PREDICTION OF DROP-TESTING PERFORMANCE OF APPLE PACKS

By D. SCHOORL, B.Agr.Sc., and W. T. WILLIAMS, Ph.D., D.Sc.

SUMMARY

The effect on bruising of apples by dropping boxes was studied in relation to (a) drop height, (b) number of drops, (c) variety (Jonathan or Delicious), and (d) package type (cases or cartons). Four conclusions can be drawn from the results:

(i) There is a critical height at approximately 2 in. At or below this height the amount of damage is independent of the number of drops and is thus substantially random. Tests based on this or lower heights are therefore invalid.

(ii) The remaining results can be fitted with the theoretically possible maximum accuracy by the expression

$$\ln\left(\frac{y}{100 - y}\right) = 2 - \frac{2}{kh + 0{\cdot}2} + 1{\cdot}0818 \ln x$$

where x is the number of drops, h the height in inches, k is 0·05 for cases and 0·02 for cartons, and y is the percentage of fruit bruised. The correlation coefficient between observed and predicted values is + 0·94, and this level is maintained for an independent set of data.

(iii) There is no evidence of varietal difference.

(iv) Tray-packed cartons are shown to be markedly superior to pattern-packed cases so far as mechanical damage is concerned.

I. INTRODUCTION

The problem: causes of damage.—There is no doubt that an undue proportion of apples are damaged at some stage between grower and consumer; one of us (D.S.), for example, has unpublished data to show that the average percentage of bruised apples is 10–15% in tray packs and 15–24% in pattern-packed cases after a journey of 1,000 miles and six handling operations. O'Loughlin (1964) estimated that such bruising costs Australia one million dollars annually, so the problem clearly merits investigation.

Bulmer *et al.* (1962) and M.T.S. Monterey (1971) have reported on the "shock environment" that packages are likely to experience. Injury of packed apples can be caused by impact, static weight or vibration. Impact damage results when boxes are dropped, or slid against other boxes; static weight is due to the weight of packages above being supported by the fruit as a result of over-packing or strength-failure of the outer container; vibration damage is caused during transport by road or rail, when the fruit experiences acceleration due to unevenness of the road surface. There is, however, general agreement that, regardless of the method of transport, the severest shocks likely to be encountered in transit result from handling operations. These result from dropping the package on to a floor, dock or platform, and it has always been assumed, for the purpose of package design, that the severest shock is to be expected when a package lands flat on a non-resilient horizontal surface.

Bruising brings about a softening of the tissue, resulting from the breakdown of cell-walls and consequent loss of turgor; with this is associated the release of polyphenols, which are oxidized to melanin-like compounds with consequent unsightly discoloration. The process has been studied in some detail by O'Brien *et al.* (1963), for vibration bruising, and by Ingle and Hyde (1968); the stress/strain relationships for apple tissue have been examined by Mohsenin (1970); Nelson and Mohsenin (1968) have made a comparative study of static and impact bruise characteristics, which showed that the depth : diameter ratio of the bruise was, as expected, greater for impact bruises. Assessment of bruising has commonly been by a rating system based largely on diameter (O'Loughlin 1964) or on volume (Mohsenin 1970).

Simulated transit systems: the present research.—It was at one time common to assess containers by actual test shipments, a method which is cumbersome, time-consuming and expensive. Guillou, Sommer and Mitchell (1962) argued that transit injury to both produce and containers can be evaluated more cheaply and quickly by simulated transit tests. Their own work reported a machine for simulating 50 drops from a height of 2 in., 60 horizontal impacts of 2 miles/hr, and 30 min of vibration at 550 cycles per min with a quarter-inch stroke. The National Safe Transit Committee of the U.S.A. (1953) prescribed an impact test for small boxes which involves dropping them on a hard floor from a height of 12 in.—once on a top corner, once on each of the three edges radiating from the corner, and once on each of the six flat surfaces. The nailed wooden bushel boxes which have been used in Queensland for many years seldom survive this test, which thus appears unduly severe.

A more general review of commercial and laboratory testing for package evaluation has been given by Schoorl (1968). A weakness apparent in many existing test procedures is their limited scope: they tend to involve dropping a package from a given height a given number of times. Such procedures make it possible to assess whether or not a package will survive conditions roughly comparable with those of the test, but they do not normally provide information as to the extent of damage to be expected under conditions which diverge considerably from the test. For such prediction to be even approximately possible, it is necessary to establish the general relationship between bruising on the one hand and both height and number of drops on the other, and to investigate the dependence of this relationship on type of package and variety.

The aim of the present research has therefore been to investigate this more general relationship for apples with two particular points in mind. First, we wish to know whether the relationship is continuous, or whether it exhibits any singularities; the most important of possible singularities would be the existence of a critical (i.e. minimum) height below which bruising was substantially random and independent of the number of drops. If such a critical height exists, then tests carried out at or below it would be of little value. We know of no work reporting a critical height, but we shall show that one exists. Secondly, we aim to find some simple numerical model to describe the relationship, so that predictions can be made. In particular, we shall seek a model in which the number of drops can be explicitly separated from height, package and variety; we shall show that such a model can be found.

II. MATERIALS AND METHODS

Two varieties of apple were used, Jonathan and Delicious. Fruits used in the tests were between $2\frac{3}{4}$ in. and $2\frac{7}{8}$ in. diameter; they were obtained from a commercial packing house, care being taken to select only bruise-free fruit. Two package types were used: tray-packed cartons of internal dimensions $19\frac{3}{4}$ in. x $11\frac{7}{8}$ in. x $11\frac{1}{2}$ in. and pattern-packed wooden bushel cases of internal dimensions 18 in. x $11\frac{1}{2}$ in. x $10\frac{1}{2}$ in. (Queensland Department of Primary Industries 1970); these were chosen because the majority of Queensland apples are packed in one or other of these containers.

Packages were subjected to a number of flat drops from various heights in randomized trials. For the critical height experiments, the heights used were 2, 3, 4, 5, 6 and 12 in.; for the main experiments, 2, 6, 12, 24 and 48 in. The largest number of drops in the critical height experiments was 243; for the main experiments the number of drops had perforce to be varied with height, a range of five numbers being taken for each variety-package-height set. For the greater heights the full range of five numbers was not always achieved; as examples we cite Delicious-cartons-6 in., where we used 1, 10, 25, 50 and 100 drops, and Jonathan-cases-24 in., where we achieved only 1, 5, 10 and 25. The equipment used was that described by Guillou, Somner and Mitchell (1962). The drop machine consists of a rotating cam lifting a package-holder through an arc; when the cam has rotated sufficiently the package holder falls onto a base. The cycle is repeated as the motor-driven cam rotates.

Bruise assessment on each apple was conducted 2–3 days after dropping of packages, a wedge section being taken out of the bruised area by a sharp knife. The largest bruise on the apple was measured for the maximum diameter and depth of bruise. An apple was considered "bruised" when a bruise 0·8 in. diameter and 0·2 in. depth was present, or if either dimension exceeded these values. The data used for curve-fitting were the percentages of bruised apples under the experimental conditions.

III. RESULTS

(a) Critical Height Experiment

The heights used were 2, 3, 4, 5, 6 and 12 in.; the number of drops were from 1 to 81 or 243 in multiples of 3. The results are presented graphically in Figure 1 as percentage of bruised fruit plotted against number of drops for each height. Each point represents the mean of 250 apples in two packed wooden cases. For every height except 2 in. there is a consistent increase in damage with increasing drop number; even at 3 in. the effect is clearly noticeable by 9 drops. For 2 in., however, there is no increase up to 81 drops; even for the quite unrealistic 243 drops there is only a very small rise. These results suggest strongly that 2 in. is indeed a critical height, at which damage is random and independent of the number of drops. We have nevertheless included the 2 in. height in the major experiment in order to obtain further evidence on this effect.

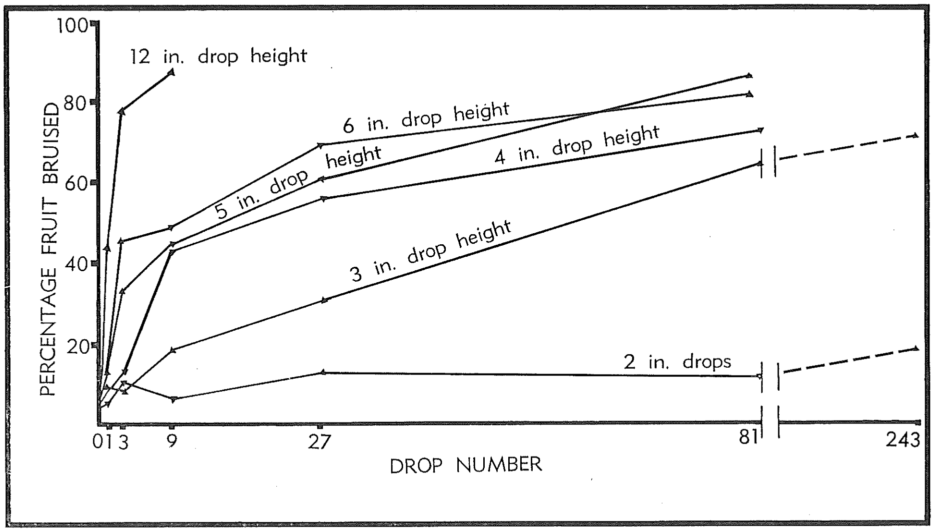

Fig. 1.—Critical height experiment: effect of height and number of drops on percentage fruit bruised.

(b) Main Experiment

The experimental design was 2 varieties (Delicious and Jonathan) x 2 packages (cases and cartons) x 5 heights (2, 6, 12, 24 and 48 in.) x (usually) five different numbers of drops. Each observation was replicated once. Agreement between replicates was only fair; the mean absolute difference between replicates was 8% for cases, 9% for cartons. However, the range of variation of differences was very great—from 0 to 25% for cases and 0 to 34% for cartons. It is obvious that this wide variation will set a limit to the accuracy of curve-fitting which is possible. We shall present the results of the numerical analyses in three stages: (i) the effect of number of drops, (ii) the effect of variety, package and height, and (iii) overall fitting and prediction.

(i) Effect of Number of Drops

Inspection of the curves relating damage to number of drops showed that for the milder treatments these were sigmoid, rising at first slowly, then more rapidly, then flattening off asymptotically towards the 100% limit. For the more severe treatments the curves appeared to rise very rapidly from the start, the first point of inflexion being absent or at least not discernible; it was easy to show that such curves were not exponential, but that they approximated to rectangular hyperbolas. These tendencies can be seen to some extent in the results of Figure 1; two typical curves from the main experiment (Jonathan, 12 in. height, cases and cartons) are shown in Figure 2. The method by which the smooth curves of this figure were computed is explained below.

We therefore seek a family of curves which are sigmoid, with an upper asymptote of 100%, and for which the rectangular hyperbola is a limiting case. The most familiar curve of this type is the Hill oxygen-saturation curve used in biochemical studies of blood; for a discussion of such curves see, for example, West *et al.* (1966). If we denote damage by y and number of drops by x, and if a and b are parameters to be determined, the general curve is then

$$\frac{y}{100 - y} = ax^b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1),$$

which is normally fitted in its logarithmic form

$$\ln \left(\frac{y}{100 - y} \right) = \ln a + b \ln x \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Expression (2) becomes infinite at the boundary values $y = 0$ and $y = 100$, and these values must be adjusted for fitting; we have replaced 0 by 0·5 and 100 by 99·5. The data for Figure 2 have been plotted after this transformation in Figure 3. The linearity is remarkable; the two regression lines have been calculated and incorporated in the figure, and it will be seen that the fit is excellent—in fact, in each case the regression line accounts for more than 95% of the total sum of squares. It is of course simple to calculate, from the parameters of the regression lines, the theoretical original sigmoid curves, and it is these which have been used in Figure 2.

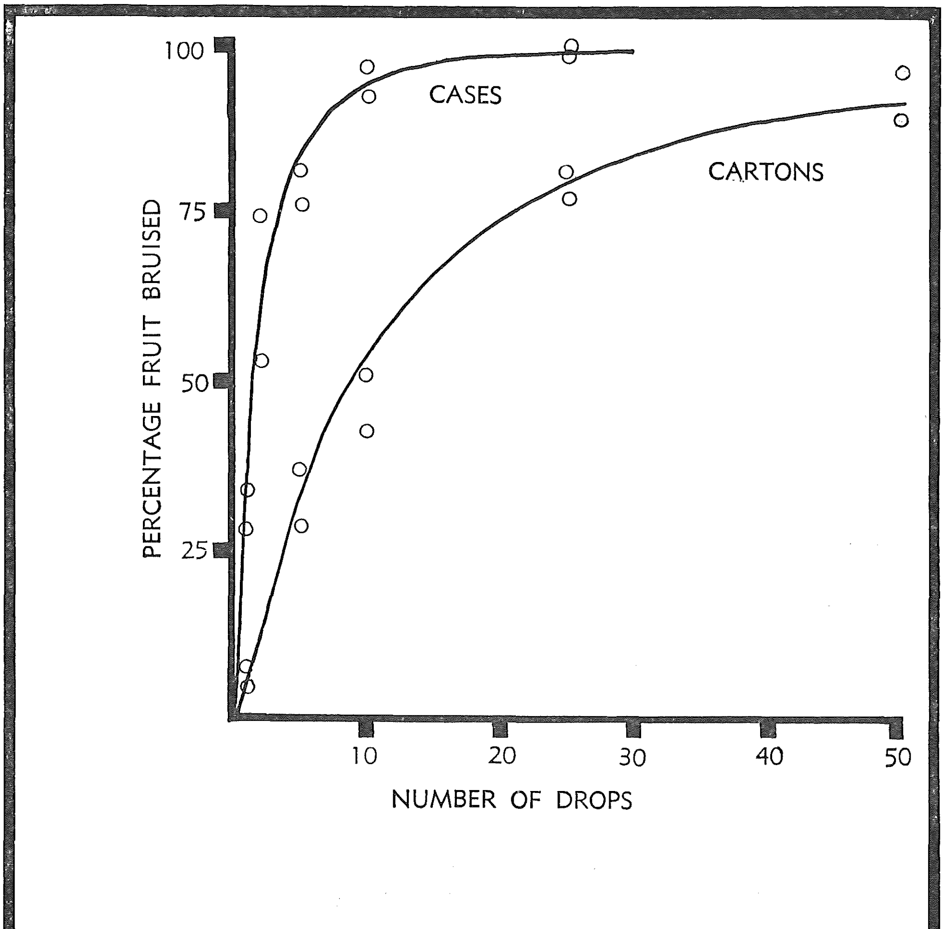

Fig. 2.—Typical curves relating damage to number of drops; Jonathan, 12 in. height, cases and cartons.

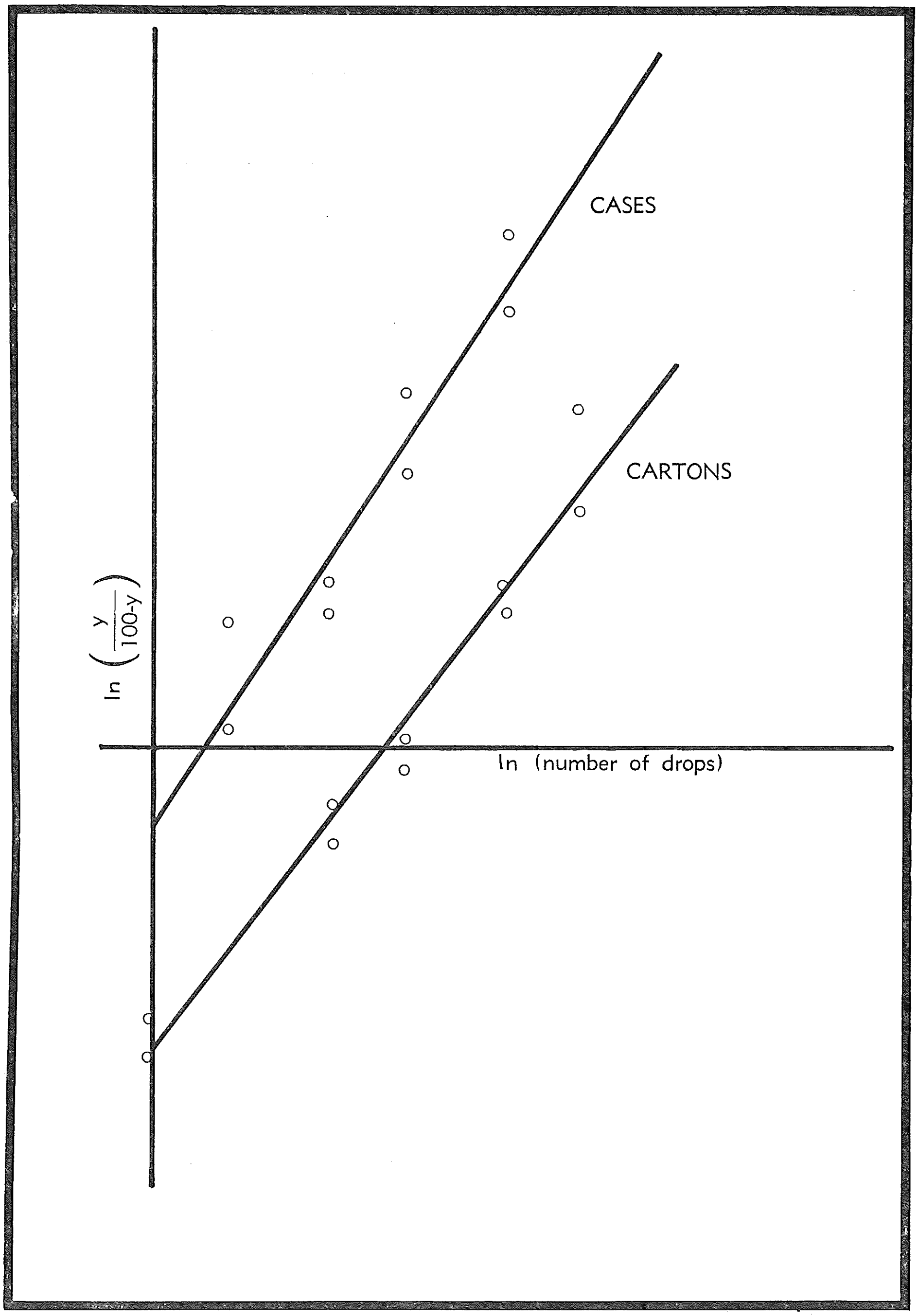

Fig. 3.—Data of Fig. 2 after transformation, with regression lines.

A further striking feature of Figure 3 is that the two lines appear almost parallel; in fact, they do not differ significantly in slope, but only in intercept. It is obviously important to ascertain the extent to which this parallelism occurs elsewhere in the system. In view of the results of the "critical height" experiment, we begin by comparing the 2 in. height results with all others. The mean of the regression coefficients of the other sets is 1·240, with range 0·762 to 2·148. The four 2 in. values are 0·143, 0·299, –0·187 and (for Jonathan cases) 1·069. Onlv the last is in scale, and even this is only marginally significant at the $P =$ 0·05 level. Moreover, it appears to be largely attributable to a single replicate for 200 drops. These results thus substantially confirm those of the previous experiment, in suggesting that the critical height is in the region of 2 in. We therefore exclude the 2 in. results from the remainder of the analysis.

The experimental design is now reduced to 2 x 2 x 4 treatments, so that we have in all 16 regressions on number of drops, with a total of 136 observations. These have been compared, by conventional analysis of variance techniques, in all 120 possible pairs. For each pair we have an estimate of the variance taken out by a single joint regression line, and of the successive improvements due to fitting first two parallel lines, then two non-parallel lines. In only 9 cases out of the 120 was there an improvement due to non-parallel lines significant at the $P = 0{\cdot}01$ level; moreover, the mean contribution to the sum of squares for these 9 was only 6·4%, so the significance reflects the excellence of fit (and hence very small error) rather than the importance of the contribution.

In view of the inherent variability of the system, we therefore regard it as best considered as a set of all-parallel lines. The best estimate of the overall regression coefficient is obtained by pooling the appropriate sums of squares for all regressions, giving a value of 1·0818. This is the value with which we shall work. It is, however, very close to unity, and expression (1) would obviously be much simplified if we were able to put $b = 1$; we shall later explore the reduction in accuracy that this simplification entails.

The last point of interest at this stage in the analysis is that we have succeeded in our aim of separating the effect due to a number of drops, which resides entirely in the regression coefficient and is independent of treatment, from the effects due to treatments (height, package and variety), which reside entirely in the intercepts.

(ii) Effects of Height, Package and Variety

We now have 16 values of the intercept (ln a), and we begin by subjecting these to analysis of variance in which the main effects of height, package and variety are compared with the pooled interactions as error. As expected, height and package are highly significant; but the variance due to variety is less than that of the error, so there is in this experiment no evidence of varietal difference. We can therefore pool the results from the two varieties and proceed to examine, for each type of package, the relationship between (ln a) and height. Again, plotting shows the relationship to be highly non-linear and asymptotic; it therefore seems reasonable to investigate the possibility of fitting an analogue of expression (1), though, since (ln a) may be negative, a logarithmic transformation is no longer available. We therefore consider the expression

$$\frac{\ln a}{A - \ln a} = k_1 + k_2 h \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3),$$

where h is the height, A is the asymptotic value of (ln a), and k_1 and k_2 are parameters to be determined. We immediately encounter two difficulties. First, we have no *a priori* knowledge of the value of A. Secondly, the (ln a) values available for fitting are themselves separated from the original data by the transformation implicit in the overall regression, and our aim is to fit the raw data, not one of its transformations. Furthermore, small errors in (ln a) will generate relatively large errors in a itself, and therefore in the overall prediction. Preliminary investigation showed that expression (3) does indeed give good linearization of the relationship, but that the goodness of fit is surprisingly insensitive to the value of A chosen. We have therefore elected to iterate for A, k_1 and k_2 simultaneously, minimizing the error, not against the 16 available values of (ln a), but against the 136 values of the original data calculated from expression (1). We are particularly interested in seeking a set of values such that, as we pass from cases to cartons, A and k_1 remain constant and only k_2 changes.

Iteration shows that the following set fulfils the required conditions: $A = 2\cdot0$; $k_1 = -0\cdot8$; k_2 (cases) $= 0\cdot05$; k_2 (cartons) $= 0\cdot02$. This can easily be shown to be equivalent to fitting, in place of expression (2), the relationship

$$\ln\left(\frac{y}{100 - y}\right) = 2 - \frac{2}{kh + 0{\cdot}2} + 1{\cdot}0818 \ln x \quad . \quad . \quad . \quad (4),$$

where x is the number of drops, h the height in inches, k takes either of the values of k_2 above, and y is the percentage of fruit damaged.

(iii) Overall Fitting and Prediction

For each of the 136 original observations, we now have a corresponding predicted value obtained from expression (4). The observed and predicted values are plotted against each other in Figure 4. The mean difference between observed and predicted values is $-3\cdot45\%$; the mean absolute difference is $7\cdot84$. This is actually slightly less than the mean absolute difference between replicates, so the theoretical maximum efficiency of fitting has been achieved. The correlation coefficient between observed and predicted values is $+0\cdot9424$. If in expression (1) we take $b = 1$ instead of $b = 1\cdot0818$, the three values in the same order become $-5\cdot63$, $8\cdot47$ and $+0\cdot9407$. The loss of accuracy is very small, and it would obviously suffice to take $b = 1$ in any future work of this type.

Although these results are a test of the efficiency of fitting, they are not a test of the efficacy of prediction, since the parameters used for fitting expression (4) have themselves been derived from the data. We now require to investigate whether the system is sufficiently robust to fit a new set of data by means of the old parameters. We have no set as comprehensive as that of the main experiment, but we have an independent set of 24 observations: these are Jonathan in cases, dropped from heights of 3, 4, 5, 6 and 12 in., the number of drops being 1, 3, 9 and (except for 12 in.) 27 and 81. These have again been compared with the values predicted from expression (4). The plot of observed against predicted values is given in Figure 5; the mean difference between observed and predicted is $-3\cdot66\%$, the mean absolute difference is $9\cdot03$, and the correlation coefficient is $+0\cdot9527$. The system is therefore robust under change of data.

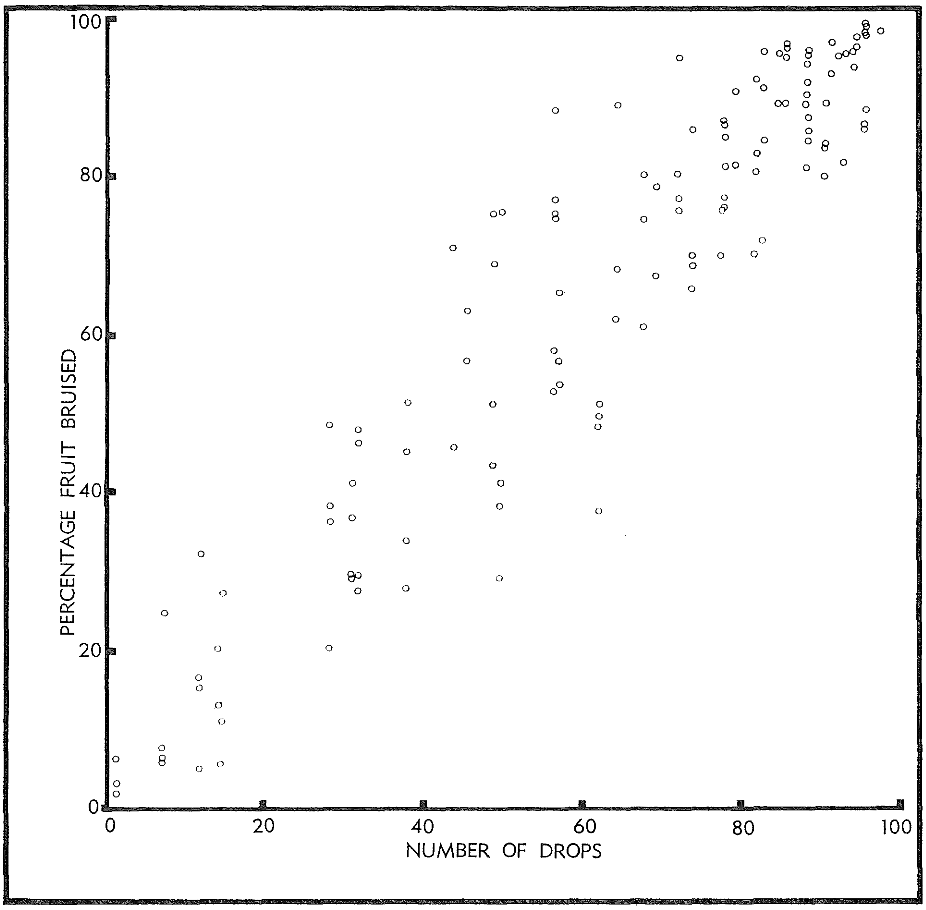

Fig. 4.—Plot of predicted against observed values of damage for main experiment (136 observations).

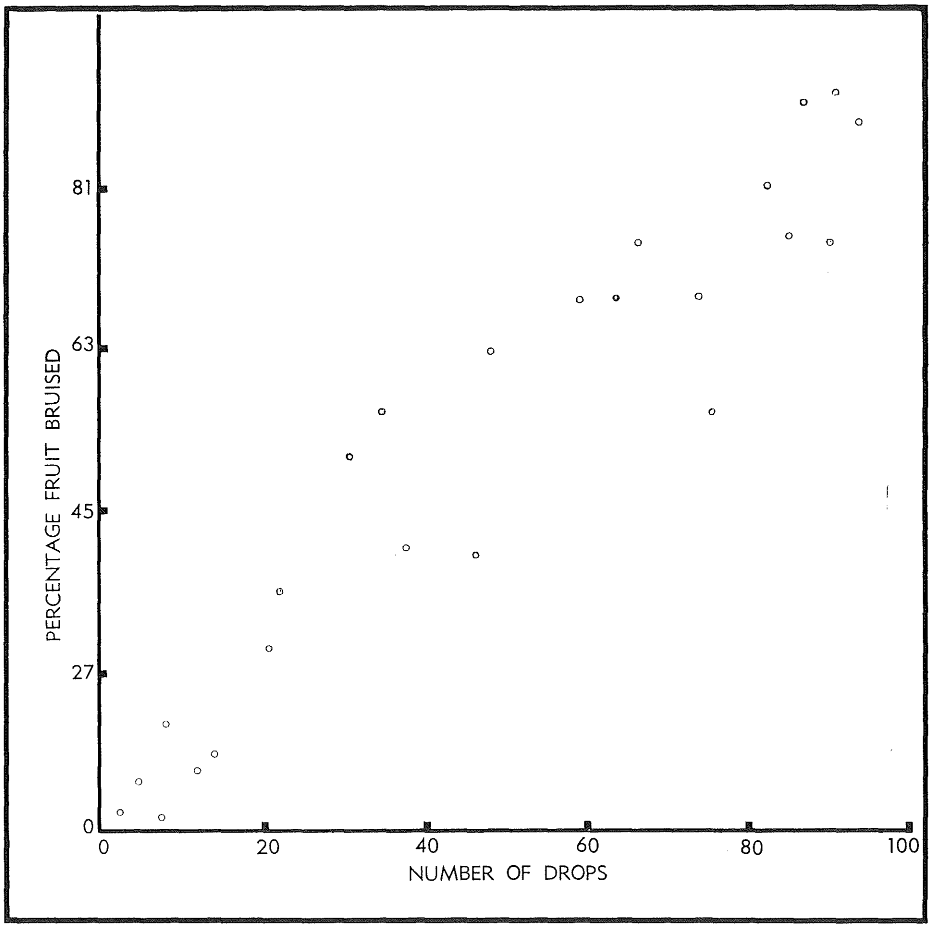

Fig. 5.—Plot of predicted against observed values of damage for independent experiment (24 observations).

IV. CONCLUSIONS

Two major conclusions emerge from these results. First, there is clear evidence of the existence of a critical height at 2 in. At or below this height bruising is independent of both number of drops and type of package, and is thus substantially random. It follows that any existing test based on a 2 in. drop height must be regarded as invalid.

Secondly, the results show that the relationship between damage (expressed as percentage of bruised fruit), drop-height and number of drops can be expressed by a relatively simple mathematical relationship with only a single variable parameter which is characteristic of package-type. Moreover, the relationship is capable of predicting damage in an experiment other than that from which the original expression was derived. It must be stressed that we have been overtly curve-fitting, not testing a theoretical model, so that the extent to which our model would fit experiments widely different from those here reported must remain open; nevertheless, the simplicity of the calculations, and the excellent fit obtained, suggest that in future work of this type an approach similar to that used here would be a profitable starting-point.

Finally, it should perhaps be noted (i) that the experiments disclose no significant differences in response between the two varieties Jonathan and Delicious, and (ii) that the results amply confirm existing experience of the superiority of tray-packed cartons over pattern-packed cases so far as mechanical damage is concerned.

V. ACKNOWLEDGEMENTS

We are indebted to Mr. G. Dolby for several helpful discussions, and to Miss Kathryn Kerridge for extensive computational assistance.

REFERENCES

BULMER, C. H., GORDON, G. A., MOWAT, J., and DEAN, K. (1962).—"Package Handling Studies." (Patra Special Research Project: Leatherhead, England.)

GUILLOU, R., SOMMER, N. F., and MITCHELL, F. G. (1962).—Simulated transit testing for produce containers. *Tappi* 45:176-9.

INGLE, M., and HYDE, J. F. (1968).—The effect of bruising on discoloration and concentration of phenolic compounds in apple tissue. *Proc. Am. Soc. hort. Sci.* 93:739-45.

MOHSENIN, N. N. (1970).—"Physical Properties of Plant and Animal Materials, Vol. 1." (Gordon & Breach: New York.)

MONTEREY, M. T. S. (1971).—"Five Step Packaging Development." California.

NATIONAL SAFE TRANSIT COMMITTEE (1953).—Procedure for testing packaging products under 100 pounds. Project 1-A. Washington D.C.

NELSON, C. W., and MOHSENIN, N. N. (1968).—Maximum allowable static and dynamic loads and effect of temperature on mechanical injury in apples. *J. agric. engng Res.* 13:305-17.

O'BRIEN, M., CLAYPOOL, L. L., LEONARD, S. J., YORK, G. K., and MACGILLIVRAY, J. H. (1963).—Causes of fruit bruising on transport trucks. *Hilgardia* 35:113-24.

O'LOUGHLIN, J. B. (1964).—The bruising of fruit during transport and storage. *4th Australian Fruit and Vegetable Storage Research Conference.*

QUEENSLAND DEPARTMENT OF PRIMARY INDUSTRIES (1970).—Deciduous fruit handbook, Part 1:50-52. (Unnumbered multilith publication.)

SCHOORL, D. (1968).—Evaluation of package performance. *5th Australian Fruit and Vegetable Storage Research Conference*:63-70.

WEST, E. S., WILBERT, R. T., MASON, H. S., and VAN BRUGGEN, J. T. (1966).—"Text-book of Biochemistry, 4th Ed." (Macmillan: New York.)

(Received for publication January 7, 1972)

Mr. Schoorl is an officer of the Horticulture Branch, Queensland Department of Primary Industries; Dr. Williams is a Chief Research Scientist of the C.S.I.R.O. Division of Tropical Pastures, Brisbane.