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DYNAMIC ANALYSIS OF "SMALLS" IN FEDEX NEXT DAY
AIR SHIPMENTS

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Ko Chin Chiang

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Master of Science degree in Packaging

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# DYNAMIC ANALYSIS OF "SMALLS" IN FEDEX NEXT DAY AIR SHIPMENTS

By

Ko Chin Chiang

A THESIS

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

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## ABSTRACT

DYNAMIC ANALYSIS OF "SMALLS" IN FEDEX NEXT DAY AIR SHIPMENTS

By

Ko Chin Chiang

The objective of this study was to measure and analyze the dynamic events that "smalls" experience when they are shipped with larger and heavier packages. "Smalls" are defined as any packaged product whose volume is less than 13,000 $cm^3$ (800 $in^3$), whose longest dimension is 350 mm (14 in), and whose weight is 4.5 kg (10 lb) or less. To measure this environment, tri-axial recorders (SENSR™ GP1) were placed in three different packages: the Rigi Bag® Mailer; the Bubble Mailer, and an E-flute corrugated box with Ethafoam cushions. The packages were shipped in the United States using FedEx Express priority overnight. The results showed that the packages experienced a total of 27 combined drops, throws, and tosses. The largest near zero G travel distance was 197.08 inches. Both the Rigi and Bubble Mailer experienced similar maximum drop heights of 48 inches whereas the box experienced 39 inches. There were no significant differences in the maximum G for all three package types. A lab test protocol was developed to simulate priority overnight service. A 60 inch drop height is recommended for the 99 percent occurrence level and 24 inches for the 95 percent occurrence level. A total of 17 drops, 8 on various faces, 5 on edges, and 4 on corner is also recommended.

The thesis is a dedication to my family and Yi-Wen Wang for their constant support and encouragement throughout the difficult times in the U.S.

## ACKNOWLEDGEMENTS

A very special thanks to Dr. S Paul Singh for his guidance while acting as my major professor and helping me throughout my pursuit of Master's degree.

I would also like to express my gratitude to Dr. Gary Burgess and Dr. Brian Feeny for their suggestions and for serving on my committee.

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# CHAPTER 1

# INTRODUCTION AND LITERATURE REVIEW

Transporting packaged commodities from one place to another is an operation that occurs daily. Millions of shipments ranging in different sizes, weights, and shapes are being delivered manually and/or mechanically. Different modes of transportation such as truck, rail, air, and sea have been employed by carrier companies to fulfill people and companies' need. Service commitments include rapid and efficient movement of shipments, reliable and cost-effective services. However, with the increasing number of goods that are shipped and handled, the logistical networks are rather complex.

## 1. 1 FEDEX, UPS, and DHL

Federal Express (FedEx), started its business in 1971, processes approximately 3.5 million packages on a daily basis (FedEx Facts, 2008). Its worldwide headquarters is located in Memphis, Tennessee. FedEx has been successful in the air transportation sector, serving millions of customers in over 220 countries. It is one of the major private U.S. companies offering a one-class service for door-to-door shipment of small parcel packages (Cheema, 1995). Priority overnight service uses a global air-and-ground network system to speed up delivery of time-sensitive shipments. FedEx has 15 global hubs in its hub-and-spoke system: 8 in the United States, 3 in Europe, 3 in Japan and Philippines, and 1 in the Middle East. The hubs are categorized into national hubs, regional hubs or mini-hubs. The hub in Memphis is the only "super hub" in the network because it sorts the most packages and has the greatest reach to various destinations

(Singh, 2007). Today, Federal Express Corporation runs a network of companies under the FedEx name worldwide. Businesses comprise FedEx Express, FedEx Ground, FedEx Freight, FedEx Kinko's Office and Print Services, FedEx Custom Critical, FedEx Trade Networks, and FedEx Services.

The name DHL was established by the three founders: Adrian **D**alsey, Larry **H**illblom and Robert **L**ynn (**D**, **H**, and **L**) in 1969. So far DHL has the world's largest and the most experienced international air express network with service to 120,000 destinations in more than 220 countries and territories (DHL History, 2008). The company owns two-thirds of the 4,400 offices throughout the world and operates more than 450 hubs supporting its extensive global coverage. The service around the world provides DHL with a significant advantage over other air express carriers where others use more third party agents in the foreign countries they serve.

United Parcel Service (UPS) was founded in 1907 with its world headquarters in Atlanta, Georgia. Today, it has become the world's largest private ground transportation company and a leader in global supply chain services (UPS History, 2008). UPS manages goods and information in more than 200 different countries and p rocesses roughly 14 millions packages everyday. In 2005, UPS expanded its Worldport, the air hub in Louisville, Kentucky, and the European air hub in Cologne, Germany to enhance the international services. Besides carrier services, UPS offers other businesses including UPS capital, consulting, express critical, logistics technology, mail innovations, and supply chain solutions.

## 1. 2 DISTRIBUTION ENVIRONMENT

Many delivery services have adapted hub-and-spoke system in the complex distribution network covering a global, national, and regional level. The hub-and-spoke system generally consists of hubs as well as local facilities. Hubs are major sorting facilities that act as an exchange point for packages traveling long distances. Local facilities play a role as a bridge point to receive or deliver packages according to their geographic area. The two are tied together to achieve a greater flexibility within the transportation system. In each hub, the package often travels through the sorting system in one of the three ways, depending on how the packages are categorized. Packages can be classified as a *small*, *regular* or an *irregular* shipping unit. *Smalls* are defined as a volume less than 13,000 $cm^3$ (800 $in^3$), and a longest dimension of 350 mm (14 in), *and* a weight of 4.5 kg (10 lb) or less (Association, 2006). There are two modes of similar sorting systems for small packages like envelopes. The packages would travel on an automated conveyor and pass through a series of chutes (Figure 1). Another automated sort system for very lightweight packages would be the packges moving on tilt trays and sliding into the chutes (Figure 2). After lightweight packages traveling through the chutes, they are usually consolidated into bags for efficient handling (Figure 3). Each bag contains about 10 to 20 packages destined for the same geographic location (Singh, 2007). Besides smalls, other sizes of packages are often moved along with the conveyor belt at the hub right after fresh off the airplanes and each unit slides down the wall to employees waiting to enter them into the sorting process. Figure 4 provides a pictorial view of the environment.

Figure 1. Small packages moving on conveyor

Figure 2. Small packages moving on tilt trays

Figure 3. Packages collected into bags from a chute by a facility worker

Figure 4. Hub sorting for small to larger size packages

During the distribution of packaged goods, the shipping environment of small parcels is typically subject to hazards due to automated sortation and multiple manual handlings. Automated sortation includes packages traveling on belts, chutes, rollers, diverters, slides or more while manual handling covers loading, unloading, and sorting. During the package transportation process, shock accounted for one of the severe hazards results from drops, kicks, throws, and otherwise mechanized handlings. However, it was revealed in a nationwide study that approximately 85 percent of all in-transit shocks derive from impacts other than drops. Automated system is therefore designed to minimize impacts to the packages (Singh, 2007). To sort packages efficiently and minimize mis-sorts, packages pass through scanning tunnels at the hub, providing up-to-date information to senders and recipients on its location and estimated arrival time (Figure 5). In addition, most packages are handled manually in local facilities; whereas, the sortation in the hub is mainly processed by automated system and generally operated during the night to meet early next day delivery.

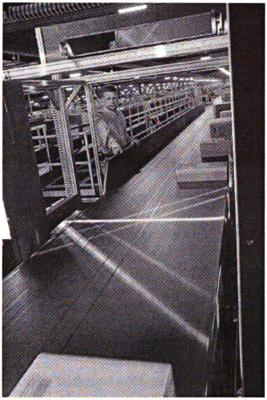


Figure 5. Package scanning tunnel

## 1.3 LITERATURE REVIEW

Many dynamic researches have been conducted on various transportation modes to comprehend the potential hazards in the distribution environment. The information collected could be used to improve packaging designs and to develop performance testing. In April 1991, Thomas M. Voss completed a study on the effect of weight and volume of packages on drop heights encountered in the United Parcel Service small parcel environment within the United States. That the findings revealed 42.1 inches was the highest drop height throughout the supply chain. Size of the package had no significant effect on the drop heights. Lighter weight packages for the smaller size experienced higher drop heights. Weight had no positive relations on the medium and larger size packages drop heights.

Jorge A. Marcondes applied the dynamic analysis of a less than truckload (LTL) shipment in vertical, lateral, and longitudinal direction. The study showed that the rear of the truck is not always the worst position for acceleration magnification in LTL. As high as 10 G's acceleration was encountered during vibration. This is due to the fact that LTL uses different trailer size and suspension as opposed to full truckload shipments.

M. Garcia, P. Singh, V. Cloquell, and K. Saha conducted a research on the international air parcel shipping environment for DHL and FedEx between Europe and the United States. The analysis was focused on whether there is a significant difference on the drop height for packages with and without warning labels. Package size of 14.96 × 13.38 × 13.38 inches and weight of 15 lbs was air shipped roundtrip from East Lansing, MI, USA to Valencia, Spain using DHL and FedEx. The research finding showed no significant difference on drop heights between the two carriers with and without label at 95% occurrence level. However, at 99% occurrence level, DHL shipments with warning label resulted in better handling, experiencing lower drop heights than packages shipped without warning labels. The drop orientations showed approximately 47% on a face followed by an edge and a corner.

In 2006, P. Singh, G. Burgess, J. Singh, and M. Kremer instrumented data recorder (EDR–3C) to measure mid-sized and lightweight packages in next-day air shipment for DHL, FedEx, and United Parcel Service. Based on a 95% occurrence level, the findings discovered that the drop occurrence and maximum drop height had no significant difference within FedEx and UPS between ground, second-day, and next-day.

Drop heights were all within the range of 18.11 – 33.86 inches. DHL drop heights were higher by up to 50 percent, but were still within the limits mentioned above. From various studies done in the past, the perception that smaller packages likely to experience higher drop heights due to the tendency of being placed on top of larger packages seems never change.

P. Singh, G. Burgess, and J. Singh measured the dynamics of air shipments of lightweight packages weighing less than 5.5 lbs with and without warning labels. The shipments conducted were from East Lansing, MI to San Francisco, CA and Orlando, FL via FedEx second-day air shipment. The data showed that package sizes and weights had no relationship with the package drop heights. The "Fragile-Handle with Care" warning labels provided no significant effect on the handling of packages. The drop orientations showed approximately 60% on a face, 30% on an edge, and 10% on a corner. The lack of correlation between the package sizes, weights, and drop heights suggests that the cause of the majority shock events is the outcome of automated handling operations, but not manual drops.

Currently in the system, no studies have been conducted on the dynamics of single packages regarded as “smalls”. The focus of this research is to measure and analyze dynamic events that occur to packages in domestic small parcel shipments, where the volume is less than 13,000 $cm^3$ (800 $in^3$), and longest dimension is 350 mm (14 in), *and* weight is 4.5 kg (10 lb) or less (Association, 2006).

This study had following two objectives:

- To measure the dynamics of “smalls” in priority overnight service for FedEx Express within United States.
- To provide recommended test levels for drop testing for packages qualifying for “smalls” in the mixed parcel shipping environment.

# CHAPTER 2

# MATERIALS, INSTRUMENT AND TEST METHODS

## 2.1 TEST INSTRUMENTATION AND PACKAGES

For this study, selection of the recorder has to physically fulfill the requirements of "*smalls*" or small packaged products. Thus, the dynamic recorder selected was SENSR GP1 manufactured by Reference LLC, Elkader, Iowa, USA (Reference LLC, 2008). SENSR GP1 is incorporated with trial-axial programmable accelerometer with features include monitoring, recording, and evaluating motions, impacts, shocks, drop orientations and temperature in vertical, lateral, and longitudinal directions. Figure 6 presents a pictorial view of SENSR GP1 tri-axial motion recording device. The data recording is divided into three areas: measurement, details, and notes. Measurement specifies the parameters to record and the reporting interval. Details define the attributes to record, recording options, and alert settings. Notes display information related to recording time and general alerts. Data recording mode samples the data into reporting interval which is defined by time segment called "Epoch". It can be user defined between 1 to 120 seconds. Choosing different epoch does not affect the sampling rate; however, recording length and storage capacity will alter accordingly.

The measuring and reporting parameters were as follows:

| | |
|---|---|
| Sampling rate per axis: | 100 Hz |
| Accelerometer range: | ±10 G |
| Temperature range: | -20°C to +80°C |
| Epoch setting: | 6 sec |
| Threshold: | 0.5 G |
| Alerts Enabled: | Vector Magnitude Max |
| Test Duration: | 7 days |

Alerts settings can be described from the following:

| | |
|---|---|
| Axis Maximum | Alert will be triggered when a single sampled acceleration value achieves or exceeds the specified value. |
| VM Max | Alert will be triggered when a single sampled acceleration value achieves or exceeds the specified value. |
| Peak Duration | This can be set up to trigger on any settable parameter including: peak acceleration input, and input duration. |
| Temperature High | Alert will trigger when the unit records a temperature equal to or higher than the specified temperature. |
| Temperature Low | Alert will trigger when the unit records a temperature equal to or lower than the specified temperature. |


Figure 6. SENSR GP1 tri-axial motion recorder

## 2.2 EXPERIMENTAL DESIGN

Test packages were instrumented with recorders (SENSR GP1) to measure the dynamic events in priority overnight by FedEx Express. The study was focused on three types of packages and each comprised with different materials to provide protection to the content. Packages include the Jiffylite® Bubble mailer#1 (Figure 7), Jiffy Rigi Bag® mailer#1 (Figure 8) manufactured by Sealed Air, and single-walled E-flute regular slotted container (RSC) corrugated board box (Figure 9) with Ethafoam 220 cushions (Dow Chemical Company, Midland, MI, USA). The first package was the Jiffylite® Bubble mailer#1, it consists 3/16" Barrier Bubble® layer for air retention and acting as cushioning (Jiffy Mailer® Products, 2008). The second package was the Jiffy Rigi Bag® mailer#1, it comprises 90 percent recycled paper fibers. The lamination provides stiffness while seamless bottom provides protection and strength. The Kraft-laminated fiberboard provides advantages of preventing movement of contents and resists bending, folding, and creasing (Jiffy Mailer® Products, 2008). The third package was the single-walled E-flute RSC corrugated board box with Ethafoam 220 cushions. The dimension of the box was designed to meet the requirements of small parcel. Cushions were epoxy glued to each of the six faces inside the box to provide adequate protection. The GP1 was placed in the bubble mailer and Rigi Bag® mailer with the top facing the packing slip, secured by using self-seal closure or cohesive self-seal. No fillers were inserted to both mailers to restrict the movement of GP1. However, for single-walled E-flute RSC corrugated board box, the GP1 was placed at the geometric center of the box with cushions placed on all six sides. The cushions provided a snug fit to the recorder.

The packages were closed with a 2 in (50.8mm) wide general-purpose plastic box sealing tape.

The size and weight of the instrument and packages were demonstrated as follows:

Size:

| | |
|---|---|
| • SENSR GP1 Recorder: | 3.935 × 2.560 × 1.140 in |
| • Jiffylite® Bubble Mailer #1: | 7.25 × 10.75 in |
| • Jiffy Rigi Bag® Mailer #1: | 7.25 × 10.5 in |
| • E-flute Corrugated Box: | 5.625 × 4.375 × 2.375 in |

Weight:

| | |
|---|---|
| • SENSR GP1 with 2×AA batteries: | 0.4875 lb / 7.8 oz |
| • Jiffylite® Kraft Bubble Mailer #1: | 0.0375 lb / 0.6 oz |
| • Jiffy Rigi Bag® Mailer #1: | 0.1375 lb / 2.2 oz |
| • E-flute Corrugated Box with Cushions: | 0.175 lb / 2.8 oz |

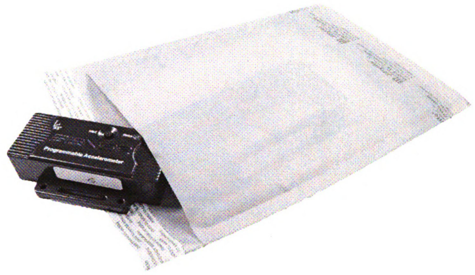



Figure 7. GP1 in Jiffylite® Bubble Mailer #1

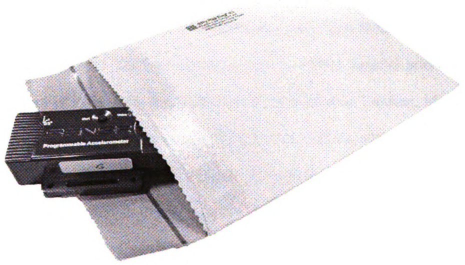



Figure 8. GP1 in Jiffy Rigi Bag® Mailer #1


Figure 9. GP1 in E-flute RSC box with cushioning material

**2.3 TEST PACKAGE SHIPMENTS**

The data was captured from two destinations: San Louis Obispo in California and Rochester in New York. The packages were sent via FedEx Express priority overnight from the School of Packaging, Michigan State University, East Lansing, Michigan. Six recorders were sent simultaneously per package type (bubble, Rigi, and box) for each round trip. With typical package movement from pickup to delivery at the recipient's address, packages always experience various sortation and transfer in different facilities. Prior to the pickup, FedEx ASTRA shipping labels were created with both the ASTRA barcode (8.5"x11" plain paper or customer specific) and URSA (a human readable code utilized by FedEx manual sorting). The ASTRA barcode shown in Figure 10 contains tracking number, service and handling, destination postal code and delivery date.


Figure 10. Rigi Bag® mailer with ASTRA shipping label

Pickup courier scanned the ASTRA barcode in School of Packaging to indicate package picked up. The FedEx truck would deliver the packages to the local station. At the station, the packages were first scanned, sorted and consolidated with other packages into an aircraft container for hub transfer. A containerized trailer vehicle (CTV) would then deliver the aircraft container to the FedEx local ramp, also known as the local airport facility. The closest one to East Lansing is located in Flint. Upon arrival to the local ramp, an automated system would assist loading the aircraft container onto FedEx feeder aircraft. FedEx feeder aircraft would then fly to its national hub in Memphis, Tennessee.

Figure 11 shows a portion of the FedEx fleet of aircraft begins the loading process at the Memphis, TN, hub. Small packages unloaded from the aircraft are generally scanned at a speed of 120 – 160 feet per minute using FedEx SuperTracker portable terminal within the facility or out on the ramp. Small documents are scanned on the ASTRA labels using an overhead laser scanner at 250 feet per minute before being manually consolidated into the bag with other small packaged products. Scanner is set up for destination station/ramp and will warn operators if mis-sort turns up. The complex system was to meet a fast pace handling environment to rearrange packages around the nation according to their geographic location.

Figure 11. FedEx national hub in Memphis, Tennessee

The sorting process took approximately three hours in the hub and promptly delivered to local ramp in the destination area. Then the packages would be sorted again to go to the local station and FedEx truck to deliver to the recipient's door. This was a typical hub-and-spoke system adopted by FedEx and most of the carriers to guarantee the priority overnight service. The recipient would return the recorders in the following day and the data were downloaded using sensware software to be stored in PC for further analysis. Total of 36 trips were measured with three package types for both destinations. The study was conducted from June to August 2007 for shipments to California and January to February 2008 for shipments to New York. A pictorial view of the delivering routes to San Luis Obispo, CA and Rochester, NY in the U.S. continent is shown in Figure 12. Package flow diagram is shown in Figure 13 to illustrate the hub-and-spoke system. A detailed package movement to San Luis Obispo and Rochester is as follows:

School of Packaging (East Lansing, MI) → local station (East Lansing, MI) → FedEx local ramp (Flint, MI) → national hub (Memphis, TN) → FedEx local ramp (Ontario, CA) → local station (San Luis Obispo, CA) → Destination (San Luis Obispo, CA)

School of Packaging (East Lansing, MI) → local station (East Lansing, MI) → regional hub (Indianapolis, IN) → local station (Rochester, NY) → Destination (Rochester, NY)

The timeline for overnight shipments stay fixed. The following describes each cycle time in the Eastern Standard Time zone (Singh, 2007).

- The package "pickup cycle" is from 15:00 - 17:00 (3:00 pm - 5:00 pm local time)
- The "station pm sort" is from 17:00 - 18:30 (5:00 pm - 6:30 pm)
- Ground transportation from the station to the local ramp is from 18:30 - 19:30 (6:30 - 7:30 pm)
- Air transportation to FedEx hubs is from 19:30 - 1:15 (7:30 pm - 1:15 am)
- The "hub night sort" is from 1:15 - 3:30 am
- Air transport from the hub to FedEx destination ramps is from 3:30 - 5:30 am
- Ground transportation from the ramp to the destination station is from 5:30 - 7:30 am
- The "station am sort" is from 7:30 - 8:30 am
- The package "delivery cycle" is from 8:30 - 10:30 am

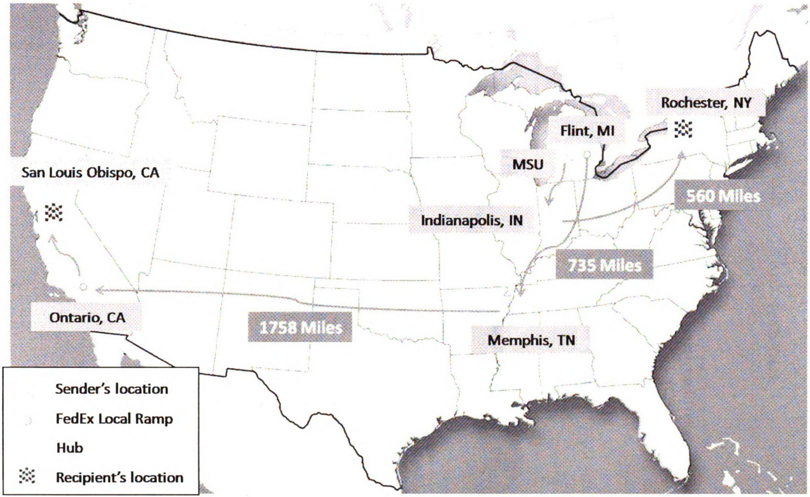



Figure 12. Shipment routes in the U.S. continent to California and New York

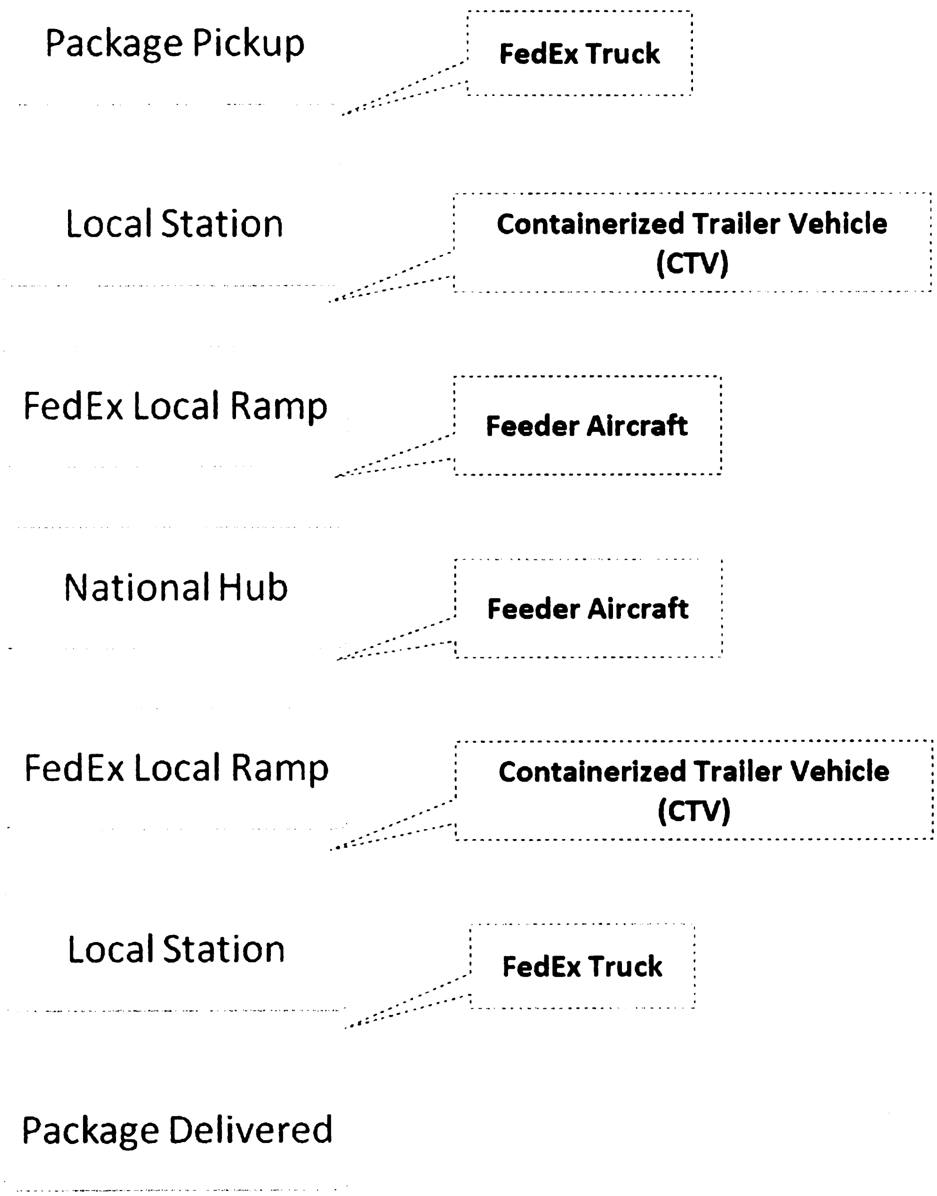



Figure 13. Parcel movement in the distribution cycle

# CHAPTER 3

# DATA ANALYSIS

## 3.1 DROP HEIGHT, NEAR ZERO G, AND OCCURRENCE LEVEL

This chapter will discuss the various dynamic data captured from this study. The data is analyzed from both field data and trial data in the laboratory and is summarized into drop height, near zero G, the occurrence level, and impact orientations. The various analytic techniques were used for predictions depending on the functions of the recorders. GP1 recorder does not have the capability like EDR–3C (Instrumented Sensor Technology, Okemos, MI) which can calculate drop height from one of the two methods: analyzing from shock pulse information or prediction from the free-fall time measurement. The theory behind free-fall time measurement is that the tri-axial accelerometer initiates the timing mechanism as soon as it experiences 1 g, the free fall state. The duration of this acceleration is recorded until it hits the ground. If a unit is released from rest and traveling straight down without applying additional forces, drop height can be calculated using the following equation:

$$h = \frac{1}{2} g t^2 \qquad (1)$$

Where

$h$ = free fall drop height, m or in
$g$ = acceleration due to gravity, 386.4 in/s$^2$ or 9.81 m/s$^2$
$t$ = free fall duration, seconds

In this study, the method used to determine drop height derives from correlating vector magnitude G based on different drop heights in the laboratory to vector magnitude G obtained from the actual trips. Preliminary drops were done on each package type (bubble, Rigi mailer, and corrugated box) using Lansmont™ drop tester shown in Figure 14 at predetermined 12, 30, and 48 inches drop heights. The highest vector magnitude G was recorded from each drop height based on several drops on each face, edge, and corner. Table 1 summarizes a maximum G from predetermined drop heights for each package type.

*Note: vector magnitude is defined as the size or quantity from one place to another. The vector direction can be referred to any direction that the recorder travels.*

Table 1. Maximum vector magnitude G from drop tester

| | Drop height | | |
|---|---|---|---|
| Package type | **12"** | **30"** | **48"** |
| Rigi Bag mailer | 15.96 | 17.43 | 20.85 |
| Bubble mailer | 14.97 | 16.78 | 18.03 |
| Corrugated box | 17.24 | 18.38 | 20.74 |

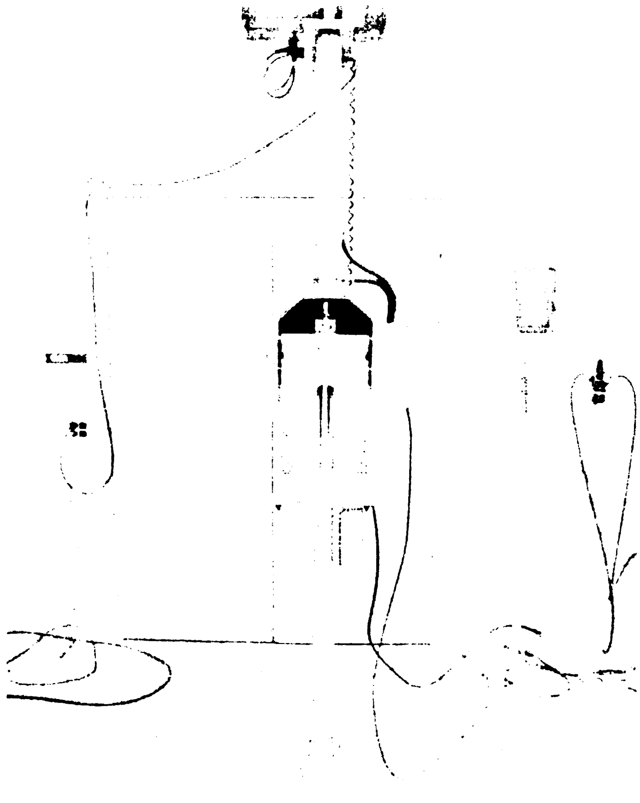


Figure 14. Lansmont$^{TM}$ drop tester

The correlation between vector magnitude G recorded in the laboratory and those obtained from the actual trips was heavily used to predict the dynamic events. This method was utilized to determine the frequencies of near zero g travels including drops, throws, and tosses with corresponding to the distances since most bumps and shocks that a package experiences in supply chain are not free-fall but impacts (Singh, 2006). This study also revealed the maximum G that each package type experienced during impacts. Various dynamic events measured are summarized in the following tables for three different packages. Table 2 and 3 present a conclusive result on the total number near zero g's that was recorded by the instrument and the maximum vector magnitude G obtained from the highest reading from each of the six recorders for individual trip. Table 4 and 5 show the total number of drops, throws, and tosses where it was conceived of averaging the near zero g picked up by the six recorders for each package type in Table 2 and 3. The maximum vector magnitude G was determined by correlating field data in Table 2 and 3 to the lab data in Table 1. The maximum vector magnitude was calculated based on 90, 95, and 99 percent occurrence level. The graphical view of the vector magnitude occurrence level is shown in Figure 15A – B. A 95% occurrence level for maximum vector magnitude of 15.94 G (California, bubble, 95%) means 95% of all Gs which were below this level.

Table 2. Dynamic events measured, California

| | One way trip to California | | | | | |
|---|---|---|---|---|---|---|
| | Total number Near Zero G | | | Maximum vector magnitude G | | |
| Sample | Rigi | Bubble | Box | Rigi | Bubble | Box |
| 1 | 24 | 32 | 12 | 16.3 | 18.24 | 15.46 |
| 2 | 18 | 29 | 31 | 16.53 | 15.94 | 19.44 |
| 3 | 22 | 28 | 18 | 18.23 | 18.97 | 17.03 |
| 4 | 19 | 16 | 13 | 16.41 | 16.54 | 16.67 |
| 5 | 21 | 29 | 13 | 20.54 | 18.17 | 17.81 |
| 6 | 21 | 29 | 15 | 18.22 | 17.83 | 17.27 |

Table 3. Dynamic events measured, New York

| | One way trip to New York | | | | | |
|---|---|---|---|---|---|---|
| | Total number Near Zero G | | | Maximum vector magnitude G | | |
| Sample | Rigi | Bubble | Box | Rigi | Bubble | Box |
| 1 | 19 | 21 | 14 | 18.34 | 16.94 | 17.44 |
| 2 | 20 | 22 | 15 | 18.85 | 19.8 | 19.15 |
| 3 | 23 | 25 | 33 | 18.36 | 16.49 | 17.08 |
| 4 | 23 | 23 | 9 | 15.77 | 18.33 | 19.06 |
| 5 | 22 | 22 | 12 | 19.47 | 19.93 | 15.04 |
| 6 | 23 | 27 | 11 | 17.57 | 21.67 | 18.82 |

Table 4. Summary of dynamic events measured, Michigan to California

| Drop data | Rigi | Bubble | Box |
|---|---|---|---|
| Number of drops, throws, and tosses | 21 | 27 | 17 |
| Maximum drop height (in) | 48 | >48 | 39 |
| Max Vector Magnitude at 99% occurrence (G) | 18.22 | 17.83 | 17.62 |
| Max Vector Magnitude at 95% occurrence (G) | 15.74 | 15.94 | 16.16 |
| Max Vector Magnitude at 90% occurrence (G) | 14.55 | 14.25 | 15.46 |

Table 5. Summary of dynamic events measured: Michigan to New York

| Drop data | Rigi | Bubble | Box |
|---|---|---|---|
| Number of drops, throws, and tosses | 21 | 23 | 16 |
| Maximum drop height (in) | 48 | >48 | 38 |
| Max Vector Magnitude at 99% occurrence (G) | 18.36 | 19.8 | 18.82 |
| Max Vector Magnitude at 95% occurrence (G) | 16.16 | 15.87 | 16.53 |
| Max Vector Magnitude at 90% occurrence (G) | 15 | 14.32 | 14.79 |

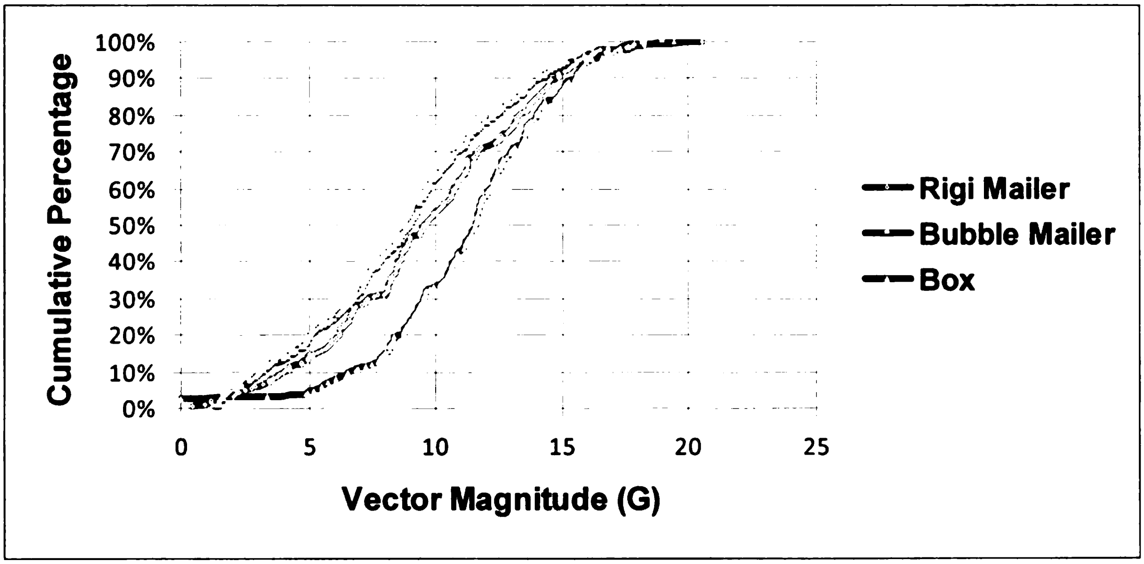



Figure 15A. Occurrence level versus vector magnitude G, California

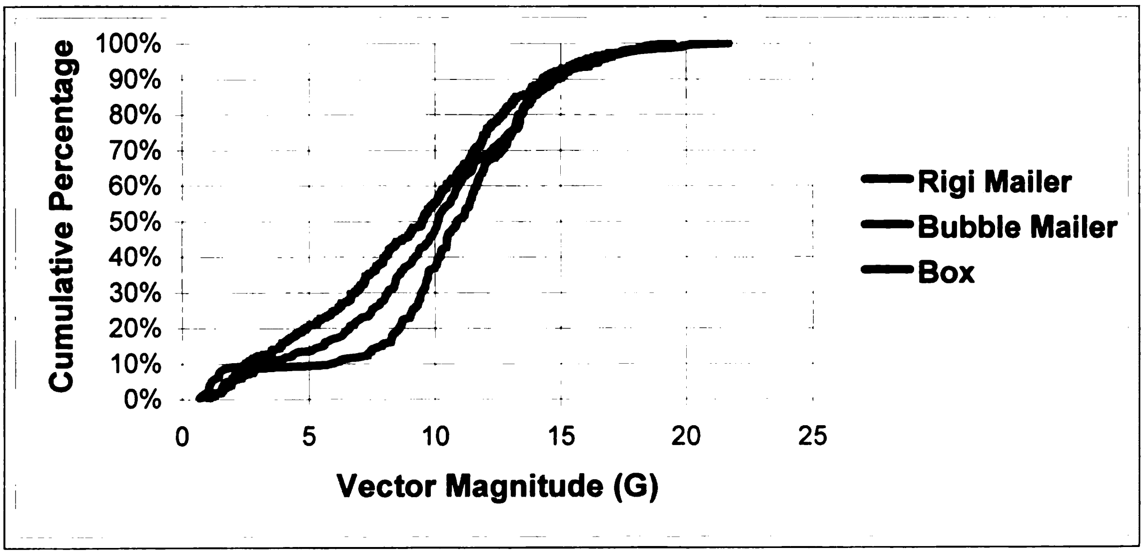



Figure 15B. Occurrence level versus vector magnitude G, New York

Table 6 presents ten highest travel distances assorted in an ascending order under near zero g condition. The findings are based on free fall calculation shown in Equation 1 where the durations were recorded by GP1. Impact orientation is differentiated mainly into face, edge, and corner drops and can be valuable information for laboratory use to simulate the shipping environment. The data shown in Table 7 is an estimation based on the ratio between individual impact orientation and the total drops that each recorder experienced for each package type. Figure 16A – B provide an overview of the distribution of the impact orientation for Rigi, bubble, and corrugated box in two destinations.

Table 6. Near Zero g travel distance in ascending order

| | One way trip: California | | | One way trip: New York | | |
|---|---|---|---|---|---|---|
| Distance (in) | Rigi | Bubble | Box | Rigi | Bubble | Box |
| Highest | 185.55 | 60.59 | 189.36 | 81.63 | 64.99 | 197.08 |
| 2nd Highest | 174.36 | 56.34 | 136.32 | 79.13 | 60.59 | 120.58 |
| 3rd Highest | 136.32 | 52.24 | 117.54 | 76.68 | 56.34 | 94.67 |
| 4th Highest | 117.54 | 50.25 | 108.68 | 62.77 | 54.27 | 86.73 |
| 5th Highest | 114.55 | 48.30 | 69.55 | 60.59 | 48.30 | 81.63 |
| 6th Highest | 102.96 | 46.39 | 64.99 | 54.27 | 40.88 | 79.13 |
| 7th Highest | 76.68 | 44.51 | 62.77 | 50.25 | 39.12 | 74.27 |
| 8th Highest | 71.89 | 42.68 | 60.59 | 48.30 | 37.40 | 62.77 |
| 9th Highest | 58.44 | 40.88 | 50.25 | 46.39 | 35.72 | 58.44 |
| 10th Highest | 54.27 | 39.12 | 48.30 | 44.51 | 34.08 | 56.34 |

Table 7. Impact orientations

| Destination | Package type | Orientation of drops (%) | | |
|---|---|---|---|---|
| | | Face | Edge | Corner |
| CA | Rigi | 62.60 | 24.39 | 14.63 |
| | Bubble | 25.47 | 55.28 | 20.50 |
| | Box | 44.55 | 31.68 | 24.75 |
| NY | Rigi | 56.25 | 25.78 | 19.53 |
| | Bubble | 29.50 | 51.80 | 19.42 |
| | Box | 50.27 | 29.95 | 20.32 |

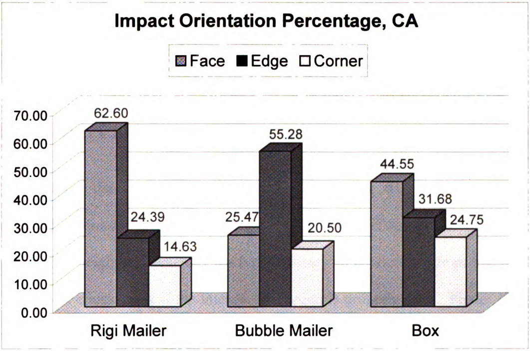



Figure 16A. Impact orientation percentage, California

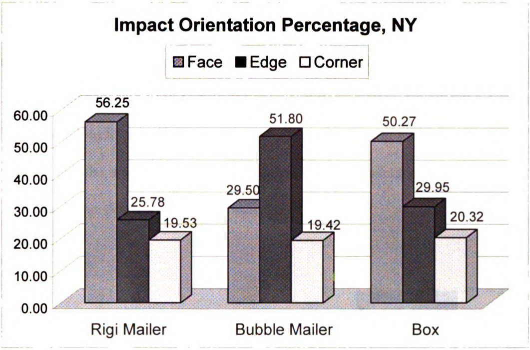



Figure 16B. Impact orientation percentage, New York

### 3.2 RELIABILITY AND ERROR ESTIMATION

Different data recorder can be used according to the prefered application. Commercial recorder like Environmental Data Recorder (EDR-3C) can be utilized to determine drop height and generally has high accuracy on predicting it from free fall time and area under shock pulse if the internal calibration is properly done. Figure 17A – B give a pictorial view on a typical shock pulse and free fall duration during impact. However, every data recorder shows some degree of error from various sampling frequency while predicting the dynamic events. This section of the chapter provides a deep analysis on package drop height estimation and the traveling speed when associated with tosses and throws. It also describes how human error and limitation of the instrument can affect the accuracy of a commercial data recorder. In a conventional shock pulse, the reported peak G by a recorder is obtained from dividing the area under half sine wave into trapezoids. If the sampling frequency is too low, less trapezoids will be captured and the area calculation would generate error leading to lower reported peak G. At times, it can skip over the peak entirely.

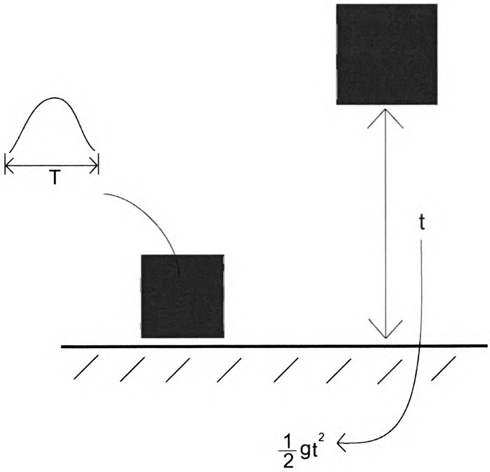



Figure 17A. Free fall time and shock pulse

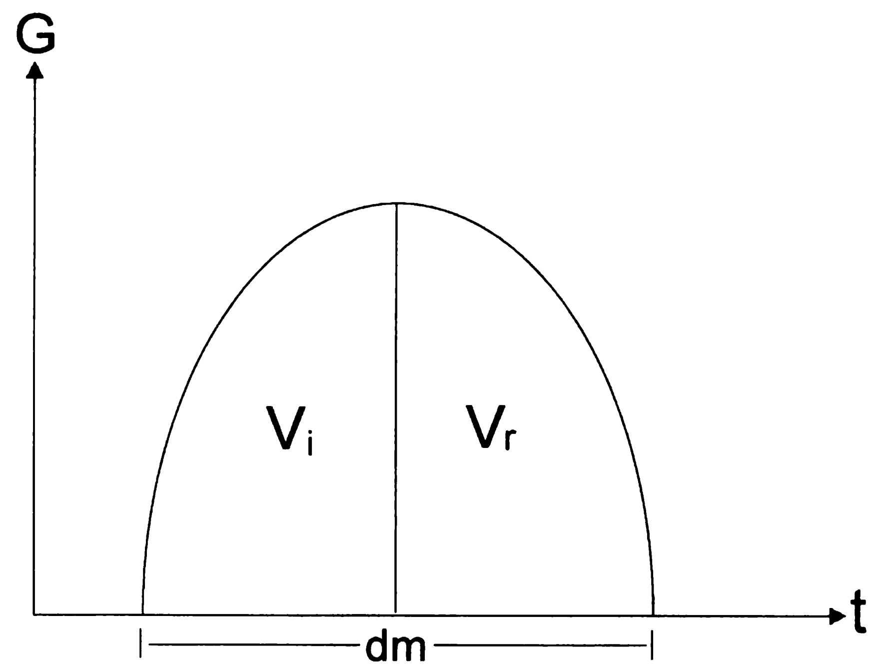



Figure 17B. Half sine shock pulse

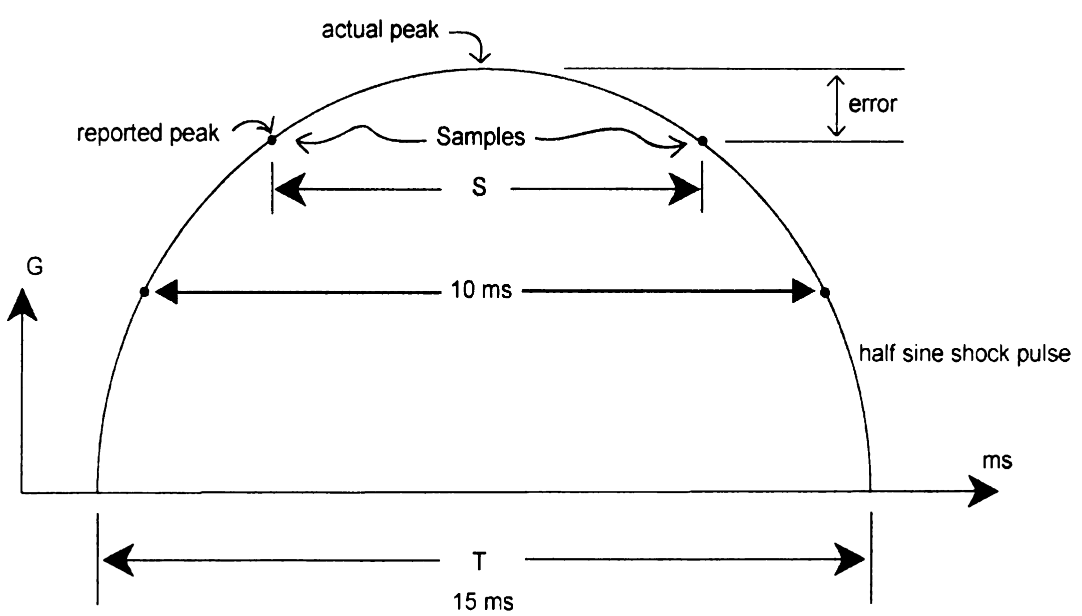



Figure 18. Peak G comparison under different sampling frequencies

In Figure 18, a half sine pulse projects two samples taken on either side and equidistantance from the peak. The actual peak G is often deemed as the largest sampled value. As long as the sample spacing "s" is small compared to the shock duration "T", the actual peak G should not be too different from the reported one (Burgess, 1995). The red sampling frequencies shown above demonstrates an example of GP1's insufficient sampling rate which could generate error and even misses predicting the real peak. Consequently, sampling error can be accounted for the actual peak given the reported peak. Equation 2 explains the relationship between predicted and actual peak G when sampling frequency is known. The reported peak G is the value of G(t) at either one of the two sampling points on either side of the peak. To find this, substitute the time t = T/2 ± s/2 into the equation where s is the time inteval between samples (s = 1/sampling frequency). Percentage error can be determined once reported peak and actual peak are defined. Beside, Equation 3 points out estimating maximum percent error from different sampling frequencies.

$$\textbf{(reported peak G)} = \textbf{(actual peak G)} \times \textbf{cos}\left(\frac{\pi s}{2T}\right) \qquad (2)$$

The percent error can be defined as 100 × (actual – reported) / (actual)

$$\textbf{Maximum \% error} = (1 - \cos\left(\frac{\pi s}{2T}\right)) \times 100 \qquad (3)$$

*Note: set the calculator for angles in "radian", not degrees because the angles of the cosine functions are dimensionless.*

Note that an actual shock pulse does not appear as a perfect half sine wave. Therefore, both Equation 2 – 3 should be only used as a guide because they are designed for perfect half sine shaped shocks. From the pictorial shock pulse illustration shown in Figure 18, it is clear that the recorded G can only be <u>at</u> the peak or <u>below</u> it. Hence, it can be presumed that data sampling process <u>always underestimates</u> the actual peak G (Burgess, 1995). This also adds the reason ± sign does not apply to percent error. To provide better understanding on both equations, two exapmples with the same presumed shock duration are shown below to compare how different sampling frequency can influence the margin of error. From the sample calculations, it is justifiable that the higher the sampling frequency is, the lower the error would be. Based on the conception described in the example, error estimation on GP1 for <u>Rigi Bag mailer</u> is determined in the following:

Example 1:

Shock duration = 10 ms

Sampling frequency = 400 Hz → Time interval between samples  s = 2.5 ms

Resulting reported peak could be as samll as 0.924 times the actual peak G. The maximum percent error is 7.6%.

Example 2:

Shock duration = 10 ms

Sampling frequency = 2000 Hz → Time interval between samples  s = 0.5 ms

Resulting reported peak could be as samll as 0.997 times the actual peak G. The maximum percent error is 0.30%.

Error estimation on GP1 for <u>Rigi Bag mailer</u>:

Typical shock duration is equivalent to 10 ms

Time interval between samples is expected to be low because mailer had less cushioning material.  Set T ≈ 15 ms

$$\text{Maximum percent error} = 100 \times \left(1 - \cos\frac{\pi \times 10}{2(15)}\right) = 50\%$$

*The calculation presents GP1 recorder could generate error as high as 50 percent when measuring peak G.  Meaning if the recorder measured 20 G, it could be as high as 40 G.*

Another scenerio would be when a package is dropped from a carrying point. Smaller the weight, higher the drop height likely to encounter. Similarly, packages like mailer can be held in one hand and has a higher probability of getting tossed throughout the distribution channel. This section explains package toss speed at a predetermined zero g time and release height. Figure 19 shows the package located at a paticular height "h" above the ground and thrown upward with speed "$v_0$" from this position.

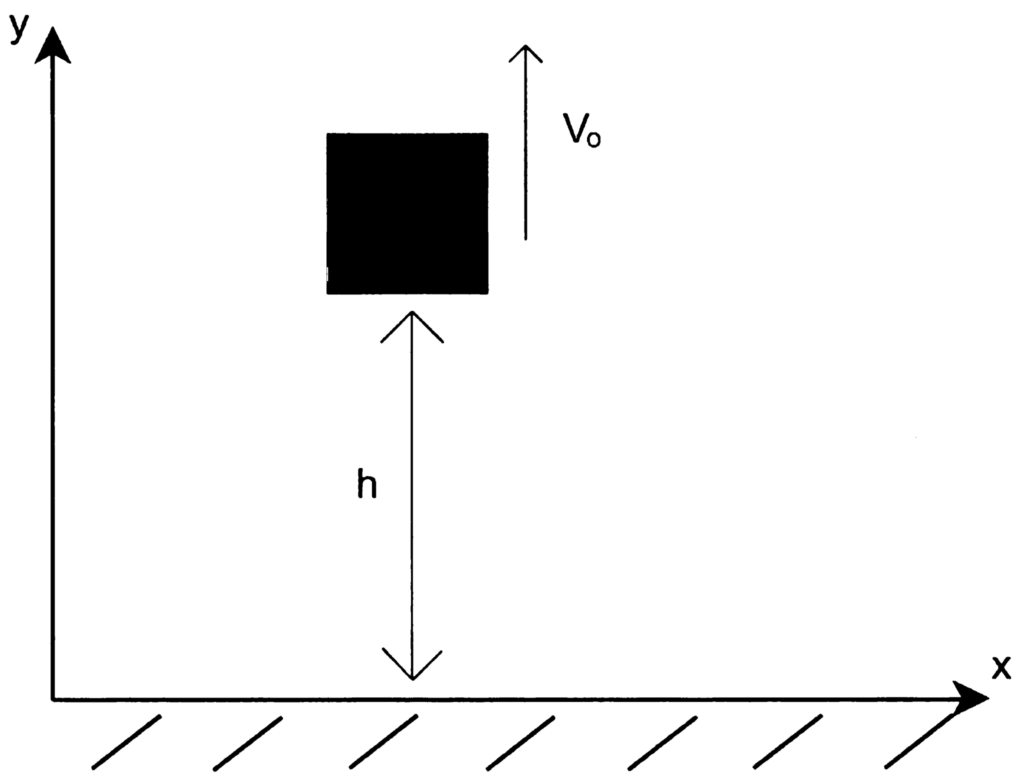



Figure 19. Package thrown upward at a specific height above the ground

As soon as the package leaves the hand, its acceleration "g" is 386.4 in/s$^2$ downward. From the law of physics, the position y and velocity $v_0$ at any time t (t = 0 when it leaves the hand) is defined in Equations 4 while Equation 5 establishes the relationship between velocity and duration of travel.

$$y = h + v_0 t - \frac{1}{2} g t^2 \qquad (4)$$

Where

y = displacement, in or m
$v_0$ = initial velocity, in/s or m/s
h = ininital drop height
g = acceleration due to gravity, 386.4 in/s$^2$ or 9.81 m/s$^2$
t = travel duration, seconds

$$v = v_0 - gt \qquad (5)$$

Where

$v$ = impact velocity, in/s or m/s
$v_0$ = initial velocity, in/s or m/s
g = acceleration due to gravity, 386.4 in/s$^2$ or 9.81 m/s$^2$
t = travel duration, seconds

During the air travel, package acceleration stays at "g" until it hits the ground, so the measured free fall time corresponds to y = 0. The relationship can be expressed in Equation 6. If the recorder measures the free fall "zero g" time as t, then the height h and velocity v could be any combination shown below:

$$0 = h + v_0 t - \frac{1}{2} g t^2 \quad \Rightarrow \quad h + v_0 t = \frac{1}{2} g t^2 \qquad (6)$$

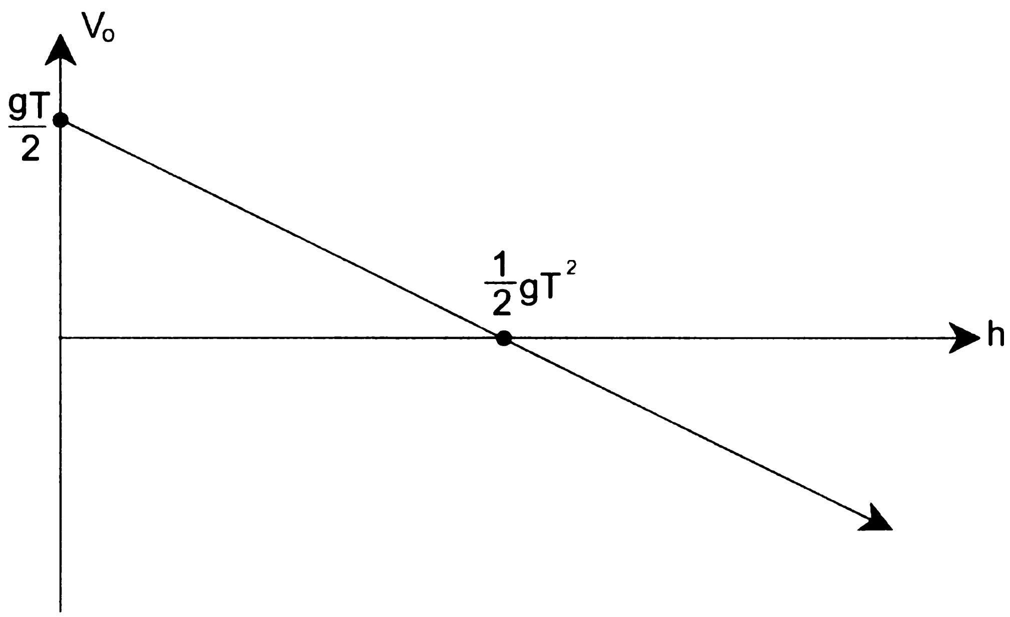
Example: suppose measured t = 0.98 sec $\qquad h + v_0(0.98) = \frac{1}{2} 386.4(0.98)^2$

| Height (in) | Velocity (in/sec) | Speed (mph) |
|---|---|---|
| 185.5 | 0 | - |
| 100 | 87.2 | 5 |
| 48 | 140.3 | 8 |
| 0 | 189.3 | 11 |

*Note: 1 mph = 17.44 in/sec*

It should be awared that all these scenarios shown above are possible if t = 0.98 s, but it is rather difficult to tell which have happened. However, the typical toss speed in the distribution environment is 11 mph.

Package can be tossed in either direction. The toss can happen in downward when $v_0$ is negative. If a mailer is tossed from 25 feet (300 inches) and $v_0$ equals – 116.8 in/sec. The mailer is likely traveling at 6.6 mph downward. So h + $v_0$ could be any combination that lies on the straight line shown below:




Now predict what the true free fall height is (Equation 7). The trajectory would be at its peak when $v = 0 = v_0 - gt$, so the time to reach peak is $t = \frac{v_0}{g}$, at which

$$y = h_{true} = h + v_0\left(\frac{v_0}{g}\right) - \frac{1}{2}g\left(\frac{v_0}{g}\right)^2 = h + \left(\frac{v_0}{2g}\right)^2$$

$$\Downarrow$$

$$h_{true} = h + \left(\frac{v_0}{2g}\right)^2 \qquad (7)$$

Where

$v_0$ = velocity, in/s or m/s
g = acceleration due to gravity, 386.4 in/$s^2$ or 9.81 m/$s^2$
h = initial thrown height, in or m
$h_{true}$ = actual thrown height, in or m

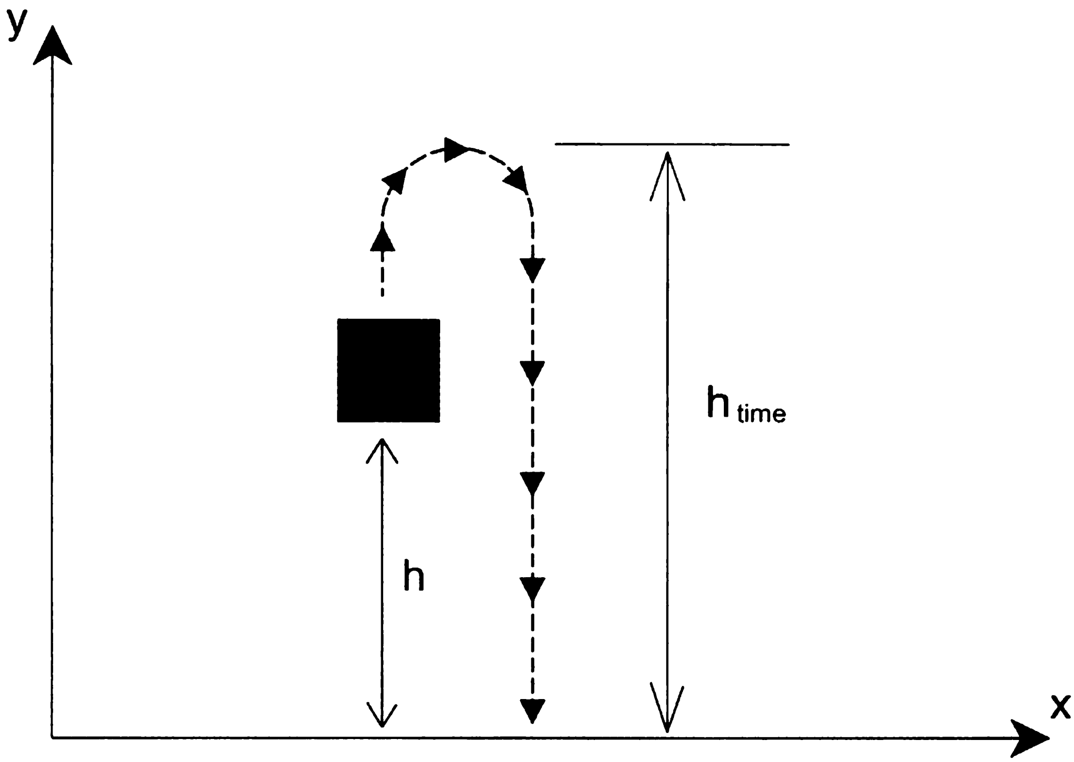



Figure 20. True free fall height in trajectory view

Examples of true free fall height were calculated from Equation 7 with t = 0.98 sec.

| Height (in) | Velocity (in/sec) | Height $_{true}$ (in) |
|---|---|---|
| 185.5 | 0 | 185.5 |
| 100 | 87.2 | 109.8 |
| 48 | 140.3 | 73.5 |
| 0 | 189.3 | 46.4 |

The impact duration is greatly affected by the amount of cushioning material and the material composed of it. GP1 in corrugated box with ethafoam acquired maximum of 20 G from the drop tester at 48 inches. The duration was measured based on ethafoam no more than 1 inch thick and was estimated for its consistency using Equation 8. From the calculation shown below, it is presumed that 78 millisecond was the shock duration experienced when packaged in a cushioned box. Yet this is way too long for the amount of cushioning under a recorder. It is equivalent to 4 inch urethane to have a shock pulse this long (Burgess, 1995).

$$v_i = \sqrt{2gh} = SF\left(\frac{dur}{2}\right)(G \times g) \tag{8}$$

Where

$v_i$ = impact velocity, in/s or m/s
g = acceleration due to gravity, 386.4 in/s$^2$ or 9.81 m/s$^2$
h = height, in or m
G = maximum g
SF = shape factor = 0.636

$$v_i = \sqrt{2 \times 386.4 \times 48} = 0.636\left(\frac{dur}{2}\right)(20 \times 386.4)$$

$$duration = 0.078\sec = 78ms$$

## 3.3 TEST PROTOCOL

This section of the chapter describes a test protocol designed to simulate the small package shipment in the testing laboratory. *'Smalls'* is defined as the volume is less than 13,000 $cm^3$ (800 $in^3$), and longest dimension is 350 mm (14 in), <u>and</u> weight is 4.5 kg (10 lb) or less. Packages fall into this category can use the following test procedures to evaluate its packaging integrity, durability, and performance. To have a meaningful result, the test is only suitable for package composed of 6 faces, 12 edges, and 8 corners. Package like envelope is not appropriately fit to this test protocol. Total number of drops was determined by the average number of drops for box type per one-way trip to both destinations (Table 4 – 5). Drop orientation was determined by percent impact orientation listed in Table 7. Predictions are as follows:

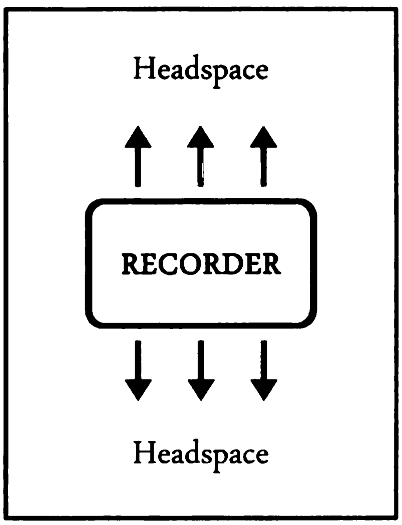
47% of drops occurred on face: $0.47 \times 17 = 8$ drops
30% of drops occurred on edge: $0.30 \times 17 = 5$ drops
23% of drops occurred on corner: $0.23 \times 17 = 4$ drops

Drop height was determined based on 95 and 99 percent occurrence level. Referring to Table 4 – 5, maximum vector magnitude was correlated to Table 1 where drop height of 30 and 12 inches is recommended for 95 and 95 percent occurrence level. However, due to 50% maximum error on predicting vector magnitude, the drop heights were doubled to simulate worse case scenario. Thus, test protocol for small priority overnight package suggests 60 inches drop height for 99 percent occurrence level or 24 inches drop height for 95 percent occurrence level, total of 17 drops, with orientations of 8 face, 5 edge, and 4 corner drops.

# CHAPTER 4

# RESULTS AND DISCUSSION

The data gathered are tabulated and expressed in graphical form. Table 1 shows the calibration drops done on the drop tester for each package type at three different drop heights. The maximum vector magnitude G for each package type was correlated with actual trip to lab calibrations to determine drop height. Both mailers shown lower vector magnitude Gs are compared to the box at the predetermined drop heights due to headspace in the mailer. Air space could potentially reduce the vector magnitude when experienced impacts. The figure shown below explains free movement of the recording device stored in the mailer could omit partial Gs to mislead that the mailers have better protection. Therefore, it does not necessarily mean that the mailers had better protection than the corrugated box with cushions.



Based on the mathematical calculation on the consistency in predicting peak G, GP1 poses potentially up to 50 percent of error. Meaning if recorder measures 20 G, it could be as high as 40 G. Table 2 – 3 represent total number near zero gs and maximum vector magnitude captured from one way trip to California and New York based on six samples for each package type. Box sample number 2 to California and sample number 3 to New York experienced significantly higher number of near zero gs compared to other samples because the packages were delayed from return shipment; where near zero g can be associated with drops, and it can also be referred to throws and tosses. Toss speed may vary with different travel velocity at designated drop height. Table 4 – 5 summarize the dynamic data in number of near zero gs, maximum drop height, and 90%, 95%, 99% vector magnitude G occurrence level. The data show that bubble mailer experienced highest combined number of drops, throws, and tosses as well as highest drop height of greater than 48 inches in one way trip. In addition, 48 inch drop height may not be the true height due to tossing at specific velocity. Occurrence level for maximum vector magnitude of 15.94 G (California, bubble, 95%) means 95% of all Gs which were below this level. Graphical representation of the vector magnitude occurrence level is shown in Figure 15A – 15B. Table 6 presents the ten highest drop heights resulted from drops, throws, and tosses in ascending order. The data revealed that air travel distance for small package shipment could go as high as 197.08 inches and it could derive from long distance thrown. Box experienced more than two times higher in near zero g travel distance than bubble mailer in first two highest travel distances. The percentage drop orientation that each package type experienced from each destination is used to develop a test protocol for lab testing purpose to simulate priority overnight service for small packaged products. In true free fall drops, the packages should land on edges and corners most of the time (Singh, 2006). Nevertheless, the test method is only suitable for package made up of 6 faces, 12 edges, and 8 corners. Figure 21 demonstrates various damages occurred on the packages studied which could derive from multiple manual handlings and automated sorting system.

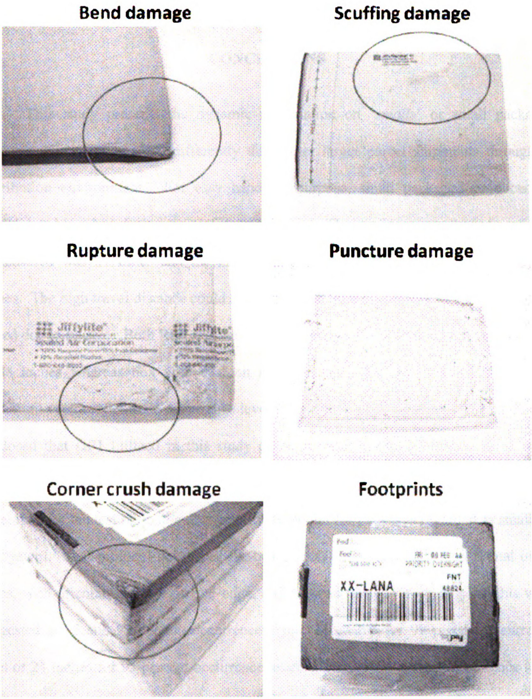



Figure 21. Damages observed throughout the distribution cycle

# CHAPTER 5

# CONCLUSIONS

This study presents the dynamic information on '*smalls*' or small packaged products which are handled differently than other larger parcel shipments throughout distribution environment. For easy handling purpose, small packaged products are consolidated in a bag during most of its transit time. The maximum number of near zero g measured was 27 times and the maximum near zero g travel distance was 197.08 inches. The high travel distance could result from the high probability of being thrown or tossed due to its size. Both Rigi and bubble mailer showed similar maximum drop height at 48 inches whereas box with cushion at 39 inches. No significant difference on maximum vector magnitude occurrence level for all three package types. The study also disclosed that GP1 utilized in this study could generate up to 50 percent error when predicting the peak G. Based on the impact orientation, a test method was therefore developed for lab testing to simulate priority overnight for packages regarded as smalls in the system. Test protocol developed for box package type recommended a total of 17 drops, with orientations of 8 face, 5 edge, and 4 corner drops. Two drop heights were suggested at 95 and 99 percent occurrence level: 60 inches for 99 percent occurrence level or 24 inches for 95 percent occurrence level. Note that 95 percent occurrence level is commonly used in industrial practice.

# APPENDIX I

Table 8. Calibration on drop orientation with corrugated box at three drop heights

| 12" | |
|---|---|
| **Actual drop** | **Recorder records** |
| Face 6 | Face 6 |
| Corner 2-3-6 | Corner 2-3-6 |
| Edge 1-6 | Corner 1-2-6 |
| Edge 4-5 | Corner 1-4-5 |
| Edge 3-5 | Corner 2-3-5 |
| Corner 1-2-5 | Edge 2-5 |
| Face 2 | Corner 2-3-5 |
| Face 3 | Edge 3-4 |
| Face 1 | Edge 1-4 |
| Corner 1-4-6 | Edge 2-3 |

| 24" | |
|---|---|
| **Actual drop** | **Recorder records** |
| Corner 1-2-6 | Edge 1-2 |
| Corner 2-3-6 | Face 4 |
| Corner 3-4-5 | Corner 3-4-5 |
| Edge 1-4 | Face 4 |
| Face 2 | Corner 1-2-5 |
| Face 2 | Corner 1-4-6 |
| Face 4 | Edge 4-6 |
| Edge 1-6 | Edge 1-5 |
| Face 4 | Corner 3-4-6 |
| Edge 3-5 | Edge 3-6 |

| 30" | |
|---|---|
| **Actual drop** | **Recorder records** |
| Face 3 | Face 3 |
| Face 3 | Edge 3-4 |
| Face 3 | Edge 2-3 |
| Edge 2-3 | Edge 3-5 |
| Edge 3-4 | Edge 3-4 |
| Corner 1-2-6 | Face 3 |
| Edge 1-5 | Corner 1-2-5 |
| Corner 1-2-5 | Corner 1-2-5 (towards face 5) |
| Face 1 | Corner 1-2-6 |
| Corner 2-3-5 | Corner 2-3-5 |

## APPENDIX II

Table 9. Free fall count from round trip to California

Bubble mailer

| | Total Number Near Zero G ( Round Trip) | Highest VM Max G |
|---|---|---|
| **1** | 63 | 18.24 |
| **2** | 57 | 15.94 |
| **3** | 56 | 18.97 |
| **4** | 32 | 16.54 |
| **5** | 57 | 18.17 |
| **6** | 57 | 17.83 |

Rigi Bag mailer

| | Total Number Near Zero G ( Round Trip) | Highest VM Max G |
|---|---|---|
| **1** | 47 | 16.3 |
| **2** | 35 | 16.53 |
| **3** | 43 | 18.23 |
| **4** | 38 | 16.41 |
| **5** | 41 | 20.54 |
| **6** | 42 | 18.22 |

Corrugated Box

| | Total Number Near Zero G ( Round Trip) | Highest VM Max G | Notes |
|---|---|---|---|
| **1** | 24 | 15.46 | |
| **2** | 62 | 19.44 | 1 day delayed |
| **3** | 35 | 17.03 | |
| **4** | 26 | 16.67 | |
| **5** | 25 | 17.81 | |
| **6** | 30 | 17.27 | |

Table 10. Free fall count from round trip to New York

Bubble mailer

| | Total Number Near Zero G ( Round Trip) | Highest VM Max G |
|---|---|---|
| **1** | 42 | 16.94 |
| **2** | 44 | 19.8 |
| **3** | 50 | 16.49 |
| **4** | 46 | 18.33 |
| **5** | 43 | 19.93 |
| **6** | 53 | 21.67 |

Rigi Bag mailer

| | Total Number Near Zero G ( Round Trip) | Highest VM Max G |
|---|---|---|
| **1** | 38 | 18.34 |
| **2** | 39 | 18.85 |
| **3** | 46 | 18.36 |
| **4** | 45 | 15.77 |
| **5** | 43 | 19.47 |
| **6** | 45 | 17.57 |

Corrugated Box

| | Total Number Near Zero G ( Round Trip) | Highest VM Max G | Note |
|---|---|---|---|
| **1** | 28 | 17.44 | |
| **2** | 29 | 19.15 | |
| **3** | 66 | 17.08 | 3 days delayed |
| **4** | 18 | 19.06 | |
| **5** | 24 | 15.04 | |
| **6** | 22 | 18.82 | |

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