7-1990

Automated Harvesting of Burley Tobacco II. Evaluation of System Performance

Larry G. Wells
University of Kentucky, larry.wells@uky.edu

George B. Day V
University of Kentucky, george.day@uky.edu

Timothy D. Smith
University of Kentucky, tim.smith@uky.edu

Repository Citation

Wells, Larry G.; Day, George B. V; and Smith, Timothy D., "Automated Harvesting of Burley Tobacco II. Evaluation of System Performance" (1990). *Biosystems and Agricultural Engineering Faculty Publications*. 180.
https://uknowledge.uky.edu/bae_facpub/180

Automated Harvesting of Burley Tobacco II. Evaluation of System Performance

Notes/Citation Information
Published in *Transactions of the ASAE*, v. 33, issue 4, p. 1038-1042.

Digital Object Identifier (DOI)
https://doi.org/10.13031/2013.31435

AUTOMATED HARVESTING OF BURLEY TOBACCO
II. EVALUATION OF SYSTEM PERFORMANCE

L. G. Wells, G. B. Day, V, T. D. Smith
MEMBER ASAE ASSOC. MEMBER ASAE MEMBER ASAE

ABSTRACT

A prototype system for fully automated harvesting of burley tobacco has been developed and tested. Three years of field testing has shown that mechanical losses associated with the system were only slightly higher than via conventional methods. The system performed reliably at a sustained harvesting rate of approximately 1.4 ha/day (3.4 acre/day), while indicating that a rate of 2 ha/day (5 acre/day) should be easily achievable. The system is operated by two workers and reduces conventional labor requirement by approximately 80-85%.

INTRODUCTION

A fully automated system for harvesting stalk-cut burley tobacco has been fabricated and tested at the University of Kentucky. The system utilizes a self-propelled harvester to place mature plants into portable holders for natural air curing. The portable curing frames (2.45 m × 4.27 m) hold plants at a density of approximately 0.023 m^2, so that 42-45 frames are required/ha (17-18/acre), depending upon field plant density.

The harvester prototype performs the functions of detaching, inverting, and notching plants for placement into portable curing frames. The harvester also dispenses the portable frames while placing plants into the slotted receivers at a uniform spacing of 7.62 cm (3 in.). Further details concerning the design and fabrication of the system, as well as other attempts to mechanize the process, are given in a companion paper (Wells et al., 1990).

EXPERIMENTAL METHODS

PRELIMINARY LABORATORY APPARATUS

Development was initiated in 1981 when an experimental inclined conveyor was fabricated and tested (fig. 1). This apparatus demonstrated the feasibility of tilting or inclining plants via transfer between two perpendicular conveyor sections.

We constructed the conveyor using specially adapted #60 ASA roller chain having 2.5 cm triangular projections or teeth extending from one side of the links (top and bottom) at each pin or roller point. We situated steel guides to provide a spacing of 0.6 cm between teeth tips of opposed chains. Thus, tobacco stalks of nominal diameter (2.5 to 4.0 cm) were substantially penetrated by the teeth for positive conveyance. The three sections of the roller chain were driven by a connected mechanical chain powered by a reversible hydraulic motor of adjustable speed.

Two sections of the opposed roller chain conveyor were mounted on a steel platform which, in turn, could be inclined at various angles relative to horizontal. The continuous inner chain passed over a 33.8 cm diameter sprocket to achieve a gradual 90° change in direction. We placed separate sections of outer chain adjacent to each leg of the inner chain. A spring-loaded curve guide was positioned at the corner to facilitate transfer of plants from one section to another.

At one end of the opposed roller-chain conveyor we mounted two opposed 45.7 cm disks constructed of 20

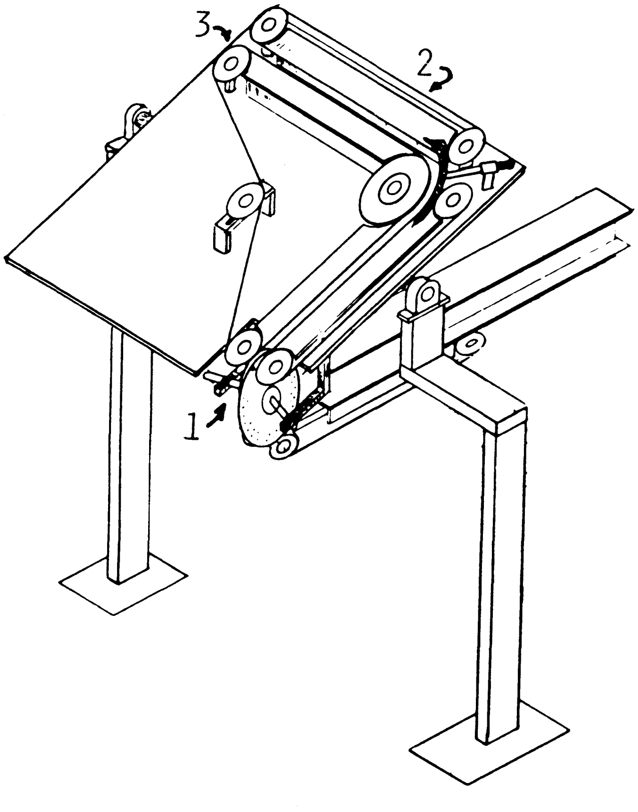

Figure 1–Experimental mechanism to convey, invert, and space plants.

Article was submitted for publication in May 1989; reviewed and approved for publication by the Power and Machinery Div. of ASAE in April 1990.

This document is published with the approval of the Director of the Agricultural Experiment Station as Paper No. 89-2-85. The investigation was conducted in connection with a project of the Kentucky Agricultural Experiment Station and was funded in part by a grant from Philip Morris, USA.

The authors are **L. G. Wells**, Professor, **G. B. Day, V**, Research Specialist, and **T. D. Smith**, Agricultural Engineer, Dept. of Agricultural Engineering, University of Kentucky, Lexington.

gauge steel (see fig. 1). The respective axes of rotation formed an angle of approximately 150° and the centers of rotation were positioned to provide approximately 90° of peripheral contact between the disks. Sharp metal spikes were fastened near the periphery of both disks. The disks were driven by a hydraulic motor of adjustable speed so that their peripheral speed was equivalent to the linear speed of the upper opposed roller chain conveyor.

We mounted these disks directly below and tangent to the opposed roller chain conveyor at one end. They were designed to grasp the portion of stalks protruding below the upper opposed roller chains and transfer the plants to a similar horizontal conveyor below, with the bases of stalks pointing upward (inverted).

An 0.8 m long, straight, horizontal section of opposed roller-chain conveyor was mounted directly below the upper conveyor (see fig. 1). The chain size, construction and teeth tip separation distance of this conveyor was identical to that of the inclined conveyor. This conveyor was driven by a separate hydraulic motor of adjustable speed.

LABORATORY TESTS

We conducted a limited series of experiments to evaluate the performance of the various components of the mechanism. We detached mature burley tobacco plants near ground level and transported them to the laboratory. The tests we conducted followed the normal or desired harvesting date, a factor which may have influenced the response of plants to mechanical handling. Approximately 400 plants were collected for the tests, with about one half of this number being utilized for preliminary adjustments of the component mechanisms.

The first series of tests were conducted to evaluate the inclined opposed roller chain pick-up conveyor. With the inversion disks removed, we inserted plants vertically into the conveyor at this point (1) (see fig. 1) such that they were conveyed upward and through the 90° turn, exiting at the end of the upper horizontal section (2). This test simulated pick up of detached plants near ground level followed by elevation and partial rotation or inversion of the plants.

Ground clearance distance, i.e., the distance between the base of a detached plant and the position at which the conveyor engaged a plant was simulated by adjusting the position of a flat plate located near the entry point of the conveyor. We varied conveyor angle relative to horizontal by rotating the steel support plate upon which the conveyor was mounted.

At the conveyor exit, the angle between each stalk axis and the conveyor chains was measured and recorded as was the distance which the base of each stalk protruded below the conveyor chains. We simulated ground clearance distances of 7.6, 10.2, and 12.7 cm and evaluated conveyor angles of 35°, 40°, and 45°. Twenty four plants were evaluated for each combination of conveyor angle and simulated ground clearance distance. The approximate linear speed of the conveyor during these tests was 46 cm/s, which was an estimate of required conveyance speed for an automatic harvester.

We conducted a second series of tests in which we used the inversion disks and reversed the direction of the upper conveyor. Plants were inserted into the upper horizontal section (2) at a predetermined angle and with a specified entry clearance distance or length of stalk extending below the conveyor chains. These tests simulated the second 90° change of direction in the upper conveyor, the subsequent downward conveyance of plants into the inversion disks, and the completion of inversion and transfer of plants into the lower horizontal conveyor.

The upper conveyor angle was set at 40°, so we inserted plants into the conveyor at 40° relative to the chains in order to recreate the partial inversion of plants expected at this conveyor angle. Entry clearance distances of 9.5 and 7.0 and 5.5 cm were achieved by adjusting the position of a flat plate positioned at the upper conveyor entry point (3). We tested 50, 51, and 20 plants, respectively, at each of the above-mentioned clearance distances. The linear speed of the upper conveyor as well as the peripheral speed of the inversion disks for these tests was approximately 46 cm/s.

FIELD TESTS OF PROTOTYPE HARVESTER

We began construction of a self-propelled prototype harvester in 1984. Initially, the prototype was equipped with automatic on-row guidance (Day and Smith, 1988), a detachment device, an inclined (45°) inverting conveyor, inversion disks and a notching mechanism. Field tests verified that those components functioned reliably and, thus, the second phase of system development was undertaken, that of automated filling and handling of portable curing frames. Portable curing frames were designed and fabricated in 1985 along with harvester component mechanisms for dispensing, filling, and unloading them. Figure 2 shows the prototype harvester in the field with portable curing frames.

Beginning in 1986, we conducted field experiments to determine leaf loss caused by the harvester prototype for comparison with that of conventional harvesting procedures. We used two varieties of burley tobacco for these experiments: KY 14, a widely-used variety, and TN 86, an experimental variety characterized by a relatively small angle between plant stalk and leaves. This characteristic ostensibly results in less susceptibility to leaf breakage due to handling of plants.

Identical experiments were conducted for three consecutive years beginning in 1986. A test consisted of marking off 100 plants within a row and counting the number of leaves on every tenth plant. The total number of

Figure 2–Prototype harvester operating in the field.

harvestable leaves was estimated as 100 times the average number of leaves/plant. The harvester then processed the plants in question and the number of detached leaves was recorded. Each test was replicated three times for each of the two burley varieties.

We harvested tobacco from each variety by conventional methods on the same day as each corresponding test involving the harvester prototype. Triplicate samples of ten cut sticks (60 plants) were harvested from each variety. The total number of leaves detached by manual handling for each sample was recorded. We estimated total number of harvestable leaves by counting leaves on every tenth plant and by multiplying the mean number of leaves/plant times 60.

In 1986 the tined conveyor, which placed notched plants into the slotted receivers, operated continuously and at a linear speed which was approximately 1/6 ground speed. Thus, the spacing between plants was reduced from approximately 46 cm in the field to 7.6 cm in the portable curing frames.

A serious problem resulted from the occasional impalement of plants exiting the notching conveyor by the conveyor tines. Although no data was recorded, we determined that between 10 and 20% of plants were damaged enough to prevent successful placement into the curing frames.

Thus, in 1987, we modified the tined conveyor to advance a distance equivalent to one plant spacing (7.6 cm) only upon the arrival of a notched plant at the exit of the notching conveyor. This modification also essentially guaranteed complete filling of the curing frame with notched plants.

Experiments were conducted in 1987 and 1988 to determine the frequency of failure to place plants into the curing frames. Triplicate tests involving the complete filling of one portable curing frame (approximately 450 plants) were conducted in 1987 for burley varieties KY 14 and TN 86. Quadruplicate tests of the same type were conducted in 1988. We recorded the number of plants not successfully placed into each curing frame in each test.

Finally, we conducted a performance test in 1988 in which we harvested approximately 0.40 ha (1 acre) of tobacco continuously via the prototype system. Eighteen portable curing frames were filled by the harvester and all essential support operations were executed. We measured and recorded the time required for loading empty frames on the harvester, unloading filled frames, turning between rows, and stoppages along with total harvesting time.

RESULTS AND DISCUSSION

A major objective of our early experimentation was to determine if burley tobacco plants could be reliably conveyed and inverted. While earlier work by Yoder (1978) had shown that plants could be elevated via an inclined opposed roller-chain conveyor grasping the plant near ground level, the subsequent inversion of plants during conveyance had not been attempted. Table 1 summarizes the results of tests involving plants going up an inclined section of conveyor and making a 90° turn at the top. Under no circumstances did the conveyor fail to deliver a plant to the exit point.

TABLE 1. Results of tests involving plants ascending an inclined conveyor with a 90° change in direction at the top

Conveyor angle (degrees)	Sim. ground clear.* (cm)	Rotation in chains† (%)	Total plants tested	Exit clearance‡	
				Mean (cm)	Standard deviation (cm)
35	7.6	4.2	24	3.7	0.6
	10.2	25.0	24	5.3	0.7
	12.2	8.3	24	8.7	0.6
40	7.6	12.5	24	3.4	0.7
	10.2	4.2	24	6.2	0.7
	12.7	12.5	24	8.5	0.6
45	7.6	25.0	24	3.1	0.6
	10.2	8.3	24	5.9	0.5
	12.7	12.5	24	8.3	0.6

* Distance between plant base and the bottom of the roller chain at the entry point.

† Change in original angle between stalk axis and chain during conveyance.

‡ Distance between plant base and the bottom of the roller chain at the exit point.

Because of the aggressive penetration of the stalks by the conveyor teeth, we assumed that no relative movement would occur between stalk and chain in the inclined conveyor. Table 1 indicates that such movement did occur for approximately 12% of plants tested. Such occurrences were somewhat more frequent at the 45° conveyor angle, while being seemingly unaffected by simulated ground clearance.

The difference between simulated ground clearance and exit clearance appearing in Table 1 was a result of the inclined opposed roller chains abruptly lifting plants at the entry point. A clear decrease in exit clearance with increasing conveyor angle is shown in Table 1.

Preliminary tests indicated that degree of plant rotation achieved in the upper conveyor had essentially no effect relative to the performance of the inversion disks. Plants placed in the conveyor at any orientation were reliably inverted (vertical, with base upward) and transferred into the lower conveyor. Thus, the occurrence of movement in the conveyor reported in Table 1 was of no consequence relative to successful inversion and transfer of plants.

Because of these findings, we only conducted tests of plant descent for an angle of inclination of 40°. Performance of the inversion disks, however, was significantly affected by entry clearance or length of stalk extending below the conveyor chains, as shown in Table 2. After testing a limited number of plants, it was apparent that the inversion disks would not grasp plants having only 5.5 cm of stalk extending below the upper conveyor chains. Similar tests at 7.0 cm resulted in a rate of failure to transfer plants from the upper to lower conveyors of 4.9%, while no failures occurred at 9.5 cm. When plants were successfully transferred, spacing within the horizontal conveyor was reliably reduced to 7.6 cm for placement into the slotted receivers.

Table 3 presents the comparison of harvesting leaf loss associated with both mechanical and conventional harvesting from tests conducted in 1986-88. The average leaf loss resulting from automated harvesting (1.65%) was

TABLE 2. Results of laboratory tests involving plants descending an inclined conveyor and transferring into a horizontal notching conveyor*

Entry clearance† (cm)	Plants tested	Conveyor failure‡ (%)
9.5	50	0.0
7.0	51	3.9
5.5	20	100.0

* Parameters fixed for these trials.
a. Conveyor angle = 40°
b. Linear speed of take-up conveyor = 46 cm/s
c. Linear speed of notching conveyor during loading = 10.2 cm/s
d. Linear speed of notching conveyor during spearing = 200 cm/s
e. Plant spacing in upper conveyor = 45.7 cm
† Distance base of stalk extended past take-up conveyor chain.
‡ Plant not conveyed to notching conveyor.

greater than for conventional harvesting (1.00%), however, this loss was a very low percentage of gross yield as compared to mechanical harvesting of crops such as hay or small grain. The average leaf loss associated with variety TN 86 (1.12%) was slightly smaller than that of KY 14 (1.51%). The loss corresponding to the three harvesting seasons (1986-88) were 0.91%, 1.89%, and 1.16%, respectively.

Table 4 presents the results of the analysis of variance of these data. Mechanical loss was significantly greater than conventional at the 0.01 level. A similar highly significant effect was indicated due to harvest year. Variety also had a significant effect upon leaf loss, however, only at the 5% level.

Two interactions were found to significantly affect harvesting leaf loss. Generally, mechanical leaf loss was near to that of conventional methods in harvesting TN 86. On the other hand, mechanical losses tended to be highest compared to conventional during 1987. We were very encouraged by these results in that one of the most significant historical obstacles to tobacco harvesting mechanization has been excessive leaf loss. These data indicate that leaf loss is not a concern for this automated harvesting system.

At the conclusion of field tests in 1986, however, we were extremely concerned about excessive failure to place notched plants into the slotted receivers. At that time the failure rate was estimated at between 10 and 20%. To address this problem, the tined conveyor was modified to advance one plant spacing (7.6 cm) upon the arrival of a notched plant at the exit of the notching conveyor.

TABLE 3. Comparison of harvesting leaf loss: Automated system vs. conventional methods

Year	Method	Variety	Leaf Loss (%)
1986	Conventional	KY 14	0.74
	Automated	KY 14	1.87
	Conventional	TN 86	0.52
	Automated	TN 86	0.49
1987	Conventional	KY 14	0.88
	Automated	KY 14	3.45
	Conventional	TN 86	1.18
	Automated	TN 86	2.06
1988	Conventional	KY 14	1.04
	Automated	KY 14	1.10
	Conventional	TN 86	1.57
	Automated	TN 86	0.92

TABLE 4. Analysis of variance: Percentage leaf loss due to harvesting method, burley variety, and harvest year

Treatment	SS	df	MS	F
Method	3.91	1	3.91	17.88
Variety	1.34	1	1.34	5.83*
Year	6.37	2	3.19	13.87†
M X V	3.17	1	3.17	13.78†
M X Y	6.20	2	3.10	13.48†
V X Y	1.53	2	0.77	3.35
MX V X Y	0.36	2	0.18	0.78
Error	5.61	24	0.23	
Total	28.49	35		

* Significant at $\alpha = 0.05$ level.
† Significant at $\alpha = 0.01$ level.

Table 5 presents the evaluation of failure to place notched plants into the portable curing frames. In 1987 there seemed to be little difference between varieties with regard to plant failure, with the average failure less than 4% of plants encountered.

Post notching failure was predominant and generally resulted from two causes: 1) plants near each end of the curing frames hit support members during frame indexing and failed at the notch, and 2) plants twisted within the receivers due to the obstruction caused by the large right rear wheel. This wheel was located below the curing frame during filling. In 1988, a significantly higher failure rate occurred with TN 86. This was partially due to TN 86 plants being appreciably larger (and longer) than KY 14. Larger plants were more likely to be obstructed by the large right rear wheel. Also, the comparatively larger diameter stalks were more frequently dropped from the inversion disks during transfer from the inclined conveyor to the notching conveyor. KY 14 in 1988 was the smallest tobacco tested and clearly showed the smallest post notching failure rate. This average failure rate (2%) was small enough to be regarded as acceptable, especially since most plants which are not placed in the curing frames can be retrieved.

The optimum location of the inversion disks is that of tangency to both the upper inclined and lower horizontal (notching) grasping conveyors. In early field tests of the

TABLE 5. Failure to place notched plants into portable curing frames

Year	Variety	Frame number	Inversion disks	Post notching	Total	Percent failure
1987	TN 86	1	0	19	19	4.24
		2	4	17	21	4.69
		3	0	12	12	2.68
						Average 3.87
	KY 14	1	3	13	16	3.57
		2	0	15	15	3.35
		3	0	19	19	4.24
						Average 3.72
1988	TN 86	1	10	12	22	4.91
		2	23	19	42	9.37
		3	20	24	44	9.82
		4	3	12	15	3.35
						Average 6.86
	KY 14	1	3	6	9	2.01
		2	3	8	11	2.46
		3	4	7	11	2.46
		4	4	0	4	0.89
						Average 1.96

harvester prototype, the inversion disks were situated in the optimum location and virtually no pre-notching conveyance failures occurred. However, in 1986, it was necessary to raise the tined conveyor as high as possible in order to more positively engage plants in the slotted receivers and to push them along without breakage at the notches. This necessitated that the notching conveyor also be raised (relative to the inclined conveyor) and, thus, the inversion disks were no longer tangent to both conveyors. We feel this change of position caused most, if not all, of the pre-notching failures recorded in Table 5.

Table 6 presents the results of a time-and-motion study of automated harvesting operations conducted in 1988. These results show a relatively low field efficiency (51%) when considered in the conventional sense of theoretical harvesting time divided by total or actual time. Clearly, off-loading filled frames and reloading empty stacks of frames onto the harvester represent a substantial percentage of time (29.5%) when harvesting actually ceases. Further, turning time was somewhat excessive (17.2%) because the prototype had limited ground speed capability (approximately 0.7 m/s) and a relatively high turning radius [≥ 10 m (30 ft)].

The actual in-row harvesting rate was approximately 1.5 plants per second, whereas the effective harvesting rate was 0.14 ha/hr (0.34 acre/hr). Assuming 10 hours of effective harvesting, then the daily rate would be 1.36 ha/day (3.4 acre/day). This represents an approximate reduction of 80-85% of conventional harvesting labor requirement.

TABLE 6. Time-and-motion-study of automated harvesting system

Event	Time required (min)	Total Time (%)
Harvest	90.4	50.96%
Turn	30.5	17.19%
Off-load	30.3	17.08%
Reload	22.0	12.40%
Down Time	4.2	2.37%
TOTAL	177.4 min	100%

CONCLUSIONS

The conclusions of the study are as follows:

1. The specialized mechanisms developed for inverting and notching mature tobacco plants performed reliably and durably.
2. Automated harvesting leaf loss was greater than that of conventional harvesting, yet acceptably low to easily warrant its use.
3. Failure to place notched plants into the curing frames was primarily caused by: a) the obstruction of the large right rear wheel, b) plants hitting track support members during indexing, and c) inappropriate positioning of the inversions disks.
4. A harvesting capacity of approximately 1.36 ha/day (3.4 acre/day) was demonstrated.

PLANNED DEVELOPMENT

The following changes are planned to enhance the performance of the prototype system:

1. The large drive wheels will be placed in front of the portable curing frames and smaller rear steering wheels will be positioned beneath the frames during filling. This should virtually eliminate failure to place notched plants in the holders presently caused by the large right rear wheel.
2. A shorter wheel base and increased turning speed should substantially reduce turning time.
3. Modification of the inclined conveyor to utilize a large diameter arc to achieve the 180° change-of-direction (as opposed to the present configuration using two 90° turns) should significantly reduce centrifugal forces on the plants and permit high harvesting speeds (up to 1 m/s).
4. Positioning the inversion disks at the optimum location of tangency to both the inclined and horizontal grasping conveyors will significantly improve their performance. The anticipated result of these modifications would be to increase harvesting speed to approximately 2 ha/day (5 acre/day).

REFERENCES

Wells, L.G., G.B. Day, V, and T.D. Smith. 1990. Automated harvesting of burley tobacco I. System development. *Transactions of the ASAE* 33(4): 1033-1037.

Yoder, E.E. 1978. Burley tobacco harvester. ASAE Paper No. 78-3536. St. Joseph, MI: ASAE.