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To the Graduate Council:

I am submitting herewith a thesis written by Richard C. Shadden entitled "Design and Evaluation of an Experimental Helical Vegetable Harvester." I recommend that it be accepted for nine quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

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DESIGN AND EVALUATION OF AN EXPERIMENTAL HELICAL VEGETABLE HARVESTER

A Thesis

Presented to

the Graduate Council of

The University of Tennessee

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

Richard C. Shadden

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ABSTRACT

This study was conducted to evaluate a basic and new principle for vegetable harvesting. A tractor mounted machine, using an auxiliary engine as the power source, was designed and constructed primarily for harvesting snap beans with limited tests on bell peppers. It incorporated a cylindrical helix and a cylindrical brush as the picking mechanism. Both laboratory and field tests were conducted to determine picking efficiency and plant and fruit damage in relation to the forward speed of the machine, the angular velocity of the helix, and the ratio of the angular velocity of the helix to that of the brush.

The average picking efficiency for peppers was 71 percent with a high of 89 percent for one trial. Statistical analysis of the results from laboratory tests and field tests on snap beans showed that all three variables significantly affected both picking efficiency and plant damage. Results from laboratory tests showed that as the speed of the helix increased and the forward speed of the machine decreased, the picking efficiency increased and plant damage decreased for the range of values tested. Results from field tests showed that a 1:4.5 ratio of angular velocity of the helix to that of the brush resulted in the

the best picking efficiency and the greatest plant damage for each level of angular velocity of the helix. The highest picking efficiency in the laboratory for snap beans was 97 percent and in the field was 87 percent. Damage to both picked peppers and snap beans was severe; however, it was concluded that the major damage was due to inadequate means for the fruit to exit from the harvester.

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CHAPTER I

INTRODUCTION AND OBJECTIVES

I. INTRODUCTION

Agriculture today is a highly professionalized business. There are approximately six million farmers in this country but actually two million farmers produce 80 percent of all the food and fiber and the other four million produce only 20 percent (21). It is through mechanization that it has been possible for so few to produce so much. In the past ten to fifteen years great strides have been made particularly in the development of mechanical harvesters for field crops. However, the development of precision harvesting equipment for fruits and vegetables is still far behind that of field crops, and yet these are high value crops which in most cases require a great deal of hand labor. Even with recent technological advances, mechanization of fruit and vegetable crops is not keeping pace with that of the major farm crops or even with that in livestock farming (2, 4). Since 1947, the average output per man-hour for all crops has increased 125 percent while that for fruits and vegetables has increased only 67 percent (20). The primary reason for this lies basically with the high labor requirements necessary for harvesting vegetables and the lack of

mechanization in that phase of production.

Vegetable crops occupy a unique position in the nation's spectrum of agricultural crops. There are twenty-seven principal vegetables grown for the fresh market. Ten of this group also go into commercial processing channels. The combined total comes from only slightly over one percent of United States harvested crop acreage. Averages for the 1962-1963 season reveal the following: acres harvested for processing and fresh market were 1,656,000 and 1,738,000 acres respectively. From this 8,660,000 tons were processed and 10,800,000 tons went to the fresh market (42). Vegetables, as this reveals, are characterized by intensive and concentrated production with yields of high tonnage per acre. And as high value crops, they have always required large amounts of hand labor, particularly during harvesting.

Labor requirements for all crops vary widely, but some vegetable crops require more than one hundred man-hours per acre (4). Such high labor requirements result in high production costs. Labor alone has cost vegetable growers from one-half to three-fourths of their gross income (42). This limits the net return to the producer and along with other production costs, storage, transportation, and display costs included in the sale price, the products seem high priced to the consumer. The problem is even further exemplified by the fact that since 1946, the price received for vegetable crops

by the producer has decreased 17 percent while the cost to produce has increased 20 percent (20). Two of the primary reasons which seem to point to the continuous rise in production costs seem to be: (1) the ever increasing uncertainties of obtaining labor and (2) the associated rise in labor costs. In vegetable production labor costs alone have increased about 34 percent over the preceeding year (20).

Harvesting of vegetables requires much hand labor and accounts for a large portion of the total labor requirements. Thus a rising labor cost and an unpredictable labor supply are chief factors which prompted producers to mechanize harvesting (11, 42). These were not the only reasons. Others included the pursuit of a more timely and faster harvest. Also the increase in the size of production units increased interest in developing harvesting equipment that would lower unit costs (21). There is now a mechanical harvester developed or under development for almost every vegetable crop. However, in all functions, most vegetable harvesters are massive, cumbersome, and expensive. This is not to say that they are uneconomical. The definition of the economical soundness of a harvester is simple. It depends on the amount of crop lost over and above the hand harvest method, the rate of harvest, and the ability of the machine to increase productivity whenever possible (14, 22). For example, even though the average yields obtained using a

once-over mechanical bean harvester in their early development was only 60 to 75 percent of those where beans were picked two or three times by hand, farmers in general were satisfied since the net return per acre was as great or greater due to the savings in labor (21).

Despite the savings in labor and the other advantages of machine harvesting, high machine costs, which is typical of vegetable harvesting equipment, could and has limited the use of these machines by producers, especially small ones. However, this problem has been somewhat eliminated in some cases by custom harvesting and processor ownership of the machines. High machine costs have caused short run production which has plagued manufacturers. The need for less expensive and better harvesting techniques is always in demand no matter what the crop to be harvested. Vegetable harvesters, being relatively new as compared to field crop harvesters, are in great need of such improvements. Not only do machine costs need to be lowered, but the machine should perform all the functions of hand laborers. Some are now omitted or inadequately done. Produce harvested mechanically may not be as clean as desired. Bruising and breakage must be minimized. Where size and color sorting is required, many vegetable harvesters are not able to fulfill this requirement. The percentage of recovery is continually being improved but even 100 percent recovery as compared to hand-harvesting should not be considered the limit (25).

II. OBJECTIVES

The objectives of this study were: (1) to design a vegetable harvester using a new and basic harvesting principle which consisted of a cylindrical helix and a cylindrical brush as the harvesting mechanism, and (2) to evaluate the principle by testing the machine on bell peppers and snap beans.

The machine was to be evaluated by testing the relationship between forward speed of the machine, the angular velocity of the helix, and the ratio of the angular velocity of the helix to that of the brush in relation to picking efficiency.

In this study, snap beans and bell peppers were used for several reasons. Both vegetables could be made readily available since they were both common to the area. Varieties of snap beans suitable for mechanical harvesting are commonplace. No mechanical harvester is presently available for picking bell peppers.

CHAPTER II

REVIEW OF LITERATURE

The very nature of most vegetables resists mechanical harvesting. One of the major obstacles concerns the maturity sequence. To cope with this, two approaches to mechanical harvesting have evolved: multiple-pick and once-over (36). Multiple-pick harvesters utilize a non-destructive principle to separate and recover fruit from the plant without destroying the plant or rendering it incapable of further production. Once-over harvesters utilize a destructive principle to separate and recover fruit from the plant and are limited to one harvest per crop since the plant is destroyed or rendered unproductive by the harvest operation. Each method has its advantages and disadvantages.

Multiple-pick or selective harvesters adapt to present varieties in that the fruit is harvested selectively as it matures. This may mean several passes through the field just as hand harvesters do. This method requires a few changes in preharvest cultural methods (42). However, a design is required to preserve the soil-plant system. This places a heavy burden on the designer. At present, such crops as asparagus and lettuce appear better adapted to multiple-harvest machines.

The once-over harvest technique does not necessitate the preservation of the soil-plant system. However, to obtain yields comparable to multiple hand harvests, much higher plant populations are necessary along with concentrated fruit set. This technique demands uniform maturity, size, and fruit location on the plant. This has led to and made it necessary for the development of varieties with these characteristics which make them adaptable to once-over harvesting. Not only are new varieties necessary, but it is also necessary to make changes in preharvest cultural methods. Many of these are not really disadvantages but are adjustments which were inevitable if mechanical harvesting was to be feasible. This is further pointed out by the fact that multiple-harvest, which is adaptable to standard varieties, is considered a short-term solution to mechanical harvesting (42).

One real problem with once-over harvesting is determining the optimum period for harvesting since it is so brief and difficult to predict (17). Such crops as snap beans and tomatoes appear to be best suited for once-over harvesting. This is true in part because varieties suitable for mechanical harvesting have been developed by plant breeders.

There are many different techniques or methods utilized in harvesting vegetables mechanically. This is necessary due

to the great physical dissimilarities encountered among the different vegetables. However, there are certain vegetables which have some similarities, and in fact are so similar that the same machine or same harvesting principle can be used to harvest more than one crop. Many times due to slight differences some adjustments or slight changes are needed to make the harvester adaptable to another crop. Lettuce and cabbage are two crops which would fit into this category. Snap beans and lima beans is another example. Not only can vegetables, as far as harvesting is concerned, be classified according to physical appearance and physical properties, but they can also be classified according to the harvesting principle used. This is true even though physically the plants and or fruit are far from being alike. Again, lettuce and cabbage have similar physical characteristics and are also mechanically harvested in general by the same method. That is by removing the heads from the soil-plant system by cutting the stem. However, asparagus, which in appearance in no way resembles cabbage or lettuce, is also mechanically harvested by cutting the spears at the proper height and stage of maturity. Leaf crops such as spinach are also harvested by cutting. Then there are the root crops such as onions, beets, and potatoes which are harvested mechanically generally by the same method.

A third category of vegetables classified according to the harvesting principle and most important to this study

are those removed by basic principles such as shaking, centrifugal force, high linear acceleration or deceleration of either the fruit or plant, raking, combing, and stripping (19). Crops harvested by these principles are snap beans, peas, lima beans, tomatoes, and cucumbers. All of these vegetables have one thing in common. They are all attached to the plant by a pedicle or at least have one point of attachment to the plant and in effect are suspended from the plant much as a pendulum. Another point of interest is that these vegetables are usually harvested mechanically by a once-over operation. There are other vegetables such as sweet corn and bell pepper which could fit into this category but they are attached to the plant in a more rigid manner.

Vegetables harvested mechanically by the earlier units and even later units have suffered breakage and bruising. If used before bruising and breakage have had time to be detrimental, these effects are of no consequential disadvantage. Therefore, the processing markets have initially received the greatest surge of mechanically harvested vegetables.

As far as processing crops are concerned the sweet corn harvester was probably the first breakthrough in mechanical harvesting of vegetables (21). Prior to this, equipment had been developed for mechanical harvesting of root crops such as beets, carrots, and potatoes. In developing the sweet corn harvester, a group from the canning industry worked very

closely with the developers and manufacturers of the machine in evaluating its performance in the field. Not only did machine manufacturers and the canning industry work together, but sweet corn breeders worked simultaneously in developing special varieties giving consideration not only to quality but adaptation to mechanical harvesting as well. The combined efforts resulted in better acre yields with lower costs in harvesting and loading. Now almost all sweet corn is harvested mechanically.

The second most important development in mechanical harvesting of vegetables was the snap bean picker. Snap beans are generally harvested by a stripping action. The credit for the basic picking principle used in all snap bean harvesters is given to a small New York canner and his wife. In the early 1940's, Mr. J. C. Ward of the Ward Canning Company, Mt. Vernon, New York, noticed his wife swinging a garden rake up through a row of beans which resulted in the removal of several beans. Their ideas were eventually developed into a commercial unit by one of the leading manufacturers of canning equipment. The basic harvesting unit consisted of a picking reel with steel fingers mounted perpendicular to and around a central shaft. The reel was operated on one side of and parallel to the row of beans. As the reel rotated and the machine traveled down the row, the fingers passed up through the bean plants in short arcs

stripping the beans from the plant (7, 21, 41). This was a once-over operation since the plants were stripped of their foliage along with the bean pods. Yeager (41), reported that the bean picker built by Mr. Ward and tested in 1949 worked satisfactorily. The machine had a unit ahead of the picking reels to trim off the top of the bean plants. This eliminated some of the foliage and decreased the amount that would end up in the harvested crop. The machine missed some beans with their point of attachment less than four inches from the ground and on stems that were so low that the lifter missed them. These problems were later eliminated with the development of varieties of beans more suitable to mechanical harvesting and with improvements in the machine.

In 1950, the Chisholm-Ryder Company of Niagara Falls, New York, purchased manufacturing rights to the mechanical bean harvester and since then has generally been considered the leader in snap bean harvesters. Five were built in 1952 and twenty for the 1954 season. By 1956 they were widely used over the United States and were sold in Canada, England, and eight other European countries. The first bean picker tested experimentally by the Chisholm-Ryder Company was tested in 1952 by Professor W. T. Tapley in conjunction with the Alton Canning Company (1). It was still not entirely satisfactory in 1955. It was tested at Geneva, New York, in 1956

to measure its efficiency in relation to cultural practices and plant varieties in order to determine what could be done to improve its efficiency. Twelve varieties of beans were used including the main processing ones grown in New York State. They were planted in replicated trials. The efficiency of the machine was calculated by determining the percentage of beans on the plants harvested by the machine. This was done by carefully picking all beans left on the plant or ground by the machine. (The percentage of beans picked by a machine should not be confused with the percentage picked by hand for it is known that labor crews cannot pick 100 percent of the beans on the plants) (1). The effect of spacing of bean plants on picking efficiency was also determined as well as the effect of different varieties. The results showed that closer spacing gave a higher yield and also a higher percentage picked. The characteristics of plants for best picking proved to be tall plants with fewer branches. There was also a correlation between height of pod on the plant and picker efficiency. Close spacing (1-1/2 to 2 inches) produced plants better adaptable to mechanical picking. Under close spacing, the plants developed a single upright stalk with very few branches, the height of the first node from the ground was greater, the length of the stem was longer, and there were fewer low branches. All factors indicated close spacing

gave a better vine for harvesting. Yields from these tests ranged up to slightly over 3 tons per acre and up to 90 percent of the beans on some varieties were picked. However, the vines were severely damaged. It was noticed that of the pods lost, a large majority were picked from the vine but lost from the machine (1).

It was during this time that plant breeders drew up specifications as to what type of bean plant they thought would be most suitable for mechanical harvesting. It was reasoned at the outset that the picking fingers would do a much better job on an upright plant without cross branches and where most of the pods were set at one time at the top of the plant. They also reasoned it would be desirable to recover 95 percent of the beans at one harvest with a mechanical picker (21). The plant breeders reasoning proved to be valid as more and more tests were conducted with mechanical bean harvesters. Carter (5), reported that the picking efficiency of the Chisholm-Ryder bean picker was dependent upon the plant. The tests were conducted on fifteen varieties provided by the Association of New York State Canners. Bean pods were picked best from upright varieties. The damage to the picked pods was slight with about 2 percent being damaged. Most of those damaged consisted of broken beans. Minges (24), stated that the desirable qualities of good concentration of yields and high placement of pods could

be obtained by uniform germination if the plant seeds were spaced closely in the row.

A savings in the cost of production was another factor considered in using mechanical bean harvesters. A savings could be accomplished if the rate of harvesting and yields were great enough as compared to those for hand harvesting to justify the extra investment necessary for the machine. The Rochelle Asparagus Company of Rochelle, Illinois, reported that in 1958 they achieved an overall cost saving of 30 percent from the cost of hand picking by using bean harvesters and jumbo wirebound pallet bins for loading (12). The bins held 550 to 600 pounds of beans. It took one man to operate the machine and one to operate the chutes to fill the bins. They loaded the filled bins on trucks with a fork-lift. This technique of harvesting and handling using three machines, twelve workers, and a fork-lift resulted in the beans being harvested more economically than could be done by 200 workers necessary for hand picking. Reed and Dutcher (29), stated that a Chisholm-Ryder bean harvester used in 1954 on a second picking harvested one acre per hour and did the work of forty to fifty men. A study on fifty-seven farms in New York during 1962 to determine the average cost per acre for hand harvesting and machine harvesting on different size allotments showed that the average cost was $22 per acre when 250 or more acres

were harvested by machine, $30 per acre when 175 acres or less was harvested by machine, and $78 per acre for any acreage harvested by hand (16). In the fall of 1965, Hood and Drew (13), used a Chisholm-Ryder Hi-Boy bean harvester to pick snap beans. It was used in conjunction with bulk bins for loading and a fork-lift to load the bins on trucks to be taken to a sizing operation. The results for this operation showed that the cost per bushel was $3.80 when using the mechanical harvester and $4.40 per bushel for hand picking. Fletcher (10), reported in 1959 on the quality of snap beans picked by a mechanical harvester as compared with those picked by hand. The beans were picked both mechanically and by hand on 225 acres. The results are shown in Table I.

Although mechanical bean harvesters generally use the same technique in picking beans there are many variations in design. Many of these variations were the result of adaptations made for local conditions. According to Duncan (7), there were eight manufacturers of bean pickers at the beginning of the 1960's. Some of these were European models. The Chisholm-Ryder and the Pix-All are the primary machines manufactured in the United States. These machines are designed to pick beans two rows at a time spaced on 36 to 38 inch centers. The Pix-All is quite the same in principle to a Chisholm-Ryder and in fact practically paralleled it in

TABLE I

QUALITY OF SNAP BEANS PICKED BY A COMMERCIAL BEAN HARVESTER AS COMPARED WITH THOSE PICKED BY HAND

Number of pickings		Grade of beans		
		2, 3, and 4's	5 and 6's	Culls
		Percent	Percent	Percent
Hand picked	9	69.9	24.4	5.8
Machine picked	58	66.5	26.0	7.4

development. It picks the beans with steel fingers mounted perpendicular to and around the length of a central shaft. Both machines travel down the rows with the picking reels to the outside of the rows and rotating in opposite directions towards the center of the machine. As the beans are stripped off they fall in a conveyor under the machine and are carried through a cleaning process and up to a loading area. Both units are mounted on tractors and are self-propelled.

A bean harvester manufactured in England is the Mather and Platt. It is a one row tractor-mounted harvester with the picking reel entirely ahead of the tractor and in full view of the operator. This harvester is unique in that the picking fingers are attached to a belt rather than a cylinder. The picking fingers are drawn up through the bean plants in a straight path rather than in a short arc. The Vegetable Research Station in Alkman, Netherlands, where the machine was on test, reported that the beans picked by this machine were cleaner, had fewer clusters, and there was less damage to the beans as compared to those harvested by other machines tested there in 1962. They were so clean that they could go to the processing line without further cleaning. The machine was driven and the picking mechanism was powered by hydraulic motors. It picked rows of beans spaced on 15-1/2 inch centers.

Two machines manufactured in the Netherlands are the Borga and the Phloger. The first prototype of the Borga was similar to a Scott-Viner beet and carrot harvester. As the machine traveled down the row, the bean plants were clamped between two endless belts, pulled out of the soil, brought upward and toward the back of the machine. At the same time the plants were rotated 180 degrees so that the beans and leaves were hanging down. The beans then passed through a stripper, the beans were removed, and then the plants were dropped back on the ground. After the 1960 season this principle was abandoned and a conventional reel was used which picked the beans without removing the plants from the soil. The unit was driven by the tractor power-take-off and was a one row harvester which would pick up to 2-1/2 acres per day with rows spaced 24 inches on center.

The Phloger bean harvester was built by a Dutch bean grower named Phloger. He used a standard picking reel, but he left off most of the cleaning attachments and built a separate stationary cleaner. The machine was a one row harvester which picked beans from rows spaced on 17-1/2 inch centers at 5-1/2 miles per hour with yields of 2 1/2 tons per acre. The cleaner had a wire covered rotating drum into which projected metal spikes. The beans were emptied into the cleaner and those which were loose were quickly discharged, but clusters were conveyed to a second rotating

drum where they were broken up before the beans were discharged.

A German produced machine manufactured by the Herbort Factory in Braunschweig, Germany, is a small one-row tractor drawn picker which was introduced in 1962. It uses a conventional picking reel and is unique in that the beans are cleaned by two different airstreams. After the beans pass through the airstreams, they reach a screen where clusters and loose beans are separated. The machine operates at 2-1/2 to 4 miles per hour and harvests up to 2700 pounds of beans per hour.

The Food Machinery and Chemical Corporation of San Jose, California, started an experimental project in 1952 to pick pole beans (27). Pole beans are different from snap beans primarily due to the type of plants they grow on and the resulting necessary cultural practices. Rather than growing on short bushy plants, pole beans grow on plants which have long runners. These runners are supported in an upright position by cords attached to poles which run the length of the row.

The outgrowth of a pole bean mechanical harvester came from a picker head developed by Max Lehmann, President of Northwest Packing Company of Portland, Oregon. His idea was first tried in a greenhouse and then on a bean farm in the

Portland area. In operation, the picker straddled the row operating a pair of picker-heads which worked simultaneously on both sides of the row. The picker-head consisted of a pair of upward-moving series of horizontal bars. These bars were staggered and close enough to overlap while working both sides of the row. The heads were spring loaded and opened slightly when passing the wooden center posts supporting the cords or string. Pole beans snapped from the vines fell into a sled-type pan at the bottom of the harvester. From there the beans were blown across the pan to a vacuum device that sucked them into a hopper. This machine was a multiple-harvest machine.

Three types of machines are now used for harvesting lima beans. They are standard stationary viners, portable viners, and most recently a two-row snap bean picker (40). The stationary viner has been the traditional method for shelling lima beans. The vines are either cut or pulled from the soil, placed in windrows, and the complete plant is hauled to the viner. A stationary viner is actually a series of three machines. The first section cleans out foreign particles, the second section threshes beans from the pods, and the third section rethreshes the pods. The stationary viner is the most effective method of harvesting limas but it has the disadvantages of having to truck the complete plants

from the field to the viner and also the threshed plants have to be disposed of.

Portable viners have been developed which have a pick-up device to load the beans from windrows and they are then conveyed to the viner section of the machine. The pods are threshed and the plant refuse and empty pods are deposited back on the field (38).

The Chisholm-Ryder Hi-Boy snap bean picker and the Pix-All snap bean picker are designed to pick lima beans also. The use of the Chisholm-Ryder Hi-Boy reportedly reduced the amount of hauling from the field to a viner by 60 percent by eliminating the plants from the transported product. Also, a viner threshing lima beans picked by a snap bean harvester, reportedly can do the work of three or more viners which are handling the complete vine (9, 21, 26).

The Chisholm-Ryder Hi-Boy is a redesigned model of the standard snap bean harvester directed primarily at harvesting lima beans. However, experience proved it also was better adapted to picking snap beans at greater ground coverage than the standard snap bean picker. It was redesigned by mounting a nylon bristle brush in line with and above and slightly in from the picking reel. The addition of these brushes required a higher tractor resulting in the name Hi-Boy. These brushes performed the stripping operation on the picking reel

and prevented "throw-out" on limas. It also reduced breakage in snap beans. The picking reel was also made longer and tapered at the lower end. The reels are mounted with the front of the reel higher than the rear. This enables the reel to strip the plants from top to bottom and eliminates some of the possibility of pulling plants out of the ground which would be more likely if the picking reel fingers stripped through the entire plant all at once. The tapered area of the reels at the lower end provides an area parallel to the ground in which are mounted three series of fingers to sweep the ground. This was necessary for an acceptable degree of picking efficiency for lima beans but was not necessary for snap beans (21).

Peas is another crop which is harvested with principles similar to those used in snap bean harvesters. The Pix-All snap bean harvester is also recommended for picking peas. Reid and Brantley (30), reported that a harvester developed at the University of Georgia in 1961 picked southern peas satisfactorily. It was designed and constructed using picker teeth moving in an oval path. The machine also utilized a device under the picking teeth called a picker plate. It consisted of stationary plate bars made from steel rods which were secured to the picker plate to provide the necessary picking action. The picking assembly traveled down the row perpendicular to the centerline of the row with the picker

plate inclined at an angle of thirty degrees to the ground. As the assembly moved down the row the picker teeth which travel in an oval path above the picker plate pulled the vines into the picking zone on the plate. The forward movement of the harvester and the movement of the vines over the plate bars by the picker teeth provide the picking action. The picked pods were then carried away by an elevator to be loaded into a truck. The picking efficiency ranged from 67 to 96 percent according to the varieties harvested. The material harvested ran about 40 to 50 percent pods which can be handled by shellers available at processing plants (30).

The tomato, which is one of the more important canning crops, is grown in most geographical areas of the United States. The proper stage for harvesting is when the tomatoes are red ripe. Varieties have been developed for mechanical harvesting (21). Lorenzen and Hanna (19), reported that the desirable type of tomato plant for mechanical harvesting was a small compact plant which stands upright and sets a high percentage of fruit in a short time. Hanna worked for many years to develop this type of plant and Lorenzen outlined the following operations which a tomato harvester must perform: (1) cut the plant root system, (2) lift the vine, (3) remove the fruit, and (4) transport the fruit to some type of receptacle (37). It was considered necessary to cut the plant below the soil surface since in the case of many

varieties, large percentages of ripe fruit would fall from the plant due to vibration when initially struck by the cutting mechanism.

Investigations into the mechanical harvesting of tomatoes began in 1942, but commercial harvesting did not start until 1960. This was primarily in California since there was a greater need and therefore a greater effort there (28). In 1950, the University of California Departments of Agricultural Engineering and Vegetable Crops began an investigation of a system for mechanically harvesting tomatoes (19). It was surmised that the separation of the fruit and vine was an important element in mechanical harvesting, but the physical properties of the plant and the fruit impose restrictions on the mechanical system that accomplishes this separation. Ripe tomatoes are soft and easily broken which makes harvesting them more difficult. With these restrictions in mind Lorenzen and Hanna (19) proposed that separation could be considered from the standpoint of basic principles such as shaking, centrifugal force, high linear acceleration or deceleration of the vine, raking, combing, viscous drag, and stripping. Tests to evaluate these different methods were conducted. Later in 1958, tests using an experimental shaker bed indicated that tomatoes could be shaken off the plant effectively at 215 cycles per

minute with a 4 inch stroke. Further work by Lorenzen and Hanna utilizing this principle tended to support this method. Their work was oriented to show the effect of frequency on separation efficiency in devices that shake the suspended vine-fruit system in vertical and horizontal planes. With vertical displacement, the fruit vine combination may be considered to approximate a spring mass system. Data obtained through experimental results was plotted as a graph with percent of fruit separated as the ordinate and frequency as the abscissa. The result was a discontinuity in the curve around a certain frequency which pointed out that the vine did display considerable elasticity and that the system had a natural frequency at the region of discontinuity. The horizontal displacement curve showed a different behavior which indicated that the effective stiffness of the vine increased as the frequency increased. This meant a higher percentage of separation energy was transmitted to the separation point as the total input energy also increased. This experimentation led to the construction of a crude machine for harvesting tomatoes.

The machine was designed to cut the plant below the soil surface, elevate the fruit to a shaker bed, remove the fruit, and catch it on a wire screen. The rods in the shaker bed were spaced on five inch centers to allow the detached fruit to fall through. The beds were sloped towards the rear

to allow the picked plants to slide off the bed onto the ground. The bed in this machine was made to shake at approximately 200 cycles per minute with a 4 inch stroke. The results proved satisfactory but the machine had shortcomings. An overhead pickup mechanism to help feed the plants into the machine was added on later models. Also, a positive means was added to assist in moving the picked plants off the machine. It consisted of an overhead chain with extended metal fingers which assisted in moving the picked plants off. Too, sorting platforms were added on later models. This machine picked from 3 to almost 10 tons per acre of number one ripe fruit whereas the average yields per acre at this time were approximately 12.6 tons per acre. However, the results for mechanical harvesters were from varieties unsuitable for mechanical harvesting (37).

Mechanical harvesters for tomatoes using the shaking principle have become so commonplace in California that 75 percent of the crop there was harvested mechanically in 1966, but only 1 percent was harvested mechanically in the rest of the country (28).

Stephenson (34) working on the premises that even with new varieties, 15 percent could be assumed to be green at harvest time, did exploratory investigations for selective separation of tomatoes in mechanical harvesters. He assumed

that with yields of 40 tons per acre and 15 percent of these being green, then there would be 6 tons or 18,000 green tomatoes to sort per acre. In the development of his machine, he utilized the fact that the development of abscisson layers in the pedicle as the fruit ripened offered advantages. The riper the fruit the more easily it was detached. With this in mind, he designed a shaking device which progressively increased the amount of shaking the plant was subjected to as it moved towards the discharge end of the shaking bed. As the vines entered the intake end, they were subjected to a 1-1/4 inch stroke, a 3 inch stroke in the middle, and 5-1/2 inch stroke at the discharge end of the shaker. From tests conducted utilizing different frequencies and different varieties, the results showed (1) increased frequency increased selective separation with all varieties with approximately 150 cycles per minute giving the best results, (2) increased length of stroke from one end of the shaker bed to the other caused selective separation, and (3) there was no consistant relationship between fruit damage, frequency, and length of stroke.

Cucumbers have been harvested mechanically both with once-over harvesters and multiple-pick harvesters. Chisholm (6) reported in 1955, that a pickle grower in Michigan had developed a harvester which would do the work of forty harvest hands and would pick 1 to 1-1/2 acres per hour. The machine

used a 12 horsepower tractor which had been lengthened and widened to accomodate the harvesting mechanism. Chains and gears operating the picking mechanism were also powered by the tractor.

The intake of the machine consisted of two conical rollers passing along each side of a row of vines. The rollers tapered from a 2 inch diameter at the front to 5-1/2 inches at the back. The vines were lifted by these rollers, and as the machine traveled down the row the vines were laid on two sets of revolving rods which passed over and around aprons. As the rods struck the cucumbers hanging from the vines, they fell onto the aprons which were also revolving. The aprons then carried the cucumbers into conveyor troughs for dumping into crates on a truck behind the picking machine. The size of cucumbers picked was determined by the speed at which the picking mechanism was run. The fastest speeds used picked cucumbers down to 3/4 inch in length for pickle use. Slower speeds picked only larger cucumbers for the fresh market. The rows were spaced 6 feet apart and the vines were left practically undamaged by the harvest operation. However, some cucumber harvesters designed for multiple harvesting have reportedly left the vines severely damaged.

A study by Bingley and Leonard (3) in 1962, showed that many multiple-pick methods of harvesting had been tried on cucumbers as a result of (1) vine damage from previous

harvesters, and (2) the inability to harvest fruit growing within 6 to 8 inches of the base of the plant. Their work consisted of evaluating two types of pickup devices and a vine trainer. The vine trainer was a pneumatic device which blew the vines in a direction perpendicular to the direction of the row. This was done when the plants were 10 to 16 inches long and were secured in that position with a small amount of soil applied by a special plow on the machine.

From previous studies made on previous machines it was believed that the pickup units caused most of the vine damage, therefore two new types were investigated. The first type pickup investigated was a vacuum elevator. It consisted of a three-ply rubberized fabric belt (perforated with 1/2 inch diameter holes) which operated around a sheet metal vacuum chamber open on the underside. The vacuum chamber sloped upward so that after the leaves were held against the moving belt, the vines were elevated to a separately moving bed. This let the cucumbers hang suspended beneath the vines and the belt delivered the cucumbers over the picking beds in an exposed picking position for the picking flights.

Although the vacuum pickup performed satisfactorily, a second pickup which was mechanical was utilized since it was better adaptable and required less space. It was designed in the shape of a frustrum of a cone and had pickup fingers

which were retractable. The frustrum design enabled the pick-up to remain close to the ground and still place vines on an inclined bed in a position perpendicular to the row. The fruit was then separated from the plants on a separating bed. The bed was positioned to allow the vines to extend to the top of and toward the upper end of the bed. Flights spaced 14 inches apart operated around the bed and removed fruit from the underside of the vine.

A once-over cucumber harvester called the Blackwelder Pickle Harvester is now manufactured by the Blackwelder Manufacturing Company of Rio Vista, California (15). The machine utilizes a unique knife vine-cutting system. The gathering mechanism first collects the larger fruit and then adjusts automatically for the smaller fruit. It picks the fruit off the vines with picking rollers and will cover two 40 inch beds simultaneously. It can deliver up to 6 tons per acre and cover up to 13 acres per day.

Humphries (17) reported on a multiple-pick cucumber harvester which used a principle for harvesting that depended on the size or mass of the cucumber. Initial investigations by him revealed that mechanical impacts generated by striking the cucumbers with a rigid member was the most effective means of developing the necessary separation forces. Considering the mechanics of impacts indicated the manner in which the

fruit should be struck to get the maximum separation force at the point of attachment of the fruit to the vine.

In the analysis the fruit was considered as a rigid body capable of rotating about a fixed axis through the point of attachment to the vine. The idealized system is shown in Figure 1. The physical relationships were based on the fact that if a blow of impulse (R) was struck at the point (X), then this would cause an impulsive reaction (R') at the point of attachment (0). This can be represented in scalar form as

$$R + R' = mrw$$

and

$$RX = K^2mw$$

where m is the mass of the fruit, r is the distance from point (0) to the center of mass, w is the angular velocity of the mass immediately after the impulse (R) is struck, and K is the radius of gyration of the fruit about the axis through (0). From these relationships then a ratio of R to R' can be expressed which is

$$\frac{R'}{R} = \frac{rX}{K^2} - 1$$

This ratio indicates that the reaction (R') has its maximum value which is equal to -R when X = 0. Furthermore when $X = K^2/r$ the reaction (R') is zero. This means that the

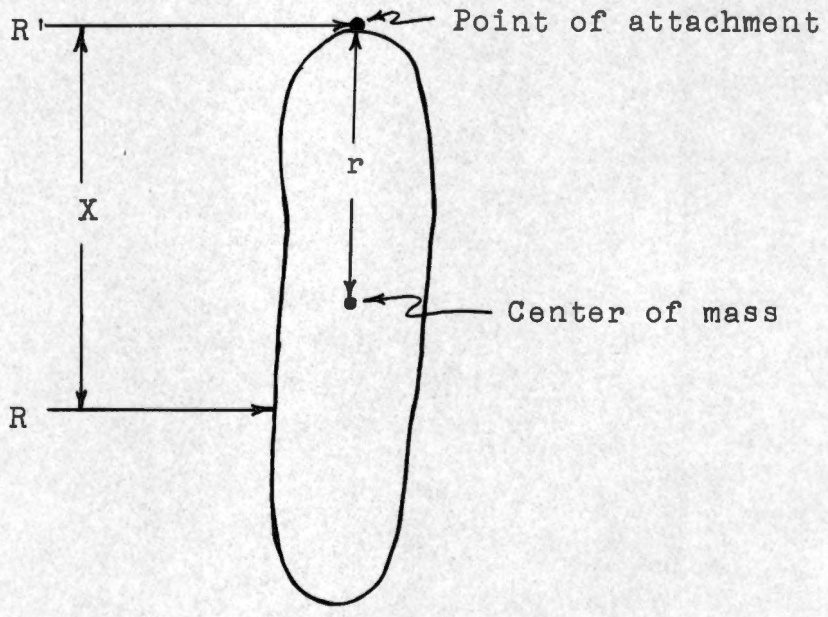


FIGURE 1. Hypothetical cucumber showing the impulsive reaction (R') when struck with an impulse (R).

blow should be struck as close to the point of attachment as possible. Since a cucumber of homogeneous mass approaches a slender rod in physical appearance, there is very little difference between K^2r and r. Therefore, blows near the center of mass should be avoided since this would produce very little reaction or no reaction at all at zero.

Laboratory studies indicated that small diameter rods would serve as a suitable instrument for delivering the impulse to the fruit. Preliminary tests were run with a short section of rod slipped under the vine at the fixed root end. The rod was moved out along the vine maintaining contact with the main stem. This resulted in the rod striking the fruit at the hypothetical point of attachment. Results showed that impacts could be used to separate the fruit from the vine with rod velocities of 2 feet per second. No appreciable fruit damage resulted and there was very little vine breakage. Utilizing these results, an apparatus was designed and constructed for simulated field use. The results were satisfactory and a machine for field use was then constructed.

The machine was constructed so that rods attached above a sheet metal bed struck the fruit as the beds were pulled under the vines. The vines were picked up by rotating brushes on the leading edge of the bed in order for the rods to pass under the vines. The resulting impacts between fruit

and rods due to the forward speed of the machine caused the cucumbers to be detached from the vines. The results showed that the probability of a cucumber being harvested depended on its mass and size. Since this method of harvesting caused very little vine damage, smaller unpicked fruit could be allowed to reach the desired size and then picked with the machine. In general, factors affecting the performance of the machine were fruit size, variety, and location of the fruit on the vine.

The implications of an ever increasing number of new developments in vegetable harvesters is inescapable. How far mechanization can go in vegetable harvesting depends on the comparative costs of performing tasks by hand or by machine.

CHAPTER III

EXPERIMENTAL PROCEDURE

I. DESIGN OF MACHINE

This study was based on a basic and new approach to vegetable harvesting. The machine designed and constructed for this study incorporated a cylindrical helix and a cylindrical brush as the harvesting mechanism. It was a once-over, one row harvester which utilized a three-point-hitch and was to be pulled by a standard farm tractor. The power unit for the harvesting mechanism was an auxiliary gasoline engine mounted on the machine. Although the harvesting principles conceived were believed to be valid for several vegetable crops, the machine constructed for this study was designed primarily to harvest snap beans. However, the machine was to be tested on bell peppers also.

The three main components of the machine were the cylindrical helix, a cylindrical brush mounted inside and parallel with the center line of the helix, and a metal cylinder which served as a housing for the helix and brush. The machine is shown in Figures 2 and 3.

In operation, the machine was to be pulled down a row of beans just clearing the ground. Viewing the machine from

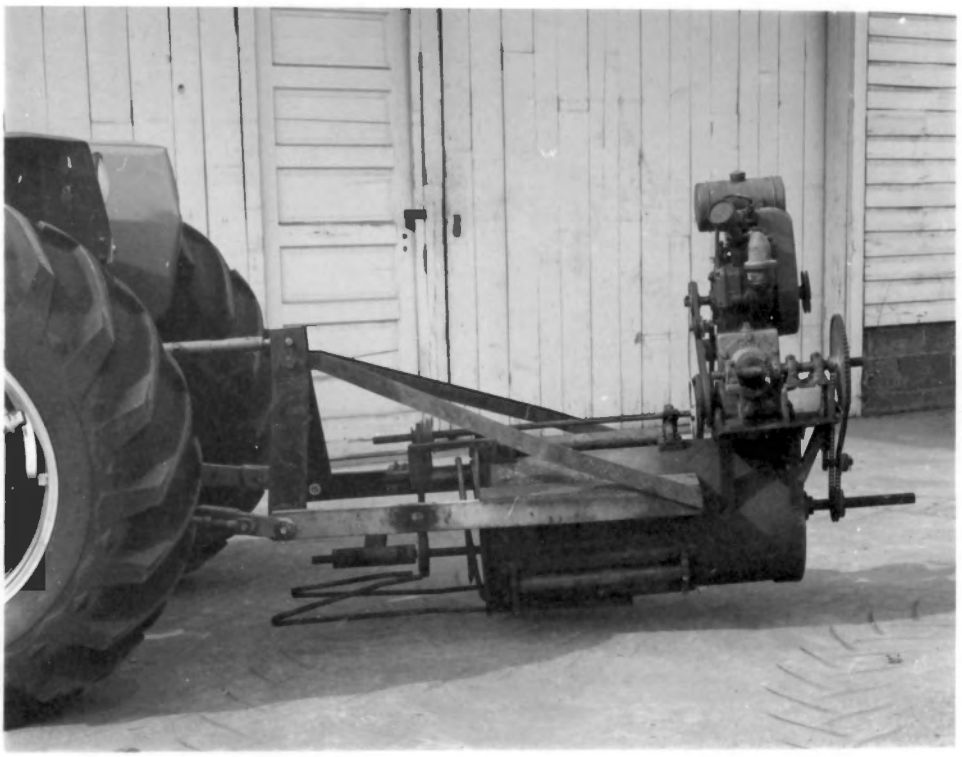


FIGURE 2. Harvester mounted on tractor and positioned as tested in the field.

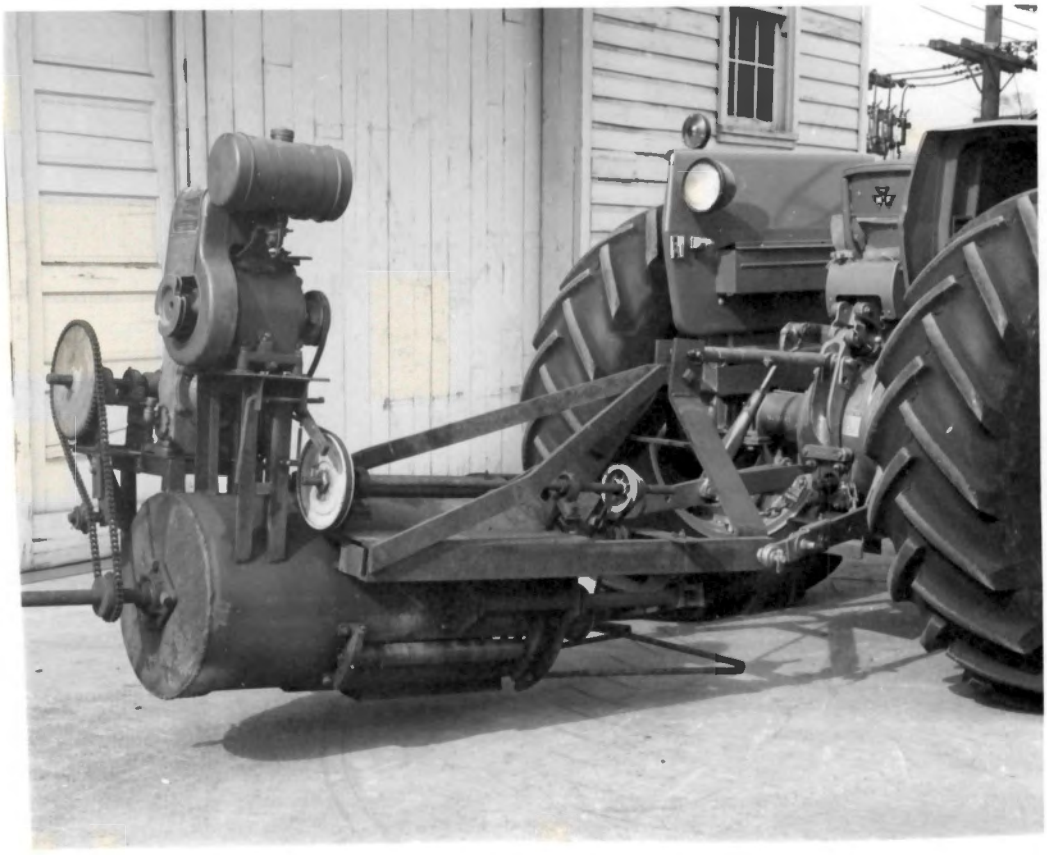


FIGURE 3. Rear view of the harvester mounted on the tractor.

the front, the helix was to rotate in the clockwise direction and the brush in a counter-clockwise direction. As the machine traveled down the row, the end of the helix was to twist through the plants pulling the plants back through a slot provided in the bottom of the housing. The plants were to be pulled through in much the same way as the screw in a jackscrew exerts force on the base causing the screw to advance through the base. But in the case in study, the helix acting as a screw would exert force on the plants to pull them through the machine. This was to be done without uprooting the plants. In passing through the machine, the plants would be subjected to forces imparted by the rotating brush. This would result in the picking action which would separate the fruit from the plant.

In determining the requirements for the helix, it was decided that it should be designed on the basis of cylindrical compression or tension springs using the formula for the spring constant

$$k = \frac{Gd^4}{8D^3n}$$

as the basic design premises where k is the spring constant, G is the modulus of rigidity, d is the diameter of the rod, D is the diameter of the coil, and n is the number of active coils in the spring (39).

Preliminary investigations revealed that bean plants were in general around 16 inches in height. Assuming that approximately 14 inches of the plant would pass through the machine, an outside diameter of 16 inches was selected for the helix. In determining the spring constant (k), it was surmised that the helix would not require a large k since it was not acting as a spring but essentially as an auger. Though there would be tensile and compressive forces on the helix, they were thought to be relatively small. The final selected design specifications were for the helix to be constructed of medium steel rod 5/8 inch in diameter and have a length of 24 inches with a 2 inch pitch or lead. One end was left plain or open and the other end was squared or closed.

A cage was constructed and attached to the squared end of the helix (Figure 4). A steel ring 1/2 inch thick with an outside diameter of 16 inches and an inside diameter of 15-3/8 inches was welded to the squared end of the helix. Four, 1-inch diameter steel rods 14.5 inches long were welded to brackets on the ring parallel to the centerline of the helix and on a diameter of 14 inches. They were spaced 90 degrees apart. The other ends of these rods were bolted to a 1/4 inch circular steel plate with a diameter of 16 inches. A 1-1/4 inch diameter steel shaft was welded in the center of this plate and parallel to the centerline which served as the drive shaft for the helix.

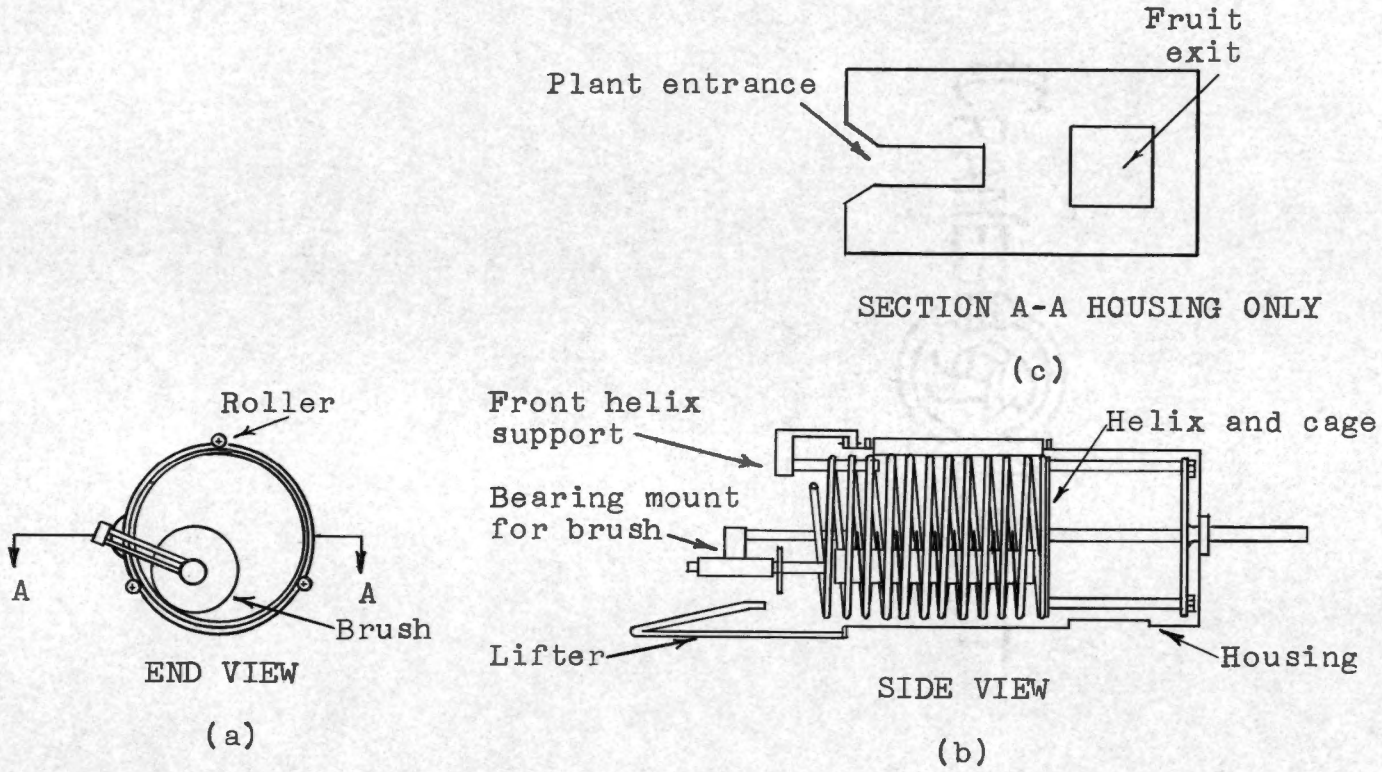


FIGURE 4. Basic components of harvester.

The helix and cage combination (hereafter referred to as the helix) was mounted inside the cylindrical housing (Figure 4b). The housing was rolled and formed from 1/8 inch steel plate. The overall length was 36 inches with an inside diameter of 17 inches and the rear end was closed with a 1/4 inch steel plate. The helix rotated inside the housing on three 18 inch steel rollers covered with 2 inch diameter plastic pipe. The plastic pipe was slipped over and cemented to the rollers with epoxy cement. These rollers were mounted in slots provided in the housing which were spaced 120 degrees apart around it (Figure 4a). A flange bearing, to accomodate the helix drive shaft, was centered and mounted on the outside of the closed end of the housing. A slot 14 inches long with a projected width of 4 inches was cut in the bottom front of the machine. This was to allow the plants to be pulled through the machine by the helix. An opening 8 x 8 inches was cut in the bottom rear of the machine under the cage and was intended as an exit area for harvested fruit. The total length of the helix and cage was 40 inches, which allowed for 4 inches or two turns of the helix to protrude from the front of the machine when the helix was mounted inside the housing.

After having mounted the helix inside the housing, the leading end of the helix, which protruded from the front end of the housing, sagged. From the point where the helix did

not rest on the rollers towards the front, the helix rested on the housing. To eliminate this problem, a short roller and bracket to support it were mounted on the top front of the machine (Figure 4b, page 40). The roller projected inside the helix as a cantilever beam and supported the first few turns of the helix in line with the rest of the turns.

The brush, which rotated inside and parallel to the centerline of the helix, had a wooden core 3 inches in diameter and was 22 inches long. A steel shaft, which was threaded and coated with epoxy cement, was screwed into one end and through the center of the wooden core a distance of 15 inches. The bristles selected for use in the brush were flat nylon strands of the type used in barn brooms. They were attached to the wooden core in bundles of approximately eighty strands on a helical pattern. The helical pattern, with a 2 inch pitch, was laid out on the core starting 2 inches from one end and ending 2 inches from the other end. This allowed a length of 18 inches for the bristles to be attached. One-half inch diameter holes 3/4 inch on center were bored with the axis of the hole directed towards the centerline of the wooden core. The bristles were imbedded in the holes with wire staples and cemented with epoxy cement. The completed brush was trimmed to a diameter of 8 inches.

A bearing bracket 9 inches long with sealed roller bearings pressed in each end was mounted on an arm in the proper position in front of the machine. The steel shaft from the brush was pressed through these bearings and the brush was suspended in a fashion similar to a cantilever beam inside the helix. The brush itself was recessed 6 inches from the forward end of the helix (Figure 4b, page 40), allowing space for the plants to be engaged by the helix before they were subjected to the action of the brush. The bracket and arm which held the bearing mount were constructed so that the brush assembly could be adjusted up and down (rotated about a pivot point) through an angle of 22 degrees. The mount was also constructed so that the brush could be adjusted through a distance of 3 inches across the front of the machine. These adjustments were deemed necessary to determine the position of the brush which would result in the best picking action. A 5-inch diameter v-belt pulley was attached to the brush shaft for driving the brush.

The power unit used in the harvester was a 2-cycle, one cylinder, gasoline engine which developed 2.5 horsepower at its maximum speed of 3600 revolutions per minute. Upon operating the machine in the field, it was found that this engine was too small, therefore it was replaced with a 4-cycle, one cylinder, gasoline engine which developed 2.5 horsepower at 1600 revolutions per minute and 6 horsepower

at its maximum speed of 3600 revolutions per minute. The engine was mounted on the top rear of the machine as shown in Figure 5. The engine through an appropriate pulley and gear arrangement powered both the brush and the helix.

The brush was driven by a pulley and v-belt arrangement with power being transferred from the engine at the rear of the machine to the front through a shaft which ran the length of the machine (Figure 5). A cone pulley was used on the front of the shaft in order to be able to change the speed of the brush.

The speed of the helix was to be much less than that of the brush, therefore, the power for the helix was transferred from a gear reduction box with a speed reduction ratio of 30:1. In order to obtain the proper rotational direction and the proper alignment of the drive shaft, the power was transferred from the output shaft of the reduction box through a set of miter gears mounted at right angles (Figure 2, page 36). A chain drive was used to power the helix. The drive sprocket was 10 inches in diameter and the sprocket on the helix drive shaft was 4 inches in diameter. This gave an increase in speed at a ratio of 1:2.5 which resulted in a final reduction ratio of 12:1 from the motor speed to the helix speed.

The drive assembly for the brush and the drive assembly

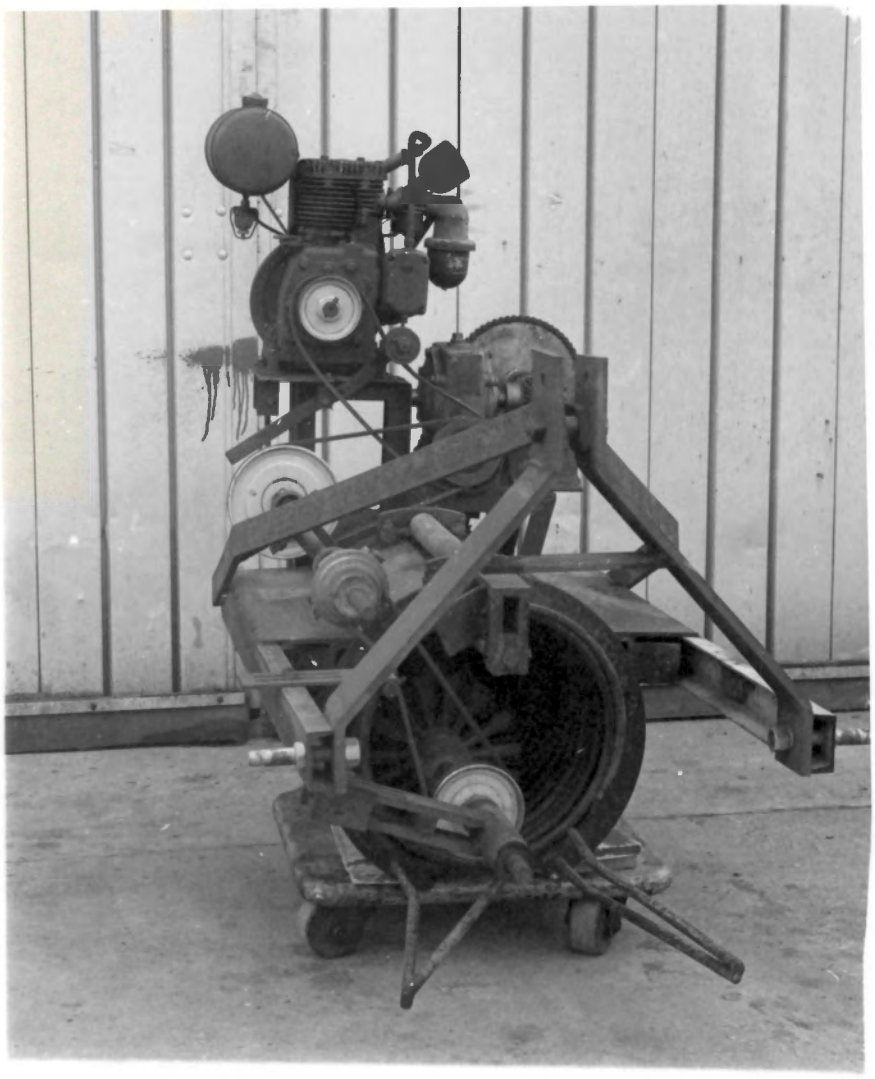


FIGURE 5. Components of harvester including engine, shaft and pulley arrangements, brush drive, and lifters.

for the helix were both driven by the same belt drive from the engine which was engaged with an idler.

Lifters were installed on the machine to facilitate the entrance of the plants into the machine. These are shown in Figure 5. They were constructed from 3/4 inch steel rod and were formed so that they would move under low foliage, gather it, and lift it to a height sufficient for the helix to engage it.

II. ANALYSIS OF FORCES

When considering the forces to which the plants and fruit would be subjected due to the action of the brush and helix, it was decided they would be primarily impact forces with friction forces being of secondary importance. That is as the helix forced the plants into the path of the brush, the fruit would be stripped from the plants due to impact forces delivered to the fruit by the brush. This was deduced since the brush and helix would be rotating at constant but different angular velocities.

Impact refers to the collision of two bodies and is characterized by the generation of relatively large forces which act over a short period of time. The principles of impulse and momentum find important use in describing the behavior of impacting bodies. For rectilinear motion along some axis, the momentum equation can be written as

$$\frac{d(mV)}{dt} = F$$

where t is time, m is mass, V is velocity, and F is force. When the force acts over a period of time, then the equation may be written in integral form. Multiplying both sides of the equation by dt gives

$$m\ dV = F\ dt$$

which may be integrated to obtain

$$m\ (V_2 - V_1) = \int_o^t F\ dt$$

where $(V_2 - V_1)$ is the change in velocity. The product of force and time (right-hand side of the equation) is defined as linear impulse, therefore the equation states that the total linear impulse equals the corresponding change in linear momentum, $m\ (V_2 - V_1)$. The impulse integral is, in the general case, a vector which may change both in magnitude and direction during the time interval. There can be component forms of linear impulse, thus taking a rectangular coordinate system with x-, y-, and z-components, the x-component becomes

$$m\ (V_{2_x} - V_{1_x}) = \int_o^t F_x\ dt$$

and similarly for the y- and z-components.

In considering impact, which is usually of short duration, extremely large forces act for a very short period of time and accurate determination of these forces is generally impossible. But if a mass (m_1) of velocity (V_1) strikes another mass (m_2), then an impact force is generated which is dependent on mass (m_1) and its change in velocity (ΔV_1). If F is the impact force generated by m_1, then the force on m_2 is -F. Referring to the equation for linear impulse, these relationships can be expressed as

$$\int_o^t F\,dt = m_1 \Delta V_1 \text{ and } \int_o^t -F\,dt = m_2 \Delta V_2$$

The fact that these impact forces will be relatively large can be shown by again referring to the linear impulse equation. Considering a very small time interval (Δt) in the expression for linear impulse and solving for F gives

$$F = \frac{m \Delta V}{\Delta t}$$

If Δt is very very small then it can be visualized that F will be relatively large.

In the mechanical system incorporated as the picking unit for the harvester in study, the velocities which would result in impact forces on the fruit were generated by the helix and brush. The helix and brush were to rotate in opposite directions at different speeds with the helix

forcing the plant into the brush. Since the brush was constructed as a helical surface, then both the helix and the brush could be represented by the same general equation.

Parametric representation of a helix in a rectangular coordinate system with x, y, and z directions can be expressed as

$$x = a \cos wt,\ y = a \sin wt,\ z = b\ wt$$

where time (t) is the parameter and w is the angular velocity. From these expressions it can be seen that the curve lies on the cylinder $x^2 + y^2 = a^2$ where a is the radius. If the helix is constructed like a left-handed screw then the constant b is less than zero and if it is constructed like a right-handed screw then b is greater than zero. Both the helix and brush in the machine were constructed as left-handed screws.

If time (t) is the variable which determines the position of a point (P) with coordinates (x, y, z) along a path (S) in space, then a helix can be represented vectorially as

$$S = x\ i + y\ j + z\ k$$

or

$$S = a \cos wt\ i + a \sin wt\ j + b\ wt\ k$$

which is the position vector of the moving point (P). Furthermore, the velocity of the point along its path can be expressed as

$$V = \frac{dS}{dt} = \frac{dx}{dt} i + \frac{dy}{dt} j + \frac{dz}{dt} k$$

or

$$V = -aw \sin wt\ i + aw \cos wt\ j + bw\ k$$

The velocity vector V has the direction of the tangent to the path at (x, y, z) and the velocities in the x, y, and z directions would then be $V_x = -aw \sin wt$, $V_y = aw \cos wt$, and $V_z = bw$. Therefore, it follows that the point (x, y, z) moves around the cylinder with angular velocity (w) and along the cylinder with linear velocity $V_z = bw$.

The first velocity to be considered for the machine was the velocity V_z for the main helix. In determining the angular velocity for the helix, there were three possible alternatives. These alternatives depended on the fact that the machine would have a forward speed (V_m) which would be determined by the speed of the tractor towing it. The first alternative was for V_z to equal V_m. The second was to let V_z be less than V_m and the third was to let V_z be greater than V_m. If V_z equalled V_m then theoretically the plants would pass through the helix in an upright position without coming in contact with the edges of the helix. If V_z was less than V_m then the helix would ride over the plants rather than augering them back through the machine. The third situation, V_z greater than V_m, was deemed to be the most

desirable since the original idea was for the plants to be forced into the path of the brush by the helix edge as they were augered back through the machine. It is known from observation that particles in a screw conveyor travel in a direction roughly perpendicular to the helical surface of the screw (31). Since the helix was formed like a left-handed screw, the turns were at such an angle that plants coming in contact with a turn would be forced over and into the brush, hence, V_z must be greater than V_m to insure this condition. However, even with V_z equal to V_m the plants would still be in contact with the helix edges due to plant spacing and density. Also with V_z slightly less than V_m, it was considered possible that the helix would tend to push the plants forward rather than ride over them, thereby possibly creating a desirable situation since the plants had to exit the machine in this direction. This suggested all three alternatives should be tested experimentally.

With V_z greater than V_m, the plant stems near the ground would be in contact with the rear edge of the helix as they passed through the machine. The direction in which the plants would be forced over without uprooting them would be roughly perpendicular to the helix edge at some angle α measured from the centerline of the helix (Figure 6). By unwinding one turn of the helix it can be seen that the slope

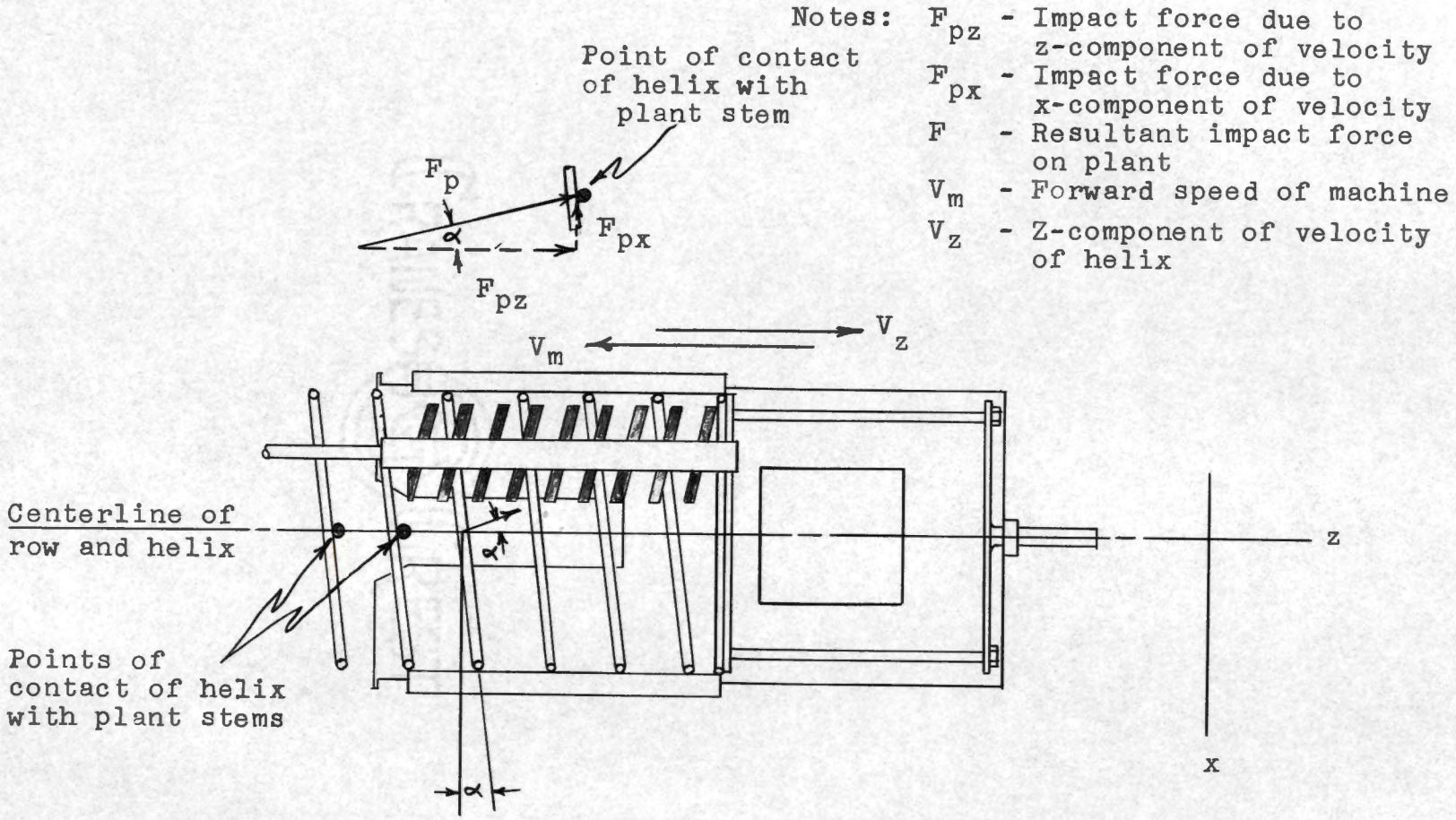


FIGURE 6. Direction plant will be forced when engaged by helix due to impact forces.

of the inclined plane formed is $\tan\alpha = 1/2\pi r$ where L is the lead or pitch and r is the radius of the helix. Therefore, a direction perpendicular to this surface forms an angle (α + 90) degrees with the x axis. Remembering that the velocity vector is tangent to the curve at a point (x, y, z), and if points of the helix which come in contact with plants are as those shown in Figure 6, then the direction the plant is forced by the helix is also roughly perpendicular to the velocity vector. But since the plant is restrained by the root system from moving in the vertical (y) direction, it can be assumed the y-component of velocity (V_y) has no effect on the direction in which the plant is forced. Therefore, the components V_x and V_z will cause an impact force on the plant stem forcing the plant in the direction shown. Then the actual angle through which the plant would be forced will not necessarily be α. This angle is difficult to determine exactly but is clearly between 0 and 90 degrees.

In analyzing the impact forces delivered to the fruit by the brush, it must be considered that the brush was constructed as a helical surface. Referring to the general vector equations for displacement and velocity for a helix

$$S = a \cos wt\, i + a \sin wt\, j + b\, wt\, k$$

and

$$V = -aw \sin wt\, i + aw \cos wt\, j + bw\, k$$

the value of the radius (a) would not be constant but would range from a minimum value of 1.5 inches (radius of the wooden core) to a maximum value of 4 inches (radius of the brush including the core). Therefore, the velocity components, V_x and V_y, would vary reaching a maximum value at the outer most point on the brush. The brush, due to the manner in which it was constructed, had a space of 3/4 inch between the bundles of bristles at the outside edge of the brush. These spaces would allow the brush to penetrate into the plant foliage as it was forced into the brush by the helix with each bundle of bristles acting as a finger. The finger was to strike a bean pod with some velocity which would result in an impact force on the fruit. The magnitude of the velocity, and consequently the impact force, would depend on how far from the center of the brush the fruit was struck. Since the spacings between the fingers were relatively small, the brush would not penetrate the plant deeply and the resultant velocity would approach the maximum velocity. The bean pod can be made analogous to a cucumber and would be separated from the plant due to impact forces as described by Humphries (22), page 28. The angle of impact would be somewhat different with the case in study. Where the cucumber was struck horizontally with a fixed rod and the resultant impact force was perpendicular to the surface of the

fruit, the impact forces delivered by the fingers in the brush to the bean would be in a direction as shown in Figure 7. The component velocities V_x, V_y, and V_z of a point on the brush cause impact forces F_x, F_y, and F_z on the bean which form the resultant force (F) acting at a distance (d) from the point of attachment (0). Then there is a reactive force (F') at point (0) which detaches the bean from the plant. The force F_p with components F_{px} and F_{pz} is the impact force on the plant stem due to the x- and z-components of velocity of the helix at that point.

Since the fingers were composed of several fibers, they would be more flexible and have a lower density than a homogeneous rod. This would result in less damage to fruit, since the object delivering the blow would be less massive and would curl around the fruit as it struck due to its flexibility. Also, since the brush would not engage the entire plant upon initial contact but would strip it gradually as the plant passed the length of the brush, the vertical forces on the plant would be limited and the possibility of uprooting the plant decreased.

Since the picking forces depended on the angular velocities of the helix and brush, the brush should have a greater angular velocity than the helix. This was theorized since the plant would be forced into the brush by the helix at some linear velocity dependent on the angular velocity of

Notes: F_x - X-component of brush impact force
F_y - Y-component of brush impact force
F_z - Z-component of brush impact force

F - Resultant brush impact force on bean
F' - Reactive impact force

F_{px} - X-component of helix impact force
F_{pz} - Z-component of helix impact force
F_p - Resultant helix impact force on plant stem

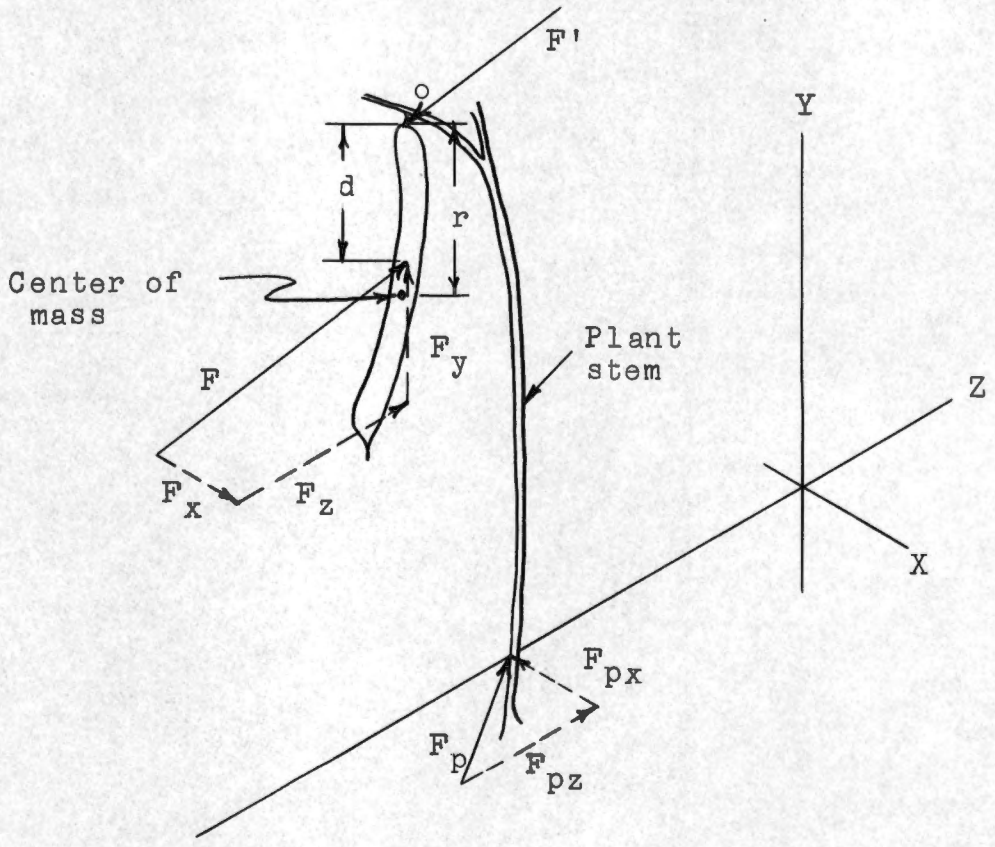


FIGURE 7. Hypothetical bean subjected to impact forces.

the helix. To insure impact forces being delivered by the brush to the fruit of sufficient magnitude to cause separation, the angular velocity of the brush needed to be greater than that of the helix.

III. TEST PROCEDURES

The harvester was tested on snap beans and bell peppers. Both laboratory tests and field tests were conducted with snap beans, but only field tests were conducted with bell peppers.

In evaluating the performance of the machine, the study took into account three variables; the forward speed of the machine (Vm), the angular velocity of the helix (H) which resulted directly in a z-component of velocity of the helix (Vz), and the ratio of the speed of the helix to that of the brush (B). Since the helix and brush were both driven by the same power unit and the power trains consisted of gears and pulleys, the angular velocities of both the helix and brush could not be varied independently. But by changing pulley sizes, the ratio of speeds could be varied independently in relation to the speed of the helix.

Field tests on bell peppers. At the time the harvester was tested on bell peppers, the power unit was a 2.5 horsepower gasoline engine. An engine speed of 3000 revolutions per minute was selected with the use of a tachometer.

The ratio of the speed of the helix to that of the engine was 1:20. This resulted from using a 6-inch sprocket on the output of the gear reduction box and a 4-inch sprocket on the helix drive. The ratio of the speed of the helix to that of the brush was 1:7.5. The resulting helix speed was 150 revolutions per minute and the brush speed was 1125 revolutions per minute. Eight tests were performed on eight rows of pepper with ten plants in each row. The total number of peppers on ten plants for each row was counted and recorded. The tractor was throttled to a forward speed of 38 feet per minute and the machine was run through the pepper plants operating approximately 3 inches above the ground. The number of peppers picked and the number damaged were counted and recorded. Peppers were counted as being damaged if they were visibly cracked.

No further tests were conducted with peppers since the helix did not appear to be structurally strong enough to harvest bell peppers.

Laboratory tests on snap beans. The harvester was tested on snap beans in the laboratory before it was field tested. The ratio of brush speed to helix speed was to be held constant, and the effects of varying Vm and Vz were to be determined.

A device as shown in Figure 8, was constructed for simulating forward speed of the harvester. Bean plants were brought from the field and mounted between 1 x 6 inch wooden boards. The boards were lined with 1/8 inch thick fabric to reduce injury to the plants' stems. Six plants were mounted between the boards on 2 inch centers and the boards were bolted together with the plants in the growing position. The harvester was hitched to the tractor and stationed at the desired height above the boards. The boards were connected to a cable and winched through guides under the harvester allowing the plants to pass through the machine. The winch was powered with an electric motor and with the use of different size pulleys and a rheostat, the winching speed (i.e. the simulated forward speed of the harvester) could be varied.

The experimental design chosen was a randomized complete block with a factorial arrangement of treatments. There were two factors which were the simulated forward speed of the machine (Vm) and the z-component of velocity of the helix (Vz). The ratio of the speed of the helix to that of the brush was held constant at 1:4.50. The simulated forward speed was at four levels and the z-component of velocity of the helix was at three levels. Using all combinations of Vm and Vz there were twelve treatments. Tests for each treatment

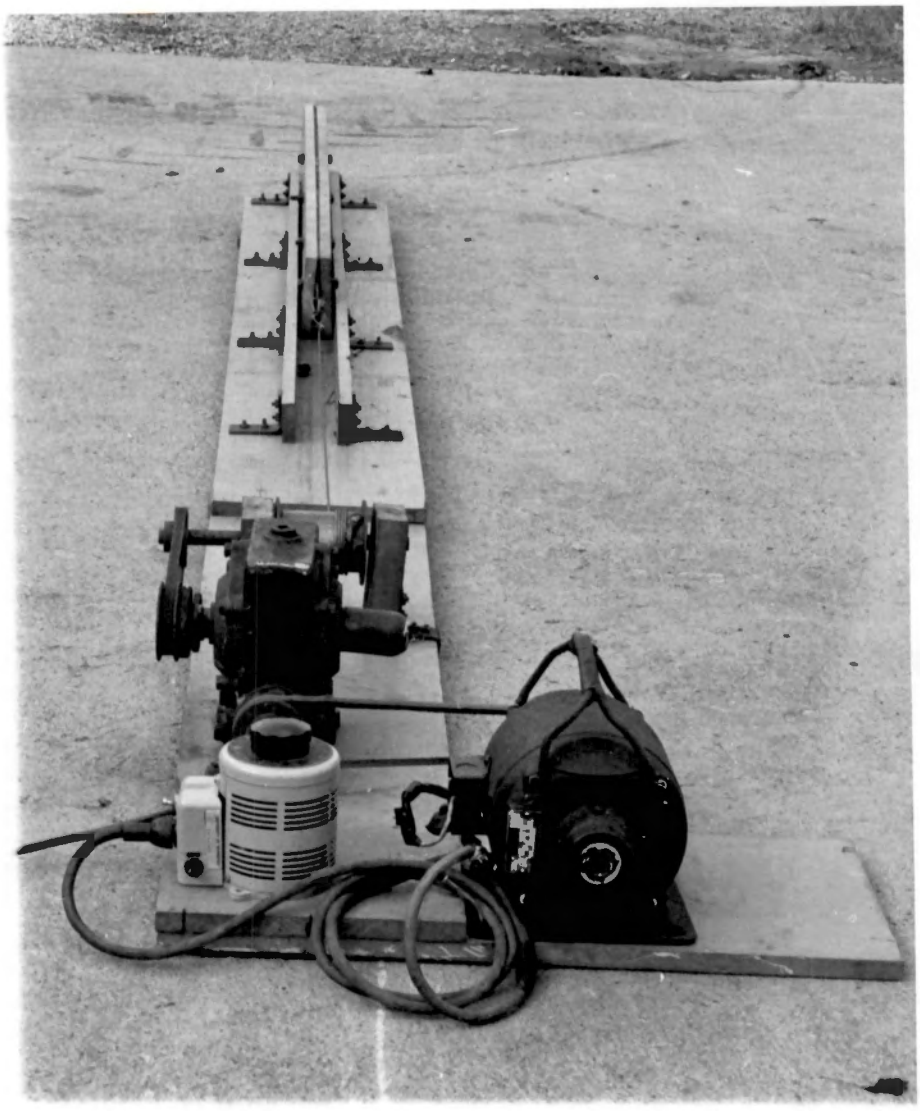


FIGURE 8. Plant holder and winch for simulating forward speed of the harvester in the laboratory.

were replicated three times. Conditions for the laboratory tests are shown in Table II.

The ratio of the speed of the helix to that of the engine was 1:12. This resulted from using a 10-inch sprocket on the output of the gear reduction box instead of the 6-inch sprocket as used in the tests on pepper. This change was made since calculations showed that the ratio needed to be decreased in order to be able to obtain a range of Vz which would allow test conditions with $Vz < Vm$, $Vz \approx Vm$, and $Vz > Vm$. Also the power unit was changed from a 2.5 horsepower to a 6 horsepower engine since stalling occurred frequently in harvesting peppers.

Three engine speeds of 2200, 2800, and 3400 revolutions per minute were selected with the use of a tachometer. The resulting helix speeds were 183.33, 233.33, and 283.33 revolutions per minute which gave velocities in the z direction of the helix (parallel to the centerline) of 30.55, 38.88, and 47.22 feet per minute. Four simulated forward velocities of the machine of 30, 33, 40, and 47 feet per minute were selected with the aid of the rheostat and different size pulleys.

Preliminary investigations before any date was taken seemed to indicate the rear of the machine should be elevated. This was accomplished by adjusting the top link of the three-point-hitch. The link was shortened so that the rear of the

TABLE II

CONDITIONS FOR LABORATORY TESTS

Treatment	Simulated velocity of machine Vm (ft/min)	Helix speed H(rpm)	Helix Z-component of velocity Vz (ft/min)	Vz/Vm	Brush speed (rpm)	Ratio (Brush to helix speed) B
Vm_1Vz_1	30	183.33	30.55	1.0183	824.85	4.5
Vm_1Vz_2	30	233.33	38.88	1.296	1049.85	4.5
Vm_1Vz_3	30	283.33	47.22	1.574	1274.85	4.5
Vm_2Vz_1	33	183.33	30.55	.9257	824.85	4.5
Vm_2Vz_2	33	233.33	38.88	1.1781	1049.85	4.5
Vm_2Vz_3	33	283.33	47.22	1.4309	1274.85	4.5
Vm_3Vz_1	40	183.33	30.55	.7637	824.85	4.5
Vm_3Vz_2	40	233.33	38.88	.9720	1049.85	4.5
Vm_3Vz_3	40	283.33	47.22	1.1805	1274.85	4.5
Vm_4Vz_1	49	183.33	30.55	.6234	824.85	4.5
Vm_4Vz_2	49	233.33	38.88	.7934	1049.85	4.5
Vm_4Vz_3	49	283.33	47.22	.9636	1274.85	4.5

machine was 7 inches above and the forward end of the helix was 2 inches above the edges of the boards. This was done to facilitate the plants in exiting the machine.

For each test, the total number of beans was counted on the six plants, they were winched through the machine, and the number of beans left on the plants, the number of beans unbroken, and the number of plants broken off at the point where they were clamped between the boards was recorded. Beans were not considered picked if there was a cluster of two or more and only those beans which were completely intact were considered unbroken. Figure 9 shows six plants after having been harvested by the machine.

Field tests on snap beans. In conducting field tests on snap beans, the forward velocity of the machine was held constant and the effects of varying the angular velocity of the helix and the ratio of the speed of the helix to that of the brush were to be determined.

The experimental design selected for field tests was a randomized complete block design with a factorial arrangement of treatments. There were two factors which were the speed of the helix (H) at three levels and the ratio of the speed of the brush to that of the helix (B) at three levels. Using all combinations of H and B resulted in nine treatments and each was replicated four times. The forward velocity of



FIGURE 9. Plants after having been harvested by machine in the laboratory.

the machine was selected as 33 feet per minute from results obtained in laboratory tests and was held constant by throttling the tractor to that speed.

The three helix speeds used were the same as those used in the laboratory tests. They were 183.33, 233.33, and 283.33 revolutions per minute and were obtained by selecting engine speeds of 2200, 2800, and 3400 revolutions per minute with the use of a tachometer. The three ratios of helix speed to brush speed used were 1:3.75, 1:4.50, and 1:5.625. They were obtained by changing the pulley size on the conical drive pulley which powered the brush. Tests conditions are shown in Table III.

Snap beans were planted in four blocks with each block consisting of ten rows of beans 30 feet long. The rows were randomized in each block. To determine the total number of beans in a row, four rows, one from each block, were chosen randomly and hand picked. The number of beans picked from each row and the number of plants in each row were counted and recorded. Using this data, a value for the average number of beans per plant of 9.87 was determined. The total number of beans in a row harvested by the machine was determined by counting the number of plants in the row and multiplying by the average number of beans per plant. The results were rounded off to the nearest whole number.

TABLE III

CONDITIONS FOR FIELD TESTS

Treatment	Helix speed H(rpm)	Ratio (Brush to helix speed) B	Brush speed (rpm)	Velocity of machine Vm (ft/min)	Helix Z-component of velocity (ft/min)
H_1B_1	183.33	3.75	687.375	33	30.55
H_1B_2	183.33	4.50	824.85	33	30.55
H_1B_3	183.33	5.625	1031.0625	33	30.55
H_2B_1	233.33	3.75	874.875	33	38.88
H_2B_2	233.33	4.50	1049.85	33	38.88
H_2B_3	233.33	5.625	1312.3125	33	38.88
H_3B_1	283.33	3.75	1062.375	33	47.22
H_3B_2	283.33	4.50	1274.85	33	47.22
H_3B_3	283.33	5.625	1593.5625	33	47.22

The harvester was tested for the nine combinations of helix speed and ratios of helix speed to brush speed. The number of beans left on the plants and the number of plants pulled out of the ground or broken off at the base of the plant were recorded. Beans in clusters of two or more were not counted as having been picked. No data was taken on the number of beans damaged since it appeared damage was extensive as in the laboratory tests and since each replication consisted of a row 30 feet long. Figures 10 and 11 show the harvester in the field and a row of beans which has been harvested by it.



FIGURE 10. Machine harvesting snap beans under field conditions.



FIGURE 11. Row of snap beans after having been harvested by the machine.

CHAPTER IV

RESULTS AND DISCUSSION

Tests were conducted on bell peppers and snap beans to evaluate the harvesting principle under consideration in this study. Tests were limited primarily to snap beans since the machine was designed primarily for harvesting snap beans. Too, tests with bell peppers indicated the machine was not structurally strong enough to withstand forces encountered with pepper plants.

I. FIELD TESTS ON BELL PEPPERS

The results showing the number and percent of peppers picked and the number and percent of peppers picked that were damaged are shown in Table IV. Only one set of conditions was tested with peppers, but eight trials were conducted under these conditions. The percent picked ranged from 45.31 to 89.41 with the mean being 70.78. The percent of peppers picked which were damaged ranged from 13.79 to 43.42 percent with the mean being 33.58. The means are the averages of eight trials and were calculated as weighted means since the total number of peppers to be picked for each trial was not the same. It was observed that in the first trial where only 45.31 percent was picked, the machine was off the row near the end of the test and missed approximately one third of it.

TABLE IV

HARVESTER'S EFFICIENCY AND DAMAGE TO PEPPERS

Trial	Number peppers on plants	Number picked	Number damaged	Percent picked	Percent picked damaged
1	64	29	4	45.31	13.79
2	51	34	7	66.66	20.58
3	68	58	17	85.29	29.31
4	66	56	23	84.84	41.07
5	71	51	18	71.83	35.20
6	68	36	12	52.94	33.33
7	85	76	33	89.41	43.42
8	78	50	17	64.10	34.00
		Weighted means		70.78	33.58

Picked peppers exited the machine from the front as well as from the rear with the majority coming out the front. Since the machine was operated near the ground level, some of the peppers which were picked and fell directly under the machine were mashed by it as it traveled over them. Also, the stage of maturity of the peppers probably resulted in increased damage since they were so ripe the ends were soft.

Clogging was a problem even though some plants were ridden over and did not totally enter the machine. In all trials, the plants were either pulled out of the ground, completely stripped of foliage, or broken. Each time, except once, when the machine clogged, the helix was compressed inside the housing; only once was it extended.

II. LABORATORY TESTS ON SNAP BEANS

In conducting laboratory tests on snap beans, two variables were considered. They were the forward speed of the machine (Vm) which was simulated in the laboratory and the speed of the helix which resulted in a z-component of velocity (Vz). A third variable, the ratio of the speed of the helix to that of the brush (B) was held constant. The results showing the percent of beans picked, the percent of beans picked undamaged, and the percent of plants broken off at the base of the stem are shown in Table V. The means shown for the three replications are weighted means since the

TABLE V

HARVESTER'S EFFICIENCY AND DAMAGE TO SNAP BEANS DURING LABORATORY TESTS

Treatment	Replication	Number beans per 6 plants	Number beans picked	Number beans unbroken	Number plants broken	Percent beans picked	Percent beans unbroken	Percent plants broken
Vm_1Vz_1	1	47	33	20	5	70.21	60.60	83.33
	2	50	42	12	4	84.00	28.57	66.67
	3	37	29	9	5	78.37	31.03	83.33
					Means	77.61	39.42	77.77
Vm_1Vz_2	1	30	19	6	3	63.33	31.57	50.00
	2	33	25	7	2	75.75	28.00	33.33
	3	33	25	9	3	75.75	36.00	50.00
					Means	71.87	31.88	44.44
Vm_1Vz_3	1	37	35	11	4	94.59	31.42	66.67
	2	46	41	11	3	89.13	26.82	50.00
	3	37	33	10	2	89.18	30.30	33.33
					Means	90.83	29.35	50.00
Vm_2Vz_1	1	37	34	10	3	91.89	29.41	50.00
	2	39	29	9	4	74.35	31.03	66.67
	3	40	32	12	4	80.00	37.50	66.67
					Means	81.89	32.63	61.11
Vm_2Vz_2	1	43	25	11	0	58.13	44.00	0.00
	2	33	25	8	1	75.75	32.00	16.67
	3	35	24	7	0	68.57	29.16	0.00
					Means	66.66	35.13	5.55

TABLE V (continued)

Treatment	Replication	Number beans per 6 plants	Number beans picked	Number beans unbroken	Number plants broken	Percent beans picked	Percent beans unbroken	Percent beans broken
Vm_2Vz_3	1	31	31	2	4	100.00	6.45	66.67
	2	39	38	10	3	97.43	26.31	50.00
	3	41	39	9	3	95.12	23.07	50.00
					Means	97.29	19.44	55.55
Vm_3Vz_1	1	41	30	16	4	73.17	53.33	66.67
	2	37	30	8	4	81.08	26.66	66.67
	3	57	42	10	4	73.68	23.80	66.67
					Means	75.55	33.33	66.67
Vm_3Vz_2	1	23	9	4	6	39.13	44.44	100.00
	2	31	19	5	4	61.29	26.31	66.67
	3	30	15	9	2	50.00	60.00	33.33
					Means	51.19	41.86	66.67
Vm_3Vz_3	1	51	43	8	4	84.31	18.60	66.67
	2	54	43	9	2	79.62	20.93	33.33
	3	38	29	8	0	76.31	27.58	0.00
					Means	80.41	20.49	33.33
Vm_4Vz_1	1	49	24	8	5	48.97	33.33	83.33
	2	47	22	5	1	46.80	22.72	16.67
	3	41	19	6	1	46.34	31.57	16.67
					Means	47.44	29.23	38.88
Vm_4Vz_2	1	33	7	6	1	21.21	85.71	16.67
	2	41	15	6	0	36.58	40.00	0.00
	3	31	6	1	0	19.35	16.66	0.00
					Means	26.66	46.42	5.55
Vm_4Vz_3	1	48	44	16	5	91.66	36.36	83.33
	2	54	39	9	5	72.22	23.07	83.33
	3	52	39	12	5	75.00	30.76	83.33
					Means	79.22	30.32	83.33

six plants used for each replication did not have the same total number of beans on them.

An analysis of variance test on the percent of beans picked, Table XI, Appendix, showed there was a significant difference at the 1 percent level of probability among treatments and no significant difference among replications. Furthermore, the main effects of Vm and Vz were significant at the 1 percent level of probability as well as the interaction Vm x Vz. That is the responses due to Vm varied with the levels of Vz significantly. Figure 12 shows the percent of beans picked as a function of Vm for the three levels of Vz. At each point, the percent beans picked is a weighted average of three replications. The percent of beans picked was greatest for each level of Vz at the lowest levels of Vm, specifically at Vm = 30 and Vm = 33 feet per minute. The best picking efficiency for all levels of Vm was obtained for Vz = 47.22 feet per minute. The poorest efficiency was obtained not for the lowest level of Vz but for the middle value or Vz = 38.88 feet per minute.

A multiple linear regression analysis was run assuming percent beans picked as a function of forward velocity of the machine (Vm) and the z-component of velocity of the helix (Vz). The equation as given by Snedecor (32) was in the form

$$\hat{Y} = \bar{Y} + b_1 (X_1 - \bar{X}_1) + b_2 (X_2 - \bar{X}_2)$$

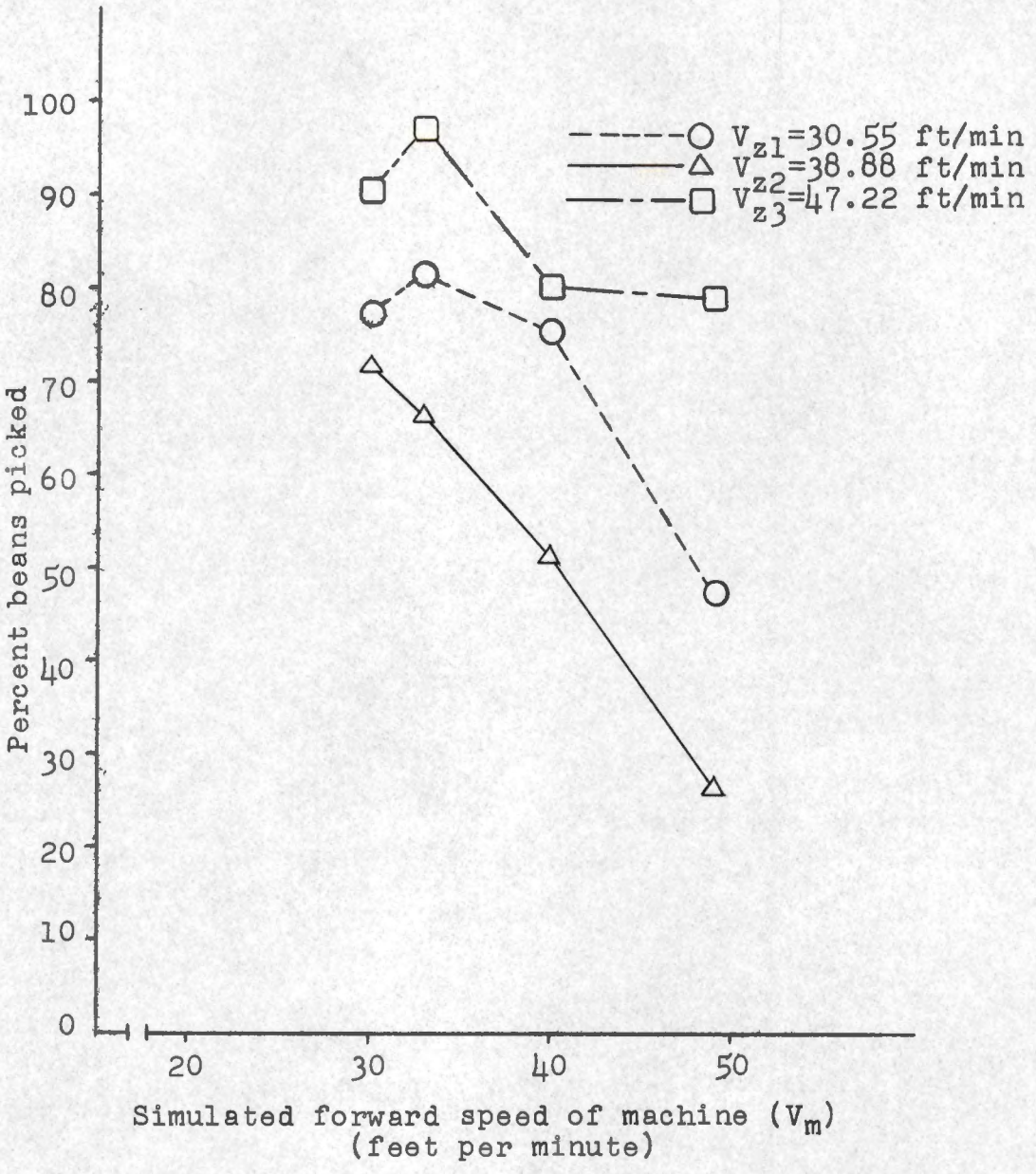


FIGURE 12. Effect of forward speed of harvester on percent of beans picked in the laboratory at three levels of Vz (z-component of velocity of helix).

where $\hat{Y}$ is the predicted value of the dependent variable (Y), $\bar{Y}$ is the mean of the dependent variable, X_1 is the first independent variable, $\bar{X}_1$ is the mean of the first independent variable, X_2 is the second independent variable, $\bar{X}_2$ is the mean of the second independent variable, b_1 is the regression of Y on X_1 independent of X_2 , and b_2 is the regression of Y on X_2 independent of X_1.

The data for percent beans picked in the laboratory (Y) resulted in the regression equation

$$\hat{Y} = 94.51 - 1.637Vm + .978Vz$$

for the ranges of Vz and Vm tested. Tests of significance showed that $b_1 = -1.637$ was significant at the 1 percent level of probability and $b_2 = .978$ was not significant at either the 1 or 5 percent level of probability. However, the total regression due to the effects of both Vm and Vz on Y was found to be significant at the 1 percent level of probability. A confidence interval for the mean percent of beans picked ($\bar{Y}$) was found to be $\bar{Y} \pm 7.98 = 70.55 \pm 7.98 =$ 62.57 to 78.53.

Correlation coefficients were determined for the effect of Vm on Y independent of Vz (r_{y1}), the effect of Vz on Y independent of Vm (r_{y2}), the effect of Vm on Y with Vz constant ($r_{y1.2}$), the effect of Vz on Y with Vm held constant

($r_{y2.1}$), and the combined effect of Vz and Vm on Y with neither Vz nor Vm independent of the other ($R_{y.12}$). The coefficients and their values along with these values squared are shown in Table VI. The correlation coefficient squared, termed the coefficient of determination, is equal to the proportion of the total variability of the dependent variable that may be ascribed to the effect of the independent variable. The coefficient of determination for the combined effects of Vz and Vm on Y is $R^2_{y.12} = .5171$ or 51.71 percent of the variation in Y can be attributed to the combined effects of Vz and Vm.

The means and separation of means by the Duncan's Multiple Range Test are given in Table VII. The results indicate the best picking efficiency was obtained for higher values of Vz/Vm. A regression analysis was conducted with the percent beans picked being the dependent variable (Y) and the ratio of Vz to Vm as the independent variable (Vz/Vm). An equation for linear regression of the form as given by Snedecor (32)

$$\hat{Y} = \bar{Y} + b\,(X - \bar{X})$$

was obtained where $\hat{Y}$ is the predicted value of the dependent variable (Y), X is the independent variable, $\bar{X}$ is the mean of the independent variable, and b is the regression of Y on X. The resulting equation was

TABLE VI

CORRELATION COEFFICIENTS AND COEFFICIENTS OF DETERMINATION FOR PERCENT OF BEANS PICKED AND PERCENT OF PLANTS BROKEN IN LABORATORY TESTS

Dependent variable	Correlation coefficient	Coefficient of determination
Percent of beans picked	$r_{y1} = -.6285$	$r^2_{y1} = .3950$
	$r_{y2} = .3495$	$r^2_{y2} = .1221$
	$r_{y1 \cdot 2} = -.6708$	$r^2_{y1 \cdot 2} = .4499$
	$r_{y2 \cdot 1} = .4493$	$r^2_{y2 \cdot 1} = .2018$
	$R_{y \cdot 12} = .791$	$R^2_{y \cdot 12} = .5171$
Percent of plants broken	$r_{y1} = -.1183$	$r^2_{y1} = .0139$
	$r_{y2} = -.0938$	$r^2_{y2} = .0087$
	$r_{y1 \cdot 2} = -.1188$	$r^2_{y1 \cdot 2} = .0141$
	$r_{y2 \cdot 1} = -.094$	$r^2_{y2 \cdot 1} = .0088$
	$R_{y \cdot 12} = .1506$	$R^2_{y \cdot 12} = .0227$

TABLE VII

MEAN PERCENT BEANS PICKED, MEAN PERCENT BEANS PICKED UNBROKEN, AND MEAN PERCENT PLANTS BROKEN FOR LABORATORY TESTS

Treatment	Means*		
	Percent beans picked	Percent beans picked unbroken	Percent plants broken
Vm_1Vz_1	77.61 b-d	39.42 a	77.77 a-b
Vm_1Vz_2	71.87 c-d	31.88 a	44.44 c-d
Vm_1Vz_3	90.83 a-b	29.35 a	50.00 b-d
Vm_2Vz_1	81.89 b-c	32.63 a	61.11 a-d
Vm_2Vz_2	66.66 d	35.13 a	5.55 e
Vm_2Vz_3	97.29 a	19.44 a	55.55 a-d
Vm_3Vz_1	75.55 c-d	33.33 a	66.67 a-c
Vm_3Vz_2	51.19 e	41.86 a	66.67 a-c
Vm_3Vz_3	80.41 b-d	20.49 a	33.33 d-e
Vm_4Vz_1	47.44 e	29.23 a	38.88 c-d
Vm_4Vz_2	26.66 f	46.42 a	5.55 e
Vm_4Vz_3	79.22 b-d	30.32 a	83.33 a
$\bar{Y}$:	70.55	32.46	49.07

* - Means followed by same letter are not significantly different at the 5 percent level of probability.

$$\hat{Y} = 21.01 + 46.74\ X$$

and Figure 13 shows percent of beans picked as a function of Vz/Vm with the predicted values as found from the regression equation depicted by the regression line. The confidence interval for the mean ($\overline{Y}$) was $\overline{Y} \pm 10.08 = 70.55 \pm 10.08 = 60.47$ to 80.63. The confidence interval for the regression coefficient was $b \pm 37.38 = 46.74 \pm 37.38 = 9.36$ to 84.12. Calculating a correlation coefficient resulted in $r = .6613$ which resulted in a coefficient of determination $r^2 = 0.4373$. That is 43.73 percent of the variation in the percent of beans picked could be attributed to the change in Vz/Vm. This indicated Vz/Vm affected the percent of beans picked and the positive regression coefficient with positive limits for its confidence interval indicated picking efficiency increased as Vz/Vm increased for the conditions tested. However, the value of the coefficient of determination and the confidence interval of the regression coefficient indicated other factors affected picking efficiency.

A nonlinear regression analysis giving an equation of the form

$$\hat{Y} = \overline{Y} + b\ (X - \overline{X}) + c\ (X^2 - \overline{X}^2)$$

resulted in the equation

$$\hat{Y} = 20.47 + 47.87X - .5835X^2.$$

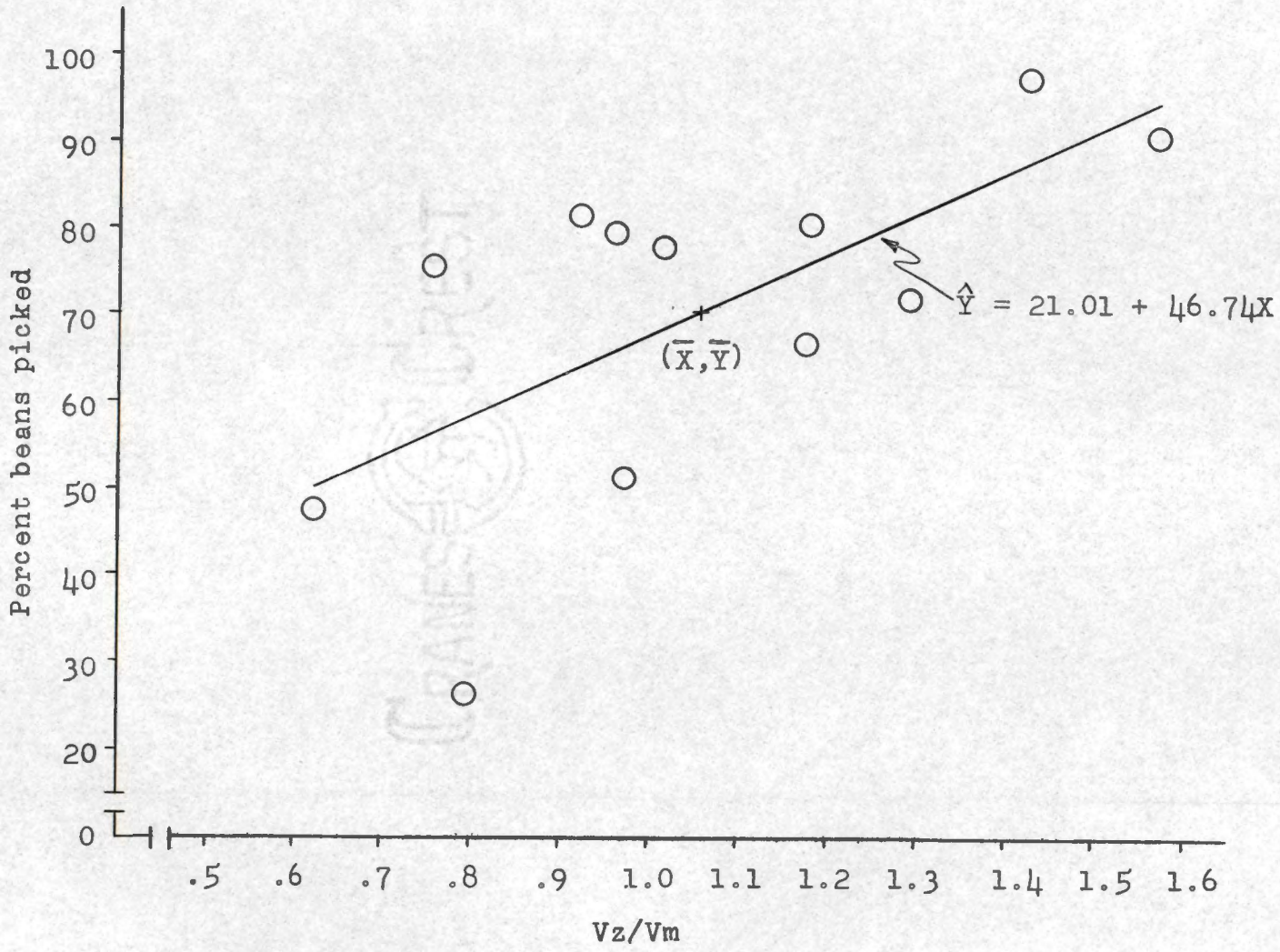


FIGURE 13. Percent beans picked as a function of the ratio of the z-component of velocity of helix (Vz) to the velocity of machine (Vm) in the laboratory.

Comparing this equation with the equation for linear regression showed there was no significant difference between the two at the 5 percent level of probability.

An analysis of variance of the percent of plants broken, Table XII, Appendix, showed there was a significant difference among treatments at the 1 percent level of probability and a significant difference between replications at the 5 percent level of probability. The main effect of Vm caused no significant difference, but the main effect of Vz and the interaction Vm x Vz resulted in significant difference at the 1 percent level of probability. Figure 14 shows percent of plants broken as a function of Vm. At each point, the percent plants broken is an average of three replications. No pattern is evident from the plotted data except to possibly infer that the lowest level of Vz resulted in the most plants broken for each level of Vm. A Duncan's Multiple Range Test to separate the means, Table VII, page 80, shows that the least amount of plants were broken for the treatments Vm_4Vz_2 and Vm_2 Vz_2. Studying the data further and remembering that Vm caused no significant difference from the analysis of variance, then the results indicate that Vz_2 and Vz_3 in general resulted in the least amount of plants broken. Comparing this with the percent of beans picked suggests that the best picking efficiency

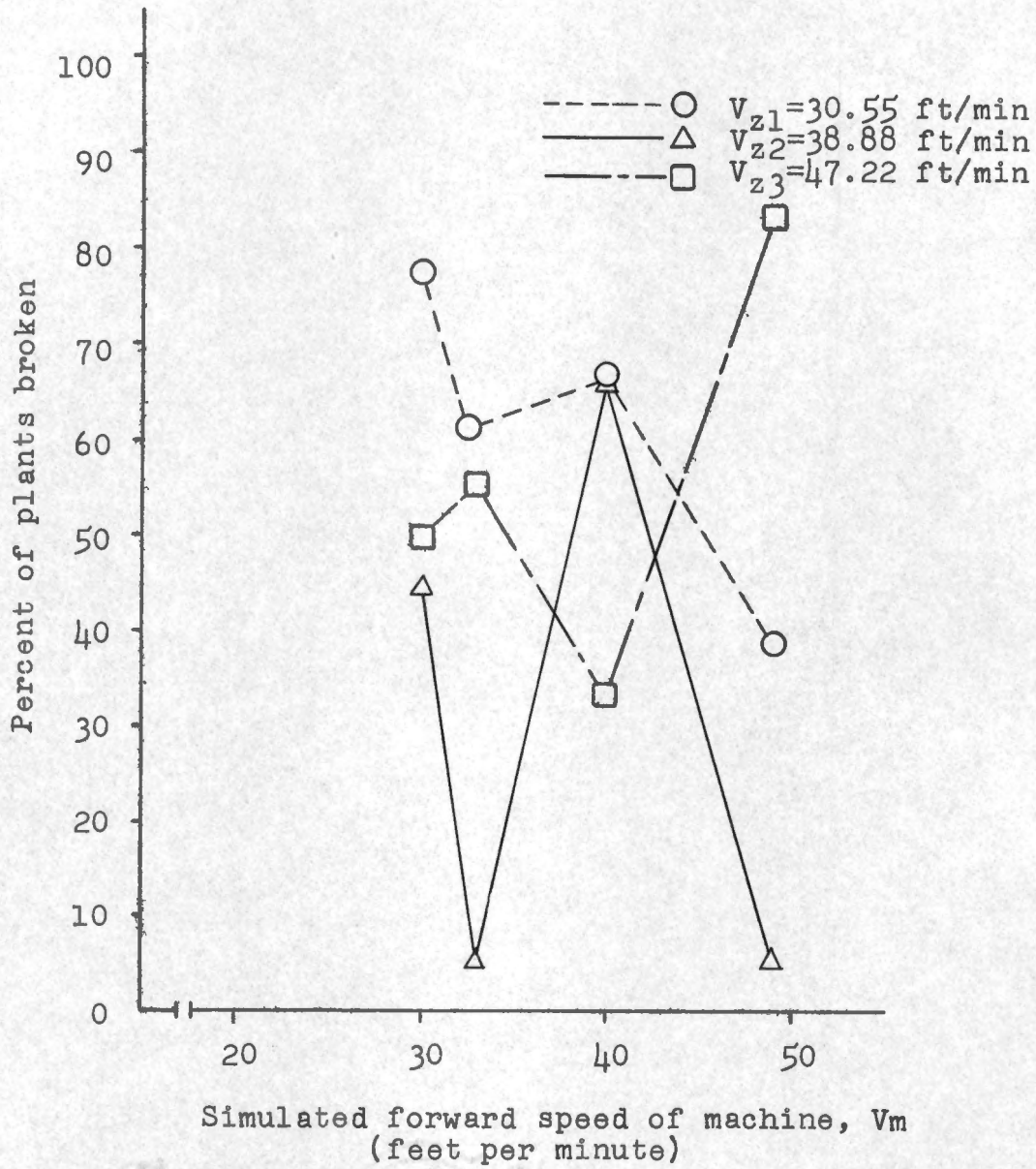


FIGURE 14. Effect of forward speed of harvester on percent of plants broken in the laboratory at three levels of Vz (z-component of velocity of helix).

occurred at the lowest levels of Vz and the least amount of plants were broken at the highest levels of Vz.

A multiple linear regression analysis was run assuming percent plants broken as a function of Vm and Vz. The resulting equation was

$$\hat{Y} = 76.77 - .3894Vm - .3319Vz$$

and was of the same form as that obtained for percent of beans picked, page 75. The regression coefficients, $b_1 = -.3894$ and $b_2 = -.3319$, were not significantly greater than zero. Neither was the total regression due to the combined effects of Vm and Vz. The confidence interval for the mean percent plants broken was $\bar{Y} \pm 16.73 = 49.07 \pm 16.73 = 32.34$ to 65.80. The regression coefficients and coefficients of determination for the regression of Y on Vm (r_{y1}), Y on Vz (r_{y2}), y on Vm with Vz constant ($r_{y1.2}$), Y on Vz with Vm constant ($r_{y2.1}$), and Y on Vm and Vz ($R_{y.12}$) are shown in Table VII, page 80. The coefficient of determination due to the combined effects of Vm and Vz was $R^2_{y.12} = .0227$. That is 2.27 percent of the variation in the percent of plants broken can be attributed to Vz and Vm.

A linear regression analysis of the percent of plants broken for one independent variable (Vz/Vm) yielded a regression coefficient, b = -2.832 which was not significantly greater than zero at the 5 percent level of probability.

The results from these analyses indicate that the effect of Vm and Vz on the percent of plants broken is not linear. However, the negative regression coefficients for percent of plants broken and the positive regression coefficient for the similar type analysis for percent beans picked indicates that picking efficiency increased and percent of plants broken decreased as Vz/Vm increased. This would seem to verify the hypothesis that when Vz > Vm, the difference in velocities, (Vz - Vm), caused an impact force on the plant from the helix edge which forced it into the brush.

An analysis of variance of the percent of beans picked unbroken, Table XIII, Appendix, showed there was no significant difference among treatments or replications. The average percent unbroken was 32.46 percent, Table VII, page 80.

Damage to picked beans was severe and ranged from broken beans to beans that were completely smashed. It was observed that all picked beans did not exit the machine from the opening provided in the bottom rear of the machine. Many fell through the slot provided for the plants to pass through the machine. Some beans, even though they were detached, exited the machine simultaneously with the plants. Still other beans were threshed around inside the machine and came out through the slots where the rollers were

attached. This difficulty in exiting the machine probably contributed to damage.

Damage to plants was severe too even if they were not broken off at the base. Branches were broken and foliage was shredded. This suggested the brush was possibly too harsh or turning too fast. Also, possibly due to the slow forward speed of travel the beans were subjected to the action of the brush for too long a period of time. That is they remained inside the machine too long. The forward speed of travel could be increased and still retain $Vz > Vm$ by increasing the pitch of the helix.

III. FIELD TESTS ON SNAP BEANS

In conducting field tests on snap beans, two variables were considered. They were the speed of the helix (H) and the ratio of the speed of the helix to that of the brush (B). A third variable, the forward speed of the machine (Vm) was held constant at 33 feet per minute. The results showing the percent of beans picked and the percent of plants pulled out of the ground or broken off at the ground level are shown in Table VIII. The means shown for the four replications are weighted means since the total number of beans on the plants in a row used for each replication was not the same.

TABLE VIII

HARVESTER'S EFFICIENCY AND MAGNITUDE OF PLANT DAMAGE DURING FIELD TESTS ON SNAP BEANS

Treatment	Replication	Number plants	Plants pulled	Total number beans	Number beans unpicked	Percent plants pulled	Percent beans picked
H_1B_1	1	105	77	1036	131	73.33	87.36
	2	123	66	1214	155	53.65	87.24
	3	114	45	1125	185	39.47	83.56
	4	70	42	691	143	60.00	79.31
					Means	55.82	84.98
H_2B_1	1	101	42	997	138	41.58	86.16
	2	103	48	1016	246	46.60	75.79
	3	92	38	908	300	43.30	66.97
	4	93	32	918	140	34.40	84.75
					Means	41.13	78.54
H_3B_1	1	101	36	997	178	35.64	82.15
	2	107	25	1056	151	23.36	85.71
	3	120	26	1184	192	21.66	83.79
	4	95	10	938	151	10.52	83.91
					Means	22.93	83.91
H_1B_2	1	80	18	790	206	22.50	73.93
	2	111	27	1096	102	24.32	90.70
	3	105	43	1036	90	40.95	91.32
	4	91	39	898	183	42.85	79.63
					Means	32.81	84.80

TABLE VIII (continued)

Treatment	Replication	Number plants	Plants pulled	Total number beans	Number beans unpicked	Percent plants pulled	Percent beans picked
H_2B_2	1	66	13	651	102	19.69	84.34
	2	113	50	1115	175	44.24	84.31
	3	107	46	1056	214	42.99	79.74
	4	111	40	1096	117	36.03	89.33
					Means	37.53	84.49
H_3B_2	1	118	28	1165	40	23.72	96.57
	2	121	39	1194	263	32.23	77.98
	3	82	17	809	144	20.73	82.21
	4	72	21	711	68	29.16	90.44
					Means	26.71	86.73
H_1B_3	1	109	14	1076	301	12.84	72.03
	2	111	30	1096	298	27.02	72.82
	3	112	17	1105	260	15.17	76.48
	4	139	7	1372	372	5.03	72.89
					Means	14.43	73.53
H_2B_3	1	79	15	780	189	18.98	75.77
	2	74	10	730	164	13.51	77.54
	3	102	24	1007	328	23.52	67.43
	4	99	16	977	230	16.16	76.46
					Means	18.36	73.93
H_3B_3	1	141	7	1392	346	4.96	75.15
	2	99	13	977	173	13.13	82.30
	3	89	5	878	233	5.61	73.47
	4	70	13	691	191	18.57	72.36
					Means	9.52	76.06

An analysis of variance on the percent of beans picked, Table XIV, Appendix, showed there was a significant difference among treatments at the 5 percent level of probability and no significant difference among replications. The main effect of B caused a significant difference at the 1 percent level of probability but the main effect of H and the interaction H x B caused no significant difference. Figure 15 shows the percent of beans picked as a function of B for the three levels of H. At each point, the percent of beans picked is a weighted mean of four replications. The percent of beans picked was greatest for each level of H at $B_2 = 4.5$. Although the difference was not significant, the largest level of H resulted in the greatest percent of beans picked for each level of B except at $B_1 = 3.75$. The middle level of H, not the lowest level, resulted in the least percent of beans picked for each level of B. These results agreed with those obtained in the laboratory. In the laboratory, the variable was Vz whereas the variable in the field was H but a component of Vz resulted directly from each level of H.

A multiple linear regression analysis was run assuming percent of beans picked as a function of helix speed (H) and ratio of helix speed to brush speed (B). The equation form was the same as that used for the multiple regression analysis of laboratory data, page 75. The resulting equation was

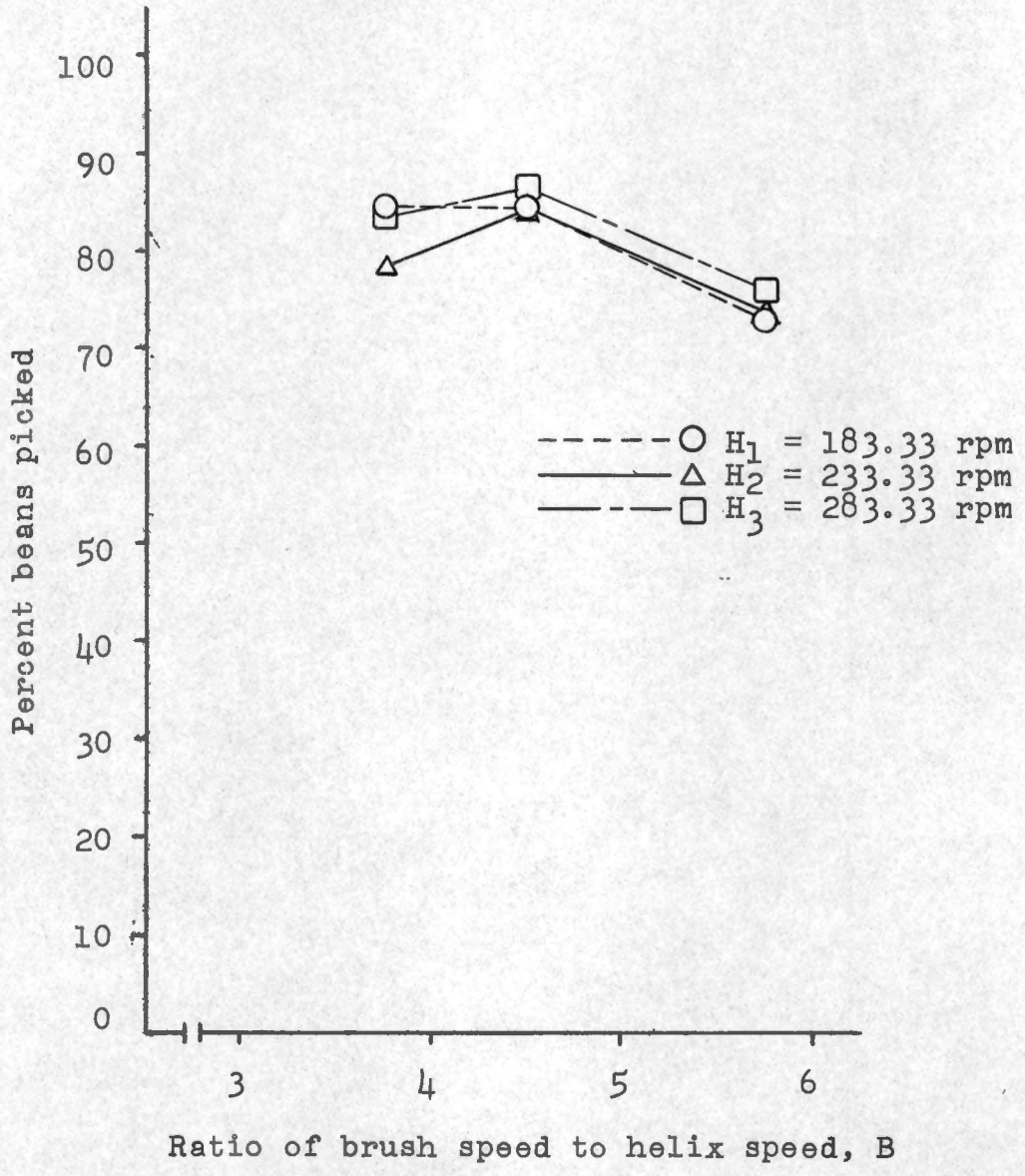


FIGURE 15. Effect of ratio of brush speed to helix speed on percent of beans picked in the field at three levels of H (speed of helix in revolutions per minute).

$$\hat{Y} = 99.65 + .0115H - 4.662B$$

for the ranges of B and H tested. Tests of significance showed that the regression coefficient $b_1 = .0115$ was not significant but $b_2 = -4.662$ was significant at the 5 percent level of probability. The total regression due to both B and H was significant at the 5 percent level of probability. The confidence interval for the mean percent of beans picked was $\bar{Y} \pm 2.54 = 80.77 \pm 2.54 = 78.23$ to 83.31.

Correlation coefficients and coefficients of determination were calculated and are shown in Table IX. The coefficient of determination for the combined effects of H and B is $R^2_{y.12} = .5396$ or 53.96 percent of the variation in the percent of beans can be attributed to the variation in H and B.

The means and separation of the means by the Duncan's Multiple Range Test are given in Table X. The results show that the best picking efficiency was achieved for $B_1 = 3.75$ and $B_2 = 4.5$ with poorest efficiency at $B_3 = 5.625$. Slightly better results were obtained with B_2 than with B_1. These results could possibly be explained in that the B_2 resulted in greater peripheral velocities of the brush than B_1 for corresponding values of H. Therefore the impact forces delivered by the brush to the beans due to differences in velocity components of the brush and helix (Vb - Vh) were

TABLE IX

CORRELATION COEFFICIENTS AND COEFFICIENTS OF DETERMINATION FOR PERCENT OF BEANS PICKED AND PERCENT OF PLANTS PULLED IN FIELD TESTS

Dependent variable	Correlation coefficient	Coefficient of determination
Percent of beans picked	$r_{y1} = .0957$	$r^2_{y1} = .0091$
	$r_{y2} = -.7284$	$r^2_{y2} = .5305$
	$r_{y1 \cdot 2} = .1396$	$r^2_{y1 \cdot 2} = .0194$
	$r_{y2 \cdot 1} = -.7317$	$r^2_{y2 \cdot 1} = .5353$
	$R_{y \cdot 12} = .7345$	$R^2_{y \cdot 12} = .5396$
Percent of plants pulled	$r_{y1} = -.4336$	$r^2_{y1} = .1880$
	$r_{y2} = -.7848$	$r^2_{y2} = .6159$
	$r_{y1 \cdot 2} = -.6996$	$r^2_{y1 \cdot 2} = .4894$
	$r_{y2 \cdot 1} = -.8709$	$r^2_{y2 \cdot 1} = .7584$
	$R_{y \cdot 12} = .8966$	$R^2_{y \cdot 12} = .8039$

TABLE X

MEAN PERCENT BEANS PICKED AND MEAN PERCENT OF PLANTS PULLED FOR FIELD TESTS

Treatment	Means*	
	Percent beans picked	Percent plants pulled
H_1B_1	84.90 a-b	55.82 a
H_1B_2	84.80 a-b	32.81 b-d
H_1B_3	73.53 c	14.43 e-f
H_2B_1	78.54 a-c	41.13 b
H_2B_2	84.49 a-b	37.53 b-c
H_2B_3	73.93 c	18.36 d-f
H_3B_1	83.91 a-b	22.93 c-f
H_3B_2	86.73 a	26.71 b-e
H_3B_3	76.06 b-c	9.52 f
$\bar{Y}$:	80.77	28.84

* - Means followed by same letter are not significantly different at the 5 percent level of probability.

greater for B_2 than for B_1. It should follow then that B_3 would result in the greatest picking efficiency instead of the lowest. It is possible though that for B_3, the brush was turning too fast and acted like a rotating cylinder so that the brush fingers could not penetrate the foliage properly.

An analysis of variance of the percent of plants pulled out of the ground or broken off at ground level, Table XV, Appendix, showed there was a significant difference among treatments at the 1 percent level of probability and no significant difference among treatments. The main effects of B and H were both significant at the 1 percent level of probability but the interaction H x B caused no significant difference. Figure 16 shows percent of plants pulled as a function of H. At each point, the percent of plants pulled is a weighted mean of four replications. The lowest percent of plants pulled occurred for B3 = 5.625 at each level of H and except for one point, treatment H_1B_1. The greatest percent of plants pulled occurred for B_2 = 4.5 for each level of H. The least percent of plants was pulled for H_3 = 283.33 at all levels of B_1. A Duncan's Multiple Range Test to separate the means as shown in Table X, verified these conclusions.

A multiple linear regression was run assuming percent of plants pulled as a function of helix speed (H) and the

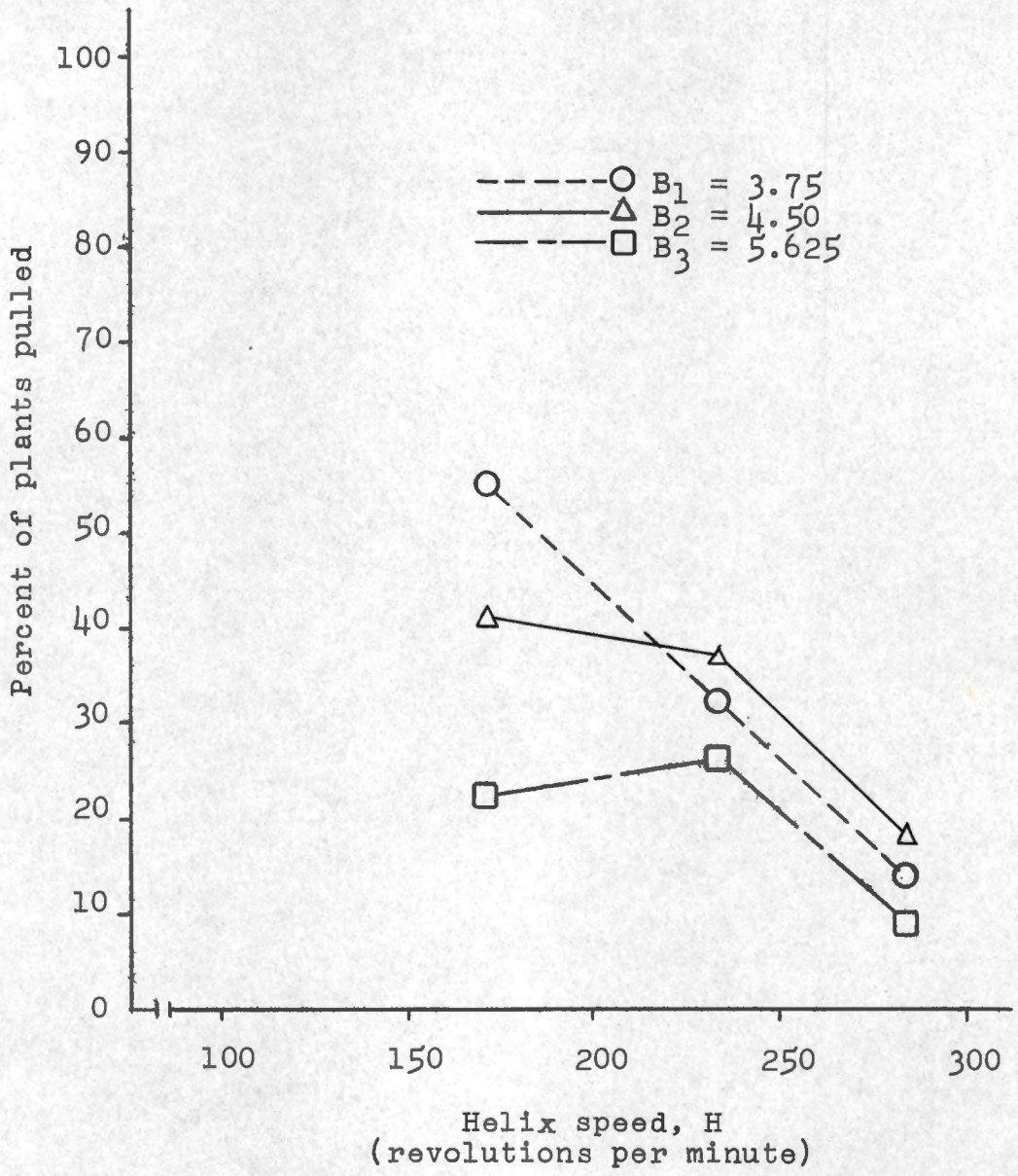


FIGURE 16. Effect of helix speed on percent of plants pulled from the ground or broken off at the ground in the field at three levels of B (ratio of speed of brush to that of the helix).

ratio of the helix speed to that of the brush speed (B). The equation form was the same as that used for the multiple regression analysis of laboratory data, page 75. The dependent variable was percent of plants pulled. The first independent variable was H and the second independent variable was B. The resulting equation was

$$\hat{Y} = 127.87 - .146H - 14.031B$$

for the range of B and H tested. Tests of significance showed the regression coefficient $b_1 = -.146$ was significant at the 5 percent level of probability and $b_2 = -14.031$ was significant at the 1 percent level of probability. The total regression due to both B and H was significant at the 1 percent level of probability. The confidence interval for the mean percent of plants pulled was $Y \pm 4.43 = 28.84 \pm 4.43 = 24.41$ to 33.27.

Correlation coefficients and coefficients of determination were calculated and are shown in Table IX, page 93. The coefficient of determination for the combined effects of H and B is $R^2_{y.12} = .8039$. That is 80.39 percent of the variation in the percent of beans picked can be attributed to the variation in H and B.

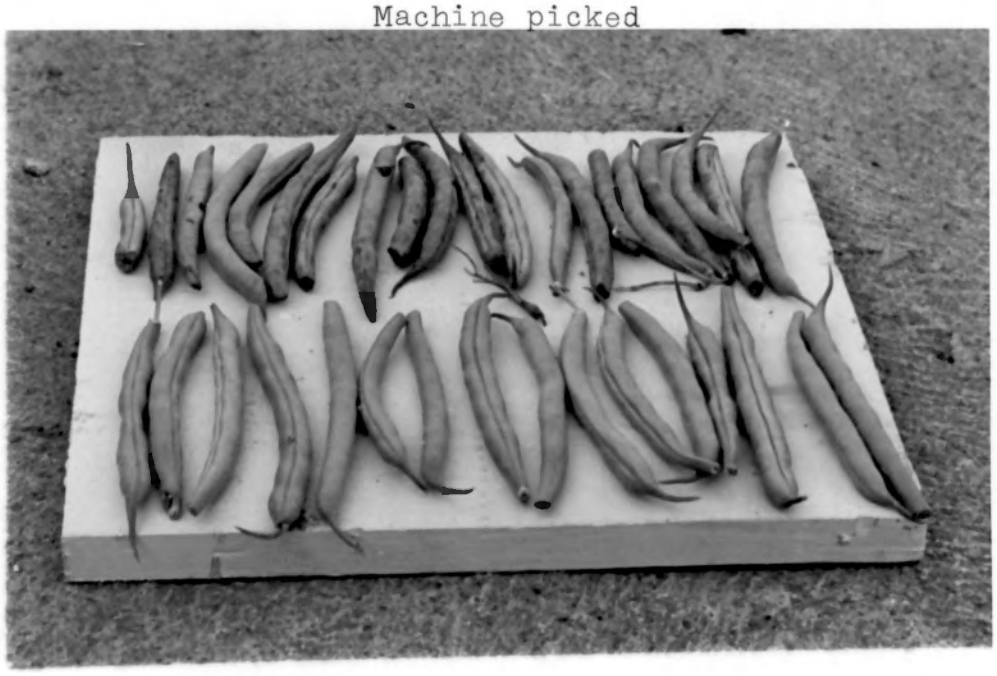
The analyses indicate that greater picking efficiency resulted in more plants being pulled. This would seem to

reinforce the conclusion that $B_2 = 4.5$ resulted in greater impact forces from the brush both on the beans and on the plants. Furthermore, since $B_3 = 5.625$ resulted in the least amount of plants pulled, this would again indicate the brush was turning too fast for the fingers to penetrate the foliage of the plant.

It was observed that damage to beans picked in the field was extensive as was in the laboratory. Clogging occurred at least once for each replication. It appeared the bean plants were compressed too much as they passed through the harvester, especially as they exited the machine. This could possibly be eliminated by using a helix with a greater pitch. Had the helix been longer, the slot in the bottom of the machine could have been extended beyond the end of the brush. As it was, the plants were still subjected to the action of the brush as they exited the machine. This probably contributed to clogging, bean damage, and plants being pulled out of the ground. Beans missed by the harvester in the field were those low on the plant.

Figure 17 compares beans picked by the harvester and beans picked by hand. The top row was picked by the harvester and the bottom row by hand. The dark color of the beans picked by the machine resulted primarily from juices from foliage damage. Also, the beans harvested by the machine laid out in the sun about 2 hours before they were collected.

Machine picked



Hand picked

FIGURE 17. Comparison of beans picked by machine with those picked by hand.

CHAPTER V

SUMMARY AND CONCLUSIONS

Many methods of harvesting vegetables have been studied. The objective of this study was to evaluate a method of harvesting using a cylindrical helix and a brush as the harvesting mechanism. The effects of forward speed of the machine (Vm), the speed of the helix (H) and its resulting z-component of velocity (Vz), and the ratio of the speed of the helix to the speed of the brush (B) on percent of beans picked, percent of plants pulled out of the soil, and percent of beans picked damaged were studied. The harvester was constructed in the Department of Agricultural Engineering Research Shop, The University of Tennessee, Knoxville, and was tested on snap beans and bell peppers provided by The Department of Horticulture.

Field tests were conducted on bell peppers with Vm, H, and B held constant. The results of eight trials showed that an average of 70.88 percent of the peppers was picked and 33.58 percent of those picked were damaged. No further tests were conducted with bell peppers since the helix was not structurally strong enough to withstand the forces involved due to the toughness of the pepper stalks.

Laboratory tests were conducted on snap beans with Vz at three levels, Vm at four levels, and B held constant. Although B was held constant, the speed of the brush was not constant but varied proportionately as the speed of the helix was varied. An analysis of variance among treatment combinations showed there was a highly significant difference among the main effects Vm and Vz and among the interaction Vm x Vz at the 1 percent level of probability. Duncan's Multiple Range Test at the 5 percent level of probability showed significant differences in percent of beans picked among treatment combinations with the lower values of Vm in combination with the higher values of Vz giving the best picking efficiency for the values tested. A multiple regression analysis showed that 51.71 percent of the variation in percent of beans picked could be accounted for in the variation in both Vm and Vz.

A linear regression analysis with the ratio of Vz to Vm (Vz/Vm) as the independent variable showed that as Vz/Vm increased the picking efficiency increased, but only 43.73 percent of the variation in percent of beans picked could be attributed to the variation in Vz/Vm.

An analysis of variance among treatment combinations of the percent of plants broken in the laboratory showed there was significant difference among the main effect Vz and the interaction Vz x Vm at the 1 percent level of

probability, but no significant difference among Vm. Duncan's Multiple Range Test at the 5 percent level of probability showed significant differences in percent of plants broken among treatment combinations with the lower levels of Vz generally resulting in the least number of plants broken. A multiple linear regression analysis showed that only 2.27 percent of the variation in the percent of plants broken could be attributed to Vm and Vz. This result along with significant difference among replications suggests the sample size of six plants for each replication was too small.

An analysis of variance among the treatment combinations for percent of beans picked broken showed there was no significant difference among the main effects Vm and Vz or the interaction Vz x Vm. Damage was extensive with the mean for twelve treatments being 32.46 percent of the beans picked unbroken.

Field tests were conducted with H at three levels (same as those for laboratory tests), B at three levels, and Vm held constant. An analysis of variance among treatment combinations for percent of beans picked showed there was no significant difference among the main effect H or the interaction H x B but the main effect of B was highly significant at the 1 percent level of probability. Duncan's Multiple

Range Test at the 5 percent level of probability showed significant difference among treatment combinations with B = 4.5 giving the best picking efficiency. A multiple linear regression analysis showed that 53.96 percent of the variation in percent of beans picked could be attributed to the variation in H and B.

An analysis of variance among the treatment combinations for percent of plants pulled out of the ground in the field showed there was a significant difference at the 1 percent level of probability for the main effects of H and B but no significant difference due to the interaction H x B. Duncan's Multiple Range Test at the 5 percent level of probability showed significant differences among treatments in percent of plants pulled out of the ground with B = 5.625 resulting in the least percent of plants pulled. A multiple regression analysis showed that 80.39 percent of the variation in percent of plants pulled could be attributed to the variation in H and B.

No data was taken on damaged beans in field tests but from observations damage was extensive as in the laboratory.

Based upon the results obtained in the experiment, the following conclusions were made. The harvesting principle was definitely applicable as a means of picking both bell peppers and snap beans. The picking efficiencies for bell peppers approached satisfactory levels for the limited tests

conducted. Picking efficiencies for snap beans in the laboratory were excellent for certain combinations of machine variables and approached those for commercial bean harvesters in the field. Damage to plants was severe for tests on peppers as well as beans. This is more of a disadvantage for peppers than for beans since varieties of beans suitable for once-over harvesting are available. Damage to both harvested beans and peppers was well below acceptable limits. Damage to peppers was not as great as that for beans.

Suggested areas for future study are:

(1) The study of a new helix design by increasing the pitch, increasing the diameter, making it structurally stronger, and increasing the length,

(2) The study of a new brush design by using different pitches and different types of fibers, and

(3) A study using either hydraulic motors or two independent power sources to independently vary the speed of the brush and helix to give an infinite number of helix speed and brush speed combinations.

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APPENDIX

TABLE XI

ANALYSIS OF VARIANCE OF PERCENTAGE OF BEANS PICKED IN LABORATORY TESTS

Source of variation	Degrees of freedom	Estimated variances	F value
Total	35		
Among treatments	11	1228.10	23.115**
Among Vm	3	1856.16	58.982**
Among Vz	2	3329.32	19.93 **
Among Vm x Vz	6	213.66	8.227**
Among replications	2	50.04	0.942 N. S.
Among treatments x replications	22	53.13	
Among Vm x Reps.	4	31.47	
Among Vz x Reps.	6	167.05	
Among Vm x Vz x Reps.	12	25.97	

**- Significant difference at the 1 percent level of probability.

N.S. - Not significant

TABLE XII

ANALYSIS OF VARIANCE OF PERCENTAGE OF PLANTS BROKEN AT THE BASE IN LABORATORY TESTS

Source of variation	Degrees of freedom	Estimated variances	F value
Total	35		
Among treatments	11	1899.47	6.653**
Among Vm	3	668.67	1.818 N.S.
Among Vz	2	3179.11	31.687**
Among Vm x Vz	6	2088.32	6.823**
Among replications	2	1396.68	4.892*
Among treatments x replications	22	285.50	
Among Vm x Reps.	4	367.81	
Among Vz x Reps.	6	100.33	
Among Vm x Vz x Reps.	12	306.07	

* - Significant difference at the 5 percent level of probability.
** - Significant difference at the 1 percent level of probability.
N.S. - Not significant

TABLE XIII

ANALYSIS OF VARIANCE OF PERCENTAGE OF BEANS PICKED UNBROKEN FOR LABORATORY TESTS

Source of variation	Degrees of freedom	Sum of squares	Estimated variances	F test
Total	35	7033.36		
Between treatments	11	2202.89	200.26	1.120 N. S.
Between replications	2	888.35	444.18	2.480 N. S.
Error	22	3942.12	179.19	

N. S. - Not significant

TABLE XIV

ANALYSIS OF VARIANCE OF PERCENTAGE OF BEANS PICKED IN THE FIELD

Source of variation	Degrees of freedom	Estimated variances	F value
Total	35		
Among treatments	8	102.96	2.970*
Among H	2	29.22	0.502 N.S.
Among B	2	353.225	32.053**
Among H x B	4	14.695	0.422 N.S.
Among replications	3	21.36	0.62 N.S.
Among treatments x replications	24	34.69	
Among H x Reps.	6	58.163	
Among B x Reps.	6	11.02	
Among H x B x Reps.	12	34.786	

* - Significant difference at the 5 percent level of probability.
** - Significant difference at the 1 percent level of probability
N. S. - Not significant

TABLE XV

ANALYSIS OF VARIANCE OF PERCENTAGE OF PLANTS PULLED FROM THE GROUND OR BROKEN OFF AT THE GROUND LEVEL IN THE FIELD

Source of variation	Degrees of freedom	Estimated variances	F value
Total	35		
Among treatments	8	838.38	9.24**
Among H	2	736.31	16.795**
Among B	2	2059.89	14.462**
Among H x B	4	278.66	3.155 N.S.
Among replications	3	17.29	0.19 N.S.
Among treatments x replications	24	90.73	
Among H x Reps.	6	43.84	
Among B x Reps.	6	142.43	
Among H x B x Reps.	12	88.33	

** - Significant difference at the 1 percent level of probability.

N.S. - Not significant

VITA

Richard C. Shadden was born December 10, 1943, in McMinn County, Tennessee, the son of H. Carl and Mary Helen Shadden. He was educated in the elementary schools of that county and graduated from Englewood High School, Englewood, Tennessee, in May, 1961. He entered the University of Tennessee in September, 1961, and received the Bachelor of Science with a major in Agricultural Engineering in August, 1966. He entered the graduate school of The University of Tennessee in September, 1966, and expects to receive the Master of Science with a major in Agricultural Engineering in June, 1969. He has been employed by the Tennessee Valley Authority as a Cooperative Student in Agricultural Engineering while an undergraduate student and as an Assistant-In Agricultural Engineering while a graduate student.

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