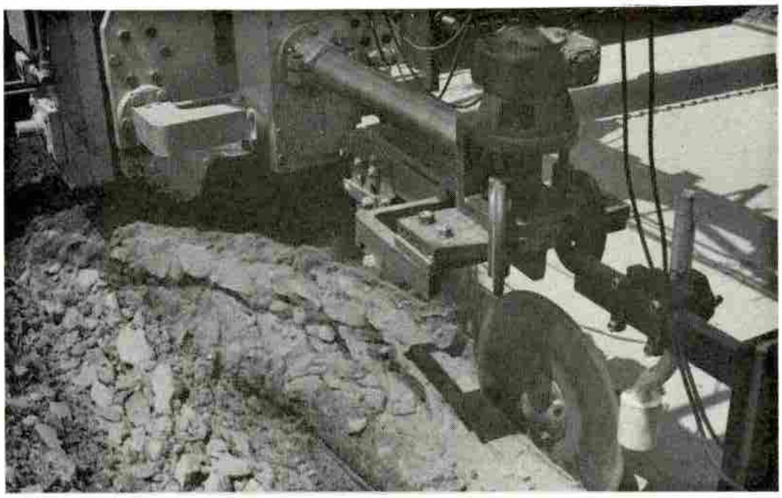
Figure 15. Model 392 plow bottom operating at 8 mph with three different approach angles in Lakeland loamy sand (width and depth of cut constant)

Top: Approach angle (ϕ) = 35°

Middle: ϕ - 10°

Bottom: ϕ - 15°





the forces recorded with the plow bottom at its design approach angle. In some cases a substantial reduction in either side or vertical force was recorded as the approach angle was reduced.

When operating in the field a reduction in the plow vertical force is not advantageous if the force is carried on the rear tractor wheels for increased traction. A portion of the plow side force is carried by the landside of the plow bottom. The frictional force of the landside with the furrow wall adds to the draft and is reduced if the plow side force is reduced. The plow side and plow vertical forces versus speed for each moldboard at four approach angles are tabulated and plotted in Appendix B.

The data from Lakeland loamy sand was the most consistent of data from all the soil types. This was due in part to the uniformity of soil preparation possible. The draft force versus speed in the sand is plotted in Figure 16. In the sand the draft force decreased for each incremental 5° approach angle reduction. The percent of draft reduction was the greatest at the higher speeds. At 2 mph the draft was reduced 20.6% by rotating the plow bottom 15° ($\phi-15^\circ$). At 10 mph the maximum draft force reduction was 36.7%, which occurred with a 15° approach angle reduction.

The plow draft force versus speed for model 392 as tested in Norfolk sandy loam is plotted in Figure 17. The maximum draft reduction below 7.5 mph did not occur with the lowest approach angle ($\phi-15^\circ$) but at $\phi-10^\circ$. The draft forces as plotted for $\phi-5^\circ$ and $\phi-10^\circ$ were less than and approximately parallel to the plot for ϕ. The draft reduction

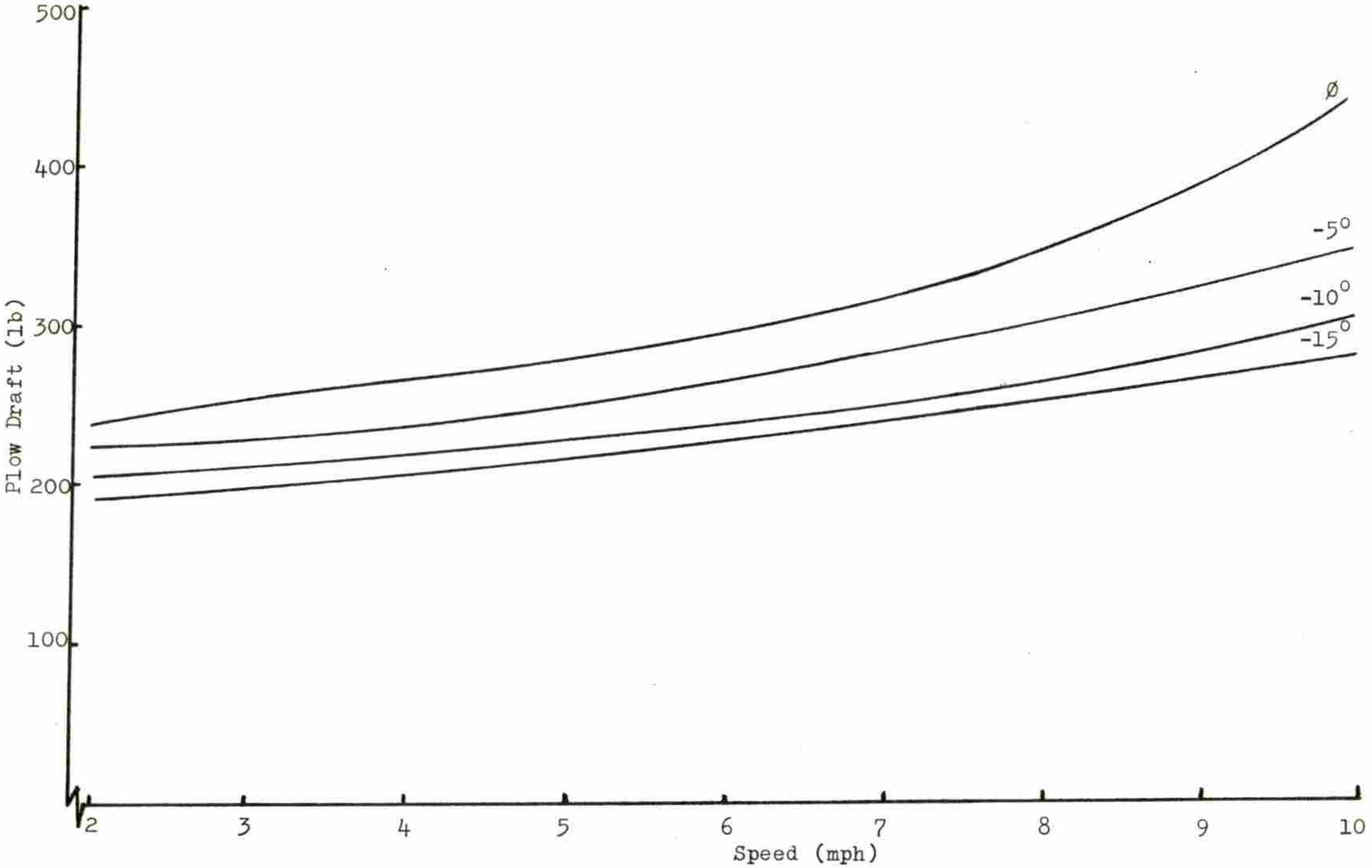


Figure 16. Plow draft versus speed for model 392 tested in Lakeland loamy sand at four approach angles ($\phi = 35^\circ$)

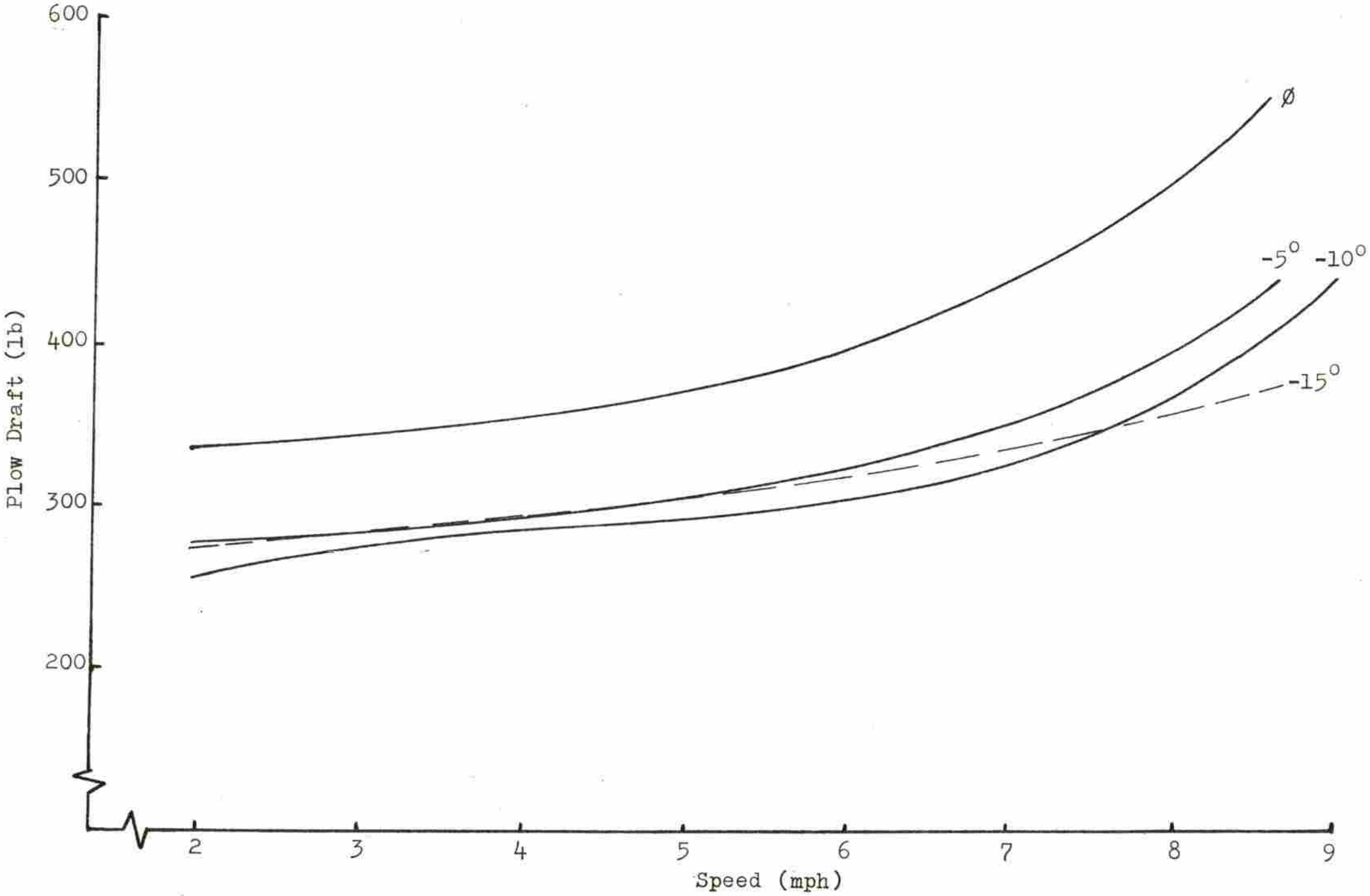


Figure 17. Plow draft versus speed for model 392 tested in Norfolk sandy loam at four approach angles ($\emptyset = 35^{\circ}$)

by reducing the approach angle 10° was 24.7% at 2 mph and 26.8% at 8 mph.

The draft force versus speed as tested in Decatur clay loam is plotted in Figure 18. The maximum draft reduction at Ø-10° was 15.2% at 2 mph and 16.5% at 8 mph. Similar to the loam, the maximum draft reduction in the clay soil did not occur with Ø-15° but at Ø-10°. It was expected that Ø-15° would give the lowest draft force. One explanation was found by observing the action of the plow bottom as it was operating in the soil. With the approach angle reduced 15° the furrow slice was not inverted at slower speeds and would fall back into the furrow after the plow bottom had passed. When the next test was conducted the plow bottom had to do additional work to push the previous soil furrow slice over. Photographs of the performance indicated that proper inversion of the soil slice did not occur with model 392 at Ø-15° until about 6 or 8 mph.

The forces of model 392 at Ø-15° in the clay were greater than the forces measured at Ø-10° for all speeds. The loam data was slightly different in that the plot for Ø-15° crossed the plot for Ø-10° between 7 and 8 mph. For speeds above approximately 7.5 mph in the loam soil the draft for Ø-15° was less than the draft for Ø-10°.

The final portion of the experiment repeated the test procedure of 5° incremental approach angle reductions in loam using both plow bottoms. Model 387 was tested at four approach angles and model 392 at an approach angle of 35° (Figure 19). The trends with the universal shape (model 387) were similar to model 392. The draft was reduced for each 5° incremental approach angle reduction except for Ø-15° at

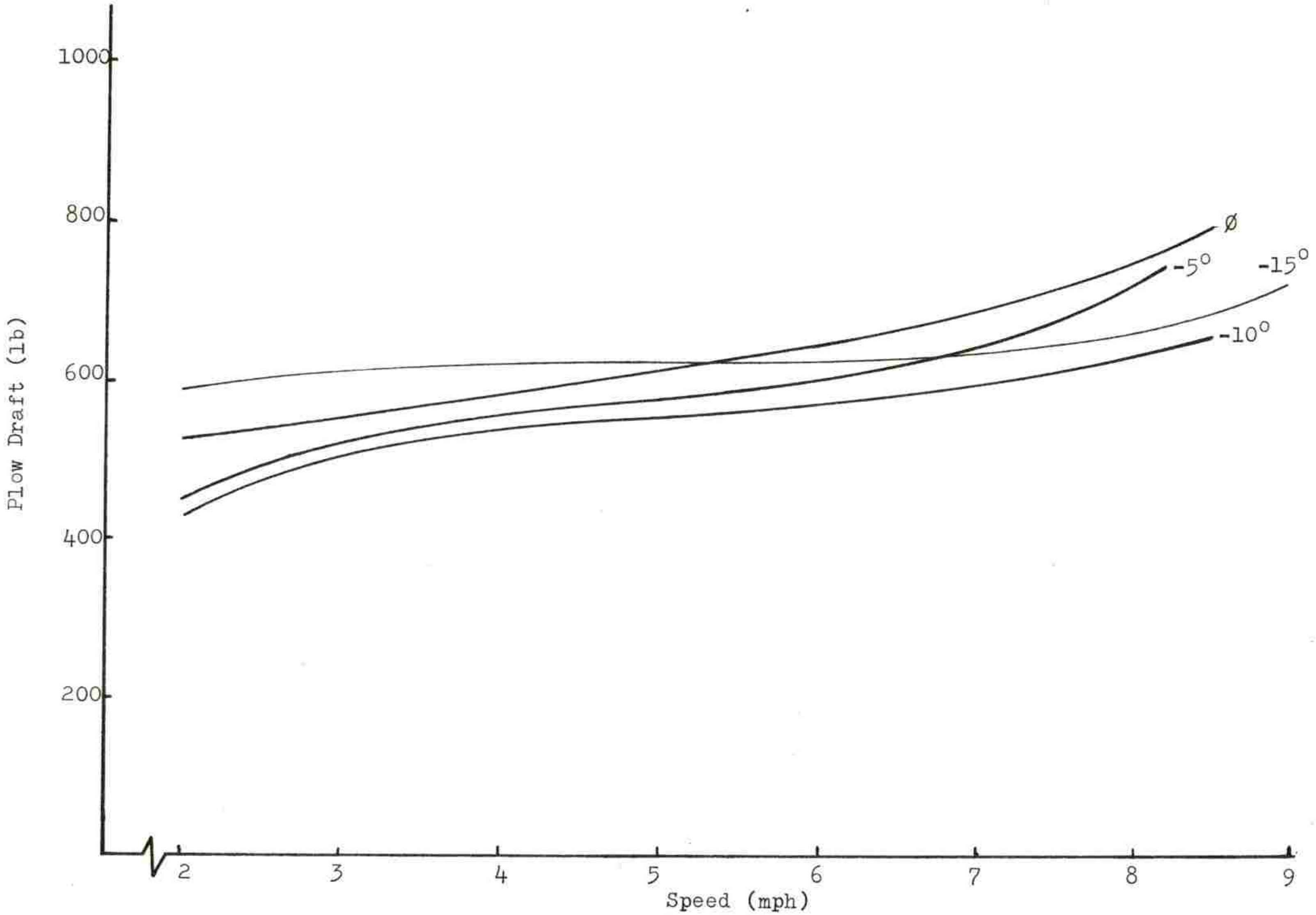


Figure 18. Plow draft versus speed for model 392 tested in Decatur clay loam at four approach angles (Ø = 35°)

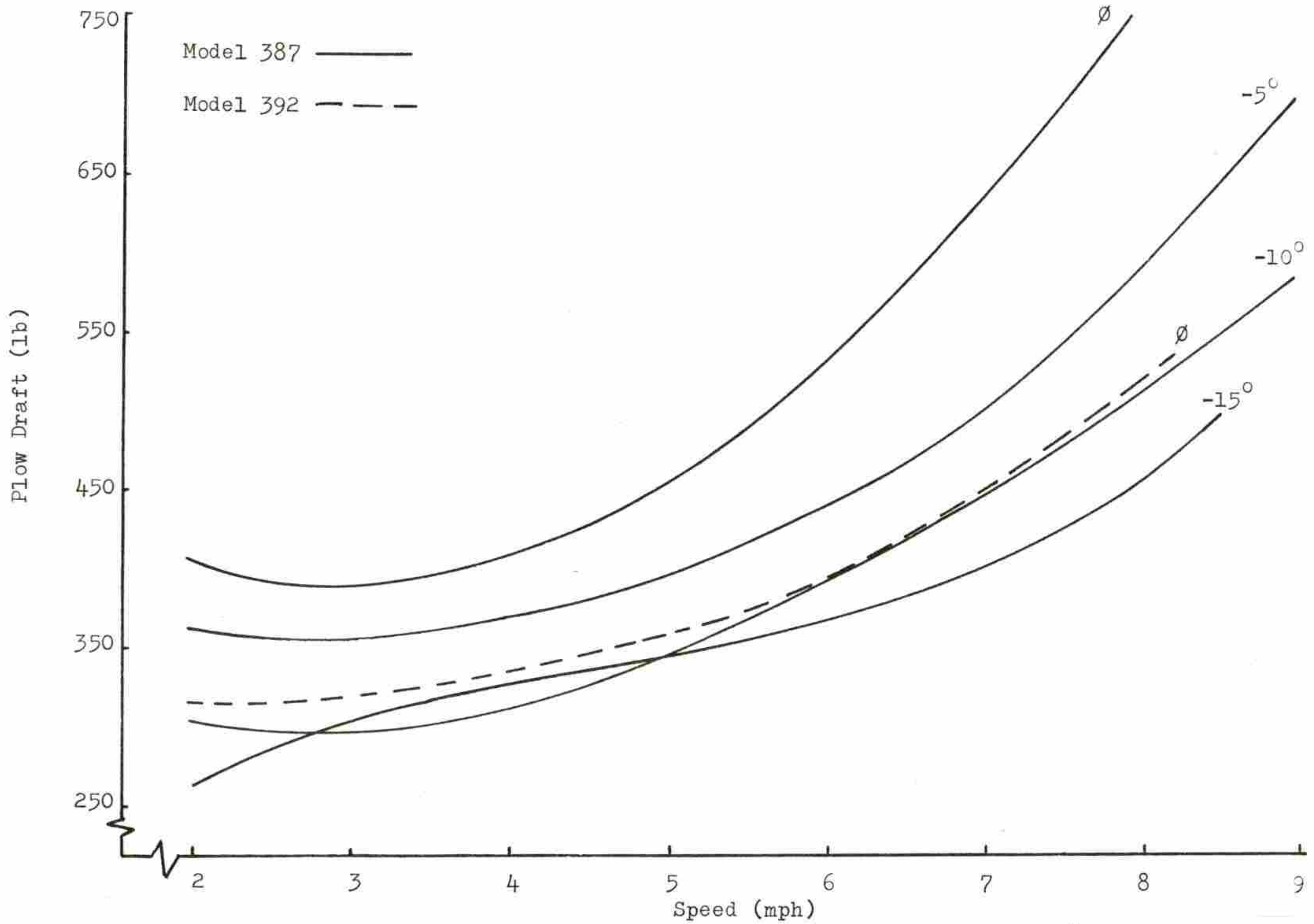


Figure 19. Plow draft versus speed for model 387 at four approach angles (Ø = 45°) and model 392 at one approach angle (Ø = 35°) tested in Norfolk sandy loam

speeds slower than 5 mph. The maximum draft reduction at 8 mph was 39.8% with the approach angle reduced 15°.

In the group of tests in the loam it was possible to compare model 392 and model 387 at their design approach angles. The high speed design when compared with the universal shape had a 23.1% and 31.4% draft reduction at 2 and 8 mph, respectively.

Another notable comparison was the draft of model 392 ($\emptyset = 35^{\circ}$) with the draft of model 387 at $\emptyset$-10° (Figure 19). Both plow bottoms in this instance were tested at a 35° approach angle and had very similar values for the draft forces at all speeds.

An analysis of variance (Tables 4 and 5) indicated a significant difference between the draft of four approach angles tested for both plow bottoms. The difference between the angle by speed interaction (Table 4) in the three soil types combined was significant indicating that soil type influenced the amount of draft reduction. This supported the observation that the percent of draft reduction in the clay was less than the reduction in the loam and sand soil types. The angle by speed by soil interaction was not significant indicating that the draft versus speed curves in a soil type were approximately parallel.

Although the percent of draft reduction as the approach angle was reduced was impressive, the major significance of this research was the ability to increase plowing speed within certain ranges and maintain a constant draft force by rotating the plow bottom. If the draft of model 392 at 4 mph was used as a base figure the forward speed could be doubled to 8 mph (in sand and loam) with no increase in draft. In the heavy clay

Table 4. Analysis of variance for draft of model 392 as a function of approach angle at 2, 4, 6, and 8 mph in all soil types combined

Source	Sum of Squares	d.f.	Mean Squares	F Value
Angle	117445.85	3	39148.62	10.77**
Error[a]	109003.18	30	3633.44	
Angle x Speed	54330.67	9	6036.74	10.30**
Angle x Speed x Soil	15299.16	18	849.95	1.45
Residual	65018.49	111	585.75	

[a] Error included angle by speed by bin preparation interaction plus replication within angle, bin preparation and soil type.

**Significant at .01 level.

Table 5. Analysis of variance for draft of model 387 as a function of approach angle at 2, 4, 6, and 8 mph in Norfolk sandy loam

Source	Sum of Squares	d.f.	Mean Squares	F Value
Angle	243163.67	3	81054.55	18.03 **
Error[a]	49429.29	11	4493.57	

[a] Error included angle by bin preparation interaction plus replication within angle and bin preparation.

**Significant at .01 level.

soil the speed could be increased approximately 50% to 6 mph and maintain a constant draft by reducing the approach angle of the plow bottom as a function of speed.

The results indicated a draft reduction was possible by rotating the plow bottom. If the draft is reduced at a specific speed the unit soil pressure on the moldboard will be decreased. In certain soil types this could possibly cause an unscouring condition because scouring is related to the specific pressure on the surface of a moldboard (Doner and Nichols, 1934). Increasing the specific pressure will usually aid the ability to scour, an example is the slat moldboard.

Although scouring performance or the ability of a moldboard to shed soil was not specifically tested it was felt that the variable plow bottom could aid in problem scouring areas in the field. If the scouring of the bottom becomes marginal the approach angle could be changed to increase the specific pressure on the moldboard surface.

The variable approach angle plow bottom could serve the dual function of reducing the draft increase at higher speeds and conversely increasing the specific pressure on the moldboard at slower speeds where scouring may be a problem. Thus the variable approach angle concept could eliminate the need for production of several different bottoms, each designed for a specific application.

CONCLUSIONS

1. The lateral and vertical movement of the soil furrow slice was reduced at all speeds for both plow bottoms with a reduced approach angle.
2. The plow side and plow vertical forces versus speed for reduced approach angles were equal to or less than the forces recorded with the plow bottom at its design approach angle.
3. The high speed shape of model 392 when compared to the universal shape of model 387 at their design approach angles in Norfolk sandy loam reduced the draft 23% and 31% at 2 and 8 mph, respectively.
4. The speed of model 392 and model 387 in sand and loam could be approximately doubled with no increase in draft by reducing the approach angle.
5. For all speeds the increase in draft as a function of speed could be markedly reduced by rotating the plow bottom. Within certain speed ranges the draft increase could be completely eliminated.

SUMMARY

One of the major hurdles to a high speed tillage system is the increase in draft force with increased forward speed. This problem tends to offset the other advantages gained from a high speed system. The first objective of this research was to determine the design parameters necessary for a high speed moldboard plow bottom. It was felt that an investigation of the design parameters would aid in developing a successful plow bottom for high speeds. The search of literature yielded a method of designing a plow for a specified speed range. A given plow shape would work satisfactorily at high speeds but not at low speeds and vice versa. This observation led to the second objective of the research, to determine the effect of different approach angles on two production moldboard plow bottoms.

The effect of varied approach angle on moldboard plow performance was tested in two separate procedures. The first procedure was field tests conducted at Iowa State University, Ames, Iowa. The second more extensive phase was conducted at the National Tillage Machinery Laboratory, Auburn, Alabama.

The field tests qualitatively evaluated plowing performance as a function of varied approach angle. The furrow profiles of two Allis-Chalmers production plow bottoms, a high speed model 392 and a universal shape model 387, were observed. The furrow profiles at approximately 4, 6, and 8 mph were compared at the design approach angles and when the approach angles had been reduced 10°. The results indicated that the furrow profile changed markedly due to decreased lateral movement of the soil with a 10° reduction in approach angle.

The tests at the NTML were conducted to quantitatively measure the performance of the same two plow bottoms. Three different soil bins which contained sand, loam, and clay soil types were used in the investigation. The plow bottoms were supported on an implement carrier which allowed for precise control of depth, width of cut, and orientation of the bottom. Test runs were at a variable speed of 0 to about 8 mph in the loam and clay and 0 to 10 mph in sand.

Both plow bottoms were tested at four different approach angles. The design approach angle of each bottom was reduced a total of 15° in 5° increments. The forces in three mutually perpendicular directions were recorded versus speed.

The results indicated that a draft reduction was possible by rotating the plow bottom. Within certain speed ranges the draft increase with increased speed could be completely eliminated.

RECOMMENDATIONS FOR FURTHER RESEARCH

Much research in high speed tillage is undertaken without quantitatively defining velocity. The increased speed of operation is qualitatively defined as faster than present operating speeds. To establish a base line for design, it is suggested that a study be undertaken to measure and evaluate present day in-field tillage operating velocities.

The present investigation has shown that a variable approach angle of the moldboard plow bottom will reduce the draft at high speeds without adversely affecting the performance of the plow. Mechanisms for controlling the amount of rotation of the plow bottoms as a function of speed should be designed and evaluated.

Scouring or the ability of a plow bottom to shed soil appeared to be satisfactory for all approach angles. Field tests to further validate the performance of the plow bottom in regards to scouring should be investigated.

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APPENDIX A: SOIL DATA

Table 6. Average soil properties for each soil bin preparation

Soil Type	Plow Bottom Model	Moisture Content[a] %	S.D.$_{mc}$[b]	Bulk Density[a] gm/cc	S.D.$_{bd}$[c]
Lakeland loamy sand	392	6.635	.4075	1.715	.0366
Lakeland loamy sand	392	5.445	.7191	1.675	.0210
Norfolk sandy loam	392	8.179	.4635	1.770	.0762
Norfolk sandy loam	392	8.568	.2685	1.763	.0932
Decatur clay loam	392	14.531	.4430	1.543	.0862
Decatur clay loam	392	14.594	.3160	1.502	.1258
Norfolk sandy loam	387 392	9.851	.4806	1.855	.0526
Norfolk sandy loam	387 392	9.387	.2186	1.819	.0518

[a] Average value based on 15 samples.

[b] Standard deviation of moisture content.

[c] Standard deviation of bulk density.

Table 7. Soil data for each sample[a] taken

Soil Type	Plow Bottom Model	Wet Weight (gm) at Sample Depth			Dry Weight (gm) at Sample Depth		
		0-2½"	2½-5"	5-7½"	0-2½"	2½-5"	5-7½"
Lakeland	392	875	851	838	824	796	784
loamy		864	866	836	813	812	783
sand		875	844	835	822	790	782
		881	877	886	828	823	825
		853	838	873	806	788	814
Lakeland	392	829	828	831	794	785	781
loamy		821	824	828	785	779	781
sand		808	820	846	775	779	797
		848	836	849	807	792	799
		822	816	844	786	772	795
Norfolk	392	932	958	902	858	881	828
sandy		944	911	857	872	841	790
loam		901	947	830	835	875	767
		916	930	845	849	861	780
		891	875	862	830	816	797
Norfolk	392	932	912	874	859	841	807
sandy		892	884	819	826	816	756
loam		944	914	870	870	840	800
		917	957	885	844	879	816
		950	950	792	873	873	727

Decatur	392	817	879	768	719	768	669
clay		853	859	769	749	750	670
loam		848	880	746	744	769	649
		861	892	796	751	777	693
		815	864	812	714	752	705
Decatur	392	876	857	709	768	749	618
clay		853	830	740	748	726	644
loam		889	859	719	777	749	626
		813	813	721	708	711	628
		891	832	734	778	724	638
Norfolk	387	964	985	931	876	895	844
sandy	392	970	981	956	882	891	863
loam		958	979	931	874	890	845
		976	979	954	891	892	868
		969	950	882	891	870	805
Norfolk	387	901	969	974	824	885	890
sandy	392	919	937	953	840	855	869
loam		959	974	908	877	888	828
		941	922	896	862	844	820
		896	944	934	823	864	854

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[a] All samples were 470 cc.

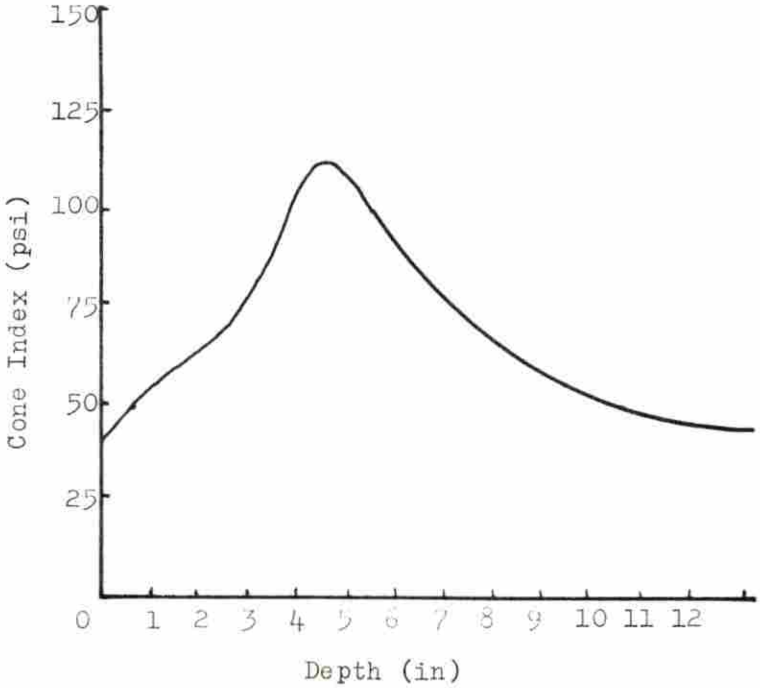

Figure 20. Penetrometer cone index versus depth for Lakeland loamy sand, preparation 1 (model 392 tested)

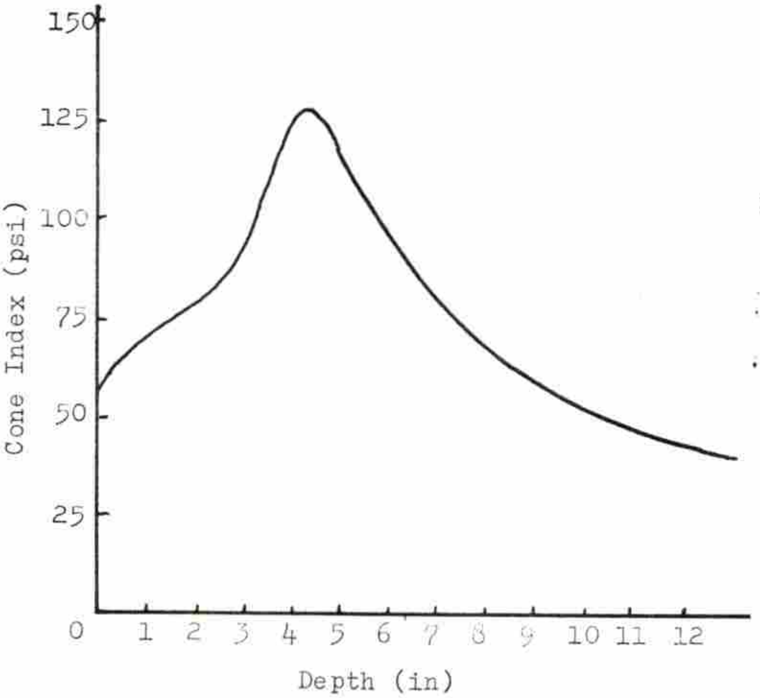

Figure 21. Penetrometer cone index versus depth for Lakeland loamy sand, preparation 2 (model 392 tested)

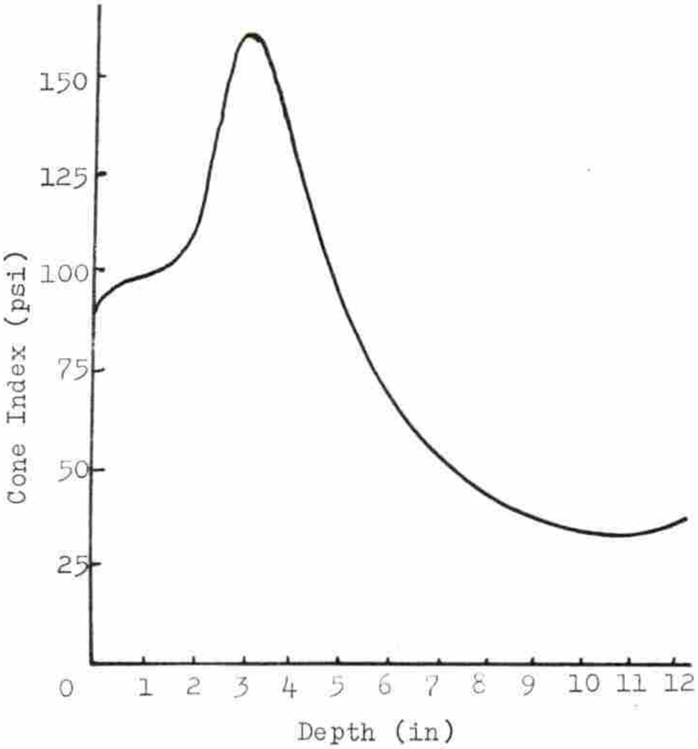

Figure 22. Penetrometer cone index versus depth for Norfolk sandy loam, preparation 1 (model 392 tested)

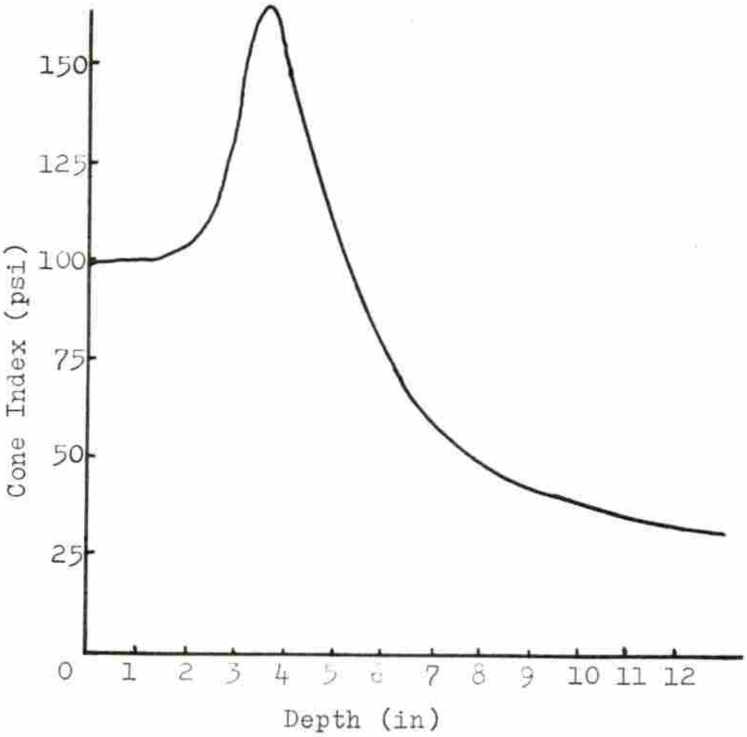

Figure 23. Penetrometer cone index versus depth for Norfolk sandy loam, preparation 2 (model 392 tested)

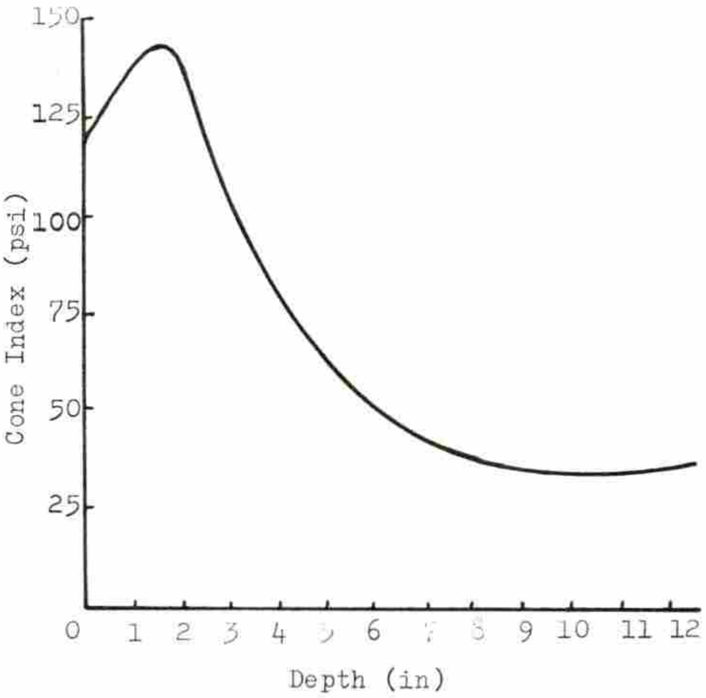

Figure 24. Penetrometer cone index versus depth for Decatur clay loam, preparation 1 (model 392 tested)

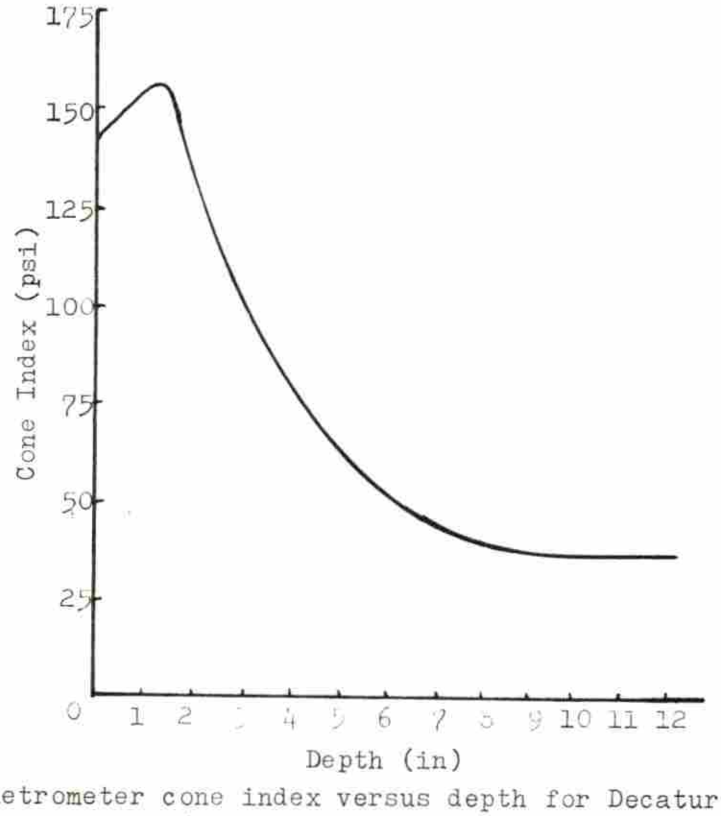

Figure 25. Penetrometer cone index versus depth for Decatur clay loam, preparation 2 (model 392 tested)

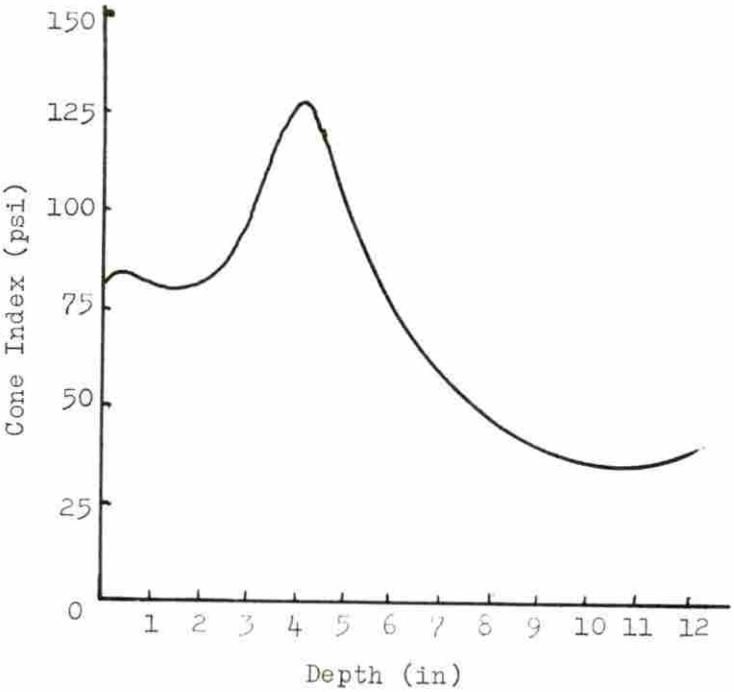

Figure 26. Penetrometer cone index versus depth for Norfolk sandy loam, preparation 3 (models 387 and 392 tested)

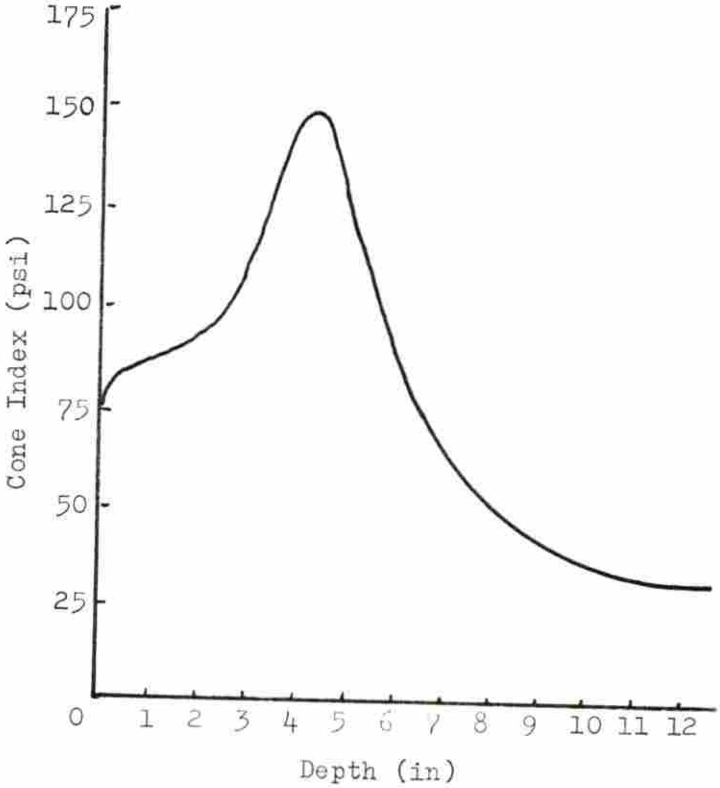

Figure 27. Penetrometer cone index versus depth for Norfolk sandy loam, preparation 4 (models 387 and 392 tested)

APPENDIX B: MOLDBOARD PLOW AND COULTER FORCE DATA

Table 8. Composite force and regression data for high speed plow bottom (model 392) tested in Lakeland loamy sand

Force	Approach Angle	Force (lb) at Forward Velocity (mph)						
		2	3	4	5	6	7	8
Plow Draft	35°	235.5	250.4	262.7	275.1	290.6	311.8	341.6
	30°	220.4	225.4	234.6	247.3	262.9	280.8	300.5
	25°	201.4	206.9	213.8	222.3	232.8	245.5	260.8
	20°	187.1	194.8	204.0	214.4	225.9	238.1	251.0
Plow Vertical	35°	118.7	125.5	135.6	147.8	161.1	174.4	186.9
	30°	110.5	118.0	128.6	140.7	152.9	163.6	171.4
	25°	116.6	116.4	120.3	127.2	135.9	145.2	153.9
	20°	94.7	96.7	101.6	108.6	117.1	126.3	135.4
Plow Side	35°	106.6	115.1	121.7	128.6	137.9	151.7	172.2
	30°	91.8	96.2	100.6	106.4	114.9	127.4	145.2
	25°	114.5	116.9	121.3	127.9	136.5	147.2	160.6
	20°	97.9	96.4	96.8	99.1	103.5	109.8	118.2
Coulter[b] Draft	35-20°	39.0	40.4	41.7	42.8	43.9	44.9	46.0
Coulter[b] Vertical	35-20°	-48.0	-51.2	-53.4	-55.1	-57.0	-59.4	-62.9

[a] Regression coefficients for equation in the form of:

$$Y_o = B_o + B_1X^1 + B_2X^2 + B_3X^3$$

where Y_o = Force (lb)
X = Forward velocity (mph).

[b] Coulter forces were not a function of approach angle so were combined for all four approach angles. The vertical forces are negative because of the sign convention used.

**Significant at .01 level, here and throughout thesis.

		Regression Coefficients[a]				F (Reg)	Total Data Points
9	10	B_o	B_1	B_2	B_3		
382.8	438.1	186.629	33.5833	-5.50869	.466553	237.0**	544
321.4	343.0	224.743	-7.62284	2.90808	-.096363	136.7**	570
278.9	300.1	193.253	3.41477	.232306	.049487	52.69**	524
264.2	277.5	177.029	3.06779	1.06722	-.036882	74.81**	582
197.3	204.8	118.485	-5.46800	3.12065	-.171078	86.71**	544
174.8	172.1	110.641	-6.60482	3.77394	-.249843	54.07**	570
160.9	165.0	134.058	-15.6287	3.82887	-.195613	40.68**	524
143.7	150.4	102.570	-8.57176	2.57840	-.124243	35.21**	582
201.5	241.8	75.5467	22.3859	-4.13519	.355870	443.9**	544
169.7	202.2	77.7795	10.0447	-1.96602	.220546	274.0**	570
175.0	192.1	115.788	-2.63946	.994394	.003265	155.6**	524
128.8	141.5	106.414	-6.04929	.882372	.007330	57.10**	582
47.1	48.4	35.2345	2.19093	-.183478	.009645	17.65**	2187
-68.0	-75.3	-36.5548	-7.92080	1.27668	-.087247	108.9**	2187

Table 9. Composite force and regression data for high speed plow bottom (model 392) tested in Norfolk sandy loam

Force	Approach Angle	Force (lb) at Forward Velocity (mph)						
		2	3	4	5	6	7	8
Plow Draft	35°	330.6	340.9	351.7	367.9	394.5	436.2	498.0
	30°	296.3	281.5	290.6	301.3	318.5	347.0	391.8
	25°	248.8	269.7	280.3	287.7	299.3	322.4	364.3
	20°	270.9	279.9	289.8	301.3	315.2	332.3	353.3
Plow Vertical	35°	135.3	148.7	166.3	186.1	206.1	224.3	238.7
	30°	123.4	141.3	149.8	154.6	161.4	175.7	203.2
	25°	115.5	122.3	130.7	141.0	152.9	166.5	181.6
	20°	87.0	96.7	105.4	113.6	121.9	130.8	140.9
Plow Side	35°	155.9	159.2	163.8	171.9	185.7	207.5	239.7
	30°	114.9	123.1	130.0	138.3	150.8	169.9	198.3
	25°	113.0	113.8	117.7	125.4	137.7	155.1	178.3
	20°	92.6	102.8	103.7	101.9	104.0	116.5	145.8
Coulter Draft	35-20°	70.8	72.7	74.5	75.9	76.6	76.5	75.3
Coulter Vertical	35-20°	-92.2	-99.3	-104.8	-108.9	-111.4	-112.5	-112.2

Regression Coefficients				F (Reg)	Total Data Points
B_o	B_1	B_2	B_3		
291.932	30.2954	-7.10473	.817251	212.6**	488
215.903	41.1808	-8.85591	.807056	131.3**	495
146.726	78.4302	-16.1188	1.21431	93.56**	498
252.171	10.3400	-.753623	.130237	37.03**	499
129.302	-5.88511	5.12071	-.334434	176.3**	488
37.1286	65.6501	-13.1280	.939548	85.04**	495
107.934	1.80201	1.01797	-.011493	69.21**	498
62.3552	14.6140	-1.33162	.091581	27.50**	499
143.793	10.0993	-2178360	.377373	243.8**	488
84.6505	22.4669	-4.53626	.438007	255.3**	495
118.310	-4.23602	.572668	.111777	104.8**	498
18.5353	61.4844	-14.4021	1.08821	26.41**	499
67.2617	1.39985	.254320	-.037933	4.092	1952
-73.4938	-10.8966	.775846	-.002223	32.18**	1952

Table 10. Composite force and regression data for high speed plow bottom (model 392) tested in Decatur clay loam

Force	Approach Angle	Force (lb) at Forward Velocity (mph)						
		2	3	4	5	6	7	8
Plow Draft	35°	510.5	544.6	574.2	604.2	639.5	685.2	746.0
	30°	440.3	506.9	545.2	570.1	596.8	640.2	715.3
	25°	433.1	495.2	535.4	561.1	579.4	597.8	623.4
	20°	581.1	603.1	611.7	614.4	618.8	632.3	662.6
Plow Vertical	35°	159.4	173.1	184.6	195.3	206.6	219.8	236.3
	30°	159.3	166.4	175.3	185.2	195.2	204.4	212.1
	25°	137.9	143.8	152.7	163.6	175.6	187.7	198.9
	20°	95.0	98.2	99.7	102.2	106.5	121.1	142.8
Plow Side	35°	167.8	169.9	180.4	196.9	216.8	237.5	256.5
	30°	164.6	174.3	186.0	200.7	219.1	242.0	270.2
	25°	145.9	151.9	160.2	170.4	182.0	194.7	208.8
	20°	113.1	134.7	143.1	142.4	137.0	130.9	128.5
Coulter Draft	$35-20^\circ$	145.9	150.1	153.2	155.1	155.6	154.7	152.3
Coulter Vertical	$35-20^\circ$	-233.4	-244.7	-253.5	-259.9	-264.2	-266.3	-266.5

*Significant at .05 level.

Regression Coefficients				F (Reg)	Total Data Points
B_o	B_1	B_2	B_3		
409.253	66.5994	-9.62270	.819911	99.97**	472
162.293	202.337	-36.6601	2.50115	106.4**	459
213.875	148.534	-21.9047	1.21730	72.36**	474
466.939	88.0272	-17.9724	1.25319	11.02*	487
119.967	25.0854	-3.14994	.229074	25.55**	472
153.634	-.912673	2.14351	-.139552	15.48**	459
138.663	-5.54177	2.89604	-.157739	35.67**	474
72.8073	19.0532	-4.87513	.448342	24.52**	487
199.317	-30.1947	8.06988	-.425228	64.40**	472
148.481	7.82012	-.142872	.133355	131.0**	459
142.431	-1.53714	1.77287	-.069603	37.35**	474
13.2397	73.0232	-12.9535	.703322	3.308	487
134.609	6.53853	-.401587	-.017423	3.339	1850
-203.027	-17.9756	1.42434	-.021065	18.63**	1850

Table 11. Composite force and regression data for high speed plow bottoms (models 387 and 392 combined) tested in Norfolk sandy loam

Force	Approach Angle	Force (lb) at Forward Velocity (mph)						
		2	3	4	5	6	7	8
Plow (387) Draft	45°	406.6	390.1	408.6	458.5	536.2	638.2	760.9
	40°	360.3	359.5	372.2	400.2	445.2	508.8	592.7
	35°	300.8	297.3	312.7	344.6	390.7	448.5	515.5
	30°	261.9	302.7	327.2	345.2	366.3	400.3	457.0
Plow (392) Draft	35°	313.0	319.0	333.3	358.3	396.4	450.2	522.0
Plow (387) Vertical	45°	148.5	163.9	182.0	201.1	219.5	235.4	247.2
	40°	130.5	144.6	159.5	175.6	193.6	213.9	237.2
	35°	132.2	137.6	155.2	179.1	203.1	221.3	227.6
	30°	100.1	129.2	147.8	160.3	171.0	184.1	204.0
Plow (392) Vertical	35°	125.1	143.2	157.7	172.2	190.4	215.9	252.3
Plow (387) Side	45°	125.2	116.9	120.9	138.2	169.6	216.1	278.5
	40°	96.8	92.2	98.0	112.3	133.6	160.6	189.9
	35°	111.0	110.3	118.9	135.6	159.3	189.1	223.9
	30°	110.5	104.9	115.6	131.4	151.0	173.7	197.0
Plow (392) Side	35°	133.6	128.4	135.2	151.8	175.9	205.3	237.7
Coulter Draft	45-30°	61.6	68.8	72.2	73.3	73.9	75.6	80.2
Coulter Vertical	45-30°	-93.0	-102.0	-107.7	-111.1	-113.1	-114.6	-116.6

Regression Coefficients				F (Reg)	Total Data Points
B_o	B_1	B_2	B_3		
558.772	-119.374	22.8370	-.594690	910.1**	503
396.085	-27.5692	4.28368	.279329	408.3**	501
374.379	-61.3512	13.0886	-.401780	366.5**	490
92.6947	123.584	-22.7232	1.62096	144.4**	473
315.798	-3.94960	.446391	.408614	144.8**	433
132.784	1.13362	3.93783	-.286426	143.5**	503
102.266	14.6605	-.456075	.091500	147.2**	501
182.085	-51.2534	15.1547	-1.00468	123.2**	490
-7.15478	74.1708	-11.7378	.720709	108.3**	473
63.4084	42.9634	-7.27660	.607194	125.4**	433
175.345	-35.3203	4.83151	.149382	899.4**	503
143.816	-37.7930	7.72151	-.284612	141.5**	501
144.058	-28.1917	6.17617	-.175569	293.2**	490
115.378	-16.5619	4.96305	-.202187	134.8**	473
188.600	-44.6276	9.29812	-.368977	140.1**	433
28.8914	24.1535	-4.45066	.279130	24.98**	2244
-61.3272	-21.2924	3.04532	-.155840	27.65**	2244

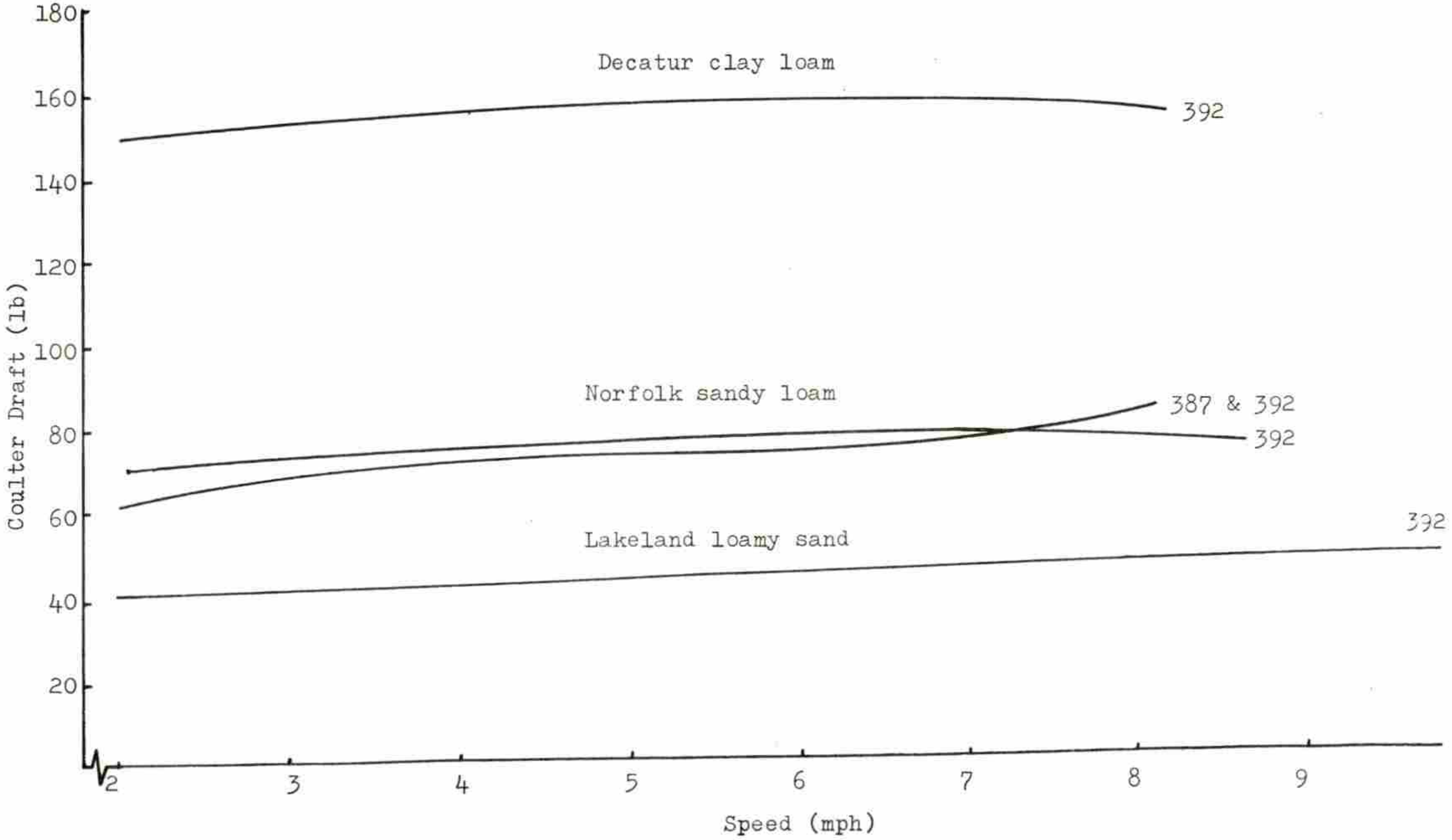

Figure 28. Coulter draft forces versus speed for model 392 and model 387 in three soil types

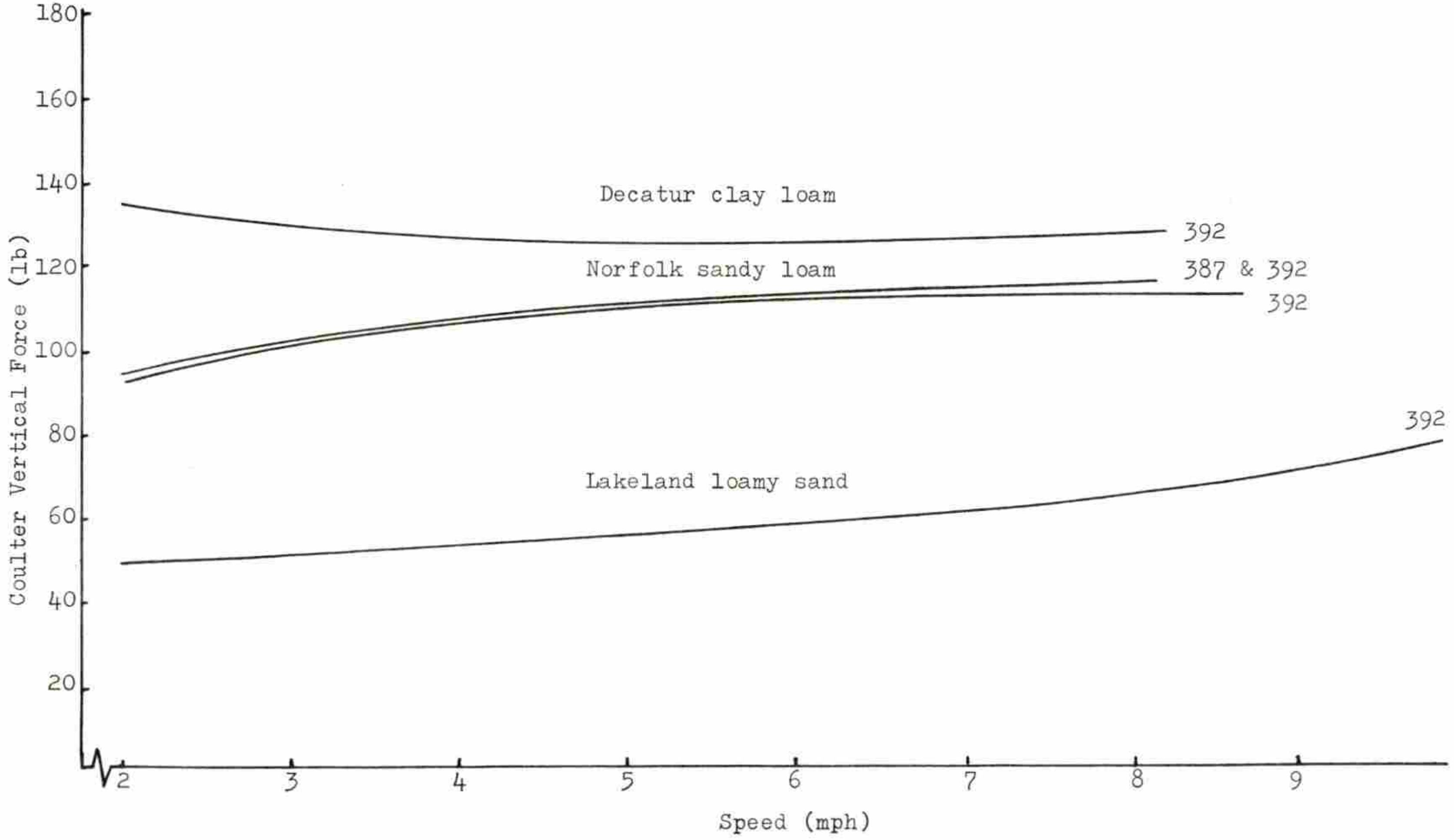

Figure 29. Coulter vertical forces versus speed for model 392 and model 387 in three soil types (forces are negative)

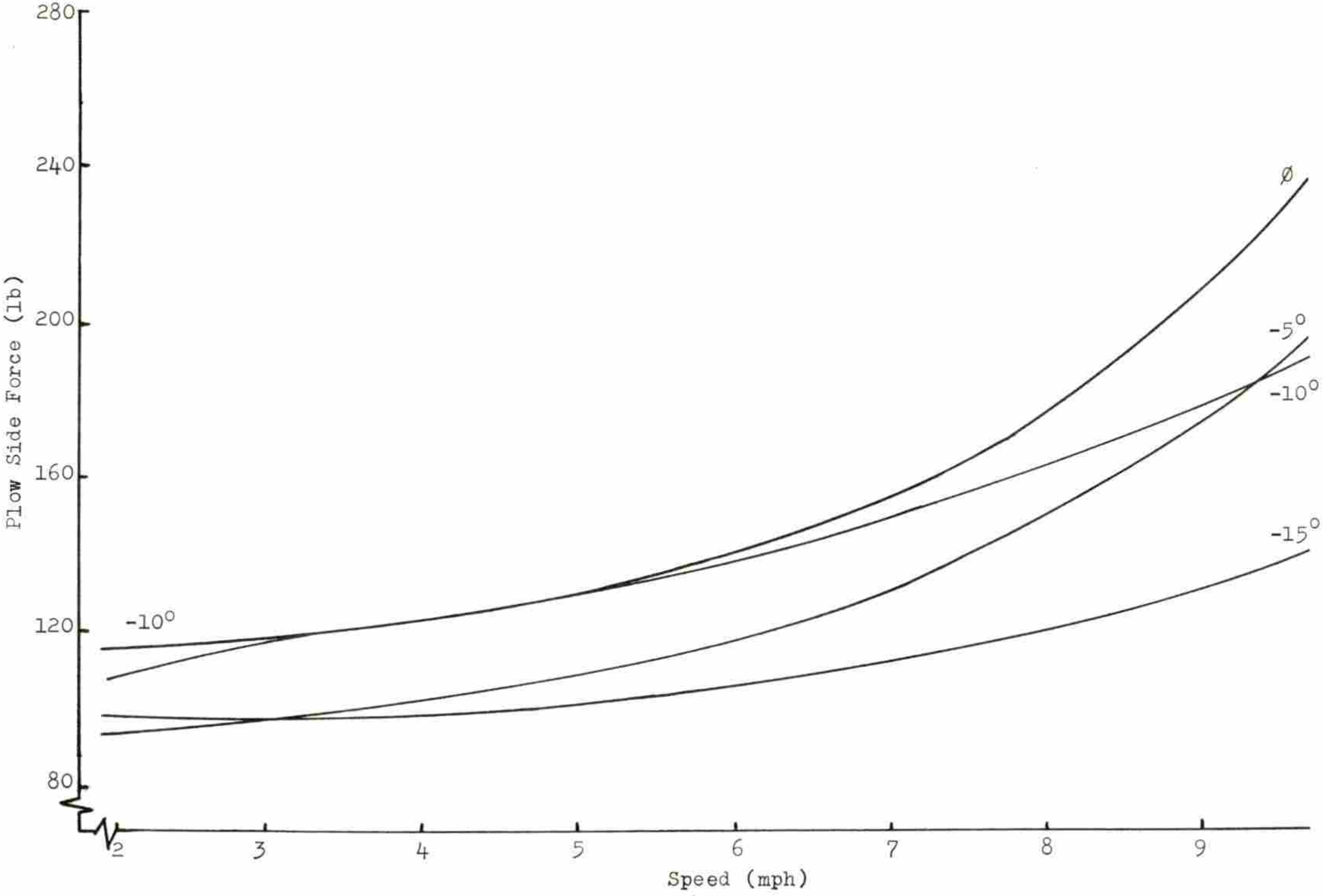

Figure 30. Plow side force versus speed for model 392 tested in Lakeland loamy sand at four approach angles (Ø = 35°)

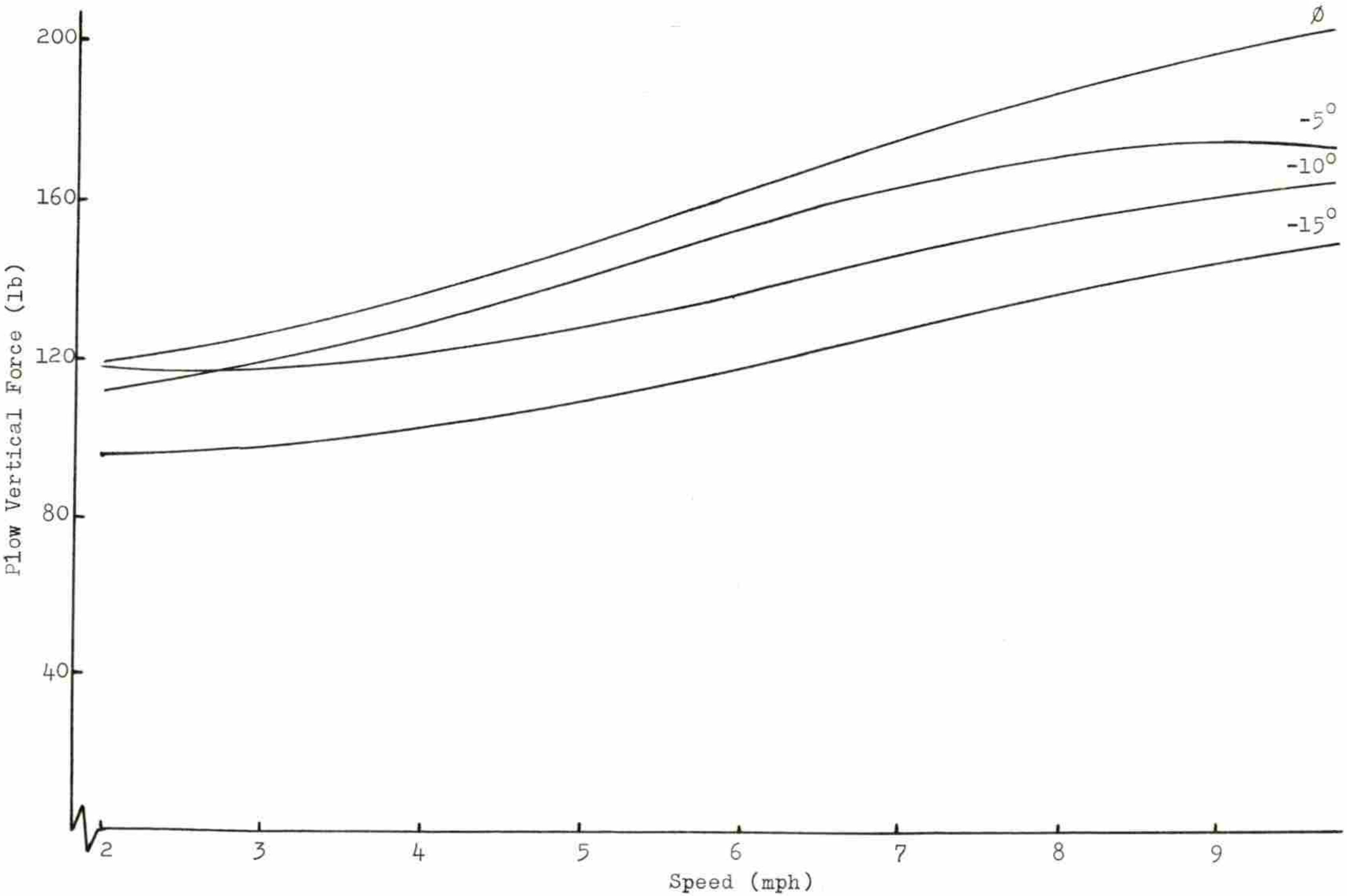

Figure 31. Plow vertical force versus speed for model 392 tested in Lakeland loamy sand at four approach angles (Ø = 35°)

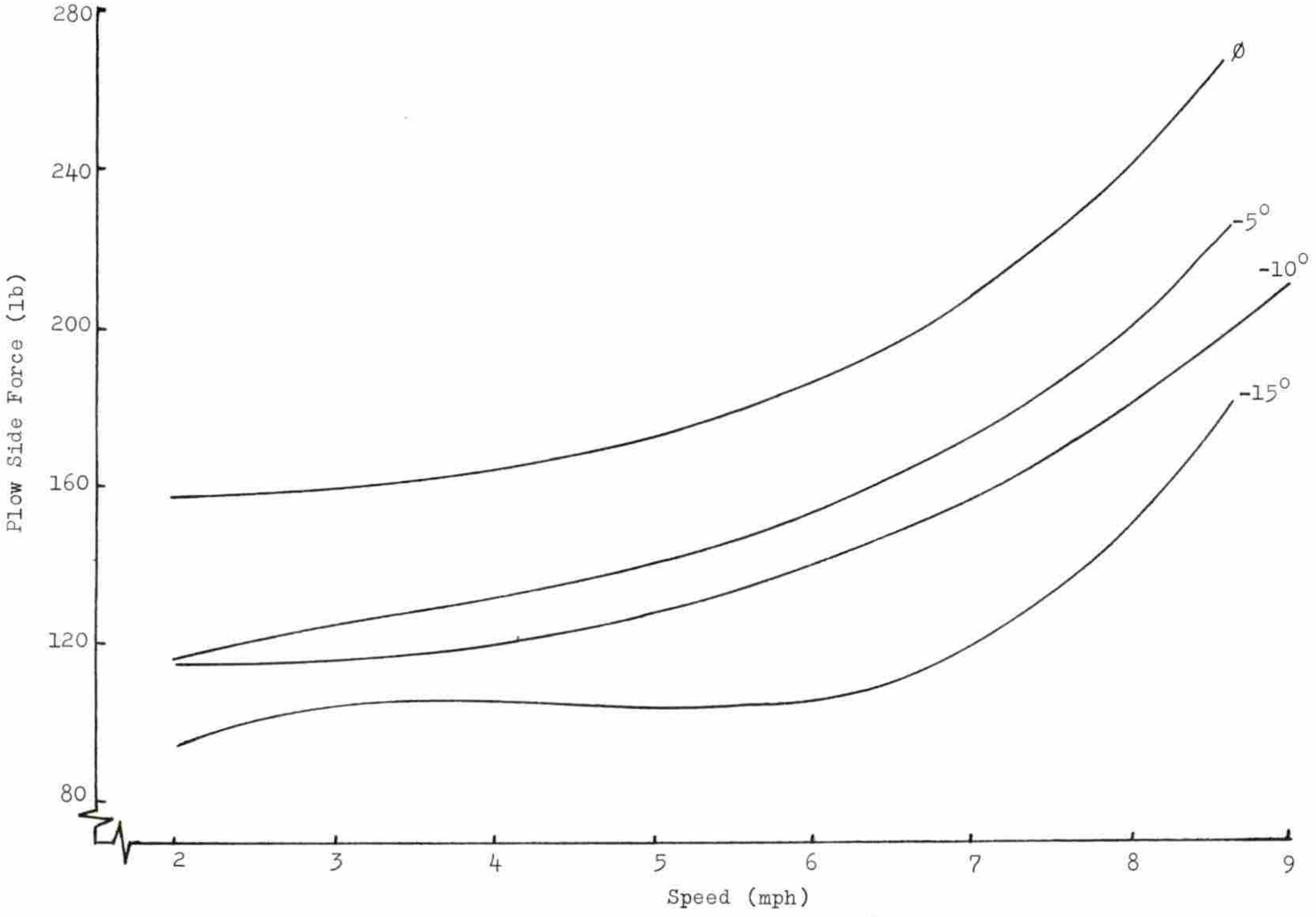

Figure 32. Plow side force versus speed for model 392 tested in Norfolk sandy loam at four approach angles (Ø = 35°)

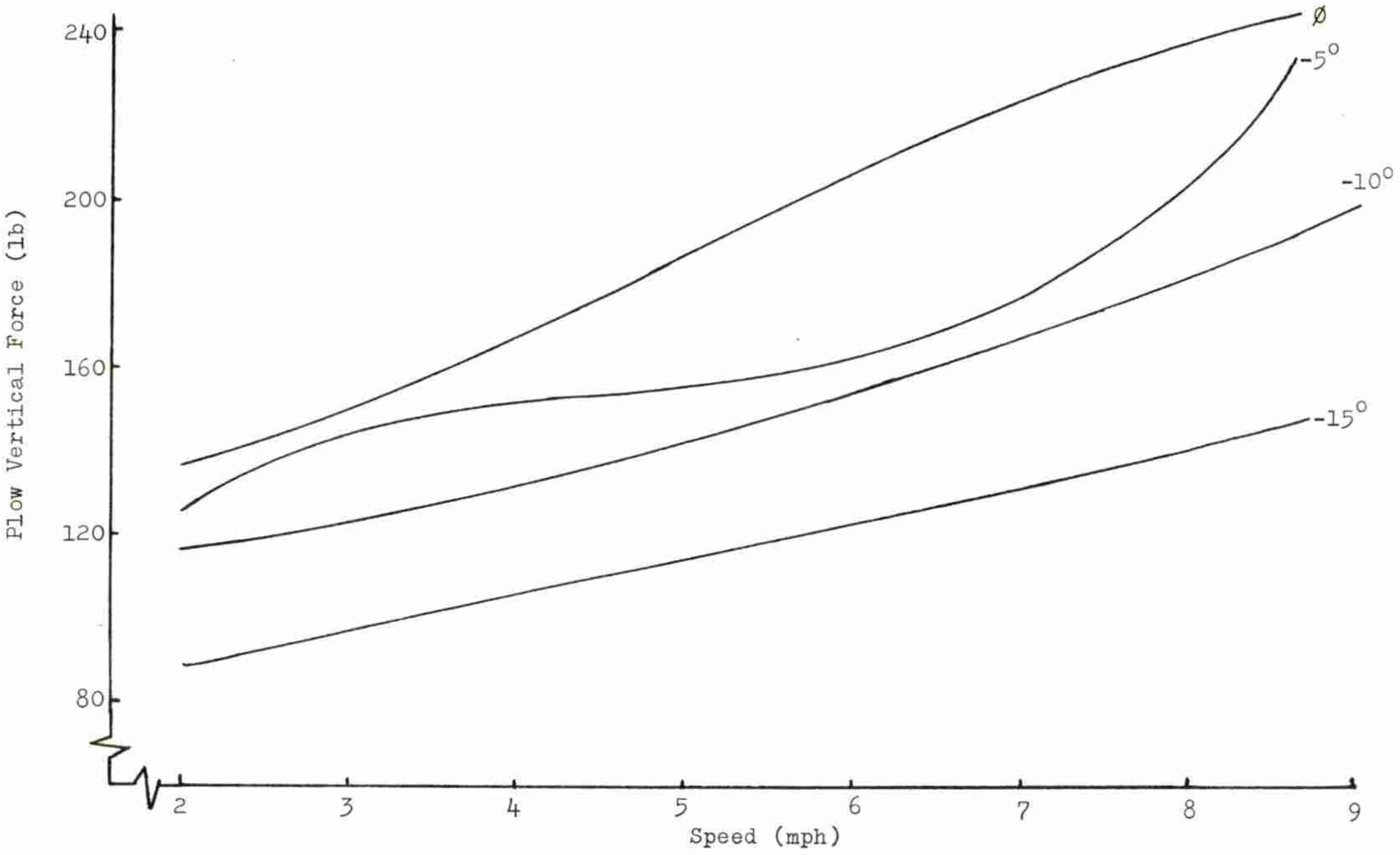

Figure 33. Plow vertical force versus speed for model 392 tested in Norfolk sandy loam at four approach angles ($\phi = 35^{\circ}$)

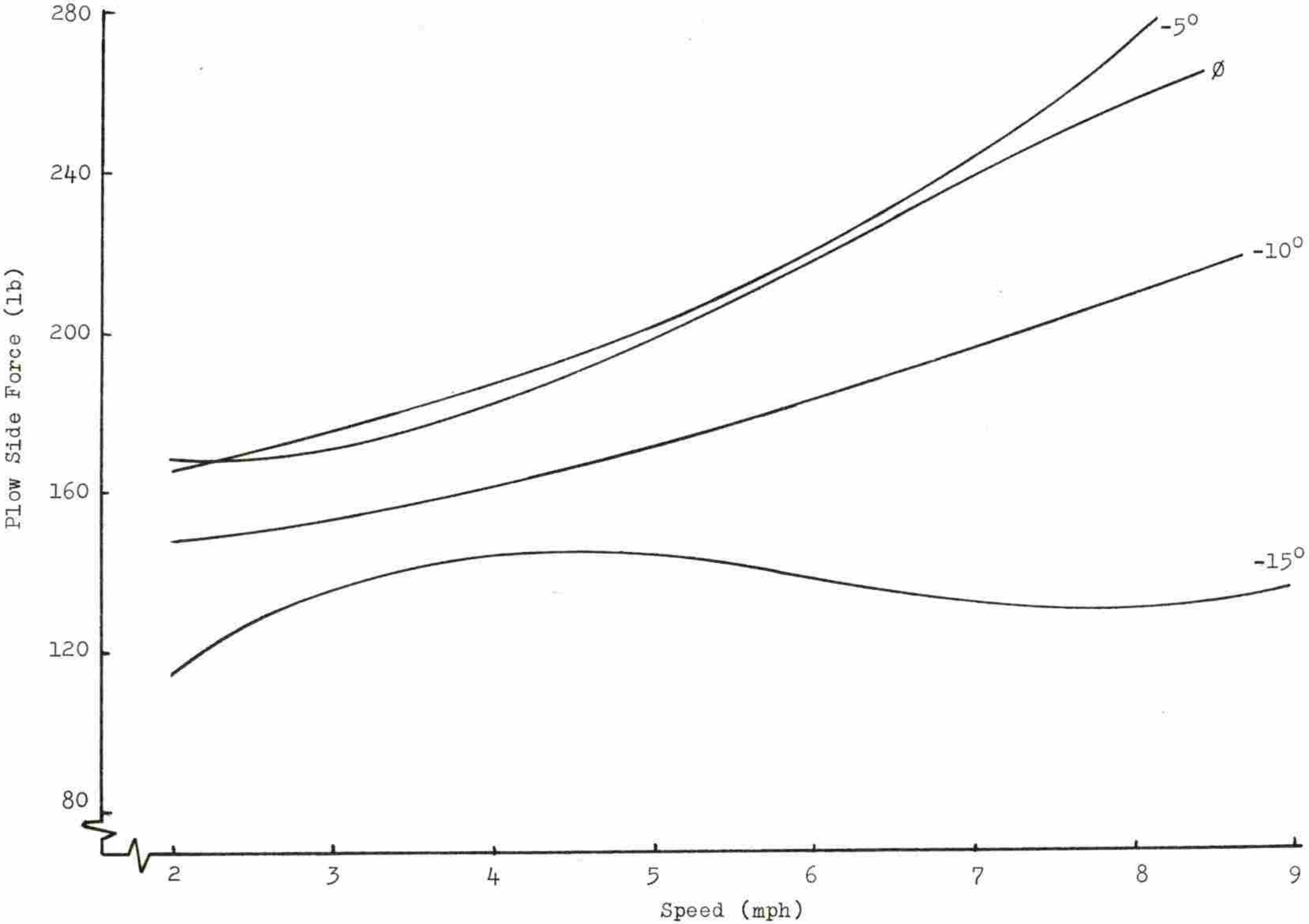

Figure 34. Plow side force versus speed for model 392 tested in Decatur clay loam at four approach angles (Ø = 35°)

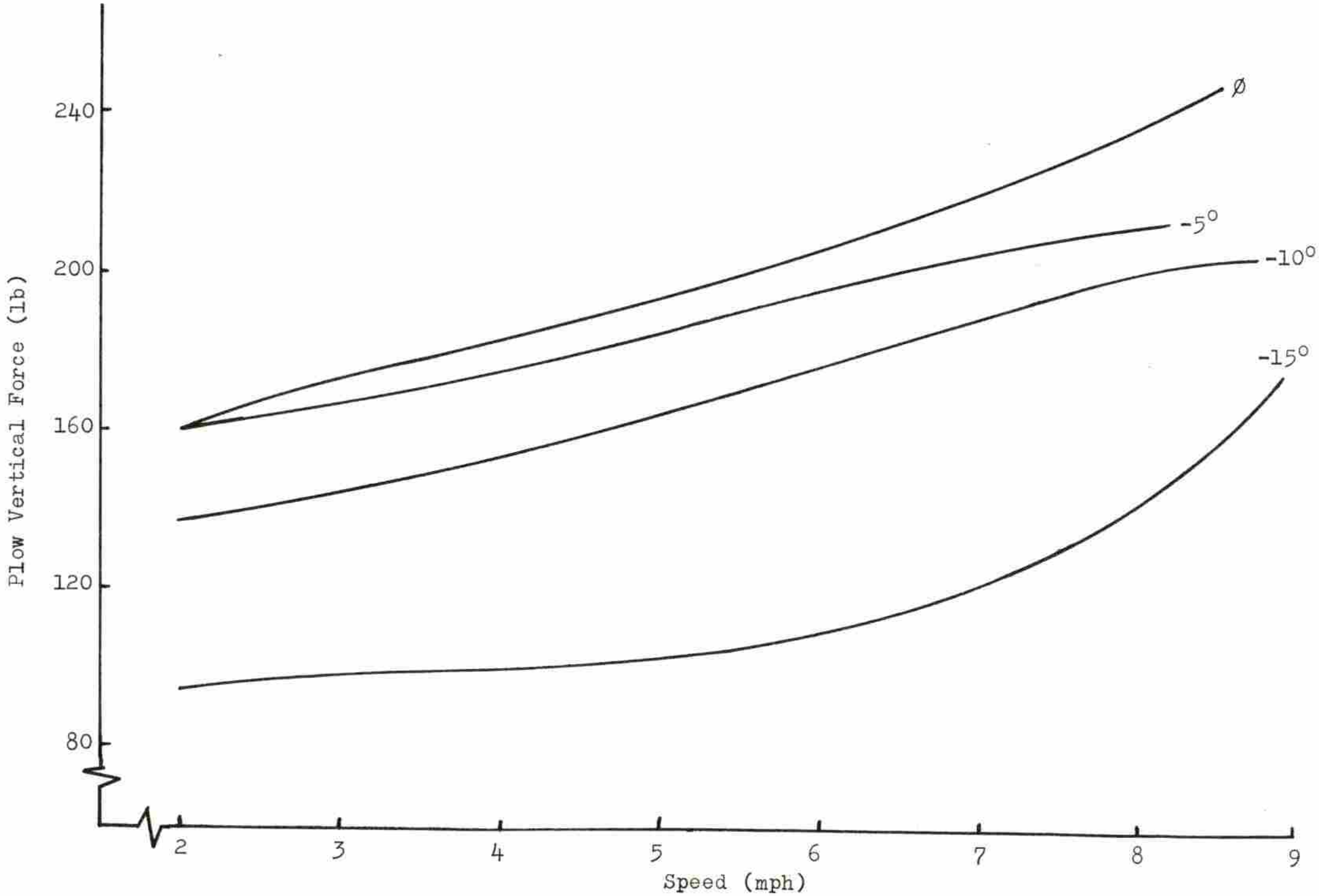

Figure 35. Plow vertical force versus speed for model 392 tested in Decatur clay loam at four approach angles (Ø = 35°)

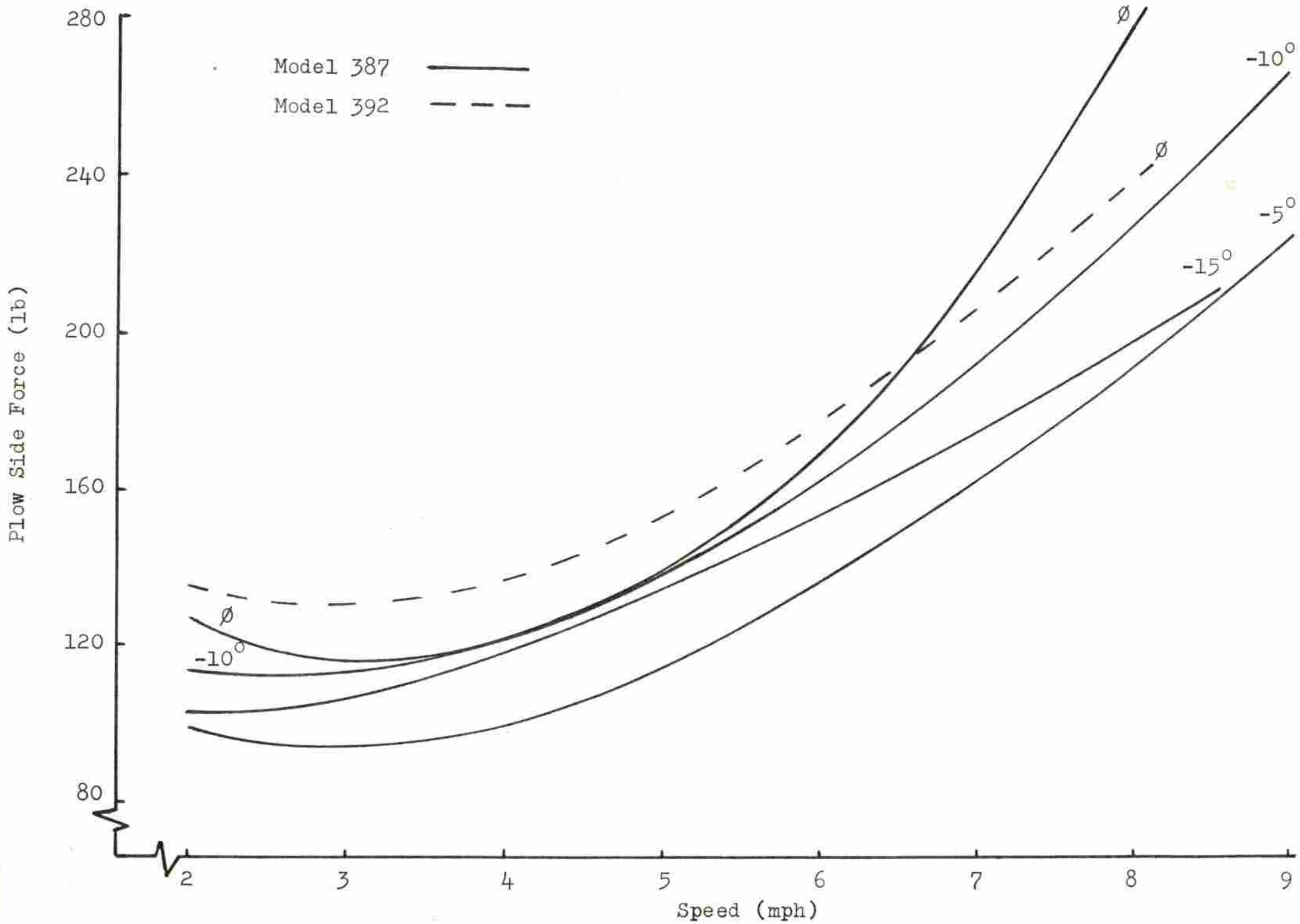

Figure 36. Plow side force versus speed for model 387 at four approach angles (Ø = 45°) and model 392 at one approach angle (Ø = 35°) tested in Norfolk sandy loam

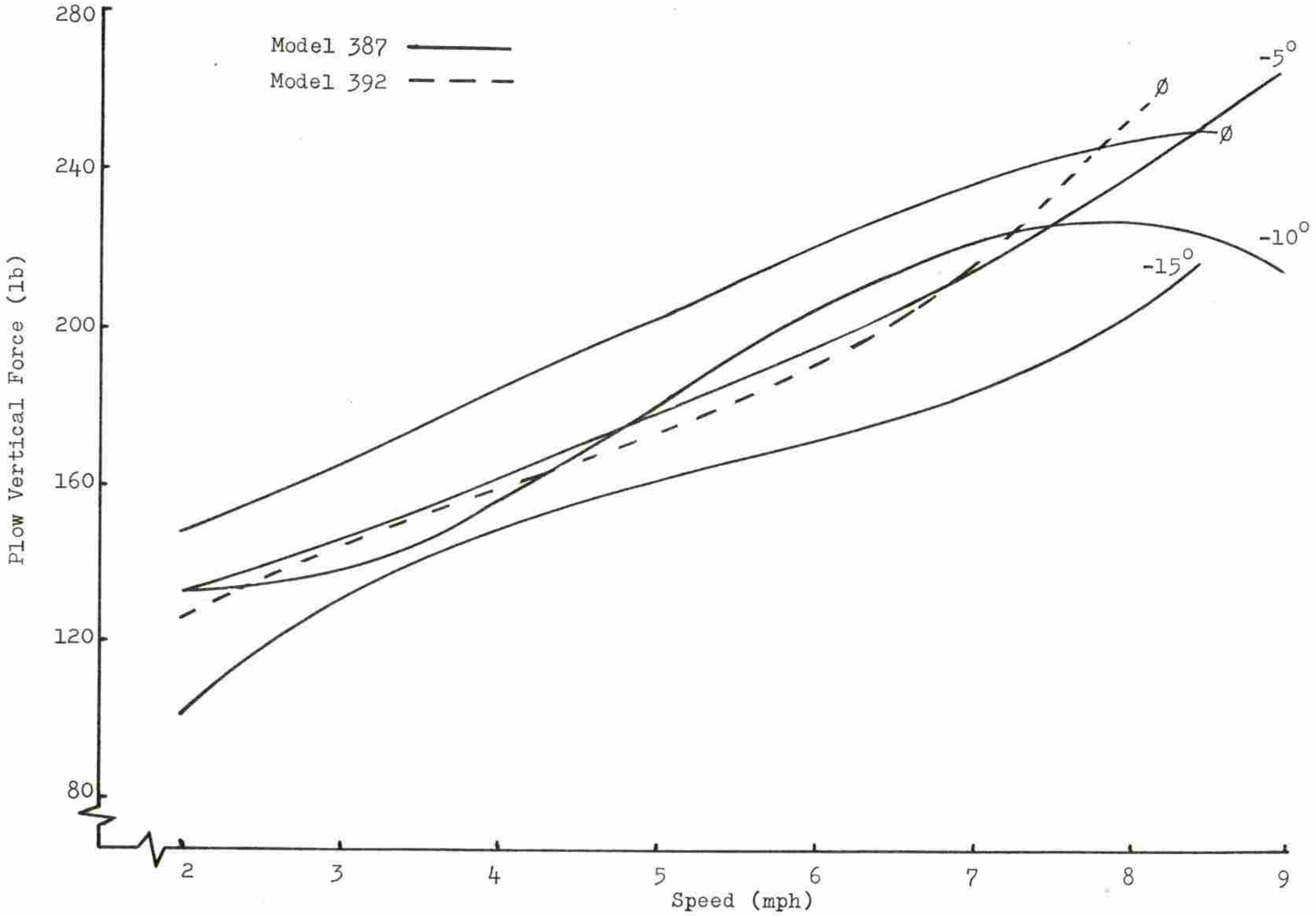

Figure 37. Plow vertical force versus speed for model 387 at four approach angles ($\phi = 45^{\circ}$) and model 392 at one approach angle ($\phi = 35^{\circ}$) tested in Norfolk sandy loam