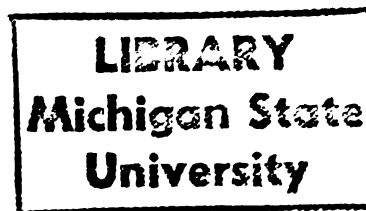


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Simulation of Packing Line Impacts for
Apple Bruise Prediction

presented by

Sidney Scott Sober

has been accepted towards fulfillment
of the requirements for

Masters degree in Agric. Engr. Tech.

H. Roland Zapp
Thomas H Burkhardt
Major professor

Date August 24, 1989

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**SIMULATION OF PACKING LINE IMPACTS FOR
APPLE BRUISE PREDICTION**

By

Sidney Scott Sober

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

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in

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1989

ABSTRACT

SIMULATION OF PACKING LINE IMPACTS FOR APPLE BRUISE PREDICTION

By

Sidney Scott Sober

Impact pulses recorded by an Instrumented Sphere (IS) as it moved with apples through 12 commercial apple packing lines were analyzed to determine peak G's and velocity change. The peak G's ranged from 20 g to 130 g (1 g = 9.81 m/s²) and velocity change ranged from 0.1 to 3.0 m/s. These impacts were simulated in the laboratory using different surfaces that were calibrated using the IS. Paula Red and Golden Delicious apples were dropped onto these surfaces and the resulting bruises were recorded.

The lowest impact threshold for bruise development was 40 g for the Paula Red apples and 30 g for the Golden Delicious apples. This occurred 1 day after harvest for Paula Red and 3 days after harvest for Golden Delicious apples. Multiple linear regression models were formulated for each variety of apple. The equations explained 85 percent of the variation in bruise diameter for Paula Red and 56 percent for Golden Delicious apples.

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1. INTRODUCTION

1.1 Importance of the Study

Mechanized fruit handling systems used in the packing of fresh produce have been in use for many years. Although mechanical packing lines have greatly increased the efficiency of sorting and packing fresh fruit, they have also increased the occurrence of damage due to mechanical impact.

The mechanical impact damage problem has been pointed out in many past studies. Held, et al. (1974) as cited by Finney, et al. (1974), reported that bruising of Golden Delicious apples caused approximately 23 percent of the fruit to fall below the standards necessary for the highest quality. Similarly, Peleg (1984) concluded that bruising losses, in some fruit and vegetable crops, may reach an estimated 30 percent of the yield.

Bartram, et al. (1983), in studying two packing houses, determined the situation to be worse. He concluded that 89 percent of the apples (Golden Delicious) were bruised after completing all mechanical packing house operations. This can be compared to 74 percent damaged before the operations. He also concluded that the average number of bruises per apple (larger than 6.4 mm in diameter) increased from 1 to 3

bruises.

The bruising and down-grading of quality, caused by apple packing lines, results in financial loss to the packing house operators. Since consumers demand unbruised fruit, improving apple quality on packing lines is of great importance to both producers and consumers.

1.2 Review of Literature

Solid, nonbiological body impacts were examined by Goldsmith (1960). Mohsenin (1970) later applied these impact theories to agricultural products. Fluck and Ahmed (1973) examined the theoretical aspects of impact and specifically related them to fruits and vegetables. They also produced an extensive bibliography of related studies. They related the impact measurements to fruit damage levels using an instrumented falling mass system. They showed that bruising resulted from a complex relationship between acceleration, velocity change and impact duration, all of which must be considered. From this work improved bruise prediction models were developed. Finney, et al. (1975), used an instrumented pendulum to improve the understanding of impact characteristics and the damage to fruit. They developed force deformation relationships to describe impacts to fruit. However, they did not apply their work to any specific fruits or vegetables. Lichtensteiger, et al. (1988), used an impact force transducer to record impact characteristics of fruit falling onto it. From these data force-time relationships were found. Many other studies

have been reported using similar configurations.

All the studies mentioned above ignored the actual conditions in apple packing houses, where most mechanical damage occurs. Brown, et al. (1987), ran unbruised apples through apple lines to determine actual bruise damage. However, the forces producing the bruises on the fruit were not measured, so bruising could not be predicted from the forces experienced by the apple.

Siyami et al. (1986) developed a data acquisition system, the instrumented sphere (IS), to measure impact characteristics on operating apple packing lines. The IS with on-board sensors, microprocessor and memory was mounted on an impact table along with apples in order to develop some bruise prediction models. The early tests and analyses were done without actual apple packing line data. A predictor model was developed for the first generation IS as follows:

$$ABD = B_0 + B_1 (AAD) + B_2(MT) + B_3(MA) + B_4(MA)^2 + B_5(DV)^2$$

Where: ABD = Average bruise diameter, mm

AAD = Average apple diameter, mm

MT = Magness-Taylor flesh firmness, kg

MA = Maximum acceleration, m/s²

DV = Velocity change, m/s

B_i = Regression coefficients

However, these tests were conducted before impact measurements could be recorded by an IS as it traveled with apples on a packing line. The impact table tests were

conducted using impacts of 30 g to 300 g, which are above conditions found in actual apple packing lines.

1.3 Objectives of the Study

The following research will continue Siyami's original research of sensing apple line impacts and formulating bruise prediction models. The specific objectives of the research are as follows:

1. To classify the impacts recorded on commercial apple packing lines,
2. To identify surface conditions and drop heights that can be used in laboratory tests to simulate the recorded impacts,
3. To identify the impact level thresholds which cause bruising for Paula Red and Golden Delicious apples,
4. To formulate regression equations from laboratory drop tests to predict average bruise diameter for Paula Red and Golden Delicious apples.

2. PROCEDURE

2.1 Collecting Apple Packing Line Data

An 89 mm IS was used to record impact pulses experienced on operational apple packing lines, Zapp et al. (1989). The self-contained unit differs from the unit used in Siyami's drop table tests in both size and internal construction. The new IS contains a triaxial accelerometer, a microprocessor, 32 K of RAM, a battery and other miscellaneous circuitry to condition the accelerometer output. The 330 gram unit is foam-filled and cast in beeswax. Due to its small size and apple like-buoyancy, the new IS was able to collect data through the entire packing line.

Four IS's were run simultaneously with apples through twelve packing houses 3 to 12 times in each packing house. Each IS was placed onto the apple packing line at the water flotation tank at the beginning of the apple packing line and continued through the undersize eliminator, washer, waxer, dryer, sizers and apple baggers. When an IS was impacted above a preset threshold, the characteristics of the shock impulse were recorded. The data recorded as an IS passed through the apple baggers were not used in this study, but instead are part of a separate on-going study.

After each completed pass through the apple packing line, the data were up-loaded to a portable computer for immediate verification, disk storage and for later detailed analysis. On each pass through the apple packing lines the IS's recorded from 8 to 50 impacts above a threshold of 50 g.

In the laboratory, the binary IS files were converted to readable impact data. From the down-loaded data, impact duration, peak G and velocity change were calculated. For all of the tests a total of 2865 impacts were recorded and analyzed. Note that in the following text velocity change specifically refers to the integration of the impact curve, or the area under the impact curve. The term "G" is used to specify the acceleration of an object. It is the acceleration of the body (m/s^2) divided by the acceleration of gravity (9.81 m/s^2). A small case g is used to denote the acceleration due to gravity, 9.81 m/s^2 . Figure 2.1 shows a typical impact curve with velocity change and peak G's.

In preliminary tests on the drop tester, apples were dropped from heights which resulted in accelerations below 20 g. It was determined that a single impact below 20 g was insufficient to produce apple bruising. Impacts above 130 g were rare and were neglected. Thus, after analyzing the packing line data, 1895 impact pulses were classified between 20 g and 130 g.

A histogram of the peak G (maximum acceleration) distribution is shown in Figure 2.2. As shown, 1664 impacts



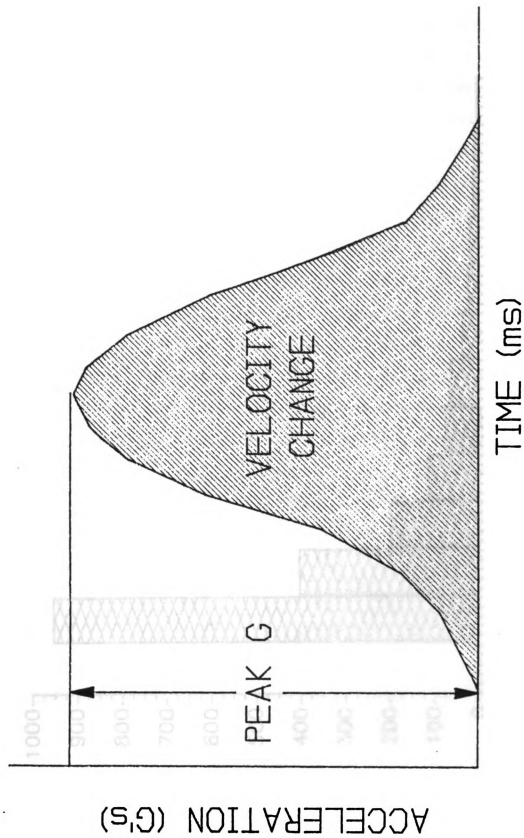


Figure 2.1 Typical Impact Curve Showing Peak Acceleration and Velocity Change

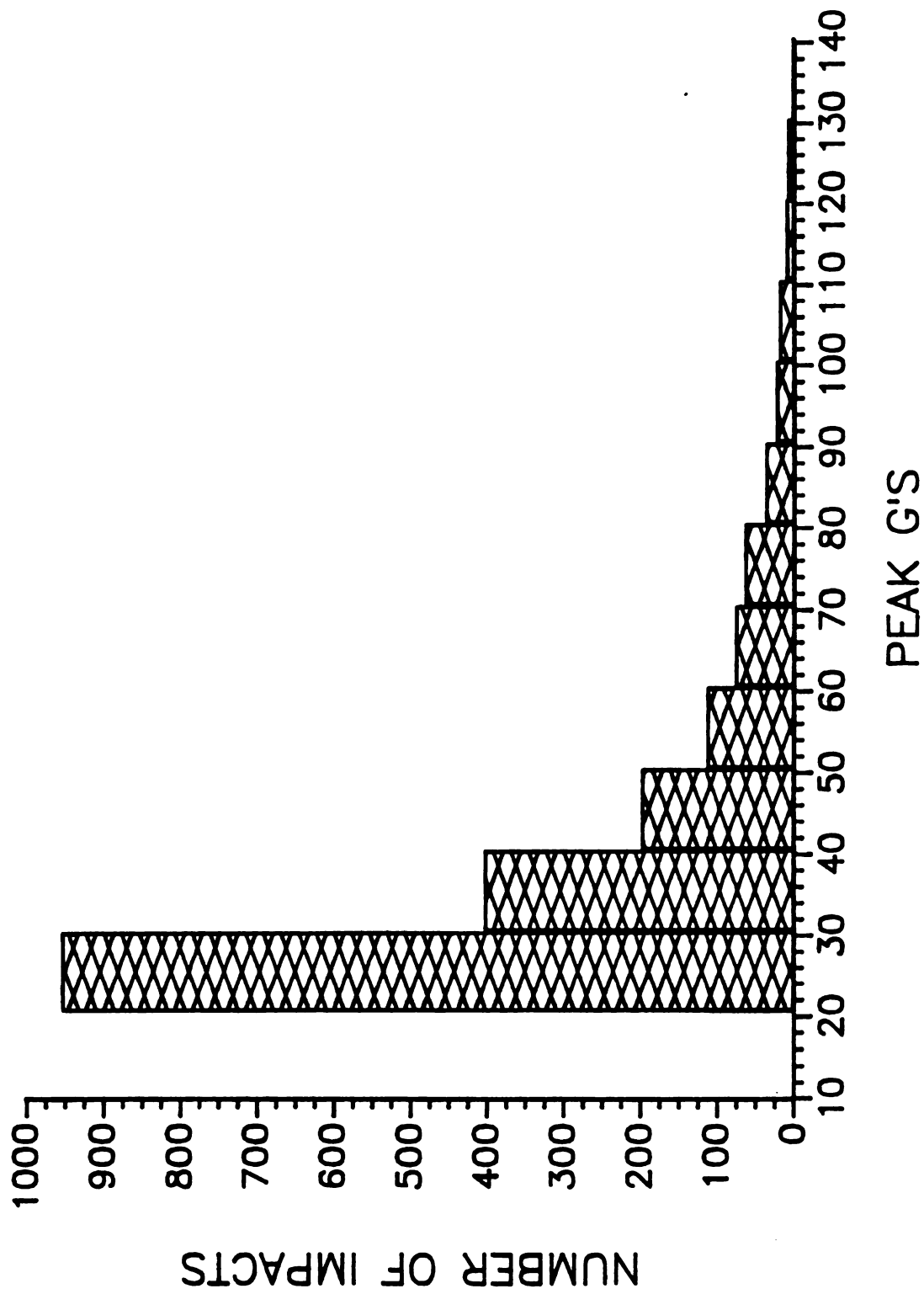


Figure 2.2 Peak G Distribution of Apple Packing Line Impacts

occurred between 20 g and 60 g. Approximately 88% of the impacts experienced in normal packing operations are accounted for in the range between 20 g and 60 g. Figure 2.3 shows the distribution of velocity change corresponding to the impacts considered in Figure 2.2. Velocity change values ranged from 0.1 m/s to 4.5 m/s (however, only 2 impacts were recorded with velocity change greater than 3 m/s). The simulated surfaces cover the approximate range of the impacts recorded on the packing lines. Figure 2.4 illustrates the distribution of impact duration for the impacts shown in Figure 2.2. The recorded values ranged between 3.07 ms and 23.04 ms. In the study reported here, the impact duration was not used in determining impact characteristics because the method of determining impact duration may incorporate excessive error due to the ambiguity in impact completion. For this reason, velocity change was identified as a more reliable measure of impact characteristics. Since velocity change is the integration of the impact curves, it tends to smooth the impact data. The error due to difficulty with determining the beginning and end of the impact curves becomes insignificant. Thus, given a certain level of maximum acceleration, the velocity change is a much better indicator of the type of impact.

2.2 Simulating Apple Packing Line Impacts

After analyzing operating apple packing line data for impact characteristics and their distributions, laboratory simulations to reproduce similar impacts were undertaken.

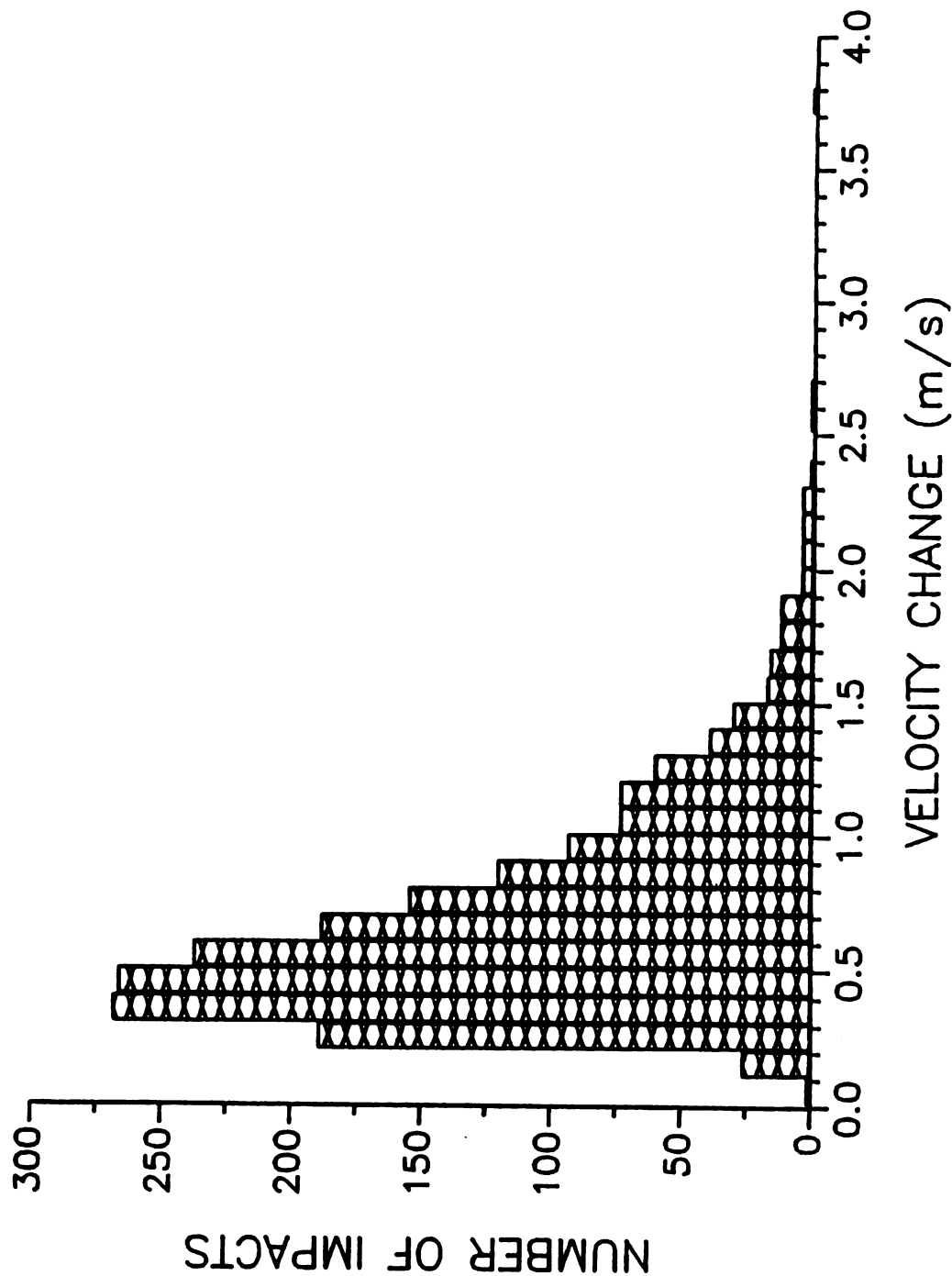


Figure 2.3 Velocity Change Distribution of Apple Packing Line Impacts

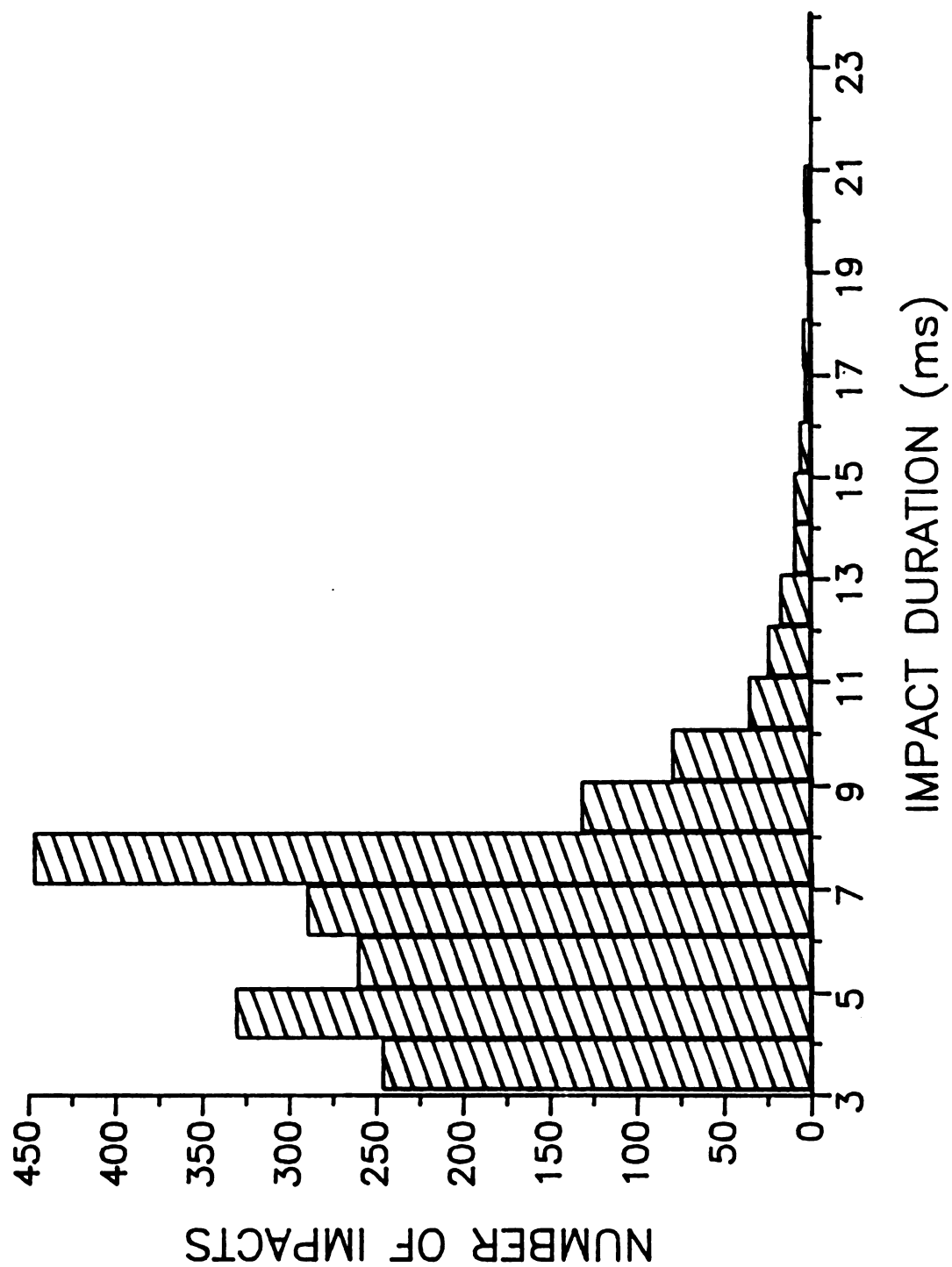


Figure 2.4 Impact Duration Distribution of Apple Packing Line Impacts

The peak G's to be reproduced ranged between 20 g and 130 g, and velocity changes spanned the range of 0.20 m/s to 2.76 m/s, since these ranges correspond to the impact levels most likely to cause bruising.

A programmable impact table originally used for reproducing calibrated shock pulses proved inadequate to replicate the type of impacts experienced on an actual operating apple packing line. This is due to a lower limit of 100 g obtained from the impact table. Thus, a free-fall drop tester which allowed lower impact levels, as shown in Figure 2.5, was used to produce the desired impact characteristics.

To arrive at the desired shock pulses, several materials, as tabulated in Table 2.1, were placed on the heavy steel plate of the drop tester. The IS was dropped onto each surface five to six times from a given height, to record the impact characteristics and to obtain an average for each combination of material and drop height. After each drop the surface was relocated to assure the contact area would not be compressed by a previous drop. This entire process is referred to as "calibrating the surface". From a nominal 20 g to 90 g; peak G, velocity change, impact duration, and drop height were recorded and averaged for each surface. As shown in Table 2.2, different surfaces have different velocity changes and drop heights for the same nominal peak G level due to their properties. After choosing the surfaces that produced the desired

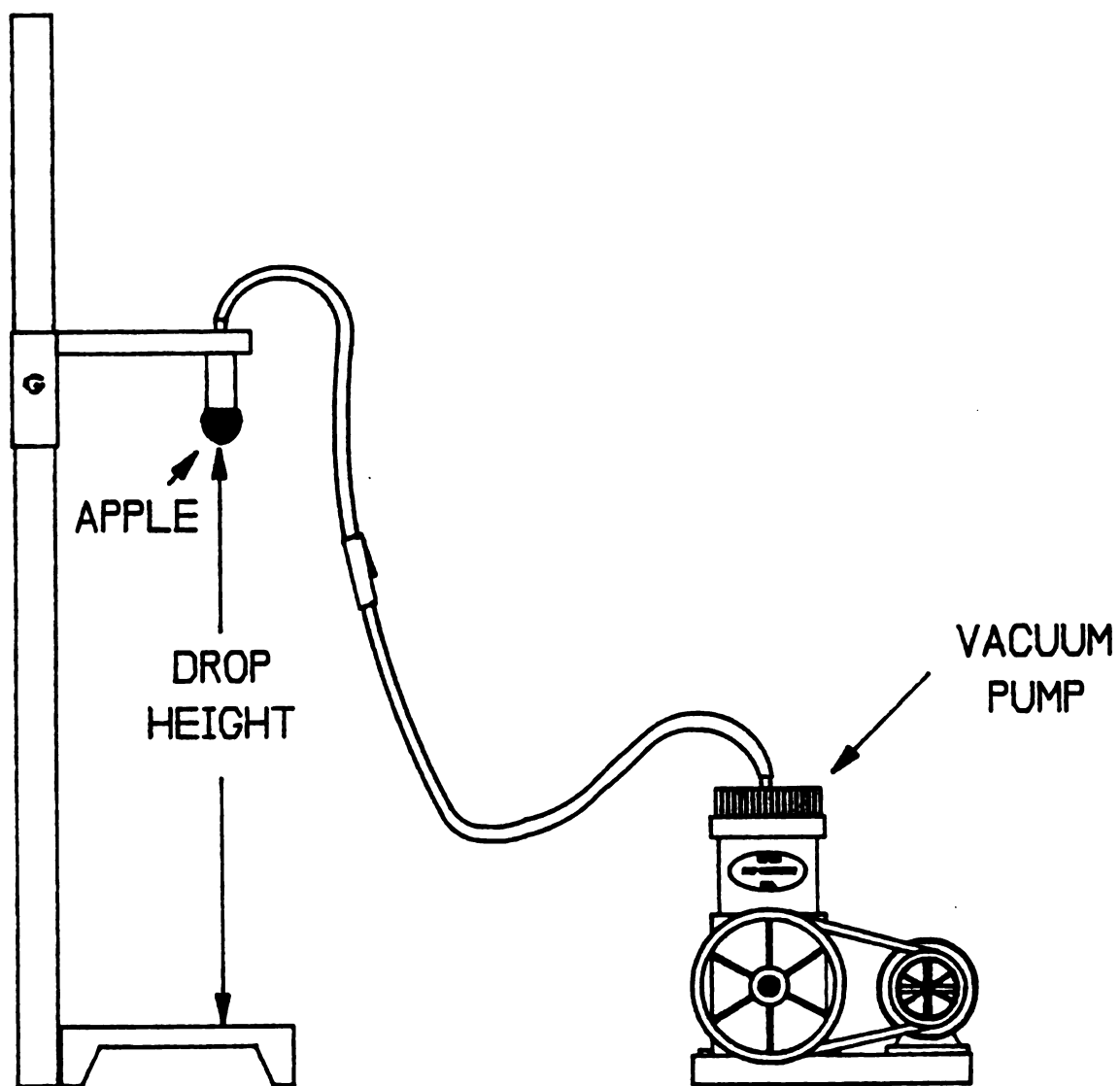


Figure 2.5 Drop Test Machine

Table 2.1 Impact Surfaces Tested*

<u>Surface num.</u>	<u>Description</u>
1	Steel Plate, 12.7 mm
2	Wood, 38 mm
3	Polymate 135 Polyurethane COS belting, over surface 1
4	Sheet Metal, 1.6 mm
5	Felt, 1.6 mm, over surface 1
6	Sheet metal covered with felt, both 1.6 mm
7	Ametek Microfoam, 2-1.6 mm plies, over surface 1
8	Ametek Microfoam, 1-3.2mm ply, over surface 1
9	222 White Ethafoam, 6.4 mm, over surface 1
10	Uniroyal ENS-FBC Ensolite, 6.4 mm, over surface 1
11	Uniroyal MLC Natural Ensolite, 6.4 mm, over surface 1

*Use of company or product name by Michigan State University or the U.S. Department of Agriculture is for information purposes and does not imply approval or recommendation to the exclusion of other which may also be suitable.

Table 2.2 Impact Characteristics of Surfaces*

Peak G's	SD	DV (m/s)	SD	Duration (ms)	SD	Drop Ht. (Cm)	Surface Number
21.3	1.18	0.20	0.01	3.8	0.16	0.25	1
20.6	1.29	0.27	0.01	5.6	0.71	0.16	2
21.4	0.28	0.33	0.01	5.4	0.00	0.24	3
21.8	1.64	0.38	0.04	4.4	0.30	0.30	4
21.1	0.82	0.52	0.01	5.6	0.09	0.60	6
21.3	1.21	0.83	0.08	7.5	0.66	1.00	7
20.7	0.88	0.90	0.01	8.3	0.23	1.42	8
21.5	0.47	1.19	0.04	9.5	0.70	2.54	9
19.2	0.15	1.18	0.02	9.9	0.17	2.54	10
20.2	0.59	1.41	0.07	10.6	1.17	5.10	11
31.7	1.18	0.34	0.01	3.5	0.16	0.30	1
31.0	3.42	0.40	0.02	4.4	0.39	0.24	2
31.4	1.23	0.44	0.01	4.6	0.28	0.40	3
29.7	1.60	0.47	0.05	3.7	0.90	0.40	4
30.6	5.08	0.36	0.02	4.3	0.17	0.33	5
30.5	0.54	0.52	0.01	5.6	0.09	1.00	6
31.4	1.43	1.03	0.06	7.3	0.54	1.70	7
31.7	2.19	1.26	0.11	8.7	0.70	1.90	8
30.1	0.88	1.52	0.09	9.8	0.51	3.80	9
29.8	0.78	1.58	0.05	9.7	0.09	4.45	10
29.2	1.05	1.92	0.10	11.6	0.42	7.60	11
40.2	3.75	0.43	0.01	3.5	0.72	0.60	1
41.4	1.45	0.50	0.02	5.1	0.99	0.48	2
42.3	1.00	0.54	0.02	5.1	1.44	0.55	3
41.1	1.17	0.71	0.01	4.5	0.40	0.80	4
40.2	3.54	0.46	0.01	4.2	0.47	0.48	5
40.4	1.63	0.90	0.06	5.0	0.40	1.60	6
41.1	2.30	1.15	0.05	6.9	1.07	2.20	7
40.6	1.47	1.31	0.04	7.5	0.31	2.85	8
39.6	2.34	1.73	0.14	9.1	0.79	5.10	9
39.8	0.35	1.90	0.01	9.9	0.55	6.35	10
40.5	1.67	1.78	0.12	9.1	0.78	10.80	11

Table 2.2 (cont'd)

Peak G's	SD	DV (m/s)	SD	Duration (ms)	SD	Drop Ht. (Cm)	Surface Number
50.5	3.29	0.55	0.01	4.0	0.28	0.80	1
50.8	2.96	0.55	0.01	4.0	0.25	0.56	2
51.5	1.95	0.63	0.01	3.6	0.36	0.64	3
50.1	4.59	0.87	0.06	3.5	0.53	0.79	4
50.2	4.70	0.56	0.01	3.7	0.34	1.20	5
51.1	2.36	1.04	0.04	4.5	0.64	2.00	6
49.8	1.09	1.33	0.01	7.9	0.80	2.70	7
50.4	1.67	1.50	0.16	8.0	1.40	3.18	8
49.6	3.18	1.98	0.12	8.4	0.56	6.80	9
50.0	0.78	2.17	0.01	8.0	0.38	8.26	10
49.6	3.18	1.98	0.13	8.4	0.56	13.40	11
60.8	5.99	0.61	0.01	3.6	0.49	1.00	1
58.7	1.40	0.62	0.01	3.9	0.17	0.79	2
60.7	3.03	0.69	0.03	5.3	1.10	0.95	3
61.1	2.17	0.98	0.03	4.1	0.75	1.60	4
60.5	1.76	0.56	0.01	3.5	0.23	0.97	5
60.5	1.85	1.16	0.03	4.5	0.68	2.50	6
60.1	4.79	1.34	0.01	6.1	0.36	3.30	7
59.8	3.68	1.54	0.06	6.6	0.47	3.81	8
60.8	1.17	2.23	0.05	8.0	0.25	7.30	9
61.2	1.32	2.39	0.05	8.3	0.22	10.00	10
71.3	2.38	0.62	0.02	3.6	0.25	1.20	1
71.3	4.85	0.78	0.01	3.9	0.17	1.11	2
70.5	2.77	0.76	0.02	3.4	0.43	1.35	3
68.8	3.09	1.04	0.02	4.4	0.70	2.00	4
71.1	2.09	0.75	0.04	3.4	0.41	1.27	5
70.6	1.80	1.36	0.02	3.7	0.11	3.00	6
70.7	1.46	1.38	0.04	5.5	0.12	3.70	7
69.5	2.26	1.59	0.02	6.4	0.30	4.20	8
69.0	2.89	2.26	0.10	7.6	0.36	8.60	9
72.8	2.72	2.55	0.06	7.9	0.40	2.55	10

Table 2.2 (cont'd)

Peak G's	SD	DV (m/s)	SD	Duration (ms)	SD	Drop Ht. (Cm)	Surface Number
80.2	2.78	0.71	0.00	5.3	1.20	0.40	1
82.2	1.36	0.86	0.02	3.2	0.62	1.27	2
80.8	1.62	0.86	0.02	2.8	0.33	1.75	3
80.9	2.31	1.42	0.02	3.7	0.81	3.40	4
81.5	2.90	0.79	0.02	3.6	0.12	1.60	5
79.5	.96	1.52	0.01	3.8	0.00	3.70	6
80.3	4.21	1.48	0.05	5.3	0.24	4.00	7
78.4	7.59	1.68	0.12	6.1	0.57	5.50	8
79.3	2.93	2.46	0.08	7.6	0.44	9.60	9
80.5	2.31	2.76	0.06	7.9	0.40	13.50	10
90.3	1.05	0.78	0.01	4.9	0.92	1.70	1
89.8	7.43	0.94	0.01	3.7	0.33	1.51	2
92.2	2.29	0.92	0.01	2.8	0.42	1.75	3
91.6	2.49	1.74	0.30	5.5	1.78	3.80	4
91.1	4.59	0.87	0.07	3.5	0.17	1.75	5
89.9	5.02	1.74	0.11	5.9	1.88	4.50	6
89.2	6.04	1.56	0.06	5.2	0.22	4.50	7
91.4	13.82	1.70	0.07	5.5	0.29	5.90	8
91.9	2.23	2.53	0.10	7.1	1.10	10.60	9
91.9	3.21	2.84	0.09	7.3	0.33	14.60	10

*See Table 2.1 for identification of each surface.

characteristics, each was calibrated up to 130 g. From inspection of the characteristics for each surface, the steel plate was chosen to reproduce impacts of small velocity change (0.20 m/s to 1.02 m/s) since it produced the smallest velocity changes at each peak G level. For medium velocity changes 2 surfaces were used to keep the medium velocity changes between the small and large velocity changes. The surface used to reproduce medium velocity change at low peak G's (20 g to 70 g) is referred to as "medium-low" and the surface used at high peak G's (50 g to 130 g) is referred to as "medium-high". Ametek Microfoam, made of 2-1.6 mm plys, was used to reproduce medium-low velocity changes (0.83 m/s to 1.38 m/s) and a single 3.2 mm ply of Ametek Microfoam was used for medium-high velocity changes (1.68 m/s to 2.08 m/s). The 2 surfaces chosen to reproduce medium velocity change surfaces fall between the small and high velocity change surfaces at each peak G level as shown by the center curve in Figure 2.6. Note that both low-medium and high medium are included in this curve. Also each point in Figure 2.6 represents the average value at each peak G level. The White Ethafoam 6.4 mm thick was used to produce the highest velocity changes (1.4 m/s to 2.76 m/s). This surface produced the highest velocity changes which corresponded to actual packing line conditions. Table 2.3 shows the impact characteristics for each material used in the test at each peak G level.

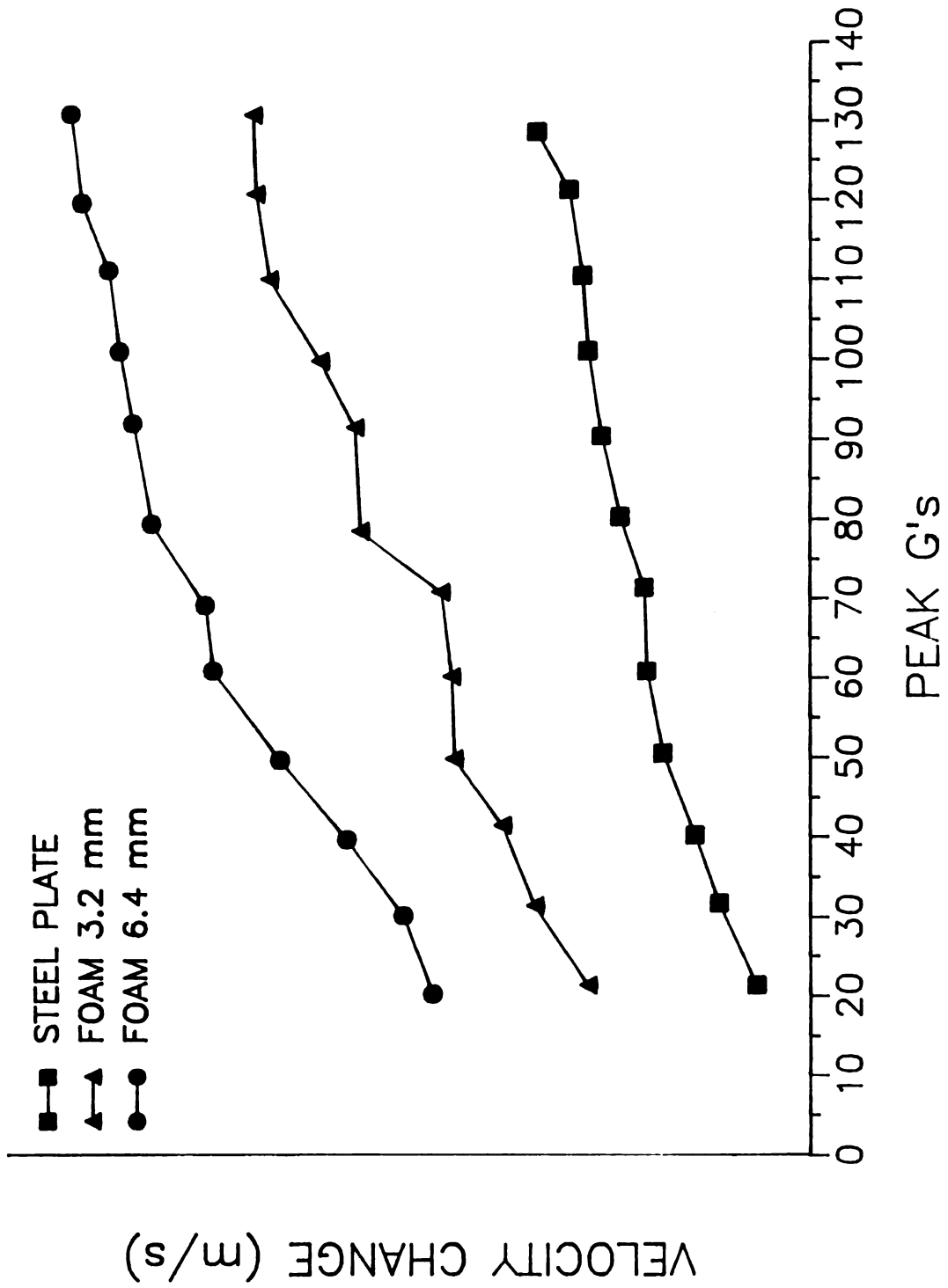


Figure 2.6 Impact Surface Characteristics Defined in Terms of Velocity Change and Peak G's

Table 2.3 Surfaces Used in Impact Simulation*

Peak G's	SD	DV (m/s)	SD	Duration (ms)	SD	Drop Ht. (Cm)	Surface Number
21.3	1.18	0.20	0.02	3.8	0.16	0.25	1
21.3	1.21	0.83	0.08	7.5	0.66	1.00	7
20.2	0.50	1.41	0.07	10.6	1.17	5.10	11
31.7	1.18	0.34	0.01	3.5	0.16	0.30	1
31.4	1.43	1.03	0.06	7.3	0.54	1.60	7
30.1	0.88	1.52	0.09	9.8	0.51	3.80	9
40.2	3.74	0.43	0.01	3.5	0.72	0.60	1
41.1	2.30	1.15	0.05	6.9	1.07	2.20	7
39.6	2.34	1.73	0.14	9.1	0.79	5.10	9
50.5	3.29	0.55	0.01	4.0	0.28	0.80	1
49.8	1.09	1.33	0.01	7.9	0.80	2.70	7
49.6	3.18	1.98	0.12	8.4	0.56	6.80	9
60.8	5.99	0.61	0.01	4.6	0.49	1.00	1
60.1	4.79	1.34	0.01	6.1	0.36	3.30	7
60.8	1.17	2.23	0.05	8.3	0.22	7.30	9
71.3	2.38	0.62	0.02	3.6	0.25	1.20	1
70.7	1.46	1.38	0.04	5.5	0.12	3.70	7
69.0	2.89	2.26	0.10	7.6	0.36	8.60	9
80.2	2.78	.71	0.00	5.3	1.20	1.40	1
78.4	7.59	1.68	0.12	6.1	0.57	5.50	8
79.3	2.93	2.46	0.08	7.6	0.44	9.60	9
90.3	1.05	0.78	0.01	4.0	0.92	1.70	1
91.4	3.82	1.70	0.07	5.5	0.29	5.90	8
91.9	2.23	2.53	0.09	7.3	0.33	10.60	9
101.0	5.53	0.83	0.06	3.0	0.63	1.80	1
99.7	9.60	1.83	0.01	6.8	0.22	6.30	8
100.9	3.03	2.58	0.01	8.2	1.04	11.90	9

Table 2.3 (cont'd)

Peak G's	SD	DV (m/s)	SD	Duration (ms)	SD .	Drop Ht (Cm)	Surface Number
110.4	0.94	085	0.03	4.5	0.12	2.00	1
109.9	6.60	2.02	0.03	7.4	0.46	6.60	8
111.0	1.70	2.62	0.01	8.9	0.13	12.40	9
121.2	2.24	0.90	0.02	3.3	0.00	2.30	1
120.6	5.07	2.07	0.02	7.9	0.25	6.70	8
119.5	2.76	2.72	0.02	8.2	1.25	14.10	9
128.5	0.67	1.02	0.02	3.3	0.00	3.00	1
130.6	3.36	2.08	0.01	6.5	1.33	7.10	8
130.7	3.47	2.76	0.01	8.9	0.13	14.40	9

*See Table 2.1 for identification of each surface.

2.3 Fruit Used in Testing

Three series of drop tests were performed using 2 varieties of apples commonly found in Michigan. Two series used freshly picked Paula Red and Golden Delicious apples. The third used Golden Delicious apples that had been held in controlled atmosphere (CA) storage for about 6 months.

The Paula Red apples were used to show the effect of impacts on a summer variety of apple found in Michigan. The Golden Delicious apples were chosen due to their susceptibility to visible bruising. Last the CA storage apples were used to find the effects of long term storage on Michigan Golden Delicious apples.

The Paula Red apples were harvested August 25, 1988 from the Clarksville Experiment Station, Clarksville, Michigan. Magness-Taylor pressure tests were conducted immediately after harvest on two paired sides of 20 randomly selected apples using an Effegi tester (Model FT-327, Effegi, 48011, Alfonsine, Italy) mounted on a drill press stand; these apples were not used in the drop tests. At harvest the average Magness-Taylor firmness was 71 N (± 4 N). The 2000 harvested apples were divided into small (116 ± 4 grams), medium (140 ± 7 grams) and large (175 ± 19 grams) size groups based upon the average of the small 1/3, medium 1/3 and large 1/3 of the apples harvested. After harvest all fresh apples were stored in a 4°C cooler throughout the testing.

The Golden Delicious apples were harvested September

30, 1988 from the Clarksville Experiment Station. At harvest the average Magness-Taylor firmness of 20 randomly selected apples was 77 N (± 4 N). The 2000 harvested apples were divided into small (142 ± 6 grams), medium (166 ± 4 grams), and large (196 ± 9 grams) size groups using the same procedure as with the Paula Red apples.

The CA Golden Delicious apples were taken from CA in April of 1988 and held in cold storage (0°C , 85% RH) until drop tested on June 31, 1988. These apples were selected from storage and not harvested. The 800 apples selected had an average Magness-Taylor reading of 44.5 N (± 5 N) for 20 apples. They were divided into small (136 ± 7 grams), medium (165 ± 4 grams) and large (201 ± 11 gram) size groups.

2.4 Drop Test Procedure

Each apple was placed at room temperature for 2 hours , for consistency, and weighed before it was dropped onto the impact surface. In Siyami's previous study, apple diameter was used to denote the size of each apple. However, as shown by Equation 2.1 it is the mass of the fruit that affects the peak acceleration experienced.

$$G = \frac{\sqrt{2hk}}{W} \dots \dots \dots [2.1]$$

Where: G = Peak acceleration, in g's

h = Drop height, cm

K = Cushion constant, kg/cm

W = Mass, kg

Grouping the apples by mass, rather than diameter, therefore helped reduce variation in the test results.

After weighing, each apple was placed in the drop tester with its cheek facing the impact surface (Figure 4) and retained in place by vacuum. The apples were carefully placed so no large irregularity on the surface would be impacted. Once the apple was placed in the tester, the height was set based on the calibration previously established using the IS, and the apple released onto the impact surface. After the initial impact the apple was caught to avoid the chance of a secondary impact. Each apple was then turned 180 degrees about the center line of its core and dropped on the opposite cheek after again setting the drop height to that of the first. The exact area of impact was marked by applying a light dusting of chalk on each impact surface prior to the drops. After the apple received 2 impacts, each impact area was circled with permanent marker and 2 Magness-Taylor firmness readings were taken adjacent to the impact areas. The apples were then allowed to sit for 24 hours in the laboratory at room temperature before analysis. This allowed sufficient time for the bruises to oxidize and be detectable.

The freshly picked Paula Red and Golden Delicious apples, were dropped onto the 3 test surfaces at 1 day, 3 days and 12 days after harvest (5 dropped twice, on opposite sides, for each surface and day). The days after harvest were chosen to show the effect of time on bruising for a

short period of time (1 day), a slightly longer period of time (3 days) and a long period after harvest (12 days). The CA stored Golden Delicious apples were dropped onto the 3 test surfaces on June 31, 1988.

2.5 Bruise Analysis

The tested apples were inspected under fluorescent light near a window, thus both artificial and natural light were present for detecting bruises. A bruise was defined as any flattening or browning on or below the surface of the apple. The apples were first inspected and classified as to whether visible surface bruising had occurred. A scalpel was then used to remove the skin from the marked impact area. In many cases, peeling revealed bruising that was not visible on the surface. After peeling the skin away, the major and minor bruise diameters were measured using a digital caliper, Figure 2.7. The bruise depth was measured with a digital caliper, after cutting out a cross section of the bruise perpendicular to the surface, and then recorded. Both bruise diameter and bruise volume were calculated from the measurements. The bruise diameter was calculated by taking the average of the major and minor bruise diameters, and the bruise volume by a variation of the formula used by Schoorl et al. (1980). The original Schoorl equation is:

$$V = \left[\frac{\pi b}{24} (3d^2 + 4b^2) \right] + \left[\frac{\pi X}{24} (3d^2 + 4X^2) \right]. \quad . \quad . \quad [2.2]$$

V = Bruise Volume, mm³

X = R - $\sqrt{R^2 - d^2/4}$, mm

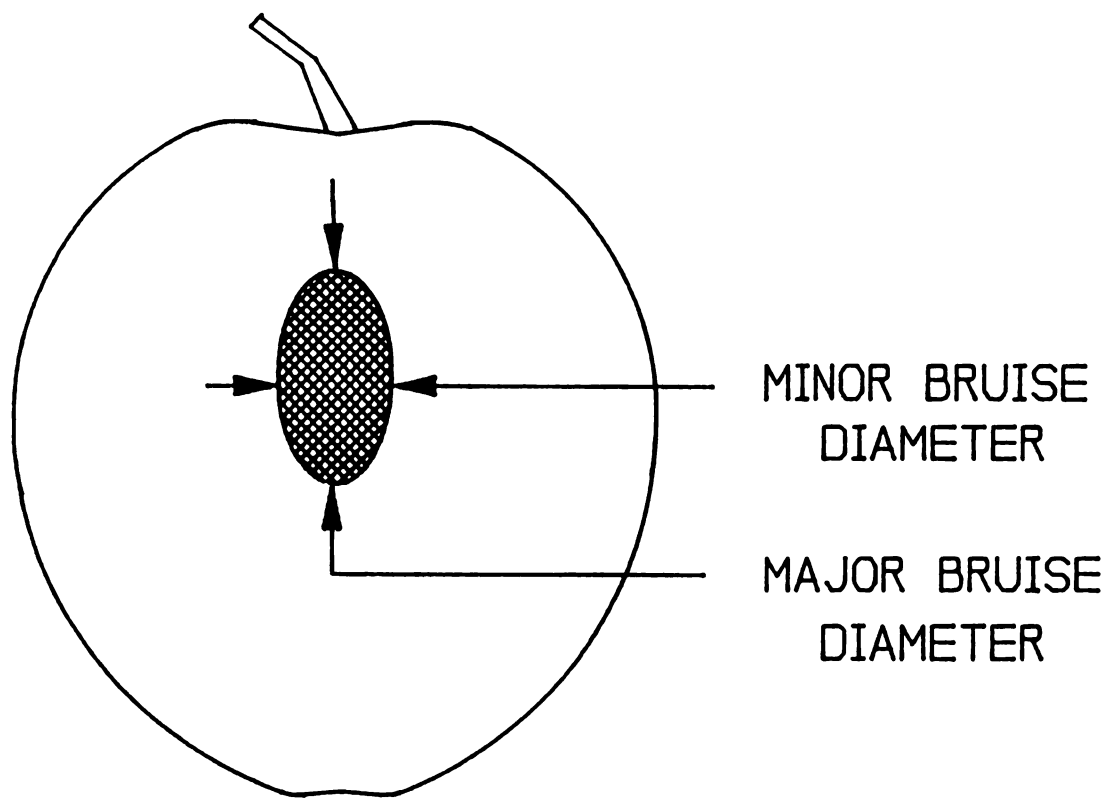


Figure 2.7 Bruise Diameter Measurements

R = Apple radius, mm

d = bruise diameter, mm

b = depth of bruise from the contact plane, mm

The variation of equation 2.2 used in this study is:

$$V = \left[\frac{\pi b}{24} (3d^2 + 4b^2) \right] \dots \dots \dots [2.3]$$

The first part of the original equation calculates the bruise volume below the contact plane and the second half calculates the volume above the contact plane, Figure 2.8. The mass of each apple was recorded and not the radius. The volume above the contact plane was assumed to be insignificant as shown by the area in Figure 2.8. and only the bruise volume below the contact plane was calculated.

It should be noted that both the bruise depth and bruise volume are only shown to illustrate the relationship of all bruise parameters when graphed. Since bruise diameter is the most widely used measure of apple quality, the focus of this study will be only on bruise average diameter and not the other bruise characteristics.

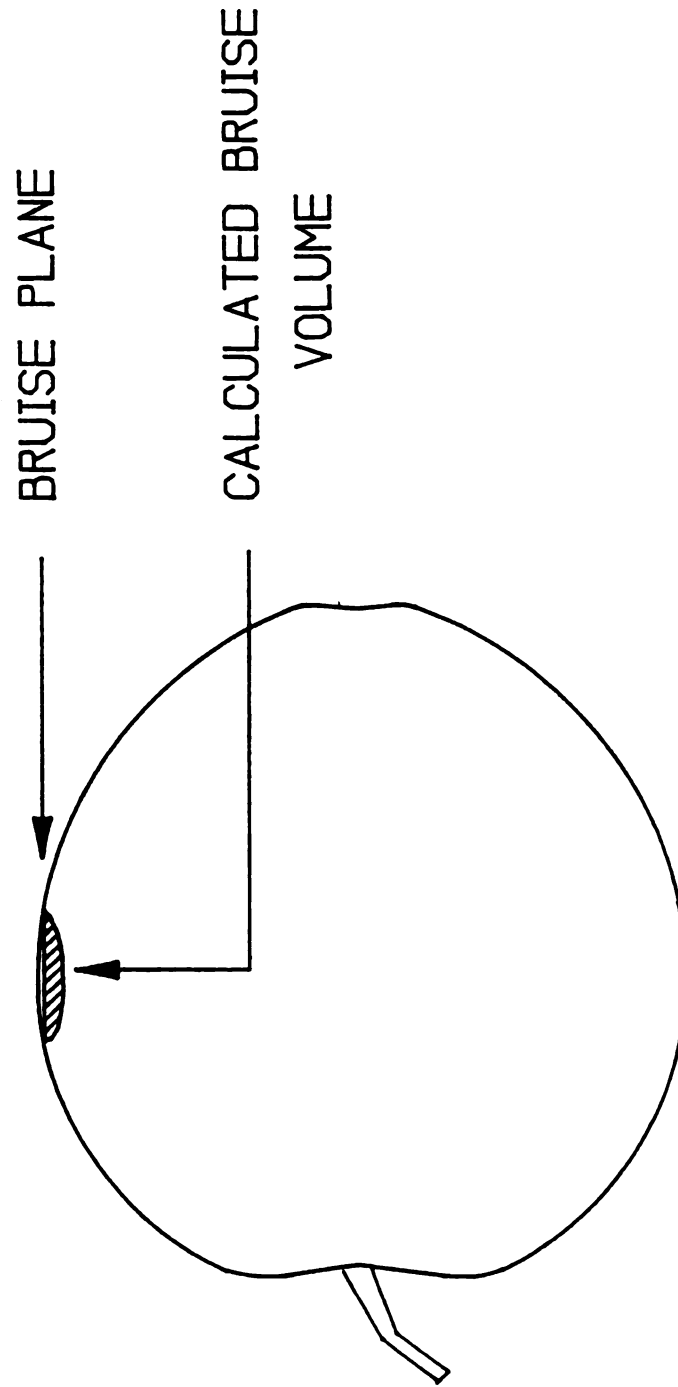


Figure 2.8 Calculated Bruise Volume

3. RESULTS AND DISCUSSION

3.1 Controlled Atmosphere Stored Apples

After all three size groups of Golden Delicious apples from the CA storage were dropped from all heights and onto each of the 3 calibrated surfaces, no bruising was visible on or below the surface of the apple.

This was probably due to the fact that the apples were soft enough (average Magness-Taylor firmness of 45 N) to act as their own cushions. Thus, by absorbing the energy of the impact no damage was incurred by the apples.

3.2 Fresh Apples: Medium and Large Velocity Change

Both fresh Paula Red and Golden Delicious apples showed no bruising on or below the surface. Thus, the medium-low, medium-high and large velocity change cases provided sufficient padding to inhibit bruising.

Even though the medium and large velocity change surfaces did not produce bruising, velocity change is still critical in apple bruising. There is still a velocity change at each peak G level at which bruising will occur.

3.3 Graphical Representation of the Data

Figures 3.1 through 3.36 show a graphical representation of the drop test data for Paula Red and Golden Delicious apples on steel. At each peak G level a

total of 5 apples were dropped, once on each opposite cheek, giving a total of 10 chances to bruise. Each point represents the average bruise characteristic of the bruises recorded for each peak G level and its standard error bar ($\pm$ one standard deviation). These characteristics include average bruise diameter, average bruise depth, average bruise volume and probability of bruising. The probability of bruising is the number of bruises recorded divided by the number of chances to bruise (10). The velocity change and duration accompanying each peak G are listed in Table 2.3. Bruise characteristics are represented in two different forms, those that were visible on the surface followed by those that were observed after peeling the skin away.

3.3.1 Paula Red Apples Tested.

Table 3.1 and Figures 3.1 through 3.18 represent the bruise characteristics for Paula Red apples. Table 3.1 shows a summary of the threshold of bruising and 100 percent bruising for each of the graphs. The fifth and sixth columns show the threshold of bruising and the average bruise diameter at that peak G level. Column 7 shows the peak G level at which 100 percent bruising occurred and column 8 shows the average bruise diameter at each peak G level.

3.3.2 General Trends in the Paula Red Apple Data

As shown by the graphs for Paula Red apples, the threshold for bruising decreases as the mass of the apples increases. Also, the peak G level where 100 percent

Table 3.1 Bruise Thresholds for Paula Red Apples

Fig. Num.	All Bruises Visible	Size	Days After Harvest	Threshold of Bruising (G's)	Avg. Bruise Dia. (mm)	100% Bruising (G's)	Avg. Bruise Dia. (mm)
3.1	Y	S	1	80	4.38	130	9.93
3.2	N	S	1	70	7.00	100	6.01
3.3	Y	M	1	80	6.37	110	9.91
3.4	N	M	1	40	4.25	90	7.95
3.5	Y	L	1	80	14.04	100	10.29
3.6	N	L	1	40	2.81	80	9.41
3.7	Y	S	3	100	7.40	130	10.71
3.8	N	S	3	70	5.40	80	6.18
3.9	Y	M	3	90	8.84	130	10.23
3.10	N	M	3	50	5.80	90	7.62
3.11	Y	L	3	80	9.19	*	11.62
3.12	N	L	3	40	5.60	130	10.67
3.13	Y	S	12	90	7.15	*	10.29
3.14	N	S	12	70	3.98	100	7.55
3.15	Y	M	12	80	7.05	130	10.44
3.16	N	M	12	60	3.78	70	5.58
3.17	Y	L	12	90	8.22	130	10.69
3.18	N	L	12	50	3.23	80	6.26

*100% bruising was never achieved.

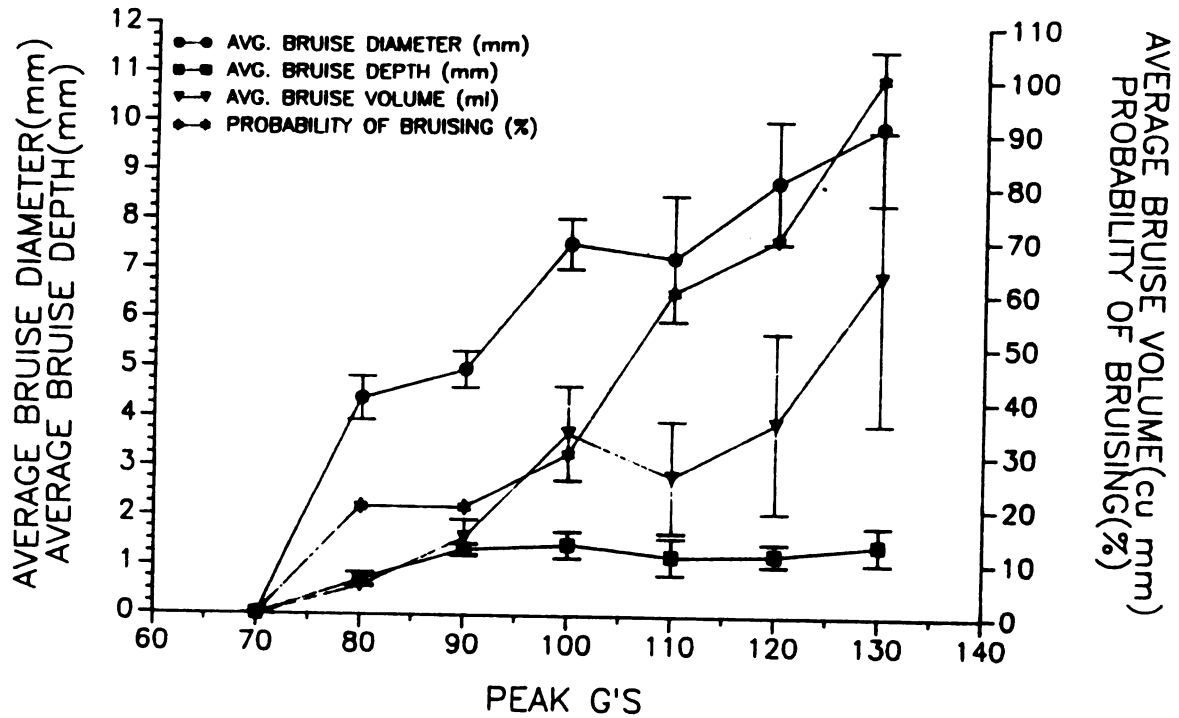


Figure 3.1 Visible Surface Bruises on Small, Paula Red Apples 1 Day After Harvest.

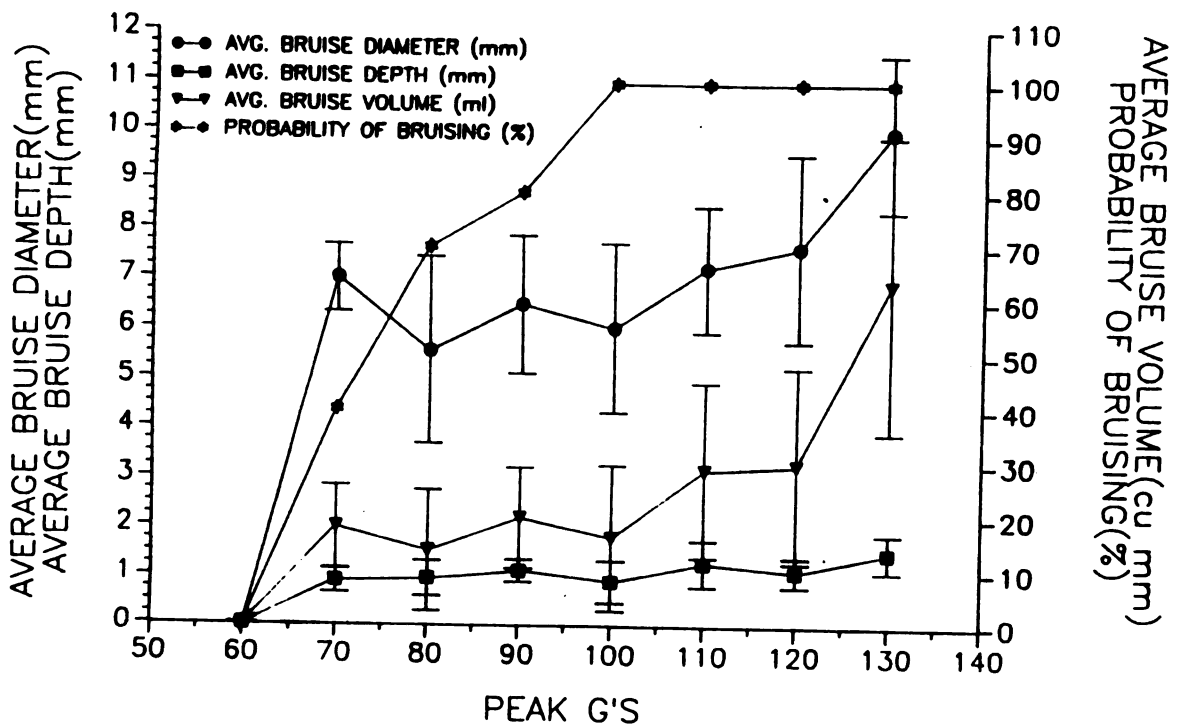


Figure 3.2 Bruises Observed After Peeling of Small, Paul Red Apples 1 Day After Harvest.

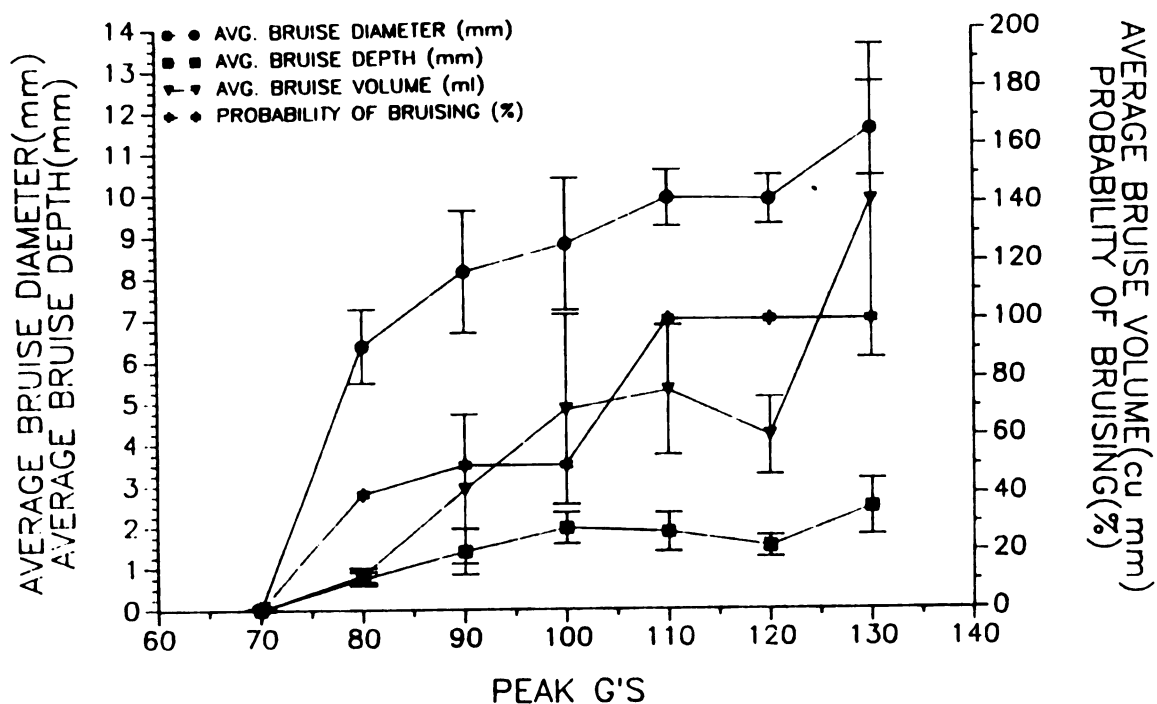


Figure 3.3 Visible Surface Bruises on Medium, Paula Red Apples 1 Day After Harvest.

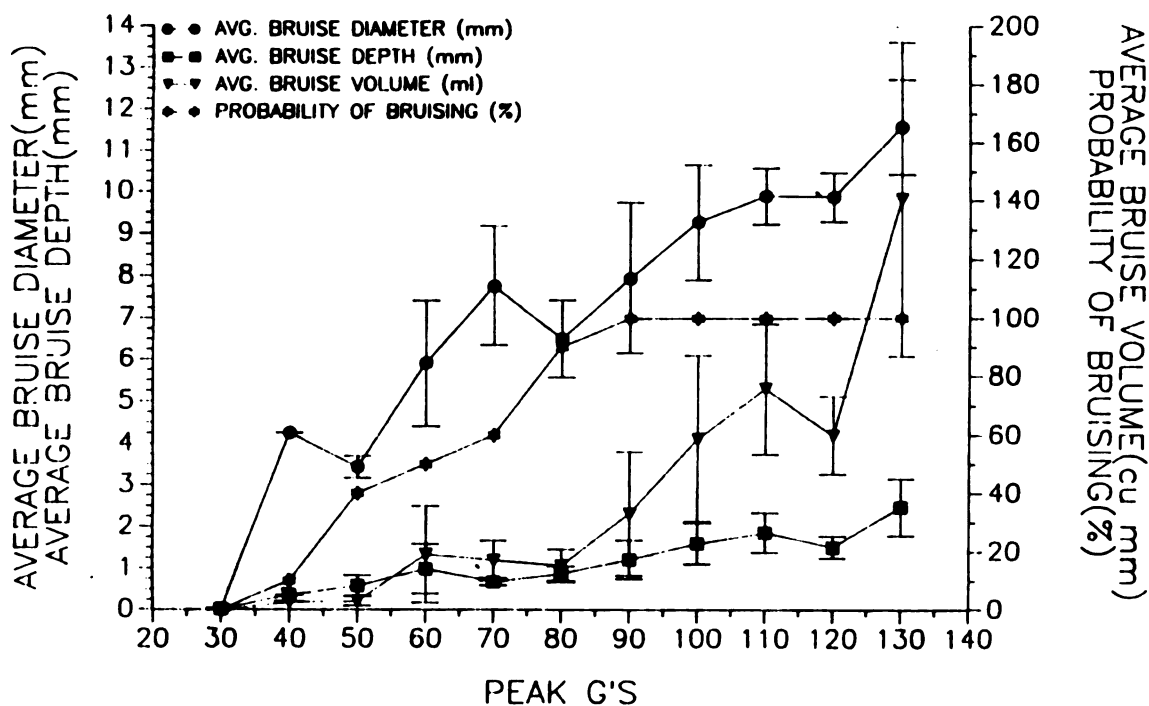


Figure 3.4 Bruises Observed After Peeling of Medium, Paula Red Apples 1 Day After Harvest.

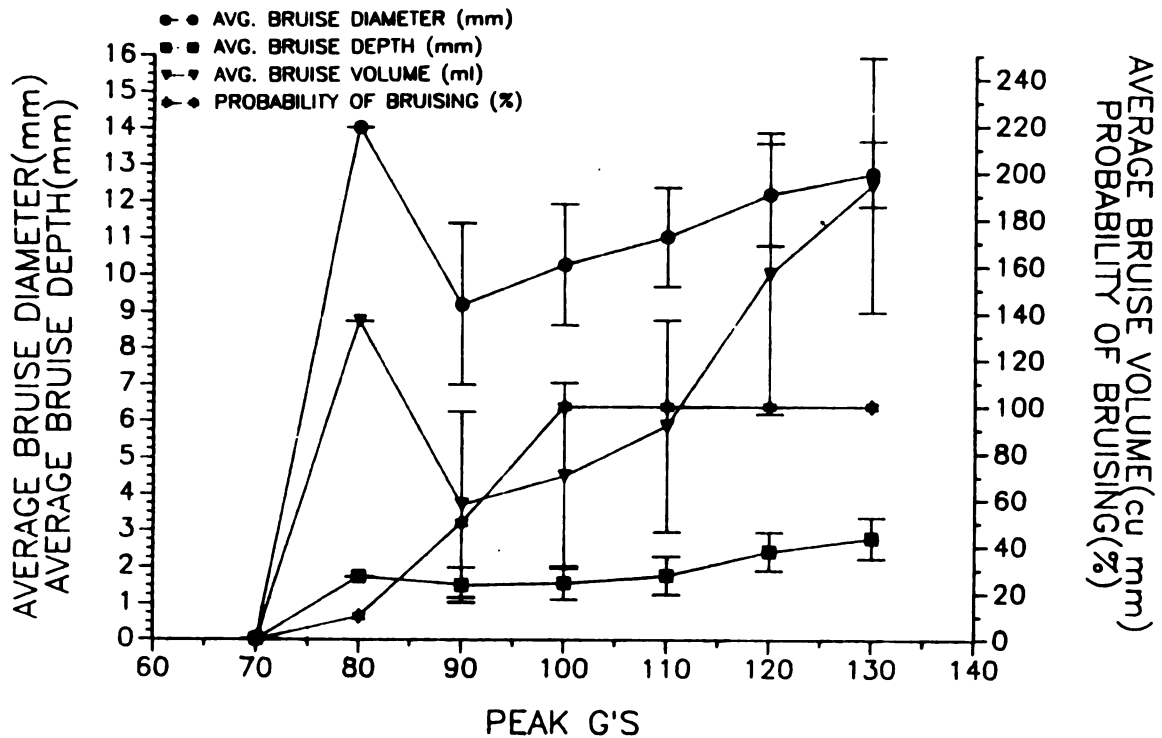


Figure 3.5 Visible Surface Bruises on Large, Paula Red Apples 1 Day After Harvest.

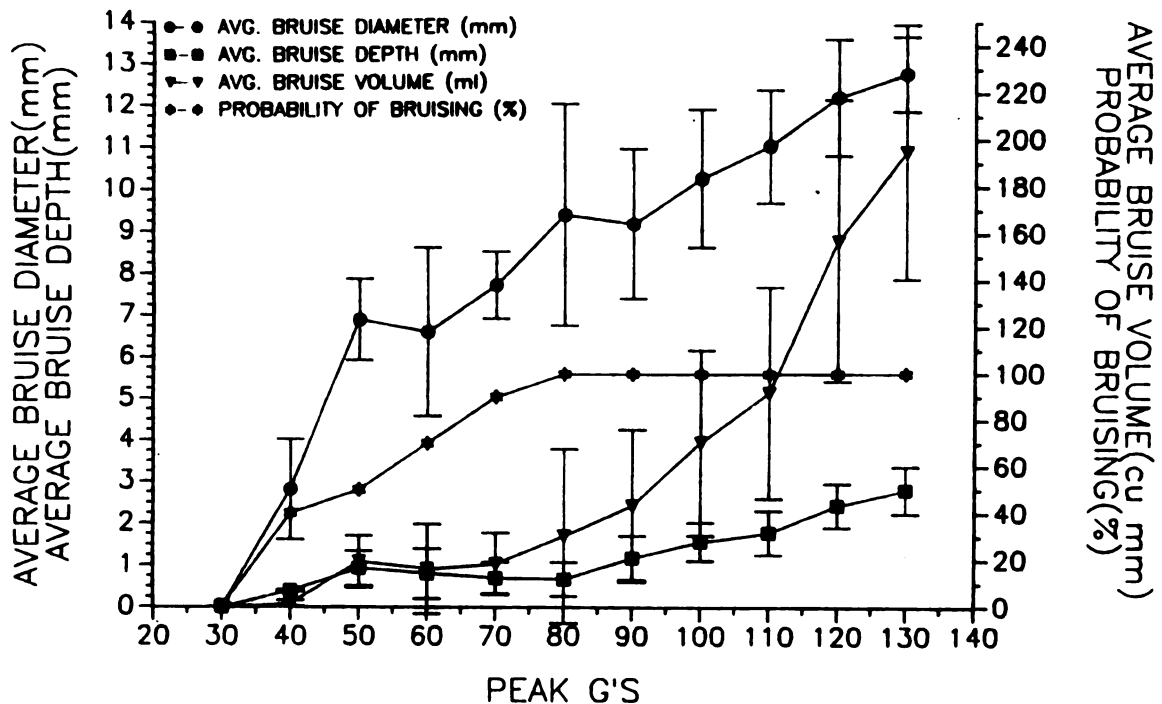


Figure 3.6 Bruises Observed After Peeling of Large, Paula Red Apples 1 Day After Harvest.

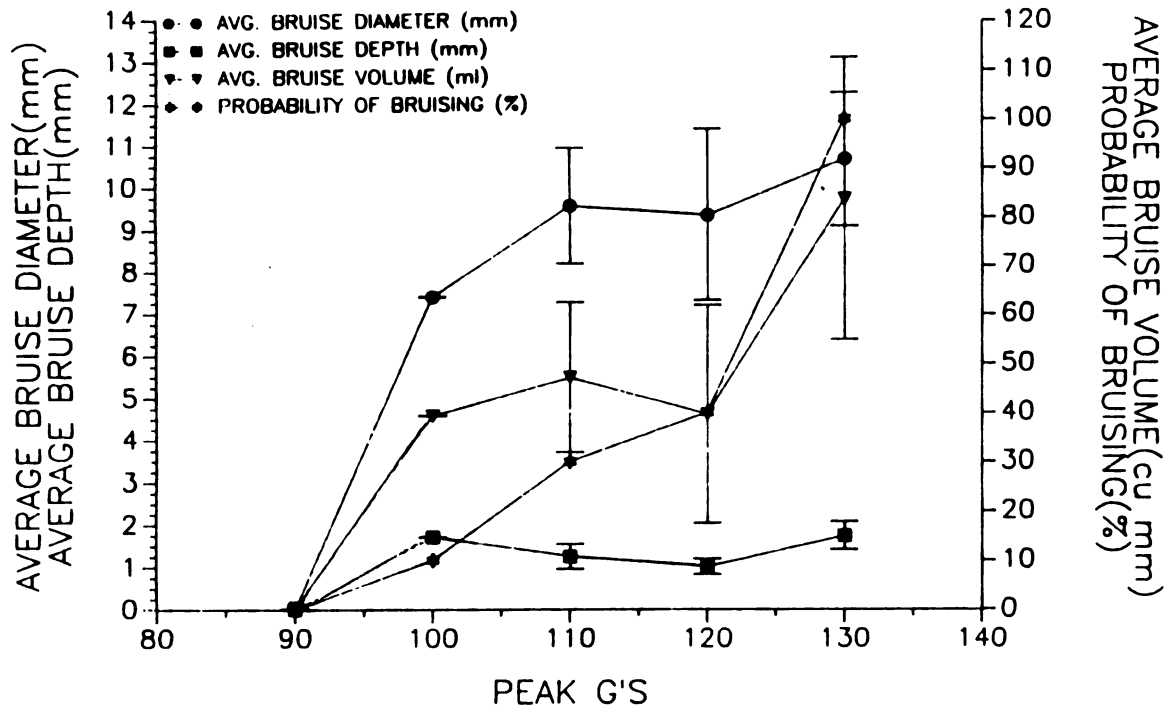


Figure 3.7 Visible Surface Bruises on Small, Paula Red Apples 3 Days After Harvest.

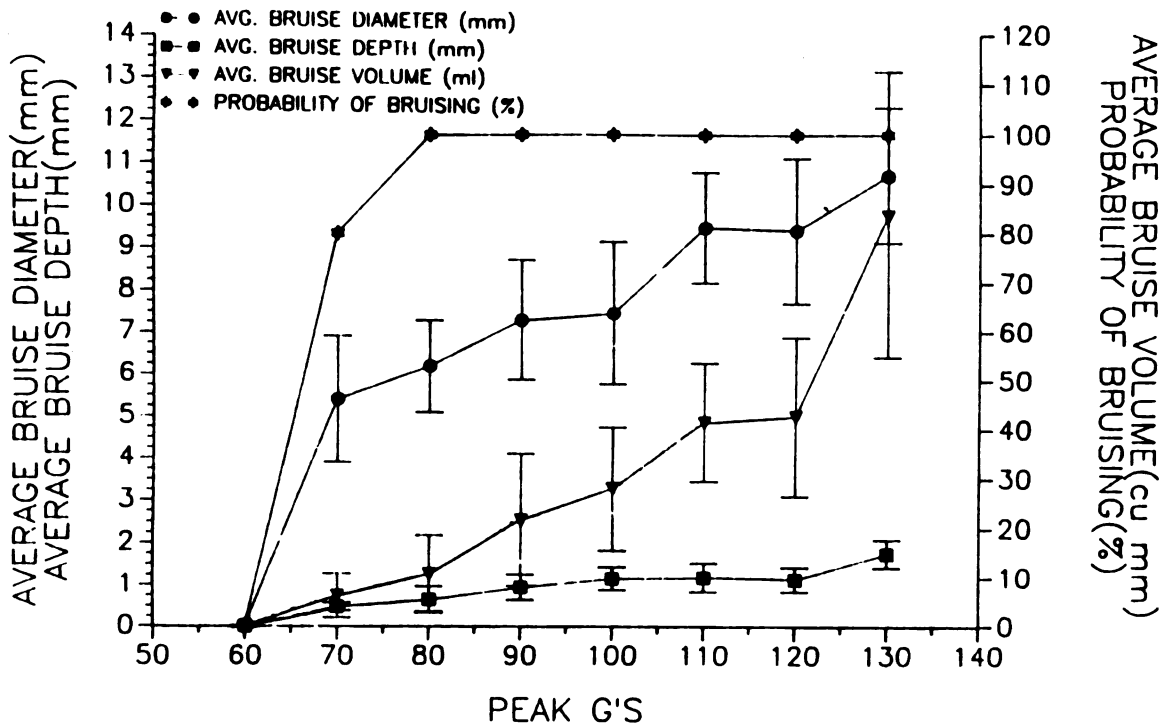


Figure 3.8 Bruises Observed After Peeling of Small, Paula Red Apples 3 Days After Harvest.

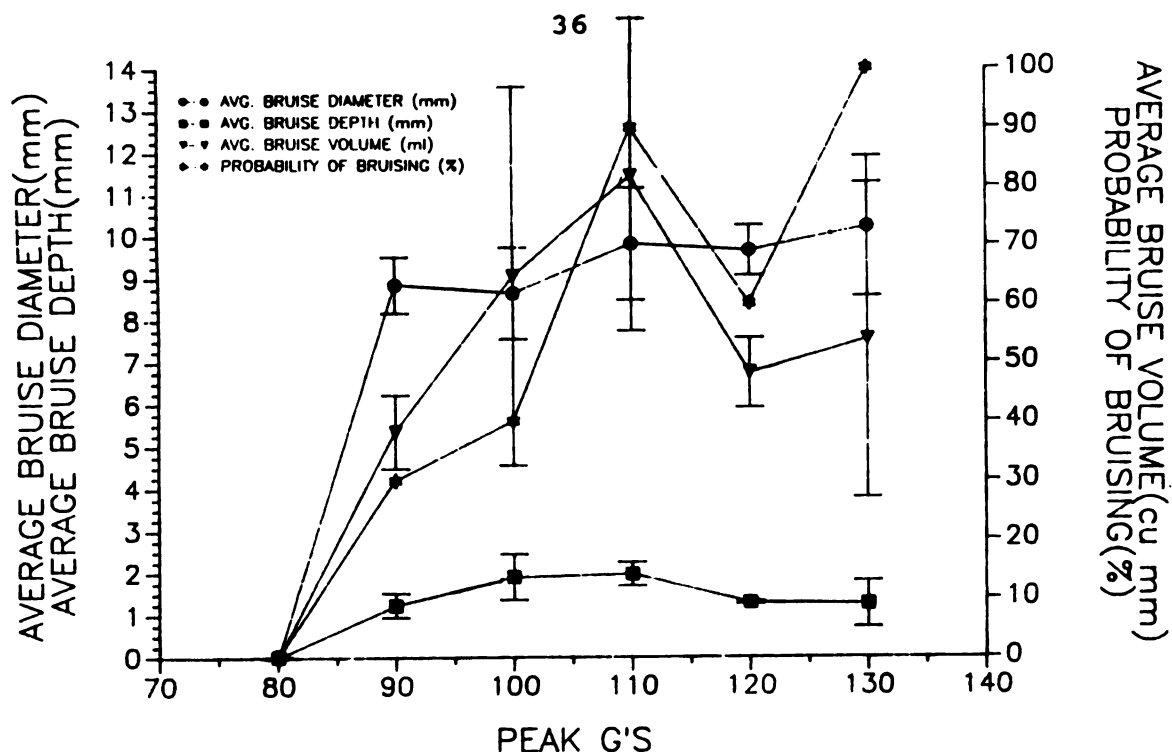


Figure 3.9 Visible Surface Bruises on Medium, Paula Red Apples 3 Days After Harvest.

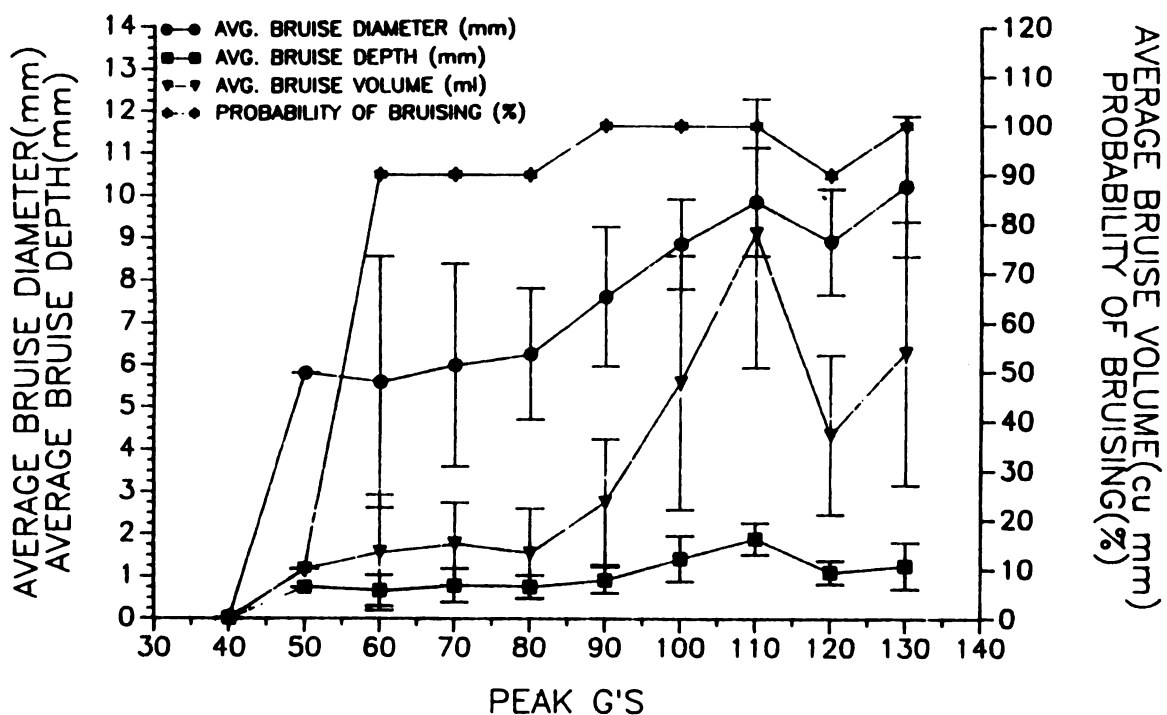


Figure 3.10 Bruises Observed After Peeling of Medium, Paula Red Apples 3 Days After Harvest.

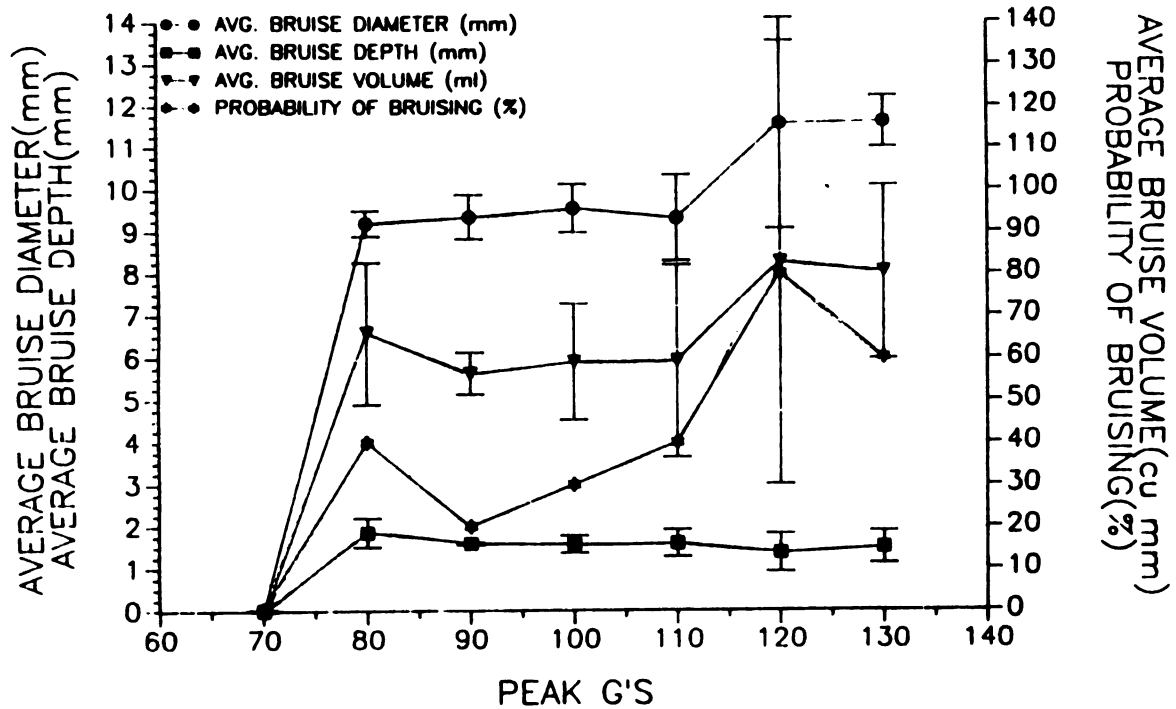


Figure 3.11 Visible Surface Bruises on Large, Paula Red Apples 3 Days After Harvest.

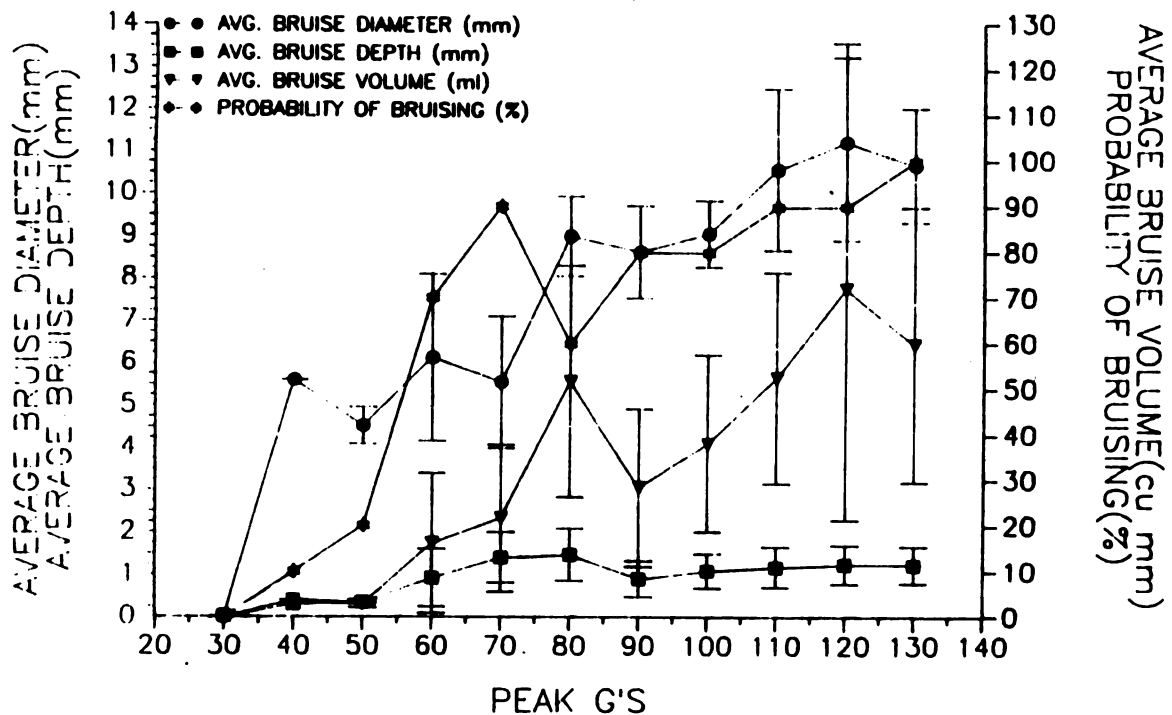


Figure 3.12 Bruises Observed After Peeling of Large, Paula Red Apples 3 Days After Harvest.

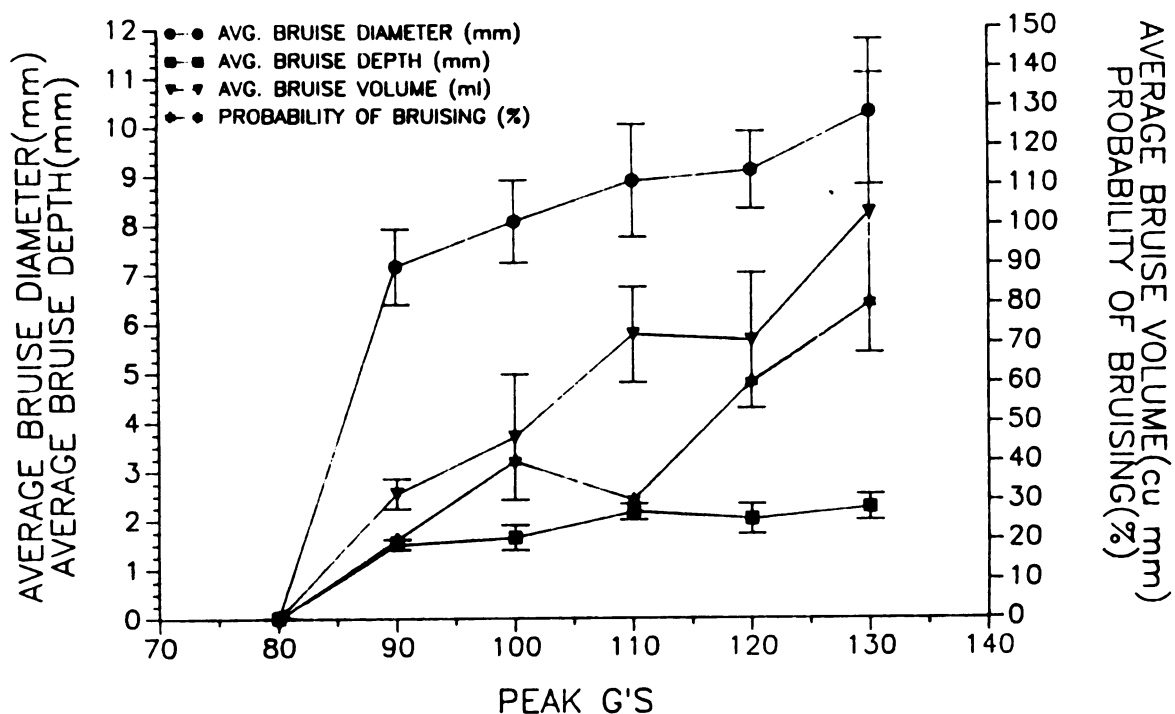


Figure 3.13 Visible Surface Bruises on Small, Paula Red Apples 12 Days After Harvest.

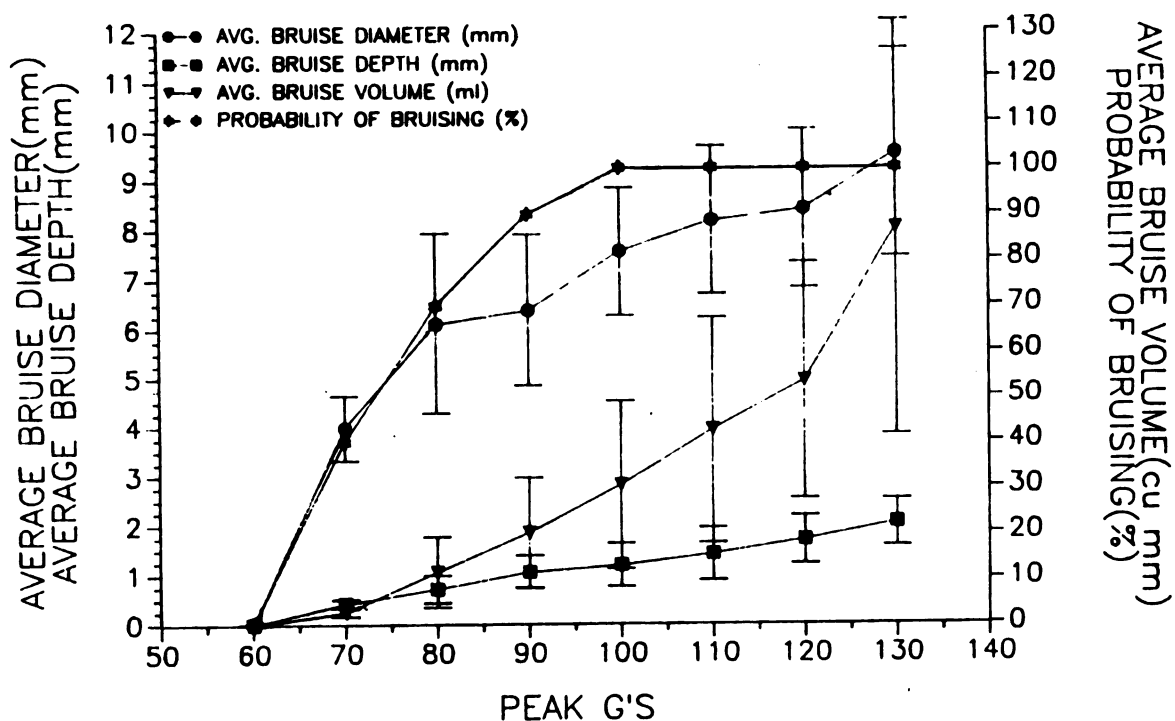


Figure 3.14 Bruises Observed After Peeling of Small, Paula Red Apples 12 Days After Harvest.

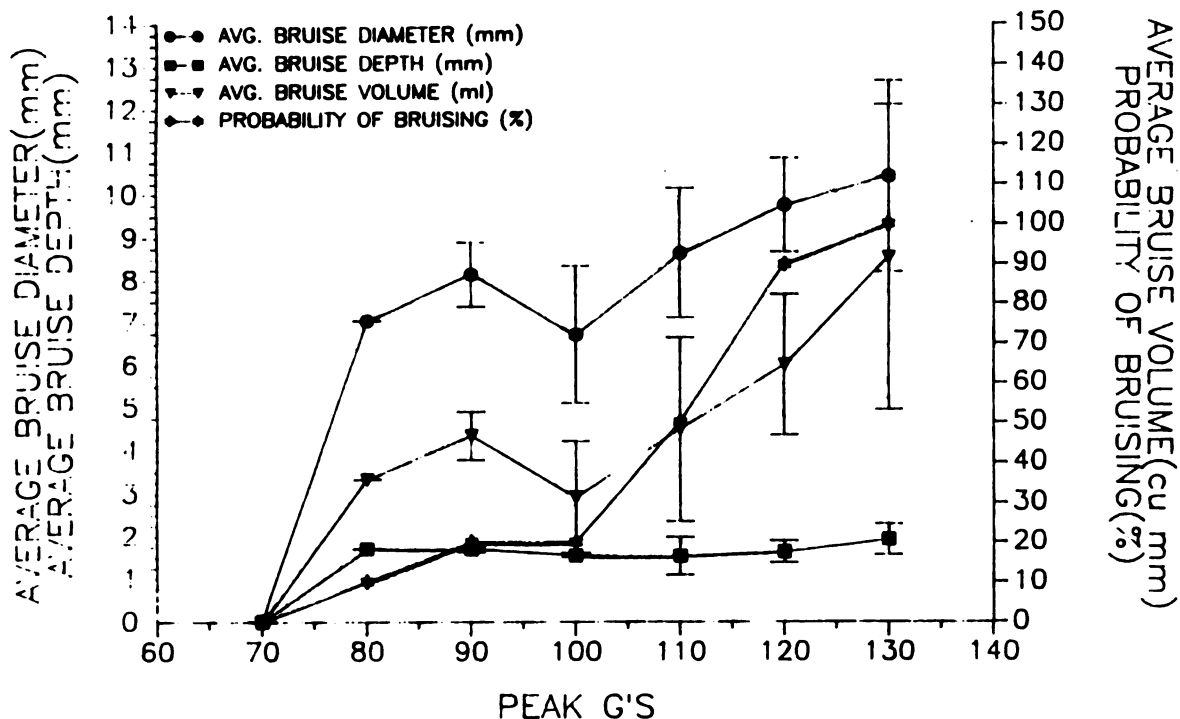


Figure 3.15 Visible Surface Bruises on Medium, Paula Red Apples 12 Days After Harvest.

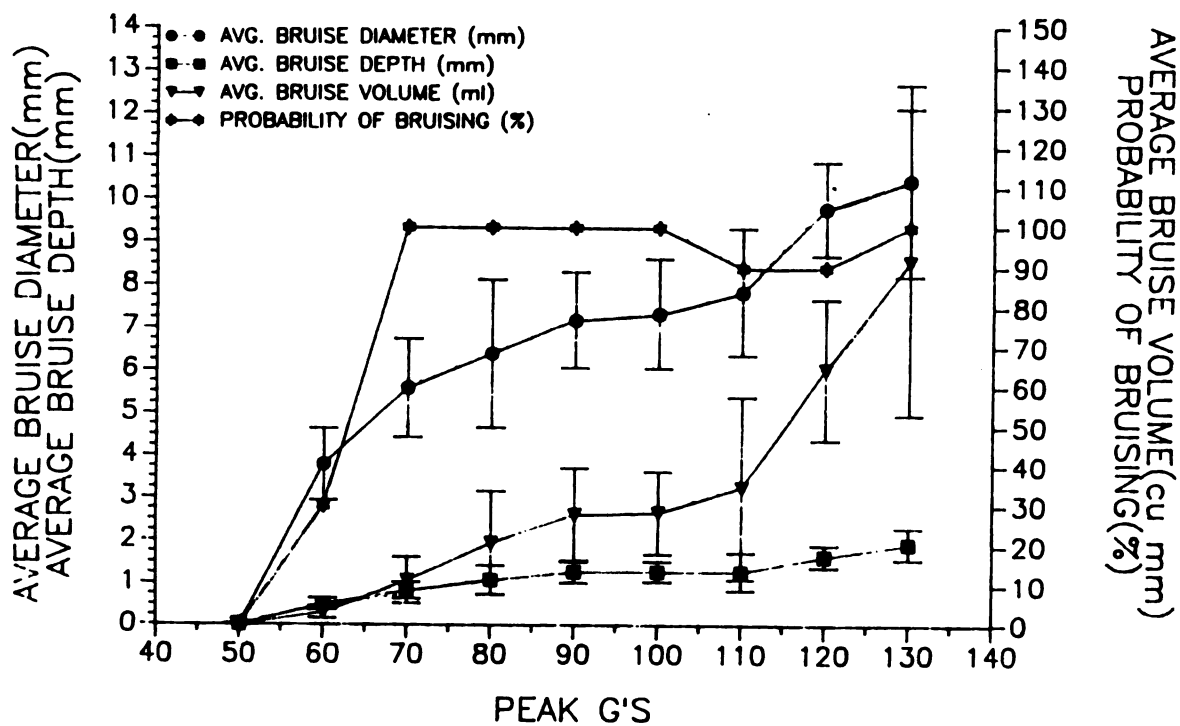


Figure 3.16 Bruises Observed After Peeling of Medium, Paula Red Apples 12 Days After Harvest.

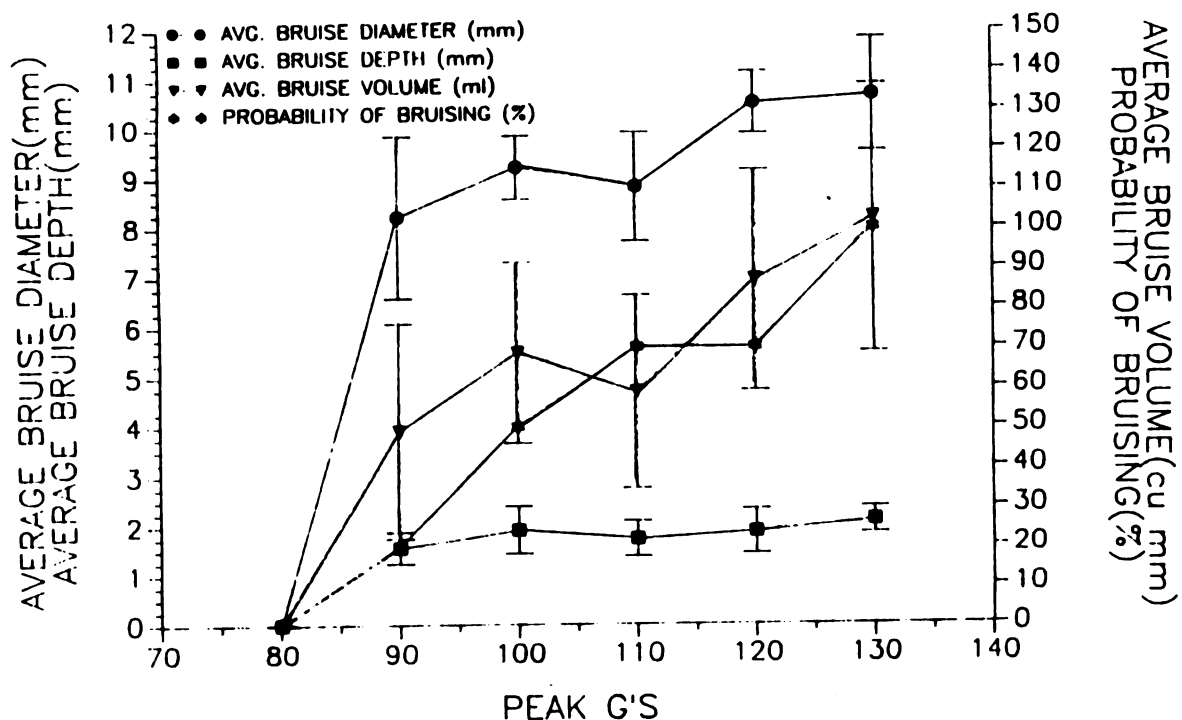


Figure 3.17 Visible Surface Bruises on Large, Paula Red Apples 12 Days After Harvest.

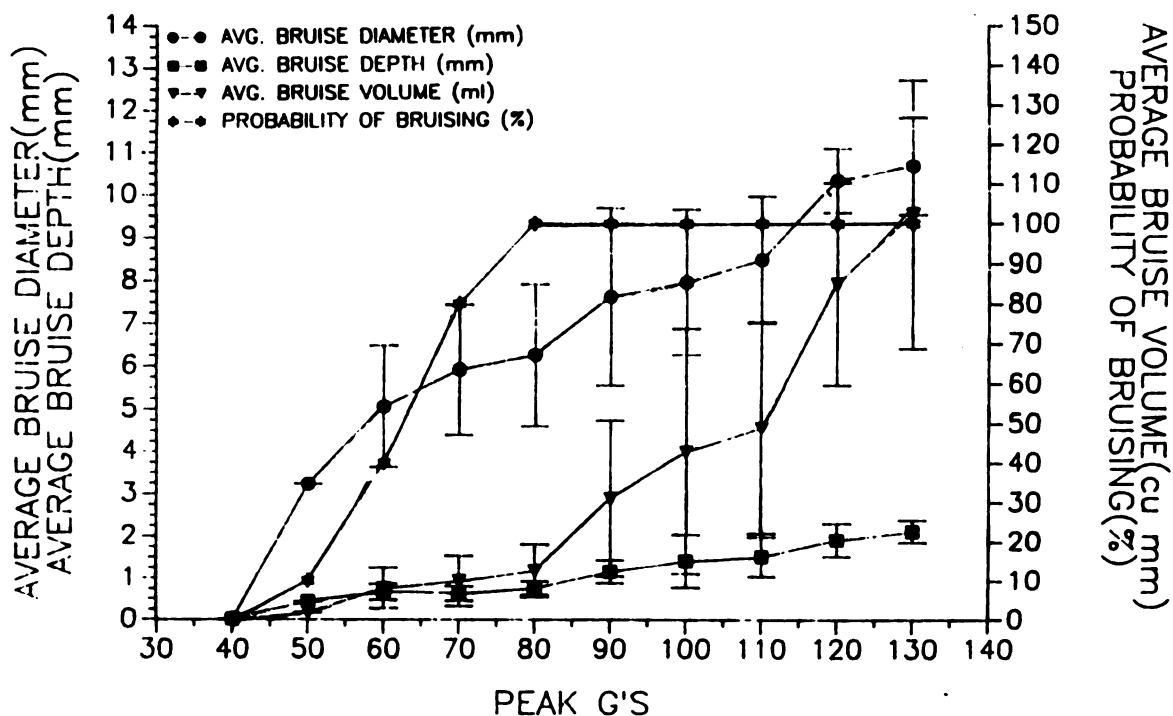


Figure 3.18 Bruises Observed After Peeling of Large, Paula Red Apples 12 Days After Harvest.

bruising occurs is lower for apples with a greater mass.

Days after harvest (1, 3 and 12 days) appear to decrease the average bruise diameter as the length of time the apples are stored increases. Also, the threshold of bruising and the peak G level at which 100 percent bruising occurs increase after the apple has been stored for a period of time. As shown by separate ongoing research, these trends may change if the period of storage was longer than 12 days.

The graphs also show that bruise depth and bruise volume increase as the peak G level increases. Note that the bruise volume tends to have a greater increase in size for each peak G level than the other characteristics tested.

3.3.3 Golden Delicious Apples Tested

Table 3.2 and Figures 3.19 through 3.36 represent the bruise characteristics for Golden Delicious apples. Table 3.2 shows a summary of the threshold of bruising and 100 percent bruising for each of the graphs. The fifth and sixth columns show the threshold of bruising and the average bruise diameter at that peak G level. Column 7 shows the peak G level at which 100 percent bruising occurred and column 8 shows the average bruise diameter at each peak G level.

3.3.4 General Trends in the Golden Delicious Apple Data

As shown by the graphs for Golden Delicious apples, the threshold for bruising moves to a lower peak G level as the mass of the apples increases. Also, the peak G level where

Table 3.2 Bruise Thresholds for Golden Delicious Apples

Fig. Num.	All Bruises Visible	Size	Days After Harvest	Threshold of Bruising (G's)	Avg. Bruise Dia. (mm)	100% Bruising (G's)	Avg. Bruise Dia. (mm)
3.19	Y	S	1	50	8.18	80	9.98
3.20	N	S	1	40	6.73	70	8.60
3.21	Y	M	1	50	9.09	70	9.51
3.22	N	M	1	50	8.24	70	9.51
3.23	Y	L	1	40	8.29	60	10.23
3.24	N	L	1	40	8.29	60	10.23
3.25	Y	S	3	50	6.28	90	9.69
3.26	N	S	3	40	6.49	90	9.69
3.27	Y	M	3	60	9.31	80	10.66
3.28	N	M	3	40	7.14	70	10.37
3.29	Y	L	3	50	10.57	50	10.57
3.30	N	L	3	30	4.16	50	10.57
3.31	Y	S	12	70	9.27	120	10.28
3.32	N	S	12	50	6.05	90	9.37
3.33	Y	M	12	70	9.59	110	11.01
3.34	N	M	12	50	6.33	110	10.69
3.35	Y	L	12	60	8.16	130	11.68
3.36	N	L	12	50	4.07	120	11.87

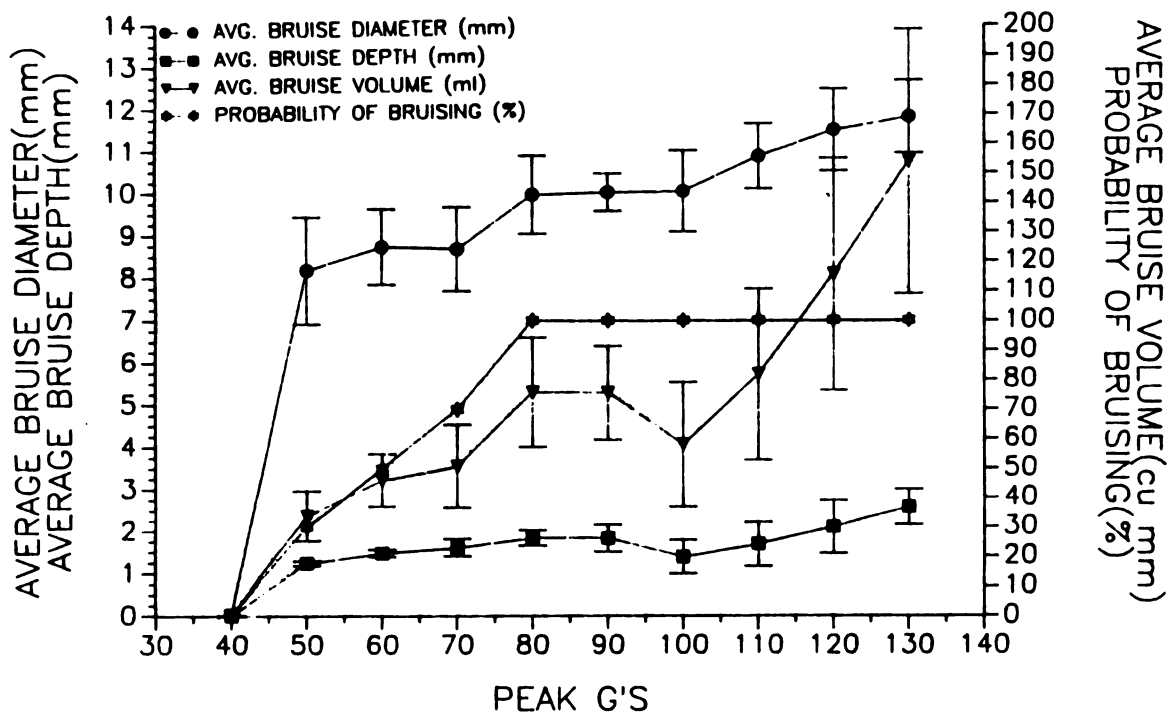


Figure 3.19 Visible Surface Bruises on Small, Golden Delicious Apples 1 Day After Harvest.

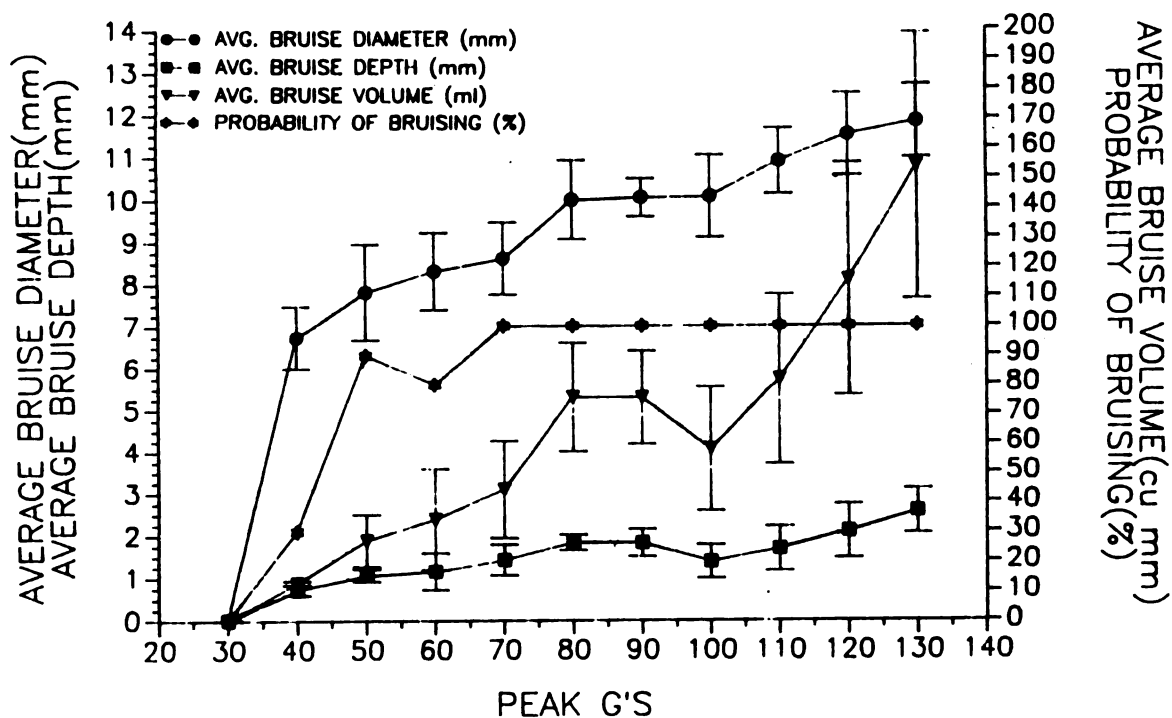


Figure 3.20 Bruises Observed After Peeling of Small, Golden Delicious Apples 1 Day After Harvest.

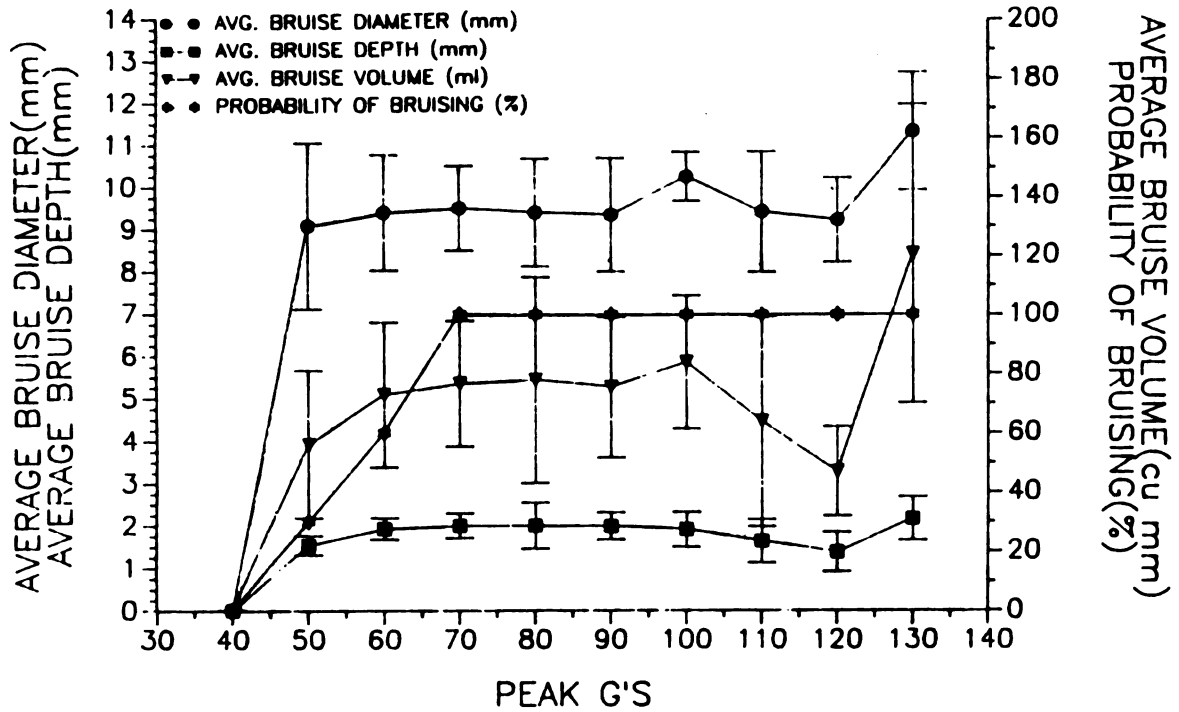


Figure 3.21 Visible Surface Bruises on Medium, Golden Delicious Apples 1 Day After Harvest.

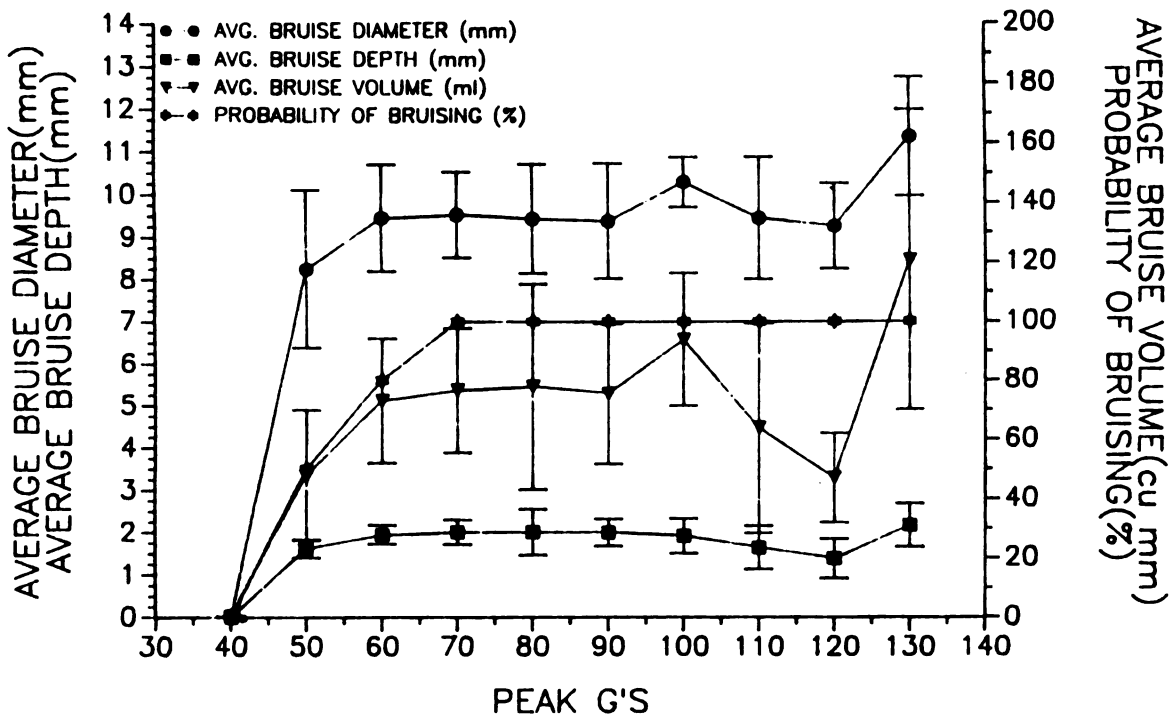


Figure 3.22 Bruises Observed After Peeling of Medium, Golden Delicious Apples 1 Day After Harvest.

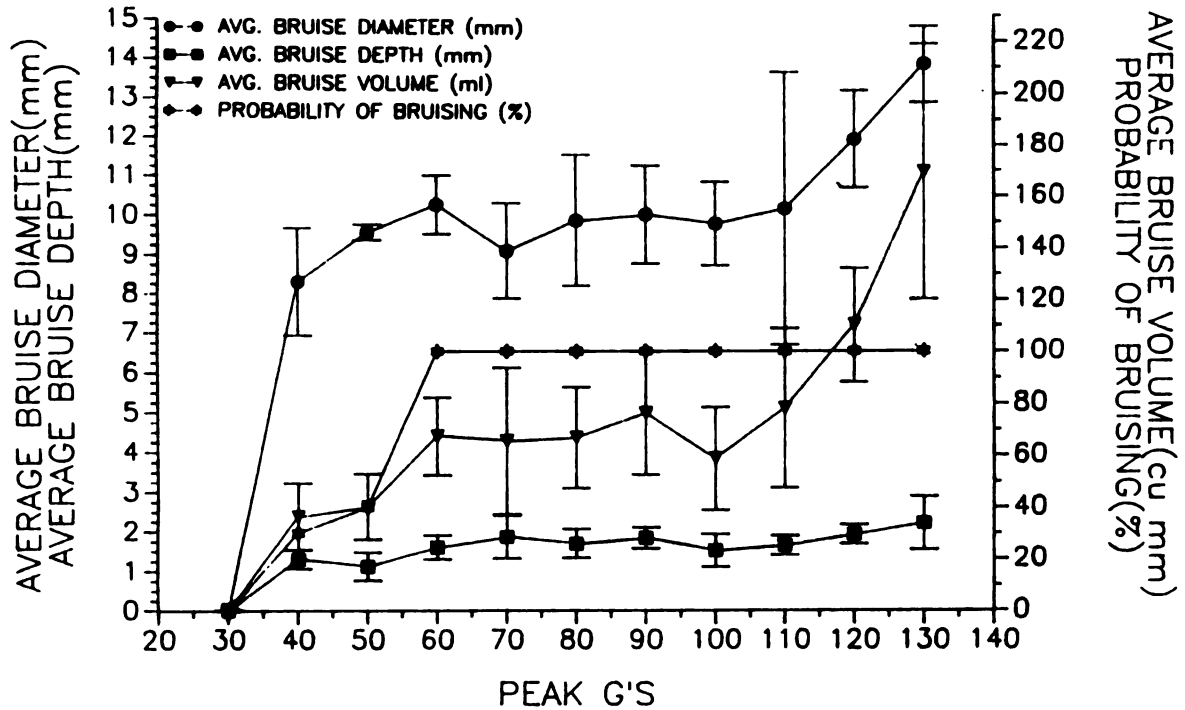


Figure 3.23 Visible Surface Bruises on Large, Golden Delicious Apples 1 Day After Harvest.

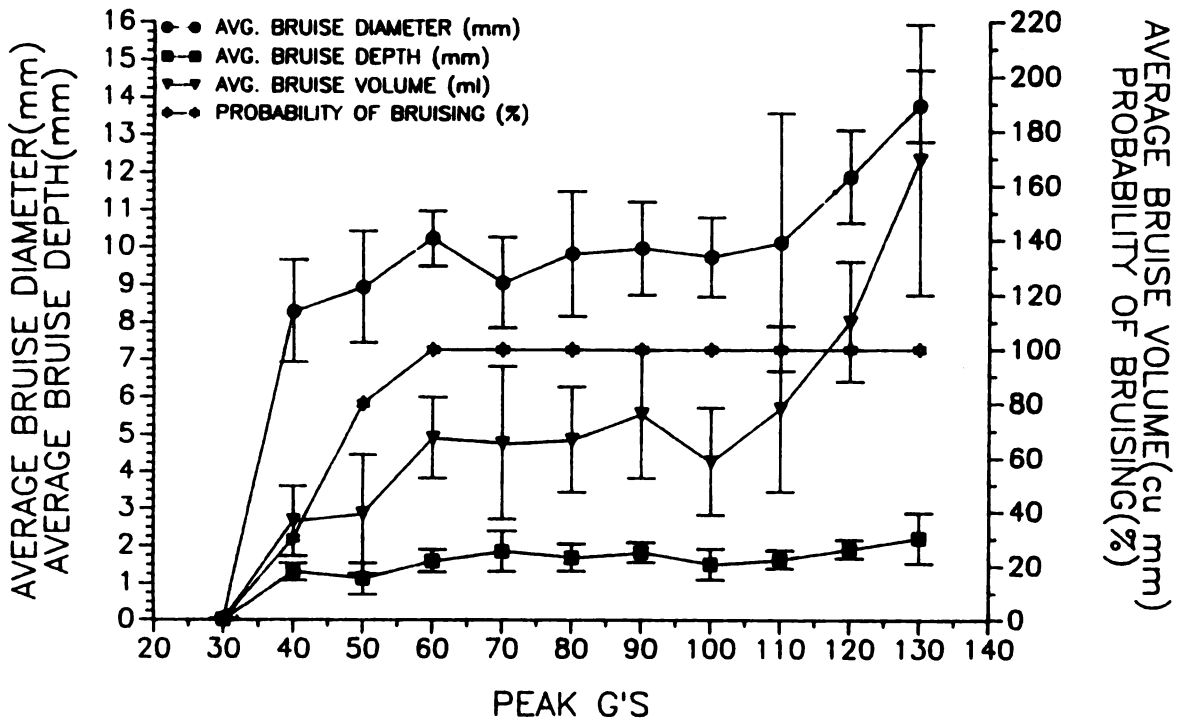


Figure 3.24 Bruises Observed After Peeling of Large, Golden Delicious Apples 1 Day After Harvest.

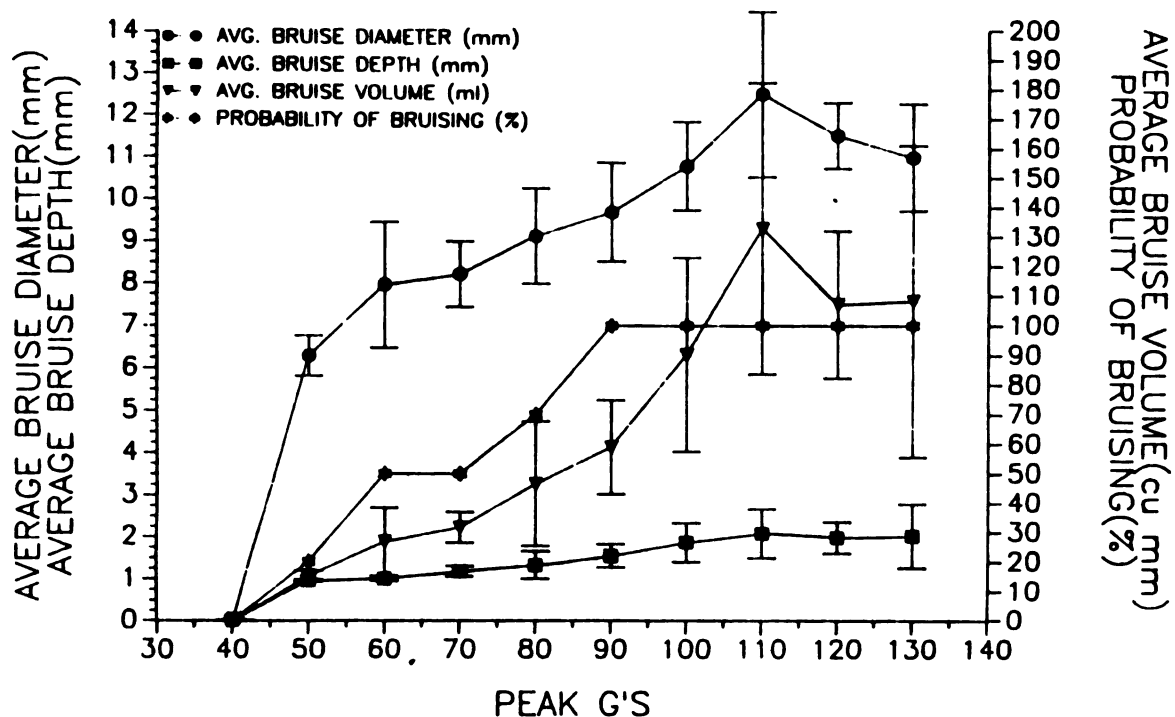


Figure 3.25 Visible Surface Bruises on Small, Golden Delicious Apples 3 Days After Harvest.

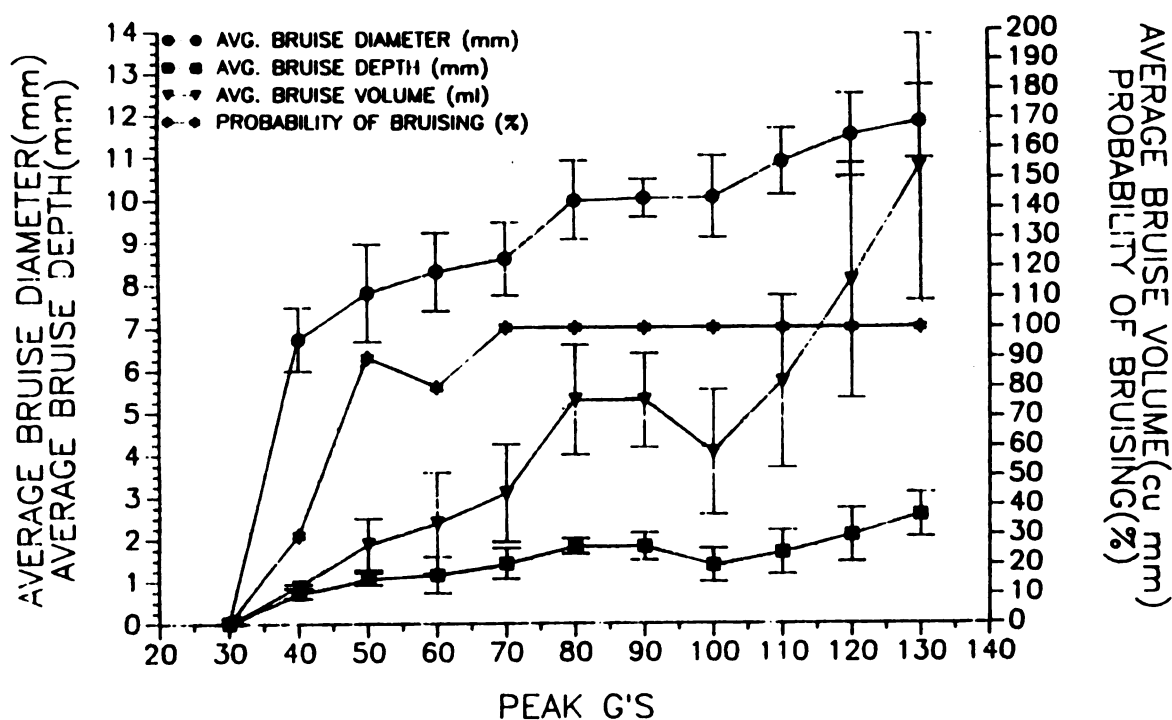


Figure 3.26 Bruises Observed After Peeling of Small, Golden Delicious Apples 3 Days After Harvest.

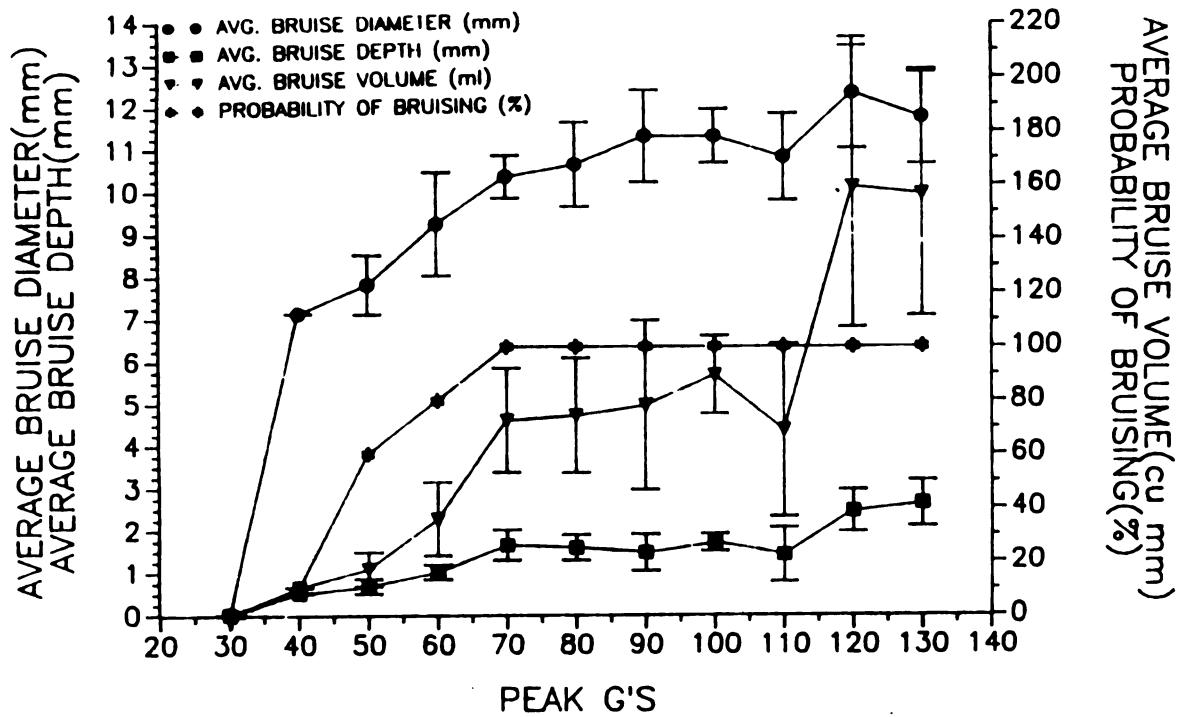


Figure 3.27 Visible Surface Bruises on Medium, Golden Delicious Apples 3 Days After Harvest.

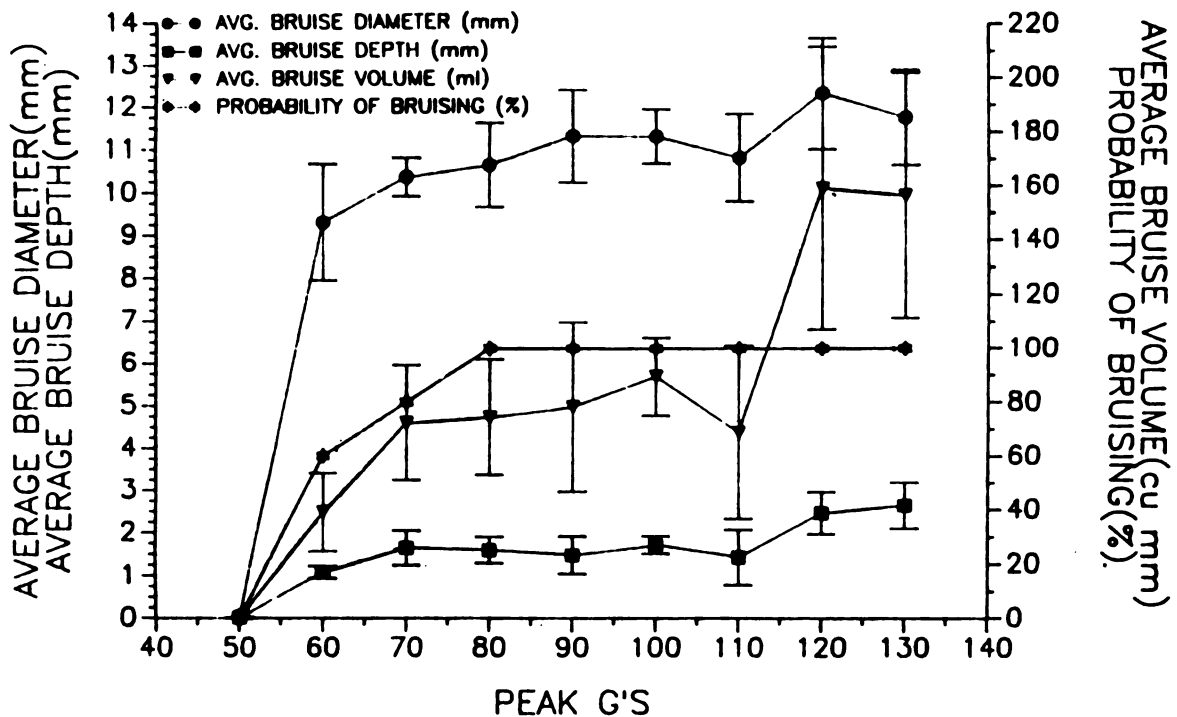


Figure 3.28 Bruises Observed After Peeling of Medium, Golden Delicious Apples 3 Days After Harvest.

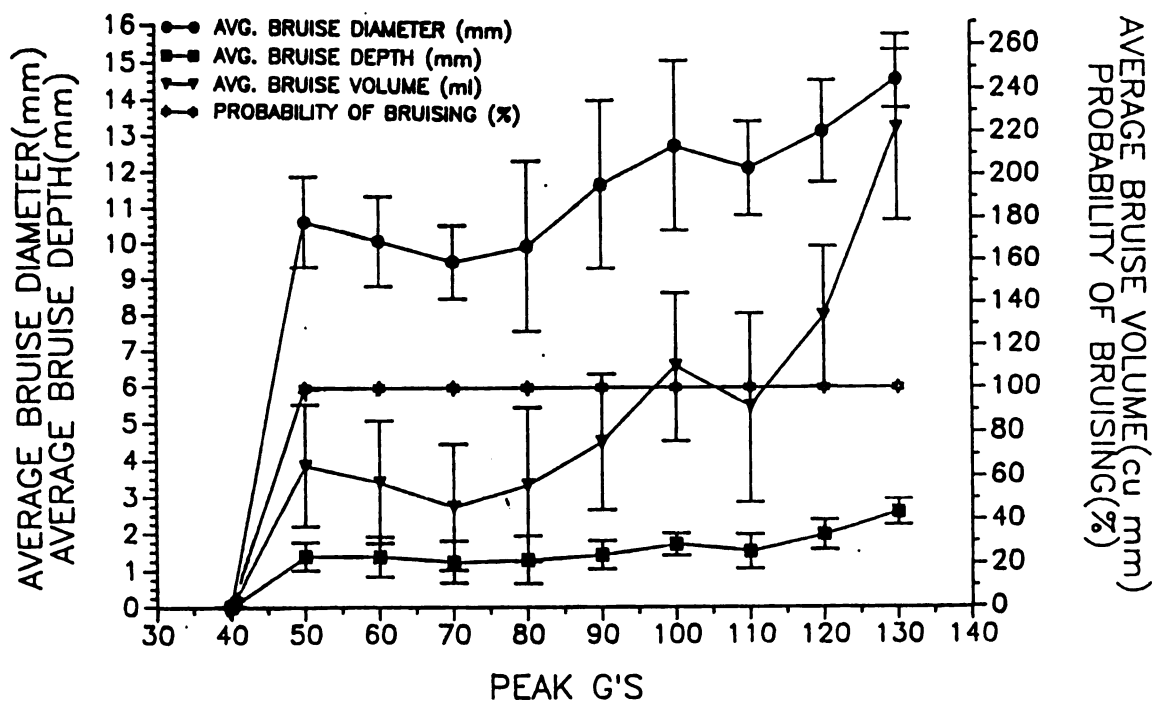


Figure 3.29 Visible Surface Bruises on Large, Golden Delicious Apples 3 Days After Harvest.

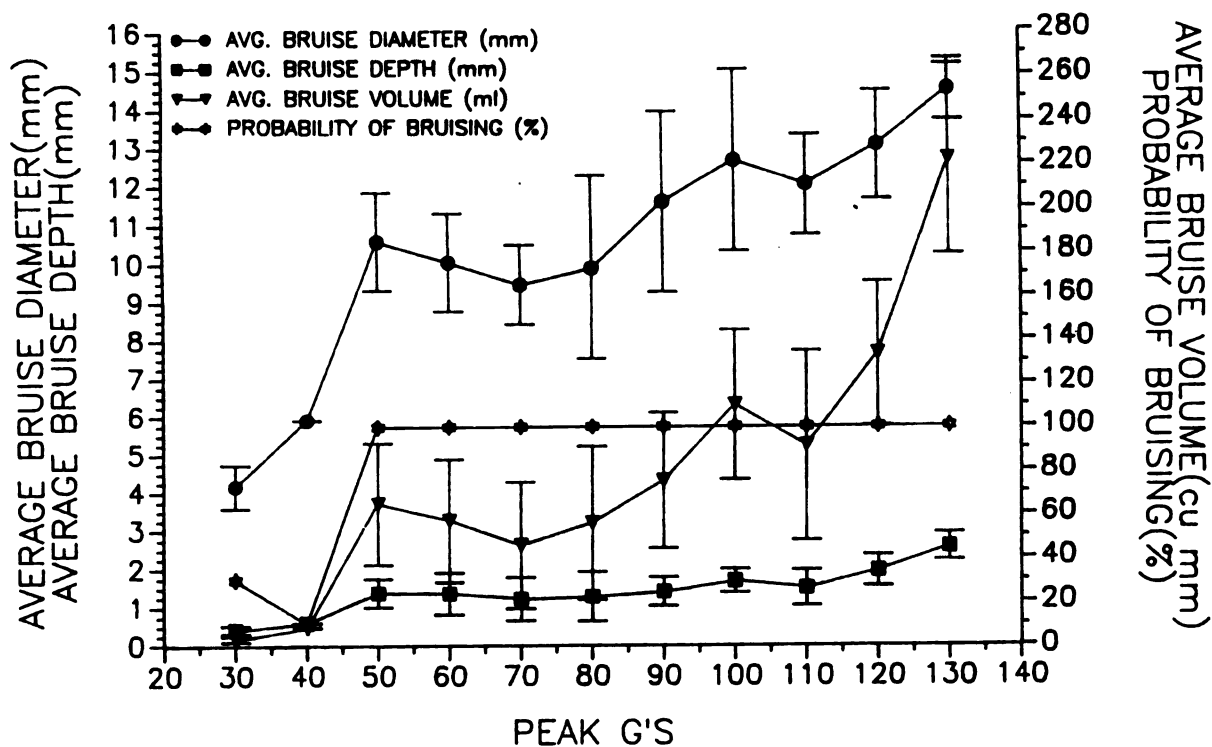


Figure 3.30 Bruises Observed After Peeling of Large, Golden Delicious Apples 3 Days After Harvest.

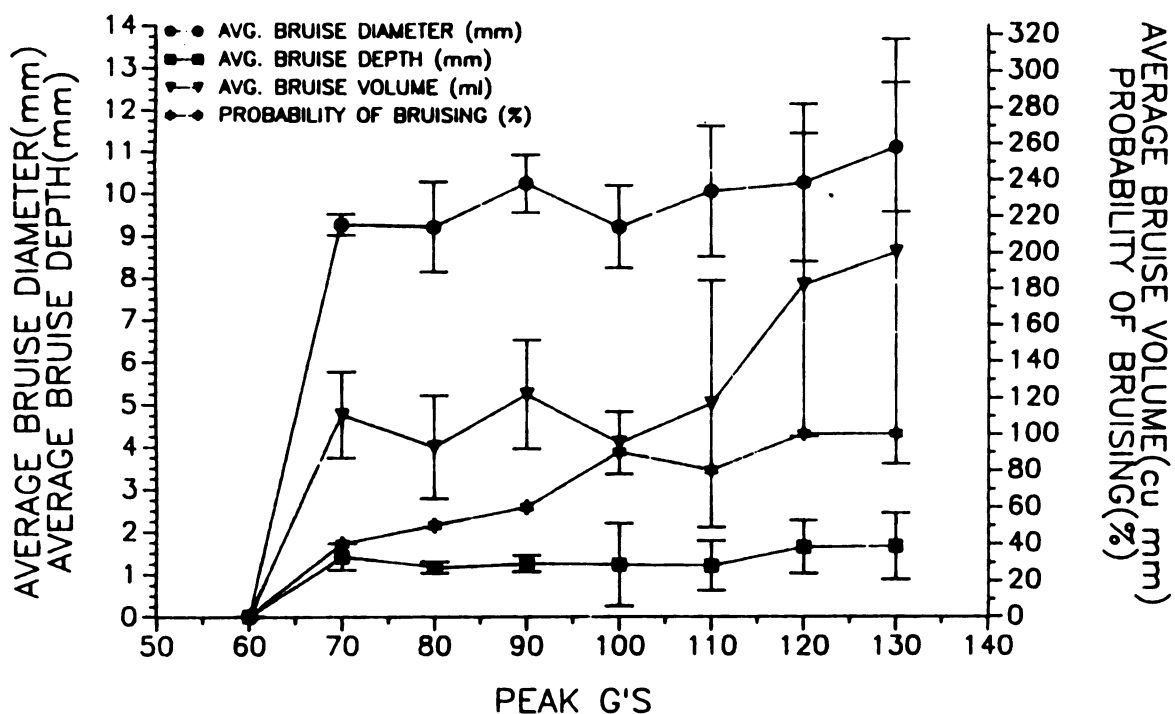


Figure 3.31 Visible Surface Bruises on Small, Golden Delicious Apples 12 Days After Harvest.

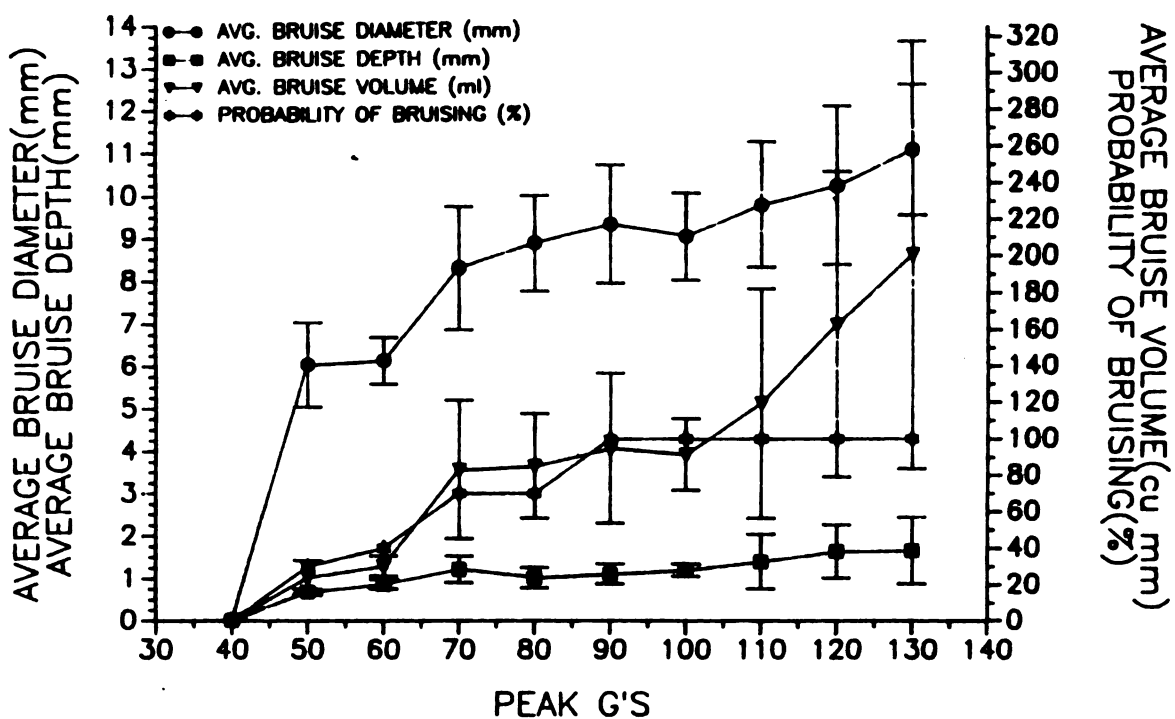


Figure 3.32 Bruises Observed After Peeling of Small, Golden Delicious Apples 12 Days After Harvest.

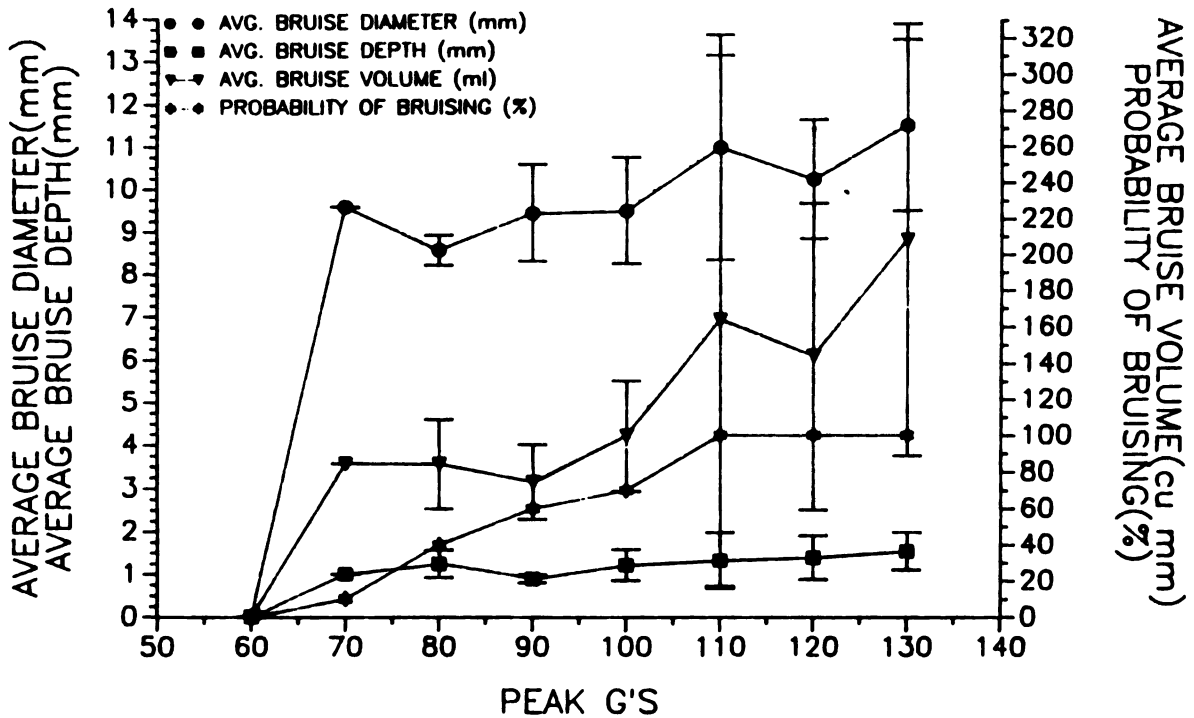


Figure 3.33 Visible Surface Bruises on Medium, Golden Delicious Apples 12 Days After Harvest.

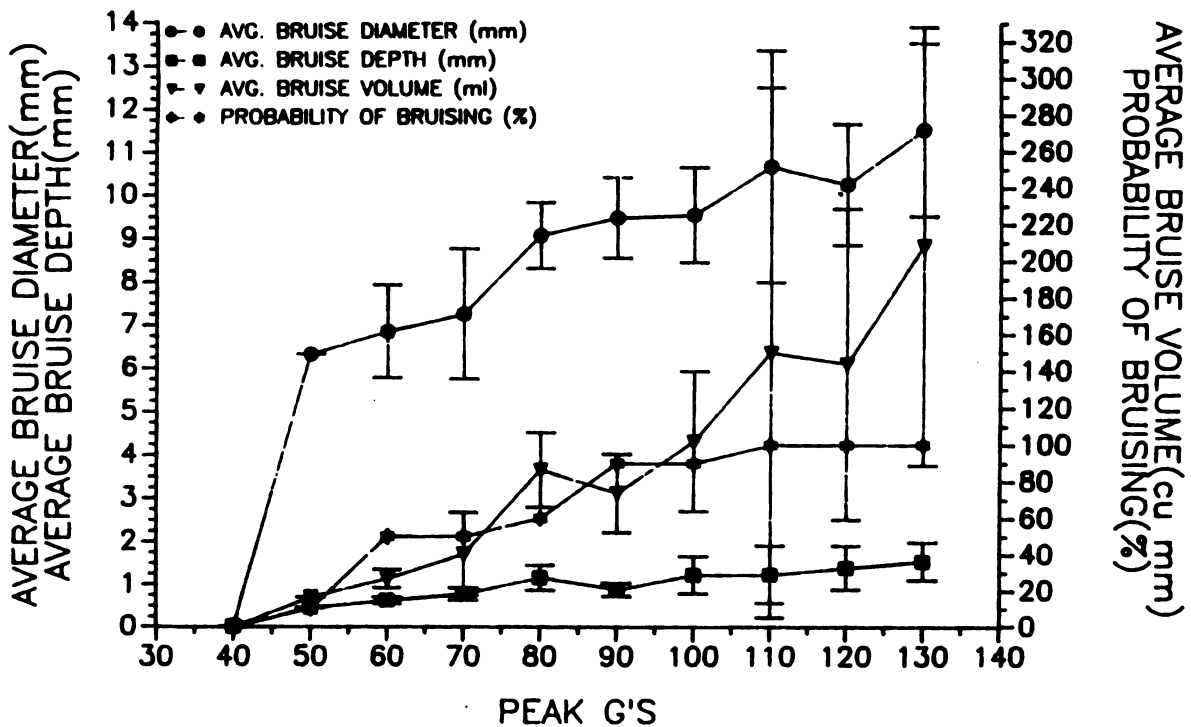


Figure 3.34 Bruises Observed After Peeling of Medium, Golden Delicious Apples 12 Days After Harvest.

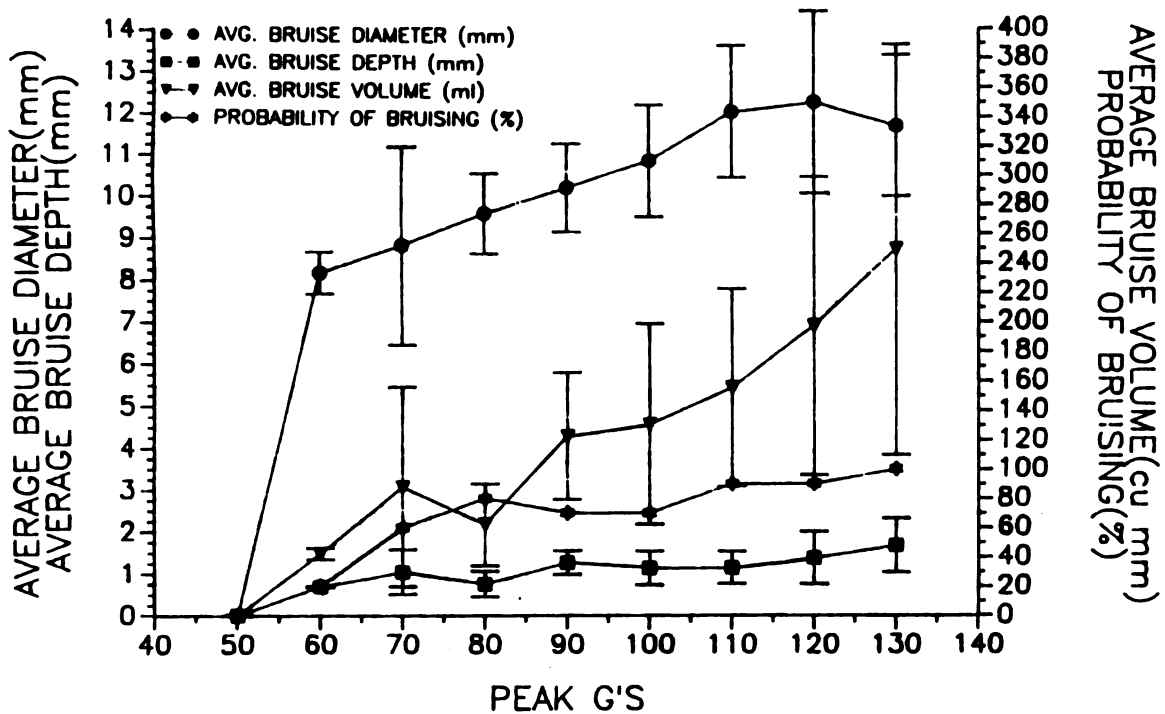


Figure 3.35 Visible Surface Bruises on Large, Golden Delicious Apples 12 Days After Harvest.

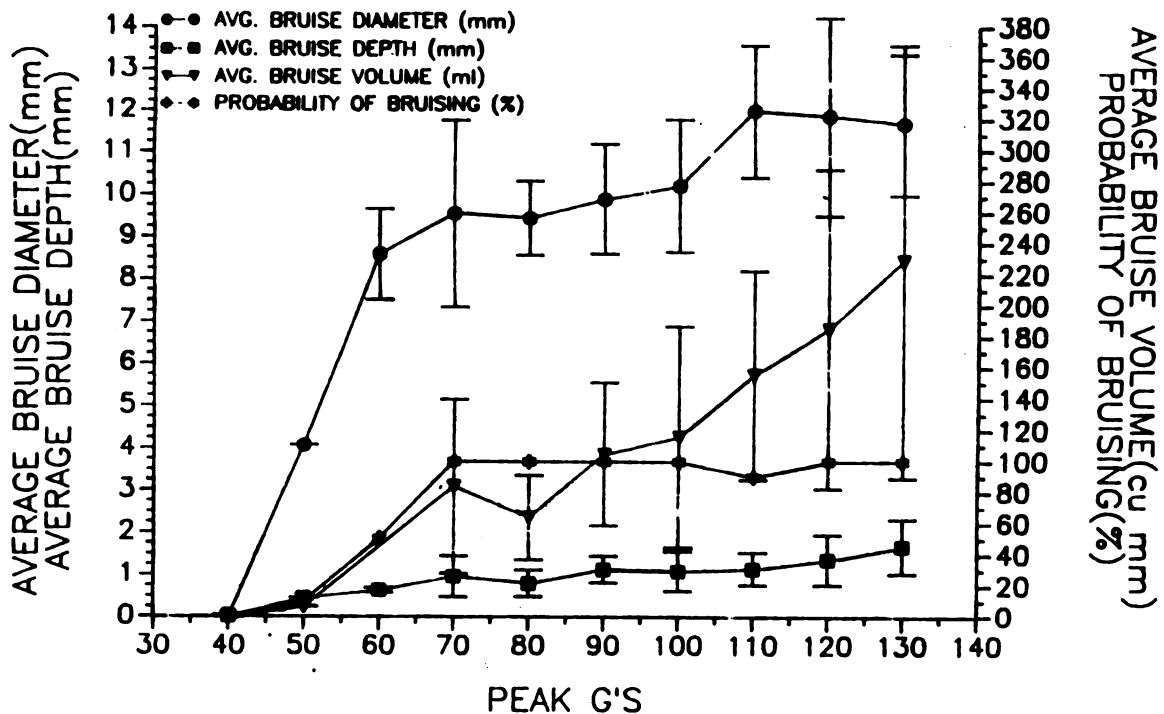


Figure 3.36 Bruises Observed After Peeling of Large, Golden Delicious Apples 12 Days After Harvest.

100 percent bruising occurs is lower for apples with a greater mass.

Days after harvest (1, 3 and 12 days) appear to decrease the average bruise diameter as the length of storage time increases. Also, the threshold of bruising and peak G level at which 100 percent bruising occurs increased after the apples have been stored for a period of time.

As with the Paula Red apples, the graphs show that bruise depth and bruise volume increase as the peak G level increases. Note that the bruise volume increases more rapidly and seems to be more responsive to the peak G level. It is also interesting to note that in the range from 80 g to 120 g there is a noticeable dip in bruise volume in almost every Golden Delicious apple test.

3.4 Minimum Thresholds of Bruising

From the above data it can be concluded that the Paula Red apples have a threshold of visible bruising at 80 g on steel. At this peak G level, 20 percent of the small, 40 percent of the medium and 10 percent of the large apples bruised 1 day after harvest. At 3 days after harvest 20 percent of the large apples bruised at this threshold, while medium and small did not bruise at this impact level.

Paula Red apples had a threshold for observable bruising after peeling at 40 g. At this level 40 percent of the large apples and 10 percent of the small apples displayed bruising 1 day after harvest. However, no medium apples bruised 1 day after harvest at this level. At 3 days

after harvest 10 percent of the large apples bruised at the 40 g threshold, with no bruising occurring in the small and medium apples.

Golden Delicious apples had a threshold for visible surface bruising at 40 g on steel. At this peak G level, 30 percent of the large apples tested 1 day after harvest displayed bruising, while the small and medium Golden Delicious apples did not bruise.

Golden Delicious apples had a threshold for observable bruising after peeling at 30 g. At this level 30 percent of the large apples tested 3 days after harvest were bruised. No other apple sizes bruised at this G level.

Although low G levels may only produce bruises below the surface of the apples, and are not visible to the consumer, apples that show bruising after peeling will still not satisfy the consumer. Therefore, apple packing lines should be designed or modified to keep impacts below the peak G at which any bruising occurs.

In the above experiments, the lowest threshold for bruising, after peeling, was at 40 g for Paula Red apples and 30 g for Golden Delicious apples. To assure that apples are not bruised on the cheek area by the packing lines, peak G levels recorded on commercial apple lines should be held below the 30 g level. An even lower level is probably necessary to avoid bruising on the small radius portions of the apple on the blossom and stem ends.

3.5 Statistical Analysis

The data used for the multiple linear regression analysis (MLRA) were from the groups of apples that displayed 100 percent bruising. Groups of apples that did not show 100 percent bruising were excluded due to the high variability of bruising near the threshold level. Thus, all values used are the average of 10 bruises to provide better estimates. All MLRA models were based on forward stepping regression analysis. Also in the following analysis " R^2 " is used to represent the coefficient of determination for MLRA models and " r^2 " is used to represent the coefficient of determination for linear regression analysis (LRA) models.

3.5.1 MLRA Model for Paula Red Apples

The dependent variable for the MLRA model is the average bruise diameter of 10 bruises at a given peak G level which caused 100 percent of the apples to bruise. There were a total of 42 cases in the analysis which left 41 degrees of freedom. See Appendix A.2 for the complete statistical report.

The independent variables available for the analysis were; days after harvest; peak G level; velocity change; apple mass; and apple flesh firmness. After analysis the resulting equation explained 84.8 percent ($R^2=0.848$) of the variation in the average bruise diameter (ABD) of the apples:

$$ABD = 0.875 + 3.04DV + 0.0345M + 0.0572G - 0.123D - 0.0789F$$

Where: ABD = Average bruise diameter of 10 apples, mm

DV = Velocity change, m/s

M = Average apple Mass, g

G = Peak acceleration, g

D = Days after harvest

F = Average apple Magness-Taylor firmness, N

Figure 3.37 shows the predicted bruise diameter versus the measured bruise diameter. The linear regression line is shown with confidence belts for the predicted bruise diameter at the 95 percent level. Thus, there is a 95 percent probability the values will be in range of the confidence belts.

The sensitivity of this model was tested by inputting values into the equation that were in the mid-range and the extremes of the data used to formulate the equation. The initial mid-range values are shown in the first line of Table 3.3. These values yield an ABD of 8.12 mm. Each variable was then changed one-by-one to its highest and lowest extremes, lines 3 and 5, holding all other variables constant. The results are shown in lines 4 and 6 of Table 3.3.

As can be seen, varying the peak g level had the most pronounced affect on the ABD. At 70 g, ABD was 6.4 mm compared to the original 8.1 mm. When the maximum values were used the peak g level again had the greatest affect. At 130 g, ABD was 9.85 mm. Also, by increasing the apple mass and days after harvest, changes of nearly 1 mm were observed in the ABD. In summary 1 day after harvest was the

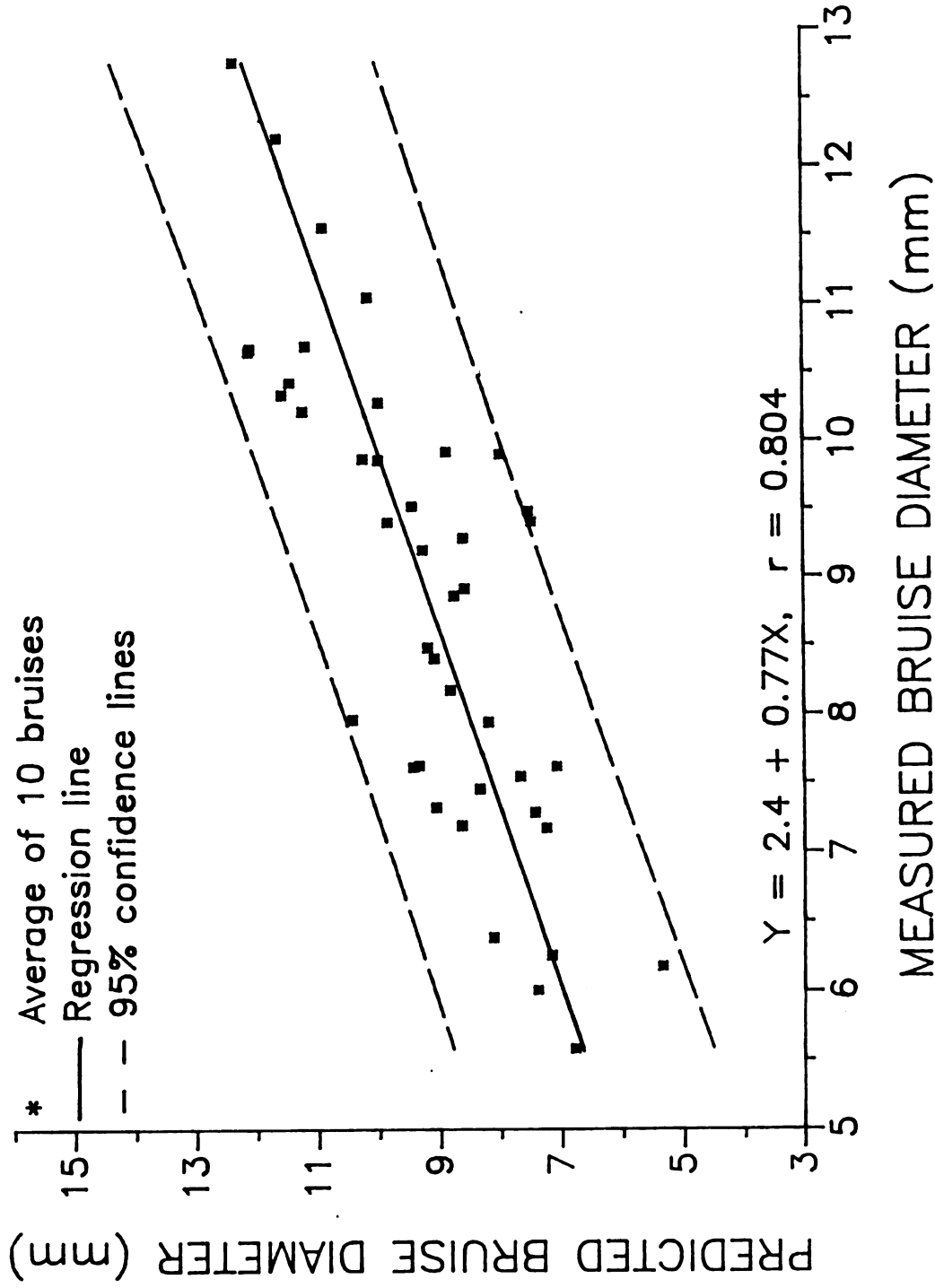


Figure 3.37 Predicted Versus Measured Bruise Diameter for
 Paula Red Apples

Table 3.3 Bruise Diameter Sensitivity, Paula Red MLRA Model

Variable and ABD Status	Independent Variable				
	DV, m/s	M, gm	G, g's	D, days	F, N
Midrange variable Value	0.83	140	100	3	71
ABD, average, mm	8.12	8.12	8.12	8.12	8.12
Minimum variable value	0.62	116	70	1	67
ABD, minimum, mm	7.48	7.27	6.40	8.37	8.44
Maximum variable value	1.02	175	130	12	75
ABD, maximum, mm	8.70	9.36	9.85	7.02	7.81
Maximum possible condition	1.02	175	130	1	75
Maximum ABD, mm	11.40	11.40	11.40	11.40	11.40

ABD - Average bruise diameter.

DV - Velocity change.

M - Average apple mass.

G - Peak acceleration.

D - Days after harvest.

F - Average Magness-Taylor flesh firmness.

most sensitive condition for Paula Red apples and large apples had larger bruises than small apples. These variable values are shown in line 7 of Table 3.3. The ABD is shown in line 8, and is very close to the 12.7 mm diameter bruise which will down-grade an apple from Extra Fancy to Fancy.

3.5.2 MLRA Model for Golden Delicious Apples

The dependent and independent variables for the Golden Delicious apples are the same as for the Paula Red apples. There were a total of 58 cases used in the analysis. See Appendix A.3 for the complete statistical report.

The resulting MLRA equation explained 56.7 percent ($R^2=.0567$) of the variation in the average bruise diameter:

$$ABD = -2.16 + 3.35DV + 0.0140M + 0.0235G - 0.0560D + 0.0704F$$

Where: ABD = Average bruise diameter of 10 apples, mm

DV = Velocity change, m/s

M = Average apple mass, g

G = Peak acceleration, g

D = Days after harvest

F = Average Magness-Taylor firmness, N

Figure 3.38 shows the predicted bruise diameter versus the measured bruise diameter, with confidence belts for the predicted diameter placed at the 95 percent level. Again, the sensitivity of the model was tested similar to the Paula Red model. The initial mid-range values are shown on the first line of Table 3.4. These values yield an ABD of 10.14 mm. The results for low and high extreme variable values, lines 3 and 5, are shown in lines 4 and 6 of Table 3.4.

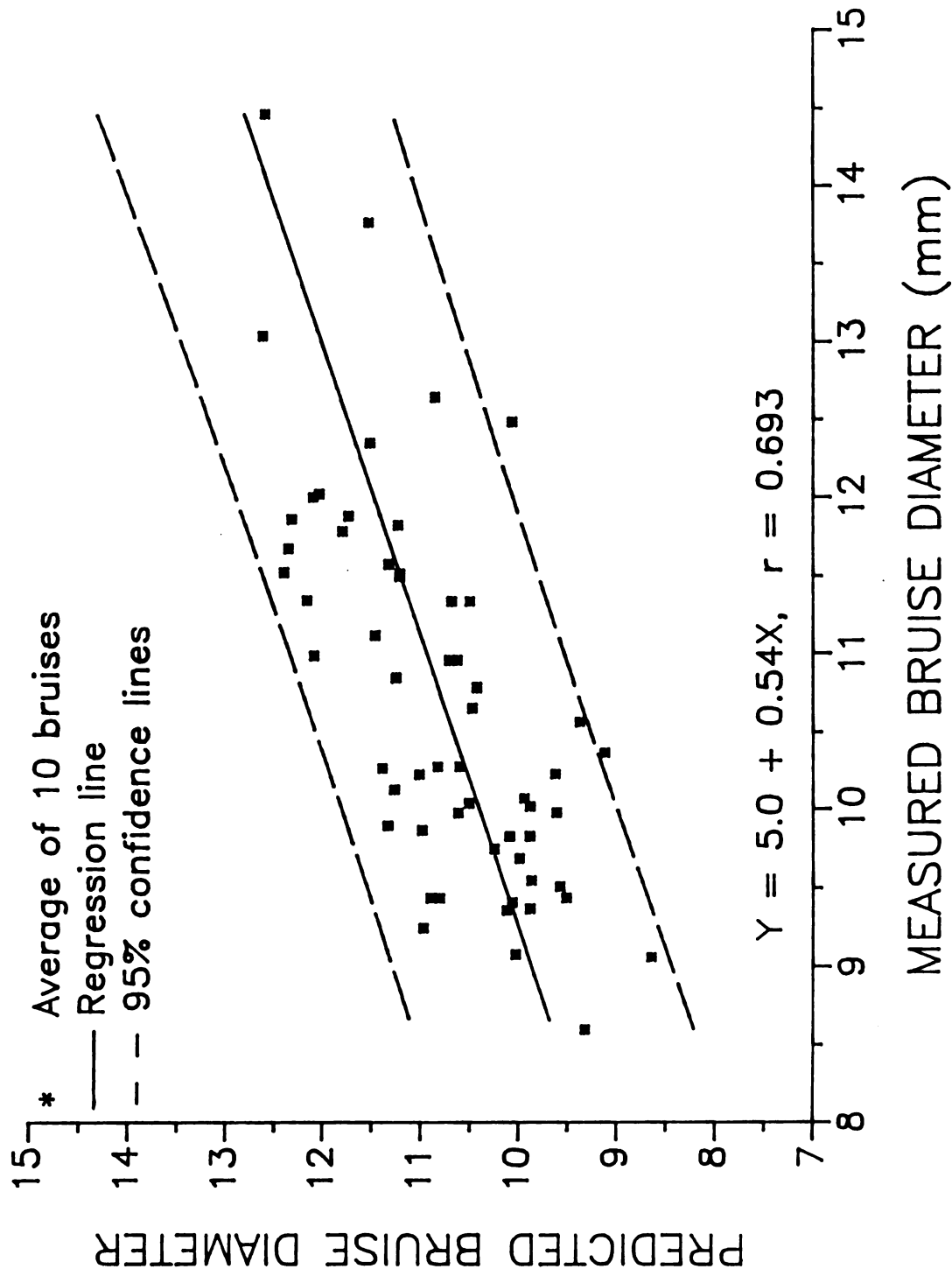


Figure 3.38 Predicted Versus Measured Bruise Diameter for Golden Delicious Apples

Table 3.4 Bruise Diameter Sensitivity, Golden Delicious MLRA Model

Variable and ABD Status	Independent Variable				
	DV, m/s	M, gm	G, g's	D, days	F, N
Midrange variable Value	0.78	142	90	3	77
ABD, average, mm	10.14	10.14	10.14	10.14	10.14
Minimum variable value	0.55	166	50	1	73
ABD, minimum, mm	9.37	9.81	9.20	10.26	9.86
Maximum variable value	1.02	196	130	12	81
ABD, maximum, mm	10.95	10.56	11.08	9.64	10.43
Maximum possible condition	1.02	196	130	1	81
Maximum ABD, mm	12.70	12.70	12.70	12.70	12.70

ABD - Average bruise diameter.

DV - Velocity change.

M - Average apple mass.

G - Peak acceleration.

D - Days after harvest.

F - Average Magness-Taylor flesh firmness.

As with the Paula Red apples, varying the peak g level had the largest affect on the ABD. At 50 g ABD was 9.2 mm compared to the original 10.14 mm. At 130, ABD was 11.08 mm. Velocity change and apple mass produced the second and third largest variation, respectively. When all variables were set to produce the maximum ABD, a bruise of 12.70 mm diameter was predicted, equal to the size which will downgrade an apple.

The regression models formulated in this experiment will be useful for predicting apple bruising from data that is easily obtained from the IS and apples on the packing lines. As indicated by the R^2 values and the graphs of the actual data, the variation in actual bruising at each peak G level was very high. This is more evident in the Golden Delicious apples than in the Paula Red apples. Thus, the Paula Red model is a better predictor. Much of this variation can be attributed to the properties of the fruit. Differences in mass, curvature, firmness and cell structure may cause comparable apples dropped from the same height to have different bruises.

3.6 MLRA Model Compared with LRA Models

In order to compare the Golden Delicious MLRA model to some LRA models; two LRA models were formulated. The first model considered only the peak G levels used in the MLRA model and the second considered only the velocity changes used in the MLRA model. The comparison is only carried out for the Golden Delicious apples since they were the most

sensitive to bruising and showed the greatest variation.

The model for bruise diameter versus peak G forces was as follows:

$$ABD = 7.2 + 0.035G \dots\dots\dots [3.3]$$

Where: ABD = Average bruise diameter, mm

G = Peak acceleration, g

This linear regression model had a correlation of $r = 0.606$, giving an $r^2 = 0.367$, as shown in Figure 3.39.

The second LRA model considered only velocity change as follows:

$$ABD = 5.8 + 6.0DV \dots\dots\dots [3.4]$$

Where: ABD = Average bruise diameter, mm

DV = Velocity change, m/s

This equation had a correlation of $r = 0.620$, giving an $r^2 = 0.384$, as shown in Figure 3.40.

In these models, peak G can explain 36.7 percent of the variance in bruise diameter, while velocity change can explain 38.4 percent of the variance. This can be compared to the $R^2 = 0.567$ for the Golden Delicious MLRA model which explains 56.7 percent of the variance in average bruise diameter.

From the above comparisons, it can be concluded that using only peak acceleration or only velocity change to predict average bruise diameter is insufficient. Instead, a complex set of relationships exist between impact and fruit characteristics that determine bruising.

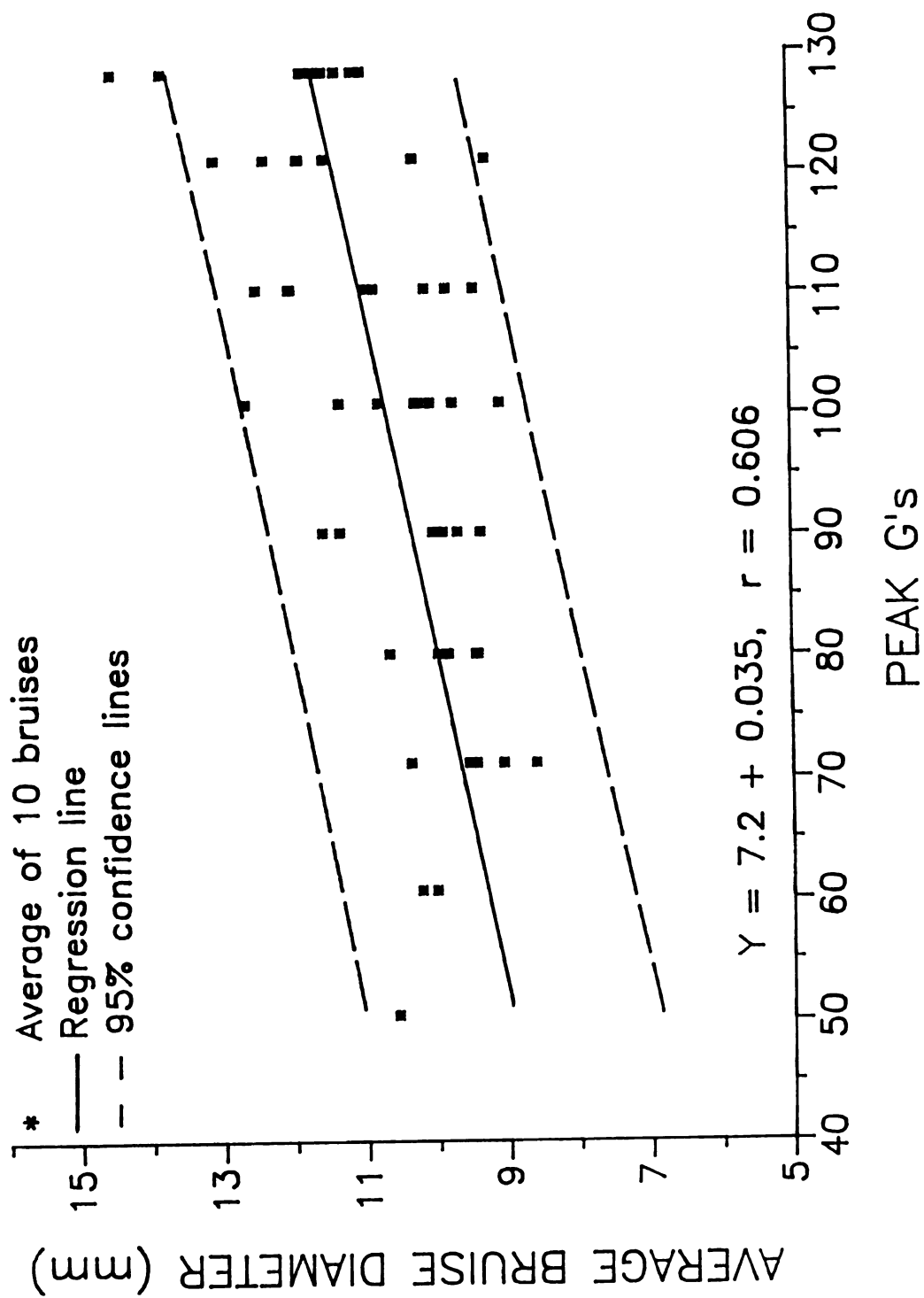


Figure 3.39 Average Bruise Diameter Versus Peak G's for Golden Delicious Apples

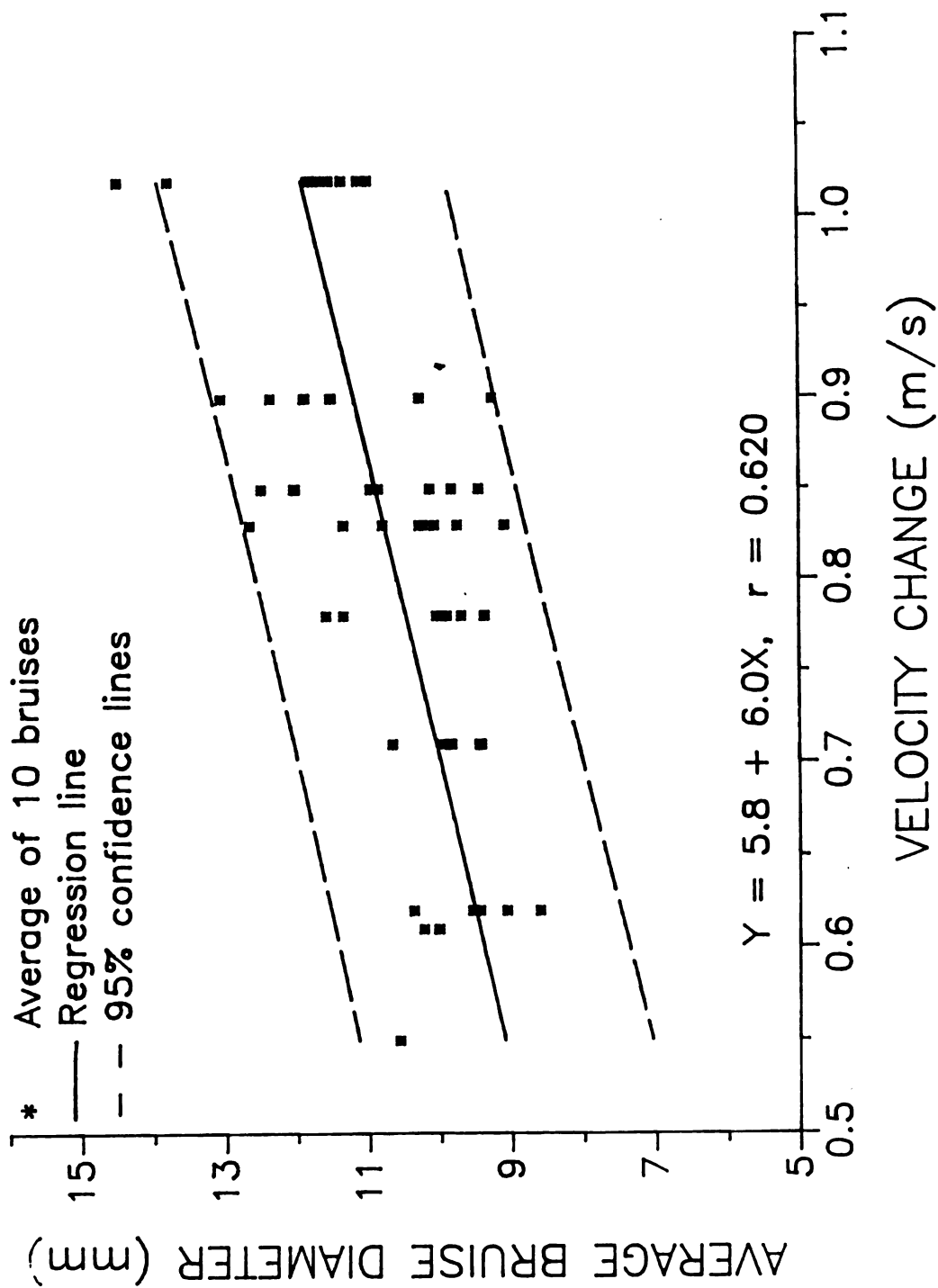


Figure 3.40 Average Bruise Diameter Versus Velocity Change for Golden Delicious Apples

4. CONCLUSIONS

The following conclusions are made from the research reported here:

1. Impacts experienced on apple packing lines are capable of producing accelerations ranging from 20 g to 130 g. Approximately 84 percent of the impacts measured on the apple packing lines were between 20 and 60 g. Velocity changes corresponding to these impacts ranged from 0.1 m/s to 4.5 m/s, with only 2 impacts above 3 m/s.

2. The threshold of visible surface bruising in Paula Red apples occurred at 80 g with large apples. All apples showed bruising at 100 g or higher. The threshold of bruising after peeling occurred at 40 g and 100 percent bruising occurred at 80 g or higher.

The threshold of visible surface bruising in Golden Delicious apples occurred at 40 g with large apples. All apples displayed bruising at 60 g or higher. After peeling the apples had a bruising threshold of 30 g and all apples were bruised at 50 g or higher.

The CA Golden Delicious apples did not display any bruising at any peak G level on any of the surfaces used.

3. Multiple linear regression models were constructed for predicting average bruise diameter on Paula Red apples

giving $R^2=0.848$ and Golden Delicious apples giving $R^2=0.565$. The multiple regression models were based on the groups of apples that demonstrated 100 percent bruising at a given G level.

Two linear regression models were also constructed for Golden Delicious apples using only peak G's or velocity change. The LRA model using only peak G's explained 36.7 percent of the variation in bruise diameter, while velocity change explained 38.4 percent of the variation in bruise diameter. It was concluded that LRA models were not sufficient to predict bruise diameter.

5. FUTURE RESEARCH

Although this research did find the threshold of bruising of apples based on peak G levels, more research needs to be conducted to isolate the velocity change at which bruising starts to occur at each G level. As outlined in the results, neither the medium or large velocity change surfaces produced bruising. Further tests must be performed to find surfaces that will produce velocity changes which will identify the threshold for bruising. From this information, bruising can be predicted if the Peak G level and velocity change are known.

Also there appears to be a large change in bruise volume with increasing peak G level. This bruise characteristic may explain bruise damage response more completely than bruise diameter alone. Future research can explore what conditions affect bruise volume and how it may be practically used to grade apples.

6. APPENDICES

A.1 Definition of the Coefficient of Determination

A.1 Definition of the Coefficient of Determination

The coefficient of determination is the amount of variation in the dependent variable that can be explained by the independent variables. It may be calculated by the following general formula:

$$R^2 = \frac{\text{SS}(\text{due to X})}{\text{Total SS}(Y)}$$

or:

$$R^2 = \frac{\text{SS}(\text{due to Y})}{\text{Total SS}(X)}$$

Where: R^2 = Coefficient of determination

SS = Sum of squares

X = Independent variable

Y = Dependent variable

A.2 Statistical Results for Paula Red Apples

A.2 Statistical Results for Paula Red Apples

List of Variables used in the MLRA Analysis

<u>Number</u>	<u>Variable</u>
1	Days after harvest
2	Drop height (not used)
3	Peak G's
4	Velocity change, m/s
5	Mass, g
6	Magness-Taylor firmness, N
7	Average bruise diameter, mm
8	Average bruise depth, mm (not used)
9	Average bruise volume, ml (not used)

The coefficient of determination was used in Chapter 3 of the text. Readers who desire additional results may find them in this appendix.

1Step 1 Variable Entered 4

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.738	F Change	47.791
R Square	.544	R Square Change	.544
Adjusted R Square	.533	Sum of Squares Change	67.26466
Std. Err. of Est.	1.18637	Percent of SS Change	54.44

Date: 05/14/89

Time: 17:00:00

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	12.430700	1.798137	.7378	.1067	6.91	.00
B(0)	-1.8356130					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Error Mean Square	F-test	Sig.
Regression	67.2646600	1	67.264660		
Residual	56.2990700	40	1.4074770	47.79	.000
Total	123.563700	42 cases from file:	100PN.PRN		

A N A L Y S I S O F R E S I D U A L S

=====

Number of positive residuals: 16
Largest positive residual: 2.86798

Number of negative residuals: 26
Largest negative residual: -2.47187

Number of sign runs: 9
Significance of sign runs test: .0001

Average absolute residual: .922671
Residual sum of squares: 56.2991

Residual mean square: 1.40748
Residual standard deviation: 1.18637

Durbin-Watson statistic: .548666
Auto-correlation coefficient: .712

1Step 2 Variable Entered 5

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.839	F Change	-1.547
R Square	.703	R Square Change	.159
Adjusted R Square	.688	Sum of Squares Change	19.64954
Std. Err. of Est.	.969397	Percent of SS Change	15.90

Date: 05/14/89

Time: 17:00:00

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	12.529710	1.469437	.7437	.0872	8.53	.00
B(5)	.30454800E-01	.6660110E-02	.3988	.0872	4.57	.00
B(0)	-6.2854600					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Error Mean Square	F-test	Sig.
Regression	86.9142000	2	43.457100		
Residual	36.6495400	39	.93973180	46.24	.000
Total	123.563700	42 cases from file:	100PN.PRN		

A N A L Y S I S O F R E S I D U A L S

=====

Number of positive residuals: 19
Largest positive residual: 2.01608

Number of negative residuals: 23
Largest negative residual: -1.56996

Number of sign runs: 9
Significance of sign runs test: .0001

Average absolute residual: .786469
Residual sum of squares: 36.6495

Residual mean square: .939732
Residual standard deviation: .969398

Durbin-Watson statistic: .617627
Auto-correlation coefficient: .675

1Step 3 Variable Entered 1

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.893	F Change	3.594
R Square	.797	R Square Change	.094
Adjusted R Square	.781	Sum of Squares Change	11.60917
Std. Err. of Est.	.811761	Percent of SS Change	9.40

Date: 05/14/89

Time: 17:00:01

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	11.834960	1.241572	.7024	.0737	9.53	.00
B(5)	.33520540E-01	.5624720E-02	.4390	.0737	5.96	.00
B(1)	-.10897720	.2596351E-01	-.3120	.0743	-4.20	.00
B(0)	-5.5264590					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Mean Square	Error	F-test	Sig.
Regression	98.5233700	3	32.841120			
Residual	25.0403700	38	.65895720		49.84	.000
Total	123.563700	42 cases from file:		100PN.PRN		

A N A L Y S I S O F R E S I D U A L S

=====

Number of positive residuals: 23
 Largest positive residual: 1.46660

 Number of negative residuals: 19
 Largest negative residual: -1.99221

 Number of sign runs: 15
 Significance of sign runs test: .0233

 Average absolute residual: .636357
 Residual sum of squares: 25.0404

 Residual mean square: .658957
 Residual standard deviation: .811762

 Durbin-Watson statistic: 1.02939
 Auto-correlation coefficient: .442

1Step 4 Variable Entered 6

Multiple Regression Analysis

Multiple R	.908	F Change	-6.138
R Square	.825	R Square Change	.028
Adjusted R Square	.806	Sum of Squares Change	3.454451
Std. Err. of Est.	.763808	Percent of SS Change	2.80

Date: 05/14/89

Time: 17:00:01

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	12.068420	1.172162	.7163	.0696	10.30	.00
B(5)	.33768720E-01	.5293432E-02	.4422	.0693	6.38	.00
B(1)	-.12495470	.2529676E-01	-.3577	.0724	-4.94	.00
B(6)	-.75083240E-01	.3085586E-01	-.1743	.0716	-2.43	.02
B(0)	-.74439310					

Analysis Of Variance

	Sum of Squares	Degrees of Freedom	Error Mean Square	F-test	Sig.
Regression	101.977800	4	25.494460		
Residual	21.5859000	37	.58340280	43.70	.000
Total	123.563700	42 cases from file:	100PN.PRN		

ANALYSIS OF RESIDUALS

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=====
Number of positive residuals:      20
Largest positive residual:        1.55655

Number of negative residuals:      22
Largest negative residual:        -1.55331

Number of sign runs:              15
Significance of sign runs test:    .0217

Average absolute residual:         .589138
Residual sum of squares:           21.5859

Residual mean square:              .583403
Residual standard deviation:       .763808

Durbin-Watson statistic:           1.17294
Auto-correlation coefficient:      .380

```

1Step 5 Variable Entered 3

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.921	F Change	-3.410
R Square	.848	R Square Change	.023
Adjusted R Square	.827	Sum of Squares Change	2.852249
Std. Err. of Est.	.721373	Percent of SS Change	2.31

Date: 05/14/89

Time: 17:00:02

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	3.0407330	4.011817	.1805	.2381	.76	.45
B(5)	.35350720E-01	.5044805E-02	.4629	.0661	7.01	.00
B(1)	-.12285880	.2390811E-01	-.3517	.0684	-5.14	.00
B(6)	-.78886530E-01	.2918685E-01	-.1831	.0678	-2.70	.01
B(3)	.57389510E-01	.2451313E-01	.5595	.2390	2.34	.02
B(0)	.87464130					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Error Mean Square	F-test	Sig.
Regression	104.830000	5	20.966010		
Residual	18.7336700	36	.52037960	40.29	.000
Total	123.563700	42 cases from file:	100PN.PRN		

A N A L Y S I S O F R E S I D U A L S

=====

Number of positive residuals: 24
 Largest positive residual: 1.34493

 Number of negative residuals: 18
 Largest negative residual: -1.69029

 Number of sign runs: 18
 Significance of sign runs test: .1635

 Average absolute residual: .533213
 Residual sum of squares: 18.7337

 Residual mean square: .520380
 Residual standard deviation: .721373

 Durbin-Watson statistic: 1.21738
 Auto-correlation coefficient: .360

A.3 Statistical Results for Golden Delicious Apples

A.3 Statistical Results for Golden Delicious Apples

List of Variables used in the MLRA Analysis

<u>Number</u>	<u>Variable</u>
1	Days after harvest
2	Drop height (not used)
3	Peak G's
4	Velocity change, m/s
5	Mass, g
6	Magness-Taylor firmness, N
7	Average bruise diameter, mm
8	Average bruise depth, mm (not used)
9	Average bruise volume, ml (not used)

The coefficient of determination was used in Chapter 3 of the text. Readers who desire additional results may find them in this appendix.

1Step 1 Variable Entered 4
(Forced Variable)

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.620	F Change	34.880
R Square	.384	R Square Change	.384
Adjusted R Square	.373	Sum of Squares Change	33.11325
Std. Err. of Est.	.974348	Percent of SS Change	38.38

Date: 05/26/89

Time: 12:25:00

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	6.0223430	1.019715	.6195	.1049	5.91	.00
B(0)	5.7725400					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Error Mean Square	F-test	Sig.
Regression	33.1132400	1	33.113240		
Residual	53.1638000	56	.94935360	34.88	.000
Total	86.2770800	58	cases from file: 100GN.PRN		

A N A L Y S I S O F R E S I D U A L S

```
=====
Number of positive residuals:      25
Largest positive residual:        2.56467

Number of negative residuals:      33
Largest negative residual:        -1.94265

Number of sign runs:              25
Significance of sign runs test:    .1430

Average absolute residual:         .767856
Residual sum of squares:           53.1638

Residual mean square:              .949354
Residual standard deviation:       .974348

Durbin-Watson statistic:           1.15957
Auto-correlation coefficient:      .415
```

1Step 2 Variable Entered 3
(Forced Variable)

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.620	F Change	-17.745
R Square	.384	R Square Change	.000
Adjusted R Square	.361	Sum of Squares Change	.7034501E-02
Std. Err. of Est.	.983101	Percent of SS Change	.01

Date: 05/26/89

Time: 12:25:01

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	5.6330380	4.677782	.5795	.4812	1.20	.23
B(3)	.23712660E-02	.2779467E-01	.0411	.4812	.09	.93
B(0)	5.8525020					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Mean Square	Error	F-test	Sig.
Regression	33.1202700	2	16.560140			
Residual	53.1567700	55	.96648680		17.13	.000
Total	86.2770800	58 cases from file:	100GN.PRN			

A N A L Y S I S O F R E S I D U A L S

=====

Number of positive residuals: 24
Largest positive residual: 2.57709

Number of negative residuals: 34
Largest negative residual: -1.95963

Number of sign runs: 23
Significance of sign runs test: .0617

Average absolute residual: .765349
Residual sum of squares: 53.1568

Residual mean square: .966487
Residual standard deviation: .983101

Durbin-Watson statistic: 1.15799
Auto-correlation coefficient: .416

1Step 3 Variable Entered 5

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.698	F Change	-.075
R Square	.487	R Square Change	.103
Adjusted R Square	.458	Sum of Squares Change	8.860987
Std. Err. of Est.	.905700	Percent of SS Change	10.27

Date: 05/26/89

Time: 12:25:02

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	5.1405150	4.312099	.5288	.4436	1.19	.24
B(3)	.98058840E-02	.2570609E-01	.1698	.4450	.38	.70
B(5)	.18532830E-01	.5638780E-02	.3303	.1005	3.29	.00
B(0)	2.3445610					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Mean Square	F-test	Sig.
Regression	41.9812800	3	13.993760		
Residual	44.2957600	54	.82029190	17.06	.000
Total	86.2770800	58 cases from file:	100GN.PRN		

A N A L Y S I S O F R E S I D U A L S

=====

Number of positive residuals: 28
Largest positive residual: 2.04892

Number of negative residuals: 30
Largest negative residual: -1.99670

Number of sign runs: 21
Significance of sign runs test: .0124

Average absolute residual: .723745
Residual sum of squares: 44.2958

Residual mean square: .820292
Residual standard deviation: .905700

Durbin-Watson statistic: 1.05363
Auto-correlation coefficient: .470

1Step 4 Variable Entered 6

M u l t i p l e R e g r e s s i o n A n a l y s i s

Multiple R	.730	F Change	-1.973
R Square	.532	R Square Change	.046
Adjusted R Square	.497	Sum of Squares Change	3.953396
Std. Err. of Est.	.872455	Percent of SS Change	4.58

Date: 05/26/89

Time: 12:25:02

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	3.7939750	4.195628	.3903	.4316	.90	.37
B(3)	.18514160E-01	.2505559E-01	.3205	.4338	.74	.46
B(5)	.13863470E-01	.5805369E-02	.2471	.1035	2.39	.02
B(6)	.63015350E-01	.2765057E-01	.2339	.1026	2.28	.03
B(0)	-1.6558710					

A n a l y s i s O f V a r i a n c e

	Sum of Squares	Degrees of Freedom	Error Mean Square	F-test	Sig.
Regression	45.9346500	4	11.483660		
Residual	40.3423800	53	.76117710	15.09	.000
Total	86.2770800	58 cases from file:	100GN.PRN		

A N A L Y S I S O F R E S I D U A L S

```

=====
Number of positive residuals:      25
Largest positive residual:        2.11713

Number of negative residuals:      33
Largest negative residual:        -2.00934

Number of sign runs:              23
Significance of sign runs test:    .0540

Average absolute residual:         .671524
Residual sum of squares:           40.3424

Residual mean square:              .761177
Residual standard deviation:       .872455

Durbin-Watson statistic:           1.25461
Auto-correlation coefficient:      .363

```

1Step 5 Variable Entered 1

Multiple Regression Analysis

Multiple R	.757	F Change	-1.165
R Square	.572	R Square Change	.040
Adjusted R Square	.531	Sum of Squares Change	3.450067
Std. Err. of Est.	.842299	Percent of SS Change	4.00

Date: 05/26/89

Time: 12:25:03

	Regression Coefficient	Std. Err. Reg. Coeff.	Beta Weight	Std. Err. Beta Weight	Student T value	Sig.
B(4)	3.3565320	4.055464	.3453	.4172	.83	.41
B(3)	.23514610E-01	.2429562E-01	.4071	.4206	.97	.34
B(5)	.14012830E-01	.5605122E-02	.2498	.0999	2.50	.02
B(6)	.70446320E-01	.2690670E-01	.2615	.0999	2.62	.01
B(1)	-.56043950E-01	.2541449E-01	-.2055	.0932	-2.21	.03
B(0)	-2.1634130					

Analysis Of Variance

	Sum of Squares	Degrees of Freedom	Mean Square	F-test	Sig.
Regression	49.3847400	5	9.8769470		
Residual	36.8923100	52	.70946760	13.92	.000
Total	86.2770800	58 cases from file:	100GN.PRN		

ANALYSIS OF RESIDUALS

```

=====
Number of positive residuals:      30
Largest positive residual:        2.02768

Number of negative residuals:     28
Largest negative residual:       -2.26639

Number of sign runs:              23
Significance of sign runs test:   .0432

Average absolute residual:        .633676
Residual sum of squares:          36.8923

Residual mean square:             .709468
Residual standard deviation:      .842299

Durbin-Watson statistic:          1.34584
Auto-correlation coefficient:     .318

```

B.1 Data for Paula Red Apples

B.1 Data for Paula Red Apples**List of Variables used in the MLRA Analysis**

<u>Number</u>	<u>Variable</u>
1	Days after harvest
2	Drop height (not used)
3	Peak G's
4	Velocity change, m/s
5	Mass, g
6	Magness-Taylor firmness, N
7	Average bruise diameter, mm
8	Average bruise depth, mm (not used)
9	Average bruise volume, ml (not used)

1	2	3	4	5	6	7	8	9
1	1.8	101	0.83	113.8	72.28	6.01	0.89	16.29
1	2	110.4	0.85	115.1	68.41	7.2	1.27	28.92
1	2.3	121.2	0.9	117.62	67.08	7.62	1.1	29.82
1	3	128.5	1.02	117.2	70.42	9.93	1.49	62.99
1	1.7	90.3	0.78	144.1	69.84	7.95	1.2	32.98
1	1.8	101	0.83	139.96	70.28	9.29	1.59	58.62
1	2	110.4	0.85	139.66	70.73	9.91	1.85	75.64
1	2.3	121.2	0.9	136.06	67.84	9.88	1.5	59.78
1	3	128.5	1.02	136.42	66.95	11.57	2.46	140.52
1	1.4	80.2	0.71	165.48	62.28	9.41	0.66	30.29
1	1.7	90.3	0.78	170.52	64.19	9.2	1.17	43.28
1	1.8	101	0.83	170.28	66.19	10.29	1.56	70.37
1	2	110.4	0.85	180.34	63.39	11.06	1.77	91.77
1	2.3	121.2	0.9	171.16	63.52	12.22	2.42	157.02
1	3	128.5	1.02	179.6	67.84	12.78	2.79	194.89
3	1.4	80.2	0.71	116.88	67.97	6.18	0.64	10.78
3	1.7	90.3	0.78	119.96	65.30	7.29	0.94	21.72
3	1.8	101	0.83	118.83	64.10	7.46	1.15	28.08
3	2	110.4	0.85	115.92	68.19	9.49	1.17	41.54
3	2.3	121.2	0.9	113.02	56.85	9.41	1.12	42.71
3	3	128.5	1.02	118.18	55.07	10.71	1.74	83.7
3	1.7	90.3	0.78	144.62	66.06	7.62	0.91	23.6
3	1.8	101	0.83	141.44	69.53	8.87	1.41	47.84
3	2	110.4	0.85	138.64	59.61	9.87	1.88	78.18
3	2.3	121.2	0.9	142.8	72.28	8.92	1.09	37.21
3	3	128.5	1.02	145.82	65.83	10.23	1.25	53.81
3	3	128.5	1.02	178.14	70.06	10.67	1.23	59.68
12	1.8	101	0.83	124.84	63.61	7.55	1.19	30.48
12	2	110.4	0.85	119.02	62.72	8.18	1.41	42.56
12	2.3	121.2	0.9	117.2	71.30	8.41	1.69	53.53
12	3	128.5	1.02	120.74	63.83	9.53	2.04	86.82
12	1.2	71.3	0.62	141.58	64.50	5.58	0.82	11.33
12	1.4	80.2	0.71	140.9	56.94	6.39	1.07	20.79
12	1.7	90.3	0.78	141.64	62.94	7.18	1.27	27.88
12	1.8	101	0.83	141.14	64.50	7.33	1.27	28.34
12	3	128.5	1.02	147.42	64.94	10.44	1.92	91.49
12	1.4	80.2	0.71	170.78	66.72	6.26	0.75	12.48
12	1.7	90.3	0.78	174.22	65.17	7.63	1.15	30.93
12	1.8	101	0.83	169.22	60.18	7.97	1.4	42.74
12	2	110.4	0.85	167.52	64.63	8.49	1.5	48.75
12	2.3	121.2	0.9	179.66	66.86	10.35	1.9	84.93
12	3	128.5	1.02	171.6	67.39	10.69	2.11	102.47

B.2 Data for Golden Delicious Apples

B.2 Data for Golden Delicious Apples**List of Variables used in the MLRA Analysis**

<u>Number</u>	<u>Variable</u>
1	Days after harvest
2	Drop height (not used)
3	Peak G's
4	Velocity change, m/s
5	Mass, g
6	Magness-Taylor firmness, N
7	Average bruise diameter, mm
8	Average bruise depth, mm (not used)
9	Average bruise volume, ml (not used)

1	2	3	4	5	6	7	8	9
1	1.2	71.3	0.62	143.3	81.98	8.6	1.42	44.24
1	1.4	80.2	0.71	145.76	76.95	9.98	1.83	75.72
1	1.7	90.3	0.78	145.54	83.63	10.04	1.82	75.51
1	1.8	101	0.83	142.52	77.84	10.07	1.38	57.98
1	2	110.4	0.85	143.28	77.18	10.96	1.68	81.71
1	2.3	121.2	0.9	144.24	77.84	11.52	2.09	115.62
1	3	128.5	1.02	142.18	78.73	11.83	2.57	153.75
1	1.2	71.3	0.62	165.48	79.98	9.51	2	76.63
1	1.4	80.2	0.71	165.48	80.07	9.41	2	77.82
1	1.7	90.3	0.78	164.78	82.20	9.36	1.99	75.41
1	1.8	101	0.83	166.64	78.07	10.28	1.91	83.83
1	2	110.4	0.85	165.38	75.17	9.44	1.63	63.8
1	2.3	121.2	0.9	166.58	78.51	9.25	1.37	46.87
1	3	128.5	1.02	166.16	78.96	11.35	2.16	120.59
1	1	60.8	0.61	189.2	80.29	10.23	1.59	87.42
1	1.2	71.3	0.62	191.12	70.95	9.06	1.85	65.52
1	1.4	80.2	0.71	193.1	75.17	9.83	1.68	66.79
1	1.7	90.3	0.78	197	74.95	9.98	1.82	76.19
1	1.8	101	0.83	198.84	72.28	9.75	1.5	58.66
1	2	110.4	0.85	191.12	75.75	10.13	0.63	78.07
1	2.3	121.2	0.9	194.12	75.31	11.89	1.91	110.8
1	3	128.5	1.02	194.34	71.84	13.78	2.2	169.55
3	1.7	90.3	0.78	139.5	77.40	9.69	1.54	58.99
3	1.8	101	0.83	143.54	76.95	10.79	1.86	90.17
3	2	110.4	0.85	142.88	75.84	12.49	1.07	132.93
3	2.3	121.2	0.9	142.26	77.75	11.5	1.97	107.17
3	3	128.5	1.02	141.48	82.65	10.99	2.01	108.32
3	1.2	71.3	0.62	165.32	81.98	10.37	1.65	72.57
3	1.4	80.2	0.71	164.82	85.41	10.66	1.59	74.37
3	1.7	90.3	0.78	165.3	82.20	11.34	1.47	78.16
3	1.8	101	0.83	164.26	82.43	11.34	1.71	89.43
3	2	110.4	0.85	164.06	79.98	10.85	1.42	68.77
3	2.3	121.2	0.9	164.14	78.20	12.36	2.46	159.27
3	3	128.5	1.02	165.08	82.51	11.79	2.64	156.54
3	0.8	50.5	0.55	197.9	80.20	10.57	1.37	64.77
3	1	60.8	0.61	196	82.65	10.02	1.35	57.07
3	1.2	71.3	0.62	195.16	82.29	9.44	1.21	45.69
3	1.4	80.2	0.71	196.74	85.54	9.87	1.27	55.86
3	1.7	90.3	0.78	195.92	85.18	11.58	1.4	75.29
3	1.8	101	0.83	194.38	82.51	12.65	1.68	110.03
3	2	110.4	0.85	197.12	84.29	12.03	1.49	91.22
3	2.3	121.2	0.9	190.98	88.43	13.05	1.94	133.32
3	3	128.5	1.02	193.34	87.10	14.48	2.56	221.64
12	1.7	90.3	0.78	140.08	76.29	9.37	1.11	94.71
12	1.8	101	0.83	143.98	71.17	9.08	1.2	91.31
12	2	110.4	0.85	140.86	72.51	9.83	1.4	119.27
12	2.3	121.2	0.9	142.08	69.97	10.28	1.64	162.25
12	3	128.5	1.02	143.44	73.40	11.12	1.66	200.45
12	2	110.4	0.85	163.72	79.71	10.96	1.23	150.14
12	2.3	121.2	0.9	160.66	76.87	10.27	1.39	143.97
12	3	128.5	1.02	167.04	81.98	11.53	1.54	208.3

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
12	1.2	71.3	0.62	192.74	87.54	9.55	0.95	83.75
12	1.4	80.2	0.71	193.92	84.43	9.44	0.79	63.77
12	1.7	90.3	0.78	193.74	85.76	9.9	1.12	104.57
12	1.8	101	0.83	192.66	83.63	10.23	1.08	115.82
12	2	110.4	0.85	196.86	85.49	12.01	1.14	155.45
12	2.3	121.2	0.9	196.66	83.09	11.87	1.35	185.24
12	3	128.5	1.02	189.8	85.76	11.68	1.67	229

7. REFERENCES

REFERENCES

1. Bartram, R., J. Fountain, K. Olsen, and D. O'Rourke. 1983. Washington State apple condition at retail, 1982-83 (Eating Quality). Proc. Wash. State Hort. Assoc. 79:36-46.
2. Brown, G. K., C. L. Burton, S. A. Sarfent, N. L. Shutle Pason. 1987. Apple Packing Line Damage Assessment. ASAE Paper No. 87-6516. ASAE, St. Joseph, MI.
3. Finney, Jr. E. E. and D. R. Massie. 1975. Instrumentation for testing the Responce of Fruits to Mechanical Damage. TRANSACTION of the ASAE 18(6):1184-1187,1192.
4. Fluck, R. C. and E. M. Ahmed. 1973. Impact Testing of Fruits and Vegetables. TRANSACTIONS of the ASAE 16(4):660-666.
5. Goldsmith. Impact, the Theory and Physical Behavior of Colliding Solids. 1960. Edward Arnold Publishers Ltd., London. 369 p.
6. Held, W. H., A. Osterloh, and G. Schauer. 1974. Bedeutung und Ergebnisse der Entnahme von Einlagerprben. Gartenbau. 21(7):203-204.
7. Lichtensteiger, M. J., R. G. Holmes, M. Y. Hamdy and J. L. Blaisdell. 1988. Impact Parameters of Spherical Viscoelastic Objects. TRANSACTIONS of the ASAE 31(2): 595-602.
8. Mohsenin, N. N. 1970. Physical Properties of Plant and Animal Materials. Gorden and Breach, Science Publishers, Inc., New York NY.
9. Peleg, K. A Mathematical Model of Produce Damage Mechanisms. 1984. TRANSACTIONS of the ASAE 27(1):287-293.
10. Schoorl D., J. E. Holt. 1980. Bruise Resistance Measurement in Apples. Journal of Texture Studies 11(4):389-394.

11. Siyami S., G. K. Brown, G. J. Burgess, J. B. Gerrish, B. R. Tennes, C. L. Burton and R. H. Zapp. 1988. Apple Impact Bruise Prediction Models. TRANSACTIONS of the ASAE 31(4):1038-1046.
12. Zapp, R., S. Ehlert, G. Brown, P. Armstrong, S. Sober. 1989. Advanced Instrumented Sphere (IS) for Impact Measurements. ASAE Paper No. 89-6046. ASAE, St. Joseph, MI.

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