

Comparison of the Different Hazards Experienced by Pallets During Material Handling

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Forest Products

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December 15th, 2022
Blacksburg, VA

Keywords: Shock, Forklift, Pallet, Material Handling, Sensors, Vibration

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ABSTRACT

Pallets play a crucial role in the supply chain with approximately 2.6 billion in circulation in the United States alone. Although often overlooked, pallets can become costly for a company if not designed correctly for their specific supply chain. Durability is an essential characteristic of pallets; it defines the expected life of the pallet in the supply chain.

Forklifts are the dominant mode of material handling for palletized products, and they are responsible for the majority of damages experienced by pallets. Despite the prominence of forklifts in the supply chain and their importance in pallet design, there is a lack of research focusing on the dynamic nature of forklifts in the field.

The objective of this research paper was to investigate the intensity of the vibrations and shock impacts that forklifts exert during material handling. Forklifts in multiple facilities were instrumented with Lansmont SAVER 3X90 and 3D15 data loggers to measure the acceleration peak, g of shock impacts, duration of impacts, random vibration intensity and RMS (g) values during forklift handling in the field. The highest vibration levels were observed for distribution facilities with an average acceleration (peak, g) of 0.353 g. Based on the results of the vibration data collection, the vibration profile for laboratory simulation was proposed.

The results of the shock measurement showed that LTL facilities recorded the highest average shock impact of all the facilities investigated, with an average acceleration value of 4.74 g with an average shock duration of 7.42 msec. The intensity of shock events measured during the FasTrack procedure was slightly greater than what was observed for the LTL facility indicating that the FasTrack simulation is slightly harsher than the field handling of pallets. Based on the results of the shock measurement, new intensity levels were recommended for the incline impact test to better represent the harshness of handling in the field.

The results of this study will be used to revise the durability testing procedures used in pallet testing standards in order to better represent the current material handling processes found in modern supply chains.

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GENERAL AUDIENCE ABSTRACT

With 2.6 billion pallets in circulation within the United States alone, pallets play a significant role in the supply chain. Pallets can become costly for a company if not designed correctly for their specific supply chain, so it is important not to overlook a pallet. Durability is an essential characteristic of pallets; it defines the expected life of the pallet in the supply chain.

The forklift is the most common mode of material handling for the transportation of palletized products within a warehousing system, and they are responsible for the majority of damages experienced by pallets. Despite the prominence of forklifts in the supply chain and their importance in pallet design, there is a lack of research focusing on the dynamic shock and vibration characteristics that forklifts experience in the field.

The objective of this research paper was to investigate the intensity of the vibrations and shock impacts that forklifts exert on pallets during material handling. Forklifts in multiple facilities were instrumented with Lansmont data loggers to measure the dynamic characteristics of both shock and vibration in the field. The highest vibration levels were observed for distribution facilities. Based on the results of the vibration data collection, a vibration profile for laboratory simulation was proposed.

The results of the shock measurement showed that Less-than-Truckload (LTL) facilities recorded the highest average shock impact of all the facilities investigated. The intensity of shock events measured during the FasTrack procedure was slightly greater than what was observed for the LTL facility indicating that the FasTrack simulation is slightly harsher than the field handling of pallets. Based on the results of the shock measurement, new intensity levels were recommended for the incline impact test to better represent the harshness of handling in the field.

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Table of Contents

1	Literature Review.....	1
1.1	<i>Pallets.....</i>	1
1.1.1	Introduction to Pallets	1
1.1.2	Pallet Industry	1
1.1.3	History of Pallets	2
1.1.4	Pallet Classifications	3
1.1.5	Pallet Materials	7
1.1.6	Pallet Durability	11
1.2	<i>Supply Chain Introduction.....</i>	22
1.2.1	Warehousing	23
1.2.2	Storage	23
1.2.3	Material Handling.....	24
1.3	<i>References.....</i>	26
2	Measurement of the Vertical Vibration Experienced by Forklifts During Material Handling	29
2.1	<i>Introduction.....</i>	29
2.2	<i>Objective</i>	30
2.3	<i>Materials and Methods.....</i>	30
2.3.1	Facilities	30
2.3.2	Forklifts.....	31
2.3.3	Floor Characteristics.....	31
2.3.4	Load Characteristics	31
2.3.5	Sensor Setup & Settings	31
2.3.6	Statistical Methods.....	32
2.4	<i>Results and Discussion</i>	33
2.4.1	Peak Acceleration (g, peak).....	33
2.4.2	RMS (g)	34
2.4.3	Probability Density Characteristic with Kurtosis Value.....	35
2.4.4	Vibration Intensity (Power Spectral Density, PSD)	36
2.5	<i>Conclusions.....</i>	38
2.6	<i>References.....</i>	40
3.	Measurement	42
3.1	<i>Introduction.....</i>	42
3.2	<i>Objectives.....</i>	44
3.3	<i>Methodology.....</i>	44
3.3.1	Warehouses	44
3.3.2	FasTrack Simulation	44
3.3.3	Forklifts.....	45
3.3.4	Sensors	46
3.3.5	Shock Data Measurement on the Forklift	46

3.3.6	Incline Impact Shock Testing.....	48
3.4	<i>Results and Discussion</i>	49
3.4.1	Field Data Results	49
3.4.2	Incline Impact Tests.....	54
3.5	<i>Conclusions</i>	57
3.6	<i>References</i>	59

1 Literature Review

1.1 Pallets

1.1.1 Introduction to Pallets

A pallet is a flat structure used as a base for the transportation of goods within the supply chain (LeBlanc, 2020). A pallet's primary use is to provide a solid base to standardize the shipment of unit loads from one location to another while also improving the efficiency of storage. Pallets have differentiating classifications based on the intended use of the pallet during the product material handling phase (See Section 1.1.3). Depending on the company's use of pallet jacks and forklifts, as well as the size and weight of their unit loads, the pallet designer must determine which pallet will be best suited for their intended applications.

1.1.2 Pallet Industry

Pallets are ubiquitous in the supply chain with over 2.6 billion (Freedonia, 2015) pallets in circulation in the United States. Although pallets can be made of different materials, pallets made of wood dominate the market with a 95% market share (McCrea, 2022). In 2016, 839 million wooden pallets were produced which included 513 million new pallets and 326 million repaired pallets (Gerber et al., 2020). This output represents an overall 14% increase (22% increase for new pallets and 5% for recycled) compared to 2011 results (Gerber et al., 2020). Wood pallets consumed 21.8% of new lumber used in the United States in 2016, which translated to 9.16 billion board feet of lumber (Madison's Lumber Reporter, 2017). However, millions of pallets end up in landfills each year, with 25.39 million in 2016 alone. Nearly 41 million pallets each year are recycled. This has gone up recently indicating increased efforts put forward by landfills to recover wooden pallets (Shiner et al., 2021). Since the pallet industry uses such a high volume of wood, it is important to look at the historical data available in regard to wood usage as this will give a sense of the overall state of the pallet industry (Gerber et al., 2020). This increase in the use of pallets worldwide demonstrates the effectiveness and acceptance of pallets in different industry applications.

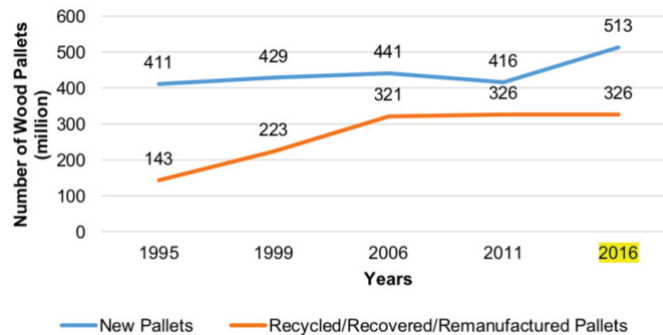


Figure 1.1: Estimation of Wooden Pallet Production (Gerber et al., 2020).

Due to the increased use of pallets, standardization was implemented. The American National Standard Institute helped to develop a list of set standards for pallets named “Material Handling 1: Pallets, Slip Sheets, and Other Bases for Unit Loads” (MH1 Committee, 2021). The standards were formed in order to give a clear definition for the terminology and nomenclature used in the world of pallets (MH1 Committee, 2021). Standardization has been an instrumental part in the growth of the pallet industry as it has created reliability amongst the main pallet manufacturers and consumers. However, pallets serve as a multipurpose product. Depending on each industry that uses it, it is very likely for sizes to vary depending on the intended purpose. In 2016, Gerber found 39% of pallets were non-standard sizes (Gerber et al., 2020).

Year	48”x40”	40”x48”	48”x48”	48”x45”	48”x42”	48”x36”	42”x42”	37”x37”	800x1200 mm	Other
2006	27%	5%	4%	2%	4%	2%	5%	2%	---	50%
2011	24%	3%	4%	---	---	2%	5%	2%	1%	60%
2016	35%	4%	7%	5%	3%	1%	5%	<1%	1%	39%

Table 1.1: Pallet Usage Based on Size (Gerber et al., 2020).

1.1.3 History of Pallets

When the lift truck was invented in 1887, it was one of the most important aspects of the evolution of material handling. However, it wasn’t until 1915 that the first high-lift fork truck was developed, which would inevitably become useful to the pallet industry (LeBlanc, 2002). While

there have been other forms of material handling equipment prior to the pallet, the combination of the pallet and forklift has had the most impactful effect on the evolution of material handling (LeBlanc, 2002). Pallets were first patented in 1932 by George Raymond and Bill House (Raymond, 2007). Pallets have been a fundamental aspect of modern commerce and material handling since the 1940s (LeBlanc, 2002). The need for handling large volumes of materials, during and after World War II for both transportation and storage, brought to the forefront the need for a palletized world, leading to the importance of the pallet industry that we know today (Leblanc,2019).

1.1.4 Pallet Classifications

1.1.4.1 Stringers

The most common class of pallets is the stringer pallet with a 79% market share (Gerber et al., 2020). Its popularity can be attributable to its lower cost in relation to a block pallet (Clarke, 2004). Stringer pallets have many main identifying parts. Stringer pallets contain a minimum of two stringers, multiple deckboards, and fasteners that hold all of the components together (Park, 2018). Stringers are wooden boards that run down the sides of the pallet, parallel to the length of the pallet, meaning that the length of the pallet is always defined by the length of the stringer itself. Stringers are typically made of nominal 2 in. x 4 in. lumber that may contain notches to allow forklift entry from the side. Deckboards run across the top and bottom decks perpendicular to the length, providing a platform for unit loads to rest upon, and they have typical widths of 3.5 in. or 5.5 in.. The thickness of the deckboards may vary depending on the weight to be applied to the decks.

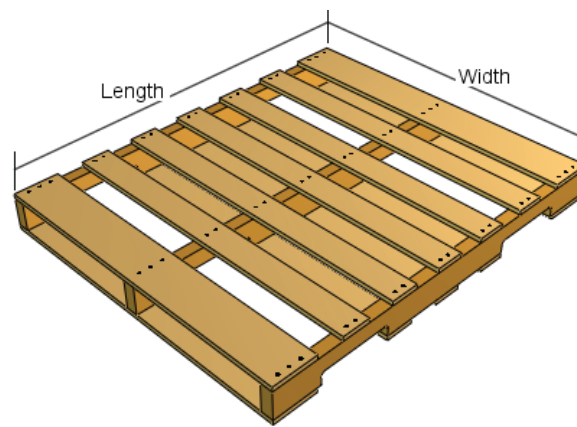


Figure 1.2: Typical Stringer Pallet (Published with permission from White and Company).

1.1.4.2 Block Pallets

Block pallets are less common than stringer pallets in the United States with only 21% of the market share (Gerber et al., 2020). Nine blocks are commonly used in a block pallet, with three columns of three blocks parallel to each other. The top deckboards are attached to three stringer boards that run parallel to the pallet length. Blocks are then connected to the bottoms of the stringer boards, then the bottom deckboards connected directly to the bottom of the blocks. The National Wooden Pallet and Container Association (NWPCA) defines a block as a rectangular, square, multisided, or cylindrical deck spacer. Each blocks name is associated with its positioning on the pallet (i.e., corner block, edge block, etc.) (NWPCA, 2014). The use of blocks replaces the need for traditional stringers in the pallet as the nine blocks allow for the unit load to evenly distribute its weight along the pallet and allow for four-way entry.

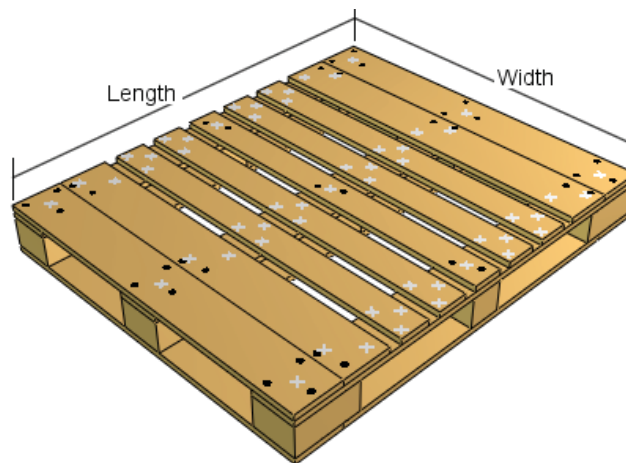


Figure 1.3: Typical Block Pallet (Published with permission from White and Company).

1.1.4.3 Use Categories

Pallets have different use categories depending on their intended purpose. The first use category is a reusable pallet. ANSI defines a reusable pallet as a pallet that is intended for more than one unit load application (MH1 Committee, 2019). A reusable pallet is generally more expensive. This is because they are typically reusable pallets made upon request with higher quality materials to allow the pallet to be used for numerous trips. However, reusable pallets,

despite the higher initial cost, may be beneficial in the long run as their “per trip” price tag could be cheaper than that of a single-use pallet (LeBlanc, 2020). The second use category of pallets is the single-use pallet. ANSI defines a single-use pallet as a pallet intended only to be loaded once for one trip (MH1 Committee, 2019). These pallets are initially cheaper as they are either repaired, refurbished, or made of thinner, lower-quality components. Although single-use pallets have lower initial costs, they could have a more expensive “per trip” price tag since they are only designed for one trip; thus, the price you pay for the pallet is the price you pay for the trip.

1.1.4.4 Entry Types

Entry types are a very important aspect of pallet selection. The three types of pallet entry are two-way, partial four-way, and full four-way. A two-way type is a pallet with openings on opposite ends of the length; thus, they are only accessible from those two sides via material handling equipment (MH1 Committee, 2019). A partial four-way pallet is a pallet that has openings on all four sides. However, the openings perpendicular to the length (notches) only have enough space to fit a fork tine, not a pallet jack. This gives the partial four-way its name as it is only accessible from all four sides by forklifts (MH1 Committee, 2019). The final entry type for pallets is a full four-way which has openings on every end, allowing for entry from every side of the pallet with both pallet jacks and fork tines. Block pallets are an example of a full four-way pallet (MH1 Committee, 2019).

1.1.4.5 Pallet Styles

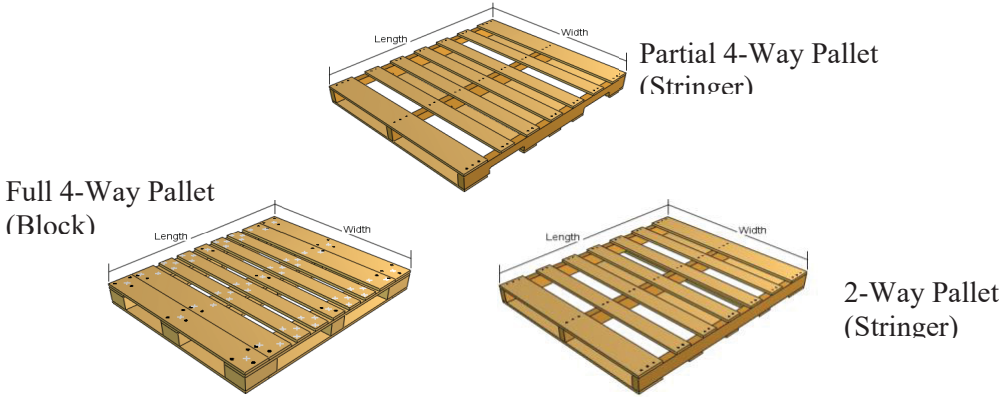


Figure 1.4: Examples of Pallets with Different Entry Types (Published with permission from White and Company).

Pallets consist of different styles as well. These styles include single face (skid), double-face non-reversible, and double-face reversible pallets (MH1 Committee, 2019). Single face pallets consist of top deckboards with stringers or blocks and no bottom deckboards. Double-face, non-reversible pallets have both top and bottom deckboards; however, the top and bottom deckboards differ in their structures. Top and bottom deckboards typically differ when it comes to the smaller number of bottom deckboards in comparison to the top deckboards. Fewer deckboards are used on the bottom of the pallet to accommodate the use of pallet jacks the wheels of which need extra openings to touch the floor, however, pallet characteristics for top and bottom deckboards vary depending on the intended use of the pallet. This creates a differentiation between the top and bottom of the pallet. Double face reversible pallets have both top and bottom deckboards that are identical in structure. This allows for the pallet to be put on either face without sacrificing the structural integrity of the pallet.

1.1.4.6 Top and Bottom Deck Structure

The structure of both the top and bottom decks play a significant role in the overall strength and durability of the pallet. Top and bottom deck styles typically vary depending on the consumer's needs for material handling.

Pallet top deck structure can be made of a varying number of deckboards or made of a solid panel that is commonly made of OSB or plywood. Depending on the size and shape of the unit load intended to be used on the pallet, a pallet manufacturer may add or remove deckboards to ensure that the weight of the load is evenly distributed. Panel decking covers the entire top surface of the pallet. This creates more uniform weight distribution and eliminates deckboard gaps that can weaken corrugated boxes (Baker et al., 2016).

Bottom decks have three typical configurations: unidirectional, perimeter base, and cruciform. For the unidirectional base design, all deckboards are parallel with each other and face one direction. Due to their design, all stringer pallets have unidirectional bottom deckboards (Morrissette et al., 2021). Unidirectional block pallets are not very common in the US, other than in the grocery industry. Perimeter base pallets have bottom deckboards running both the length and the width of the pallet. The bottom deckboards are “butted” together, with no overlap. Cruciform pallets have an equal number of bottom deckboards running parallel to the length and

the width creating a cross-like structure on the bottom of the pallet. This design is more common for plastic pallets. Flush pallets are another classification of pallet when the top and bottom deckboards are even with the stringers. When the top deckboards of the pallet are not flush to the stringers and overhang, this is known as a single-wing pallet. When both the top and bottom deckboards are non-flush and overhand the stringers, thus is known as a double-winged pallet.

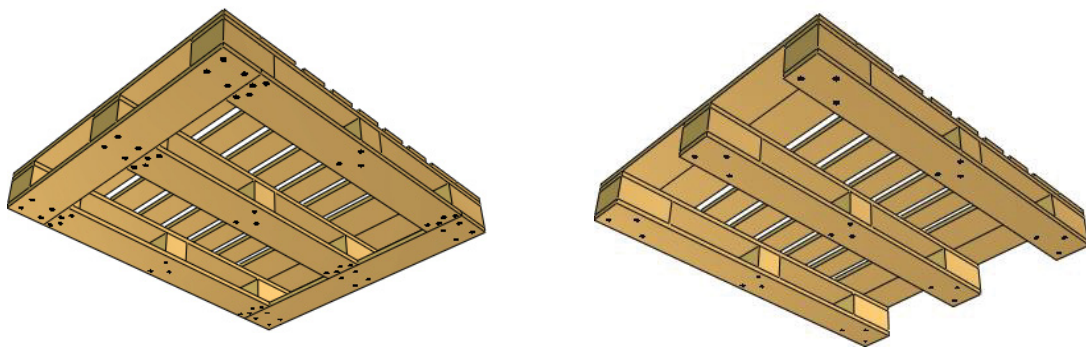


Figure 1.5: Examples of Perimeter Base (a) and Unidirectional Base (b) Pallet Designs (retrieved from Best Pallet).

1.1.5 Pallet Materials

There are several different material categories that can be used to manufacture pallets. Pallet materials will vary based on the intended use of a pallet. Properties such as purchase price, strength, durability, and reusability are, respectively, among the most important aspects of material selection (McCrea, 2016). Pallet designers must prioritize their pallets most applicable properties in order to choose the correct material for its application.

1.1.5.1 Solid Wood

Wooden pallets are the most popular pallet used, with 93 of companies reporting the use of wooden pallets (McCrea, 2020). Some of the main reasons for the popularity of wooden pallets include low purchase price, strength to weight ratio, and reparability. Wooden pallets are easy to manufacture allowing for easy implementations of desired designs. Wooden pallets can be repaired. Broken parts can be easily repaired or replaced to further the lifespan of the pallet.

Although wood pallets have many advantages, they also have several disadvantages, such as fastener withdrawal and splintering which may cause injury or damage to either products or operators (Gerber et al., 2020). Wooden pallets are further broken down into two main categories: hardwood and softwood. The use of hardwood or softwood pallets is completely dependent on lumber availability in the region. While softwoods are the dominant species on the west coast, hardwoods dominate the east coast (Figure 7) (Gerber et al., 2018). Hardwood lumber used in 2016 for pallets totaled about 4.13 billion board feet or 45% of wood used in pallet production and 5.03 billion board feet of softwood lumber was used in pallet production making up the other 55% (Gerber et. al., 2018).

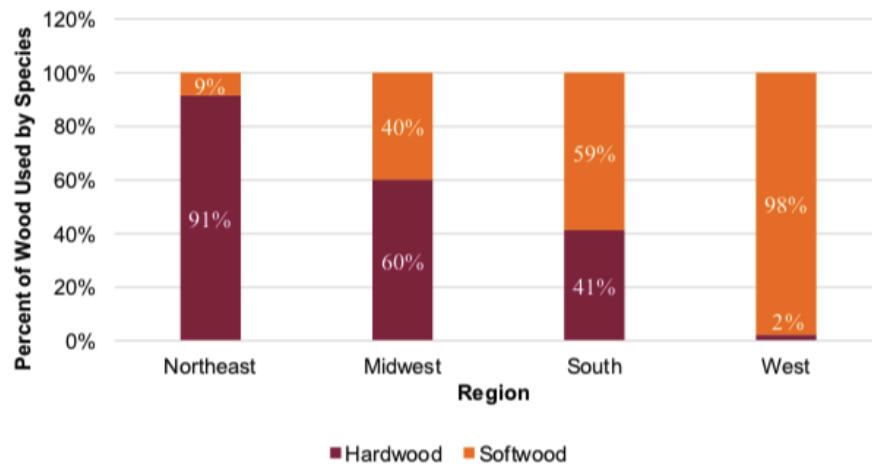


Figure 1.6: Percent of Wood Used by Species (Gerber et al, 2018)

1.1.5.2 Plastic

Plastic pallets were first introduced to the material handling industry in the early 1960s. Mainstream production started in the late 1960s to early 1970s (Leblanc, 2019). Plastic pallets are used by 37% of pallet consumers (MCCREA, 2020). In 2020, only 16% of companies surveyed said they planned on renting pallets from a recovery provider (MCCREA, 2020). It was found that of those manufacturers who were surveyed, they reported around 66% of their plastic pallets came from virgin resin, whereas only 34% came from recycled resins (Bugledits, 2019). Plastic pallets are made from many different types of plastics, but the two most common types of plastic used for pallets are high-density polyethylene (HDPE) and polypropylene (PP) (Bugledits, 2019). Between these two types of plastics, the Fredonia report estimated demand for plastic pellets for pallet

manufacturing will reach 124 million pounds by 2024 (Freedonia, 2015). It was estimated that around 84.5% of those plastic pellets were HDPE, while the remaining plastic types were miscellaneous. Plastic pallets are made with a variety of manufacturing processes including injection molding, structural foam molding, profile extrusion, rotational molding, compression molding, and thermoforming (MH1 Committee, 2019).

Higher performance plastic pallets are usually injection molded. High pressure injection molding uses virgin plastic that is melted down in a barrel before being injected into a mold. The mold is sealed together with large amounts of pressure before being injected (Kiefer, 2019). At the time of injection, the cylinder that will inject the plastic into the mold will be heated up allowing the plastic to melt and be poured into the mold to cool and solidify. This form of plastic pallet manufacturing has the highest production time in comparison to any other molding method (Kiefer, 2019).

Structural foam molding may also be used in the process of manufacturing plastic pallets. This process is a cheaper alternative to injection molded pallets, and it allows for high load capacity as well. During the injection molding process, a liquid resin is injected with a chemical blowing agent in order to expand the liquid resin into the molding cavity.

Rotational molding involves the process of pouring plastic resins into a mold that is heated and rotated simultaneously. This allows the resins to adhere to the inner surface of the mold in order create uniform thickness and seamless parts which may result in a higher quality pallet than other alternatives (CEC, 2015).

Compression molding is the process of molding plastic into an open, heated cavity. Once the plastic is placed into the cavity, compressive forces are added to the mold at about 800 psi to 2000 psi. (Tranpak, 2019). After the mold is compressed, the parts are removed from the cavities in order to be placed together.

Thermoforming is the process of taking thin plastic sheets and heating them to create high material manipulation properties, which is then laid over a cast in order to form. Once the plastic cools, the parts are able to be removed and put together. Thermoforming can be further broken down into two types. One uses compression forces and the other uses vacuum forces. This type of plastic pallet manufacturing results in a high-quality pallet.

Plastic pallets, like wooden pallets, have both advantages and disadvantages associated with them. Plastic provides insect and mold free pallets, unlike wooden pallets in which are not

always mold and insect free. This is beneficial to industries that need to maintain hygienic conditions, such as the grocery industry. Plastic pallets are also weather resistant, making them a good option for outside storage. Disadvantages of plastic pallets include purchase price, inability to repair, and low friction. Plastic pallets may range from as low as \$10.00 per pallet for expendable plastic pallets, and upwards of \$80.00 to \$100.00 for high-quality plastic pallets. (LeBlanc, 2019) Due to the nature of manufacturing plastic pallets, they are not able to be repaired. Most plastic pallets come as one solid unit, rather than having multiple components like wooden pallets, which inhibits the ability for repairs. The low friction of plastic pallets allows for slipping which, in many industries, may cause damage to a product or unit load shifting, resulting in potential safety hazards.

1.1.5.3 Wood Composites

There is a 12% usage of wood composite pallets amongst companies (MCCREA,2020). Wood composite pallets consist of different forms, such as: oriented strand board (OSB), particleboard, and laminated veneer lumber (LVL), which consist of 2-4% of the global market (Li, 2018). Wood composites consist of wood flakes, wafers, or particles that are then molded together with the use of adhesives (MH1 Committee, 2019). Due to wood composites use of variable wood species, it increases the overall homogeneity of the pallet, which is one of the main problems faced with solid wood pallets (Li et al., 2018). Composite pallets are typically more expensive than solid wood pallets as the manufacturing process is more extensive. Composite pallets, however, are usually cheaper than metal or plastic pallets (Li et al., 2018). Composite pallets have numerous advantages such as being insect free, having a smooth deck surface, and providing good durability. Composites become less beneficial in terms of its splintering, fasteners, and low recyclability.

1.1.5.4 Metal Pallets

Metal pallets have a 6% usage rate amongst companies surveyed (MCCREA, 2020). Metal pallets, however, only consist of under 1% of the total market share for pallets (Freedonia, 2017). Aluminum is one of the most common materials used in the construction of metal pallets due to

its high strength to weight ratio in comparison to other metal materials. In addition to aluminum pallets, carbon steel and stainless steel may also be used. Carbon steel has the lowest cost in comparison to aluminum and stainless steel, which may cost up to 2-3 times more than a standard wooden pallet (Clarke, 2004). Metal pallets have many useful advantages such as durability, stiffness, sanitation, and recyclability (Clarke, 2004). Although considered a very high-quality pallet, metal pallets also have disadvantages. Some of these disadvantages include rusting, a high purchase price, and a high weight. Metal pallets typically have specific intended uses such as pharmaceutical, due to its high sanitation levels, and automotive industries, due to its impressively high strength characteristics (Clarke, 2004).

1.1.5.5 Paper Based

Paper-based pallets hold less than 4% of the total market share for pallets (MCCREA, 2020). Paper-based pallets come in different forms such as corrugated, honeycomb, solid fiberboard, and molded pulp (LeBlanc, 2017). Paper-based pallets are very lightweight, reducing costs for industries that are trying to reduce air-freight shipping costs. In addition to the advantage of being a lightweight option for pallets, paper-based pallets are highly recyclable which is very sought after in today's pallet industry. Due to the nature of paper-based pallets, they are greatly affected by weather conditions such as moisture. Moisture increases to paper-based pallets dramatically reduce the strength of the pallet. In addition to its susceptibility to moisture, major disadvantages include low stiffness and low durability.

1.1.6 Pallet Durability

1.1.6.1 PEP Study

Due to the overwhelming exchange of pallets between major pallet consumers, a basis was needed to correctly compare pallet designs between one pallet and another. One of the most successful attempts to correlate pallet performance concerning design characteristics was developed in 1968. In conjunction with the National Wood Pallet and Container Association and

Better Management Services, this study evaluated the performance of varying pallet designs with the overall goal of establishing the National Pallet Exchange Program (PEP) in which methods and procedures would be outlined to evaluate a pallet's usefulness (Wallin et al., 1972).

The five primary facets of interest within the PEP study were the field service testing of pallets, laboratory testing and quality control standards, identifying pallet patterns, and updating material handling methods used in common exchange programs (Wallin et al., 1972).

Major shipping routes, determined through a series of meetings, involving Better Management Services and the National Wood Pallet and Container Association, were investigated to give the best results for the pallet study (Wallin et al., 1972). One of the most important aspects of this study was to simulate as best as possible the handling environment that each pallet goes through during its handling phase. To do this, pallets would be shipped to and from different types of plants, shipped in both trucks and railcars, and were varied in terms of their unit loads and what products were being carried. Because this research was being conducted under time constraints, researchers selected products and unit loads that had a fast turnaround time, rather than choosing products that would sit for multiple weeks in warehouse storage. Throughout the nine months of the study, 21 different firms were analyzed. Shipping routes in Indianapolis, Indiana, and Peoria, Illinois, and San Francisco, Lodi, Oroville, California were investigated. Loaded cars were shipped from Indianapolis to Lodi, from Peoria to San Francisco, and from Oroville to Indianapolis. In between each new route and upon arriving at the facility, the already loaded pallets would be removed and replaced with new pallets to go to the next shipping route location. All of these shipment routes were done via railcar. However, in June of 1970, all of the shipping routes for this project were discontinued; thus, the study was changed for a short-haul truck movement to further the investigation on the pallets.

All shipment regions received varying serial numbers to organize information. The data was collected by distributing six different forms of data collection cards which the twenty-one participating facilities would fill out and send back for the study. These six cards recorded: Shipment information, Pallet Use Information, Replaced Parts Data, Original Parts Information, Pallet Damage Information, and Pallet Repair Information.

This study researched varying information based on a sample of 2,291 pallets (116 transferred in) of 25 different designs, which were studied in 16 different material handling environments. The data collected recorded the characteristics of each component, damage

descriptions, component repair and replacements, and the total number of handlings for each pallet. The basic constructions used in this study consisted of:

1. Plywood deck pallets with softwood stringers (Five Designs)
2. Plywood deck pallets with hardwood stringers (One Design)
3. Softwood Lumber Pallets (Four Designs)
4. Hardwood Lumber Pallets (Eleven Designs)

The results of this study were first analyzed by computer and placed in numerical order in regard to the information that was given. The information recorded that was used in the computer analysis consisted of the serial numbers of parts in correlation to their components, type of structure, type of damage, location of damage, date of damage, and place of damage. The damages observed during the study were mainly joint failures and breaks. The study identified any break as a complete separation that extended through two of the dimensions of the part or extended through a fastener (Wallin et al., 1972). Each break was then broken down into types such as longitudinal break, diagonal break, or cross break. The frequency of damages and the severity of the damages was collected. The severity of damages measured the extent to which a pallet or a pallet component was damaged. The severity was broken down into nine categories with three different correlating classes of damage. The classes consisted of minor damage which did not affect structural strength (Classes 1-3), moderate damage which caused a weakening of the structural integrity of the pallet but did not require repairs (Classes 4-6), and severe damage which caused major weakening of the pallet and rendered the pallet inactive until repair (Classes 7-9). See associated damage costs in Table 2 (Wallin et al., 1972).

$\text{Log } Y = .59667 + .17609 X$									
Severity Classes:	Minor			Moderate			Severe		
Severity Codes:	1	2	3	4	5	6	7	8	9
Damage Cost - \$:	.059	.089	.133	.200	.300	.450	.675	1.013	1.519

Table 1.2: Severity Classes and Damage Cost (Wallin et al., 1972)

After the initial research, many consistent factors of damage were found. Of the 2,979 damages recorded throughout the study, it was found that the majority of the damage pallets endured during handling occurred mainly on the bottom deckboards (Wallin et al., 1972). The

main damage types include cross breaks, longitudinal breaks, diagonal breaks, and joint failures. To further study the damages, each damage was categorized in terms of its main contributor.

Cross Breaks

Cross breaks accounted for only 6.8% of total damages to top and bottom deckboards and 9.2% of total damages to stringers. The cross break damages that occurred to deckboards consisted of 45% to the edges of a plywood top deck, 7.6% to lumber top deck endboards, 22.1% to bottom end deckboards, 2.3% to the center of plywood top decks, 5.2% to lumber top deck centerboards, and 18.6% to bottom deck centerboards. Of the cross break damages done to stringers, 90% occurred at the edge of the stringers (Wallin et al., 1972). Of the total cross breaks found in the study, 81% occurred to the top and bottom deckboards, and 19% occurred in the stringers.

Longitudinal breaks

Longitudinal breaks accounted for 3% of total damages found in top and bottom deckboards and 70.4% of total damages to stringers. The longitudinal breaks experienced by top and bottom deckboards were mainly found on top deck endboards (23.4%), bottom deck endboards (50.6%), top deck centerboards (2.6%), and bottom deck centerboards (23.4%) (Wallin et al., 1972). Of the longitudinal breaks found in stringers, 86% were found in edge stringers (Wallin et al., 1972). Of all the longitudinal breaks found, 20.2% were found in the deckboards and 79.8% were found in the stringers.

Diagonal Breaks

Of all damages found in this study, it was found that diagonal breaks accounted for 30.1% of damages found in top and bottom deckboards, and 18.7% of all damages to stringers. Diagonal break damages experienced by top and bottom deckboards were found on top deck end boards (21.7%), bottom deck endboards (43.1%), top deck centerboards (10.6%), and bottom deck centerboards (24.7%) (Wallin et al., 1972). Of the diagonal break damages found in stringers, 70% occurred in edge stringers. Of all the diagonal breaks, 90.4% occurred in the deckboards and 9.6% occurred in the stringers (Wallin et al., 1972).

Joint Failures

Of all damages found during the study, 60.1% of damages to top and bottom deckboards and 1.6% of damages to stringers were due to joint failure. Of the joint failure damages that occurred to deckboards, 21.9% appeared in the top deck endboards, 38.4% to bottom deck endboards, 13.8% to top deck centerboards, and 25.9% to bottom deck centerboards. Joint failures in correlation to stringers happened 71% of the time to edge stringers. Of all of the total joint failures found in this study, 99.5% occurred in the top and bottom deckboards, and 0.4% occurred in the stringers.

The most seen deckboard damages during this study consisted of joint failures. They contributed to 55% of all damage seen to top deck endboards, 59% of all damages seen in bottom deck endboards, 69% of damages in top deck centerboards, and 62% of damages in bottom deck centerboards (Wallin et al., 1972). The second most common type of failure was the diagonal break. Thirty percent (30%) of deckboard damages were diagonal breaks. Longitudinal breaks accounted for 4%-15% of total damages found during this study. Lastly, cross breaks accounted for 1%-4% of total damages (Wallin et al., 1972).

As for stringers, 70% of stringer damages were longitudinal, 19% were diagonal breaks, 9% were cross breaks, and 2% were joint failure (Wallin et al., 1972).

The damage frequency and severity that affected the pallets provided information that was instrumental in the development of pallet durability standards. Further, information that correlated the cost of repairs with the associated damages would be used to develop a cost associative model to compare the use of pallets in terms of their durability.

1.1.6.2 Wallin and Whitenack's Durability Model

Wallin and Whitenack used the results of the 1972 PEP study to create an econometric model to predict the durability of the pallet. Wallin's durability model uses the costs of damages that occurred during pallet use to predict the overall durability of the pallet.

Due to the variations within the pallet industry, when creating a cost model, many primary assumptions had to be made to standardize the cost model. The assumptions include:

1. The model is designed to predict and evaluate the urban-industrial market.
2. The standard 48 in. x 40 in. notched stringer pallet was of primary concern concerning the cost model.
3. The price of a pallet is a dependent direct function of cost

4. The price is the measure of the quality of a pallet
5. Usage amount remains consistent
6. Frequency of damage is a direct function of use
7. Severity of damage is an inverse function to price and quality
8. Life expectancy is correlated to a pallets price
9. A decrease in pallet worth is a function of price
10. The life of the pallet is independent of the repairs

The durability of a pallet was defined as a pallet's **economical life**. A pallets economical life corresponds to the number of trips it survives while the cost per use is at a minimum. In Wallin's model, the total cost of pallet use, which is composed of the purchase price and the total damage cost, divided by the total number of trips gives the cost per use of the pallet (Cao, 1993). The equation for average cost per trip of a pallet can be seen below in equation 1.

$$A = (P + C_t)/U \text{ (Equation 1.1)}$$

Where:

P = purchase price of a pallet

C_t = total damage cost

U = number of times the pallet was used one-way

To determine the total damage cost, C_t , the average damage cost (C_d) was taken in **relation to frequency of that damage (F)** (Equation 2).

$$C_t = (C_d)(F) \text{ (Equation 1.2)}$$

Where:

C_t = total damage costs (cost to repair pallet based off damage)

C_d = the average damage costs

F = damage frequency

Furthermore, the average damage cost was calculated based on the **severity of the damage (s)**, and economic coefficient (**c**) that considered the cost fluctuation of repair process based on various economic factors, and a design constant (**b**) (Equation 3).

$$C_d = cb^s \text{ (Equation 1.3)}$$

Where:

S = the damage severity of a pallet

b = a design constant = 1.5 for lumber deck pallets

c = economic coefficient

C_d = the average damage cost

The average cost per trip of a pallet (A) was calculated based on equation 4:

$$A = (P + cb^s ((1+r)^u - 1))/U \text{ (Equation 1.4)}$$

Where:

P = purchase price of a pallet

c = economical coefficient

b = pallet design constant b = 1.5 for lumber pallets

r = damage rate of the pallet

S = damage severity of the pallet

U = number of times the pallet was used one-way

This model indicates that a specific design of a pallet should be used until the average cost of use (A) is at a minimum (Wallin and Whitenack, 1984). This occurs when the slope of the average cost curve is zero which can be obtained when the derivative of Equation 4 is zero.

Therefore, damage frequency and damage severity both play a critical role in calculating the durability of a pallet.

Damage frequency is defined by the number of times a pallet sustains damage during its life (Wallin and Whitenack, 1984). The design of a pallet affects the overall frequency during which components on the pallet get damaged. Damage frequency in the PEP study was calculated as the total number of damages divided by the total number of pallets tested. In the 1984 study, Wallin and Whitenack found that damage frequency is similar to compounded interest in the way that it accumulates over time (Wallin, 1984).

The **damage severity** was also measured due to its relation to the cost of repairs (Wallin and Whitenack 1984). This study developed a damage severity scale in which each damage severity class had an associated damage cost (Table 2). Wallin also developed an equation that could be used to predict damage frequency and severity based on the following pallet design factors (Wallin, 1984):

- F(1) - composite joint separation factor
- F(2) - Composite joint shear factor
- F(3) – Joint integrity factor

- F(4) – Shook quality factor
- F(5) – Selective placement factor
- R(1) – Stringer strength factor
- R(2) – Deck strength factor
- R(3) – Deck construction factor
- R(4) – Handling environment factor. The equation for damage severity and damage frequency can be found in Equations 5 and 6.

Damage Severity

$(S) = [1+F(1)][1+F(2)][1+F(3)][1+F(4)][1+F(5)] * [1+R(4)/2][2.0]$ (Equation 1.5) (Wallin, 1984)

Damage Frequency

$(r)=[1+F(1)][1+F(2)][1+F(3)][1+F(4)][1+F(5)]* [1+R(1)][1+R(2)][1+R(3)][1+R(4)][.01]$ (Equation 1.6) (Wallin, 1984)

1.1.6.3 Cao's Investigation into Panel Deck Pallet Durability

The main research objective of Cao's study was to validate Wallin's durability model for pallets with structural panel decking, in which 100 different pallets and 15 different designs were tested (Cao, 1993). The model validation was needed because the original PEP study only contained a limited number of this type of pallet. This emphasized the need for more data to observe the effectiveness of Wallin's model on panel deck pallets.

FasTrack is a simulation of those impacts that a pallet experiences in the material handling environment of the grocery sector (Cao, 1993). It was originally created by Proctor and Gamble Co., and was further developed at the William H. Sardo Jr. Pallet and Container Research Laboratory at Virginia Tech. The test procedures included seven different stations and 13 handling steps. The pallets were loaded with a 1,500 lb payload and were handled with both an electric pallet jack and an industrial forklift (Cao, 1993).

The same forklift operator was used in all testing. Each pallet was inspected for damage both prior to and after the testing cycles. The test was to be terminated after a maximum of 30 cycles or when the pallet was no longer functional due to the damages that occurred during testing (Cao,1993). The types of damages include (Cao, 1993):

1. Cracks – any separation within a pallet component
2. Missing parts – components of a pallet are no longer attached
3. Break – a complete separation either completely along the width of the pallet or length of the pallet.
4. Joint Failure – Nail head pop out or nail head pull through

Because no repairs were conducted in FasTrack testing, the total damage costs from testing doesn't represent the actual relationship between total damage cost and cycles (Cao, 1993). In order to make Cao's FasTrack findings comparable to the PEP Study results, Cao needed to develop a method to include the effect of repairs. In order to facilitate this analysis, damages were given a severity level related to the cost of repairs. The severity levels for each occurring damage were assigned based on a program written in Statistical Analysis System (SAS) (Cao, 1993). The criteria for repair were based upon the repair procedures published by companies such as the National Wood Pallet and Container Association (NWPCA), Canadian Pallet Council (CPC), and Commonwealth Handling Equipment (CHEP) Each recorded damage was compared with the criteria for repair inputted into the software and a repair decision was made, each repair being associated with a repair cost (Cao, 1993).

To evaluate the total cost of damages for the investigated pallets, the damage frequency and damage severity were collected for the pallet. Repair costs were partitioned into 5 severity classes: 6-10 were those which required repair, and classes 1-5 were severity levels which were too low to be considered for repair. A cost value was assigned to each level. The entire range for all repair costs was from \$0.36-\$6.40. Not all damage severity levels were applicable to all components. This was unlike what was done during the PEP study. The PEP study allowed for damages to be of the severity levels defined. This was not accurate since the repair costs of a deckboard should never exceed the cost of its replacement.

Since no repairs were conducted during testing, the maximum number of damaged parts was always less than the total number of components used to make a pallet, which is not always the case in real-world environments (Cao, 1993).

Once Cao determined the damage cost per cycle for each of the investigated pallets, Wallin's Model was used as a basis for comparison in order to validate the results from FasTrack using a base

pallet, as seen in Figure 1.8. The observed and predicted total damage cost as a function of test cycle can be seen in Figure 1.9.

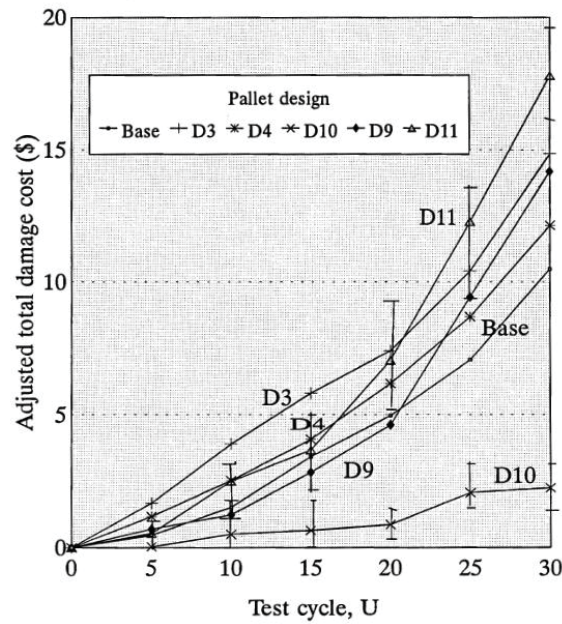


Figure 1.7: Base Pallet Compared vs. Other Designs (Cao, 1993).

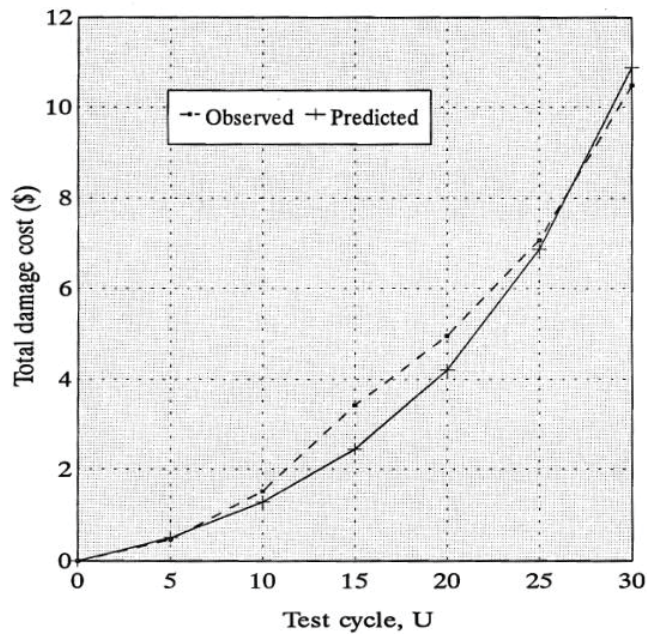


Figure 1.8 Observed and predicted total damage cost as a function of test cycle (Cao,1993).

Upon finding that Wallin's model worked for the pallets being tested, Cao then estimated the purchase price for the pallets and gave them a correlating economical life as seen in Table 1.3.

Pallet Design	Estimated price (\$) ¹	Correlation coefficient	Economic Life (cycle) ²	Solution Tolerance
Base	20.00	1.0860	32.32	0.026
D1	20.00	1.0923	30.21	0.004
D3	20.00	1.0992	28.20	0.004
D2	22.00	1.0984	27.54	0.002
D4	22.00	1.0914	29.55	0.004
D8	25.00	1.0900	31.00	0.003
D10	30.00	1.0405	70.20	0.001
D13	25.00	1.0818	33.50	0.008
D7	20.00	1.0797	32.90	0.002
D11	20.00	1.1044	25.40	0.003
D15	20.00	1.0908	29.03	0.015
D6	18.00	1.1738	15.33	0.002
D9	18.00	1.0952	27.02	0.001
D12	18.00	1.1471	19.90	0.002

Note:

- 1 -- the purchase prices of these pallets are roughly estimated.
- 2 -- the economic life is a theoretical solution based on the solution tolerance. In practice, the economic life is rounded to an integer

Table 1.3 Estimated Price and Economical Life (Cao, 1993).

The economic model used to predict the economic life of a panel deck pallet is based on the relationship between total damage costs and test cycles, which was derived from testing pallets in FasTrack (Cao, 1993). The calibration for this model was performed using two different methods. The first method was to compare the number of physical handlings a pallet experienced in FasTrack with those found in actual commercial handling systems (Cao, 1993). The second method was to test a pallet of known durability within FasTrack the same way that CPC pallets were being tested.

Thirty cycles were selected because a previous testing of the CPC pallets in FasTrack revealed that 30 FasTrack cycles represents six years of use (Cao, 1993). By the comparison of these two pallets, it was discovered that FasTrack pallets may experience rougher handling than experienced during field use. (Cao, 1993).

The durability model for panel deck pallets include two sub-categories. One is the model of economical use, as discussed earlier, and then, there is the structural design model. The pallets' structural properties considered for this model were:

- Panel shear resistance through the thickness

- Bottom deck strength
- Pallet strength in the length
- Fastener withdrawal resistance
- Fastener shear resistance
- Pallet classification number (Identifies specific pallet style)

The structural design model is derived by multiple regression analysis (Cao, 1993). In order to evaluate the reliability of a structural design model, two new panel deck designs with six replicates for each design were tested in FasTrack. The PD design consisted of plywood decks and laminated plywood blocks, whereas the OD design has OSB decks and laminated OSB blocks. The two different designs, PD and OD, are of the same full 4-way, nonreversible, panel deck pallet structure.

1.2 Supply Chain Introduction

The supply chain consists of all processes included in delivering goods or services to a customer (CIPS, 2020). Supply chain is an overarching term that encompasses different subcategories within the supply chain. Global supply chain management market size in 2019 was valued at \$15.85 billion. It is predicted to reach 37.41 billion by 2027 (Wu,2022). The ever-growing market of supply chain management shows the importance of the supply chain on a global scale. Main steps of the supply chain include:

- Sourcing – This is the step in the supply chain where, depending on what product or project is being produced, raw materials are collected (Sharma, 2020).
- Manufacturing – Manufacturing consists of assembling the product, testing, and packing the product (Sharma, 2017).
- Delivery – Delivery of goods from one location to another, either direct to customer or to warehouses (Sharma, 2020).

Pallets are commonly used to move goods throughout the supply chain. At each of the steps, pallets can be stored in warehouses, located at the place of raw material production, manufacturing,

or further downstream. Between warehouses, pallets are moved using a variety of transportation methods including truck, rail, air, or maritime transportation.

1.2.1 Warehousing

Warehouses may be defined as a space where goods are received, stored, and distributed (Bartholdi, 2017). There is large variability between warehouses, so it is important to identify the main types of warehouses (Mejias, 2019):

- Retail Distribution Centers – direct customers are retail stores.
- Service Parts Distributions – customers are dealerships and/or repair shops.
- E-commerce Distribution Centers – warehouses in which they receive orders from online customers which will then be distributed directly to those customers.
- 3PL Warehouses – warehouses under contract with many customers who outsource from this one distribution center.
- Perishable Warehouses – these warehouses typically store perishable items such as food and other products that require refrigeration.

Although there is variability between the operations of several types of warehouses, operations typically seen across all warehousing include receiving, putting away, storage picking, packing, and shipping.

Each one of these operations is instrumental in the efficiency of distribution. The two main types of functions of a warehouse are storage and material handling. Storage Solutions defines material handling as the movement, storage (storing of goods for later distribution), and control and protection of materials, goods, and products throughout the process of manufacturing, distribution, consumption, and disposal (SS, 2012).

1.2.2 Storage

Racking systems are quite common in warehousing practices. Racks are usually made from structural steel and are manufactured to enable easy assembly within warehouse facilities (Howie,

2008). The most common warehouse racking system is called a load beam rack (Mejias, 2019). A pallet is placed between the openings of the beam supports with the stringers/blocks resting on the beams (Howie, 2008).

Drive-in or Drive-Through Racks are the second most common rack system (Mejias, 2019). This rack system is used primarily with high-density storage because it allows unit loads to be stored multiples deep in the rack system. Drive-In racks can only be accessed from one side while drive-through rack systems allow drivers the ability to both load and remove unit loads from both sides of the racking system further increasing storage efficiency (Mejias, 2019).

Push back racks are another common type of racking system. Push back rack systems utilize rollers, which allow for a unit load on the racking system to be pushed back when another unit load is placed onto the racking system (Mejias, 2019). Pallets placed on push back racks experience more support because the pallet is supported by three beams instead of two as commonly seen for selective racks.

Flow racks use gravity to move the pallets/unit loads. The unit load is lifted on to the higher side of the racking system which allows for the pallet to slide down and be picked up from the lower side when needed. This type of storage system has the highest performance level of all high-density storage systems (Mejias, 2019).

Automated storage and Retrieval Systems (As/Rs) are of typical use in warehouses that are highly automated. With this type of racking system, both the retrieval and storage of unit loads that come into the facility are fully automated. This allows for quick and efficient management in warehouses where both space and time are critical.

1.2.3 Material Handling

The movements of goods within warehouses are done using different forms of material handling equipment. The most typical material handling equipment seen across all warehouses is the forklift. Forklifts are motorized vehicles with fork tines on the front which allow for the lifting of heavy unit loads (Mejias, 2019). Forklifts come in a variety of unique designs based of their intended use within the warehouse (Howie, 2008). There are different types of forklifts, such as counterbalance, reach truck, order picker, multidirectional forklifts, and other types that may be

designed specifically for an intended application. The most common forklift, however, is the counterbalance forklift (Tareq, 2018).

Another important part of material handling equipment within the palletized world is the pallet jack. Pallet jacks are typically used to move unit loads from one place to another minimizing the need for the forklifts in certain operations. To allow access with a pallet jack, which generally has a height of 3.25 in., the pallet design needs to have at least 3.5 in. pallet openings. Thus, two-way pallets are only accessible by pallet jacks on the width end of the pallet and partial four-way pallets are only accessible via pallet jack from the width side and via forklift on the length side.

In conjunction with the forklift and the pallet jack, another form of material handling equipment is a conveyor. A conveyor allows for the smooth transportation of unit loads within a warehouse space (MH1, 2019). Conveyor systems, along with the use of forklifts and pallet jacks allow for maximum efficiency within a warehouse. Conveyors can be categorized based on their power source. Gravity conveyors utilize gravity to move unit loads to their intended destinations; therefore, they always require a decline. Thus, they take up more space within a warehouse. Meanwhile, powered conveyors use hydraulic or electric power to move the unit loads, thus they do not need a decline and can also move unit loads up an incline. Conveyors can be differentiated based on the type of mechanism that interfaces with the pallet including wheels, rollers, and chains.

- Wheel Conveyor – consists of multiple wheels along a plane in order transfer the unit load from one place to another
- Roller Conveyor – consists of rollers placed perpendicular to the plane of the conveyor
- Chain Conveyor – consists of chains spanning the outside lengths of the conveyor for ease of transportation

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2 Measurement of the Vertical Vibration Experienced by Forklifts During Material Handling

2.1 Introduction

Pallets are ubiquitous in the supply chain with over 2.6 billion pallets in circulation in the United States (Freedonia, 2015). Although pallets can be made of different materials, pallets made of wood dominate the market with a 95% market share (McCrea, 2022). A 2016 study showed that 839 million wooden pallets were produced consisting of 513 million new pallets and 326 million repaired pallets (Gerber et al., 2018). This output represents an overall 14% increase compared to 2011 results (22% increase for new pallets and 5% for recycled) (Gerber et al., 2018). Wood pallets are important for the U.S. economy because they consume 21.8% of new lumber used in the United States, which translated to 9.16 billion board feet of lumber in 2016 (MLR, 2018).

Warehousing is an essential part of most supply chains where goods are stored between transportation steps. The movement of goods within a warehouse is conducted using different forms of material handling equipment. The most used material-handling equipment used across all warehouses is the forklift (Meijas, 2019). Forklifts come in a variety of unique designs based on their intended use within the warehouse including counterbalance, reach truck, order picker, multidirectional forklifts, and other types that may be designed specifically for their intended applications (Howie, 2008).

Similarly to other transportation modes, forklift produce vibration during operation. Although the vibration environment produced by other transportation modes such as truck (Dunno, 2014), rail (Singh et al., 2012), and air (Borocz and Singh, 2018) are extensively studied by many researchers, there is a lack of information on the vibration environment produced during forklift transport. The first study that investigated the level of vibration during forklift handling in a laboratory setting was conducted by Huang et al. (2021). This study investigated the vibration produced by gas, reach, and electric forklifts in laboratory conditions. Each forklift went through a series of handling scenarios to determine the effect of different variables such as unit load weight, speed, road conditions, and sensor location (Huang et al., 2021). It was found that the highest vibration intensities were in the 3-4 Hz range, and the gas forklift had the highest intensity

vibrations. The study also found that, with an increase in payload, the vibration levels seem to decrease; and an increase in speed increased vibration levels (Huang et al., 2021). A follow-up study by Borocz et al. (2021) was conducted which expanded the number of investigated forklifts and proposed a Power Spectral Density (PSD) profile that can be used during laboratory simulation of the forklift handling. These research projects provided a basic understanding of the vibration levels seen during forklift handling and how different variables affect that vibration; however, there is still a lack of information on the vibration environment experienced during forklift handling in a field environment.

2.2 Objective

The objective of this research was to characterize the vibration environment during forklift handling of palletized loads in different types of facilities

2.3 Materials and Methods

To measure the impact vibration levels during forklift handling, Saver 3D15 (Lansmont Corp, Monterey CA, USA) and Saver 3X90 (Lansmont Corp, Monterey CA, USA) data loggers were used for the data collection. The data loggers were attached to different forklifts found in the facilities that participated in this study. The sensors were left in the facilities for 1-2 weeks to record the acceleration peak, change in velocity, duration, and RMS (g) values. Upon retrieval of the data loggers, a statistical analysis was performed to identify the behavior of vibration intensities.

2.3.1 Facilities

Three different facilities were investigated during this study including an automotive manufacturer, a distribution facility, and a pallet manufacturer. Each facility had differing operations within their supply chain. Within the distribution facility, multiple data acquisition trips were made at different times. The results from the different trips were summed up to give cumulative results for the facility.

2.3.2 Forklifts

Forklift type and model varied between the facilities: the types of fork lifts in the field testing included a Yale ERP040 electric forklift, a Hyster CT2 electric forklift, and a Toyota 8FDU gas forklift. The Yale ERP040 is a solid, 3-wheel, counterbalanced, sit-down, electric forklift with a capacity of 3,000 - 4,000lbs (YMH, 2022). The Hyster CT2 is a solid, 4-wheel, sit-down, electric-controlled powershift, counterbalanced forklift with a capacity of 4,000 - 5,000lbs (Hyster, 2022). The Toyota 8FDU is a 4-wheel, air-pneumatic, sit-down, gas forklift with a load capacity of 3,000 - 6,500lbs (Toyota, 2022). All forklifts used during the study featured no suspension system. Figure 3 displays each forklift model used during field data collection.

2.3.3 Floor Characteristics

Floor characteristics varied between facilities. Floor materials such as concrete, asphalt, and dirt were identified.

2.3.4 Load Characteristics

Due to the high payload variability each forklift experienced during duration of each data collection period, payload ranges were not exact. However, the estimated range of payload between the three facilities was around 800-2500 lbs.

Characteristics:	Facility 1	Facility 2	Facility 3
Facility type	Distribution	Manufacturing	Pallet Manufacturer
Forklift	Yale ERP040	Hyster CT2	Toyota 8FDU
Floor condition	Concrete/Asphalt	Concrete	Concrete/Dirt

Table 2.1: Summary table of the characteristics of the investigated warehouses.

2.3.5 Sensor Setup & Settings

Lansmont 3X90 and 3D15 data loggers (Lansmont Corporation, Monterey, CA, USA) were used to record vibration measurements. The significant difference between the 3D15 and 3X90 data loggers is the internal accelerometer type. The Lansmont 3D15 utilizes a triaxial MEMS (Micro-Electro-Mechanical System) accelerometer, and the Lansmont 3X90 utilizes a triaxial

piezoelectric sensor. Piezoelectric accelerometers have the capability of capturing data more efficiently at higher frequencies in comparison to MEMS accelerometers. MEMS accelerometers utilize an inertial mass, when force is applied, the electronics provide an output proportional to the force acting on the sensor. The sensor settings used in the study are shown in Table 2.2. It is important to note that the trigger level for the Saver 3D15 and Saver 3x90 were different, as the 3D15 consistently records a 1 g acceleration due to gravity and the 3x90 does not.

The sensors were mounted using two strips of double-sided mounting tape (Scotch Corporation, Saint Paul MN, USA) on the back of the fork tine carriage as seen in Figure 2.1.



Figure 2.1: Location of Sensor of Fork Tine Carriage.

Settings	3D15 (MEMS)		3X90 (Piezoelectric)	
	Signal Triggered	Timer Triggered	Signal Triggered	Timer Triggered
Memory Allocation	30%	70%	30%	70%
Record Time	2s	2s	2s	2s
Sampling Rate	500 samples/sec	500 samples/sec	500 samples/sec	500 samples/sec
Sample Size	1,000 samples	1,000 samples	1,000 samples	1,000 samples
Trigger Level	1.2 g	1.2 g	0.2 g	0.2 g
Filter	250 Hz	250 Hz	250 Hz	250 Hz
Pre-Trigger	50%	50%	50%	50%

Table 2.2: Setting for the Vibration Dataloggers.

2.3.6 Statistical Methods

Data was analyzed using SaverX (Lansmont Corporation, Monterey, CA, USA), JMP (SAS Institute, Cary, NC, USA) and Matlab (MathWorks, Natick, MA, USA) software packages.

Vibration events with less than 0.02 G_{rms} and acceleration events with more than 2 g were filtered out as anything above 2 g could be considered a shock event rather than vibration.

Empirical cumulative distribution functions (CDF) plots were fitted using a Weibull distribution. The Weibull distribution for these plots was used as it was best for fitting the data collected for the CDF plots (Rouillard, 2020). The equation for Weibull- fitted data can be found in Equation 1. The parameters for Equation 2.1 goes as follows: $\alpha > 0$ is the scale parameter, $\beta > 0$ is the shape parameter, where $F(x)$ is the probability density, x is the random variable, and e is the natural logarithm).

$$F(x|\alpha, \beta) = \int_0^x \beta \alpha^{-\beta} t^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^\beta} dt = 1 - e^{-\left(\frac{x}{\alpha}\right)^\beta}$$

Equation 2.1: CDF Weibull Fitted Equation. The

2.4 Results and Discussion

2.4.1 Peak Acceleration (g, peak)

The field data was collected from three different types of facilities: a distribution center, a manufacturing facility, and a pallet manufacturer. The acceleration (peak, g) values observed during the study are presented in Table 2.3.

The mean peak acceleration values in the field were relatively similar between facilities. The mean peak acceleration values were the lowest for the pallet manufacturing facility (0.264 g) and the highest for the distribution facility (0.353 g). The acceleration (peak, g) values at 98% also revealed that peak accelerations experienced by the forklift can be as high as 1.65 g as seen in Figure 2.2. The distribution of the values is right skewed, meaning that the values are most frequent towards the lower end of the acceleration (peak, g) values. The majority of the peak acceleration values occurred in a low acceleration range below 0.5g.

The mean acceleration (peak, g) values for the gas forklift type were different from Huang et al.'s findings (Huang, 2021). The gas-powered forklift which was used in the pallet manufacturer experienced a lower average of 0.264 g when compared to Huang study. the distribution facility, which utilizes an electric forklift, had an average peak acceleration closest to the gas-powered forklift in the Huang et al. study (Huang, 2021). In an uncontrolled environment, this difference may be attributed to differing forklift operators; they may cause a difference in values from facility to facility.

Warehouse:	Acceleration (peak, g)			
	Mean	98%	95%	90%
Distribution	0.353	1.51	1.01	0.67
Manufacturing	0.274	1.65	0.84	0.46
Pallet Manufacturer	0.264	1.13	0.81	0.57

Table 2.3: Occurrence Levels of Acceleration (peak, g) Data Measured During Forklift Vibration for the Three Investigated Facilities.

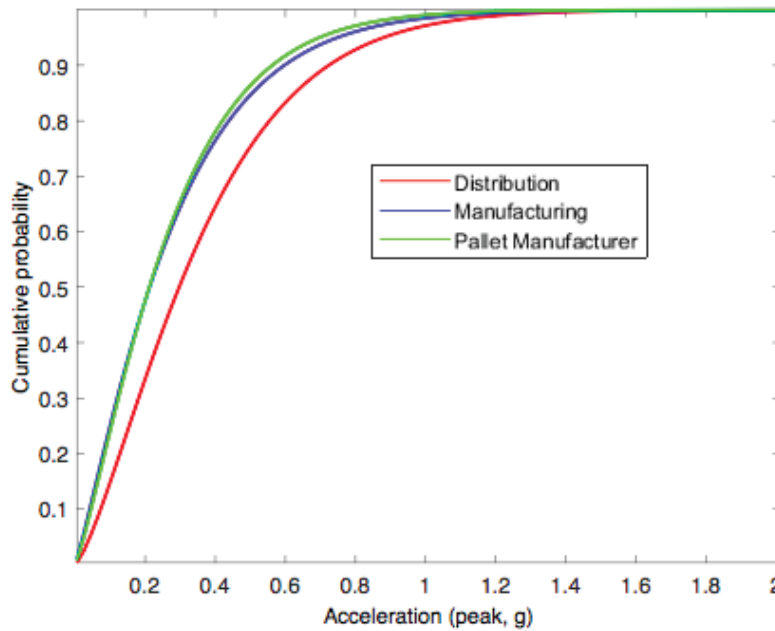


Figure 2.2: Combined CDF Plots for Acceleration (peak, g) for the Three Investigated Facilities.

2.4.2 RMS (g)

The results of the RMS values measured for the investigated facilities is presented in Table 2.4 while the combined CDF for RMS (g) values can be found in Figure 2.3. The mean RMS (g) ranged between 0.060-0.062 g while the maximum values were between 0.421-0.497 g. The mean RMS (g) values were 24% lower than was reported by Borocz et al. (2022) who reported values close to 0.09 g. Meanwhile, the maximum and the 98th percentile of the RMS values measured during this study were greater than what was observed under laboratory conditions found in

previous studies. An explanation for this trend could be that, during the field forklift handling operations, the forklift travels over uneven floors and thresholds which results in low-probability but high-intensity events that were recorded by the sensor.

Facility:	RMS (g)				
	Maximum	Mean	98%	95%	90%
Distribution	0.497	0.060	0.222	0.164	0.113
Manufacturing	0.421	0.060	0.150	0.100	0.093
Pallet Manufacturer	0.436	0.062	0.226	0.168	0.120

Table 2.4: Occurrence levels of RMS (g) Values Measured During Forklift Vibration for the Three Investigated Facilities.

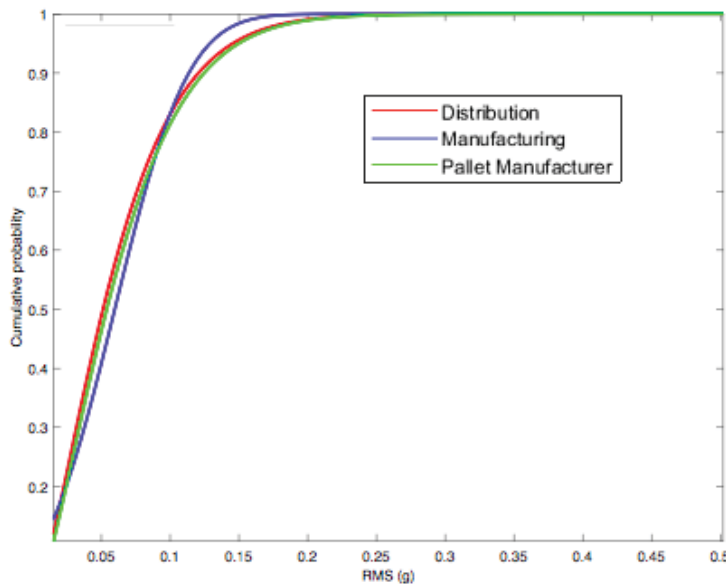


Figure 2.3: Combined CDF plots for RMS (g) for the three investigated facilities.

2.4.3 Probability Density Characteristic with Kurtosis Value

The high positive kurtosis levels, when compared to a standard kurtosis level of 3 for normal distribution, show a leptokurtic shape during the field data collection (Table 2.5). Leptokurtic shapes of kurtosis have values that rarely deviate too far from the mean, meaning the values are very similar in intensity. Facility 3 shows the highest levels of Kurtosis, meaning

that its values are stacked closest to the mean value when compared to distribution and manufacturing facilities.

Facility	Mean G_{rms}	Kurtosis
Distribution	0.091	35.57
Manufacturing	0.098	26.38
Pallet Manufacturer	0.084	49.11

Table 2.5: Summary table of mean G_{rms} (g) and Kurtosis values for the three investigated facilities.

2.4.4 Vibration Intensity (Power Spectral Density, PSD)

Power density levels were computed as a function of frequency based on the random vibration acceleration levels, for the vibration analysis,. The mean power density within a range of frequencies of a spectrum may be determined by its G_{rms} values, which is based on the number of samples of a bandwidth. The G_{rms} can be defined as an acceleration value (g) within a frequency, based on the number of samples. Computing PSD is done using a method called Fourier transformation.

Transportation modes such as rail and truck have been investigated to determine the vibration levels for packaging that uses such transportation. One study investigated different truck and rail routes from Hungary to Mexico, India, and China. It was found that the overall G_{rms} for trucks in Europe on different routes ranged from 0.118 - 0.176 G_{rms} and 0.059 – 0.082 G_{rms} for rail (Borocz, 2019). The combined total G_{rms} for all types of transportation within the route ranged from 0.109 – 0.139 G_{rms} (Borocz, 2019). Although these values are significantly higher than what forklifts experience in the field, it is still important to characterize the vibration that occurs from forklifts to unit loads in the field.

The G_{rms} values calculated for the investigated facilities are presented in Table 2.5. Huang et al. (2021) observed G_{rms} values ranging between 0.024-0.090 g^2/Hz when the sensor was attached to the carriage of the forklift. The lowest G_{rms} value occurred from a combination of electric forklifts, concrete road conditions, a speed of 2 mph, and a payload of 2,500 lbs. The highest G_{rms} value occurred from a combination of the gas forklifts, asphalt road conditions, a

speed of 4.82 km/h, and a payload of 1,500 lbs. The G_{rms} range for data collected during this study was 0.084-0.098 G_{rms} (Table 2.5). This is on the uppermost portion of the range as Huang et al. (2021) found during his study. The lowest G_{rms} value came from the pallet manufacturer which utilized a gas forklift. These findings were different than what was found by Huang et al. as they measured the highest vibration results for the gas forklift (Huang et al., 2021).

The Power Spectral Density (PSD) plot for the field measurement is presented in Figure 2.4. The highest peak value occurred between 4-8 Hz which is slightly higher than what was reported by Huang et al. (2021) at 3-4 Hz. The recommend vibration profile accumulated from the Huang et al. study can also be seen below in Figure 2.4, which displays the difference in the field data collected for this study and previously investigated lab results. Forklifts in the field drive to and from different locations within the facility, and they are not always handling unit loads. Due to this, the carriage is able to shake more without any weight on the fork tines leading to metal-on-metal higher frequency events and more energy intensive singular events, as seen in the higher average G_{rms} values. This could be responsible for the lower peak intensities and higher frequency vibrations seen between the facilities investigated. Although the G_{rms} calculated for the field measurements were mostly in line with what was reported by Borocz et al., the intensity of the highest peaks in the summary PSD showed vibrational intensity values much lower than in former studies (Huang et al., 2021, Borocz et al., 2022).

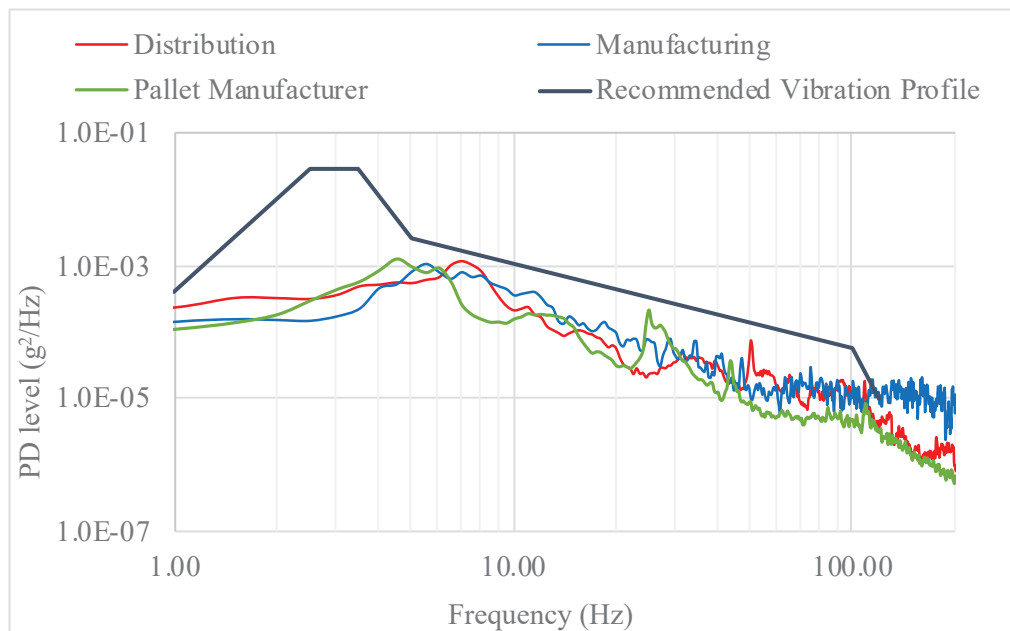


Figure 2.4: PSD Plots of Vertical Vibration for the Three Investigated Facilities.

2.5 Conclusions

The conclusions of the study are presented below:

- The highest intensity of random vibrations was found to occur between 4-8 Hz which is slightly higher than what was observed in previous laboratory studies. The reason for the higher frequency could have been the result of the deadhead travel when the forklift are traveling without a payload.
- The mean G_{rms} values of random vibration in the frequency range of 1 – 200 Hz for the measured forklift vibration were in the same range of 0.084-0.098 that was found for the laboratory conditions in previous studies.
- The peak acceleration values observed in the field showed high-level skewness towards the lower values but still exhibited much greater maximum values than what was measured for laboratory conditions. The increased number of lower-intensity, peak-acceleration values could be caused by more frequent empty travel by the forklift.
- More forklift traveling empty when compared to previous studies may have an effect on the much smaller values that were seen in the field. Contrary to previous studies, the highest vibration levels occurred in the distribution facility which utilized a sit-down, electric forklift.
- The highest acceleration (peak, g) values were the highest for the distribution center followed by the manufacturing facility and the pallet manufacturer.
- The G_{rms} values found during the study were also within close proximity to the ranges in previously mentioned studies; however, they were consistently toward the upper limit of those ranges.
- Based on the statistical characteristic of random vibration, events found during field data collection followed a non-gaussian distribution for all facilities.

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3. Measurement of the Horizontal Shock Impacts Exerted by Forklifts During Material Handling

3.1 Introduction

Having the capacity and knowledge of how to ship products effectively plays a significant role in an organization's ability to compete on a global scale. The prominence of shipping products has grown significantly over the last few decades, especially in regard to international shipping (Gunnarsson, 2021) with an increase in off-shoring practices (Oldenski, 2014). The most common way of shipping products internationally is in a unit load form with nearly 80% of products shipped within a supply chain in unit load form (Raballand and Aldaz-Carrol, 2007). A unit load is composed of a pallet, a product's packaging, and unit load stabilizers.

As unit loads move through a supply chain, they are exposed to a variety of handling environments. Hazards experienced by unit loads such as vibration, shock, and compression are seen quite commonly throughout all supply chains. Modes of transportation (i.e. ship, air, rail, truck), type of storage system, and types of material handling equipment used all play a significant role in the frequency and magnitude of hazards that unit loads experience. Understanding the effects that these hazards have on a unitload or pallet is a critical step to ensure the protection of goods as they move through the supply chain.

The vibration and shock environment during transportation is widely investigated by many researchers. Most studies focused on characterizing the over-the-road (Lepine and Rouillard, 2015; Borocz and Singh, 2018; Dunno, 2014; Jarimopas et al., 2005), rail (Singh et al., 2012; Singh et al., 2007), and air (Borocz and Singh, 2018) vibration environment. However, recent studies investigated the level of shock produced during trailer braking and turning (Dunno and Ge, 2021; Dunno and Ge, 2022; Borocz et al., 2022). Despite the significance of material handling in the supply chain, there is a lack of research studies that investigated the vibration and shock environment during material handling. One of the most common modes for handling methods for pallets within a supply chain is the use of a forklift (Mejias, 2020). The necessity for more information regarding the effects forklifts have on unit loads led to a recent study by Huang et al. This study investigated the dynamic vibration characteristics that forklifts exert on unit loads while being transported during material handling (Huang et al., 2021). In addition to the vibration environment during forklift transport, the shock intensity during pallet marshaling operation was

investigated by Rodriguez et al. (1994) in a laboratory setting. The study explored the variables that lead to changes in shock impacts, such as forklift type, speed of impact, and the weight of unit loads (Rodriguez et al., 1994). A more recent study was conducted which explored the same variables by Masis et. al. at Virginia Tech, however the sensor was placed on both the forklift and the unit load in order to quantify the differences in shock based on the previously mentioned variables. (Masis, 2022)

Pallet durability is an important pallet characteristic to determine a pallet's usability. Implementing higher-durability pallets into a supply chain may reduce material usage and spending for a company (Bengtsson, 2015). The durability of the pallet is mainly affected by its interaction with the forklift. Pallets that are handled in a harsher environment by less trained operators do not last as long as pallets handled in a gentler environment by a more trained workforce (Wallin, 1972).

It is important to be able to replicate what a pallet might experience in the field, so that when testing in a laboratory setting, a company may be able to gauge their pallet or unit load's functional capabilities. There are currently a few different ways to estimate the durability of a pallet in a laboratory setting. The creation of a simulated material handling environment, FasTrack, in 1993 aided in showing how many trips a pallet can withstand over its useful life (Cao, 1993). FasTrack simulates a pallet going through a series of simulated trips, utilizing material handling equipment, such as forklifts and pallet jacks. Multiple standards have also been developed to replicate the environment that a unit load may go through in the field in order to observe common damage modes that may occur to a pallet. The ISTA 3B testing standard contains a pallet marshaling segment, in which a unit load goes through a series of handling sequences simulated by a forklift. (ISTA, 2017). To further simulate damages that are found in the field, testing standards such as ASTM D1185 (ASTM, 2017) and ISO 8611 (ISO, 2021) utilize an incline impact tester (ISO, 2021; ASTM, 2017). The tests in these standards replicate the impacts caused by forklifts on the lead deckboards, blocks, and stringers of the pallet.

The intensity at which these pallets are being tested is of crucial importance; however, the FasTrack simulation, ISTA, and ISO standards do not include a variable intensity level for testing. ASTM, however, does give some guidelines on the intended intensity of impacts that pallets should experience during testing.

The current ASTM D1185 (ASTM, 2017) standard calls for an impact speed of 50 in/s; however, it is only supported by a limited number of studies. To evaluate whether or not these impacts can quantifiably replicate what is experienced in a field environment, it is useful to understand the g-force that occurs when a pallet is impacted. In an attempt to better understand the forces experienced by a unit load that leads to damages, a study by Rodriguez et al. (1994) investigated the lateral shock that unit loads experience when impacted by a forklift or pallet jack by recording the shock impacts via sensors. This study found that the average peak acceleration experienced by the unit load was nearly 36 g with a duration of 4.3 ms (Rodriguez et al., 1994). This study helped to expand on an area lacking substantial research. However, being able to quantify the shock forces seen in the field, not just in a laboratory setting, would be essential to increase the reliability of standardized testing.

3.2 Objectives

- Characterize the intensity of horizontal shock impacts exerted by forklifts during material handling in the warehouses investigated and during the FasTrack simulation.
- Evaluate the ability of the FasTrack procedure to simulate the horizontal impacts experienced by forklifts during material handling.
- Determine the required impact level for the incline impact tester to be able to simulate the intensity of horizontal impacts experienced by forklifts and the incline impact tester during the material handling in the field.

3.3 Methodology

3.3.1 Warehouses

The difference between shock impacts exerted via forklifts between different types of facilities, manufacturing, distribution, and LTL facilities were investigated. Each facility investigated had different variables within their own operations. The distribution and LTL facilities were investigated at two different locations for the same company, the results were then summed up based on facility type.

3.3.2 FasTrack Simulation

The FasTrack simulation was originally created to simulate the handling environment pallets see within the grocery sector of material handling (Cao,1993). Proctor & Gamble created

the first iteration of this test, which it was further developed for use at the William Sardo Laboratory, now The Center for Packaging and Unit Load Design (Cauffield and Fogler, 1989). The pallets are loaded with a 1,500 lb payload and is put through a series of racking, horizontal impacts, and stacking simulations. The pallets are handled with both an electric pallet jack and an industrial forklift through the FasTrack procedure (Cao, 1993). The pallet typically goes through a total of 30 cycles, or until the pallet breaks, although some clients prefer to test very durable pallets for many more cycles than that.

3.3.3 Forklifts

Forklifts investigated in the field were dependent upon which forklifts each facility type used during operation. The distribution facility investigated in this study used a Yale ERP040 forklift. The Yale ERP040 forklift is a pneumatic, 3-wheel, counterbalanced, sit-down, electric forklift with a capacity of 3,000 - 4,000 lbs. (YMH,2022) The manufacturing facility utilized a Hyster CT2 forklift. The Hyster CT2 is a solid-wheel, 4-wheel, sit-down, electric-controlled powershift, counterbalanced forklift with a capacity of 4,000 - 5,000 lbs (Hyster, 2022). Finally, the LTL facility utilized a Mitsubishi FG15N forklift. The Mitsubishi FG15N forklift is a counterbalanced, 4-wheel pneumatic, forklift with an internal combustion engine, and has a load capacity of 3,000-7,000 lbs. For data collection of FasTrack shock impacts, a Toyota 8FBE15U forklift was used, which is pictured below in Figure 3.1. The Toyota 8FBE15U is a counterbalance, cushion/pneumatic, electric powered, 3-wheel, sit-down forklift, with a load capacity of 3,000 lbs. The forklift used in the FasTrack simulation can be seen below in Figure 3.1.



Figure 3.1: Forklift Utilized During the Fastrack Data Collection.

3.3.4 Sensors

To collect shock impact data from the field and FasTrack during forklift handling, a Lansmont Saver 3D15 (Lansmont Corp, Monterey CA, USA) and Lansmont Saver 3X90 (Lansmont Corp, Monterey CA, USA) were used. The Saver 3x90 and 3D15 utilize the Lansmont SaverX (Lansmont Corp, Monterey CA, USA) software for data retrieval and event summary selections. The Saver 3D15 uses a triaxial Micro electro-mechanical system (MEMS) accelerometer with a range of 50 g, and a 128 MB memory capacity. The Saver 3x90 utilizes a triaxial piezoelectric accelerometer with a range of 200 g, and has a 128 MB memory capacity. Both 3D15 and 3x90 have a weight of 16.7 oz and their dimensions are 3.7 in. x 2.9 in. x 1.7 in..

To collect the shock levels on the incline impact tester, a Dytran model 3035B2G (Dytran Instruments Inc., Chatsworth, CA) single axis piezoelectric accelerometer was used. This accelerometer has a reference sensitivity of 48.20 mV/g and a range of 100 g.

3.3.5 Shock Data Measurement on the Forklift

The Lansmont Saver 3x90 and Saver 3D15 were used to record the acceleration (peak, g), duration (msec), and change in velocity (in./s) that the forklifts in facilities exert while handling pallets and unit loads in the field. Scotch double-sided adhesive tape (3M, Maplewood, MN) was used to attach the sensors to the back of the fork tine carriage as seen below in Figure 3.2.



Figure 3.2: Sensor Placement for Field Data Collection.

The sensors were left attached to the forklifts for approximately 1-2 weeks per data collection trip. The settings applied to the saver 3D15 and Saver 3x90 can be found below in Table 3.1.

Record Time	100 msec
Signal Pre-Trigger	20%
Memory Allocation	100% Signal Triggered
Sampling Rate	5,000 samples/second
Sampling Size	500 samples
Filtering Frequency	250 Hz
Trigger Level	0.5 g

Table 3.1 Data Collection Settings for Saver Sensors.

Upon retrieval of the sensor from the field, the data was analyzed using Lansmont’s SaverX software (Lansmont Corp, Monterey CA, USA). To filter through the events recorded during each data collection trip, a minimum acceleration (peak, g) was selected to filter out any data that was too low to be considered an entry impact. The acceleration values used to filter out data were selected based off the minimum acceleration results from each forklift type, which was investigated by a previous laboratory study published by Masis, 2022. The values used to filter out data was 1.43 g for the manufacturing facility, 1.45 g for the LTL facility, and 1.43 g for the distribution facility. Once the events of interest were manually selected, the correct peak was selected within the software to ensure accuracy in the results, as the SaverX software automatically chooses peaks within each event. Peaks were chosen based of the visual characteristics of shock impacts of interest, based on previous laboratory testing. This same method of filtering out data was used for FasTrack testing. Pallet fasteners were additionally hammered back in during FasTrack testing, which is different than how the pallets may have been treated in the field.



Figure 3.3: Simulated Unit Load Utilized for the FasTrack Simulation (1,500 lbs).

3.3.6 Incline Impact Shock Testing

To record shock impact data on the incline impact tester, a single axis piezoelectric accelerometer was attached to the back carriage of the simulated fork tines as seen in Figure 3.4. This was the most similar application point for sensor placement used for both the FasTrack and field data collection.

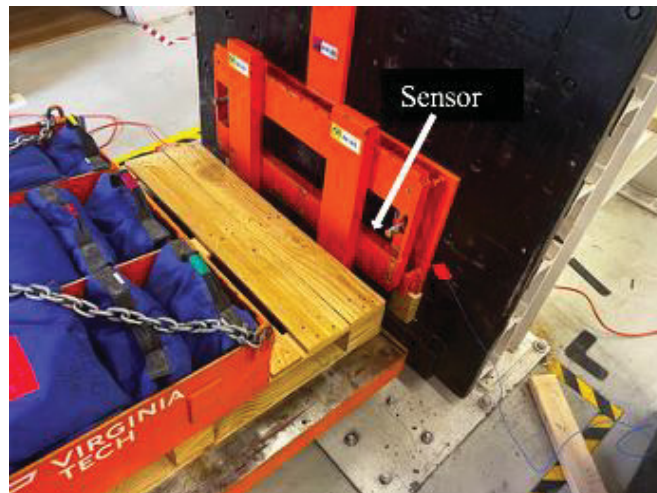


Figure 3.4: Incline Impact Sensor Placement

A nominal 48 in. x40 in. southern yellow pine pallet was impacted on the incline impact tester using 1 in. height increments starting at 12 in., and continuing through a total of six height increments. There was a total of three impacts at each incremental drop height. As the wooden pallet began to accrue damage, the lead deckboard would be replaced to remove any inconsistencies in the data due to damages. The lead deckboard was attached using screws so that upon damage to the pallet, the deckboard could be quickly removed and replaced. The pallet was

first loaded with a weight of 500 lbs. Two different fork tine orientations were investigated. The first measurements were completed following the requirement of ASTM D1185 (ASTM, 2017) testing standard where the fork tines were tilted down 4° below the top deck surface of the pallet. The underside of the lead edge of the pallet top deck board contacts the flat portion of the fork tines eight inches from the heel and slides uphill into the heels of the fork tines. This creates an upward sliding motion when the pallet contacts the fork tines, slowing the pallet down before contacting the simulated fork tines due to friction. The second set of measurements were completed by orienting the fork tines parallel to the top deck surface of the pallet to more accurately compare to the impacts which were investigated in the field. This removes the sliding action when the simulated fork tine contacts, allowing for the first point of contact to be between the lead top deckboard and the fork tine heel. For the wooden pallet, the lead deckboard was replaced as damage occurred, as damage to the pallet influenced acceleration (peak, g) results. The speed of the incline impact tester (in./sec), as well as the acceleration (peak, g) and duration (msec) of the shock impact were recorded for each drop. The shock values retrieved from the accelerometer were recorded using the Lansmont Test Partner 3 software (Dytran Instruments Inc., Chatsworth, CA).

3.4 Results and Discussion

3.4.1 Field Data Results

The acceleration values were collected during material handling operations conducted in three different types of warehousing facilities and during the FasTrack handling simulation. The summary table of the acceleration shock duration values for the investigated facilities are presented in Table 3.2. The cumulative density function (CDF) plot for the acceleration values at the investigated facilities can be seen below in Figure 3.4.

Over the four-week span of investigating the distribution facility and LTL facility only 25 and 245 events of interest were recorded, respectively. Over a three-week span, the manufacturing facility had 246 events. Events of interest were based off the visual characteristics of a shock impact, which can be defined as a sudden peak in the longitudinal axis, with little to no movement on the vertical and horizontal axis before or after the peak.

Percentile	Distribution		LTL		Manufacturing	
	Acceleration (peak, g)	Duration (msec)	Acceleration (peak, g)	Duration (msec)	Acceleration (peak, g)	Duration (msec)
60 th	2.22	9.00	4.83	7.2	3.70	6.00
80 th	4.29	15.80	6.60	10.56	4.76	6.00
90 th	5.13	27.20	7.80	13.58	5.46	8.00
95 th	9.05	31.25	9.22	15.54	6.53	8.00
Mean	2.80	10.73	4.74	7.42	3.50	5.44
Maximum	10.13	32.40	21.4	32.2	8.38	14.00

Table 3.2: Acceleration and Duration Values Measured for Three Investigated Facilities.

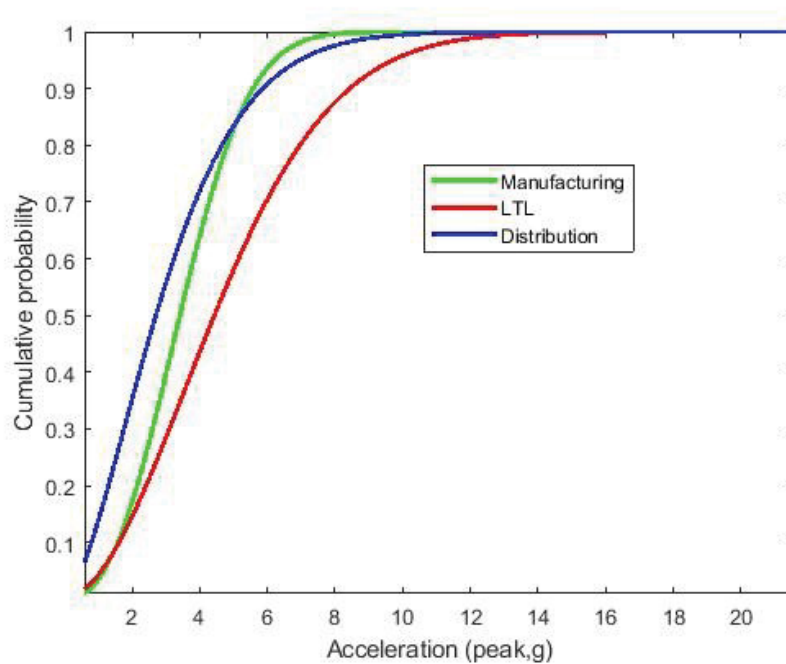


Figure 3.5: CDF Plot for the Peak Acceleration Values Measured for the Three Investigated Facilities.

The LTL facility that was investigated showed an average acceleration value of 4.74 g with an average duration value of 7.42 msec. The LTL facility yielded the highest acceleration results when compared to the manufacturing and distribution facilities investigated in the field. The maximum g-force recorded during the investigation at the LTL facility was 21.4 g. The 90th and 95th percentile of g-force recorded during the investigation of this LTL facility were 7.80 g and 9.22 g respectively. This LTL facility was investigated for four-weeks and yielded 245 events that were of interest.

The manufacturing facility investigated had an average acceleration value of 3.5 g and an average duration of 5.44 msec. The maximum acceleration value recorded during the study at the manufacturing facility was 8.38 g. The 90th and 95th percentile of acceleration values during the investigation at the manufacturing facility was 5.46 g and 6.53 g respectively. Over the 3-week period in which the manufacturing facility was investigated, a total of 246 events that were of interest and analyzed.

FasTrack Values		
Percentile	Acceleration (peak, g)	Duration (msec)
60th	5.32	7.80
80th	7.85	9.20
90th	10.26	11.00
95th	12.21	13.60
Mean	5.35	7.22
Maximum	20.28	21.20

Table 3.3: Acceleration and Duration Values Measured for FasTrack Simulation.

The FasTrack material handling simulation was investigated for three weeks, and recorded a total of 414 events that were of interest. The average acceleration value that was recorded during the investigation of FasTrack was 5.35 g with an average duration of 7.22 msec. The 90th and 95th percentile of acceleration values recorded were 10.26 g and 12.21 g respectively. FasTrack had a maximum acceleration value of 20.28 g. The summary table showing the acceleration and shock duration values is presented in Table 3.3. The cumulative density plot for the acceleration values can be seen below in Figure 3.5.

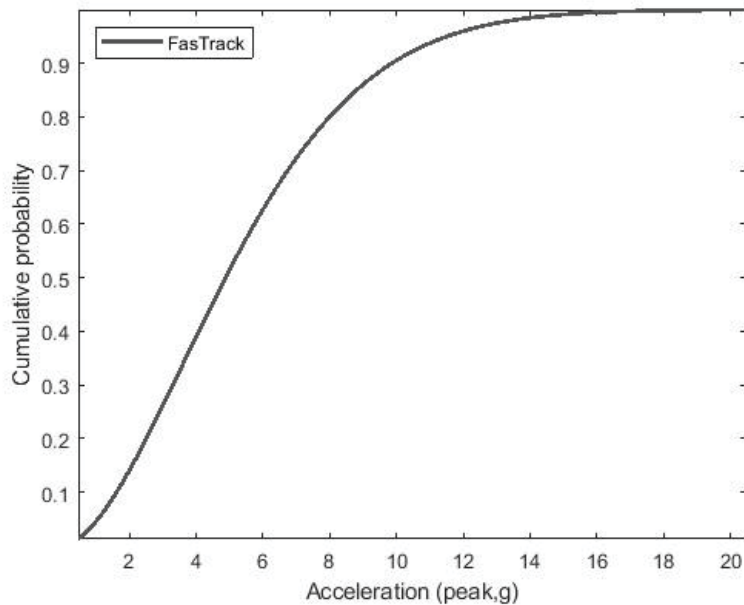


Figure 3.5: CDF Plot for Peak Acceleration Values Measured for the FasTrack Simulation.

Figure 3.6 below shows the combined CDF plot for the acceleration values for FasTrack and all three field facilities investigated. The shock events recorded during the Fastrack simulation were the most similar to values recorded in the LTL facility, with a mean peak acceleration value of 4.74 g and mean duration of 7.42 msec as seen in Table 3.4 below, whereas FasTrack yielded a mean peak acceleration value of 5.35 g and a mean duration of 7.22 msec. The LTL facility had the highest maximum g force acceleration value of all the facilities with a maximum of 21.4 g on a singular event, whereas FasTracks highest g force value recorded on a singular event was 20.28 g. This indicates that the conditions created during the FasTrack simulation are harsher (12-32%) than what generally can be observed in the field.

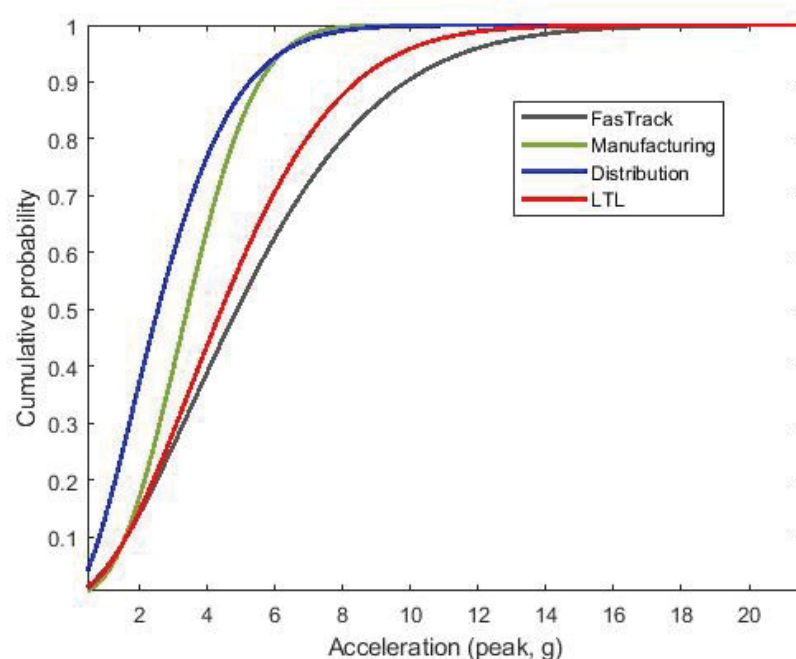


Figure 3.6: Combined CDF plot for Acceleration Values Measured for FasTrack and the Three Investigated Facilities.

Percentile	FasTrack		LTL	
	Acceleration (peak,g)	Duration (msec)	Acceleration (peak,g)	Duration (msec)
60 th	5.32	7.80	4.83	7.2
80 th	7.85	9.20	6.60	10.56
90 th	10.26	11.00	7.80	13.58
95 th	12.21	13.60	9.22	15.54
Mean	5.35	7.22	4.74	7.42
Maximum	20.28	21.20	21.4	32.2

Table 3.4: Comparison Between Peak Acceleration and Duration Values Measured for the LTL Facility and FasTrack

Through the investigation of these facilities, it was found that the LTL facility had the highest intensity of impacts on average at 4.74 g. Following the LTL facility, manufacturing facilities had the second highest average acceleration value at 3.5 g, with distribution facilities recording the lowest acceleration values with an average of 2.8 g. This being said the LTL facility also had the highest percentage of horizontal impact events that were of interest with 245 events recorded over a 4-week period. Contrary to the LTL facility, the distribution facility recorded the lowest number of events with only 25 events being of interest over 4 weeks. The LTL facility had the most horizontal (tied with manufacturing) impacts as well as the highest g-force value on

average while the lowest intensity impacts occurred at the distribution facility and also yielded the least amount of total impacts.

In terms of duration values seen during this investigation, the average duration (msec) for each facility was between 5.44 msec (manufacturing) and 10.73 msec (distribution), in which manufacturing facilities had the lowest duration of impact and distribution facilities had the highest.

3.4.2 Incline Impact Tests

The incline impact tests were first investigated using the four-degree slope as per the ASTM D1185 (ASTM, 2017) standard. The incline impact tests were done using only wooden pallets to measure shock values, as the majority of the pallets used in the facilities were wooden (McCrea, 2022). It was found that due to the slope of the incline impact tester, it resulted in much smaller duration values for each impact than what was observed during field trial investigation when a sensor was attached onto the forklifts. The average duration found during the initial incline impact measurement using the four-degree angle was approximately 5 msec, which is considerably lower than what was found during the field investigations as previously discussed in section 3.4.1. which on average was 7.86 msec. This may be due to the fact that there is a vertical component during the impacts on the incline impact tester, whereas in the field, no vertical movements were observed during field data collection.

The velocity of the incline impact tester was tracked in correlation to peak acceleration values, as the velocity of the incline impact tester is the best mode for controlling the impact intensity during testing. Therefore, it was important to correlate the velocity of the incline impact tester to peak accelerations of impacts to better understand the effect of velocity on impact intensity. The measured acceleration (peak, g) and velocity (in./s) values for wooden pallets are presented in Figure 3.9 and Figure 3.10 using a 4° slope. After completing the initial incline impact measurements using the 4°, the angle of the fork tines on the incline impact tester was modified to make it parallel to the top of the pallet to try to better replicate what was seen in the field. This change in the slope of the fork tines resulted in duration (msec) values that better resembled those that were recorded during field data collection, with an average duration of approximately 7 msec. This data was then fitted to attain a linear equation that would be able to give a velocity (in./s) that would return a desired acceleration (peak, g) value based on the

previously discussed field data. The correlations between impact velocity and acceleration using fork tines that were parallel to the top deck of the pallet are presented in Figure 3.10. The R^2 value in relation to the parameters (acceleration (peak, g) and velocity (in./s)) was 0.753 and 0.958 for the no sloped and 4° sloped fork tine simulators respectively. This shows that although different shock and duration were present when switching between different testing setups, the relationship between acceleration (peak, g) and velocity (in./s) remained significantly strong for both shock measurements. This demonstrates that velocity (in./s) on the incline impact tester is a good way of predicting shock impact values during incline impact testing. Through this correlation, a velocity (in./s) may be chosen to use during incline impact testing that produces a desired shock impact intensity that a pallet might experience during field material handling environments based on the values recorded during this study.

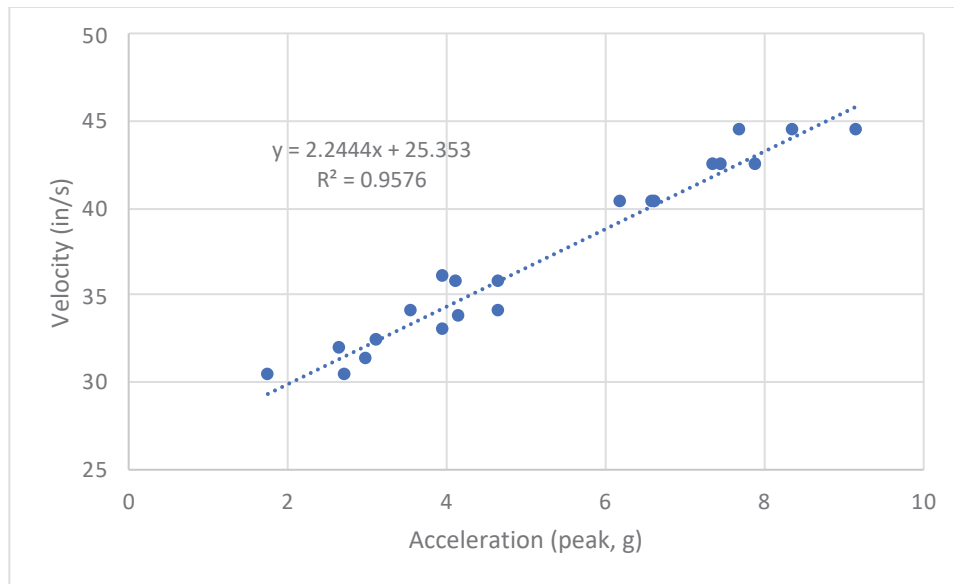


Figure 3.9: Peak Acceleration vs Impact Velocity Chart for the Incline Impact Test with Sloped Fork Tines Using Wood Pallet.

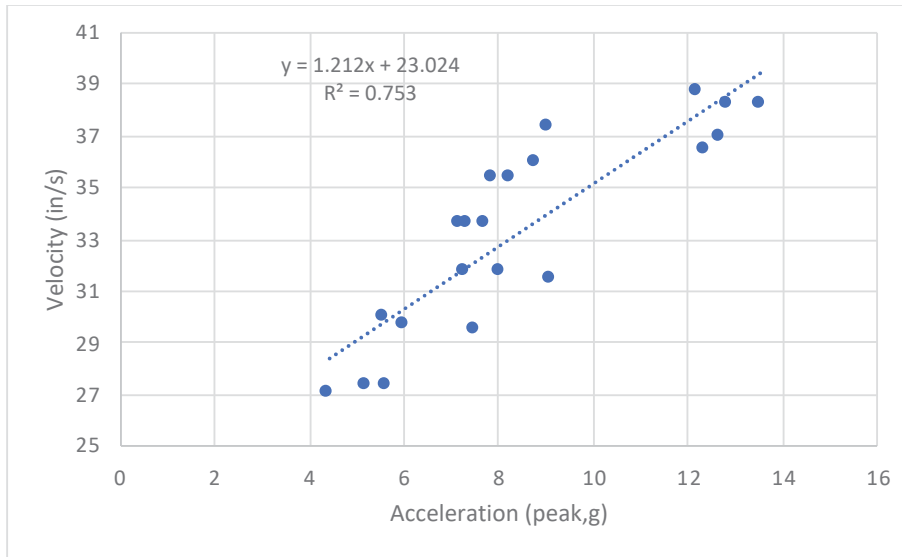


Figure 3.10: Peak Acceleration vs Impact Velocity Chart for the Incline Impact Test Without Sloped Fork Tines using Wooden Pallets.

The equations listed above in Figure 3.9 and Figure 3.10 can be used to predict a certain velocity based off a desired shock intensity level. If a pallet user identifies that their pallet will be sent through a more controlled and less harsh environment, the user would be able to select a less intense sequence of incline impact tests, such as the 60th percentile of data, that would better replicate the handling environment that their pallet will go through. If a pallet user identifies they would like to simulate the average shock impact values seen during the field investigation, the user can select the incline impact velocity associated with the mean acceleration (peak, g) value of the cumulative field data to simulate the average intensity of shock impacts seen in the field.

The incline impact predicted velocities associated with the cumulative data recorded in this study can be seen below in Table 3.5 for wooden pallets. The CDF plot for the cumulative field data can be seen below in Figure 3.11.

Wooden pallet linear equation: $y = 1.212x + 23.024$		
Percentiles:	Cumulative (peak, g)	Predicted Velocity (in./s)
60 th	4.12	28.02
80 th	5.57	29.77
90 th	6.83	31.30
95 th	7.88	32.57
98 th	9.58	34.64
99 th	12.55	38.24
Mean	4.06	27.95
*Maximum	21.4	48.96

Table 3.5: Predicted Incline Velocity Based on Field Acceleration Values.

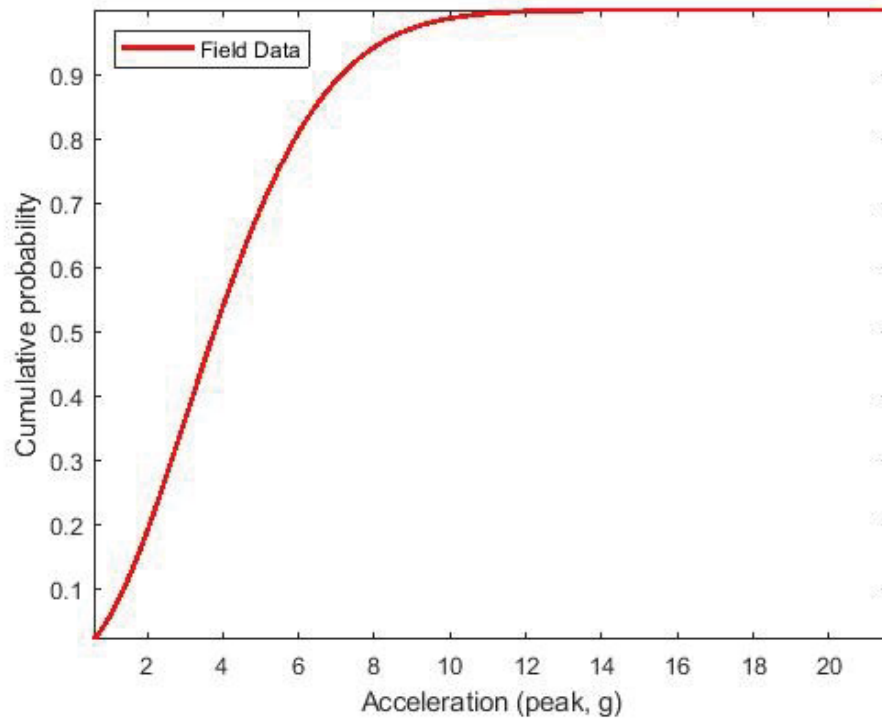


Figure 3.11: CDF Plot of Cumulative Field Data.

3.5 Conclusions

The conclusions of the study are presented below:

- The average duration of shock impacts in the Less-Than-Truckload (LTL), the distribution, and the manufacturing facility were between 5 - 11 msec.
- The shock duration (msec) during FasTrack simulation was similar to what was observed in the field with a mean of 7.22 msec.
- The LTL facility had the highest overall intensities in the field, with a singular shock event of 21.4 g, and an average of 4.74 g. Meanwhile, the distribution facilities had the lowest average g-force value of all the facilities investigated.
- FasTrack produced slightly higher acceleration values than what was found in the LTL facility with an average acceleration (peak, g) value of 5.35 g (11.4 % increase) indicating that the FasTrack simulation was the harsher of the material handling processes.
- Shock events measured in the field were found to be primarily horizontal with no adjacent vertical peaks.
- The when the required 4° slope was used for the fork tines during the incline impact test the measured shock durations were different than what is seen in the field, while orienting

the simulated fork tines parallel to the lead deckboard produces shock durations more similar to field results.

- There is a strong positive correlation between velocity (in./s) and acceleration (peak, g) on the incline impact tester, with an R^2 value of .75 and .96 for non-sloped and sloped fork tines, respectively.
- The recommended impact speed in ASTM D1185 is harsher than 99% of the impact acceleration observed in the field. The impact speed to represent 90% of the events would only be 31.30 in./s, when compared to the recommended 50 in./s.

The results of the study indicate that the FasTrack simulation reproduces the harsher handling processes in the field. In addition, the results of the study provide the distribution of impact intensities that packaging engineers can use to create different levels of handling during durability simulation.

Limitations

- The acceleration (peak, g) values may differ when investigating different facilities due to the weight of unit loads being variable.
- Only three different types facilities were investigated during this study, with a total of five facilities. Having a more robust dataset may help to produce more reliable results.
- The skills of the forklift operators working in the investigated facilities were not assessed during this study, as operators changed between facilities, as well as between forklifts.
- Most data recordings were done during a small window of time, as facilities may decrease or increase their forklift usage depending on the time of the year.
- The coefficient of friction values were not investigated for each facilities' differing floor characteristics, which may play a role in the shock values that were collected.
- The mass of the various forklifts and the incline impact tester backstop are different.

3.6 References

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