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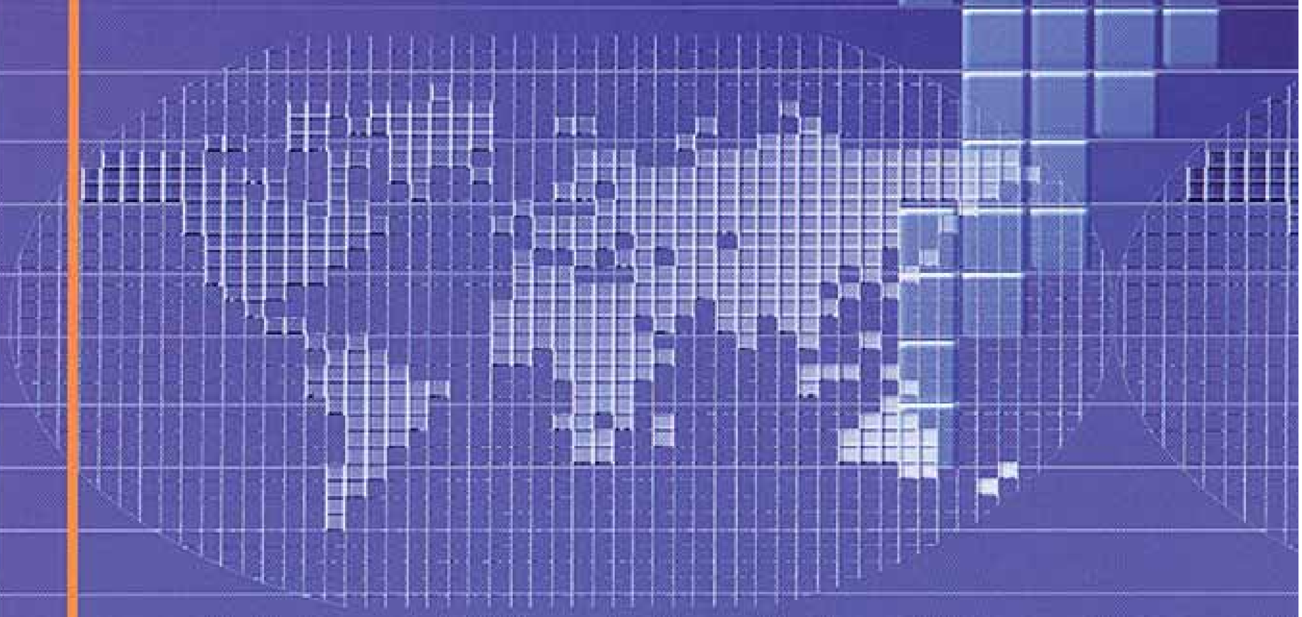

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Bottle Bill, Californians and Recycling—A Survey

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ABSTRACT: Since its original adaptation into law by Oregon in 1972, the "Bottle Bill" or "beverage container deposit law" has been enacted in 11 states in the U.S. This practice, primarily used to ensure a high rate of beverage container recycling or reuse and to reduce litter, has also been embraced by 15 other countries. The 11 states with this law account for almost 50% of all beverage containers recycled in the U.S. The beverage containers collected through a deposit system typically suffer lower pre-recycling damage and contamination, thereby reducing the discarded percentage. This study was undertaken to increase the understanding of recycling and redemption habits of Californians as related to the beverage containers included in the state's Bottle Bill. A 15-question survey was used to gather data related to several key psychographic traits such as beverage preferences and redemption awareness, motivation to recycle, recycling habits and attitudes and recycling beliefs and intentions. Though a majority of the respondents (94.31%) understood the deposit or recycling related information placed on the beverage containers, not all could correctly identify the types of beverages mandated with deposits. It was also found that a 5 cent increase in the redeemable deposit amount was a key motivation for recycling and that women were much highly motivated to do so than men. This paper discusses several other psychographic findings as well.

1.0 INTRODUCTION

"BOTTLE BILL" or "beverage container deposit law", initiated by Oregon in 1972, has since been enacted in 11 states in the U.S. These laws require a minimum refundable deposit on beer, soft drink and other beverage containers in order to ensure a high rate of recycling

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or reuse and to reduce litter. With its origins stemming from deposits charged to guarantee that the beverage industry received their reusable glass bottles to be washed, refilled and resold, the deposits on beverage containers is not a new concept. Neither is it restricted to the U.S. alone. According to BottleBill.org, fifteen other countries have national or state deposit laws [1]. Table 1 below highlights the redemption rates for various types of beverage containers resulting from different types of systems adopted by six such countries [2].

Bottle bills provide a privately funded collection infrastructure for beverage containers and put the responsibility of packaging waste on the producers and consumers rather than the taxpayers. Beverages are ideal targets for imposing the mandatory refundable deposits on single use beverage containers as they compose 40–60% of the litter in the U.S. [1]. The initial success of deposit laws set in Oregon and Vermont in response to the growing litter problem from throwaway beverage

Table 1. Leading International Beverage Container Recycling Programs.

Country	System Type	Redemption Rate
Australia (South)	Beverage Container Deposit-Return	70%—plastic, 85%—glass & aluminum
Canada (British Columbia)	Beverage Container Deposit-Return	78%—non-refillables, 95%—refillable beer
Canada (New Brunswick)	Beverage Container Deposit-Return	72%—non-refillables, 97%—refillable beer
Canada (Ontario)	Beverage Container Deposit-Return	67%—overall, 94%—beer containers
Canada (Quebec)	Beverage Container Deposit-Return	70%—beer & carbonated drinks, 98%—refillable beer
Finland	Beverage Container Deposit-Return	75%—non-refillables, 95–98% refillables
Finland	Packaging Waste Collection	75% of all materials
Germany	Beverage Container Deposit-Return	95–98%—non-refillables, 96%—refillable beer
Germany	Packaging Waste Collection	66–90% depending on material type
Sweden	Beverage Container Deposit-Return	88%—aluminum, 72%—PET (<1L), 90%—PET (>1L), 92%—glass
United Kingdom	Packaging Waste Collection	57%—all packaging materials

containers has resulted in 11 states presently employing the mechanism to encourage consumers to return these containers for recycling.

Table 2 summarizes the bottle bills in these states. A few of these states have either already repealed or are in the process of repealing the bottle bills [1]. Columbia's deposit law, the only municipal container deposit ordinance in the U.S., was repealed in April of 2002. Delaware's deposit law was effectively repealed by Senate Bill 234. Consumers will cease paying deposits on December 1, 2010, and refunds will cease on February 1, 2011.

Figure 1 shows the percentage of beverage containers recycled by the 11 states with bottle bills versus the rest of the U.S. using the data from 2006 [1]. With almost 50% of the total beverage containers recycled by the bottle bill states alone it is evident that these mandatory refundable deposits are efficient in increasing recycling and thereby reducing litter.

Bottle bills have proven to prevent litter and promote recycling while creating jobs, encouraging producer and consumer responsibility and producing high quality recyclable materials. Though not everything collected for recycling actually gets converted into new products, beverage containers collected through a deposit return system typically have been observed to suffer lower pre-recycling damage and contamination, thereby reducing the discarded percentage of these containers. A study for glass recycling observed the percentage of collected glass

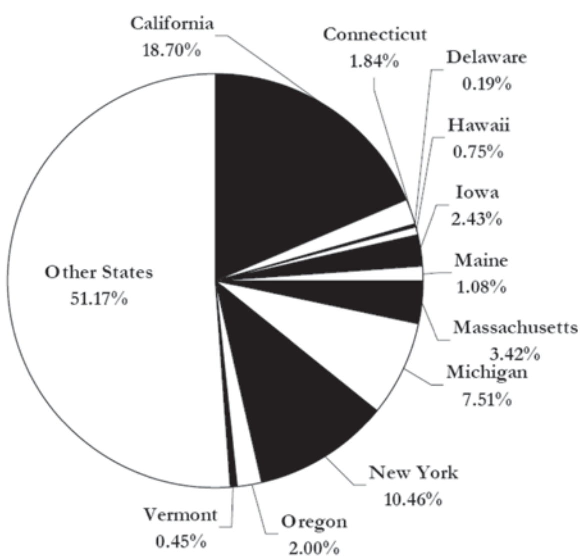

Figure 1. *Beverage Containers Recycled in the U.S. (2006) [1].*

Table 2. Bottle Bills in the U.S. [1].

	Beverages Covered	Containers Covered	Deposit	Redemption Rate
California	Beer, malt, wine & distilled spirits coolers, all non-alcoholic beverages, except milk. Excludes vegetable juices over 16 oz.	Aluminum. glass, plastic and bi-metal. Exempts refillables	(10¢: 24oz. and greater) and (5¢: under 24oz.)	52% in 1988 to 82% in 2009
	Reclamation system: State certified redemption centers, registered curbside operations, drop-offs.			
Connecticut	Beer, malt, carbonated soft drinks, and bottled water	Any individual, separate, sealed glass, metal or plastic bottle, can, jar or carton containing a beverage. Excluded are containers over 3L containing noncarbonated beverages, and HDPE containers	5¢	No statistics available
	Reclamation system: Retail stores and redemption centers.			
Delaware	Beer, malt, ale, soft drinks, mineral water, soda water	All beverage containers under 2qt. Excludes aluminum	5¢	No statistics available
	Reclamation system: Retail stores and redemption centers.			
Hawaii	All nonalcoholic drinks, except for milk or dairy products, and limited alcoholic drinks (beer, malt beverages, mixed spirits, mixed wine).	Aluminum, bi-metal, glass, plastic (PET and HDPE only) up to 68 oz.	5¢	76% in fiscal year 2010
	Reclamation system: Certified Redemption Centers operated by privately owned by State permitted Solid Waste facilities.			
Iowa	Beer, carbonated soft drinks & mineral water, wine coolers, wine & liquor	Any sealed glass, plastic, or metal bottle, can, jar or carton containing a beverage	5¢	overall 86%
	Reclamation system: Retail stores and redemption centers.			
Maine	All beverages except dairy products and unprocessed cider	All sealed containers made of glass, metal or plastic, containing 4 liters or less, excluding aseptics	Wine/liquor: 15¢ All others: 5¢	No statistics available
	Reclamation system: Retail stores and redemption centers; Dealers may refuse containers if they have an agreement with a nearby redemption center.			

(continued)

Table 2 (continued. Bottle Bills in the U.S. [1].

	Beverages Covered	Containers Covered	Deposit	Redemption Rate
Massachusetts	Beer, malt, carbonated soft drinks, & mineral water	Any sealable bottle, can, jar, or carton of glass, metal, plastic, or combo. Excludes biodegradables.	5¢	70.3% in FY2009
		Reclamation system: Retail stores and redemption centers.		
Michigan	Beer, soft drinks, carbonated & mineral water, wine coolers, canned cocktails	Any airtight metal, glass, paper, or plastic container, or a combination, under 1 gallon	10¢	overall 96.9%
		Reclamation system: Retail stores.		
New York	Beer, malt, carbonated soft drinks, water, wine coolers	Airtight metal, glass, paper, plastic, or combination of the above, under 1 gallon	5¢	(Beer 77.4%) (Soft drink 61.6%); (overall 70.2%)
		Reclamation system: Retail stores and redemption centers.		
Oregon	Beer, malt, carbonated soft drinks, & bottled water	Any individual, separate, sealed glass, metal or plastic bottle, can, jar containing a beverage	Standard refillable: 2¢; all others 5¢	overall 84%
		Reclamation system: Retail stores.		
Vermont	Beer, malt, carbonated soft drinks, mixed wine drinks; liquor	Any bottle, can, jar or carton composed of glass, metal, paper, plastic or any combination (Biodegradables excluded)	liquor: 15¢ All others: 5¢	overall 85%
	Reclamation system: Retail stores and redemption centers, If retailer is located conveniently near a licensed center and thereby gains state approval, retailer may refuse containers.			

by end markets for the single stream (comingled), dual stream (paper and containers) and deposit return systems [3]. Figure 2 highlights the findings with three end markets—recycled (containers and fiberglass), glass fines (sandblasting, landfill daily cover and road base) and trash (landfill). It can be seen that the color-sorted materials from the deposit return system results in the highest percentage (98%) of recycling of glass.

A similar report from plastics recyclers finds that the deposit return system has a yield rate of approximately 85% in comparison to 68-70% for single stream and 75–78% for the dual stream systems (Figure 3) [3].

The bottle bill requires a redeemable deposit to be paid by consumers when purchasing a select group of beverage containers. Figure 4 shows a typical deposit initiation and redemption process [1]. During the deposit initiation, the retailer pays the mandated deposit for all pertinent beverage containers to the distributor or bottler and recovers the same from the consumers as they purchase the containers from them. The consumers receive a refund upon returning the empty containers either to the retail store, to a redemption center or a reverse vending machine. The retailers and redemption centers recoup the deposits from the distributor or bottlers along with additional handling fee, which generally ranges from 1–3 cents per container.

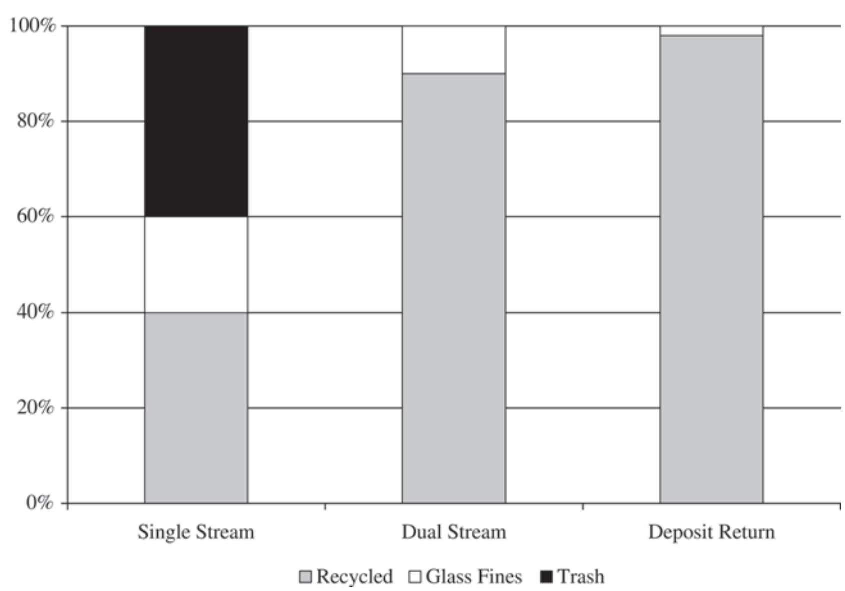

Figure 2. *End Markets for Collected Glass [3].*

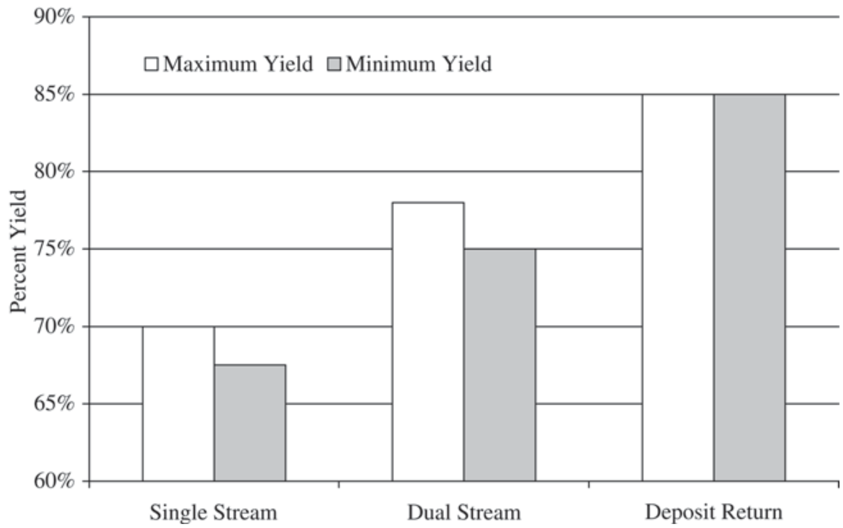

Figure 3. *Estimated Yield Rates from Collected Plastic [3].*

Since its enactment in California in 1988, the CRV or California Redemption Value or the redeemable deposit has been changed several times—1¢ for all sizes (1988); 2¢ for all sizes (1989); 2.5¢ (< 24 oz), 5¢ (> 24oz) (1992); 4¢ (< 24 oz), 8¢ (> 24oz) (2004) and 5¢ (< 24 oz), 10¢ (> 24oz) (2007) [1]. As a result the recycling rate of beverage containers has increased to 82% in 2009 from 56% at the inception of the law in 1988 in California [2].

The CRV (deposit) paid by the distributors or bottlers to the California Department of Resources Recycling and Recovery (CalRecycle) is

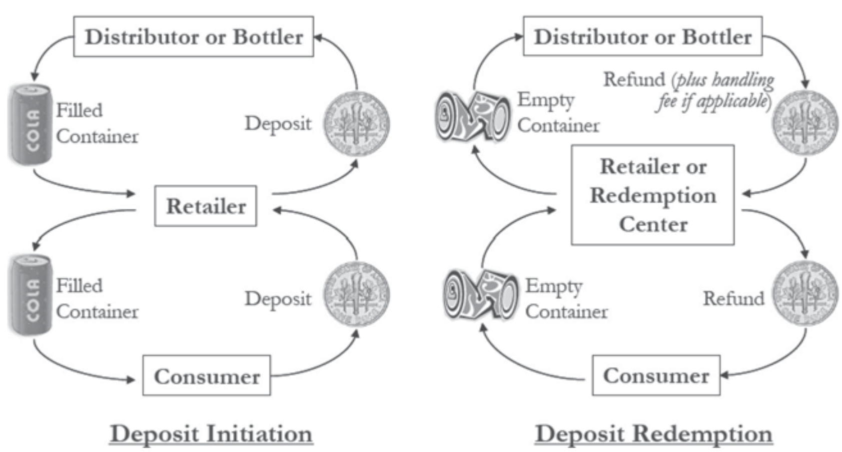

Figure 4. *Typical Deposit Initiation and Redemption Process [1].*

recovered by them from the retailers who in turn recover the same from the consumers. The redemption of the CRV for spent beverage containers follows a reverse flow i.e. consumer to the retailer or redemption center to the distributor/bottler to CalRecycle. While the large beverage retailers are not required to refund the deposits in house, it is interesting to observe that most of the beverage container recycling (55–65%) occurs at pre-existing private sector recycling centers [2]. The remainder of the recycling of these containers occurs through curbside recycling (20%) and supermarket based recyclers (25%) [2]. At the beverage container recycling centers Californians have the right to be paid per container when bringing in 50 containers or less in a single load. More commonly though, the recyclers use their discretion to make payment based on weight of the materials delivered for redemption [1].

This study was undertaken to increase the understanding of recycling and redemption habits of Californians as related to the beverage containers included in the state's Bottle Bill. A 15-question survey was used and is included in Appendix A. Data was gathered related to several key psychographic traits such as beverage preferences and redemption awareness, motivation to recycle, recycling habits and attitudes and recycling beliefs and intentions.

2.0 METHODOLOGY

130 respondents from a California based university completed the 15-question survey. Respondents were both undergraduate and graduate students. Undergraduate students were asked to complete the surveys in a classroom setting during their class time and 100% compliance was received. The graduate students were asked to complete the surveys online on a voluntary basis. 89 surveys received were reported as completed by undergraduates and 37 as completed by graduate students. Four respondents did not report their grade level. The respondents ranged in age from 18 to over 40. With regard to gender, 65% of the respondents were male and 35% were female with 4 respondents not listing their gender. Figure 5 summarizes the demographical breakdown of the survey participants. The respondents were asked about their beverage purchasing and current recycling behaviors. They were asked about their awareness, attitudes, and their use of the recycling redemption process in California. The questionnaire was followed up with demographic questions.

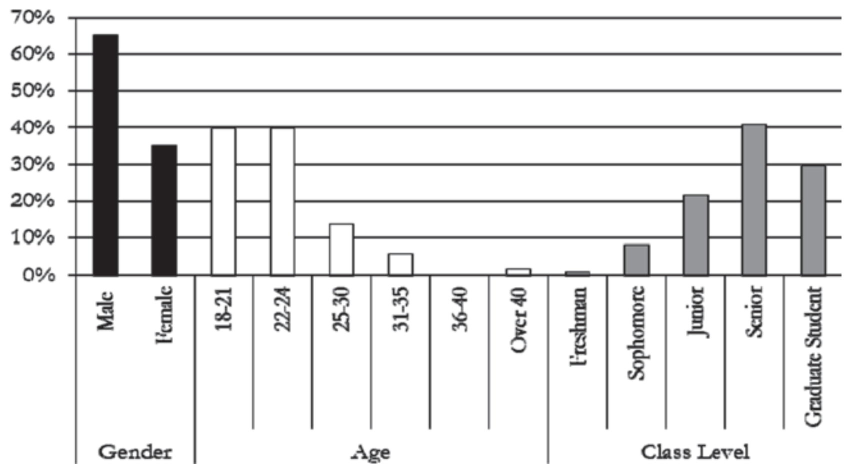

Figure 5. *Demographic Information of the Survey Participants.*

3.0 RESULTS AND DISCUSSION

3.1 Familiarity with Redemption Information on Beverage Packaging Labels

Question 1 related to familiarity with the deposit related information placed on beverage containers. An example (Figure 6) was included in the survey and the participants were asked "What is the meaning of the information on the yellow label?" A majority of the participants (94.31%) were able to identify that the label related to recyclability and/or redemption information.

Figure 6. *Figure Used for Question One of the Survey.*

3.2 Beverage Preferences and Redemption Awareness

Questions 2 and 3 of the survey were used to gauge the beverage purchasing preferences (Which of the following beverages do you purchase on a regular basis?) and their recyclability/redemption awareness (Do you know which of the following beverage containers can be recycled for a refund?). Figure 7 and Table 3 summarize the results.

Table 3 reveals a relatively large range in the perception of the awareness of redeemable beverage containers, from a high of bottled water (86.4%) and Beer/Malt Beverages (86.9%) to a low of Milk (41.5%) and Coffee/Tea Drinks (38.5%). For all containers the majority view is correct, however, a large minority are incorrect in their perceptions of what recyclables have redemption value. For example, there is no redemption for milk and coffee/tea.

3.3 Redemption Values and Motivation to Recycle

Awareness of deposit payment for < 24 oz and > 24 oz bottle size was addressed with the following question, "When you purchase a container with a CRV on the label, you pay an additional recycling or redemption fee. Are you aware how much that fee is per container when the container is (< 24 oz. / > 24 oz.)?" The results are reported graphically in Figures 8 and in Table 4.

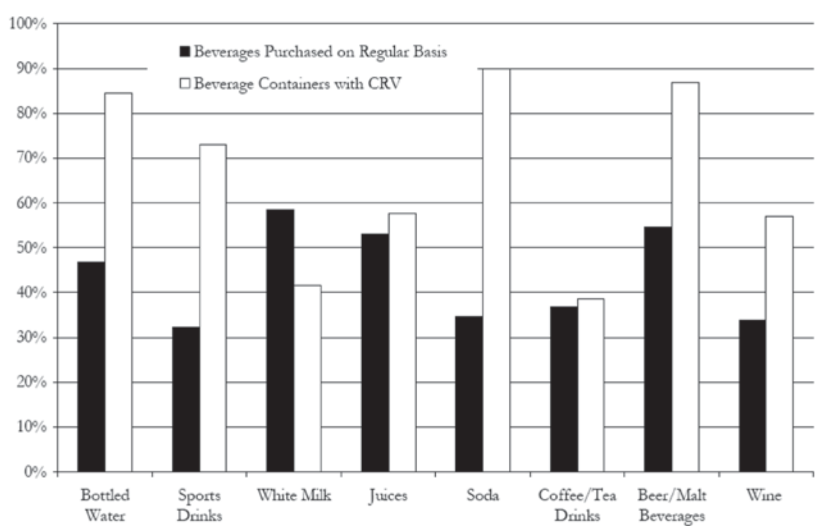

Figure 7. *Beverage Purchasing Preferences and Recycling Awareness (Positive Responses).*

Table 3. Beverage Containers Purchased on a Regular Basis & Awareness of Redeemable Beverage Containers.

	Beverage Containers Purchased on a Regular Basis			Awareness of Redeemable Beverage Containers		
Beverage		**Frequency**	**Percent**		**Frequency**	**Percent**
Bottled Water	No	69	53.10%	No	20	15.40%
	Yes	61	46.90%	Yes	110	84.60%
Sports Drinks	No	88	67.70%	No	35	26.90%
	Yes	42	32.30%	Yes	95	73.10%
White Milk	No	54	41.50%	No	76	58.50%
	Yes	76	58.50%	Yes	54	41.50%
Juices	No	61	46.90%	No	55	42.30%
	Yes	69	53.10%	Yes	75	57.70%
Soda	No	85	65.40%	No	13	10.00%
	Yes	45	34.60%	Yes	117	90.00%
Coffee / Tea Drinks	No	82	63.10%	No	80	61.50%
	Yes	48	36.90%	Yes	50	38.50%
Beer / Malt Beverages	No	59	45.40%	No	17	13.10%
	Yes	71	54.60%	Yes	113	86.90%
Wine	No	86	66.20%	No	56	43.10%
	Yes	44	33.80%	Yes	74	56.90%

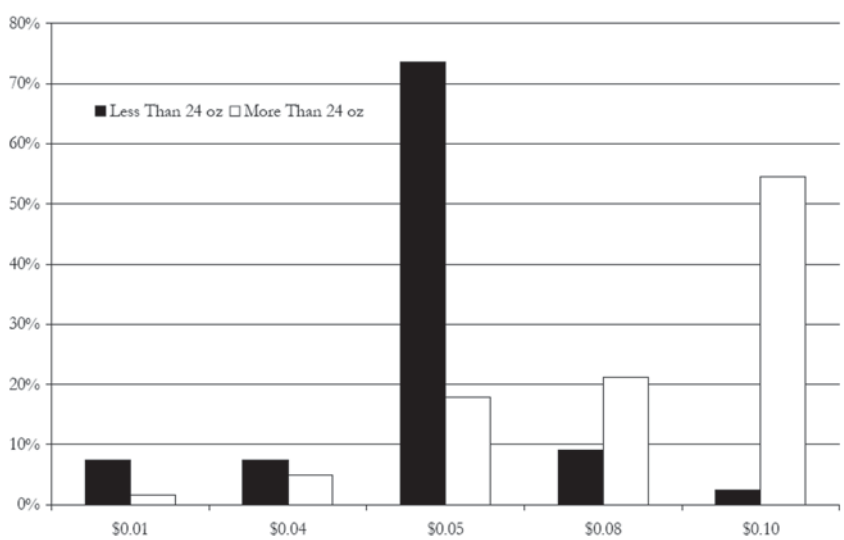

Figure 8. *Understanding of Redemption Value as Associated to Size of Beverage Containers.*

Table 4. Awareness of Deposit Payment by Beverage Container Size. (When you purchase a container with a CRV on the label, you pay an additional recycling or redemption fee. Are you aware how much that fee is per container when the container is?)

	< 24 oz.			> 24 oz.		
	Frequency	**Percent**	**Valid Percent**	**Frequency**	**Percent**	**Valid Percent**
$0.01	9	6.9	7.4	2	1.5	1.6
$0.04	9	6.9	7.4	6	4.6	4.9
$0.05	89	68.5	73.6	22	16.9	17.9
$0.08	11	8.5	9.1	26	20	21.1
$0.10	3	2.3	2.5	67	51.5	54.5
Total	**121**	**93.1**	**100**	**123**	**94.6**	**100**
Missing values	9	6.9		7	5.4	
	130	**100**		**130**	**100**	

One purpose of this study was to investigate the impact of redemption value on motivation to recycle for a refund. For this purpose we asked participants to report their level of agreement to the following question: What redemption value would motivate you to recycle for a refund? With the following conditions: (1) $0.10 for less than 24 ounces, (2) $0.15 for less than 24 ounces, (3) $0.15 for more than 24 ounces, and 4) $0.20 for more than 24 ounces. A seven point agreement scale was used with endpoints, strongly agree = 1 and strongly disagree = 7, so a smaller score reflects greater motivation to recycle for a refund. The results are displayed in Figure 9 and Table 5.

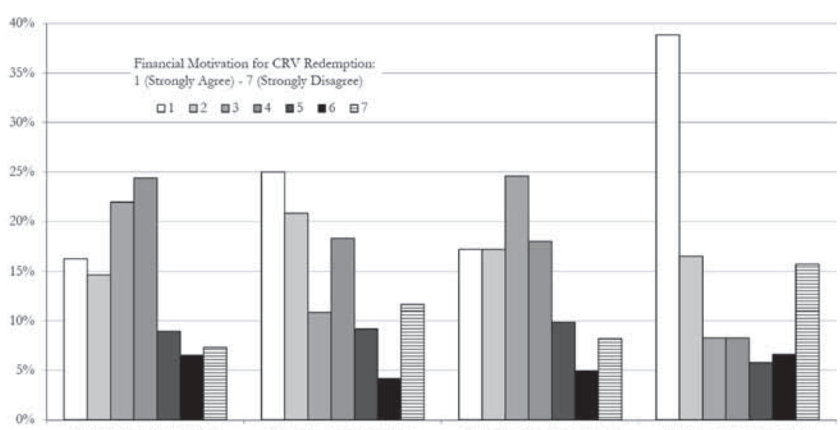

Figure 9. *Influence of Incentive on Motivation to Recycle for a Refund.*

Table 5. Incentives and Motivation to Recycle.

	Mean	SD	SE
$0.10 for LESS than 24 ounces	3.51	1.71	0.16
$0.15 for LESS than 24 ounces	3.26	2.00	0.18
$0.15 for MORE than 24 ounces	3.38	1.76	0.16
$0.20 for MORE than 24 ounces	3.07	2.26	0.21

The mean motivation for $0.10 for less than 24 ounces was 3.51 (sd = 1.707), and the mean motivation for $0.15 for less than 24 ounces was 3.26 (sd = 1.998), the mean motivation for 0.15 for more than 24 ounces was 3.38 (sd = 1.756), and the mean motivation for $0.20 for more than 24 ounces was 3.07 (sd = 2.258) (Table 5).

To estimate the impact of a 5 cent increase, we performed a paired variable t-test on the difference between mean motivations; the results are reported in Table 6.

In both tests 5 cents was found to be a significant motivator. The mean difference for less than 24 ounces is 0.252 and is statistically signification, $t = 1.919$, $p = 0.0285$. The mean difference for more than 24 ounces is 0.311 and is statistically signification, $t = 2.422$, $p = 0.0085$. Both tests are one-tailed tests. The tests show that the consumer is motivated to recycle for a refund more so if the refund were 5 cent higher in both container sizes. The motivation scales reported in question 9 were pooled to form an overall motivation to recycle and summing the responses to the four scales allowed achieving this. The resulting scale reflects an average price of 15 cents for an average 24 ounce bottle.

One variable of great interest are gender differences. For example, women in the U.S. are responsible for 80% of all household shopping [4]. Given these tasks and responsibilities, we expected to find gender differences in the motivation to recycle. To investigate this possibility, the motivation scale cited above was divided into three sections (High motivation, neutral, and Low motivation) and cross tabulated with gender. The results are reported graphically in Figure 10 and in Table 7.

Table 6. Mean Increase in Motivation to Recycle Given 5 Cent Increase in Redemption Value.

	Δ Mean	SD	SE	*t*	df	Prob.
$0.10 to $0.15 < 24 ounces	0.252	1.433	0.131	1.919	118	0.029
$0.15 to $0.20 > 24 ounces	0.311	1.401	0.128	2.422	118	0.009

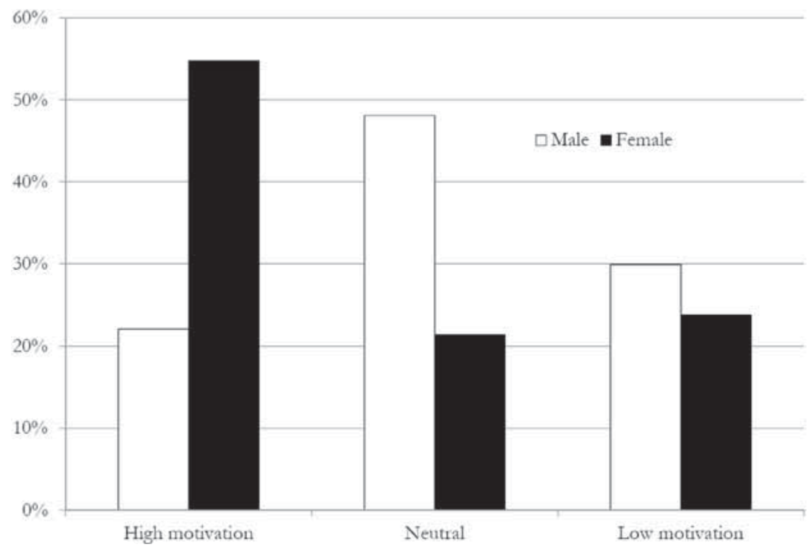

Figure 10. *Motivation to Recycle Given Incentive by Gender.*

As revealed in Table 7, women appear to be more motivated to recycle for a refund than men. A test of the statistical significant of this relationship shows that it is statistically significant, $X^2 = 13.98$, df = 2, and $p < 0.001$.

3.4 RECYCLING HABITS AND ATTITUDE

To investigate how respondents recycle, the following question was asked, How do you generally recycle?, with the following response options: I put recyclable materials in a bin outside my home for pick-up, I take recyclables to a drop-off location where I get a refund, I take recyclables to a drop-off location where I do not get a refund, I take recyclables to bins at another location, and other. The results are reported in graphically in Figure 11 and in Table 8. The primary method is home pickup (77.7%).

Table 7. Motivation to Recycle Given Incentive by Gender.

	Male	Female	Total
High Motivation	17 (22.10%)	23 (54.80%)	40 (33.60%)
Neutral	37 (48.10%)	9 (21.40%)	46 (38.70%)
Low Motivation	23 (29.90%)	10 (23.80%)	33 (27.70%)
Total	**77**	**42**	**119**

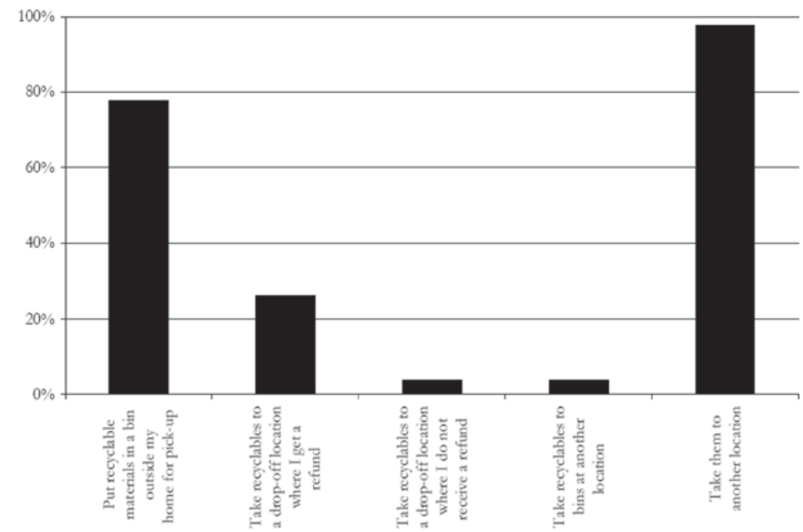

Figure 11. *Methods of Recycling.*

Reasons for not returning materials for a refund were addressed by the following question; If you do not return your recyclables for a refund, why not?, with the following response options: I don't know where to take them, The redemption value is not worth the effort, I just forget, It's too inconvenient, The redemption locations are dangerous, I would rather have them picked up, There is no refund center within 10 miles of my home, and other. The results are reported in Figure 12 and in Table 9. The primary reason was found to be inconvenience (34.1%).

3.5 RECYCLING BELIEFS AND INTENTIONS

The survey was designed to indentify recycling beliefs and inten-

Table 8. Methods of Recycling.

	Male	Female	Total
I put recyclable materials in a bin outside my home for pick-up	No	29	22.30%
	Yes	101	77.70%
I take recyclables to a drop-off location where I get a refund	No	96	73.80%
	Yes	34	26.20%
I take recyclables to a drop-off location where I do not receive a refund	No	125	96.20%
	Yes	5	3.80%
I take recyclables to bins at another location	No	125	96.20%
	Yes	5	3.80%

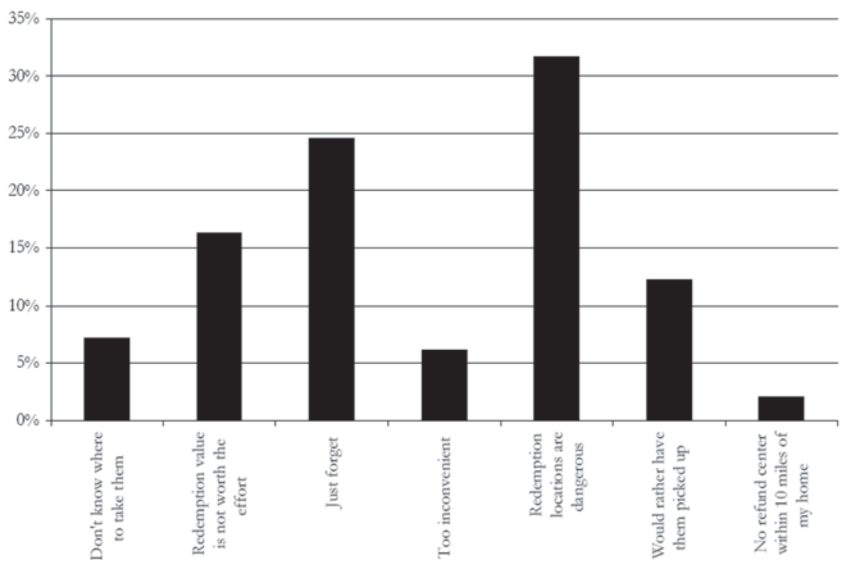

Figure 12. *Reasons why People do not Recycle for a Refund.*

tions. For this purpose, we asked three questions with a true/false response: "I often feel that I am wasting money when I don't return my recyclables for the redemption value", "If a redemption center were closer to my home I would be more likely to return my recyclables", "If I had the option of putting my bottles in a conveniently located vending machine for redemption, I would be more likely to return my recyclables". The results are provided in Figure 13 and Table 10. Nearness to home and a conveniently located vending machine are the top choices, 66.4% and 85.7%, respectively.

Table 9. Reasons why People Do Not Recycle for a Refund.

	Frequency	Percent	Valid Percent
Don't know where to go	16	12.3	17.6
Redemption not worth effort	24	18.5	26.4
Just forget to do	6	4.6	6.6
Inconvenient	31	23.8	34.1
I use home pickup service	12	9.2	13.2
No refund center near home	2	1.5	2.2
Total	**91**	**70**	**100**
Missing Values	39	30	
	130	**100**	

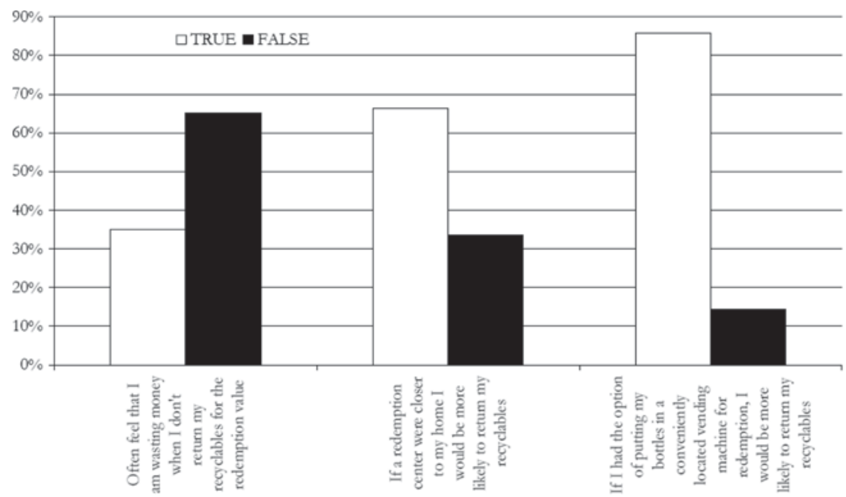

Figure 13. *Recycling Beliefs and Intentions.*

4.0 CONCLUSIONS

A survey was conducted by the Packaging and Marketing programs at Cal Poly State University to evaluate the understanding of the deposit law as well as purchasing and recycling and redemption habits of its students. While it was observed that a majority of the respondents (94.31%) had prior knowledge of the concept of CRV, they were not particularly aware of the beverages subject to it. As an example, 42% of the respondents wrongly assumed that white milk was subjected to CRV.

A majority of the respondents correctly knew the actual deposits paid for less than 24 oz. (74%) and greater than 24 oz. (55%) beverage containers at retail. It was surprising to observe that even with the

Table 10. Recycling Beliefs and Intentions.

		Frequency	Percent
I often feel that I am wasting money when I don't return my recyclables for the redemption value.	True	44	34.9%
	False	82	65.1%
If a redemption center were closer to my home I would be more likely to return my recyclables.	True	83	66.4%
	False	42	33.6%
If I had the option of putting my bottles in a conveniently located vending machine for redemption, I would be more likely to return my recyclables.	True	108	85.7%
	False	18	14.3%

appropriate knowledge of the deposits paid by them at retail, only 26% of them redeemed the same. 78% of the respondents put the CRV containers in the comingled recycling bin for curbside service. It was also observed that women appeared to be more motivated to recycle for a refund (55%) than men (22%). In response to the question regarding why they did not redeem the deposit, the biggest response (32%) was that they did not feel the redemption center locations were convenient followed by they just forget (25%) and the redemption value was not worth the effort (16%).

Incremental CRV and closer vicinity of the redemption centers were observed to be added incentives to redeem the deposit as 65% of the respondents did not feel that they were wasting their money by not redeeming the deposit and 66% stated that they would be more motivated to redeeming it if the centers were closer to their residences. An overwhelming 86% of the respondents claimed that they would redeem the CRV if conveniently located reverse vending machines were made available.

Though over 82% (17.2 billion) CRV beverage containers were returned for recycling in California in 2009, up by 1.1 billion containers as compared to 2008 [2], the redemption rate and consequently the total number of beverage containers recycled can be significantly increased by improving the redemption site locations and quality as well as through advertising campaigns to better educate the consumers regarding the CRV policy.

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6.0 APPENDIX A. SURVEY QUESTIONS.

1. What is the information on the yellow label [CRV label]?

2. Which of the following beverages do you purchase on a regular basis (check all that apply)

   Bottled Water (carbonated or uncarbonated)
   Sports Drinks
   White Milk
   Juices
   Soda
   Coffee/Tea Drinks
   Beer/Malt Beverages
   Wine
   Other, Please specify

3. Do you know which of the following beverage containers can be recycled for a refund? (Check all that apply)

   Bottled Water (carbonated or uncarbonated)
   Sports Drinks
   White Milk
   Juices
   Soda
   Coffee/Tea Drinks
   Beer/Malt Beverages
   Wine

4. When you purchase a container with a CRV on the label, you pay an additional recycling or redemption fee. Are you aware how much that fee is per container when the container is less than 24 oz.?

   $0.01
   $0.04
   $0.05
   $0.08
   $0.10

5. When you purchase a container with a container with a CRV on the label, you pay an additional recycling or redemption fee. Are you aware how much that fee is per container when the container is 24 fluid oz. OR MORE?

   $0.01
   $0.04
   $0.05
   $0.08
   $0.10

6. How do you generally recycle?
   I put recyclable materials in a bin outside my home for pick-up.
   I take recyclables to a drop-off location where I get a refund.
   I take recyclables to a drop-off location where I do not get a refund.
   I take recyclables to bins at another location.
   If you take them to another location, please specify.

7. If you do not return your recyclables for a refund, why not?
   I don't know where to take them.
   The redemption value is not worth the effort.
   I just forget.
   It's too inconvenient.
   The redemption locations are dangerous.
   I would rather have them picked up.
   There is no refund center within 10 miles of my home.
   Other, please specify.

8. Do you recycle at any of the following places? (Please check all that apply)
   Home
   Work
   School
   Home of family or friends (even if you have to carry the recyclables away)
   When dining away from home
   When shopping at convenience stores
   When eating or drinking on the run
   When vacationing
   Other, please specify

9. What redemption value would motivate you to recycle for a refund? 1 = strongly agree, 7 = strongly disagree
   $0.10 for less than 24 ounces
   $0.15 for less than 24 ounces
   $0.15 for more than 24 ounces
   $0.20 for more than 24 ounces

10. I often feel that I am wasting money when I don't return my recyclables for the redemption value.
    True/False

11. If a redemption center were closer to my home I would be more likely to return my recyclables.
    True/False

12. If I had the option of putting my bottles in a conveniently located vending machine for redemption, I would be more likely to return my recyclables.
    True/False

13. What is your gender?
    Male/Female

14. Please check the box with corresponds with your age.
    18–21
    22–24
    25–30
    31–35
    36–40
    Over 40

15. What is your class level?
    Freshman
    Sophomore
    Junior
    Senior
    Graduate Student

Packaging Requirements for Less-Than-Truckload Shipments to Reduce Damage—Machinery and Machine Parts, Doors and Windows and Miscellaneous Items

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ABSTRACT: This paper provides results from a major damage assessment study that analyzed challenges products endure during shipping and handling in the less-than-truckload logistics environment. The study shows the various package forms, handling and loading challenges that carriers experience when shipping a multitude of mixed products as part of daily shipments, and recommendations to reduce or avoid damage and avoid personal injury. This paper presents findings for machinery and machine parts, doors and windows, and miscellaneous items. It is the last of a series of three papers focusing less-than-truck load shipments of various commodities. The paper reviews findings from various shipments, and provides recommendations on both packaging and loading methods based on product type to safely load and transport less-than-truckload shipments, and to reduce damage claims without compromising safety of personnel handling and performing loading and unloading functions.

1.0 INTRODUCTION

EVERY day thousands of tons of commodities are transported around the country via motor carriers. A large majority of this freight is moved through the less-than-truckload (LTL) distribution environment, which has very unique characteristics that are inherent to how the system functions. This paper is the last paper in a series of three papers. The authors have retained the same introduction and results of the LTL survey in all three papers so readers can review the background information on LTL shipments and damage independents with each paper.

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Carriers are faced daily with the challenge of optimizing the available space in the trailer with the largest number of shipping units that can be shipped without causing damage and compromising safety. This is sometimes a difficult task if the carrier does not truly comprehend the protective capabilities and the integrity of the package that has been placed in shipment with other packages from other customers, all moving in the same truck. One leaking pail, or broken glass products, can compromise several other packages in their vicinity, and so damage is often progressive in LTL shipments.

Previous studies conducted with collaboration with Michigan State University School of Packaging have shown that LTL shipments will be susceptible to damage due to a lack of proper packaging and improper loading methods [1,2]. Vibration levels measured in LTL shipments have also shown that these levels are significantly higher than those in other types of truck shipments (Figure 1) [3,4]. Results from recent studies have shown that vibration levels measured in LTL trailers and pup-trailers are higher than those recommended truck shipments [5,6] and in industry standards [7]. As a result the International Safe Transit Association (ISTA) developed a new test method that used the new vibration data to better represent this unique shipping and handling environment [8]. This test method "Project 3B: Packaged-Products for

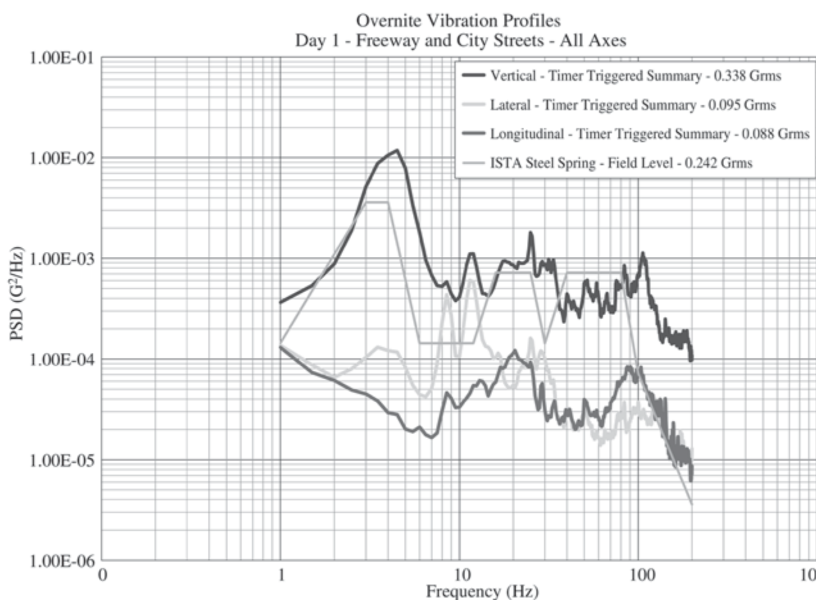

Figure 1. *Vibration Levels in LTL Shipments Compared to Truck Load Test Methods [7].*

Less-Than-Truckload (LTL) Shipment" is a general simulation test for packaged-products shipped through a motor carrier (truck) delivery system, where different types of packaged-products, often from different shippers and intended for different ultimate destinations, are mixed in the same load. Project 3B is appropriate for four different types of packages commonly distributed in LTL shipments: Standard 200 lb (91 kg) or less, Standard over 200 lb (kg), Cylindrical, and Palletized or Skidded [8]. Requirements may include atmospheric conditioning, tip-over, shock and impact, random vibration with top load, concentrated impacts, and fork lift handling.

Packaging requirements, for freight transported via LTL, are defined in the *National Motor Freight Classification (NMFC)*. Each commodity description in the *NMFC* specifies minimum packaging requirements to ensure the products can be handled and protected in the motor carrier environment. The descriptions may be as simple as "in boxes," "in drums," "in boxes, crates, or on a lift truck skid or pallet". The *NMFC* does not stipulate what interior packaging is required, since that is dependent on too many factors that are inherent with a particular product. It is the shipper's responsibility to develop interior packaging that will protect and contain the product during handling and distribution.

However, despite the *NMFC*'s minimum packaging requirements, there are a variety of commodities that are inherently difficult to handle or stow, susceptible to damage, highly fragile, or problematical to develop packaging that is appropriate to adequately protect it from the rigors of this distribution environment. The goal when setting the minimum packaging requirements for commodities is to provide proper containment. When freight is damaged, a damage claim is often filed against the carrier by the shipper or consignee of the freight. The shipper or consignee generally determines the value of the damaged freight and will request the carrier to reimburse all or a portion of the monetary value of the freight. Obviously, the payment of damage claims to shippers can become very expensive for many carriers.

In trying to understand how packaging and different loading methods can affect damage claims, six LTL motor carriers were surveyed and asked the questions mentioned in the next section regarding their company's history. Overall, the survey has proven that there are some commodities that are generally more susceptible to damage and have more liability factors than other commodities. Packaging can play a very important role in not only preventing damage to the products, but also facilitate in the safe handling and stowing of the products for carriers. This study contains pictures from "actual" LTL shipments that depict the type of freight and packaging that is commonly seen in the LTL environment for paint, copiers and televisions.

2.0 MOTOR CARRIER SURVEY AND RESULTS

Six LTL motor carriers were surveyed and asked the following questions regarding their company's history and practices. The responses received from these six carriers varied, mainly due to the size and coverage area of the company. For confidentiality purposes, the companies are only identified as A, B, C, D, E, or F.

1. What are the top three commodities or commodity groups (as described in the *NMFC*) with the most claims?
2. Approximately what percentage of all claims does each of the commodities or commodity groups named in number 1 represent?
3. Approximately how much money does your company spend each year in claims?
4. What is your company's claims ratio?
5. What percentage of claims does your company pay and deny?
6. How often does insufficient packaging account for the denial of a claim?
7. What is the most common reason for damage claims rejections?

The six carriers were very forthcoming with proprietary information regarding the information requested. These six carriers spend approximately $50 million combined each year in claims that range from $33,000 to $31 million. Three companies' claims-ratio ranged from 0.76% to 1.30%, with an average of 1.02%. Claims-ratio is calculated by dividing the dollars paid in claims by total overall revenue generated for all shipments. On average, these six carriers pay 65% of the claims filed, while denying only 35%. For one company over 80% percent of all claims were related to furniture alone.

Based on this survey, furniture was found to be the most frequently damaged commodity group, as four out of the six carriers named this as their top issue and concern. Furniture, as a whole, can be very fragile, large, and can be awkward in size and shape. The *NMFC* provides for specification-based packages for most furniture types, as well as Item (Rule) 181, which is a test procedure that simulates the LTL environment and was designed specifically for furniture and furniture parts. However, shippers often do not utilize these standards and use a minimal amount of packaging which may not help protect the products from scratches, dents, and scuffs. Company C reported that furniture represents 81% of all their damage claims, while Companies D and F indicated that furniture was responsible for about 11 percent of their damage claims. Of Company C's 81% of all claims, 60% of the claims were denied due to insufficient packaging. Additionally, many types of furniture can be expensive and have a high value per pound.

Electronics, electrical equipment and supplies, and machinery were also identified by the carriers as commodities with the most claims. Not unlike furniture, some of the products can also be quite fragile. However, the fragility is often determined by a particular component within the product. These products may also be very large, which would hinder the manufacturer from developing packaging that can sufficiently protect the entire unit.

Companies C and F indicated that certain types of paper goods are also liable to damage due to a lack of packaging. Company C denies 100% of damage claims on these goods based on insufficient packaging. While paper goods are dense freight with few negative handling and stowing issues, when they are not packaged properly the product can be subjected to damage from handling and the external environment. Company A reported 20% and Company E reported 29% denial of claims due to insufficient packaging. In the case of Company A, this is the most common reason for claim denial. Of the 84% of Company E's claims are filed for damage, while 16% is for loss of product.

Overall, this survey has proven that there are some commodities that are generally more susceptible to damage and have more liability factors than other commodities. The packaging can play a very important role in not only preventing damage to the products, but also facilitate in the safe handling and stowing of the products for carriers. Unfortunately, as depicted by the figures that follow, manufacturers are not always packaging their commodities in a way that is appropriate for the LTL environment. In many instances, the pictures prove why the numbers presented by the carriers in the survey are accurate and representative of the issues carriers face on a daily basis.

3.0 DAMAGE ISSUES AND PREVENTIVE METHODS WITH SHIPMENTS OF MACHINERY AND MACHINE PARTS

Machinery and machinery parts are named in the National Motor

Freight Classification (NMFC) as a category with “all of various minimum packaging requirements”. However, most of them permit these commodities to be shipped on pallets or just without packaging and loose. Obviously, the size and configuration of many machines prohibit the use of appropriate packaging that would completely enclose the product, which tends to result in higher percentage of damage claims. There are some manufacturers who attempt to package their products in wood crates in an effort to more fully protect their machinery or machinery parts. Also, these machines are generally expensive and can be costly for carriers if damage occurs during handling or transit. Depending on the type of machine, it may also have a number of fragile components such as gauges, trays, handles, electronic controls, etc. If those components are not covered with packaging, they could get damaged by impacts or vibration during handling or transportation.

When shipped on pallets, as in Figures 2(a) through 2(f), the item of machinery is much easier for carriers to handle, as they can lift the machine or part by mechanical means. Even though the products are shipped on pallets, if they are not securely attached to them, or if the pallets are not of sufficient materials and construction for the carriers to safely handle the products, the products are no easier to handle than if they were shipped loose. Pallets have to be properly designed to provide proper load bearing, not increase the risk of instability, and of sufficient strength to interface with material handling equipment. Item (Rule) 265 of the NMFC defines the appropriate construction requirements for lift truck skids, pallets, or platforms.

Whether tendered loose or on a pallet, most machines and their parts do not provide a flat load-bearing surface for a carrier to load freight on top of. Additionally, due to the unique size of every machine item, the carrier may not be able to load freight adjacent to the machine, which can prevent the carrier from loading a trailer to capacity. Another consideration that must be evaluated is the size of the pallet utilized for a particular commodity. If the product does not fit completely on the pallet, such as those found in Figures 2(e) and 2(f), the product can be damaged or can damage other freight adjacent to it. On the other hand, if there is too much extra space on the pallet, the shipper can be penalized with additional freight charges, since the density is calculated based on the outermost dimensions, including the surface are of the pallet. Therefore, it is more beneficial for manufacturers to tender their freight on pallets that are of appropriate size and strength for the machines and parts they are shipping.

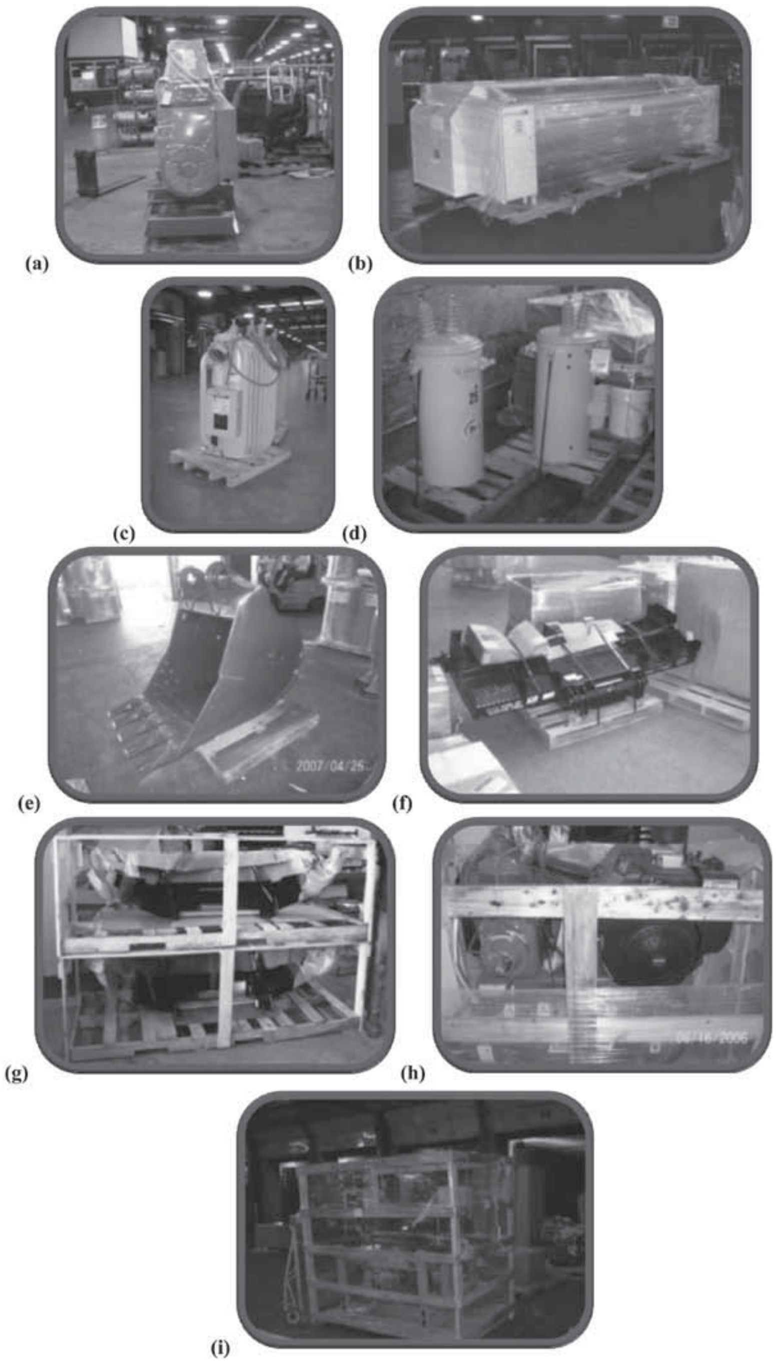

Figure 2. *Shipments of Machinery and Machine Parts.*

As indicated, some manufacturers try to build crates around their products, but often do not know the appropriate construction requirements for crates in order to be in compliance with the NMFC. Item (Rule) 245 specifies how wood crates and wire-bound crates must be constructed in order to be of sufficient strength to survive multiple handlings that LTL freight is subjected to. Item 245 includes diagrams of three-way locking corners, which are critical to the strength and integrity of a crate. The "crates" seen in Figures 2(g), 2(h) and 2(i) are examples of non-complying NMFC crates for a number of reasons. First, they are not constructed with three-way locking corners. Second, they do not have horizontal, vertical, and diagonal cross members of sufficient number and strength to thoroughly protect all sides of the product and maintain the integrity of the crate. Third, they do not protect the top and, therefore, do not provide the carrier a flat load-bearing surface on which to load additional freight. Therefore they have a higher risk of damage in a LTL shipment, or potential for increased freight costs for specialized transportation and handling.

4.0 DAMAGE ISSUES AND PREVENTIVE METHODS FOR SHIPMENTS OF DOORS AND WINDOWS

Due to their different sizes and materials, and the various surface finishes/features, doors and windows can be difficult to package for safe shipment in the LTL environment. An important parameter to consider is to be able to properly secure or block and brace these large heavy and flat product configurations in the available space in a trailer or inter-modal container. The package configuration can be greatly affected how the carrier handles and stows the freight. Manufactures who direct ship in their own trailers can stay with minimum packaging (stretch wrap) or reusable cushioned blanket wraps, to fully enclosed packaging with corrugated boxes and foamed cushions for LTL shipments. More often than not, doors and windows are shipped in an upright position in order to prevent other freight from being stacked on them. This also prevents doors and windows with glass sections to be safely shipped as glass cannot be loaded flat.

Figures 3(a) through 3(h) show the various configurations that manufacturers use when shipping doors and windows in upright positions. They are often tendered on pallets or platforms to assist in handling. Since the carriers are unable to stack freight on top of, and sometimes

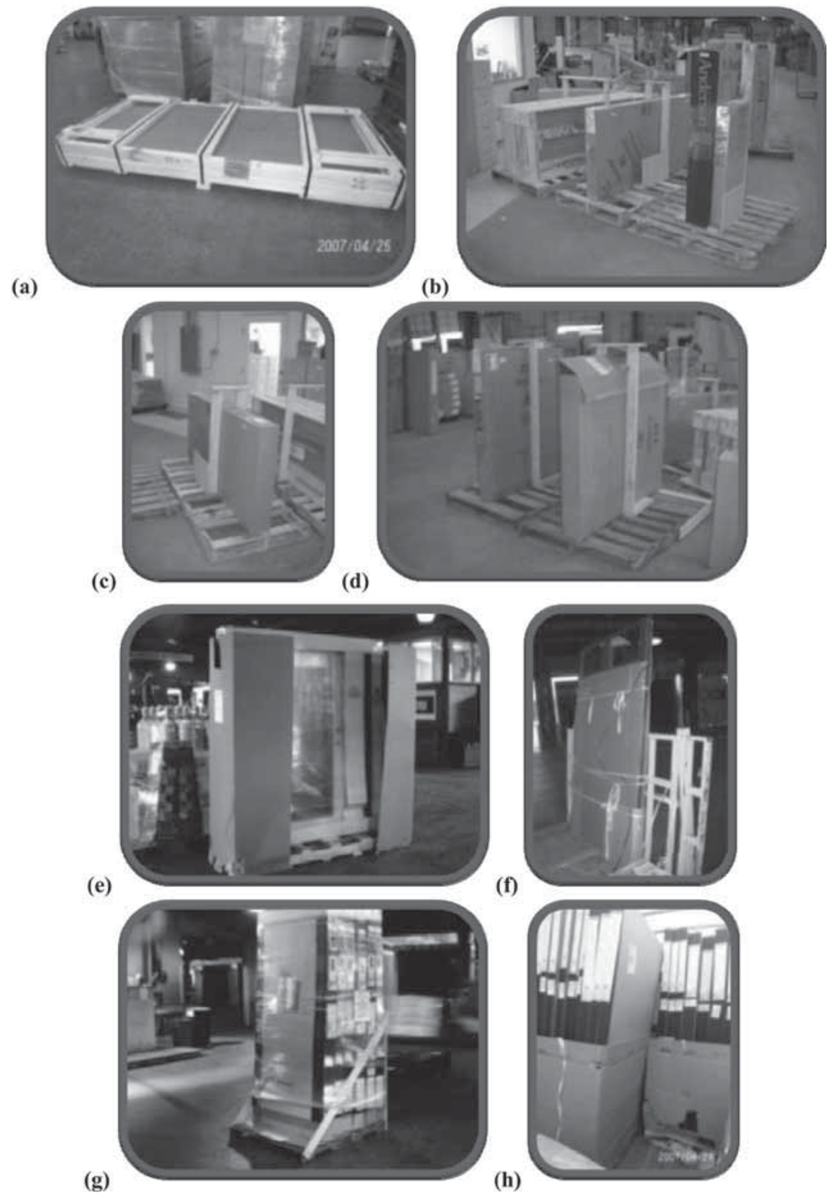

Figure 3. *Shipments of Windows and Doors.*

next to these types of shipments of doors and windows, they lose a large amount of valuable space inside the trailer for other freight. Additionally, the load density of the trailer drastically drops when the pallet size and height of the freight is computed for shipping efficiencies.

Despite the different configurations, the doors and windows are often packaged in fiberboard boxes with interior packaging to prevent damage. Unfortunately, not all manufacturers invest in the same amount of packaging and materials to sufficiently cover and protect all sides of the products, as in Figures 3(e) through 3(h). Certain manufacturers accept a higher risk of damage to cost savings attributed from lesser packaging. The door in Figure 3(e) is attached to the pallet and the sides seem to be well protected, however, the glass in the middle has no packaging to protect it. Also, if the door is not resting on a material that will absorb vibration, the glass or frame may suffer damage during transit. The window in Figure 3(f) has fiberboard panels to protect most of the glass, except for the top and sides. Also, since it was not shipped on a pallet, the window would have to be handled manually and be braced within the trailer so as not to fall during transit. Therefore, the carrier's package handlers would have to be extra careful to ensure that it does not get crushed by other freight. This type of package makes it difficult for the carrier to handle and load trailers quickly and easily during their cross-dock operations.

Figure 3(a), is one of the few shipments that shows a door being shipped flat inside a crate-type container. This container allows the door to be easily handled with material handling equipment and also allows for top-stacking of other lightweight freight. It would not be recommended to stack heavy freight on top, of course, due to the fragility of the product and not knowing the strength of the bottom container. This packaging also greatly increases the density of the freight, which can benefit the manufacturer and shipper.

Figures 3(g) and 3(h) are of two shipments of doors that were possibly from the same manufacturer. In Figure 3(h), the manufacturer protected the bottom third of the doors with fiberboard, covering the pallet, which may have prevented damage. These doors are well unitized and therefore the density of the shipment is much greater than the other configurations shown. These types of package shipments are commonly used to ship product to building construction club stores such as Lowe's and Home Depot.

5.0 DAMAGE ISSUES AND PREVENTIVE METHODS FOR SHIPMENTS OF MISCELLANEOUS ITEMS

LTL motor carriers see a lot of random freight that is too large to be shipped via small parcel, but is unique, and often a one-time shipment. Regardless, the freight still needs to be classified in accordance with the NMFC and packaged according to the applicable minimum packaging requirements to meet tariff classification.

Figure 3(a) shows a package with a display of an astronaut in a glass case. The shipper tendered this display in a four-sided "crate" that did not meet the construction requirements of Item (Rule) 245 for crates. The display is on casters, and from the figure, it is difficult to know if the display was braced within the crate. Without any protection on the two large sides or any interior cushioning, this display is highly susceptible to damage.

Figure 3(b) contains two rolling ladders that are commonly found in stores for employees to reach merchandise on higher shelves. Due to the large size and configuration of these ladders, the manufacturers shipped them on a pallet, which is appropriate in size for the products. However, the pallet is longer than standard pallets, which can require longer forks for mechanical equipment to properly handle the freight. The manufacturer also did not secure the ladders to the pallet, nor did they protect any of the fragile components, such as the casters. Since the ladders are not attached to the pallet, if the pallet is not picked up carefully, the ladders may slide off. Also, carriers may have a difficult time loading freight adjacent to the ladders and will not be able to stack freight on top.

The tractor spray accessory shown in Figure 3(c) was tendered in a metal "crate." The minimum packaging requirements for this particular commodity requires products be shipped in boxes or crates. However, this metal framework does not meet the definition or specifications of crates, as defined in the NMFC. The tractor is resting on the ground, so there is no easy access point for mechanical equipment to lift the product and its surrounding crate without potentially damaging it. Also, none of the components were protected from the environment with packaging materials or covering.

The all terrain vehicles (ATV) in Figure 3(d) were only wrapped in plastic wrap then set on pallets for shipment. Considering these products having fragile components and are on wheels, the manufacturer could have put additional protective packaging around them, as well as secured them to the pallets. It is possible that they could shift or even roll off the pallets during transit, which can cause damage to them and adjacent freight.

The numerous warning labels on the crate in Figure 3(e) are just a

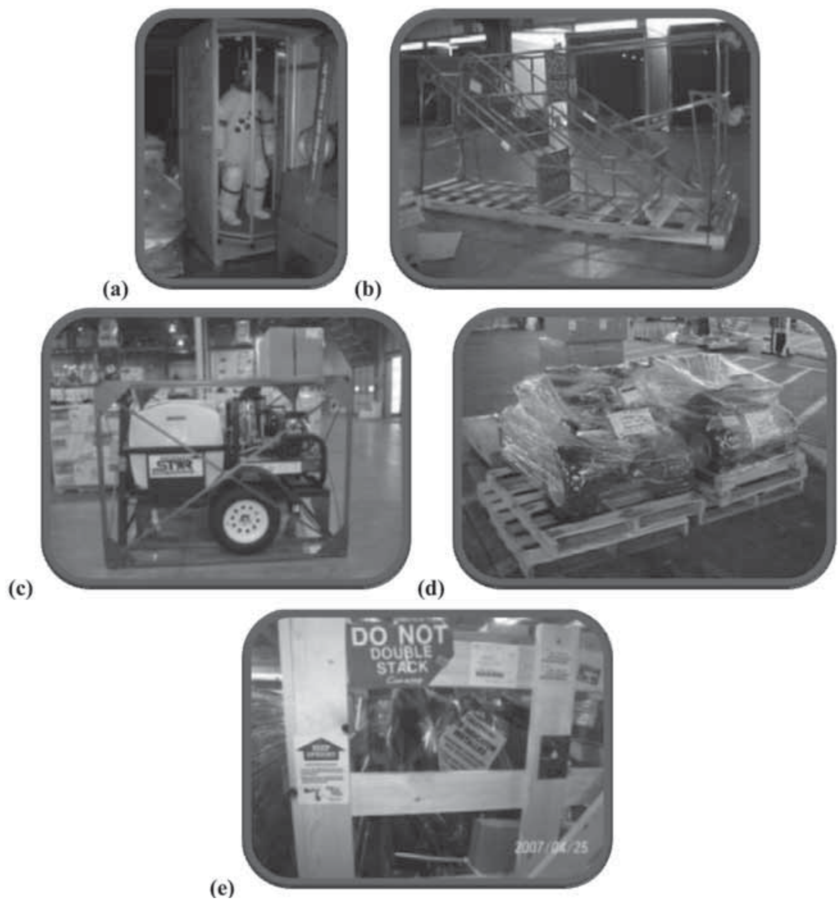

Figure 4. *Shipments of Miscellaneous Items.*

few examples of the types of handling and loading restrictions carriers are faced with on a daily basis. Not only do carriers try to address the need to make sure the freight is handled according to these precautionary markings, but they also have to ensure that certain types of freight, such as hazardous materials, are not shipped together. These restrictions can make it very difficult for a carrier to completely fill a trailer if the available freight is not compatible. Some manufacturers also insist on using "damage indicators," which are sensors that detect extreme impacts, vibration, tilting, temperature, or even humidity. The term "damage indicator" is not appropriate because even if the sensor detects an event, the product itself may not be damaged in any way, and on the contrary damaged equipment may not trigger an indicator.

6.0 CONCLUSIONS

The study concludes the following:

- Packaging and loading methods are critical in reducing damage and injury during transportation and handling of LTL shipments.
- LTL shipments must be properly blocked and braced with other packages or using load securement methods such as straps, retaining bars, air-bags, or dunnage.
- Loads will shift in LTL shipments if void spaces exist in filled trailers.
- LTL shipments produce significantly high level of vibration during transport as compared to fully loaded trailers, and as such must be tested to higher levels of pre-shipment testing.
- It is critical to properly design wood crates and pallets in accordance with NMFC to provide adequate protection of doors, windows, and uniquely shaped fragile items for LTL shipments.
- Packages and crates should be designed to permit top loading of lighter and smaller freight on top to optimize shipping densities. Failure to do this can result in tariff surcharges or damage.
- Due to the size and weight, single packages have less energy associated with them during loading and unloading as compared to palletized and unitized loads, and therefore are associated with smaller damage claims and are less hazardous to operator safety. Large and heavy unitized/palletized shipments may require additional warnings or markings for safe handling.
- Palletized shipments require the product and packages to be secured to the pallet, and ensure that the pallet is of appropriate size and strength to keep the load stable during handling and transportation.

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Biodegradation of Steam-treated Polylactic Acid (PLA) Under Composting Conditions

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ABSTRACT: Biodegradation of steam-treated thermoformed polymer polylactic acid (PLA) under composting conditions was investigated. Treatments involved subjecting plastic PLA samples to steam at 120°C for 0, 1, 2, 3 and 4 hours. Ground steam-treated PLA was mixed with compost, filled in perforated jars, and assessed for biodegradation at 58°C via the "Method of Perforated Jars" developed in this work. Kinetics of PLA biodegradation in compost were adjusted to the logistic model with three parameters. To assess effectiveness of steam treatment, weight loss of PLA samples was determined in compost for 14 days. Degradation rates were compared with those of corrugated paperboard and virgin wood. Results showed that steam treatment is an excellent method to increase PLA biodegradation rate in subsequent composting processes. Increased performance was attributed to both "head start" and "acceleration" effects. Ground and treated PLA (120°C x 3h) achieved 60% of biodegradation after 14 days in compost. Flat sheets of treated PLA (120°C x 4h) degraded faster than wood and corrugated paperboard, loosing up to 94.9% of initial weight after 14 days in compost. The logistic model fit experimental data of PLA biodegradation well. Significant findings of this work are the shortening of compostability time of steam-treated PLA, and the development of a convenient method to assess biodegradation of polymers under composting conditions, which is referred to as the "method of perforated jars."

INTRODUCTION

POLYLACTIC ACID (PLA) is a biobased polymer derived from renewable resources, such as corn, and able to biodegrade to carbon dioxide and water (Drumright, 2000). Compostability of PLA has been discussed by different authors, and the agreement is that it occurs at temperatures around 58°C after several weeks (Kale et al., 2006; Mas-

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sardier-Nageotte et al., 2006; Greer, 2006). Nevertheless, time to complete PLA breakdown may be too long compared with time frame of typical organic feedstock, and represents a potential bottleneck to composting operations. Commercial PLA packages have been shown to be incompletely degraded after 28 days of composting (Kale et al., 2006; Massardier-Nageotte et al., 2006).

Reactions that occur during PLA biodegradation in a composting process occur in three stages summarized in Figure 1. First, PLA hydrolyzes producing lower molecular weight PLA. This stage requires water and energy, but the presence of microorganisms is not essential. Then, low molecular weight PLA hydrolyzes further to produce oligomers and lactic acid. During this second stage, biological activity joins hydrolysis in breaking down PLA and is aided by appropriate temperature, moisture and oxygen levels. The third stage is carried out only by biological activity and produces carbon dioxide and water (Lunt, 1998). Depending on pH and specific microbes present, radicals may also be produced and combined with the biomass to integrate humic acids in the compost. Also, a small part of the carbon dioxide fraction dissolves in wet compost forming carbonic acid and carbonates.

The motivating hypothesis of this work is that treatments capable of disrupting the polymer matrix and/or reducing molecular weight should result in reduced overall composting time. Additionally, in the event that composting time is reduced, experiments were designed to determine whether pretreatments accelerated conversion kinetics or simply provided a head start to the composting process that subsequently proceeded at the typical rate. Means by which biodegradation time is shortened are graphically described in Figure 2. The "head start" effect is shown in Figure 2. A typical curve representing PLA biodegradation in the composting process can be described through 3 phases: (a) a lag period, (b) an accelerated biodegradation phase, and (c) a decelerated biodegradation phase until reaching a plateau. A "head start" effect would shift the curve in time, so that the lag period would be shortened or eliminated, but the trend of the curve would be maintained. So, a

$$\text{PLA} \xrightarrow{\text{Heat, } O_2\text{, moisture}} \text{PLA (low } M_w\text{)}$$

$$\text{PLA (low } M_w\text{)} \xrightarrow{\text{Heat, mo, } O_2\text{, moisture}} \text{Oligomers + lactic acid}$$

$$\text{Oligomers, lactic acid} \xrightarrow{\text{Heat, mo, } O_2\text{, moisture}} CO_2 + H_20$$

Figure 1. *Main reactions in PLA biodegradation.*

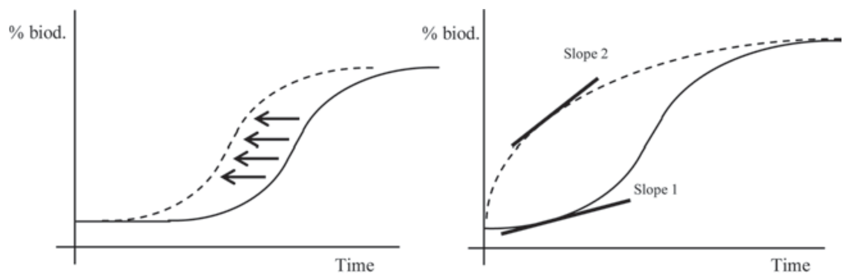

Figure 2. *Means to reduce biodegradation time. Left: head start effect; right: acceleration effect.*

"head start" effect would be expected to displace the entire curve to the left. As a consequence of this "head start" effect, overall biodegradation time will be reduced. The "acceleration" effect is also illustrated in Figure 2. Here, biodegradation rate must be carefully analyzed once the lag period is complete. The slope of the curve (in the earlier phase) represents initial biodegradation rate, and is an indicator of how rapidly carbon dioxide is evolving. The dashed curve depicts biodegradation evolution of PLA exhibiting the "acceleration" effect, represented by a steeper slope.

The main objective of this research was to evaluate effects of steam treatments on kinetics of subsequent PLA aerobic biodegradation, and to determine whether or not treatment will allow PLA to completely degrade within the time frame of normal organic feedstock. Determination of PLA biodegradation in compost was performed via the "method of perforated jars" described in this work.

MATERIALS AND METHODS

Material

Thermoformed PLA drinking cups (Fabri-Kal, Inc., Kalamazoo, MI) were obtained from TREEO Center at the University of Florida. Cup dimensions were measured using a caliper (Mitutoyo Model CD-6 CS, Mitutoyo Corp., Japan) and are provided in Figure 3. Wall thicknesses were 150–200µm and bottoms were about 750µm.

Steam Treatment of PLA

Drinking cups of PLA were prepared as flat sheets and ground using an Urschel 3600 grinder (Urschel Laboratories, Inc., Valparaiso, IN)

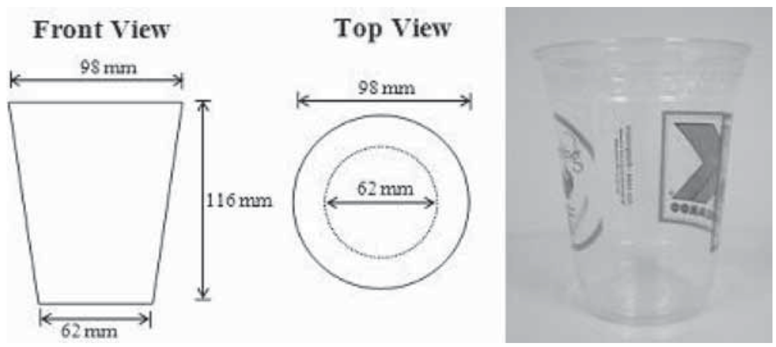

Figure 3. *Drinking cup made of PLA.*

with a 3 mm screen. Ground PLA and flat sheets were placed inside jars. Lids of jars were adapted with two holes (about 1 cm diameter) to allow steam transfer. Jars were placed in a vertical still retort where steam was fed and temperature controlled with a pneumatic system. Samples of ground PLA remained in the retort for 1, 2 and 3 hours at 120°C. Flat sheets of PLA remained for 3 and 4 hours at 120°C. After treatment, samples were quickly cooled in air to room temperature and dried in an oven at 105°C for one hour. Average molecular weight of steam-treated PLA from three replications was determined using the method of intrinsic viscosity in accordance to ASTM D2857 (ASTM, 1996), using chloroform at 30°C as solvent and a calibrated capillary viscosimeter (Cannon-Ubbelodhe Type N°25, State College, PA). Constants for the Mark-Houwink model [Equation (1)], which relates molecular weight, M, to the intrinsic viscosity, [μ], were k = 0.0153ml/g and a = 0.759 (Dorgan et al., 2005).

$$[\mu] = kM^{a} \tag{1}$$

Method of Perforated Jars

In perforated jars containing biomass (PLA-compost), oxygen enters through the holes to be consumed as part of the aerobic process. Biomass generates and releases carbon dioxide and water, which are diffused through the holes to the environment. A molar balance of carbon dioxide in the system can be written as in Equation (2).

$$\eta\ CO_2 \text{ generated} = \eta\ CO_2 \text{ diffused} + \eta\ CO_2 \text{ headspace} \tag{2}$$

The number of moles, η, diffused represents the average of moles flowing through the holes. This value can be estimated by Equation (3), derived from Fick's first law that states that the flux or rate of transport of an ideal gas is linearly related to its concentration gradient (Robertson, 2006).

$$\eta\ CO_2 \text{ diffused} = D_{ef}\,[CO_2]\,\Delta t \tag{3}$$

where D_{ef} is the overall effective coefficient of diffusion, $[CO_2]$ is the concentration of carbon dioxide, and Δt is the time interval between readings, which was 24 hours. Values of $[CO_2]$ were data recorded daily using a gas analyzer Pac Check® 650 (Mocon, Inc., Minneappolis, MN). Value of Def was determined experimentally and found to be 0.00031 moles/h/%. For this purpose, jars with similar features as those used for PLA biodegradation assessment were filled with 20ml of DI water and some carbon dioxide. Jars were closed using the 5-hole perforated lids and stored at 58°C. Each 0.5 h, carbon dioxide concentration was determined in headspace and effusion rate values expressed as moles CO_2 effused per hour were estimated. The value of D_{ef} was obtained from the slope of the plot of effusion rate against $\%CO_2$ in headspace.

The number of moles in the headspace can be estimated by Equation (4) which is derived from the universal gas law (Tsimpanogiannis and Yortsos, 2002).

$$\eta\ CO_2 \text{ headspace} = \frac{p_{CO_2} V_{hs}}{RT} = \frac{p_{atm}[CO_2]V_{hs}}{RT} \tag{4}$$

where p_{CO_2} is the partial pressure of CO_2 in headspace, patm is the atmospheric pressure, V_{hs} is the free volume in headspace, R is the universal gas constant, and T is the absolute temperature. Volume of the headspace was estimated by subtracting the volume occupied by the biomass from the total volume of the jars.

Production of CO_2 solely from PLA is the difference between CO_2 produced from the mixture PLA-compost and CO_2 produced from the compost itself (control). The carbon mass can be determined by multiplying the number of moles of CO_2 produced by 12, which is the molecular weight of carbon. Finally, total biodegradation is the ratio of carbon mass evolved as CO_2 to initial carbon mass in PLA, and can be expressed as in Equation (5). From molecular weigh estimation, carbon mass in PLA is half of its total mass.

$$\%\text{biod.} = \frac{\text{Mass of carbon in evolved } CO_2}{\text{Mass of carbon in polymer}} \times 100\% \tag{5}$$

Steam-treated PLA Biodegradation in Compost

Ground steam-treated PLA at 120°C for 0, 1, 2 and 3 hours was used in this experiment. Mason jars of 936cc capacity provided with 5 holes (× 1/16″) in the lids were filled with 100g of 6-month mature compost and 10g of ground PLA samples. Figure 4 shows pictures of the filled jar and perforated lid. Compost was originally developed using a standard organic matter feedstock recipe consisting of freshly cut grass (58%), saw dust (11%), virgin corrugated board (11%) and mature compost (20%). Controls were jars containing only 100g of compost. Sealed jars were stored at 58°C for 31 days in a Lab-Line® L-C Incubator (Lab-Line Instruments, Inc., Melrose Park, IL). Routine practices such as agitation and moisturizing was done daily to maintain uniformity conditions and biological activity. The amount of water to be added was such quantity that compensated the weight loss of the compost due to dehydration. Concentration of gases in the headspace was determined

Figure 4. *Jar filled with biomass and perforated lid.*

daily using a gas analyzer Pac Check® 650 (Mocon, Inc., Minneapolis, MN). For this practice, the needle of the lab instrument was inserted through the hole inside the jar, and a sample of air in the headspace was sucked and brought to the sensor. The "Method of Perforated Jars", based on principles of gas diffusion and developed in this work, was used to obtain kinetics of PLA biodegradation from data collected.

Emprirical Model for Steam-treated PLA Biodegradation in Compost

Data of biodegradation were plotted and adjusted to the logistic model with three parameters shown in Equation (6). Parameters were estimated using nonlinear regression performed with SigmaPlot v.10. Ideally, parameter a should be 100. Parameter b is associated with the lag period, and the parameter x_o represents the time at which half of the biodegradation would be completed. For untreated PLA, large values of parameters b and x_o were expected, whereas for treated PLA smaller values were expected.

$$\%\text{biod.} = \frac{a}{1+(t/x_o)^{-b}} \tag{6}$$

Weight Loss of Steam-treated PLA in Compost and Comparison with Other Common Feedstock

Flat sheet samples of PLA treated with steam at 120°C for 3 and 4 hours were used for this experiment. They were cut in circular shapes (~12.5 cm^2) and wrapped in nylon screen envelopes. Also, flat sheets of same area made of wood and virgin corrugated paperboard were prepared. All samples from different materials were dried, weighed and immersed in water for 10 minutes. Wet samples were placed individually into perforated mason jars (cap.936cc) containing 200g of 6-month mature compost. Closed jars were stored in a Lab-Line® L-C Incubator (Lab-Line Instruments, Inc., Melrose Park, IL) for 14 days at 58°C.

Periodically, jars were gently shaken to ensure uniform contact of samples with compost, and water was injected to maintain proper moisture content of the biomass. Samples were covered by the compost at all times to promote biological activity. At the end of the experiment, samples were removed from the jars, carefully washed, dried and weighted.

Weight loss, w, of each individual sample was determined using Equation (7), where W is the final weight and W_o is the initial weight.

$$w = \frac{W_o - W}{W_o} \times 100\% \tag{7}$$

RESULTS AND DISCUSSIONS

Steam Treatment of PLA

Table 1 shows impacts of steam treatment on PLA molecular weight. As expected, longer treatment times resulted in lower molecular weights. Additionally, brittleness increased with increasing treatments.

Steam-treated PLA Biodegradation in Compost

Figure 5 shows kinetics of steam-treated PLA biodegradation under composting conditions. On average, rates of biodegradation increased as steam treatment became more severe. These results confirm that a pre-composting treatment capable of reducing PLA molecular weight increases biodegradation rates in subsequent composting processes. This figure also suggests that both "head start" and "acceleration" effects contribute to overall enhanced biodegradation rates. As steam treatment increased, "head start" and "acceleration" effects also increased.

During experiments, oxygen concentration in the headspace was monitored and found to be at or above 18% at all times. Agitation permitted good aeration and mixing, and good agitation techniques were required to minimize clumping. Unfortunately, clumping occurred in jars containing PLA treated with steam for 3 hours at 120°C during the last days of composting. Clumping appeared to slow biodegradation during those last days.

According to standards, "biodegradabililty" requires 60% con-

Table 1. Molecular Weight of Steam-treated PLA.

Treatment	$M_w/M_{w,o}$ (%)
120°C x 1h	39.0
120°C x 2h	20.6
120°C x 3h	12.9
120°C x 4h	5.7

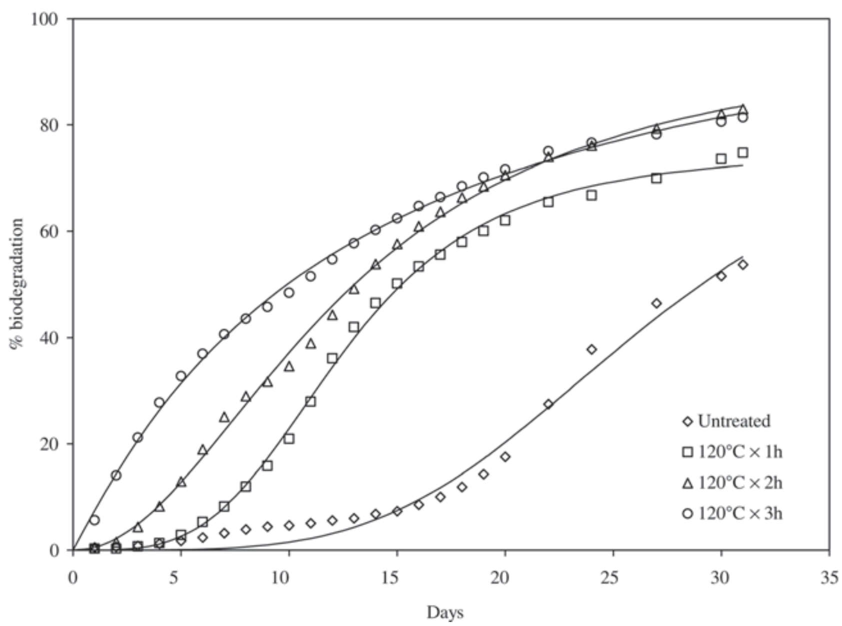

Figure 5. *Biodegradation of steam-treated PLA over time in compost.*

version. In this regard, samples treated at 120°C for 3, 2 and 1 hours reached biodegradability after 14, 16 and 19 days, respectively. Untreated samples did not achieve biodegradability even after 31 days. Even when total biodegradation was not yet achieved, PLA had apparently disappeared, and it could be said that breakdown was complete. However, continued production of CO_2 attributed to PLA material suggests the presence of PLA, probably as oligomers, and lactic acid.

It was also observed that more severe treatments (i.e. 120°C × 3h) did not create a lag period for adaptation or conditioning. In these samples, the rate of biodegradation was very high at the beginning of the experiment and then decreased over time. In contrast, PLA samples less severely treated (i.e. 120°C × 1h) showed a sigmoidal behavior, represented by a lag period, accelerating and decelerating stage.

Materials must fulfill three conditions to be compostable (De Wilde and Boelens, 1998) including (1) rapid breakdown, (2) not modify compost usability, and (3) it must physically disintegrate. Samples of steam-treated PLA appear to have fulfilled these conditions. The 31-days biomass, consisting of biodegraded treated PLA in compost, had similar appearance, texture and odor as compost without PLA. The pH of the final biomass (~6.6–6.8) did not change (Table 2). Pictures of the

Table 2. pH of Biomass (compost + biodegraded PLA).

Sample	pH
Compost	6.7
Untreated	6.6
1h @ 120°C	6.6
2h @ 120°C	6.6
3h @ 120°C	6.8

compost with and without treated PLA are shown in Figure 6. There was no apparent difference between the two compost samples, although plant growth yield tests, which were not done in this study, may provide a definitive indication.

Empirical Model for Steam-treated PLA Biodegradation in Compost

Nonlinear regression to fit experimental data to the logistic model was obtained using SigmaPlot v.10. Outputs are shown in Table 3. Parameters of the model are related with the pattern and magnitudes of the biodegradation curves.

Parameter *a* is the plateau, which is the maximum value of biodegradation that can be achieved. In all cases the value of *a* is close to 100, which is the theoretical plateau. The parameter *b* is associated with the lag period, so smaller values indicate shorter lag times. This matches experimental results, where more severe pretreatments resulted in lower values of *b* (for instance, steam-treated PLA at 120°C × 3h got

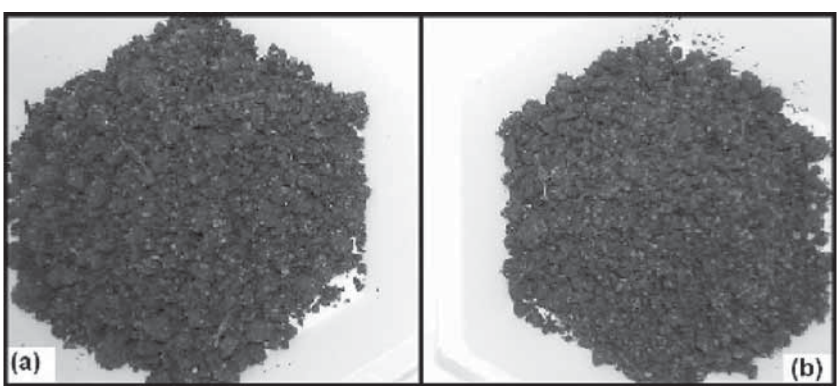

Figure 6. *Biodegraded PLA in compost: (a) compost by itself, (b) compost + PLA (not seen anymore).*

Table 3. Parameters of the logistic model (%biod = a / (1 + (t/x$_o$)$^{-b}$).

	Untreated	1h @ 120°C	2h @ 120°C	3h @ 120°C
a	84.01	75.15	96.91	113.8
b	4.103	3.612	2.04	1.05
x_o	26.45	12.57	12.61	12.49
R-square	0.9819	0.9981	0.9981	0.9981

the shortest value of *b*, and untreated PLA the highest). Finally, the parameter x_o is the time at which half of the biodegradation is completed. Thus, larger values of x_o indicate longer total times for biodegradation. Figure 5 shows that experimental data fit the model well.

Weight Loss of Steam-treated PLA in Compost and Comparison with Other Common Feedstock

Figure 7 shows results of weight loss of steam-treated PLA, wood and virgin corrugated paperboard in 6-month mature compost. Treated PLA samples were the only ones that broke apart inside the compost. Screened envelopes were designed to retain broken parts for further weighting. After 14 days, steam-treated PLA achieved weight losses of 94.9% (120°C × 4h) and 86.4% (120°C × 3h), whereas wood and cor-

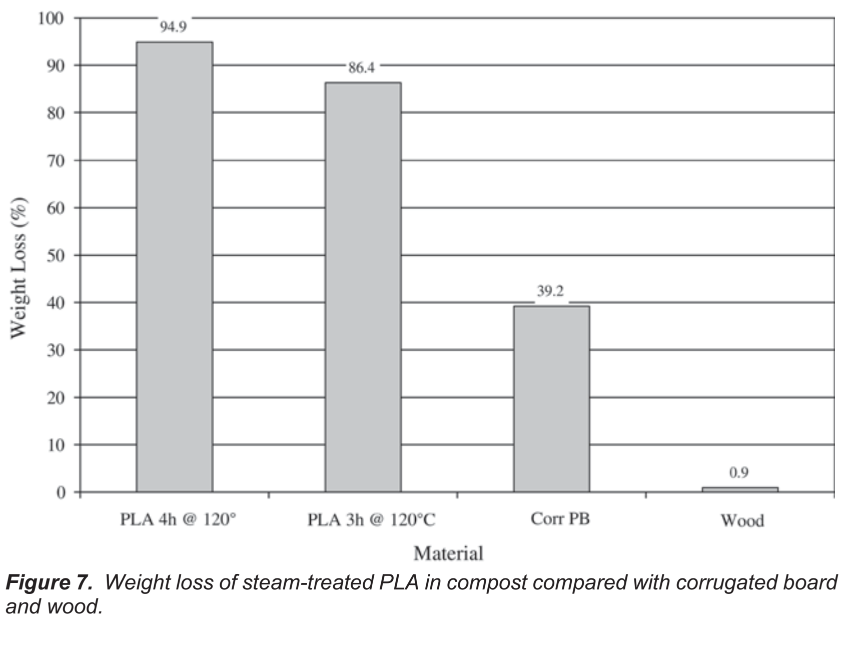

Figure 7. *Weight loss of steam-treated PLA in compost compared with corrugated board and wood.*

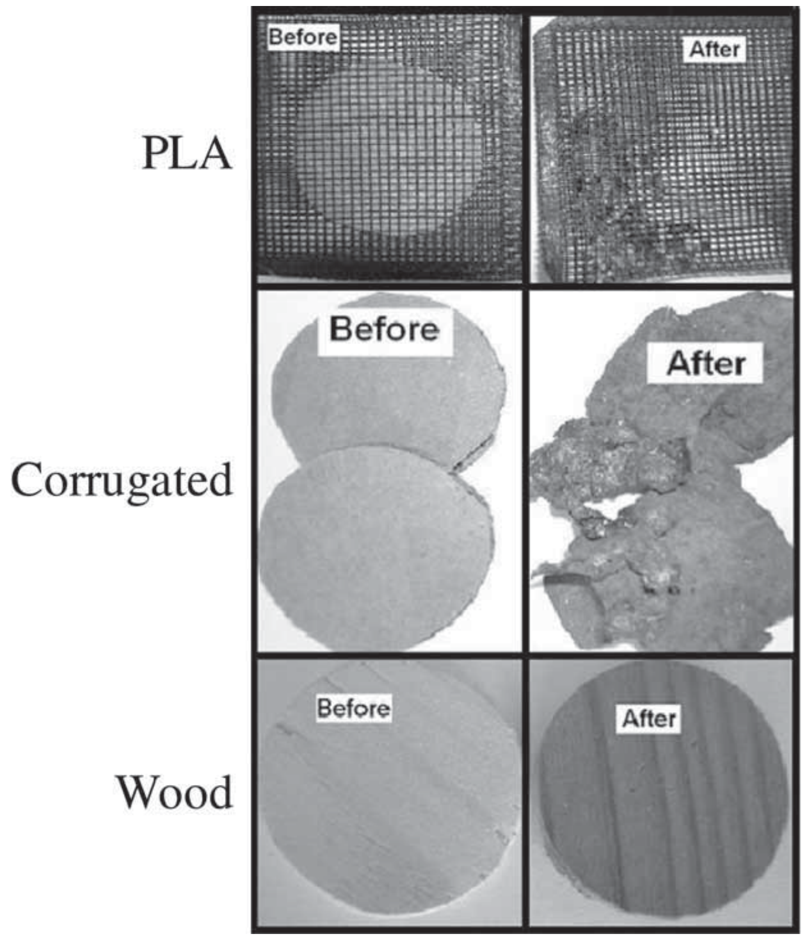

Figure 8. *Steam treated PLA (120°C x 3h), corrugated paperboard and wood subjected to compost for 14 days.*

rugated board achieved values of 0.9% and 39.2%, respectively. These results demonstrate that PLA subjected to steam (120°C × 3 and 4 h) breaks down much faster than wood and virgin corrugated paperboard, which are usually accepted in composting facilities. Figure 8 shows pictures of these samples, and it was observed that steam-treated PLA was most greatly affected.

CONCLUSION

It has been demonstrated that steam-treated PLA is affected significantly in compost, breaking down even faster than common organic feedstock universally accepted in composting facilities such as wood and virgin corrugated paperboard. Polylactic acid treated with steam at 120°C for 3, 2 and 1 hours, achieved degradability (60% of conversion to CO_2) after 14, 16 and 19 days, whereas untreated PLA did not achieve biodegradability even after 31 days.

Degradability was evidenced by complete PLA disappearance. Additionally, resulting compost did not appear to be affected by a loading of about 10% by weight PLA in compost.

Characteristics of the final compost when steam-treated PLA was initially present were similar than those of the compost by itself. PLA appeared to have met the three requirements for compostability including fast breakdown, total disintegration and no alteration.

Biodegradation kinetics of PLA fit very well using the proposed logistic model with three parameters, and provides valuable information for understanding biodegradation behavior. Determined parameters confirmed that pre-composting treatments that reduced PLA molecular weight provided "head start" and "acceleration" effects during subsequent composting process.

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Damage Evaluation of Nonlinear Packaging System with Critical Component

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ABSTRACT: The shock characteristics of nonlinear packaging system with critical component under the action of half-sine acceleration pulse were investigated. The dynamical model of the system was developed, and the numerical results of the dynamical equations were obtained. Then, to evaluate the damage potential of shock to critical component, a new concept of damage boundary surface was proposed, with the critical velocity line, the critical acceleration line and the frequency ratio of critical component to main body as the three basic coordinate parameters. Based on the results, the effect of the frequency ratio, the fragility in addition to the damping ratio on damage boundary of critical component was discussed. It's shown that all of their effects are noticeable. The strong frequency ratio dependence nature of the effect was found. By increasing the defined system parameter, the safe region of critical component can be broadened. Moreover, the damage boundary of critical component can effectively controlled by altering the damping ratio of the critical component and cushioning pad. The results lead to some insights into the design of cushioning packaging.

1.0 INTRODUCTION

The fatigue damage of products are usually caused by shock, to avoid damage during transportation, products are commonly cushioned to transport. The damage boundary concept introduced by Newton [1] (1968) has been widely utilized in packaging design. However, the basic assumptions of the theory, such as the SDOF assumption, may not always be true due to the complexity of products configuration and the diversity of cushioning materials. Researchers developed some modified versions of the concept. Burgess [2] (1988) suggested a FDB method to describe the effect of multiple shocks on damage of prod-

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ucts. Wang [3] (1998) introduced the concept of displacement damage boundary to reflect the fact that the deformation of cushioning materials is usually limited. Wang [4,5] (1999) investigated the shock characteristics of typical nonlinear packaging system, and obtained the SRS and DBC of them. Lu [6] (2007) developed the concept of bruising fragility and bruising boundary for fruits and other similar viscoelastic products. Few works [7] focuses on the problem of MDOF.

However, most products, especially those mechanical and electronic products, are composed of large numbers of elements, and the damage generally occurs firstly at the so-called critical component. It's more accurate to treat the critical component, the main body of product and the cushioning packaging as an intact system. Taking the nonlinear characteristics of most actual cushioning materials into account, and products are commonly cushioned by EPE, EPS, corrugated paperboard and so on, it's very important to obtain the dynamical characteristics of these kinds of cushioning packaging. In this paper, we will discuss the shock characteristics of nonlinear packaging system with critical component and its damage evaluation approach.

2. MODELING AND EQUATIONS

The packaging system consists of two masses connected by viscoelastic elements as shown in Figure 1. The rigid mass m_2 is assumed to represent the mass of the main body of the product, to which the mass of critical component m_1 is attached by a linear spring of stiffness k_1 and linear viscous damper c_1; k_2 and c_2 denote respectively the stiffness coefficient and the damping ratio of the cushioning pad; x_1, x_2, μ denote respectively the displacement of the critical component, the main body and the foundation.

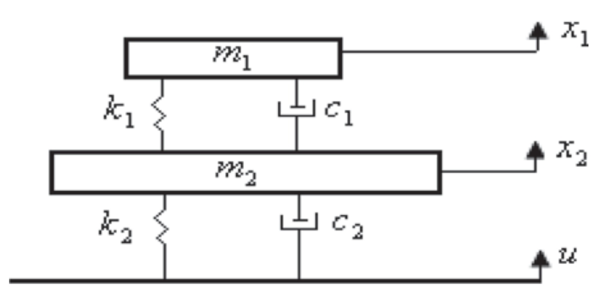

Figure 1. *The dynamical model of packaging system with critical component.*

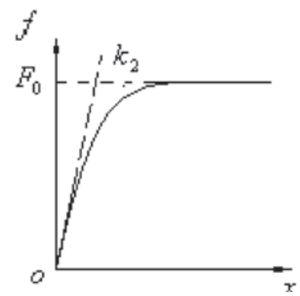

Figure 2. *Relationship for hyperbolic tangent cushioning materials.*

The motion of the system is governed by

$$m_1\ddot{x}_1 = k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) \tag{1a}$$

$$m_2\ddot{x}_2 = f(u - x_2) + c_2(\dot{u} - \dot{x}_2) - k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) \tag{1b}$$

where, $f(\bullet)$denoting the relationship between the restoring force and the deformation for hyperbolic tangent cushioning materials is shown in Figure 2. This relation can be described as:

$$f(x) = F_0 \text{th} \frac{k_2 x}{F_0} \tag{2}$$

where F_0 and k_2 denote respectively the limit value of the restoring force and the linear elastic coefficient of the cushioning materials.

The base excitation pulse $u''(t)$ is assumed to be a half-sine pulse which can be described as:

$$u'' = u''_{0m} \sin(\pi t / t_0)\Delta H(t, t_0)$$

where u''_{0m} and t_0 denote the pulse peak and pulse duration, respectively. By introducing: $\delta_1 = (x_2 - x_1)/L$, $\delta_2 = (u - x_2)/L$, $\tau = t/T$, where,

$$T = \sqrt{m_2 / k_2}, \quad L = F_0 / k_2$$

and,

$$\omega_1 (= \sqrt{k_1 / m_1}), \quad \omega_2 (= \sqrt{k_2 / m_2})$$

are defined respectively as frequency of the critical component and main body; while

$$\zeta_1 \left(= \frac{c_1}{2\sqrt{m_1 k_1}} \right) \text{ and } \zeta_2 \left(\frac{c_2}{2\sqrt{m_2 k_2}} \right)$$

and denote respectively damping ratio of the critical component and cushioning pad; λ_1 (= ω_1/ω_2) and λ_2 (= m_1/m_2) are defined as frequency ratio and mass ratio.

Substituting all of the parameters defined above into Equations (1a, 1b) and Equation (3) yields the dimensionless form of the motion equations:

$$\ddot{\delta}_1 = F(\delta_2) + 2\zeta_2\dot{\delta}_2 - (\lambda_2+1)\lambda_1^2\delta_1 - 2(\lambda_2+1)\lambda_1\zeta_1\dot{\delta}_1 \tag{4a}$$

$$\ddot{\delta}_2 = \ddot{U} + \lambda_2\lambda_1^2\delta_1 + 2\lambda_1\lambda_2\zeta_1\dot{\delta}_1 - F(\delta_2) - 2\zeta_2\dot{\delta}_2 \tag{4b}$$

$\ddot{U}$ denotes the dimensionless base excitation acceleration, which can be expressed as:

$$\ddot{U} = \beta u''_{0m}\sin(\pi\tau/\tau_0)\Delta H(\tau,\tau_0) \tag{5}$$

where $\beta = T^2/L = m_2/F_0$ was defined as the system parameter.

3. RESULTS AND DISCUSSIONS

By applying the *Runge-kutta* method, the numerical results of the dimensionless motion Equations (4a) and (4b) can be obtained. Based on the results, the effect of frequency ratio and mass ratio on the shock response of packaging system can be discussed, and then we can get the shock characteristics of the critical component.

3.1. Influencing Factors Analysis

When taking critical component into account, the frequency ratio (λ_1) and mass ratio (λ_2) may be two important influencing factors of the response of nonlinear packaging system. Figures 3(a) and 3(b) in turn depicts the calculated peak response acceleration of the critical component (α_1) as function of frequency ratio (λ_1) and mass ratio (λ_2).

The effect of frequency ratio on the shock response of critical component is noticeable as shown in Figure 3(a).With the rise of frequency ratio, the peak response acceleration of the critical component increases first and decreases afterwards at the same mass ratio, implying that there exists some sensitive frequency ratio [$\lambda_1 = 1$, in Figure 3(a)] which should be avoided when designing packaging. Another interesting phenomenon can be observed from Figure 3(a) is that the worst-case value of the maximum response acceleration of the critical component at the

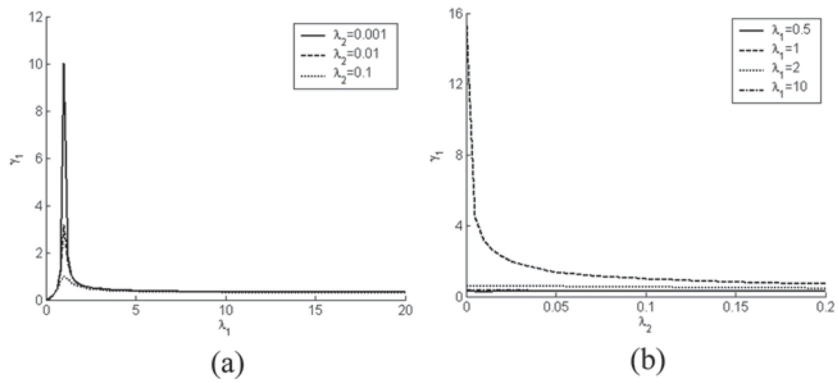

Figure 3. *Peak response of critical component (α_1) as a function of frequency ratio (λ_1) and mass ratio (λ_2): (a) Frequency ratio; (b) Mass ratio. Here* $\beta u''_{0m}$ *= 0.5,* τ_0 *= 0.5,* $\zeta_1 = 0$, $\zeta_2 = 0$, $\gamma_1 = \alpha_1/\beta u''_{0m}$ *.*

sensitive frequency ratio can be effectively lowered by increasing the mass ratio.

Figure 3(b) shows that the effect of mass ratio on shock response of the critical component may be significantly influenced by frequency ratio. As can be seen, the peak response acceleration falls greatly at a frequency ratio of 1, while it seems to be steady at other values of frequency ratio. That may be due to the smallness of the mass ratio.

3.2. Traditional Damage Boundary Curve

As shown in Figure 4, the traditional concept of damage boundary curve is applied here to nonlinear packaging system with critical component, with $V_1 = \beta u''_{0m}\tau_0/A_c$ denoting the critical velocity with

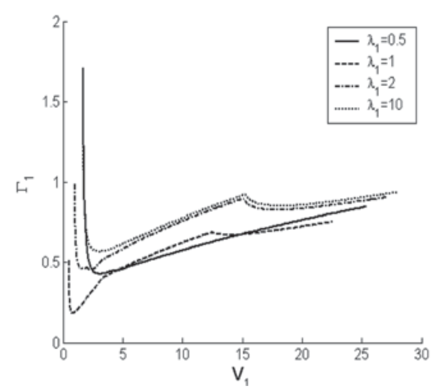

Figure 4. *DBC of Critical component at different frequency ratio (λ_1). Here* $\beta u''_{0m}$ *= 0.5,* λ_2 *= 0.1,* $\zeta_1 = 0$, $\zeta_2 = 0$.

$\Gamma_1 = \beta u''_{0m}\tau_0 / A_c$ being a denotation of the dimensionless critical acceleration, A_c is the fragility of critical component. As shown in Figure 4 and studied above, the frequency ratio is an important parameter influencing the safe region of critical component, which differs much with that of main body.

3.3. Damage Boundary Surface Concept (DBS)

When taking the critical component into account, traditional two-dimensional DBC concept should be expanded. To evaluate the shock characteristics of critical component, we suggest a damage boundary surface concept, which incorporates not only the critical velocity and the critical acceleration, but also frequency ratio (λ_1). Figure 5 shows the damage boundary surface of critical component at different dimensionless pulse peaks.

From Figure 5, we can see that the safe region of critical component at each frequency ratio increases with the rise of the dimensionless pulse peak, while existing concave at some coordinates (λ_1,V_1), imply-

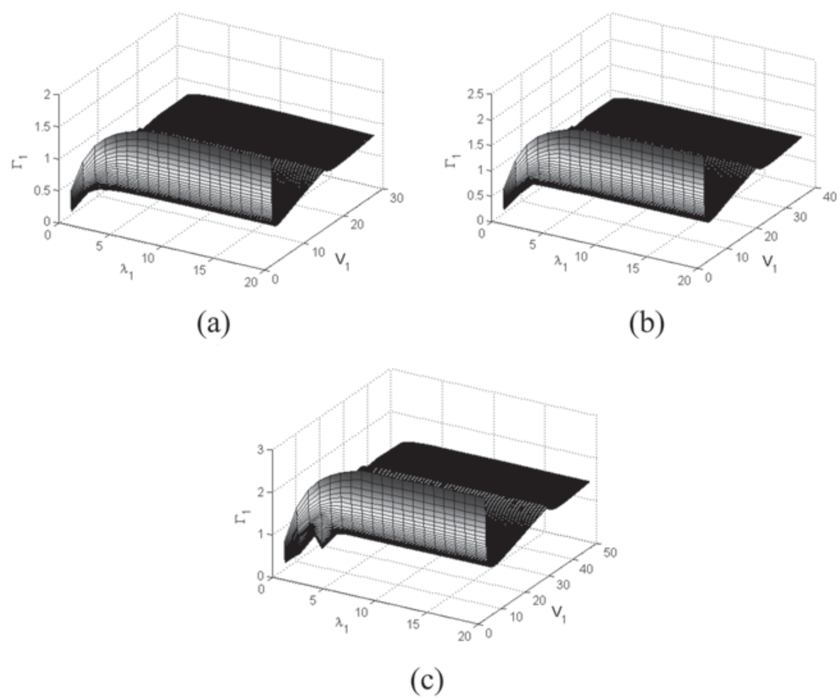

Figure 5. *DBS of critical component at different values of pulse peak ($\beta u''_{0m}$): (a) $\beta u''_{0m}$ = 0.5; (b) $\beta u''_{0m}$ = 1; (c) $\beta u''_{0m}$ = 1.5. Here λ_2 = 0.1, $\zeta_1 = 0$, $\zeta_2 = 0$.*

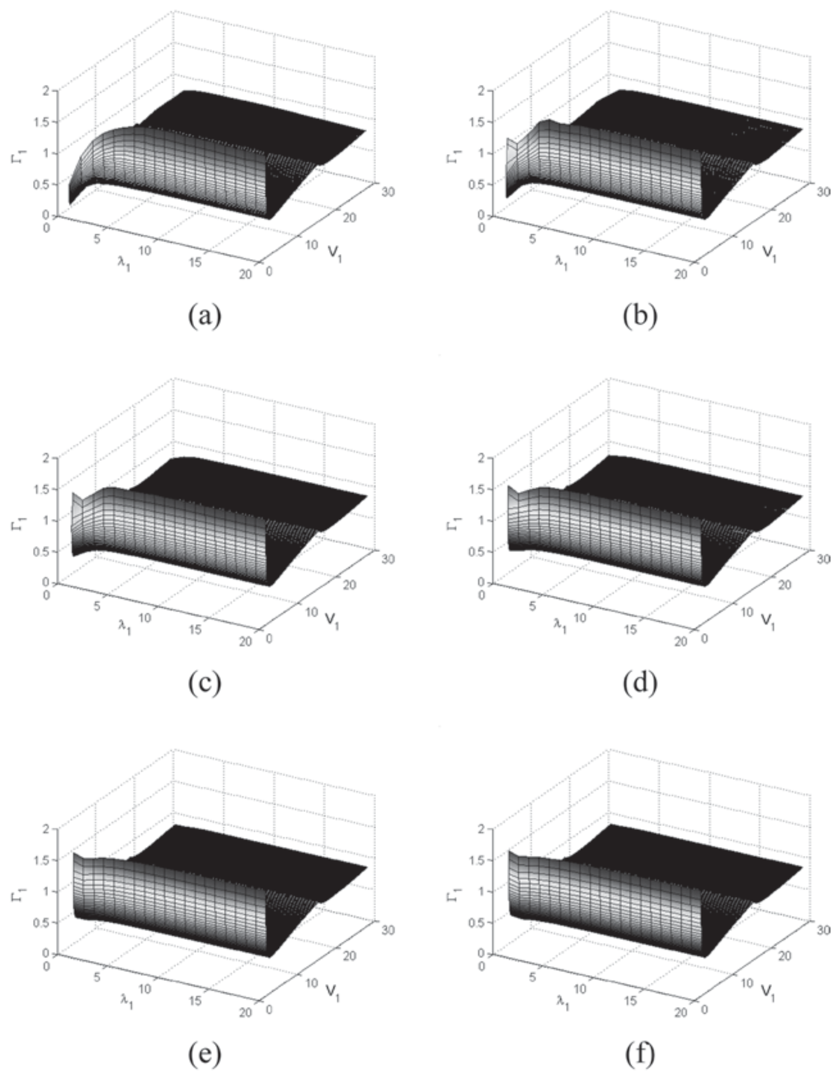

Figure 6. *Effect of damping ratio of critical component (ζ_1) on DBS of critical component: (a) ζ_1 = 0, (b) ζ_1 = 0.1, (c) ζ_1 = 0.3, (d) ζ_1 = 0.5, (e) ζ_1 = 0.8, (f) ζ_1 = 1. Here, λ_1 = 0.1, $\zeta_2 = 0$.*

ing the strong frequency ratio dependence nature of the shock response of critical component. Taking the relationship among $\beta u''_{0m}$,the defined system parameter (β) and the pulse peak (u''_{0m}) into account, the safe region of the critical component can be effectively broadened by increasing the system parameter. This phenomenon may be probably explained by the fact that the peak of $\ddot{x}_{2m}$ approaches F_0/m_2 by increasing when neglecting $\beta u''_{0m}$ the effect of critical component[5].

3.4. Effect of Damping Ratio of Critical Component on DBS

The effect of damping ratio of critical component (ζ_1) on DBS of critical component is shown in Figure 6. With the rise of the damping ratio of critical component, the concave of DBS of critical component can be effectively eliminated, and safe region of critical component can be broadened at low frequency ratio ($\lambda_1 < 4$ in Figure 6), while the case of higher frequency ratio ($\lambda_1 \geq 4$ in Figure 6) may not be so noticeable.

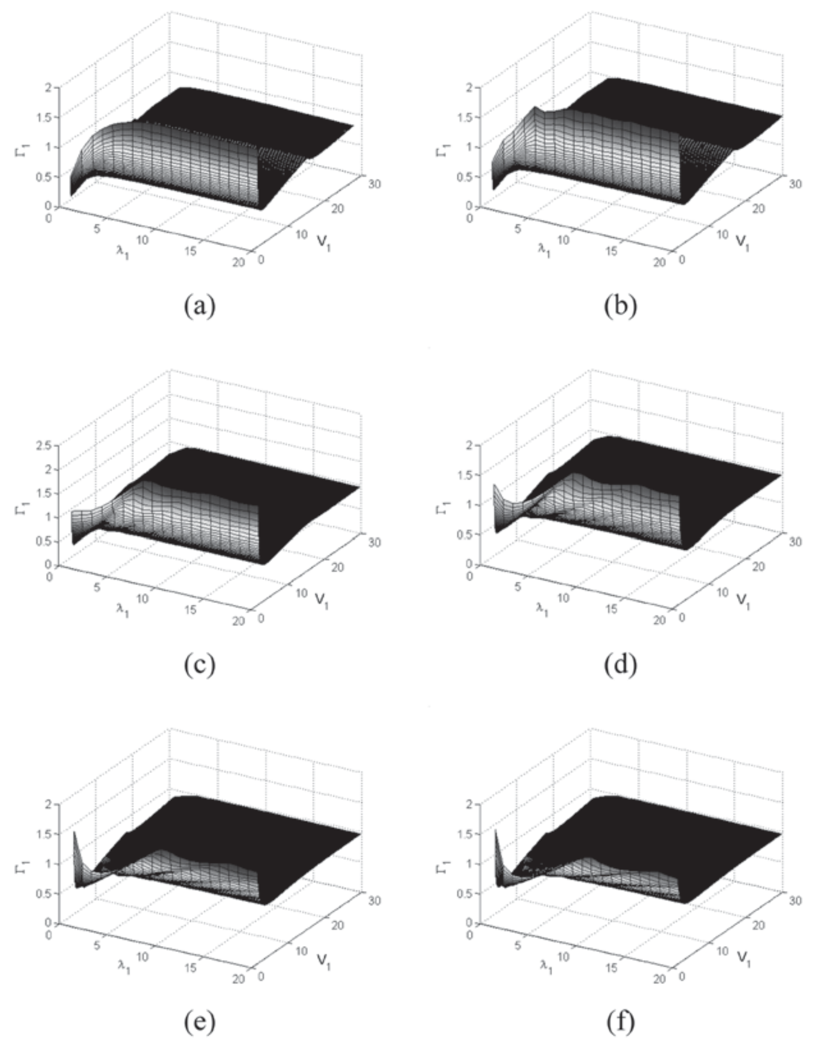

Figure 7. *Effect of damping ratio of cushioning pad (ζ_2) on DBS of critical component t: (a) $\zeta_2 = 0$, (b) $\zeta_2 = 0.1$, (c) $\zeta_2 = 0.3$, (d) $\zeta_2 = 0.5$, (e) $\zeta_2 = 0.8$, (f) $\zeta_2 = 1$. Here, $\lambda_2 = 0.1$, $\zeta_1 = 0$.*

3.5. Effect of Damping Ratio of Cushion on DBS

Figure 7 depicts the DBS of the system at different values of the damping ratio of cushioning pad (ζ_2). The concave of DBS of critical component can be effectively eliminated by increasing the damping ratio of cushioning pad. And the safe region of critical component can be effectively broadened by increasing the damping ratio of pad when frequency ratio is low ($\lambda_1 \leq 1$ in Figure 7), while the critical velocity line falls with rise of the critical acceleration line at high frequency ratio ($\lambda_1 > 1$ in Figure 7).

4. CONCLUSIONS

It's more accurate to model the packaging system as a nonlinear system of double degree of freedom, since the damage of many products occurs firstly at the critical component and the nonlinear characteristics of many cushioning materials should be considered. This paper discussed the influencing factors of hyperbolic tangent packaging system, and the strong dependence nature of the shock characteristics of critical component on frequency ratio is found. The damage boundary surface (DBS) concept was proposed to describe the damage potential of shock to the critical component, taking the effect of frequency ratio into count. The effect of system parameter, damping ratio of critical component and damping ratio of cushioning pad on the DBS of critical component are all found to be noticeable. And the damping ratio of critical component and cushioning pad are found to cooperate with the frequency ratio when affecting the shock response and damage boundary of the critical component. When designing a cushioning packaging for a product with known mass ratio (λ_2) and frequency parameter (ω_1), we can weaken the shock response of critical component by altering the frequency ratio and damping ratio of cushioning pad.

5. ACKNOWLEDGMENT

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Table 5. Comparison of state-of-the-art matrix resins with VPSP/BMI copolymers.

Resin System	Core Temp. (DSC peak)	Char Yield, %
Epoxy (MY720)	235	30
C379: H795 = 14	285	53

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