Estimating Tote Drop Height & Impact Acceleration from a Transportation Recorder

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Abstract: Healthcare products are often shipped from a distribution center to a retail store in plastic totes. Previous research on plastic tote distribution at the Healthcare Packaging Consortium has suggested that the use of bubble wrap and air pillows at tote bottom and top, respectively, reduces impact. In addition to the use of bubble wrap and air pillows, monitoring tote handling would also have the potential to reduce distribution damages. A transportation recorder was used to aid this study. Equations were developed from the drop test data to estimate drop height and impact acceleration at tote bottom from impact acceleration obtained from the recorder.

Keywords: Plastic tote distribution, transportation recorder, drop height, impact acceleration

Introduction

Healthcare products are often shipped in partially-filled plastic totes from a distribution center to a retail store. Product damages have often occurred during this phase of the distribution process. The product damaging problem was validated and organizing the tote contents was recommended [1]. Placing a bubble wrap sheet at tote bottom while filling the upper part of the tote with air pillows, was found to be very effective in preventing damages [2].

Monitoring tote handling is another area that would help in preventing product damages. Two useful pieces of information are: (1) when and how high a tote was dropped during the distribution and (2) what the maximum impact acceleration was during the distribution. The first allows the shipper to pin point mishandling locations, thus improvements can be made, such as proper handling training. The second could be useful for cushion/package design.

A transportation recorder (also called saver) is a useful device for monitoring tote handling. Conventional commercial recorders are shown in Figure 1. Typically, a recorder can record shock/impact, temperature, and humidity. Some recorders are capable of determining drop heights; however, they do not measure these heights directly [3]. In a previous study [4], drop heights were correlated to recorder's impact accelerations experimentally through drop test. However, the previous study only covers drop heights from 12" to 24". Through the study this equation was developed: $y = 0.5243x - 3.4853$, where y = estimated drop height (inches) and x = saver's impact acceleration (g).

Measuring impact acceleration at tote bottom often cannot be completed directly since a typical recorder can measure impact acceleration up to 100g to 200g. A drop of the hard plastic tote on a hard surface can result in an impact acceleration of more than 200g even with a drop height as low as 24". Thus, the recorder must be cushioned and impact acceleration obtained is relative depending on the amount of cushioning. Measuring the real impact acceleration at tote bottom is also complicated by the various vibrations of the thin plastic shell used at tote bottom, as will be seen later in this paper.

This paper reports a study using a transportation recorder to determine experimental tote drop heights (from 12" to 48" drop heights) and impact accelerations at tote bottom. A simple recorder setting was used. Equations for estimating drop height and impact acceleration were developed for such recorder setting.

Figure 1. Transportation Recorders (Savers)

Recorder Setting

The recorder used in this study was the 3M30 Plus from Lansmont (the first one shown in Figure 1), which has a 100g maximum impact acceleration. In order to prevent the plastic tote from exceeding 100g of impact acceleration, eight layers of 5/16" bubble wrap were placed underneath the recorder. The recorder and layers of bubble wrap were placed in a single-wall corrugated box and topped off with peanut cushion foams as shown in Figure 2. The box was then taped to the bottom of a plastic tote, which was dropped by a drop tester as shown in Figure 3. The number of bubble wrap layers was determined by dropping a tote with the recorder with different number of layers as shown in Figure 4. It was determined that eight layers would suffice. This allows some space above the recorder and at the same time prevents the impact acceleration from exceeding the 100g capacity. This setting would work well with a recorder with higher capacity, such as 200g recorder.

Figure 2. Recorder Setting

Figure 3. Placing the Recorder in a Tote for Drop Test

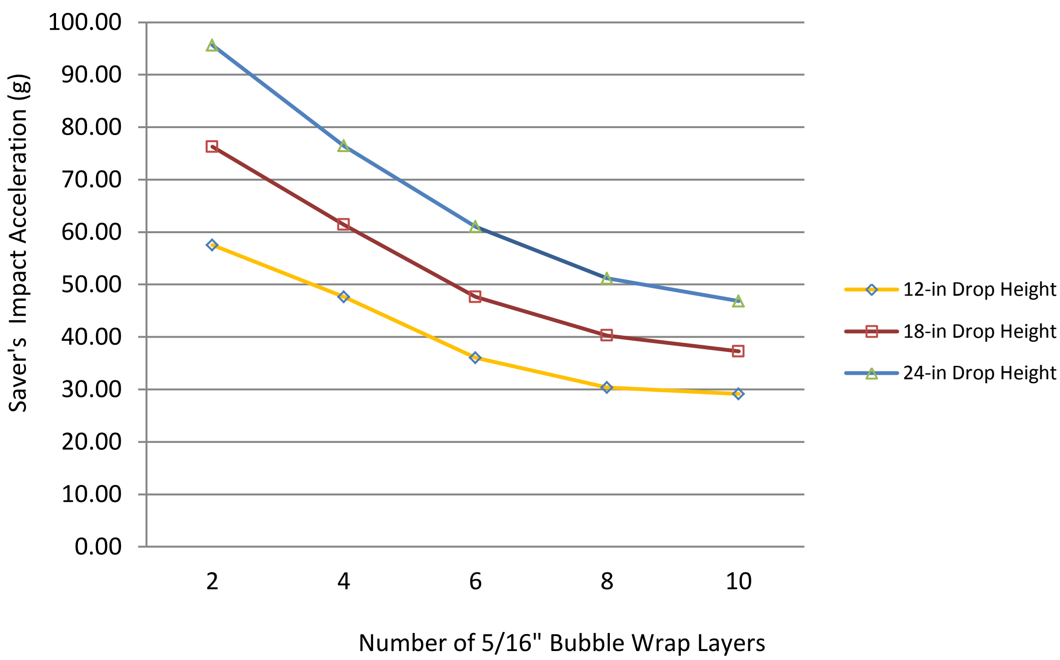

Figure 4. Determination of 5/16" Bubble Wrap Layers underneath the Recorder

Drop Height Estimation from Recorder's Impact Acceleration

A tote with a recorder, set as mentioned above, was dropped at various known drop heights, 30 drops per drop height. Drop heights were then plotted against the corresponding recorder's impact acceleration. A previous study [4] covered drop heights from 12" to 24" and an equation was developed: **y = 0.5243x – 3.4853** (R^2=0.969), where y = estimated drop height (inches) and x = saver's impact acceleration (g). In the current study, the drop height range was 12" to 48" which would cover most situations. It should be noted that all drops made in this and previous studies were flat-bottom drop. The data is summarized in Table 1. A new equation was developed: **y = 0.5082x - 2.7711** (R^2=0.9989).

Table 1. Average Recorder's Impact Acceleration from 30 Drops per Drop Height with 8 Layers of 5/16" Bubble Wrap underneath the Recorder

Drop Height (in)	Average Recorder's Impact Acceleration (g)
12	30.67
15	35.33
18	39.76
21	45.52
24	52.37
27	58.15
30	64.73
33	70.63
36	76.72
39	82.27
42	88.40
45	94.38
48	99.32

The two equations yield comparable results against 85 validation drops as shown in Figure 5. Both underestimate drop height slightly when drop heights are more than 28". The average errors of both equations for the 85 validation points are less than 3% with the worst % error of about 8%. Realistically, tote drop heights would be in the 12" to 24", in which both equations give quite accurate height estimation.

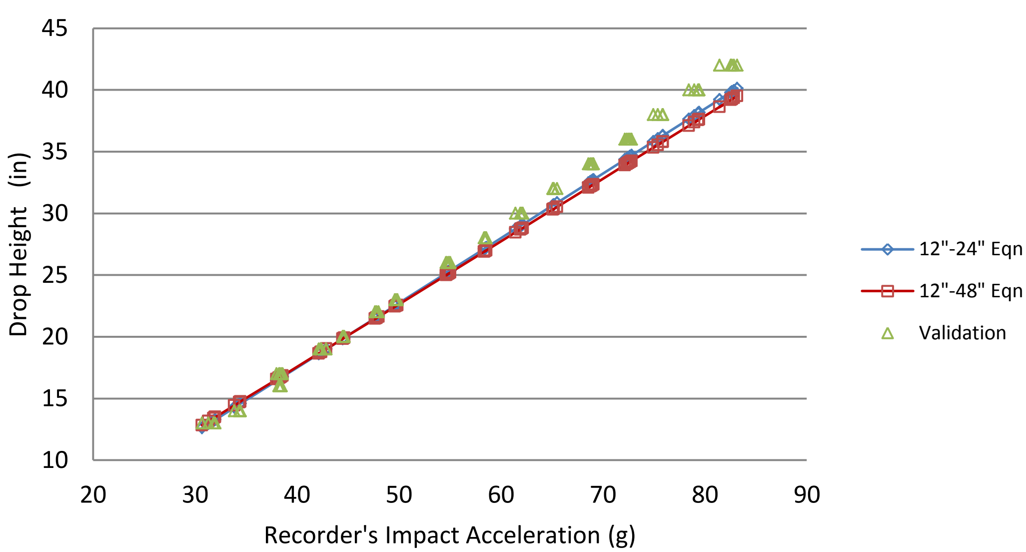

Figure 5. Validation of Drop Heights Using 85 Drops

Estimation of Impact Acceleration at Tote Bottom

At the beginning of this study, a single-axis accelerometer was mounted directly to the interior tote bottom without any cushion. The goal was to measure impact accelerations at tote bottom directly from drop tests with known corresponding drop heights. The attempt failed due to the inconsistency of impact acceleration measured. For example, at 18" drop height the standard deviation of 30 drops was about 40% of the average impact acceleration. This was due to the thin plastic panel used at tote bottom. However, the consistency improved significantly when a cushion was provided. Since the 5/16" bubble wrap was used in a previous study [2], the same wrap was used in a standard deviation study shown in Figure 6.

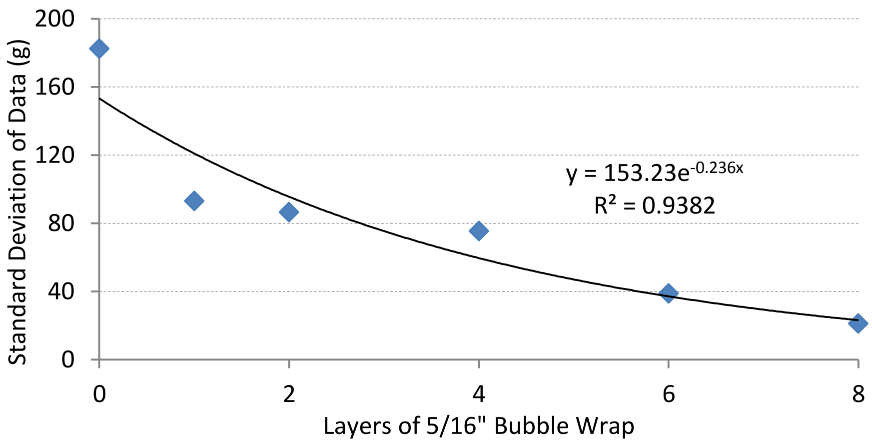

Figure 6. Standard Deviation Study (18" Drop Height)

It is not desirable to provide more than one layer of bubble wrap at tote bottom due to cost increase and interior tote space reduction. Furthermore, one layer of 5/16" bubble wrap placed at tote bottom was recommended in the previous study. Thus, the goal of the study was shifted to the estimation of impact acceleration at tote bottom with a single layer of 5/16" bubble wrap sheet.

In the first attempt, impact accelerations were measured directly by placing a 2000g single-axis accelerometer at the bottom of tote with one layer of 5/16" bubble wrap underneath. A computer CD was used as a platform to mount the accelerometer. Thirty drops were made for each drop height from 12" to 24" with 3" increment. Results are shown in Table 2 and Figure 7.

Table 2. Direct Measurement of Impact Acceleration with One 5/16" Bubble Wrap Layer

Height (in)	Average Acceleration (g)	SD (g)	SD as % of Average Acceleration
12	203	51	25
15	267	85	32
18	320	93	29
21	412	148	36
24	506	189	37

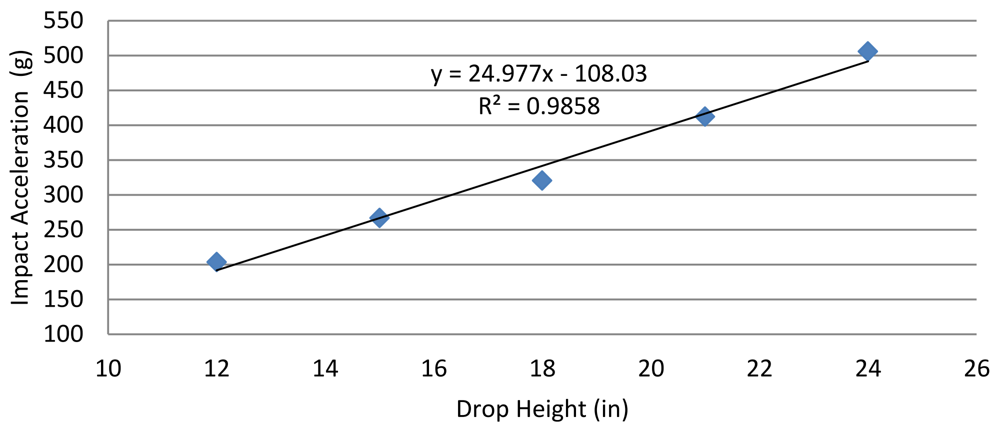

Figure 7. Estimating Impact Acceleration from Drop Height – Direct Approach

As can be seen in Table 2, the standard deviations were still somewhat high but better than those with no-cushion at all. For example, at 18" drop height the standard deviation as percentage of average impact acceleration was reduced from 40% to 29% by placing one 5/16" bubble wrap layer underneath. Since the inconsistency of data remained high, an indirect method was developed. The indirect approach used test data with 3 to 8 bubble wrap layers which gave more consistent data than 0 to 2 layers. Averages of twenty drops were then used to plot the curves shown in Figure 8.

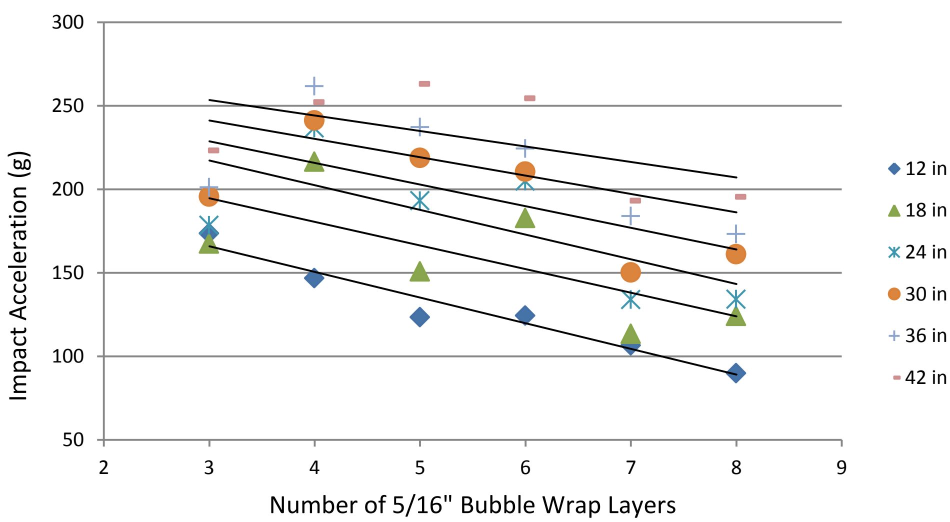

Figure 8. Indirect Approach of Determining Impact Acceleration at Tote Bottom with One Layer of 5/16" Bubble Wrap

Equations of trend lines were then developed, as shown below, where x = number of 5/16” bubble wrap layers and y = the corresponding impact acceleration. When x = 1, the value of y represents an estimated value of impact acceleration at tote bottom with one layer of bubble wrap cushion.

$$y = \begin{cases} -15.349x + 211.89 & \text{for drop height } = 12\text{"; when x} = 1 \text{ layer, y} = 196.54\text{g} \\ -14.107x + 236.85 & \text{for drop height } = 18\text{"; when x} = 1 \text{ layer, y} = 222.74\text{g} \\ -14.794x + 261.56 & \text{for drop height } = 24\text{"; when x} = 1 \text{ layer, y} = 246.77\text{g} \\ -12.932x + 267.4 & \text{for drop height } = 30\text{"; when x} = 1 \text{ layer, y} = 254.47\text{g} \\ -11.008x + 274.18 & \text{for drop height } = 36\text{"; when x} = 1 \text{ layer, y} = 263.17\text{g} \\ -9.25x + 281.15 & \text{for drop height } = 42\text{"; when x} = 1 \text{ layer, y} = 271.90\text{g} \end{cases}$$

The estimated impact accelerations with one-layer of bubble wrap were then plotted against corresponding drop heights, as shown in Figure 9. Thus, an equation was developed to estimate impact acceleration at tote bottom from a known drop height granted the one layer of 5/16” bubble wrap is used.

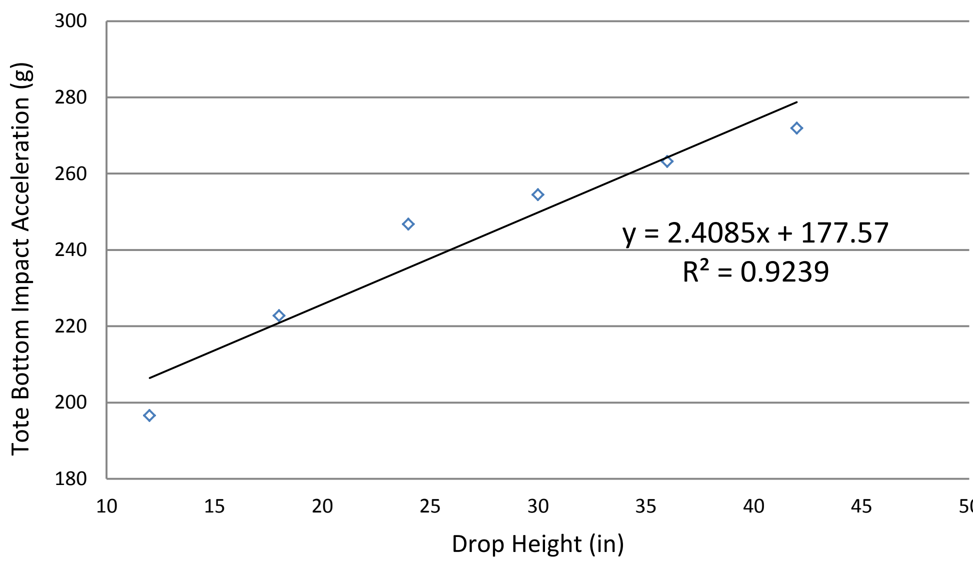

Figure 9. Interior Tote Bottom Acceleration Estimation – Indirect Approach (12”- 42” Study Range)
(One layer of 5/16” bubble wrap is placed at tote bottom)

If the study range was narrowed down to 12” – 24” range for comparison with the direct approach mentioned earlier, a similar equation can be developed as shown in Figure 10.

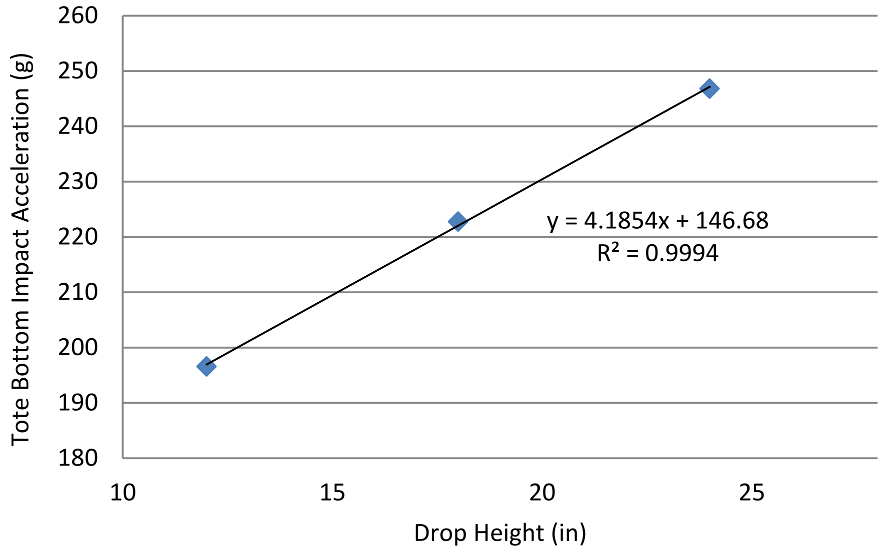

Figure 10. Interior Tote Bottom Acceleration Estimation – Indirect Approach (12”- 24” Study Range)
(One layer of 5/16” bubble wrap is placed at tote bottom)

The height estimation equations were validated with the same 85 drops previously shown in Figure 5. In Figure 11 each diamond marker represents a validation drop while the lines represent estimations from direct and indirect approaches. As mentioned earlier the validation drop data is very inconsistent due to the vibration of the thin plastic tote panel used at tote bottom. As can be seen from Figure 11, the two estimations using the indirect approach give a much better representation than the estimations found using the direct approach. The indirect approach with the 12”-24” study range (having 43 validation points above & 42 points below) is slightly better than the 12” – 42” range (having 48 validation points above & 37 points below).

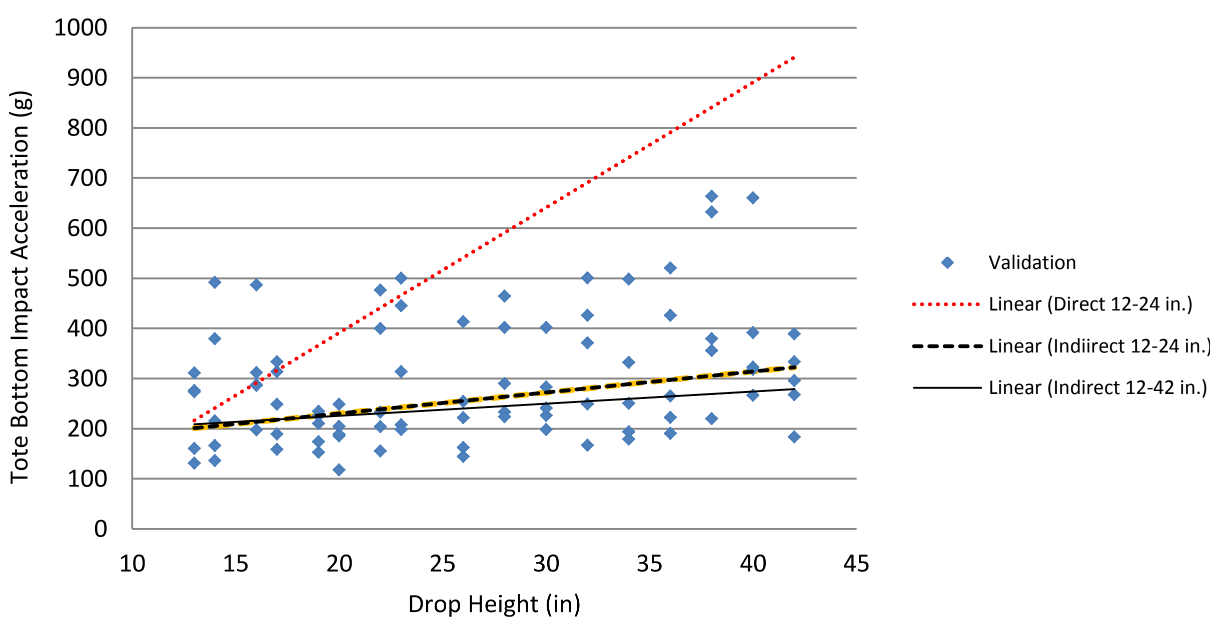

Figure 11. Validation of Tote Bottom Impact Acceleration

Discussions & Conclusions

This paper recommends the use of a transportation recorder to monitor tote handling, which would improve the handling and ultimately result in product damage reduction. A transportation recorder would be placed the same way as used in this study in a dummy tote, which would be shipped along with other totes filled or partially filled with products. However, there is no guarantee that the dummy tote would be handled the same way as the other totes in the same shipment.

Impact accelerations are then retrieved from the recorder. Drop heights for peak impact accelerations can be estimated with ease using the equation developed in this study. As mentioned earlier, the two equations for drop height estimation (i.e., one derived from drop tests from 12" – 24" drop heights and another derived from drop tests from 12" – 48" drop heights) are comparable. The validation, however, indicates that the former yielded slightly better height estimation at higher drop heights. Thus, the former equation, which was developed in a previous study, is recommended, i.e.

$$\mathbf{y = 0.5243x - 3.4853}$$

where x = impact acceleration retrieved from a transportation recorder (g)
and y = estimated drop height (inches)

It should be noted again that only flat-bottom drops were used in this study. If a tote is dropped on an edge or a corner, the impact acceleration would be higher since it is harder at edge and corner. Thus, the estimated drop height from the above equation would be off somewhat. Nevertheless, the estimated drop height would still provide some insight on how a particular tote was handled.

Once a drop height is estimated from the above equation, impact acceleration at interior tote bottom with a layer of 5/16" bubble wrap can be estimated by the following equation:

$$\mathbf{y = 4.1854x + 146.68}$$

where x = drop height (inches)
and y = impact acceleration at tote bottom given that a layer of 5/16" bubble wrap sheet is utilized (g)

The validation data indicated that some actual drops would give impact acceleration far off from the estimated value obtained from the derived equation. However, nothing can be done about this inconsistency of data due to the vibration of the thin plastic panel used at tote bottom, as discussed in the paper. Nevertheless, the impact acceleration estimated from the above equation could be useful for packaging professionals in a proper cushion design.

Some may wonder about the role of tote weights. A previous study [5] has shown that tote weights do not affect the impact acceleration. However, a heavier tote has more mass, thus results in a larger impact force for the same impact acceleration. Thus, in this current study only empty totes were used.

Last but not least, tote design may affect the equations developed in this study. This would be a good study area in the future.

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