Investigation into Pallet Durability Throughout the Hazards that Pallets Experience During Regular Use and Handling

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ACADEMIC ABSTRACT

Pallet durability is a key characteristic with significant impact on a company's supply chain. Physical durability is defined as the number of trips that the pallet will accomplish before requiring repairs. Numerous studies have focused on understanding how durability is affected by different pallet components and warehouse environment characteristics. The VPI FasTrack is a testing sequence created to predict the performance of a pallet in a warehouse environment through different handling modes. However, this simulation has not been updated since its creation in 1993; therefore, a revision is needed to make it more closely reflect the behavior of a pallet in terms of durability.

The objective of the current research was to investigate the ability of the FasTrack procedure to replicate the damages caused by material handling and storage systems in modern warehouses. This investigation was conducted through visual inspections of the damages seen on pallets used in the field, and pallets tested with FasTrack. The results of this study show the differences between the simulation-tested pallets and those from the field. The FasTrack simulation focuses heavily on top lead deckboard and stringer damage. The occurrence of damage modes such as splits and missing wood, were identified for these components. It was found that most of the damages from this simulation are created due to forklift handling.

Because of substantial forklift handling damages, an experimental design was developed to investigate the effects of entry speed, payload, forklift type, and pallet design on the stresses exerted on a pallet, measured in terms of peak acceleration. The factors with the greatest effect on forklift peak acceleration and pallet peak acceleration were identified. The research shows that the acceleration in the pallet is approximately 4.4 times greater than the acceleration recorded in the forklift; however, the model of pallet acceleration based on forklift acceleration as a predictor shows poor performance.

Different modifications to FasTrack are proposed according to the findings of this research. It is advised that they continue the FasTrack procedure past the point of repairable damage in a pallet, which is the usual practice when pallets are handled in the field. Further investigation of steps such as the flow rack and the stack storage are proposed, due to their low damage output during the simulation. The experimental design also showed that different damage severity levels from the FasTrack simulation are possible with variations in top load and entry speed. These changes could improve the ability of the VPI FasTrack to replicate the damages that pallets experience in the field.

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GENERAL AUDIENCE ABSTRACT

Pallet durability refers to the number of uses that can be expected from a pallet before it needs to be repaired. Durability is an important performance characteristic, with a direct effect on the supply chain for any company. By further understanding how the warehouse environment and material handling systems affect pallet durability, companies can significantly reduce costs and improve their supply chain operations.

The FasTrack procedure was created to satisfy the need for an effective durability simulation procedure. Created in 1993, FasTrack features different handling modes and interactions with handling equipment to reproduce the damages that a pallet could suffer in a real warehouse environment. However, warehouse environments have changed since the creation of FasTrack, which makes it important to assess the performance of this procedure in predicting pallet durability.

The goal of this research was to investigate the ability of the FasTrack procedure to replicate the damages caused by material handling and storage systems in modern warehouses. This study was conducted through visual inspection of damaged locations, damage types, and damage severity levels for pallets used in the field and for pallets tested with FasTrack. The results obtained show differences between FasTrack and the field. The damage distribution in FasTrack for components of the pallet such as stringers and top lead deckboard is significantly higher than that measured in the field. The interaction of the pallet with the forklift could explain common damage modes, such as splits and missing wood, which were identified as the most damaged components in the pallets.

An experimental design was developed to investigate the effects of entry speed, top load, forklift type, and pallet design on the stresses produced during interactions between forklifts and pallets. This interaction was measured in terms of horizontal shock impact acceleration. The most influential factors for forklift and pallet peak accelerations were identified with this study. An opportunity to predict pallet acceleration with forklift acceleration was identified, which could allow further investigation of the FasTrack simulation compared to the field.

The results of the investigation show that FasTrack does not accurately reproduce the damages that pallets experience in the field. To improve the performance of the VPI FasTrack, the research proposes a revision of the steps during which damage output is low, such as the flow rack and the stack storage. The experimental design identified forklift entry speed and top load on the pallet as potential variables that could be customized in FasTrack, reflecting different severity levels based on a customer’s unique environment characteristics. These changes could improve the correlation of the damages seen from the FasTrack simulation and the field, which would grant the industry a more reliable prediction of pallet durability.

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Chapter 1 Literature Review and Research Objectives

1.1. Pallets

Defined as a “portable, horizontal, rigid, composite platform used as a base for assembling, storing, stacking, handling, and transporting goods as unit load” (MH1 Committee, 2005), pallets are a vital component in every industry that requires its goods to be stored or transported. The pallet industry in the United States is constantly growing; it’s driven by pallets’ major role in manufacturing, warehousing, and their functions in construction and other activities (The Freedonia Group, 2015).

In the early years, pallets had no bottom deckboards and were known as skids. From that point, several improvements, such as the addition of more deckboards, have enhanced its performance in handling systems, with increased durability, strength, and stiffness (LeBlanc and Richardson, 2003). The role of pallets during World War II proved their utility as a cheap solution for transporting food and supplies (Quesenberry et al., 2020). Since then, pallets have established themselves in the industry, with increasing demand in the United States and the rest of the world.

The number of pallets in the US during 2019 totaled 2.6 billion units and were predominantly made from wood, accounting for “84% of the total stock and 93% in sales, in unit terms” (The Freedonia Group, 2015). However, even though wood pallets are still the predominant, materials such as plastic and metal are slowly becoming more important due to characteristics like increased strength and resistance to environmental hazards (fungi and insects) that make them ideal for many industries (The Freedonia Group, 2015).

Due to its importance in the supply chain as a base for material storage and transportation, pallets are characterized according to factors such as their size, their intended use, class, and many more. These characterizations are possible thanks to the efforts of the Material Handling Standards Committee, responsible for the standardization of nomenclature, materials, and components for pallets. The committee is part of the American National Standards Institute (ANSI).

1.2 Pallet characterization

1.2.1 Class

The initial classification for pallets as defined in *ANSI MH1-2016 Pallets, Slip Sheets, and Other Bases for Unit Loads* is the Pallet Class. In this aspect, a pallet is classified as a Stringer Pallet when it is built with a double-deck, with stringers spacers between its decks (MH1 Committee, 2005). In the United States, the Stringer Pallet class is more popular (J. Clarke, 2004). The other important class is the Block Pallet; a pallet with blocks between its decks or beneath the top deck (MH1 Committee, 2005).

The main difference between pallet classes is dictated by the use of stringers (continuous beams) or blocks between the top and bottom deckboards. For stringer pallets, the use of these nominal 2x4 (1.5 in. x 3.5 in.) beams (most common size) may limit access with equipment such as pallet jacks or forklifts if there is no notch to allow access from all sides of the pallet (see entry type). Depending on the properties of said notch, the pallet may lose some of its strength, which can compromise the pallet's effectiveness. However, stringer pallets have less manufacturing complexity, resulting in lower production costs (J. Clarke, 2004). In the case of block pallets, six or nine blocks (most common) attached the deckboards allow access from all sides, granting flexibility in handling systems. Block pallets' advantage is that they allow for greater accessibility, as well as increased durability and strength when compared with stringer pallets. The disadvantage of the Block Pallet class over the stringer is that ir requires more complex manufacturing processes, which leads to a more expensive pallet.

(National Wooden Pallet and Container Association, 2016)

Figure 1.1. Block Pallet (left) and Stringer Pallet (right). The Stringer Pallet is illustrated without side notches, which limit forklift access only from the front or back.

1.2.2 Bottom deck construction

Based on the configuration of the bottom deck, four main constructions are described in *MH1-2016 Pallets, Slip Sheets, and Other Bases for Unit Loads*. The unidirectional construction is identified as when the bottom deckboards follow either the length or width of the pallet. The two-directional construction is that in which the bottom deckboards are oriented in both directions (length and width of the pallet) and the bottom deckboards overlap the stringerboards. The

Unidirectional construction is more popular among stringer pallets, but block pallets can also be built with this type of base (Morrissette et al., 2021).

The last two classifications according to the bottom deck construction are the perimeter and cruciform bases. For the perimeter base, three of the bottom deckboards are parallel with either the length or width of the pallet, while the two of the deckboards are perpendicular to the first three deckboards. Meanwhile, the cruciform base is similar to the perimeter base with an additional connector board. This type of construction can be seen in plastic pallets (Morrissette et al., 2021). Two different classifications according to the base are represented in Figure 1.2:

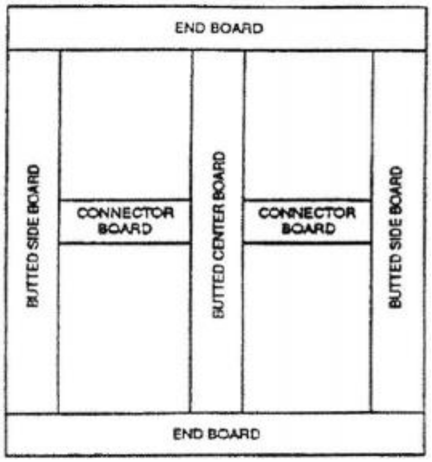


Figure 1.2. Perimeter and cruciform bottom deckboard constructions

1.2.3 Style

The standard identifies single face, and double face pallets, both reversible and non-reversible styles. Single face pallets feature deckboards on one side, destined to hold loads on one side only. When talking about double face pallets, non-reversible pallets feature deckboards on both sides, but only one of them is intended for holding load. The side that is not suitable for holding a load can be identified, as it usually has fewer deckboards. The double face, reversible pallets feature deckboards on both sides and can hold the load on both. Only non-reversible pallets can be handled using a pallet jack.

(National Wooden Pallet and Container Association, 2016)

Figure 1.3. Single face (left), double face, non-reversible (middle) and double face reversible pallet (right).

1.2.4 Entry type

According to their interaction with handling systems, pallets are classified as two-way or four-way. Two-way pallets can only be accessed from the ends of the pallet (on its length). Four-way pallets can be subdivided in partial four-way, a stringer in which handling equipment (forklift) can access from both ends, but the notch makes it inaccessible for a pallet jack. Finally, Full four-way pallets feature openings on both sides and ends (W x L) which grant accessibility with regular handling equipment, such as forklifts and pallet jacks. Block pallets are included within this category. The representation of the different entry types is presented in Figure 1.4:

(National Wooden Pallet and Container Association, 2016)

Figure 1.4. 4-way entry: Partial (left) and full (right)

1.2.5 Top deckboard overhang

Pallets are classified as flush when the top and bottom deckboards are even with the stringers. When the top deckboard is non-flush, the pallet is categorized as a single wing pallet. When both the top and bottom deckboards are non-flush, the pallet is called a double wing.

(National Wooden Pallet and Container Association, 2016)

Figure 1.5. Flush (Left), single-wing (middle), and double wing pallet (right)

1.2.6 Intended use

According to their intended use, it is possible to identify single-use pallets for one unit load trip, while Reusable pallets are designed for multiple unit loads (MH1 Committee, 2005). Stringer pallets can be either reusable or single-use, while block pallets are commonly for multiple unit loads.

1.3 Pallet size

Pallet size is measured in terms of length and width. For the MH1 standard, the size is defined as "overall dimensions of a pallet, stated in terms of length, followed by width and height.". To understand how these dimensions are measured, the MH1 standard sets a variety of guidelines. For a stringer pallet, the length is determined by the dimension of the side going the same direction of the stringer boards. In the case of a block pallet, the length is considered to be the side of the pallet that is parallel to the stringer board (MH1 Committee, 2005). When dealing with a pallet without stringer boards, the length is measured as the longest side of the pallet. Once the length has been identified, the width of a pallet is measured as the side perpendicular to the length. The overall height of the pallet is the dimension from the bottom deckboards to the top deckboards, measured from the bottom to the top. (MH1 Committee, 2005).

It is possible to find different sizes that better fit specific regions, as well as industries that require a specific pallet size. *ISO 6780: Flat pallets for intercontinental materials handling* specifies a size for each region:

Table 1.1. Regional size for pallets according to ISO 6780

	Dimensions	
Region	**in. x in.**	**mm x mm**
North America	48x40	1219x1016
Europe, Asia	47.24x39.37	1200x1000
Australia	45.90x45.90	1165x1165
North America, Europe, Asia	42x42	1067x1067
Asia	43.30x43.30	1100x1100
Europe	47.24x31.50	1200x800

Within the United States, the 48 in. x 40 in. is the most popular sized pallet, accounting for 35% of the total production each year (Gerber et al., 2020). However, other sizes are important depending on the industry in which they are used. Table 1.2 presents the different sizes used by industry in the US:

Table 1.2. Pallet size according to industry

Pallet size (in. x in.)	**Market Share (%)**	**Industry**
48x40	35	Grocery
48x48	6	Drums
42x42	5	Chemical
48x45	5	Automotive

40x48	4	Military
48x42	3	Chemical/Beverage
Other	42	Various

(Gerber et al., 2020)

The sizes vary from industry to industry, and among regions. However, actual sizes come from trends towards pallet size standardization (J. Clarke, 2004). As a regional effort, the grocery industry in the US standardized the use of the 48 in. x 40 in., which is widely used today in food and many other industries. Other criteria have been used to reach a standard (such as metric dimensions), recognition by ISO, and suitability for handling systems. This is the case of the EIPS Computer Industry Pallet Task Group, which selected the 1200 mm x1000 mm for its operations (J. Clarke, 2004). Aspects such as new technology in warehouses, shipping practices, and standards play a major role in the size each industry selects for its pallets.

When referring to market share, Gerber mentioned that the greatest percentage is of the 48 in. x 40 in. pallets used in groceries, followed by drums, chemical, and automotive industries. A relatively high percentage is other sizes, however, used in different industries.

1.4 Materials used for pallets

Technological advances, innovations, and changes in the market have had a significant impact on the materials used to create pallets; however, pallets were historically made of wood (J. Clarke, 2004). As wood has a significantly higher market share, its growth is limited; which leaves space for plastic, metal, and other materials to start developing (The Freedonia Group, 2015).

1.4.1. Wood

According to Freedonia, wood is still the predominant material for manufacturing pallets. As of 2019, 84% of the total pallet stock was comprised of wooden pallets, and these make up 93% of sales in terms of units (The Freedonia Group, 2015). Its popularity arises from the balance between its mechanical properties and low cost, which makes it attractive to the industry (The Freedonia Group, 2015).

Solid wood used to build pallets can be classified as hardwood or softwood; these two types species of wood can be differentiated according to their seeds. From a botanic perspective, hardwood is classified as Angiosperm, meaning its seeds are kept within the ovary of the flower; as for softwoods, these species are gymnosperms (or conifers) meaning their seeds are not enclosed in the ovary of the flower (Forest Products Laboratory, 2010). From their anatomy, hardwoods contain vessels, making them porous wood. In the case of softwoods, they do not contain vessels in their structure, so they are classified as nonporous. Finally, hardwoods usually have wider leaves that are lost in the autumn or winter, while softwoods feature cone-bearing plants with needle-like, evergreen leaves (Forest Products Laboratory, 2010). The most common classes for each species in the United States are presented in Table 1.3:

Table 1.3. Wood species classes in the US

North American Hardwood	North American Softwood
High-density eastern hardwood (Green ash)	Douglas-Fir
Medium-density hardwood (Big leaf maple)	Hem-Fir
Western Hardwoods (California black oak)	SPF
Low-density hardwood (Aspen)	Low-Density Softwoods
Eastern oaks	SYP

(MH1 Committee, 2005)

Softwood is purchased in two common commercially available lumber sizes: 2 x 4 (actual size 1.5 in. x 3.5 in.) and 2 x 6 (actual size 1.5 in. x 5.5 in.). Softwood lumber is typically bought kiln dry, up to 19% moisture content. Hardwood is characterized by its higher weight and stiffness (Clayton et al., 2019). However, due to its higher price, these species are usually bought as cants, with lower quality. These cants typically range from 8” to 16”, and can be bought kiln dried or green.

It is important to highlight that wood used to manufacture pallets is regional, which means not all species are available in specific areas. A map of the common species for various regions in the United States is presented in Figure 1.6:

(Park, 2015)

Figure 1.6. Wood species by region

The importance of wood as the main material in pallet construction is based on its good overall performance regarding physical properties, in balance with its price. It is important to highlight that the parameters used to describe pallet performance include strength, stiffness, and durability (MH1 Committee, 2005). Wood pallets are common because they represent a good balance of these parameters, and they are readily available (J. Clarke, 2004). Elements such as a pallet’s functionality in terms of its size, weight, and interaction with handling equipment shall also be considered. The performance of a wooden pallet is also linked to the wood species and grade.

Wood is easy to use when it comes to building pallets; designers can use software such as the Pallet Design System to prototype pallets (J. Clarke, 2004). This software allows creating pallets in a variety of combinations while giving the user the ability to perform analysis to help optimize pallet performance based on structure, load, and interaction with equipment used in the user's facilities.

Another critical aspect in favor of using wood for manufacturing pallets is its production flexibility, which allows manufacturers to change its deckboards, wood species, fasteners to suit users' needs. Lastly, wood can be recycled at the end of its life, allowing one to take advantage of this material for other purposes (LeBlanc and Richardson, 2003).

Wood has an established set of advantages that make it a significant option in the pallet market. These advantages can be summarized as wood is a recyclable, cost-effective, flexible material that can be modified to fit the user's requirements. However, wood also features disadvantages that require attention in order to prevent problems in the overall design of packaging systems.

Within these potential problems related to wood, biological factors are relevant. As wood is a natural material, it is subject to organisms that may produce a negative impact on its properties and functionality. Mold, sapstain, and decay are usually caused by fungi; microscopic organisms that require organic material and water for their sustenance (Forest Products Laboratory, 2010). These organisms decompose organic matter, discoloring wood pallets. Its spores grow in environments with a moisture content greater than 20%, and temperatures within 20°C - 32°C (Hammer, 2003). Mold does not immediately affect the structural integrity of the wood, but it creates a sanitary problem characterized by the dark discolorations and odor on the material. These fungi also increase the absorption properties of wood, which makes it more susceptible to future colonization (Forest Products Laboratory, 2010).

Insect infestation may also present a problem when working with wooden pallets. Take, for instance, the Ambrosia Beetle, which, as its larvae grow in the wood, produces black or blue stained holes (Hammer, 2003). While insect infestation might not compromise the structure, they constitute a sanitary problem incompatible with many industries (pharmaceutical for example). According to the Wood Handbook, there are counter measures, such as good housekeeping practices and drying procedures that are effective against mold and insects, but these countermeasures also represents an increase in cost for the pallets (Forest Products Laboratory, 2010).

The International Standard for Phytosanitary Measures covers mold and pest control regulations for wood in packaging applications. The ISPM 15 features a series of guidelines that apply to crates, boxes, and pallets (among others) to prevent the propagation of pests and other sanitary risks to local species. The regulations are based on the range of fungi and insects that can infest wood, the efficacy of the treatment, and the commercial/technical feasibility (International Plant Protection Convention, 2021).

1.4.2. Plastic

A plastic pallet can be made entirely of plastic, plastic composites, and new or repaired components (MH1 Committee, 2005). As with wooden pallets, plastic pallets can be single-use or reusable, and their entry types are similar to those seen in wood (two-way, partial, and full four-way). An important feature of this type of pallet is that they can be “nestable”, without a bottom deck, and containing hollow cups or other spacers that allow the adjacent pallet to fit securely together when stacked (MH1 Committee, 2005).

Apart from wood, plastic is the second most used material for manufacturing pallets with a third of users in the United States (Bond, 2018). When consulting the customer on this selection, the advantages of not having nails, while being easily stacked were both mentioned. Another important factor when selecting a plastic pallet is its increased durability, which is tied to its reusable, cleanable, and recyclable nature (Bond, 2018). Customer requirements and usage restrictions on wood were also factors taken into consideration when choosing plastic.

Plastic has been increasing in popularity for sanitary reasons among industries such as pharmaceutical, food, and beverage due to its resistance to insects and fungi (Horvath, 2015). Plastic pallets can also be easily cleaned if they ever do become contaminated. According to Freedonia, plastic pallets will see an increase in demand from 2019 to 2024, with a resin expectation of 1125 million pounds. HDPE is expected to be the most important resin for these pallets. As for the market share, Rehrig Pacific and ORBIS of Menasha are among the most important plastic pallet producers in the US (The Freedonia Group, 2015).

Plastic such as Poly Propylene (PP) can be either recycled or virgin, but virgin is generally preferred as the recycling process decreases the stiffness and strength of the pallet (Bugledits, 2019). To improve the structural properties of plastic pallets, fiber reinforcements can be added. Pallets including these reinforcements are classified as a ”composite” pallet (Bugledits, 2019).

Plastic pallets share similarities with wooden pallets in their common sizes: 48 in. x 40 in. is the most common (55%), followed by 48 in. x 45 in., with 29% (Bugledits, 2019). For plastic pallet manufacturing, the most popular methods include high-pressure injection molding (63% of cases) compression molding (17%), and low-pressure injection molding (15%). The main advantage of high-pressure injection over the other options is its ability to manufacture pallets with lower weight in faster cycle times, but the cost of tooling is high (Bugledits, 2019).

Among the major disadvantages of plastic pallets is that their manufacturing process is expensive, which results in higher-cost pallets (Horvath, 2015). This results in a market where larger firms or companies owned by bigger corporate entities, take the lead (The Freedonia Group, 2015). Contrary to wooden pallets, plastic is not as flexible, and its manufacturing process is slower. As far as physical properties go, plastic has lower friction and stiffness, which could lead to problems with stability and long term racking storage.

(MH1 Committee, 2005)

Figure 1.7. Pallets made from plastic

1.4.3. Metal

Pallets manufactured with steel, aluminum, or similar metals are classified as metal pallets (MH1 Committee, 2005). These pallets are usually similar in size and form to wooden/plastic pallets so that they can function with the same standard handling equipment. However, specific designs can be manufactured, to suit specific purposes within the industry. As with wooden pallets, metal pallets can be reusable; they are classified as multiple use if they last more than ten trips or limited use if they last ten trips or less. Single-use metal pallets are often manufactured to minimize cost and are expected to last one trip (MH1 Committee, 2005).

The market share for metal as a manufacturing material is not as vast as wood. Even though the data relating to the metal pallet market is not comparable to wood, its structural and sanitary properties make metal an increasingly favored option. Freedonia reports expected growth in metal from 9.6 million units in 2019 to 10.9 million as of 2024. However, manufacturers rarely specialize in only metal pallet construction; most make other products as well, such as bins, boxes, and crates (The Freedonia Group, 2015). Additionally, it is more common to see smaller companies involved in metal pallet manufacturing, and these manufacturers usually focus on local markets (The Freedonia Group, 2015). LM Containers (M-D Building Products) and SSI Schaefer Systems International (Fritz Shäfer, Germany) are leading companies in metal pallet manufacturing.

Most metal pallets are made of aluminum or steel. Steel has consistent strength and durability, as well as being immune to bug infestations. Its nonflammability and resistance to contamination due to being a non-porous material, are useful in various industries as well (MH1 Committee, 2005). To look at steel specifications, standards ASTM A 1008/A1008M-08 and ASTM A 1001/A 1011 M-08 are recommended.

Similar to steel, physical properties make aluminum a valuable option for manufacturing pallets. The main difference between these materials is the strength, density, and strength per unit volume (MH1 Committee, 2005). Aluminum is lighter than steel, but it is also weaker. aluminum will be more resistant to corrosion, while also preventing bacterial growth on its surface. Regarding cost, steel has the advantage of being cheaper but aluminum can be recycled infinitely without affecting its integrity or mass (MH1 Committee, 2005). The customer's choice are based on which material will satisfy their requirements for the intended application - which can include strength, weight, and resistance to environmental hazards.

When compared to other materials for pallets, metal presents greater strength, stiffness, and durability than wood, while also being washable and resistant to insects, which are advantages previously only seen in plastic. Metal offers great protection to the load and does not depend on fasteners. However, the main disadvantages include its high price compared to other materials and its increased weight. Metal can also present sharp edges and low friction, which are safety hazards in handling systems. When interacting with its environment, the biggest threat to metal pallets is corrosion; metal is susceptible to rusting.

1.4.4. Paper-based Pallets

Pallets made using corrugated/paper-based board, can be either single-use or reusable. The most popular materials in this category include corrugated fiberboard/paperboard; a board with kraft liner-board glued to a fluted medium (MH1 Committee, 2005). Solid fiberboard and honeycomb are also popular. Fiberboard is made of layers of paperboard together to increase their strength; while honeycomb is characterized by its hexagonal cell pattern to increase strength on the load-bearing side (MH1 Committee, 2005).

The advantages of paper-based pallets are their relatively stable weight and size compared to wood pallets. Corrugated pallets feature a lighter weight, which makes them useful in airfreight (Leblanc and Richardson, 2003). The main disadvantage of this material is its susceptibility to damage in humid environments; water is a threat to its performance.

1.5 Pallet durability

1.5.1 Definition

The durability of a pallet can be defined in terms of the number of trips that can be performed carrying a unit load, before requiring repair (MH1 Committee, 2005). Based on this definition, pallets are classified for single or multiple uses (reusable pallets). However, Wallin defines it from an economic life approach, which is the number of uses required to guarantee the cost per use is the minimized (Wallin & Whitenack, 1984). After that point in the life of the pallet, it becomes more expensive to repair it than just buy a new pallet. From a physical life perspective, a pallet’s durability is expressed as the number of trips before the damages make the pallet unusable.

The “number of uses” for a pallet depends on handling. A handling is defined as a single pick up, movement, and set down of a pallet, without taking into consideration if the pallet is empty or loaded (MH1 Committee, 2005). To move a pallet from a plant to another, an average of five handlings are needed. These movements/handlings are also called trips, and one year of pallet use typically consists of twenty trips (Wallin & Whitenack, 1984). Damages to pallets also depend on the unit-load handling environments. Pallets are subject to different hazards based on variable manufacturing processes, as well as warehouse and shipping practices (White & Wallin, 1987).

According to ASME MH1, in the 1997 version, durability is an important element included in the performance characteristics of a pallet, which determines its economic value. These performance characteristics also include strength, stiffness, and stability. These are the basis of the PDS software (American Society of Mechanical Engineers, 1997).

1.5.2 Related Concepts

Durability is related to a variety of concepts that can have an effect on and/or serve as a basis to understand durability. Among these concepts is the definition of damage, which is a critical element in durability assessments. Damage can be defined as a failure, harm, or deterioration, due to the use of the pallet, that reduce its physical properties. The damage will accumulate according to the use that is experienced by the pallet. It is measured in two main categories: frequency and severity. (American Society of Mechanical Engineers, 1997).

There is an associated cost and a cost per damage in pallet repair operations. The associated cost is the result of pallet repairs over the economic life of the pallet. The cost per damage is the specific cost to repair a type of damage (American Society of Mechanical Engineers, 1997). Damage frequency and damage severity are related to the durability of the pallet. Damage frequency refers to the number of damages sustained by a pallet during its lifetime (Wallin & Whitenack, 1984). Damage severity refers to the intensity of these damages. The PEP study, found a correlation between damage frequency and variables such as wood species, butted leadboards on pallets, moisture content, and fasteners (Wallin et al., 1972).

The PEP study computed damage frequency as the total number of damages found, divided by the total number of pallets tested. Based on Wallin (Wallin & Whitenack, 1984) equation 1 presents the relation of the damage frequency with the number of trips:

$$F = a^{U} - 1 \qquad (1)$$

Where a represents the damage factor (unique to each pallet), and F is the number of damages. The number of trips is represented with U (Wallin, 1984).

Damage severity is important because different levels of damage may compromise a pallet's strength, structure, and ability to fulfill its purpose differently. Damage severity also affects the cost of repair. To measure the severity, the PEP study presents a scale considering the severity level (minor, moderate, and severe), the component of the pallet suffering the damage, and the description of the damage in each case. This scale considered numbers 1-3 as minor damages, 4-6 as moderate; and 7-9 as severe damages.

The severity of the damage is related to the final cost of damage. The PEP study relates the severity scale with cost values coming from empirical data. A regression model for the cost (C_d) based on the severity of damage (S_d) is presented in equation 2:

$$Log\ (C_d) = a + b\ (S_d) \qquad (2)$$

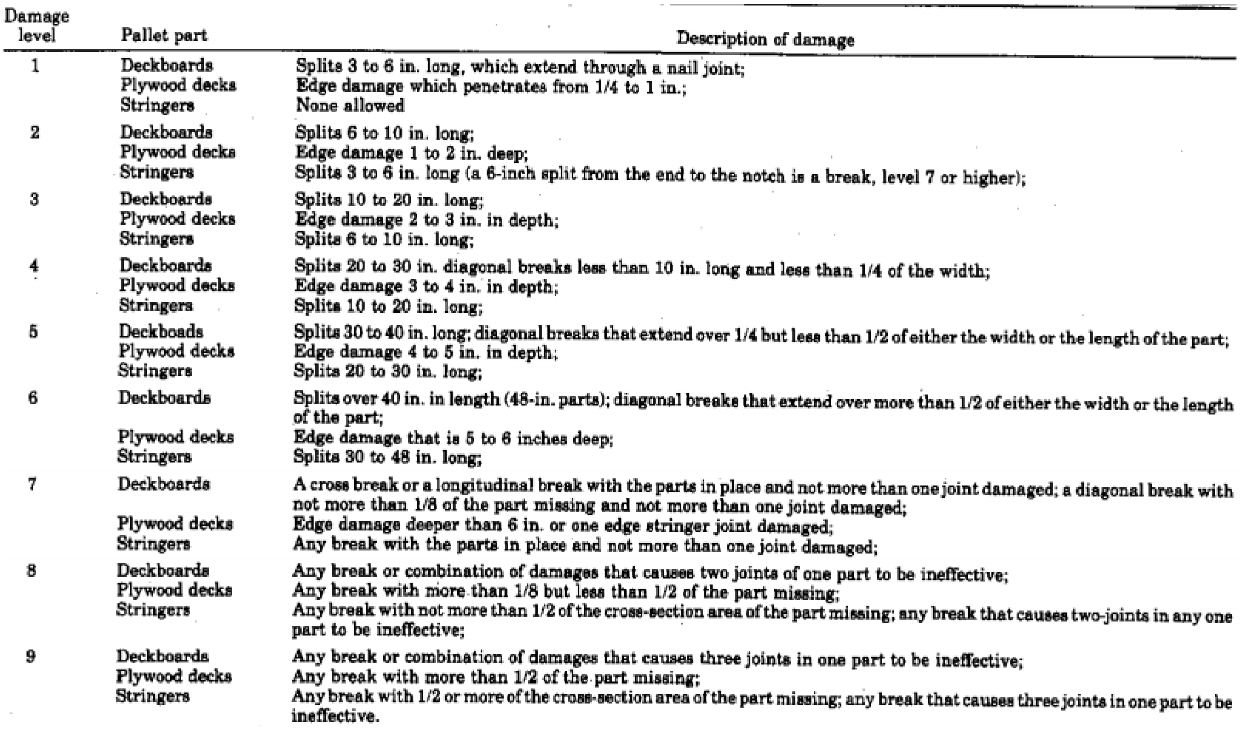
With this equation, the damage costs according to severity are in Table 1.4:

Table 1.4. Damage costs according to the severity of damage

Severity Class	Severity Code	Damage Cost ($)
Minor	1	0.059
	2	0.089
	3	0.133
Moderate	4	0.200
	5	0.300
	6	0.450
Severe	7	0.675
	8	1.013
	9	1.519

(Wallin et al., 1972)

Higher levels of severity are related to higher damage costs. Fastener quantity, fastener quality and wood species also affects severity. In their work, White and Wallin (1988) present the severity of damage scale, with the principal damages associated with each category:



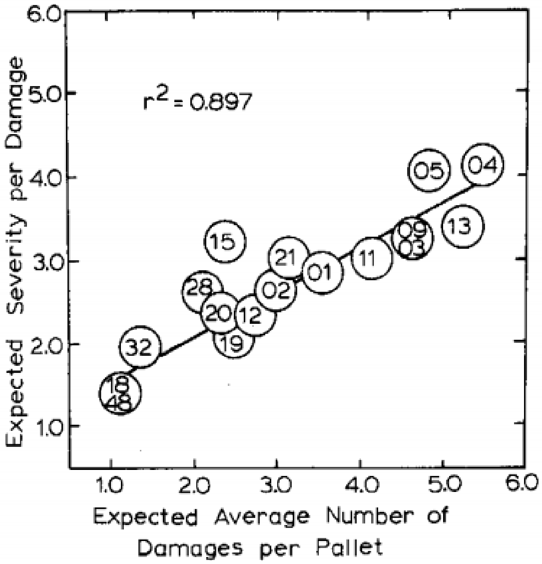
Damage level	Pallet part	Description of damage
1	Deckboards	Splits 3 to 6 in. long, which extend through a nail joint;
	Plywood decks	Edge damage which penetrates from 1/4 to 1 in.;
	Stringers	None allowed
2	Deckboards	Splits 6 to 10 in. long;
	Plywood decks	Edge damage 1 to 2 in. deep;
	Stringers	Splits 3 to 6 in. long (a 6-inch split from the end to the notch is a break, level 7 or higher);
3	Deckboards	Splits 10 to 20 in. long;
	Plywood decks	Edge damage 2 to 3 in. in depth;
	Stringers	Splits 6 to 10 in. long;
4	Deckboards	Splits 20 to 30 in. diagonal breaks less than 10 in. long and less than 1/4 of the width;
	Plywood decks	Edge damage 3 to 4 in. in depth;
	Stringers	Splits 10 to 20 in. long;
5	Deckboads	Splits 30 to 40 in. long; diagonal breaks that extend over 1/4 but less than 1/2 of either the width or the length of the part;
	Plywood decks	Edge damage 4 to 5 in. in depth;
	Stringers	Splits 20 to 30 in. long;
6	Deckboards	Splits over 40 in. in length (48-in. parts); diagonal breaks that extend over more than 1/2 of either the width or the length of the part;
	Plywood decks	Edge damage that is 5 to 6 inches deep;
	Stringers	Splits 30 to 48 in. long;
7	Deckboards	A cross break or a longitudinal break with the parts in place and not more than one joint damaged; a diagonal break with not more than 1/8 of the part missing and not more than one joint damaged;
	Plywood decks	Edge damage deeper than 6 in. or one edge stringer joint damaged;
	Stringers	Any break with the parts in place and not more than one joint damaged;
8	Deckboards	Any break or combination of damages that causes two joints of one part to be ineffective;
	Plywood decks	Any break with more than 1/8 but less than 1/2 of the part missing;
	Stringers	Any break with not more than 1/2 of the cross-section area of the part missing; any break that causes two-joints in any one part to be ineffective;
9	Deckboards	Any break or combination of damages that causes three joints in one part to be ineffective;
	Plywood decks	Any break with more than 1/2 of the part missing;
	Stringers	Any break with 1/2 or more of the cross-section area of the part missing; any break that causes three joints in one part to be ineffective.

(White & Wallin, 1987)

Figure 1.8. The severity of damage description

The scale in Figure 1.8 presents damages to stringers and deckboards and plywood decks. These results are based on the assessment of 17 different pallet designs, varying in component width, thickness, wood species, and the number of fasteners.

The severity of damage and the damage frequency are related. White and Wallin (1988) plotted the expected average number of damages per pallet and found that nearly 90% of the variation in the severity of damage is explained by changes in damage frequency. This plot is in Figure 1.9:



(White & Wallin, 1987)

Figure 1.9. Severity of damage vs damage frequency.

The R^2 obtained in the model is approximately 0.9, which supports a strong relationship between severity of damage and damage frequency. As a pallet receives damage more often, the severity of the damages is expected to increase as well. The cumulative damage per number of handlings in Figure 1.10. The relationship between the number of trips before the first damage and the cumulative damage is significant ($R^2 = 0.74$).

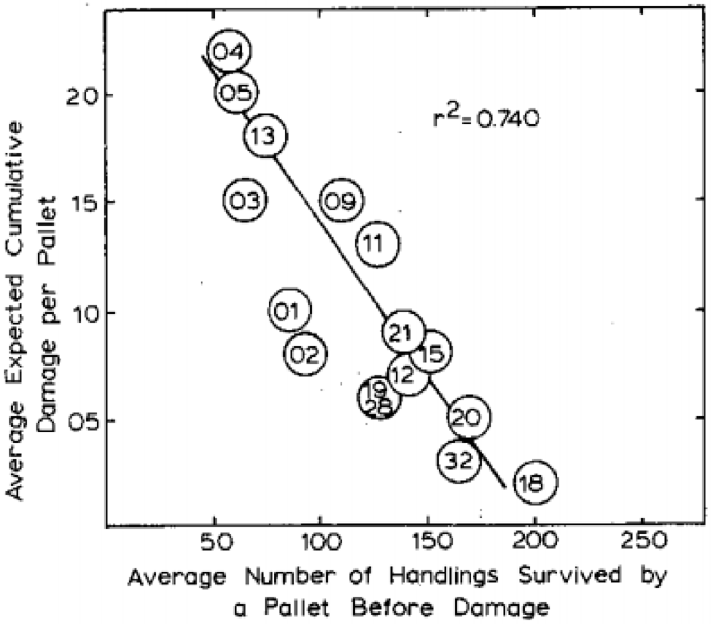


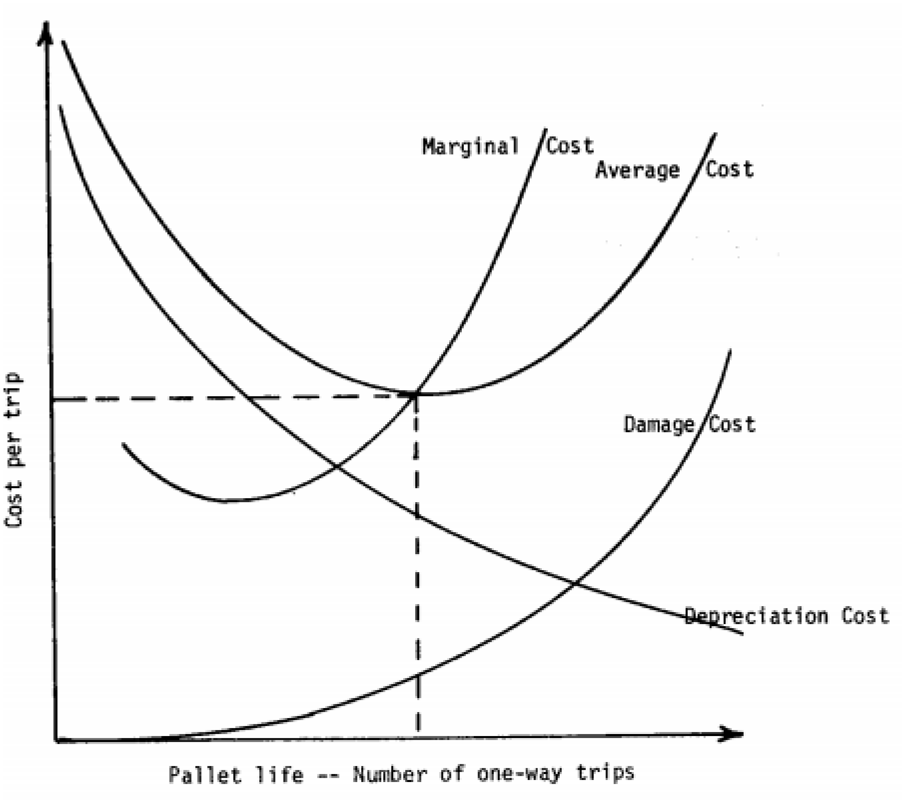
Figure 1.10. Expected cumulative damage vs handlings before damage

Source: (White & Wallin, 1987)

Durability is defined from an economic standpoint; the number of trips (U) a pallet can be used, along with the severity and the damage rates, to provide an average cost per trip of the pallet:

$$A_t = \frac{P + c * b^S * F}{U} \qquad (3)$$

Where P is the purchase price of the pallet, c and b are the economical and pallet design coefficients respectively. F is the number of damages in equation 1, and b=1.5 when using lumber pallets. S is the severity of damage. The economic model of durability is in Figure 1.11:



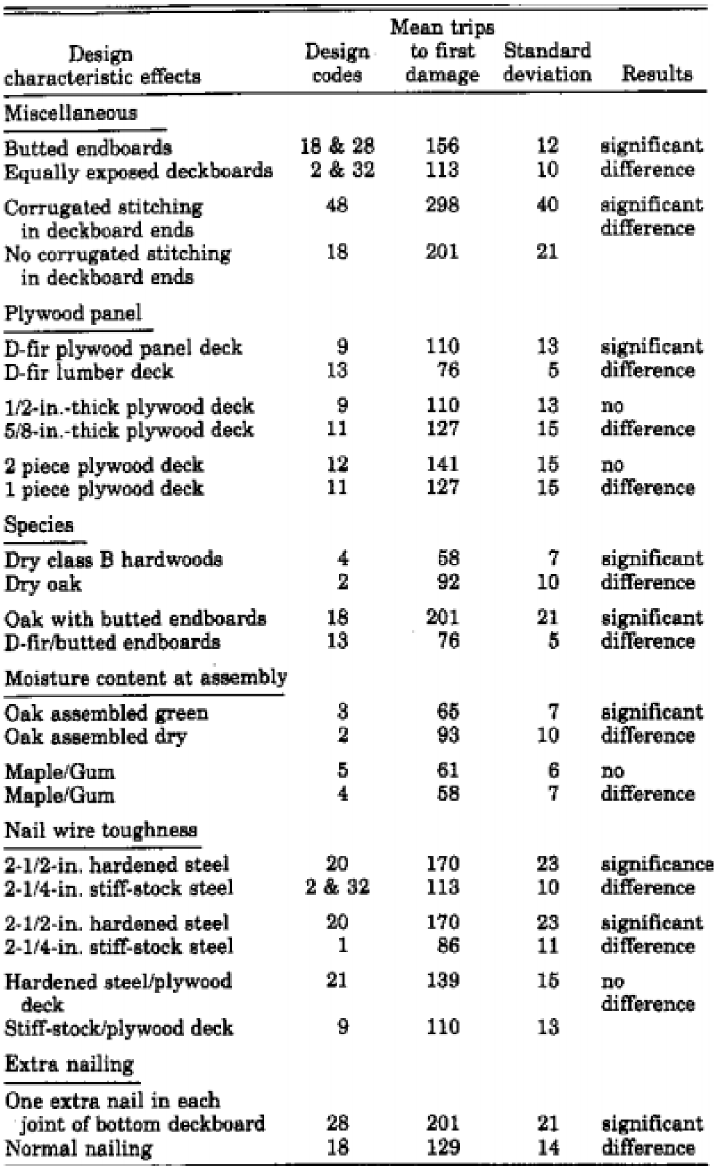
(Wallin & Whitenack, 1984).

Figure 1.11. Economic model for pallet life and cost per trip

The minimum cost is obtained when the slope of the average cost is zero. This minimum cost is also obtained when the average cost is equal to the marginal cost of the pallet. The optimal life of a pallet can be established if the user finds the U value at the minimum average cost (A) of the pallet.

1.5.3. Variables that affect durability

White and Wallin (1988) evaluated 17 pallet designs, recording the number of handlings each pallet survived before damage occurred, and the severity and frequency of damages once the damages occurred. Their results are in Figure 1.12.



Design characteristic effects	Design codes	Mean trips to first damage	Standard deviation	Results
Miscellaneous				
Butted endboards	18 & 28	156	12	significant difference
Equally exposed deckboards	2 & 32	113	10	
Corrugated stitching in deckboard ends	48	298	40	significant difference
No corrugated stitching in deckboard ends	18	201	21	
Plywood panel				
D-fir plywood panel deck	9	110	13	significant difference
D-fir lumber deck	13	76	5	
1/2-in.-thick plywood deck	9	110	13	no difference
5/8-in.-thick plywood deck	11	127	15	
2 piece plywood deck	12	141	15	no difference
1 piece plywood deck	11	127	15	
Species				
Dry class B hardwoods	4	58	7	significant difference
Dry oak	2	92	10	
Oak with butted endboards	18	201	21	significant difference
D-fir/butted endboards	13	76	5	
Moisture content at assembly				
Oak assembled green	3	65	7	significant difference
Oak assembled dry	2	93	10	
Maple/Gum	5	61	6	no difference
Maple/Gum	4	58	7	
Nail wire toughness				
2-1/2-in. hardened steel	20	170	23	significance difference
2-1/4-in. stiff-stock steel	2 & 32	113	10	
2-1/2-in. hardened steel	20	170	23	significant difference
2-1/4-in. stiff-stock steel	1	86	11	
Hardened steel/plywood deck	21	139	15	no difference
Stiff-stock/plywood deck	9	110	13	
Extra nailing				
One extra nail in each joint of bottom deckboard	28	201	21	significant difference
Normal nailing	18	129	14	

(White & Wallin, 1987)

Figure 1.12. Durability hypothesis test according to design characteristics

According to the PEP study, butted boards seem to reduce the damage frequency for both hardwood and softwood pallets. In hardwood pallets, reduction due to the use of butted boards accounted for 20%, while softwoods presented the drastic damage frequency reduction of 90% (Weigel, 1998). As seen on the hypothesis test, butted endboards have a significant effect on the mean number of trips required for a pallet to show its first damage occurrence, making pallets more resistant to damage (White & Wallin, 1987).

The PEP study found that, on average, pallets built with hardwood species had a higher damage frequency compared to softwood pallets. This increased damage frequency was up to 50% higher (Weigel, 1998). In lumber pallets, wood species has a significant effect on durability; pallets made of oak were better than maple and gum by 38%, and vastly superior than pallets made of Douglas-fir, by 165% (White & Wallin, 1987). For pallets that share a similar design, this increased durability is assumed to be related to the physical and mechanical properties of the wood species used to build them.

Pallets with green boards were affected by up to60% more damage frequency than dry pallets (Weigel, 1998). It was found that air-dried hardwood lumber improved durability by 43% compared to green decking. However, this variation is most significant in dense hardwoods. Regarding intermediate-density wood species, moisture content did not have as significant an effect (White & Wallin, 1987).

Damage frequency is also affected by both fastener type and number of fasteners per joint (Weigel, 1998). Steel nails were shown to reduce damage frequency by 12% compared to stiff-stock nails. Pallets using three nails per joint were reported to suffer 5% higher damage frequency when compared with pallets with four nails per joint. The number of fasteners and their location in the pallet was proven to influence pallets' resistance to damages, improving them up to 56% just by adding an extra 5% to 6% more fasteners (White & Wallin, 1987).

ASME (1997) established a relation between the findings in the PEP study, and their influence over damage severity (s) and damage frequency (r). These pallet damage factors include:

$F(1) = Fastener\ withdrawal\ resistance$

$F(2) = Fastener\ shear\ resistance$

$F(3) = Connection - splitting\ resistance$

$F(4) = Shook\ quality$

$F(5) = Shook\ quality\ placement$

$R(1) = Flexural\ strength\ of\ stringers$

$R(2) = Flexural\ strength\ of\ decks$

$R(3) = Deck\ construction$

$R(4) = Material\ handling\ environment$

Factors F (1), F (2), and F (3) are related to fasteners and their shear/ withdrawal resistance. The material (design or structure), and the flexural strength of stringers and decks are in factors F (4), F (5), and R (1) to R (3) respectively. The handling system influences the durability of the pallet, as included with the R (4) factor.

Based on factors F and R, damage frequency (r) is defined as:

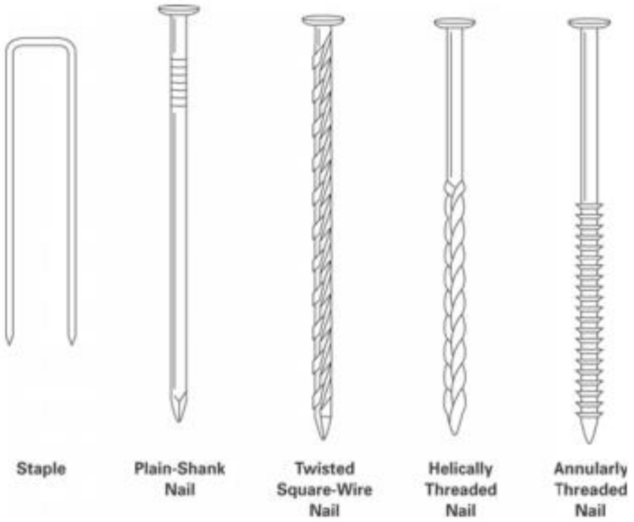
$$r = [1 + F(1)][1 + F(2)][1 + F(3)][1 + F(4)][1 + F(5)]x[1 + R(1)][1 + R(2)][1 + R(3)][1 + R(4)][0.01] \qquad (4)$$

Damage severity is obtained with:

$$S = [1+F(1)][1+F(2)][1+F(3)][1+F(4)][1+F(5)]x\left[1+\frac{R(4)}{2}\right][2.0] \quad (5)$$

1.5.4. Fastener Effect on Durability

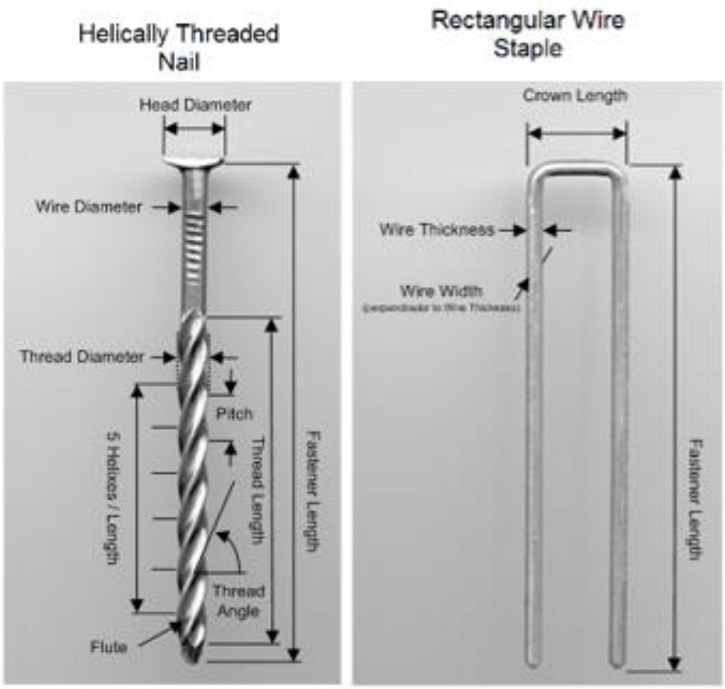
There are several classifications for driven nails, which include plain shank nails, as well as helically and annularly threaded nails. Fluted and twisted square wire nails are also counted in the driven nails' category. In the case of staples, these are differentiated by their round wire or square wire legs (MH1 Committee, 2005). Different fastener types are in Figure 1.13.



(MH1 Committee, 2005)

Figure 1.13. Different fastener types

Fasteners are specified with either a description of their physical and mechanical properties, specification of their connection design properties, or a combination of both. These physical characteristics are in Figure 1.14.



(National Wooden Pallet and Container Association, 2016)

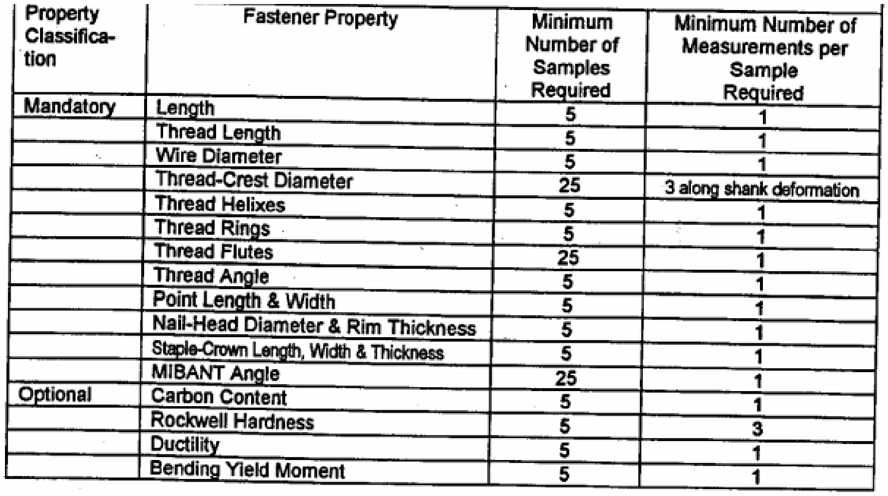
Figure 1.14. Physical characteristics for measurement (nails and staples).

The most important characteristic of a nail includes the head diameter, whose shape is most commonly oval instead of circular. The head diameter is the average of the smallest and largest diameters (Stern & White, 1997). The wire diameter is defined as the distance across the non-threaded portion of the nail, without considering the gripper marks (MH1 Committee, 2005). For plain-shank, helically-threaded, and round wire nails, the wire diameter can be obtained with a micrometer. The thread crest diameter is the distance measured from crest to crest in the nail. He diameter is measured in three different locations to account for any deformation in the nail. A total of 25 randomly selected nails is required as as a minimum for fastener sampling (Stern & White, 1997).

The thread angle is measured from a plane perpendicularto the axis of the fastener, usually obtained after rolling the nail against a sheet of carbon paper. Another way of obtaining its value is with the following equation:

$$TA = ARCTAN\left[\frac{F}{TD*\pi*\frac{H}{TL}}\right] \qquad (6)$$

Where F is the number of flutes along the nail shank, TD is the thread crest diameter (average value in inches) and H is the number of helixes along the shank. TL represents the thread length, in inches. It is recommended that the angle be rounded to the nearest degree (Stern & White, 1997). To properly characterize a fastener, the proposed sampling design is in Figure 1.15:



Property Classification	Fastener Property	Minimum Number of Samples Required	Minimum Number of Measurements per Sample Required
Mandatory	Length	5	1
	Thread Length	5	1
	Wire Diameter	5	1
	Thread-Crest Diameter	25	3 along shank deformation
	Thread Helixes	5	1
	Thread Rings	5	1
	Thread Flutes	25	1
	Thread Angle	5	1
	Point Length & Width	5	1
	Nail-Head Diameter & Rim Thickness	5	1
	Staple-Crown Length, Width & Thickness	5	1
	MIBANT Angle	25	1
Optional	Carbon Content	5	1
	Rockwell Hardness	5	3
	Ductility	5	1
	Bending Yield Moment	5	1

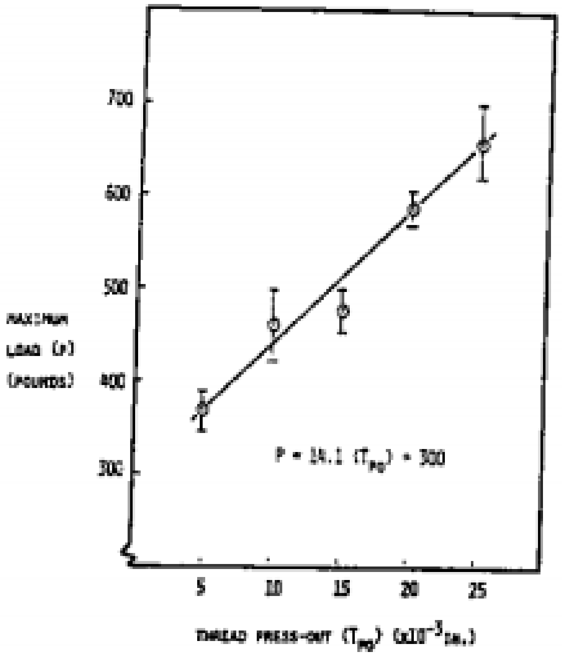
Figure 1.15. Fastener sampling.

This provides enough information about the physical and mechanical properties of the fastener. As optional measurements, the carbon content, ductility, and Rockwell hardness can be obtained as well.

To measure the resistance of a fastener to bending, the MIBANT test is performed. This test has been proven to be reliable when compared to other methods that measure the bending resistance of fasteners (MH1 Committee, 2005). The bend angle is based on a 3.5 lb. weight; however, weights of 2 lb. and 0.75 lb. can be used with the tester (requiring a correction factor of 1.75 and 4.70 respectively). Lighter weight is used when the fastener is “too soft”, obtaining an angle past the reasonable angle (46°).

The National Wooden Pallet and Container Association (NWPCA) classifies fasteners based on their bending resistance. This classification divides hardened steel nails (angles 8°-28°), stiff stock nails (29°-46°), and soft steel nails (46° and up). The most significant components for fastener quality are the wire diameter-thread crest diameter difference, and the bending resistance, which have a close relationship with the most common failure causes in pallets: head-pull through resistance and withdrawal resistance (White, 1990).

Average withdrawal resistance as a function of thread crest diameter press out is in Figure 1.16.



(White, 1990)

Figure 1.16. Average adjusted maximum withdrawal resistance

The thread crest diameter is an important characteristic for withdrawal resistance. Pull-through failure is often due to the species of the wood and its thickness, as well as the fastener's head diameter. As the nail bends, it will split the wood; the deckboard pulls off and leaves the nail in the stringer. The more the nail bends, the more common it is to find this failure (White, 1990).

A series of equations are used to compute the performance characteristics of the fasteners. These formulas compare the performance of a nail to the characteristics of a base nail, which is a representative standard. In the case of the base nail, it is a helically threaded nail made of steel with a length of 1.75 to 2.5 in. (MH1 Committee, 2005). The wire diameter and thread crest diameter are 0.0112 in. and 0.132 in. respectively, with a 60° thread angle. The fastener has four thread flutes and 5.25 helixes per inch of penetration. This standard nail is known as the $1^{3/4}$ to $2^{1/2}$x112 AA, and its withdrawal resistance is known to be 100. The fastener withdrawal index (FWI) is computed as follows:

$$FWI = 221.24\ (WD)[1 + 27.15\ (TD - WD) * (\frac{H}{TL})] \qquad (7)$$

Where WD and TD are the wire diameter (average) and the thread crest diameter (average) in inches. H is the observed number of helixes in the fastener, and TL is the thread length. For fasteners with set physical properties (WD, H, and TL), the effect in the withdrawal index is produced by the difference between thread crest diameter and wire diameter (White, 1990).

The shear index is a measure of the estimated shear resistance for a determined fastener. This measurement is based on a comparison to a base fastener; depending on the wire diameter and the impact shear resistance of the nail, which is obtained with the MIBANT test. The base fastener in this case has a MIBANT angle of 20°. The computation of this index is given by:

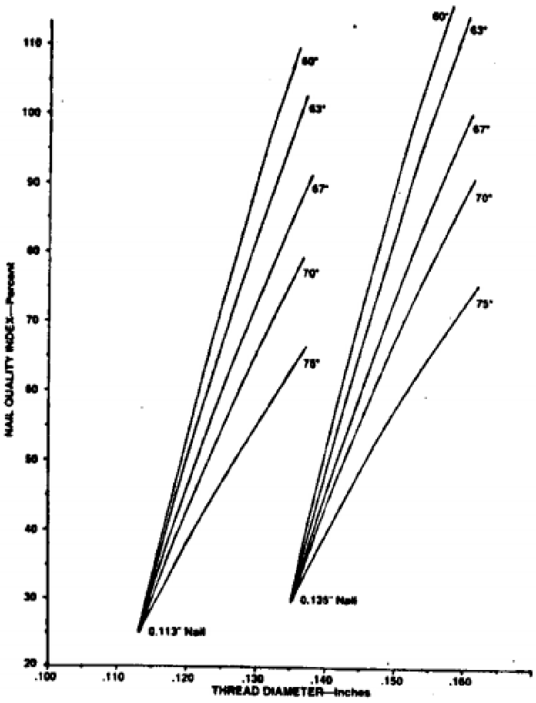
$$FSI = \frac{263.260WD^{1.5}}{(3M+40)} \qquad (8)$$

Where WD is the wire diameter for the specific fastener (either measured as an average or computed), and M is the MIBANT angle, measured in degrees using the standard weight for the test (3.5 lb.).

The FWI for fasteners is presented as a fraction of the base nail. An FWI=50 means that the current nail is 50% as resistant as the base nail. To better understand the relation between the FWI and the physical properties of the nail, Figure 1.17 is presented. In this case, the thread diameter for 0.113 in. and 0.135 in. nails are compared, along with different thread angles. To achieve a performance of 80% that of the base nail with a 0.113 in. nail, it is required that the nail have an angle of 67° and approximately 0.130 inches in thread diameter.

The fastener withdrawal resistance, F (1), is a computation based on three elements: the FWI, the moisture content (MC), and the specific gravity (GS) of the wood. The relationship between these concepts is shown through the FWR. The fastener withdrawal resistane measures the influence of the strength of the joints, and its effect on both severity and frequency of damage (Wallin & Whitenack, 1982a).

To obtain the Fastener Withdrawal Resistance (FWR), it is necessary to consider the FWRF (fastener withdrawal resistance for a single nail) and the head pull-through resistance for a single fastener (HPR). This is because the FWR is obtained as the lesser value of these two. Both the FWRF and HPR consider moisture content and specific gravity in their computations.



(Wallin & Whitenack, 1982a)

Figure 1.17. Fastener withdrawal index for 0.113" and 0.135" nails.

The shear resistance factor is referred with F(2). The fastener shear resistance factor relates the shear resistance index,the moisture content, and the specific gravity of the wood. The connection between the shear index, the specific gravity, and moisture content is derived from the FSR.

The shear resistance factor measures the stiffness of the fasteners and the nailing pattern (Wallin & Whitenack, 1982b). This factor is obtained with the load required to shear the fasteners when a torsional load is applied parallel to the deck. The number of fasteners used and the MIBANT angles are important for fasteners. The couples are computed based on the number of fasteners per joint:

Table 1.5. Fastener couples in the pallet

Fasteners/Connection	2	3	4	5
Couples/Connection	1	3	4	5

(American Society of Mechanical Engineers, 1997)

The pallet joint shear resistance computation relates the shear resistance of a base pallet, with any other pallet. The base pallet is built with dense hardwoods, and 13/16 in. deckboards. Its specific gravity is 0.60, and the moisture content 25% (Wallin & Whitenack, 1982b). The pallet uses 0.113 in. helically threaded, hardened-steel nails. The formula is:

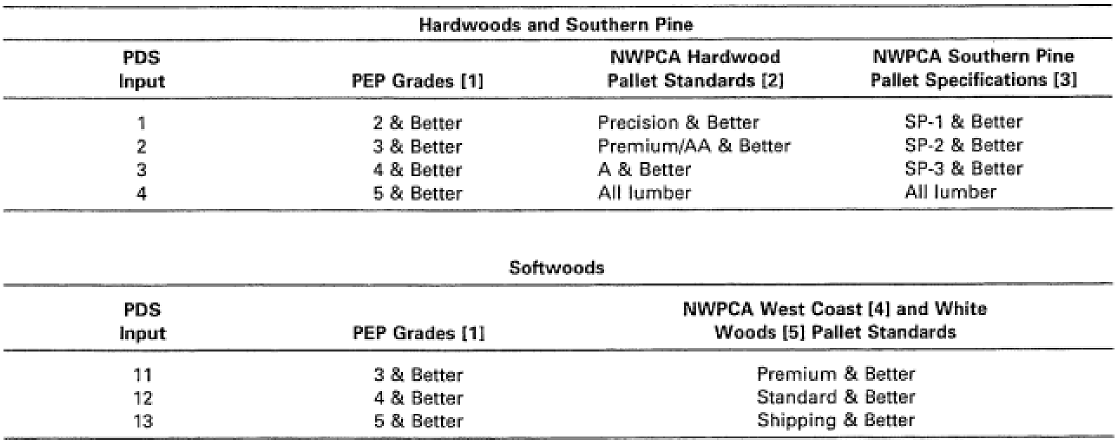
$$F\ (2) = \left(\frac{53\ 376}{FSR}\right)^{0.5} - 1 \qquad (9)$$

The factor for connection-splitting resistance F (3) is computed with the wire diameter location, as well as thickness and specific gravity of the deckboards. For pallets whose edge stringers' width is greater or equal to 47.625 mm (as well as winged-type and block pallets) F (3) is 0.00 (American Society of Mechanical Engineers, 1997).

1.5.5. Material Effect on Durability

The factor F(4) is shook quality and is strongly related to the PEP grade of the wood; which is the minimum quality accepted for the components of the pallet. The pallet can be graded from 1 to 5 - with the highest quality represented by 1. In the case of pallets built with multiple grades, F(4) = 0.12* (Average grade). For pallets manufactured with minimum grades F(4)= 0.08* (minimum grade).

Factor F(5) is selective placement and takes into consideration the effect of placing high-quality wood on the edges and ends of the pallet, which are the components exposed to the most damage. When PEP grade 1 is used on inner boards and PEP grade 2 or superior is used for edge-stringer locations, this factor is 0; otherwise, F(5) = 0.10. The PEP grades used for wood are presented inFigure 1.18.



Hardwoods and Southern Pine

PDS Input	PEP Grades [1]	NWPCA Hardwood Pallet Standards [2]	NWPCA Southern Pine Pallet Specifications [3]
1	2 & Better	Precision & Better	SP-1 & Better
2	3 & Better	Premium/AA & Better	SP-2 & Better
3	4 & Better	A & Better	SP-3 & Better
4	5 & Better	All lumber	All lumber

Softwoods

PDS Input	PEP Grades [1]	NWPCA West Coast [4] and White Woods [5] Pallet Standards
11	3 & Better	Premium & Better
12	4 & Better	Standard & Better
13	5 & Better	Shipping & Better

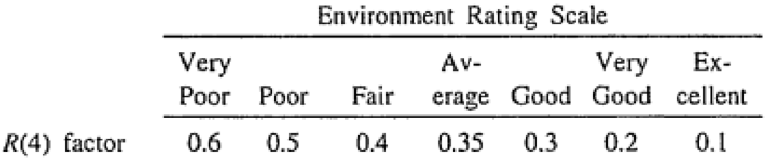
(American Society of Mechanical Engineers, 1997)

Figure 1.18. PEP Grades for wood

R factors 1 and 2 are related to flexural strength, for the stringers and decks respectively. The factor for deck construction R (3) accounts for the effect of deck improvements done to reduce pallet damage.

1.5.6. Effect of Material Handling on Durability

R (4) is the effect of the handling environment**.** Handling equipment, facilities, handling practices, and pallet repairs have an effect on pallet durability. ASME determines this factor by evaluating 17 handling system characteristics, as well as establishing a scale according to the environment's performance.



Environment Rating Scale

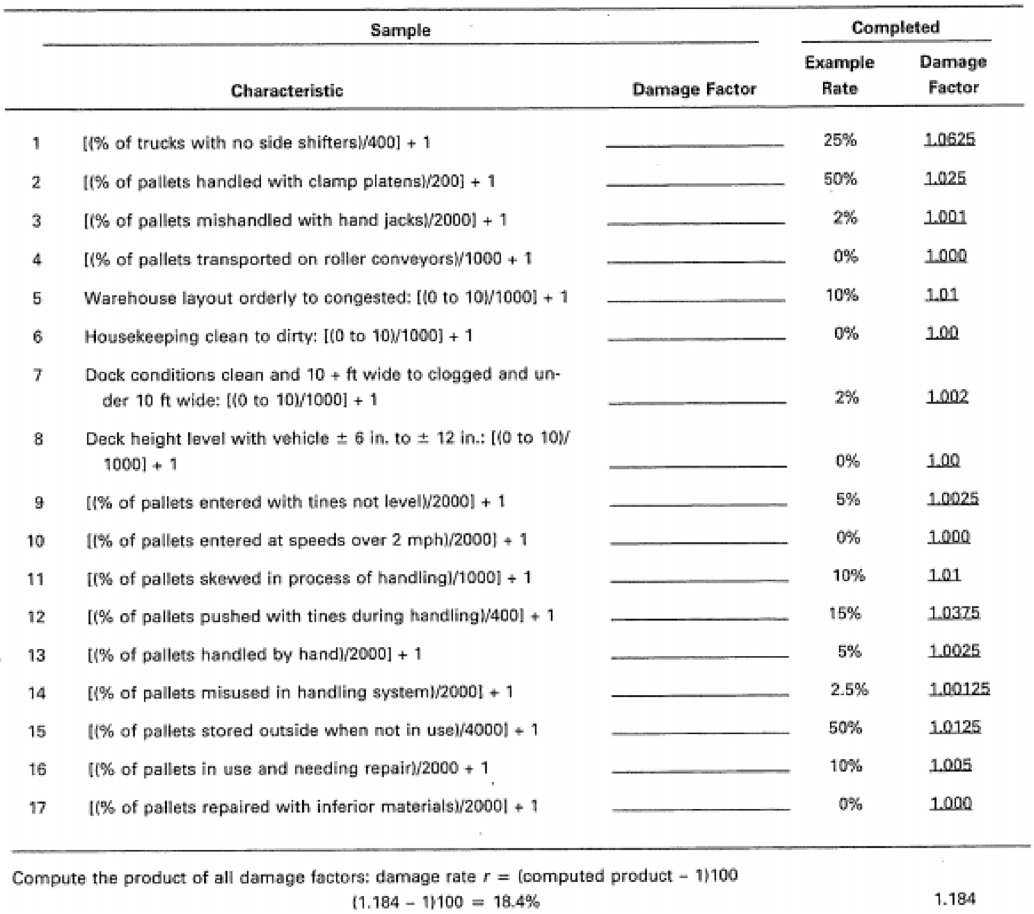
	Very Poor	Poor	Fair	Average	Good	Very Good	Excellent
R(4) factor	0.6	0.5	0.4	0.35	0.3	0.2	0.1

(American Society of Mechanical Engineers, 1997)

Figure 1.19. R (4) Rating scale.

The characteristics for handling environment evaluation are in Table 1.6.

Table 1.6. Elements for measuring handling conditions



	Sample		Completed	
	Characteristic	Damage Factor	Example Rate	Damage Factor
1	[(% of trucks with no side shifters)/400] + 1	________	25%	1.0625
2	[(% of pallets handled with clamp platens)/200] + 1	________	50%	1.025
3	[(% of pallets mishandled with hand jacks)/2000] + 1	________	2%	1.001
4	[(% of pallets transported on roller conveyors)/1000 + 1	________	0%	1.000
5	Warehouse layout orderly to congested: [(0 to 10)/1000] + 1	________	10%	1.01
6	Housekeeping clean to dirty: [(0 to 10)/1000] + 1	________	0%	1.00
7	Dock conditions clean and 10 + ft wide to clogged and under 10 ft wide: [(0 to 10)/1000] + 1	________	2%	1.002
8	Deck height level with vehicle ± 6 in. to ± 12 in.: [(0 to 10)/1000] + 1	________	0%	1.00
9	[(% of pallets entered with tines not level)/2000] + 1	________	5%	1.0025
10	[(% of pallets entered at speeds over 2 mph)/2000] + 1	________	0%	1.000
11	[(% of pallets skewed in process of handling)/1000] + 1	________	10%	1.01
12	[(% of pallets pushed with tines during handling)/400] + 1	________	15%	1.0375
13	[(% of pallets handled by hand)/2000] + 1	________	5%	1.0025
14	[(% of pallets misused in handling system)/2000] + 1	________	2.5%	1.00125
15	[(% of pallets stored outside when not in use)/4000] + 1	________	50%	1.0125
16	[(% of pallets in use and needing repair)/2000 + 1	________	10%	1.005
17	[(% of pallets repaired with inferior materials)/2000] + 1	________	0%	1.000

Compute the product of all damage factors: damage rate r = (computed product − 1)100

(1.184 − 1)100 = 18.4% 1.184

(American Society of Mechanical Engineers, 1997)

1.6 Material Handling Equipment

Pallets are often the preferred means of supporting loads. However, pallets need to interact with handling environments throughout their life, either by storing products in the warehouse, within a shipping container, or transporting products from one part of a company to another. It is essential to determine the damages associated with a material handling system, if the user wants to estimate the durability of a pallet (Cao, 1993). Both the damage frequency and severity are linked to the material handling system, more specifically, to its quality (Wallin & Whitenack, 1984). The factor for handling environment conditions, R (4), reflects that hostile handling environments will have a greater impact on reducing a pallet's durability when compared to handling systems with higher quality (American Society of Mechanical Engineers, 1997).

The typical unit load material handling system is comprised of packaging, a unit-load base, and unit load handling equipment (White, 1997). Packaging is dependent on the product, varying from corrugated boxes, to bags, among others. The unit load base is frequently the pallet. Handling equipment is comprised of forklifts, pallet jacks, conveyors, and other means of moving the load.

A different group oversees designing and optimizing the performance of the package, the pallet, or the handling system. These groups, however, have little interaction with each other, often underestimating the role of the unit load in terms of the handling equipment, which results in a decrease in both functionality and economy (White, 1997). When one component is modified, the performance of the others is affected. Noth the efficiency and effectiveness of the system depend on the quality of, and interaction between, the components (White, 2005).

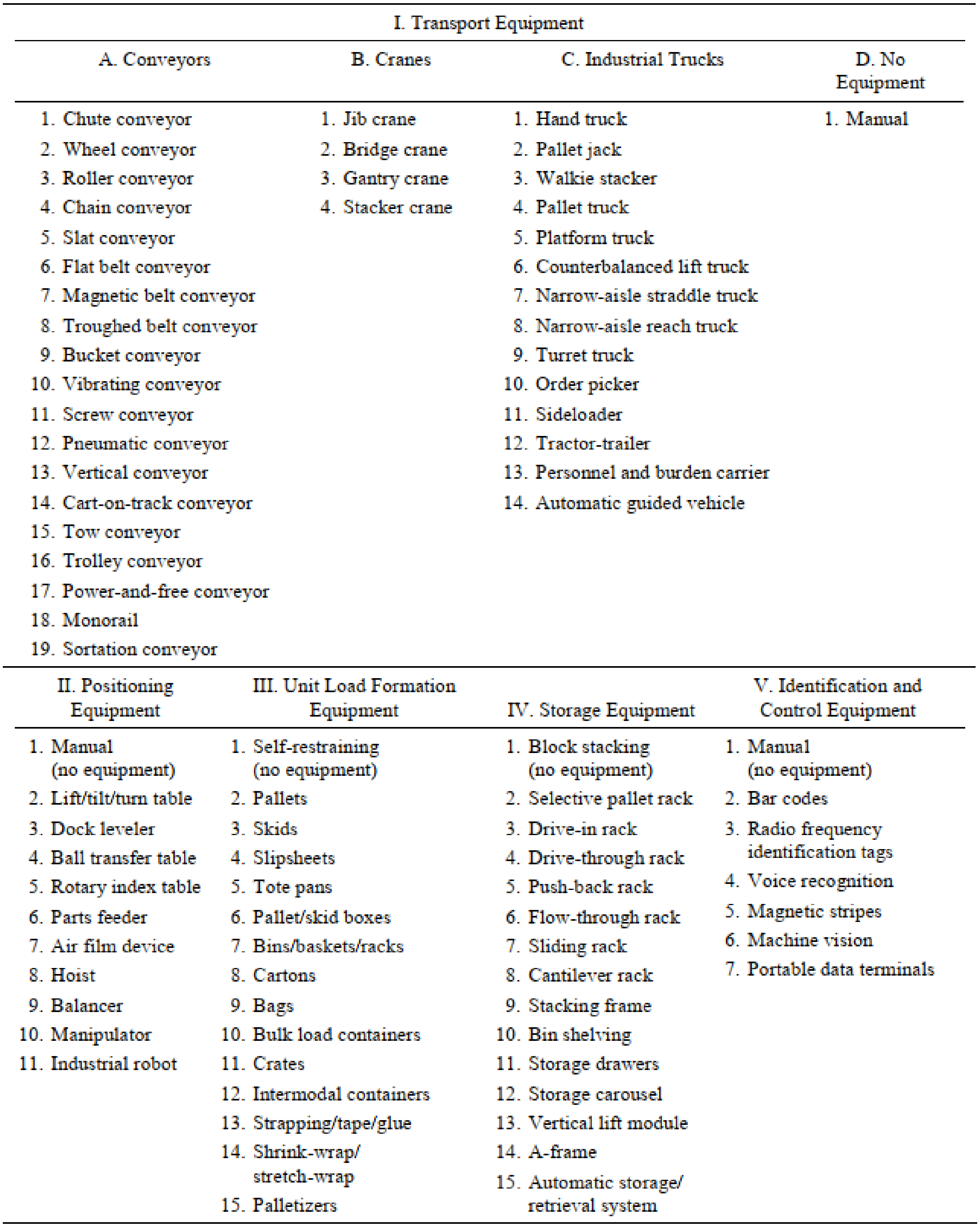
Focusing on the pallet as the crossing point between packaging and handling system, several interactions must be taken into consideration. Different static and dynamic stresses are present due to the role of the pallet in the system; vibration, shocks, impacts, compressive forces, and load shifting (White, 2005). Vibration is common during shipping and activities involving conveyors, while shocks and impacts are common during operations involving forklifts. Warehouse racks as well as other, different types of storage, and shipping, all affect the compressive forces.

An efficient materials handling system requires the effective use of the pallet and the fork-trucks or hand-jacks in order to transport the manufactured goods (Loferski et al., 1988). Failure to understand the way these components interact with each other can be costly; for example, if a pallet experiences a catastrophic failure while supported in a rack, economic damages will depend on the product it is supporting and how valuable it is. If the product is a hazardous material, it can even threaten the life of the employees. Therefore, it is important to recognize and understand the differences in the equipment used in material handling systems.

Unit loads can be moved in four different ways: using a lifting device under the mass, inserting a lifting element into the body of the unit load, squeezing the unit load between two lifting structures, and finally, suspending the load (Tanchoco & Agee, 1990). The most common method is a lifting device under the load, which is often a forklift or many other industrial vehicles. Clamps and cranes are usually the referenced equipment when talking about a unit load that is moved by squeezing, while the use of hooks and slings are good examples of suspended loads.

Material handling equipment can also be categorized according to its function. Five major groups are identified: transport, positioning, unit load formation, storage, and identification/control equipment (Kay, 2012). A classification of the most common equipment for each category is in Table 1.7.

Table 1.7. Material handling equipment classification



I. Transport Equipment			
A. Conveyors	B. Cranes	C. Industrial Trucks	D. No Equipment
1. Chute conveyor	1. Jib crane	1. Hand truck	1. Manual
2. Wheel conveyor	2. Bridge crane	2. Pallet jack	
3. Roller conveyor	3. Gantry crane	3. Walkie stacker	
4. Chain conveyor	4. Stacker crane	4. Pallet truck	
5. Slat conveyor		5. Platform truck	
6. Flat belt conveyor		6. Counterbalanced lift truck	
7. Magnetic belt conveyor		7. Narrow-aisle straddle truck	
8. Troughed belt conveyor		8. Narrow-aisle reach truck	
9. Bucket conveyor		9. Turret truck	
10. Vibrating conveyor		10. Order picker	
11. Screw conveyor		11. Sideloader	
12. Pneumatic conveyor		12. Tractor-trailer	
13. Vertical conveyor		13. Personnel and burden carrier	
14. Cart-on-track conveyor		14. Automatic guided vehicle	
15. Tow conveyor			
16. Trolley conveyor			
17. Power-and-free conveyor			
18. Monorail			
19. Sortation conveyor			

II. Positioning Equipment	III. Unit Load Formation Equipment	IV. Storage Equipment	V. Identification and Control Equipment
1. Manual (no equipment)	1. Self-restraining (no equipment)	1. Block stacking (no equipment)	1. Manual (no equipment)
2. Lift/tilt/turn table	2. Pallets	2. Selective pallet rack	2. Bar codes
3. Dock leveler	3. Skids	3. Drive-in rack	3. Radio frequency identification tags
4. Ball transfer table	4. Slipsheets	4. Drive-through rack	4. Voice recognition
5. Rotary index table	5. Tote pans	5. Push-back rack	5. Magnetic stripes
6. Parts feeder	6. Pallet/skid boxes	6. Flow-through rack	6. Machine vision
7. Air film device	7. Bins/baskets/racks	7. Sliding rack	7. Portable data terminals
8. Hoist	8. Cartons	8. Cantilever rack	
9. Balancer	9. Bags	9. Stacking frame	
10. Manipulator	10. Bulk load containers	10. Bin shelving	
11. Industrial robot	11. Crates	11. Storage drawers	
	12. Intermodal containers	12. Storage carousel	
	13. Strapping/tape/glue	13. Vertical lift module	
	14. Shrink-wrap/ stretch-wrap	14. A-frame	
	15. Palletizers	15. Automatic storage/ retrieval system	

(Kay, 2012)

1.6.1. Conveyors

Conveyors are used to transport materials and/or unit loads in manufacturing or distribution operations (MHI, n.d.). Conveyors can be horizontal, vertical, or inclined, depending on the needs of the company and the nature of the distribution process. Conveyors are usually hydraulic or powered by electricity/ gravity and use rollers or belts to transport the load.

Wheel, roller, and gravity conveyors are commonly seen in the industry. Kay refers to the wheel conveyor as the economical option when compared to the roller. It is intended for light applications, and features flexible/expandable version (Kay, 2012). The roller conveyor can be either powered (regular) or non-powered (gravity). This type of conveyor is not limited by space and allows uphill movement; however, it requires the material to have a rigid surface.

Gravity conveyors feature low maintenance and operating costs as a clear advantage. A disadvantage for this equipment occurs when handling fragile products (Peters et al., 1998). Distance, product size and weight, flow rates, and control requirements are critical when defining which conveyor type is the best.

1.6.2. Cranes

Cranes are used in the transportation of materials following a vertical/horizontal path (Kay, 2012). The main difference between conveyors and cranes is that the volume of the material for cranes is not as high as conveyors. The advantage for cranes when compared to conveyors is that cranes allow for flexible movements of loads, while also being able to handle varying loads.

There are five main types of cranes: the single and double girder bridge, single girder gantry cranes, jib cranes, and overhead stacker cranes (Peters et al., 1998). In the case of girder bridge cranes (both single and double), they vary in the maximum span (20-50 feet single, up to 100 for the double) and can handle from 1 to 15 tons (single), or up to 100 tons in the case of the double girder bridge.

Gantry cranes are flexible, with light and heavy performance operations. Jib cranes are not intended for heavy-duty cases and are used in a light-moderate performance with a 10-ton capacity and 20-feet span. The overhead crane is used in a variety of cases, ranging from light to heavy use. This type of crane is usually the most expensive (Peters et al., 1998).

1.6.3. Industrial Trucks

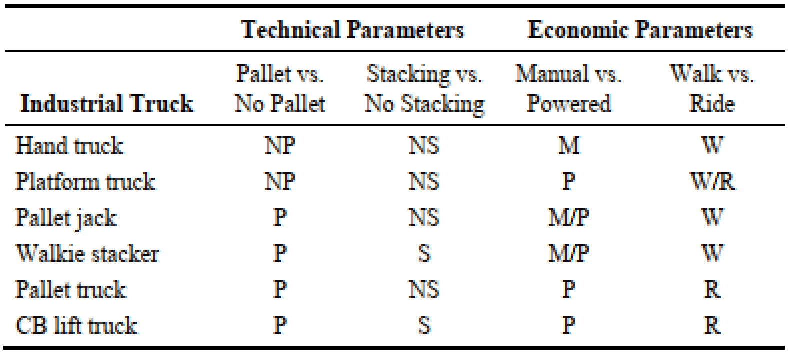
Industrial trucks are normally used for moving unit loads over different paths, in cases where the objective is to maneuver with the load (Peters et al., 1998). A truck's flexibility is superior to that of conveyors and cranes, and it also allows for vertical/horizontal movement for cases where load volume is intermittent (Kay, 2012). Two-wheel hand trucks, pallet jacks, and forklifts are included in this category.

The counterbalance truck is the most versatile (Bartholdi & Hackman, 2019). It can travel at a speed of up to 70 ft/minute and requires an aisle of approximately 20-22 feet to be handled effectively. Other units, like the reach truck and the turret truck, are equipped with tools to help retrieve the unit load; both can operate in smaller aisle to be operative and can reach greater heights, up to 40-45 feet. The predominant use of the forklift is due to its flexibility for indoor and outdoor use, and also because they have various load capacities available (Kay, 2012). The counterbalance forklift features 5 degrees of freedom, meaning it can perform horizontal movement (translation and rotation), vertical lift, mast tilt (forward and backward) as well as fork translation to adjust for the load.

Other equipment, like the hand truck, is designed to handle low volume with human strength. Pallet jacks can manipulate non-reversible pallets; and they can be either manual or electric with varying fork length (36 in., 42 in., 48 in.) and width. The fork thickness is commonly 3 ¼ in. and the lifting height is 7.5 in.

A comparison between different types of industrial trucks and their parameters is presented in Table 1.8.

Table 1.8. Industrial truck comparison



	Technical Parameters		**Economic Parameters**	
Industrial Truck	Pallet vs. No Pallet	Stacking vs. No Stacking	Manual vs. Powered	Walk vs. Ride
Hand truck	NP	NS	M	W
Platform truck	NP	NS	P	W/R
Pallet jack	P	NS	M/P	W
Walkie stacker	P	S	M/P	W
Pallet truck	P	NS	P	R
CB lift truck	P	S	P	R

Source: (Kay, 2012)

Pallet jacks cannot be used with every pallet type; the pallet must be non-reversible. In the case of double-faced, non-reversible pallets, they cannot have deckboards where the wheels of the pallet jack are intended to go, as that would affect the integrity of the pallet. The forks of the pallet jack cannot be used in the notches, as the height of the forks and the wheels does not allow this.

1.6.4. Racks

A pallet rack is generally used for bulk storage, but it is also used in support scenarios where picking is common (Bartholdi & Hackman, 2019). Each level of rack grants individual support for the pallet, providing access to different unit loads. Racks can also be adjusted to meet the needs of the warehouse.

There are different types of racks, according to the purpose of the operations that are conducted in the warehouse. Commonly used racks include single-deep (as presented in the next figure) and double-deep racks. These allow access to the unit load at the cost of aisle space, which ultimately produces honeycombing (loss of space in the warehouse). A drive-in rack allows the forklift within its frame, allowing pallets to enter from one lane and leave from the other. This is consistent with a first-in-first-out policy (FIFO). However, it requires pallets to be strong as the operation handles them by the edge (Bartholdi & Hackman, 2019). The drive-in or drive-thru rack is used in the grocery industry to get a maximum amount of storage (Pacetti, 1986).

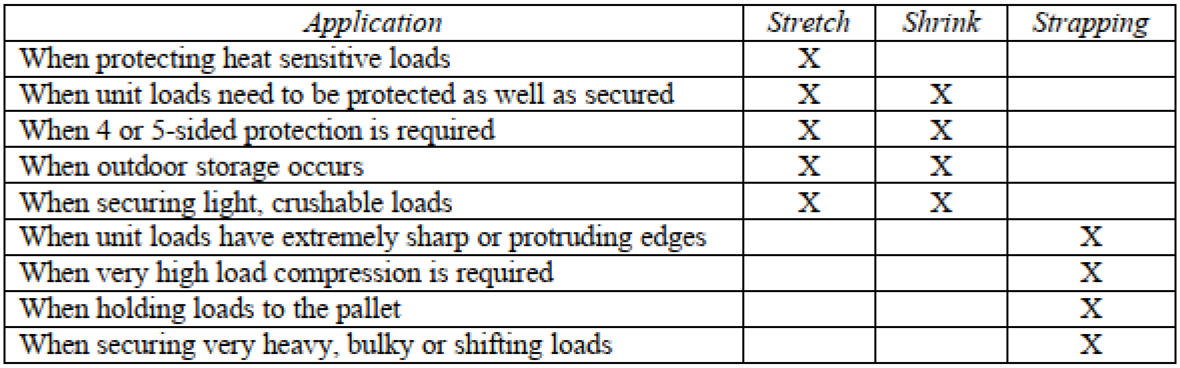
1.6.5. Unit load formation equipment

This equipment gives shape to the unit load, stacking layers of cartons, cases, or bags onto pallets in predetermined patterns (Peters et al., 1998). Several elements affect the unit load formation equipment, such as pallet characteristics and the properties of the product. Location also plays an important role, as available floor space and proximity to other operations may affect the equipment.

A popular type of load formation equipment is the palletizer, which is commonly divided into row stripping, vacuum head, and robotic palletizers. The difference between these three is the means of forming the unit load. In the vacuum head palletizer, the product is placed on the pallet through the use of pneumatic suction cups that grip the product until it is released in the desired position. For the row palletizer, the machine forms a row and then a pusher moves it towards the first row of product. After the required number of rows have been formed, the palletizer puts them on the pallet. The robotic palletizer may use a cartesian, articulated, or gantry design to form the unit load which allows for complex movements while forming the unit load (Peters et al., 1998).

Load stabilizing systems prevent danger when dealing with unstable loads. Common stabilizing systems include stretch wrap, shrink wrapping systems, and straps. Peters et al (1998), present a comparative table for these systems:

Table 1.9. Unit load stabilizing systems comparison



Application	*Stretch*	*Shrink*	*Strapping*
When protecting heat sensitive loads	X		
When unit loads need to be protected as well as secured	X	X	
When 4 or 5-sided protection is required	X	X	
When outdoor storage occurs	X	X	
When securing light, crushable loads	X	X	
When unit loads have extremely sharp or protruding edges			X
When very high load compression is required			X
When holding loads to the pallet			X
When securing very heavy, bulky or shifting loads			X

(Peters et al., 1998)

For stretch wrapping, a tight wrap of plastic is wrapped around the load. There are different stretch wrappers in the market, which vary in terms of automation, maintenance, and product usage. The stretch wrapping process can be done manually, semi-automatically, and fully automatic in some cases.

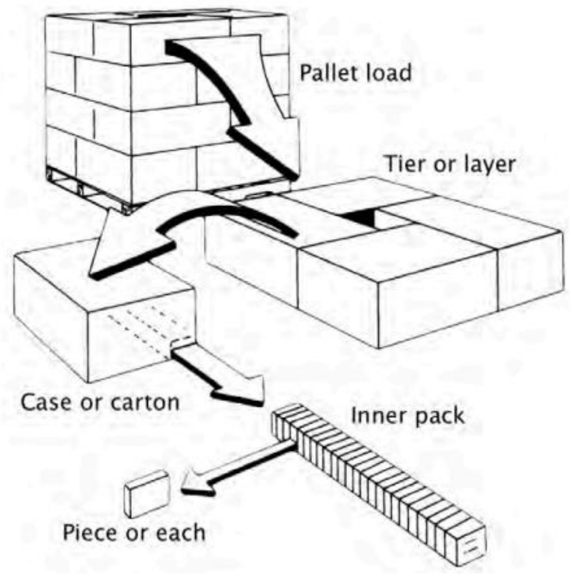
Shrink systems encapsulate the unit load, which grants improved protection. There are two ways of shrink-wrapping; manual (in which the operator uses a portable heat gun) and automatic, which could involve heat frames, heat closets, or tunnels. Finally, strapping involves tying bundles, coils, or other containers together. This is seen as the low-cost alternative and can include steel or plastic straps, tied using either automatic systems (strapping machines), semi-automatic, or manual strapping.

1.7 Warehousing

A warehouse is defined as a location or predetermined space, which is used to deposit, store, or stock items, merchandise, or commodities (Merriam-Webster, 2020). Warehouses are common in multiple industries, such as manufacturers, transport businesses, and retailers. Warehouses are means to respond to demand changes and variability that require a stockpile of products to overcome but also give a buffer against sudden changes in supply (Bartholdi & Hackman, 2019).

Warehouses are divided according to their usage. When the customer is a retail store and product flow is considerable, the warehouse is classified as a retail distribution center. A service parts distribution center is used to store expensive parts or equipment for automobile, airplane, and medical industries. Catalog fulfillment warehouses receive small orders that may come from phone or the internet; while 3PL and Perishable warehouses refer to facilities that specialize in outsourcing and food, flowers, or short life-span products respectively (Bartholdi & Hackman, 2019).

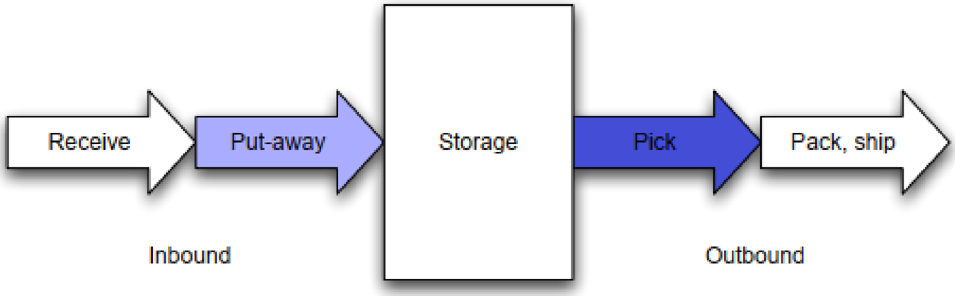
Warehouse functionality, the type of equipment that will be used, and the material flow are dependent on factors such as inventory characteristics, number of products, service requirements, and the capital/labor cost. Pallets play an important part in the supply chain as well. They support large unit loads of products in earlier steps, and the product then moves on to smaller unit loads as it advances through the supply chain, as seen in Figure 1.20.



(Bartholdi & Hackman, 2019)

Figure 1.20. Unit load break down through supply chain

The product is handled in smaller units as it advances in the supply chain. All along the supply chain, interactions between the pallet, package, and product and the handling equipment are present. For storing the product, a warehouse may be dedicated or shared storage. When each location is reserved for a specific product, the storing mode is classified as dedicated. This mode favors order-picking and warehouse layout, but it does not use space efficiently. Shared storage features multiple locations for a single product. As soon as there is space available, the product is assigned and thus, better utilization of the space is achieved. This strategy presents a challenge, however, as product locations are in constant change, which creates the need for a warehouse management system for the employees to use to find the products. Figure 1.21 is a representation of the operations conducted within the warehouse.



(Bartholdi & Hackman, 2019)

Figure 1.21. Warehouse operations

1.8 Durability Assessment

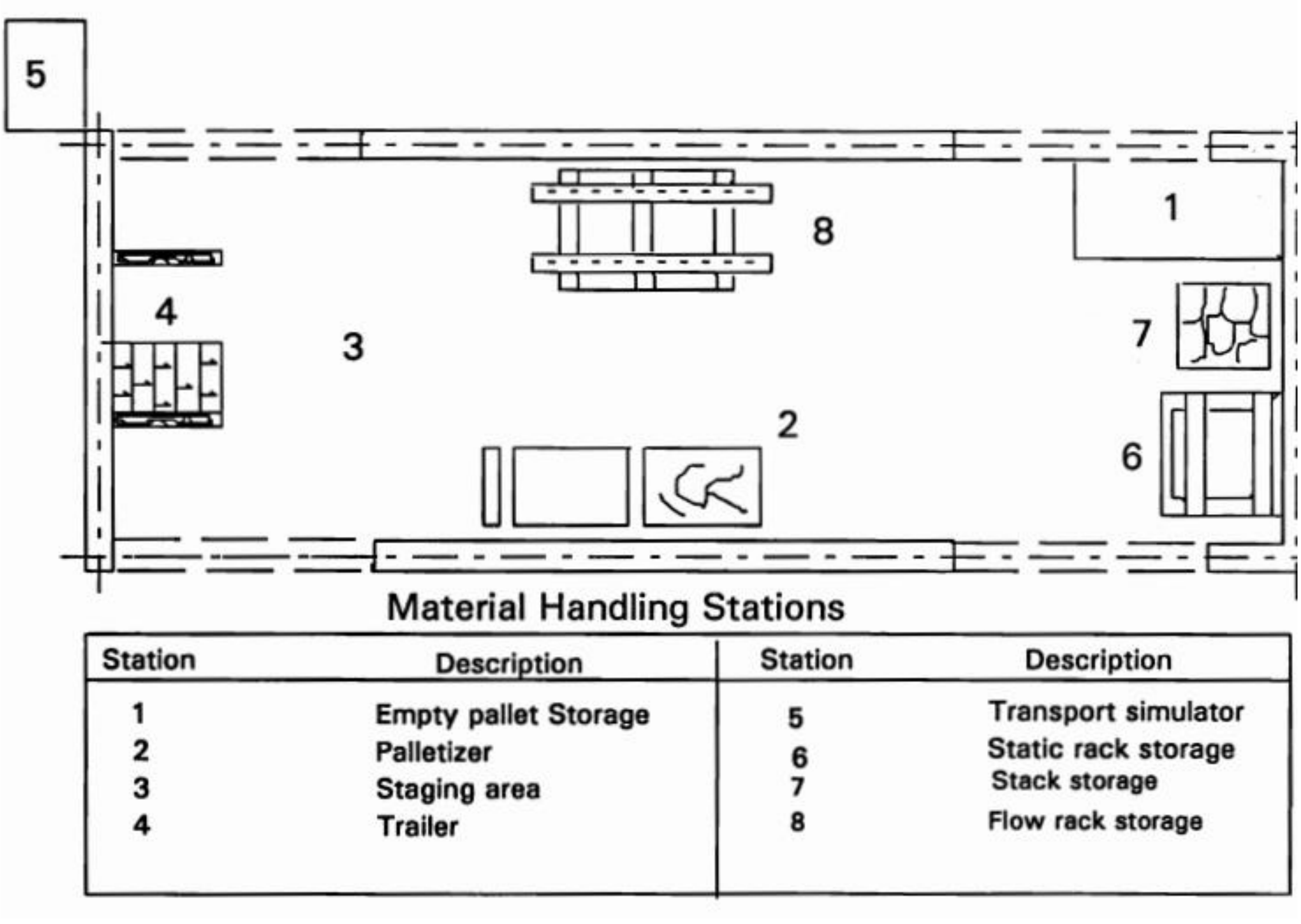
1.8.1 VPI FasTrack

The Virginia Tech FasTrack Handling Cycle procedure simulates the possible sources of damage that a pallet would experience in a real environment. Designed originally by Procter & Gamble to predict the durability of plywood deck pallets, it includes a simulation of the handling devices and operations from a real material handling system. Elements such as forklifts, pallet jacks, trailers, and storage racks are simulated during this procedure.

The procedure created in the William H. Sardo Jr. Pallet and Container Research Laboratory includes:

1. Empty storage area: an area destined for storage and stack of empty pallets.
2. Palletizer: Used to load or unload a pallet.
3. Staging Area: Area destined to slue and turn pallets, allowing the forklift to enter its ends/sides and to transfer the pallet with a pallet jack.
4. Trailer: A simulated 102” trailer opening with plywood sides. Before entering the trailer, a pallet needs to be staged. The pallet is then moved in and out endways and sideways to resemble a confined space.
5. Static Racked Storage: To simulate a warehouse rack; the span can be adjusted.
6. Flow Rack: an inclined rack to support the pallet on two rollers of 5/8” wide and set 26” apart on center. The pallet is rolled on an 8 feet conveyor until it reaches the metal stoppers with the bottom leading deckboards.
7. Stack: simulating a warehouse stack storage for loaded pallets

Figure 1.22 presents an overview of the FasTrack arrangement:



Material Handling Stations

Station	Description	Station	Description
1	Empty pallet Storage	5	Transport simulator
2	Palletizer	6	Static rack storage
3	Staging area	7	Stack storage
4	Trailer	8	Flow rack storage

Figure 1.22. FasTrack Handling Stations

In early stages of its design, FasTrack was divided into cycles, each cycle comprised of 12 handlings that simulate the whole distribution system. To test a design, 30 plywood deck pallets were tested for 30 cycles, which would simulate 5 years of use in the grocery industry of the United States. The step followed for Fastrack are:

1. Drop empty pallet from 5 ft high stack every 5 cycles.
2. Pick up the pallet and set it down at the palletizer in the 40in direction of the pallet.
3. Transfer load.
4. Pick up loaded pallet from the 40” wide end and set down on staging area.
5. Slue pallet in the shipping staging area by forklift, picking it from the 48” side and loading it into the trailer.
6. Unload the unit load from the trailer and set it down in the receiving stage area.
7. Pick up the pallet with the electric pallet jack, re-loading it in the trailer.

8. Unload the unit load from the trailer and set it down in the receiving stage area using the electric pallet jack. When the pallet is a full 4-way, repeat step 7 with side entry

9. Lift unit load with the forklift and set down onto the static rack, spanning for the 48” pallet length.

10. Lift unit load from the rack and set it on top of stacked bags

11. Lift unit load by forklift from stack storage and set down into a gravity feed flow rack. Pallet rolls until hitting the stopper

12. Lift unit load from the flow rack and place it in the palletizer to be unloaded.

13. The empty pallet is lifted with the forklift and returned to idle pallet storage.

The pallet is inspected for damages before the commencement of each cycle, then inspected for damages after the conclusion of each cycle. Damage recorded includes location and type, factors involved, and severity of damage. The test was considered finished when the pallet was no longer suitable due to damage levels, or after 30 cycles.

Damages are seen in two failure classifications: those related to the lumber, and those in the panels (Cao, 1993). From the lumber assessment, the most frequent damages were splits, broken parts, cracks, and joint failure. For panels, edge dent, veneer tear off, and crack or joint failure comprised most of the damages. Cao (1993) groups damages in the following categories:

a. **Cracks:** separations in the components of a pallet that extend in any direction. When the separation occurs in the joints, it will reduce their effectiveness. In panels, the author defined them as veneer separation.

b. **Missing parts:** When a portion or a complete component is missing from the pallet. In a panel deck, this failure is presented as an edge dent or veneer torn off. To measure the missing parts, length and width are taken into account.

c. **Breaks:** a complete separation of a component across width or length. The difference between the break and the crack is that a break no longer keeps the parts attached. As is the case with missing parts, breaks are measured with their length and width.

d. **Joint Failure:** This failure occurs either when a nail pops out (nail shank withdrawal), or as the nail head pulls through. This causes a clear reduction in the effectiveness of the joint, and the damage will vary according to the number of fasteners affected.

1.8.2. ISO 8611

ISO 8611 presents different tests to measure the physical durability of a pallet. The Corner drop test (test 9) is focused on the diagonal rigidity of the top deck of a pallet, as well as its resistance to impacts derived from a specific height. This test features a free drop from a determined height (h), which will produce an impact on the corner of the pallet. This drop test shall be conducted a minimum of three times, on the same pallet from the same height (International

Organization for Standardization, 2011). It is important to measure the length (l) from corner to corner of the pallet, in a diagonal direction. This measurement will be taken as a basis to measure the rigidity of the pallet. The test will finish after the three drops have taken place, or when the pallet shows clear damages that affect its functionality.

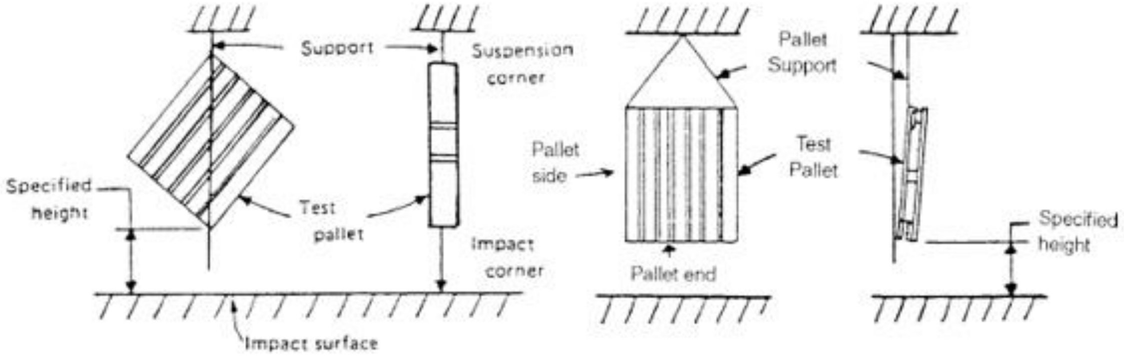
Other tests such as Test 10: Shear Impact focus on determining how the structure of the pallet resists horizontal impacts. This is done by evaluating damages to deckboards and stringer boards from the top and bottom of the pallet. This test puts the pallet on an inclined plane along with a specific load; both are released, from a distance L, until they reach the point of impact. The damages that occur in the different components of the pallet are recorded.

Test 11: Top Deck Edge Impact measures the resistance of the top deck to potential impacts produced by interaction with handling equipment such as forklifts. It utilizes a similar setup as Test 10, but it features the alignment of fork openings at the end of the backstop, which are positioned to impact the lead end deckboards of the pallet upon release. The impact stops will be located at the midpoint between blocks or stringers. A similar test setup is presented in the Block Impact test (Test 12) which is focused on determining the resistance of blocks, stringers, and other connections to the impacts from handling equipment. All of these tests feature the pallet being released from a specific distance, and hitting the stopper in the backstop.

1.8.3. ASTM 1185

Under the section of Dynamic Testing, different tests are focused on determining the stability of the unit load when it interacts with the handling environment. Taking elements from handling and shipping, each test puts the pallet under various hazards that it might face during the distribution process (American Society for Testing and Materials, 2017).

Freefall Drop Tests put pressure on the pallet corners and edges respectively, focused on determining its resistance to impacts. These tests are based on the possibility that a pallet might be dropped during unstacking or removal. According to this standard, free fall drops shall be conducted from a height of 40 in. (1 meter) aimed at a rigid block, which can be made of concrete, steel, or a similar suitable dense material. The procedure consists of six drops, were corners and eges of the pallet are impacted.

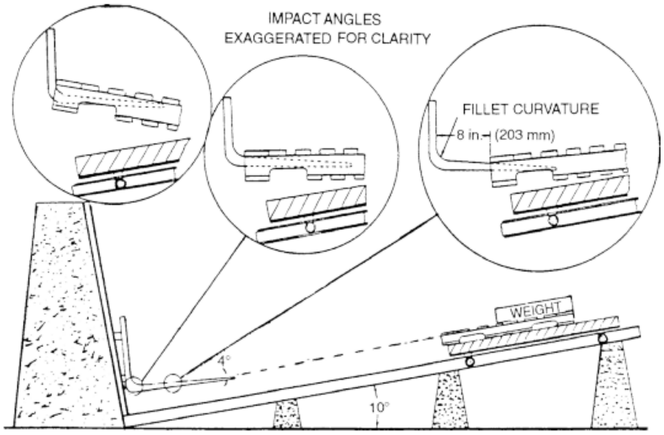


(American Society for Testing and Materials, 2017)

Figure 1.23. Free-Fall Drop Tests

The Incline Impact tests put pressure on pallet deck edges, blocks, and stringers, to determine their resistance to impacts from handling equipment such as forklifts and pallet jacks. The conditions simulated in these tests include fork heel impacts on deck edges, forklift impacts on corner posts or stingers, and a fork-tine tip pressure.

The procedure involves putting the pallet on a carriage, positioned in such a manner that the velocity at the time of impact can be determined. The stopper is equipped with hazards that represent fork tips; and the impacts shall be performed at an impact speed of 50 in./s (1270 mm/s) featuring two impacts for each component (fork-heel, fork-toe, and lead-edge resistance).



(American Society for Testing and Materials, 2017)

Figure 1.24. Incline-Impact resistance test setup

Vibration tests on loaded pallets determine the effect of vibration forces from transportation systems on the components of a pallet. Load stability is also considered. Vibration tests include the pallet load resonance test, which puts the pallet in both loaded and unloaded scenarios, applying vibration at a 3 Hz frequency and a constant acceleration of 0.25 to 0.50 g. The frequency is increased until the 100 Hz limit is reached or until the unit load presents clear signs of damage or instability; the test is repeated twice.

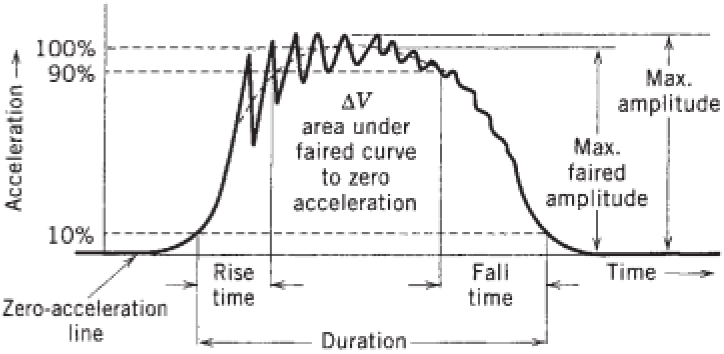
1.8.4. ISTA 3B

The ISTA 3B standard is used to evaluate the performance of packages under the effect of vibration, shocks, and stress produced from the interaction with handling and transportation environments. Some tests considered within this standard feature stressing pallets, especially on shock testing sequences. In this sequence, the pallet is handled with a forklift and is subjected to impacts on the blocks/stringers with the tip of the fork tine. The purpose of the test is to evaluate the stability of the unit load; however, this interaction with the forklift is represented in other standards as important when it comes to assessing the durability of pallets (International Safe Transit Association, 2017). In Test Block 15, the pallet is moved with the forklift while it is being lifted by only one edge. The pallet is pushed/pulled a minimum of 40 in. (1 meter) in this position, which puts stress on the blocks/stringers and the bottom deckboards of the pallet.

1.9 Shock Damage

Shock is described as a drastic change in a particular element in a short period of time (Fiedler, 2007). In the packaging environment, this term is referenced to describe sudden stops in transportation, drops, and impacts in distribution, as well as drastic temperature changes in warehousing environments. Traditionally, shocks are explained through the acceleration, the duration, and the change in velocity. Acceleration is described as the rate of change of velocity in a body with respect to time (American Society for Testing and Materials, 1998). Acceleration is measured in inches per second squared (in/s^2) in the imperial system, or meters per second squared (m/s^2) in the metric system. Similarly, acceleration is also measured in Gforce values, based on the gravitational attraction of the Earth (386 in/s^2, 9.8 m/s^2).

The change in velocity is the sum of impact and rebound velocities in the shock pulse (American Society for Testing and Materials, 1998). This element is easier to understand as the area under a standard shock pulse curve (Figure 1.25). The duration of the impact is measured in milliseconds (ms).

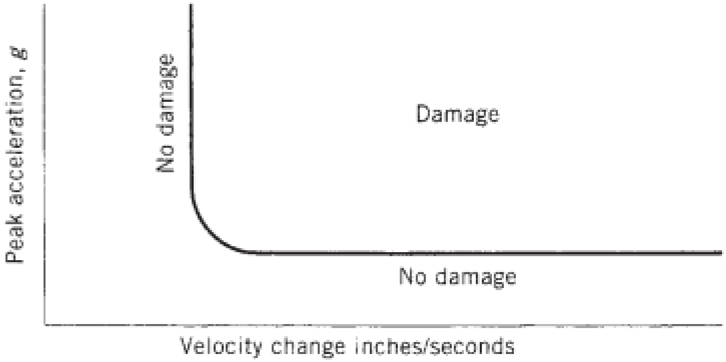


(Fiedler, 2007)

Figure 1.25. Standard Shock Pulse Interpretation

The shock pulse curve is presented as a sudden rise and a reduction in acceleration, over a period of time. However, the waveform may vary depending on the characteristics of the shock event. The haversine shock wave or the half-sine is produced by an elastic cushion acting as a linear spring. The terminal peak sawtooth is often produced when the shock impact involves non-rebounding cushions. Finally, the trapezoidal waveform is created by when the cushioning material is torn rather than compressed (Fiedler, 2007).

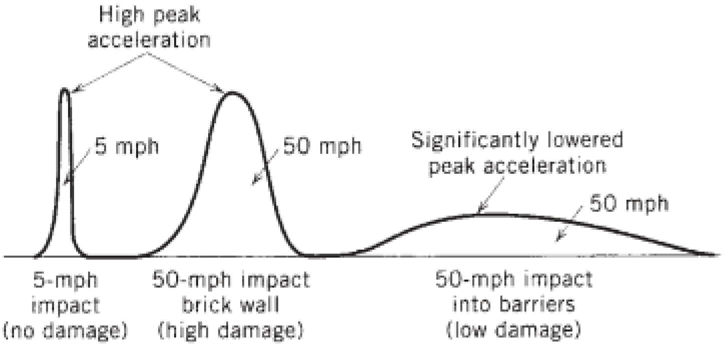
In addition to the shape of the curve, the dynamics between acceleration, duration, and change in velocity are critical to understanding the effect that shock events have on an object. Damage in an object is produced when the shock event involves the necessary energy to induce damage, and the rate of exertion of said energy into the object is greater than the object's ability to absorb it. The amount of energy in a shock event is measured by the change in velocity, while the rate refers to the acceleration. This dynamic is often presented as a damage boundary curve for different products (Figure 1.26). The damage boundary curve identifies the acceleration level and the velocity change that will result damages to the product during a specific shock event.



(Fiedler, 2007)

Figure 1.26. Damage Boundary Curve

The impact velocity for a shock event is also critical to understanding the effect that it might have on a product. As presented in Figure 1.27, events with high acceleration values over a short period of time will often result in no damage to a product. However, an event in which the acceleration is high, and the duration is long enough to surpass this boundary, will result in significant damages. With a significantly longer event duration and a low acceleration value, minimal damage will be seen in the product. This is often the function of cushioning materials, which are used to protect products in packages from the effect of shock impacts.

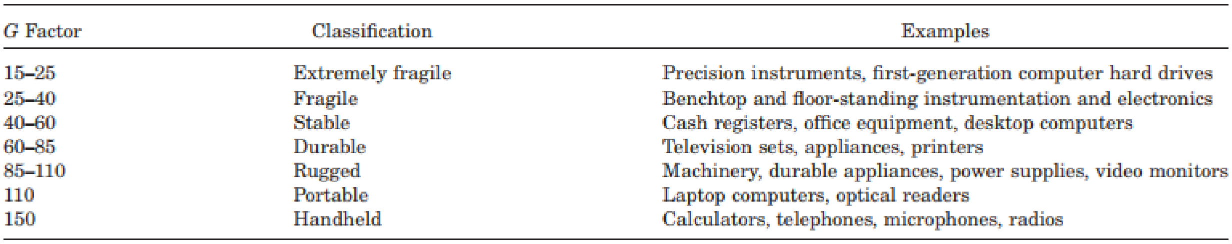


(Fiedler, 2007)

Figure 1.27. Effects of impact velocity and cushioning on damage

Shock peak acceleration is used as a reference for the fragility of a product. Table 1.10 presents the different acceleration levels at which products will experience damage when suffering from the shock event. These products have different classifications depending on their G factor.

Table 1.10. Benchmark Fragility Levels of Products



G Factor	Classification	Examples
15–25	Extremely fragile	Precision instruments, first-generation computer hard drives
25–40	Fragile	Benchtop and floor-standing instrumentation and electronics
40–60	Stable	Cash registers, office equipment, desktop computers
60–85	Durable	Television sets, appliances, printers
85–110	Rugged	Machinery, durable appliances, power supplies, video monitors
110	Portable	Laptop computers, optical readers
150	Handheld	Calculators, telephones, microphones, radios

(Fiedler, 2007)

1.9.1. Shock in the distribution environment

Traditionally, shock is considered a difficult parameter to characterize as it must be separated from vibration data, and the notion of shock has been different for various investigators (Ostrem & Godshall, 1979). The identification of shock impacts due to events such as potholes is not as clear as rail crossing due to the differences in shock pulse. Similarly, shock impact has been reported in terms of peak acceleration, shock spectrum, or spectral analysis depending on the application in various studies (Ostrem & Godshall, 1979).

Gens (1974) studied the frequency and amplitude of accelerations exerted on cargo during forklift handling. Trucks with capacities of 2000 lbs, 3000 lbs, 4000 lbs, and 7000 lbs were studied. Combinations of pneumatic and solid tires, as well as gasoline engines and electric motors, were considered as well. Many discrete excitations present in the recorded, and responses up to 10 g in amplitude below 20 Hz and up to 40 g at 100 Hz were found (Gens, 1974). The ratio of the capacity of the vehicle to the weight of the load as the factor with the greatest influence on the response, and there was little effect due to a change in tires.

When considering shock assessment, Ostrem (1979) mentions the phenomenon of shock bounce as very damaging to packages. However, there was no correlation between the vibrations recorded on the vehicles and the shocks due to bouncing on the package (Ostrem & Godshall, 1979). Further study was encouraged.

The effect of impact speed on the load has also been investigated. As a minimum, a speed of 2 mph is required for automatic couplers to actuate, however, speeds as high as 4 mph are extremely undesirable due to the high probability of damage to the cargo (Ostrem & Godshall, 1979). Impact speeds were also reported for a variety of shipping means, such as aircraft, ship, railroad, and truck. Based on an extensive data collection process, it was determined that 99% of impacts were below 10 miles per hour, while 50 percent were above 5.3 miles per hour (Ostrem & Rumerman, 1965). Railroad car coupling and humping operations as the severest in terms of shock response. The study of terminal handling cargo such as lift trucks, dollies, and manhandling, as its effect on packages had not been measured.

Shock and vibration in transportation systems were analyzed to find a viable data-processing method for these dynamics forces. For instances when the vibration and shock levels were compared to the number of occurrences, the Weibull distribution was proven as the best suited (Hasegawa, 1989).

Rodriguez, Singh, and Burgess (1994) measured the lateral impact levels produced when unit loads are handled with forklift trucks. The study focused on an evaluation of the adequacy of the levels defined in the ASTM-D4003 standard for pallet marshalling, which simulates impacts on pallets due to forklift trucks. A set of ten repetitions were produced on unit loads formed by boxes, bins, and drums. This study described the events in terms of shock acceleration and duration in terms of fork truck weight, impact speed, pallet weight, and impact condition, showing average shock levels of 37.2 G and an average duration of 4.3 ms.

Three different conditions were implemented for pallet weight, based on corrugated boxes (500 and 1,500 lbs), bins (600 and 1,200 lbs) and drums (2,000 lbs). Additionally, speeds selected for the study included an average operating speed (0.7 mph) and a severe condition speed in which the driver was encouraged to drive as fast as possible without resulting in injury (a maximum speed of 4 mph was recorded). For the impacts, a counterbalanced truck weighing 67,00 lbs was used (Rodriguez et al., 1994). The levels recommended in the ASTM standard in terms of shock impact acceleration and duration were found to be excessive, and a poor representation of pallet marshalling operations. The levels recommended by the authors were short durations (approximately 5 ms events), as well as an impact level determined by the fork truck impact velocity (V_t), the ratio between fork truck weight and pallet weight (R), and coefficient of restitution (e) as follows:

$$\overline{G_p}\ x\ T = 31\ \left(\frac{1+e}{1+R}\right)\ *\ V_t \qquad (10)$$

Where $\overline{G_p}\ x\ T$ denotes the average acceleration recorded in the pallet multiplied by the duration of the event.

The ASTM D4003 standard was designed to present the different test methods for programmable horizontal impact testing for shipping containers and systems, and was updated based on the findings by Rodriguez et al. The standard determines the capacity of the package to resist horizontal impacts conducted in a laboratory environment (American Society for Testing and Materials, 1998). Two methods are identified in the standard: rail car switching impacts and Marshalling Impact Tests of Unit Loads. This standard also describes acceleration and duration levels that represent the typical responses found during pallet and forklift interactions, based on the equation provided by Rodriguez et al. Duration was found to be between 1 ms – 5 ms, as well as 8 ms – 13 ms based on different levels of the coefficient of restitution. When the impact conditions are not known, the standard recommends a 15 G, 10 ms event as the most representative of a marshalling operation (American Society for Testing and Materials, 1998)

Guadagnini and Blumer (2011) examined shock transmissibility on palletized products, focusing on direct and indirect forklift handlings. Forklifts were selected as the main focus for the study due to their importance in warehouses and distribution facilities, but also because of their potential to deal damage to both operators and unit loads at relatively low speeds. Lansmont 3X90 dataloggers were used for data collection from different locations on the unit load. Raw data were filtered using a 500 Hz frequency to satisfy the rules of the industry, where a frequency of 1/10 the sampling rate is encouraged in analyzing shock events (Guadagnini & Blumer, 2011).

The authors performed three replicates for each test. The difficulty in identifying patterns in the data was highlighted by the study. However, it was found that a pallet being carried by a forklift is most likely to see damage on the side against the forklift backrest; and the recorders on the backrest side of the pallet configuration registered high acceleration values. Similarly, the duration at the point of impact was found to be shorter than the values registered at points where the force of the impact had to be transmitted (Guadagnini & Blumer, 2011).

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1.11 Research Objectives

For this investigation, the following general objectives were considered:

General Objective

Investigate the ability of FasTrack simulation to replicate the damages caused by material handling and storage systems in modern warehouses.

Specific Objectives

- Quantify common damage modes, damage severity, damage frequency for common pallet designs used in the industry and compare them to the damage modes simulated by FasTrack. – Chapter 2
- Investigate the effect that forklift type, top load, pallet design, and entry speed have on the horizontal shock impact exerted by the forklift on the pallet on their interaction. – Chapter 3

Chapter 2 Comparison of Damage to Wood Pallets in Use with Damages Occurring Using the VPI FasTrack Simulation of Pallet Use

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2.1 Abstract

The durability of a pallet affects the amount of use a pallet can withstand before functionality is lost. Having a reliable prediction of durability can be used to determine the effect of pallet performance on supply chain operating costs. This research focused on the VPI FasTrack, which is a simulation used to measure pallet durability or resistance to rough handling. The specific objective of this research was to correlate damage modes, severity, and frequency on pallets from the FasTrack simulation with the same damage data from pallets used in the field. Based on this comparison, we recommended changes to the FasTrack simulation that will better represent field use. Several 48 in. X 40 in. Grocery Manufacturers of America (GMA) type pallets were inspected from the field and were compared to historical pallet information from FasTrack. Inspected pallets from the field showed high damage occurrence on the stringer notches. Pallets tested via FasTrack exhibited significantly more top deck and end board damage and less stringer damage than observed in the field. An explanation for these differences, based on the interaction of pallets with handling equipment, is highlighted. Further investigation into the severity of forklift handling damages from the FasTrack simulation could be used to improve the procedure for predicting durability in the field.

2.2 Introduction

Pallets are crucial components of unit load-based supply chains. Pallets are horizontal, rigid structures, used as bases for assembling, storing, stacking, handling, and transporting goods as unit loads (MH1 Committee, 2005). According to the Freedonia group (The Freedonia Group, 2015), wood is the predominant material with 84% of the total pallet stock in 2019 and 93% of sales. Other materials such as plastic and metal are gaining market shares due to characteristics such as improved strength and resistance to environmental hazards like mold and insects.

Pallet performance is measured by strength and functionality. Durability is a functionality characteristic. Durability is the ability of the pallet to resist damages from impacts experienced in shipping and handling environments. One pallet durability metric is the number of trips, or supply chain cycles, that a pallet remains functional, prior to requiring repairs (MH1 Committee, 2005). Wallin (1984) defines durability in terms of the economic life of a pallet. He treated the pallet as a capital asset that is amortized, and should be replaced, when the average cost per use is at a minimum. Past this point, the cost of continued maintainance will be greater than the cost of a replacement pallet.

To better understand the relationship between pallet design and performance, the National Wooden Pallet Manufacturers Association (now NWPCA) partnered with the USDA Forest Service, Virginia Tech, and Better Management Services of New York to conduct the Pallet Exchange Program (PEP) study (Wallin et.al., 1972; Sardo and Wallin, 1974). Between 1968 and 1971, the damages to 877 pallets of 17 different designs, used in five different supply chains were recorded after each use. This resulted in 150,206 pallet handlings (White and Wallin, 1987). The primary metrics used to evaluate the effect of pallet design were damage frequency and severity (White and Wallin, 1987). Damage frequency is defined as the number of damages sustained by a pallet during its lifetime; whereas, damage severity represents the extent of the damage that the pallet experiences (Wallin & Whitenack, 1984). Wood species selection, reinforcement of end deck boards, wood moisture content, and the number and quality of fasteners were the factors that most affected pallet durability (White and Wallin, 1987). Using the correlation between these factors, the damage frequency and severity, and the elements mentioned before, an empirical model for predicting durability was created (Wallin and Whitenack, 1984).

The model outlined in the MH1, 1997 standard includes nine different factors that can predict the economic life of a pallet from damage severity and frequency. Fastener shear and withdrawal resistance, connection-splitting resistance, pallet part (shook) quality and placement, flexural strength for stringers and deckboards, deck construction, and handling environment are all included in the model (American Society of Mechanical Engineers, 1997). Pallet durability predictions in commercial the pallet design software that are used today are based, in part, on the data and models from the PEP study.

Virginia Tech and Procter & Gamble partnered to develop an accelerated rough-handling test that simulated pallet handling in unit load supply chains (Cao, 1993). The VPI FasTrack procedure subjects pallets to common stresses related to the handling environment using typical warehouse and handling equipment such as forklifts, pallet jacks, conveyors, and racks, among others. Cao also estimated that 30 FasTrack cycles would simulate five years of service for a pallet in the grocery industry (Cao, 1993).

Part 3 of MH1 "Pallets Slip Sheets and Other Bases for Unit Loads (2016)" lists pallet damage limits that significantly reduce a wood pallet's strength and functionality. Also included are recommended repair practices that restore pallet strength and functionality. These criteria are used as a reference during the VPI FasTrack procedure to determine whether the pallet can continue being tested or if it should be discarded after a specific number of cycles.

The VPI FasTrack has been used to compare the performance of different pallet designs and to identify design changes that could improve pallets' resistance to rough handling.
Examples of FasTrack use are found in the research conducted by Clarke, White, and Araman (2005). During this research, the VPI FasTrack was used to compare the performance of new and repaired pallets of three different qualities (A, B, C). Clarke et al. found that new, remanufactured, and grade A pallets were similar in resistance to rough handling (2005). Moreover, the authors identified top end deckboards and stringers as the main focus for initial repairable damage in the pallets subject to testing.

Material handling practices and pallet designs have significantly evolved since the early studies including the PEP study. Industries are automating their manufacturing and warehousing activities, continuously improving the efficiency (Mejías, 2019). Based on this research, 3% of warehouses and storage facilities around the United States are fully automated, and 20%-to-30% are now semi-automated.

2.3 Objective

The objective of this investigation was:

- Quantify common damage modes, damage severity, damage frequency for common pallet designs used in the industry and compare them to the damage modes simulated by FasTrack.

2.4 Materials and methods

To quantify the damages during pallet inspection, a data collection tool was developed. This tool can be used to gather information about the different pallet components: top lead deckboards (TLD), top interior deckboards (TDB), bottom lead deckboards (BLD), bottom interior deckboards (BDB), side stringers (SS), and center stringers (CS). These pallet components are shown in Figure 2.1 :

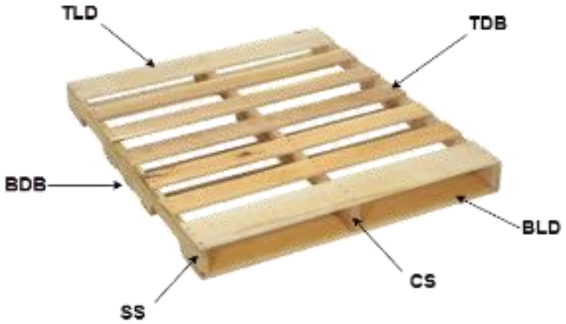

Figure 2.1. Investigated pallet components

Three major damage categories were investigated: splits, breaks, and missing wood. The descriptions of the damage categories are below:

a. **Split:** Separation of a component in any direction, though commonly along the length. Also referred to as a "crack" by Cao (Cao, 1993).

b. **Break:** A partial or full separation of the component, either obliquely or across.

c. **Missing wood:** A portion of, or a complete component, is missing from the pallet

For each damage type, a severity scale was developed, containing two levels: medium and high severity. Damages ranked high severity are ones that compromise the strength or functionality of the pallet, thus requiring the pallet to be repaired. The damage levels that warrant pallet repair in Part 3 of the ANSI standard were used to develop the damage descriptions for the high severity level. Meanwhile, damages with a medium severity level do not compromise the strength or functionality of a pallet, but their presence suggests that the component is being hit consistently. A description of damages in each severity level are in Table 2.1 and Table 2.2.

Table 2.1. Description of the damages for each of the damage modes and pallet components included in the **medium severity** level.

Damage mode	**Component**	**Damage Description**
Split	**Deckboards**	More than ½ the length or width, but it can be securely fastened. Splits extending through a nailed joint, greater than 1/3 of length/width and cannot be securely fastened.
	Stringers	Splits along the stringer, more than 1/3 of length and ½ the height or width
Missing wood	**Deckboards**	1 connection compromised, exposing 1 or more shanks, Not broken yet. Missing wood along ¼ the length, more than ¼ board width
	Stringers	1 shank is visible at a joint. More than 1/3 of the width and height of the stringer
Breaks	**Deckboards**	One deckboard is broken along ½ of its width, but the deckboard is still attached to the pallet
	Stringers	Breaks are present in the stringer, but the stringer is still in place and no nails are visible. Up to one exposed shank.

Table 2.2. Description of the damages for each of the damage modes and pallet components included in the **high severity** level.

Damage mode	**Component**	**Damage Description**
Splits	**Deckboards**	More than ½ the length or width, which cannot be securely fastened
	Stringers	More than ½ the height or width and more than half the length. Notches: Full width splits of any length in stringer notches
Missing wood	**Deckboards**	More than 2 connections of the same component, exposing 1 or more shanks or 1 connection completely broken. More than ¼ of the board width and ½ the length.
	Stringers	If more than one nail shank is visible at any one joint More than ½ of the width and height of the stringer and full length of the foot
Breaks	**Deckboards**	Completely broken deckboards, stringers, blocks, or stringer boards. One deckboard is broken, either obliquely or across
	Stringers	A stringer/block is broken to such an extent that more than one nail is visible

2.4.1 Pallet Inspection

This study included only the GMA/GPC pallet design, which is a 48 in. x 40 in., three-stringer, partial four-way, double-sided, non-reversible, flush, wooden pallet design (Stern, 1979). However, the pallets had a different number of top and bottom deckboards, different component dimensions and quality, and were manufactured from different lumber species. Pallets from two different sources were investigated: FasTrack and the field. To obtain representative pallet data from the FasTrack simulation, the damage found on pallets tested in the FasTrack simulation between 2017 and 2020 was quantified. Pallets evaluated using the FasTrack simulation were tested until the damages caused by the simulation required the repair of the pallet. The pallets were grouped into three quality grades (grade A, B, or C). Overall, 152 grade A, 69 grade B, and 98 grade C pallets were investigated. The descriptions of the quality grades are listed below:

a. **Grade A:** Pallets with stringer metal plate repairs, but no companion members. Deckboard repairs are acceptable, but the top and bottom lead boards are a nominal 6 inches wide.

b. **Grade B**: Pallets with at least one (but no more than two) full/half-length companion member (s). Plugs are not acceptable, but metal and deckboard repairs are accepted.

c. **Grade C:** Pallets that did not meet the above criteria for an A or B grade.

To obtain representative pallet damage data from the field, used pallets were collected from three different retail facilities in North Carolina. The pallets were picked-up from a pallet repair facility; they were randomly pulled from the incoming cores prior to any pallet repair operation. The pallets were classified based on the same grade categories as the FasTrack pallets. Overall, 201 grade A, 187 grade B, and 42 grade C pallets were investigated from the field.

2.4.2 Statistical Methods

The output of damages per pallet was analyzed for each source (field and FasTrack) with Minitab 19 (Minitab LLC, State College, PA). Additional processing of the data and elaboration through graphics used to evaluate trends and the behavior of the data were done with Microsoft Excel (Microsoft Corporation, Redmond, WA). The historical data used for the FasTrack inspections was aggregated using a weighted average, based on the number of pallets inspected from each quality grade group (A-C).

2.5 Results and discussion

2.5.1 Pallet Damages observed in the Field

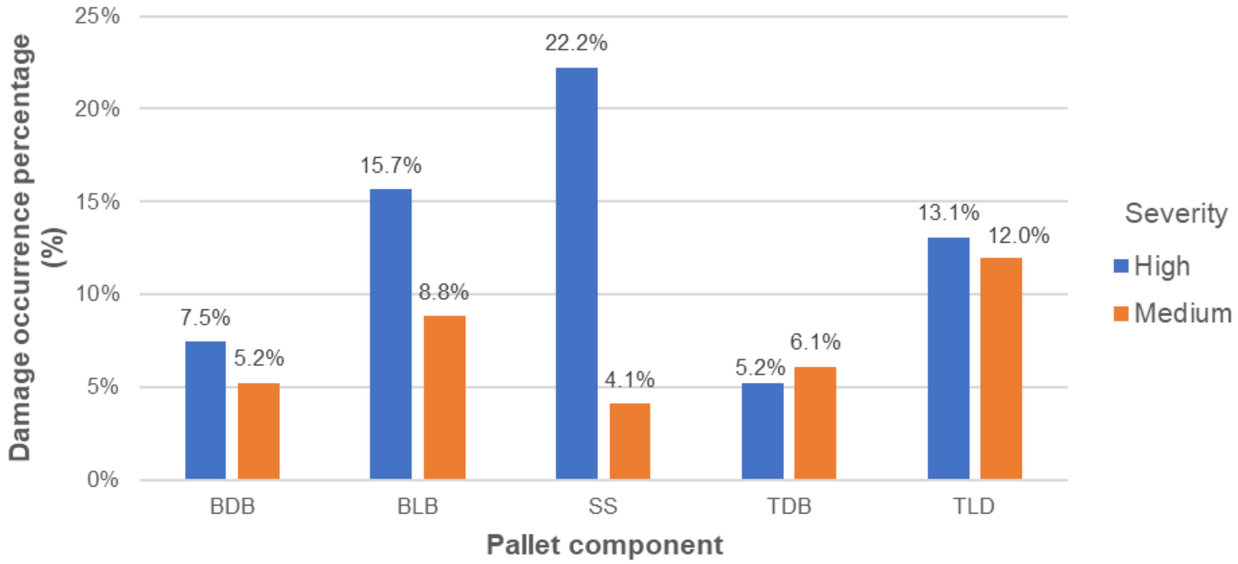

Figure 2.2. Damage occurrence from pallets in the field, by severity level

The inspection results for the investigated damage locations and severity levels, are in Figure 2.2. The observed trend of the damage locations for both medium and high severity damages is that they are mostly similar. The exception is the damages observed on stringers (SS), which sustained high severity damages (22.2%) much more frequently than medium severity damages (4.1%). Stringers are the most commonly damaged pallet component. Bottom end deckboards (BLB) also experienced a greater number of high severity damages (15.7%) than medium severity damages (8.8%). The damages observed for top end deck boards (TLD), top interior deck boards (TDB), and bottom deckboards (BDB) are all similar in magnitude.

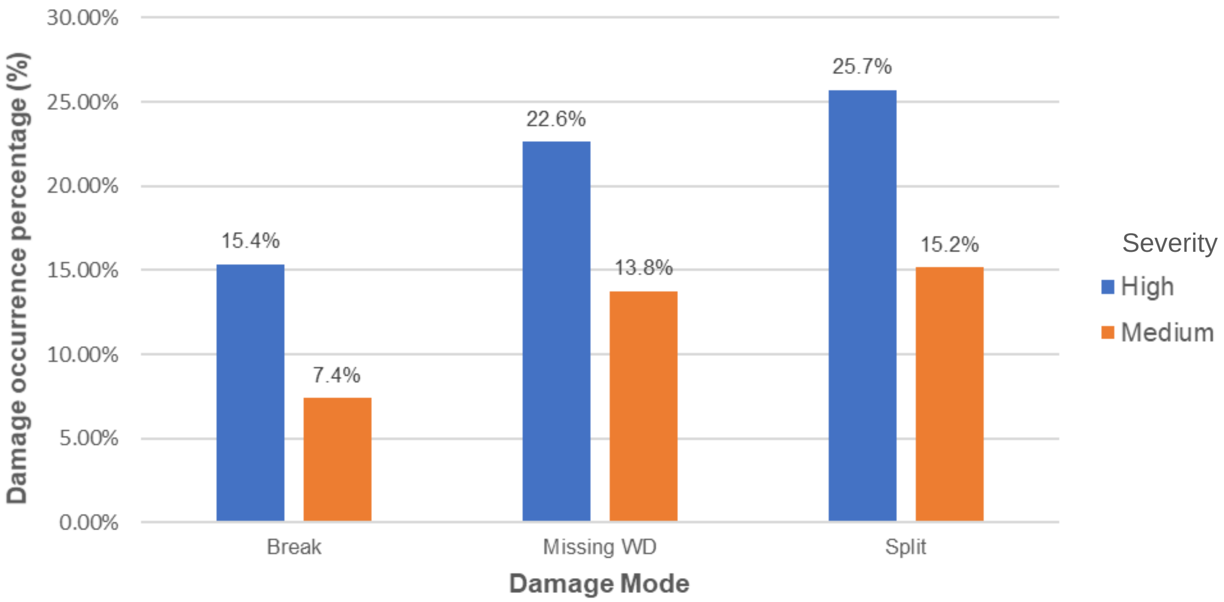

Figure 2.3. Damage mode occurrence percentage by severity level.

Damage modes by severity level are shown in Figure 2.3. Splits are the most frequent damage, followed by missing wood and breaks at the medium severity. This damage mode hierarchy is similar at the high severity. High severity damages occur 8-10% more often than medium severity damages.

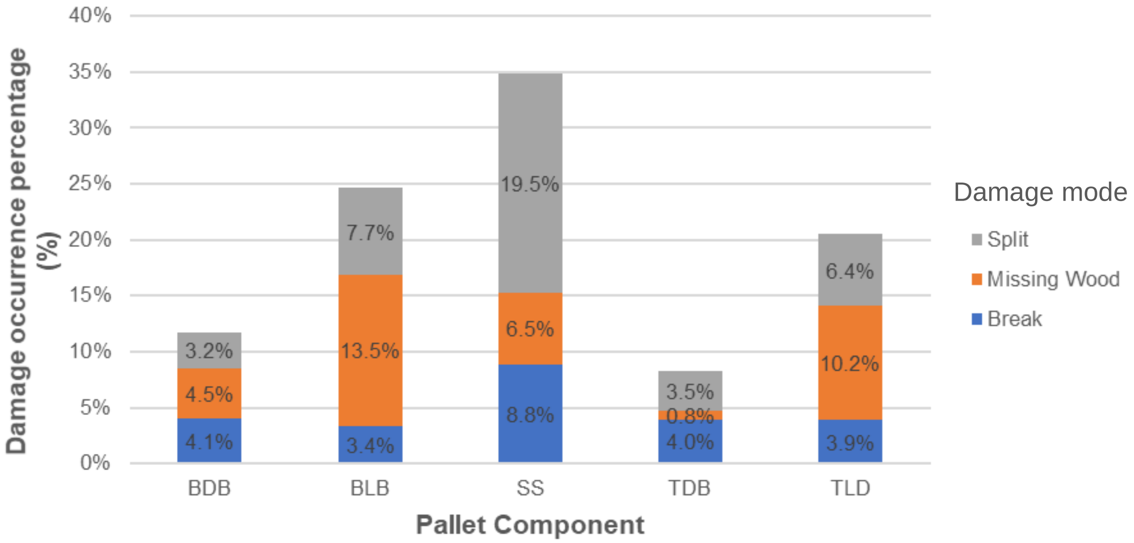

Figure 2.4. Damage mode by pallet component (high severity only)

Figure 2.4 shows the mode of damage by pallet component. Only high severity damages are presented. The most commonly damaged component at this severity level was found to be the stringer (SS). Splits are the most frequent damage mode (19.5%), followed by breaks (8.8%) and missing wood (6.5%). Breaks are more common in stringers than in the rest of the components of a pallet. Missing wood (10.2% - 13.5%) followed by splits (6.4% - 7.7%) and breaks (3.4%-3.9%) were more common in top (TLD) and bottom end deckboards (BLB).

Most of the damage to pallets is caused by impacts during forklift or pallet jack handling or when a pallet is dropped. However, splitting at pallet notches can be the result of bending stresses when pallets are placed in storage racks. (McLeod, 1995; Mejias, 2019).

Additionally, lead deckboards are damaged due to banding, especially in scenarios where the end boards are not covered by packaging (ABF Freight System Inc., 2017). Tension of the strapping will lift and fracture end deckboards, especially when the load does not cover the end board.

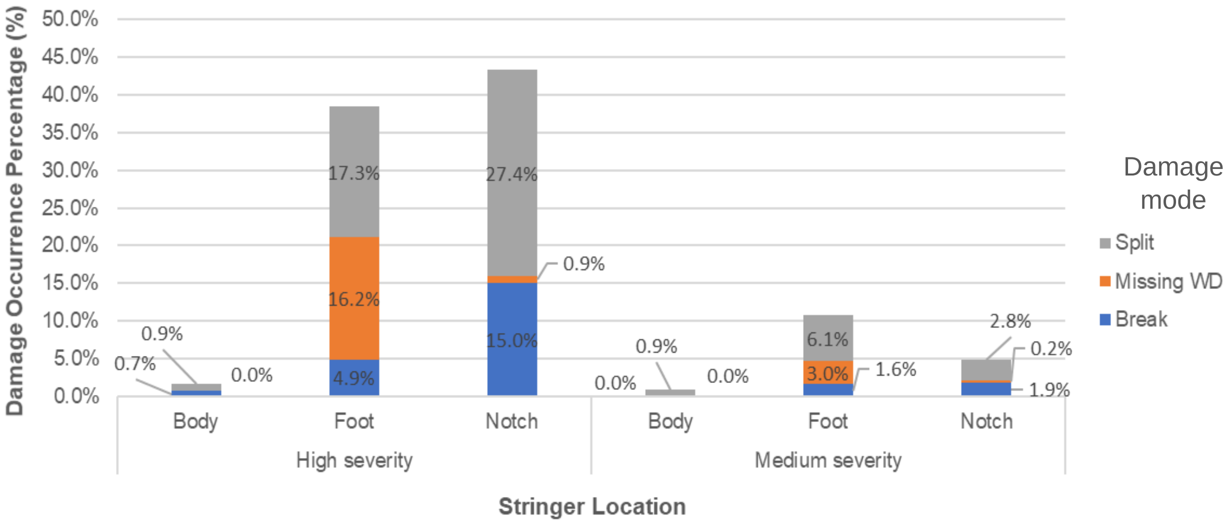

Figure 2.5. Damage mode by damaged stringer location according to severity level.

Figure 2.5 shows the results of observed damage modes according to specific regions of the stringers. These regions are defined in Figure 2.6. At medium severity levels, the foot of the stringer is the most frequently damaged location at 10.7% and splits the most common damage mode (6.1%), followed by missing wood (3%) and then breaks (1.6%). Notches are the second most commonly damaged location at 4.9%. This location is affected mostly by splits (2.8%) and breaks (1.9%). As damage severity increases, there is a dramatic increase in the occurrence of damages at the stringer foot (38.4%) and notch (43.3%) respectively. In the case of the stringer foot, splits (17.3%) and missing wood (16.2%) are the most common damages. In the case of the notches, splits (27.4%) and breaks (15%) are the most common damages. Regardless of the severity level, the body of the stringer is rarely affected. In addition, the main causes of damages are the same, independent of severity level.

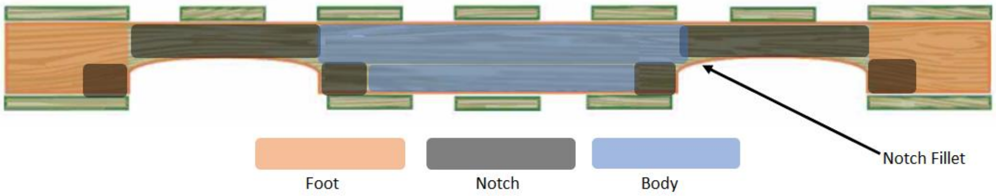

Figure 2.6. Stringer regions considered for pallet inspection

Damages to the stringer foot are usually from the direct impact of a forklift tine at the moment of entry (Clarke et al., 1993). Storage and transportation of a loaded pallet can result in damages to the body and the notch of the stringer. As Clarke et al. mentions, failure modes are generally localized splits along the grain when they occur on the body of the stringer, while bending-type failures are more common in the notches.

2.5.2 Comparison of Pallet Damages between the Field and FasTrack

The FasTrack simulation is stopped when the damage to the pallet requires repair. To establish an equivalent comparison with pallets from the field, the assessment for FasTrack and field compares the behavior for high severity damages only. Therefore, the damage percentage in the figures does not add to 100%.

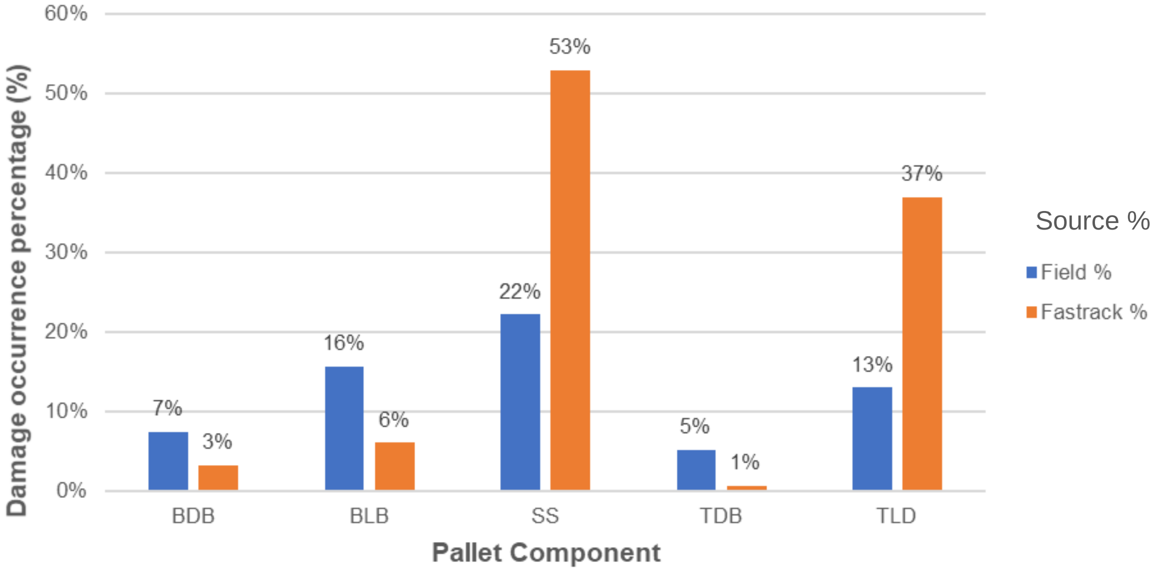

Figure 2.7. Damage occurrence percentage by damaged pallet component for Fastrack and Field (high severity).

Figure 2.7 shows the results of the damage, by component, from the pallets used in the field compared to similar the pallets tested in the FasTrack simulation. There are similar trends. The stringers (SS) are the most damaged components in both. For FasTrack, top end deckboard (TLD) damage is more frequent. Bottom end deckboards are more frequently damaged in the field.

The differences between FasTrack and the field are more prominent in terms of damage occurrence rates. Damages observed from Fastrack reflect an emphasis in top end deckboards

(TLD) (37% > 13%) and stringers (SS) (53% > 22%), while the damages to the bottom end (BLB), top (TDB) and bottom (BDB) interior deckboards were less prominent from FasTrack than the field.

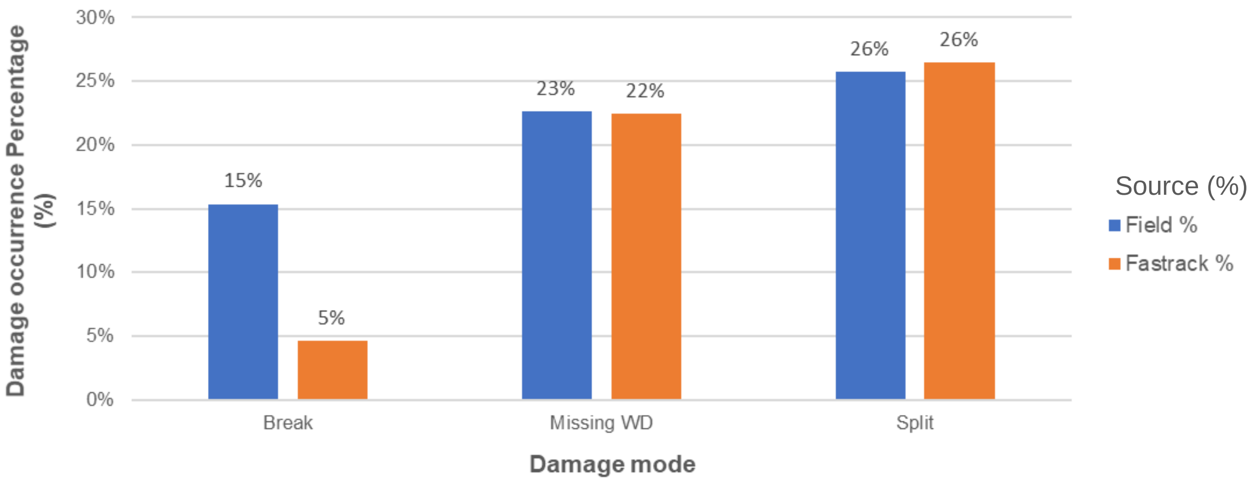

Figure 2.8. Comparison of damage mode for pallets tested in the FasTrack and observed in the field (High severity)

Figure 2.8 shows the damage modes, compared. Splits were the most common damage mode (26.1% in the field, 26.9% in FasTrack) followed by missing wood (22%-23%). The results observed for the pallets tested with the FasTrack procedure are similar to those observed in the field for splits and missing wood. However, there was a significant difference in the percentage of breaks. Breaks rarely occurred during the FasTrack simulation, but they were common in pallets used in the field (5% < 15%).

The lower frequency of breaks during the FasTrack simulation could be explained by the conditions simulated by FasTrack. While considered in the procedure, the racking and stacking conditions in the simulation might not put enough stress in the pallets tested. It is important to remember that this is an accelerated durability simulation during which the pallet carries a 1,500 lb. payload (Cao, 1993). Greater loads may be placed on pallets in the field. Also, FasTrack cannot simulate misuse, which may occur in the field.

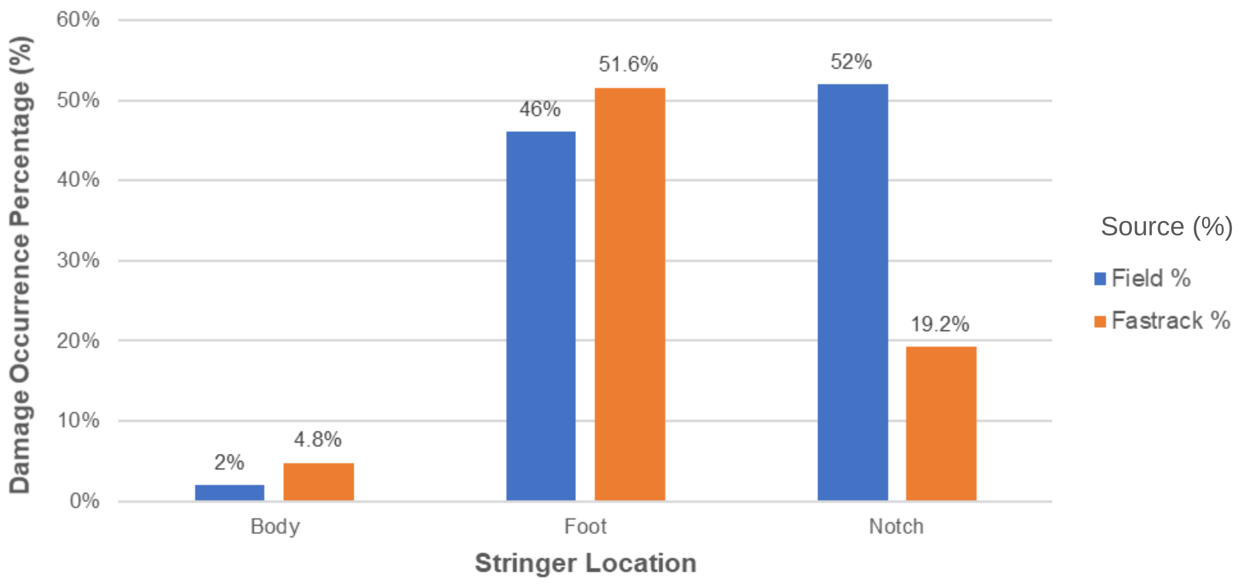

Figure 2.9. Location of stringer damages from filed observations and FasTrack testing. (High severity).

Figure 2.9 shows the observed location of stringer damages from the field and the FasTrack. The results indicate similar damage rates for the stringer foot and body. The most significant difference between FasTrack and the field was seen in the damages to the notches of the stringers. The notches were damaged in 52% of the pallets from the field. However, FasTrack notch damage is only 19.2%. The FasTrack procedure accurately represents damages in the foot and the body of the stringer, but it underestimates the damages to the stringer notches.

The fillet of the notch is shown in Figure 2.6, and is a location of concentrated stress that is a function of the radius of curvature. The less the curvature, the greater the stress at that location when the stringer is subjected to bending. In supply chains, the bending stresses occur when pallets are placed in free-span storage racks or when empty pallets are dropped and hit the floor at an angle. Both of these are simulated during FasTrack. The intensity or frequency of these handlings during FasTrack may have to be increased to reflect the damages occurring in the field.

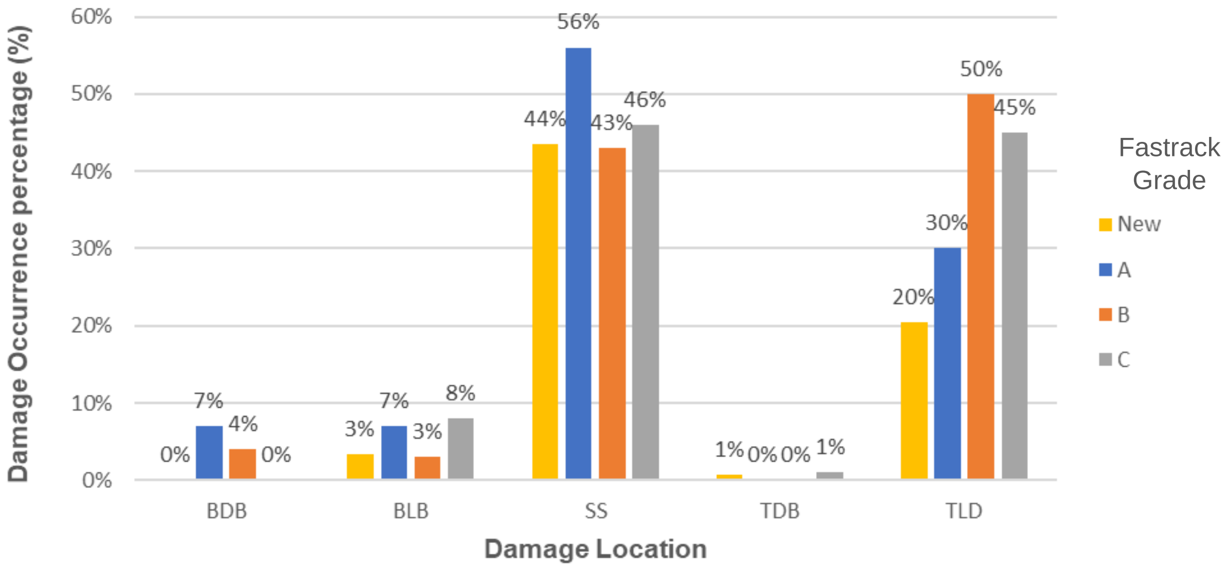

Figure 2.10. Damaged location percentage by pallet quality in FasTrack.

The results of the inspections conducted on the different qualities of pallet tested with the FasTrack procedure are presented in Figure 2.10. In general, stringers (SS) are the most damaged components (43%-56%), followed by top end deckboards (TLD) (30%-50%). Bottom end deckboards (BLB) are damaged less (3%-8%). Interior components of the pallet are rarely damaged, with bottom deckboards (BDB) in grade A and B used pallets exhibiting slightly more damage (4%-7%).

There is a slightly greater tendency of stringer damage in Grade A pallets, while top end deckboards seem to be more damaged in the B and C grades. It seems the companion components used to repair B and C grade pallets actually improves end deckboard resistance because they are attached to the stringers at more locations when repaired. Bottom deckboards are less damaged in all grades than stringers and top end deckboards.

2.6 Conclusions

- The high percentage of damage occurrence in the stringers reflects that this component is the most vulnerable in the pallet.
- The medium and high severity damage location distribution on pallets from the field shows that components fail due to continuous impacts during handling. In the stringers, the difference between medium and high severity indicates that this component can fail after it is exposed to less damage during handling and distribution.
- Damage modes did not change between medium and high severity. This indicates that the pallets fail because the initial damage worsens to the point that the pallet requires repair.
- The FasTrack procedure does not accurately replicate the damage seen in pallets from the field. The simulation emphasizes damage to the stringers and lead deckboards, but it underestimates the damage to the rest of the components of the pallet.
- The damage to the stringers and top lead deckboards suggests that interactions with the forklift causes greater stress to these components than the rest of the pallet.
- Breaks are rarely produced in FasTrack. This indicates that conditions such as rack and stack storage in the simulation do not put enough stress on components like the notch.
- Testing repaired pallets in FasTrack shows that top lead deckboards and stringers are the most damaged components. This shows that FasTrack will yield consistent results regardless of pallet repair quality.

The results of this investigation show significant differences between the damages seen in pallets from FasTrack and those from the field. However, the simulation was stopped after stringers and lead deckboards were damaged, which left other components undamaged. The interactions between pallets and forklifts puts significant stresses on the pallet, which are reflected in the high damage occurrence rates to the stringers and top lead deckboards. Further research into the intensity of this interaction is necessary to identify potential areas of improvement for the FasTrack simulation.

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Chapter 3 The Effect of Forklift Type, Pallet Design, Entry Speed, and Payload on the Horizontal Shock Impact Exerted During the Interaction Between Pallet and Forklift

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3.1 Abstract

Shock impact damage is a distribution hazard that affects packages and unit loads. An effective understanding of the factors that influence shock impact damage due to the interaction between a pallet and a forklift can be used to improve the VPI FasTrack simulation. This research focused on the study of the effects produced by forklift type, pallet design, entry speed, and top load on the horizontal shock response measured during the impact of a pallet with a forklift. The objective of the study was to identify which were significant effects for the pallet and the forklift, as well as to find a model to predict pallet acceleration response based on data measured on the forklift. The results show the average acceleration response of the forklift was 2.98 G. For the pallet, the acceleration response was 13 G. The average duration of the impacts was 10-12 ms. While interactions were found, their effect on acceleration due to factors such as entry speed, forklift type, and top load reflect a significant opportunity to improve the intensity at which pallets are tested in the FasTrack simulation. The study presents a procedure to equip with dataloggers the forklifts used for FasTrack; datalogger measurements could then be used to monitor the intensity of the simulations, and then compare the results with those collected from customer warehouses. Differences in acceleration levels produced by forklifts and pallet materials were found. Further research is encouraged to model the relationship between pallet acceleration and forklift acceleration response.

3.2 Introduction

As presented by Guadagnini et al., vibration transmissibility in a unit load has been a consistent research focus of packaging and handling investigations. However, the investigation of shock transmissibility in unit loads has not been as extensive (Guadagnini & Blumer, 2011).

The interactions between pallets and forklifts may represent significant losses in both pallets and the products on them whenever improper handling leads to damaged unit loads. Fiedler highlights that shock damage to packaging is commonly seen from handling drops (Fiedler, 2007). Understanding how these forces affect packaging has led to packaging designs which are better-capable of withstanding stresses thru specific sources, such as cushioning. Similarly, understanding the implications of shock events for pallets and unit loads could lead, not only to better designs specifically created to resist these impacts, but also to improved testing sequences. This may be used to further improve the performance of pallets during the handling and distribution of goods and to better characterize the conditions seen in real-life scenarios.

Rodriguez et al. (1994) investigated the effect that shock impacts have on unit loads. By equipping sensors to both the pallet and the packages, the authors measured shock impact damage for three different unit load configurations. The study measured impact conditions for different levels based on driver experience, operating speed, and load weight, using a counterbalanced forklift truck. Rodriguez, et al. developed a criterion for the conditions necessary to simulate horizontal impacts. They determined that the levels recommended by ASTM D 4003, at the time, were excessively severe (Rodriguez, et al., 1994). The authors also recommended the use of an equation based on impact velocity, pallet weight, forklift weight, and coefficient of restitution to determine impact levels in the simulation of pallet marshalling (Rodriguez et al., 1994).

Understanding the potential effects that multiple factors have on pallet and forklift interactions, provides warehouses with a reference point for determining the most influential elements causing damage to their pallets and products. A clear picture of how these factors affect pallets and handling equipment could help warehouses prioritize which improvement efforts will ultimately increase the durability of their pallets and keep products in an optimal state for the customer. Moreover, additional information on the acceleration response of both the pallet and forklift could be used to improve current standard methodologies and create better testing procedures to predict durability.

A high percentage of top lead deckboard and stringer damage was found for pallets tested in the FasTrack simulation. For this simulation, splits and missing wood are the most common damage modes. The interaction between the pallet and the forklift has a significant contribution to both the damaged locations and the damage modes seen from the FasTrack procedure. An investigation of the factors involved during impacts to a pallet would provide FasTrack with valuable information regarding the intensity of the impacts in the simulation. Furthermore, an understanding of how a pallet's response is related to the acceleration response of the forklift, presents an opportunity for future research to be developed around the handling equipment, rather than the pallet, providing significant savings in measurement methods cost and more efficiency investigation efforts.

3.3 Objective

The objective of this investigation was:

- Investigate the effect that forklift type, top load, pallet design, and entry speed have on the horizontal shock impact exerted by the forklift on the pallet on their interaction

3.4 Materials and methods

3.4.1 Forklifts

The forklift types utilized for the study included a Clark model CQ30L Gas forklift, Clark model TMG15 electric forklift, and a Crown model RR 5715-35 Reach truck (Figure 3.1). The specifications of the forklifts are in Figure 3.1.

Figure 3.1. Forklifts used in the study (left to right: Gas, Electric, Reach)

Table 3.1. Specifications of the forklifts used in the study

	Fork truck		
Specifications	**Gas Forklift**	**Electric Forklift**	**Reach Truck**
Model	CQ30L	Clark TMG15	Crown RR 5715-35
Weight (lbs)	8220	7056	5269
Wheel type	Pneumatic	Cushion	Polyurethane
Payload capacity (lbs)	6000	3000	3500
Production year	2009	1998	2013

3.4.2 Pallet Designs

The FasTrack simulation is utilized for testing the durability of different pallet designs, which commonly involve variations in both material and pallet construction. The most common materials tested with the simulation procedure are wood and plastic. Therefore, two pallet designs were investigated during this study including a wooden and a plastic pallet design. The wooden pallet design selected for the study consisted of a 48 in. x 40 in., multiple-use, block class, non-reversible, perimeter base pallet (Figure 3.2). Th wooden pallet design had an average weight of 51.8 lbs., and it was made of kiln-dried, Southern Yellow Pine. The number of components and the dimensions of the components of this pallet are presented in Table 3.2. The plastic pallet design was a 48 in. x 40 in. nestable, block class, non-reversible pallet (Figure 3.2). This pallet design had an average weight of 24.33 lbs., and it was manufactured by the Orbis corporation (Menasha Corporation, Oconomowoc, WI). Because the friction between the pallet design and the floor could influence the results, the static coefficient of friction between the bottom of the pallet and the concrete floor was measured for both pallet designs using the method outlined by O'Dell et al.

(1998). The coefficient of friction for the wooden pallet was 0.62. The coefficient of friction for the plastic pallet was 0.34. The specifications for the pallet designs are in Table 3.2.

Table 3.2. Wooden pallet specifications

Component	Quantity	Length (in.)	Width (in.)	Height (in.)
Top lead deckboard	4	40	5.375	0.75
Top deckboards	5	40	3.5	0.625
Bottom lead deckboard	2	40	5.375	0.75
Bottom deckboards	3	40	5.5	0.625
Stringer board	3	48	5.5	0.625
Blocks (lead)	6	7.5	4.937	3.5
Blocks (middle)	3	3.75	4.937	3.5

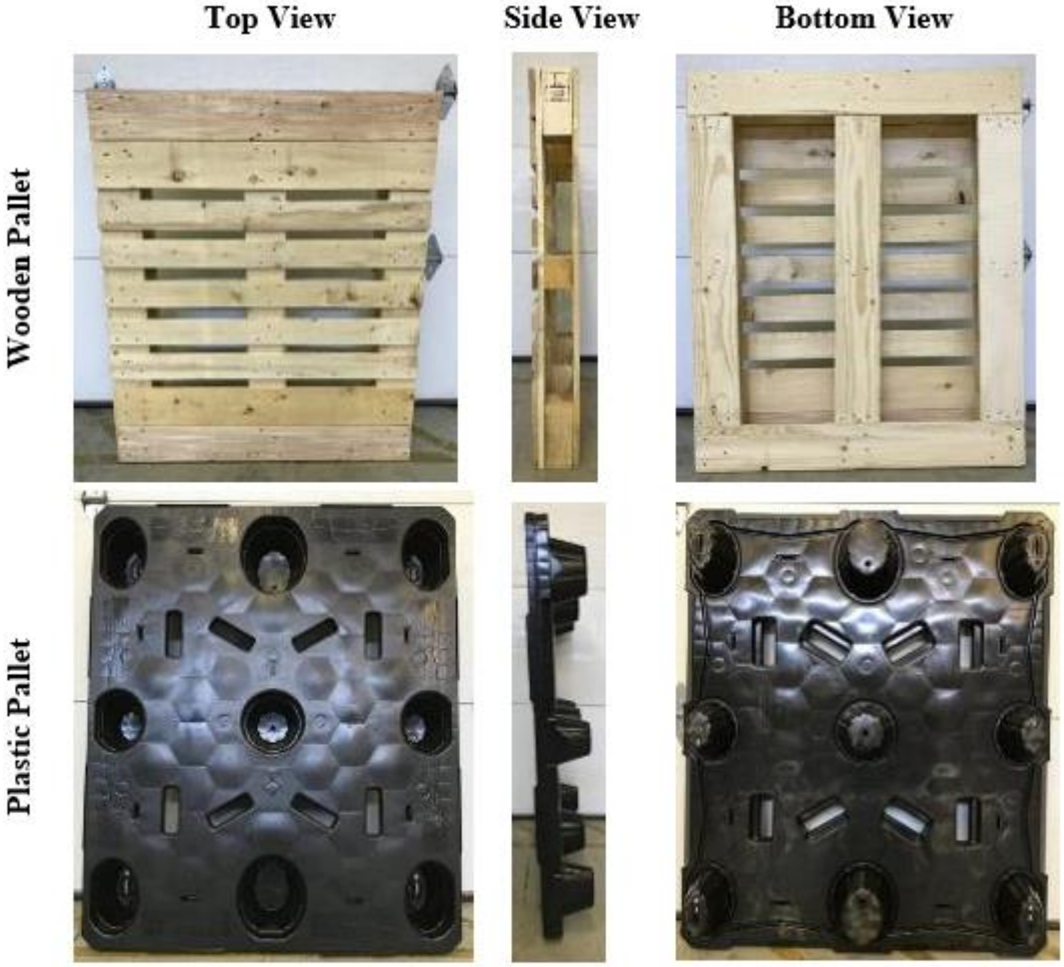


Figure 3.2. Representative top, side, and bottom views of the two investigated pallet designs

3.4.3 Data Collection

Acceleration levels were measured with Lansmont SAVER 3D15 and SAVER 3X90 dataloggers (Lansmont Corporation, Monterrey, CA). The SAVER 3X90 datalogger was mounted to the back of the fork tine carriage using Scotch permanent outdoor/exterior mounting tape (3M Maplewood, MN). The measurements for the pallet were recorded with the SAVER 3D15 datalogger, positioned on the top lead deckboard for both designs (2 in. measured from the 40 in. side, and 9 in. measured from the 48 in. side of each design). The sensor was secured to the pallet using Scotch permanent outdoor/exterior mounting tape (3M, Maplewood, MN). The location of both sensors is shown in Figure 3.3. Data was collected from all three axial directions. The channel parallel to the direction of the impact was used as trigger. The settings used for the dataloggers were:

- Recording time: 2 s
- Sampling rate: 500 samples/s
- Sample size: 1000
- Signal-pre trigger: 50%
- Trigger level: 0.5 G
- Anti-Aliasing Filter Frequency: 250 Hz

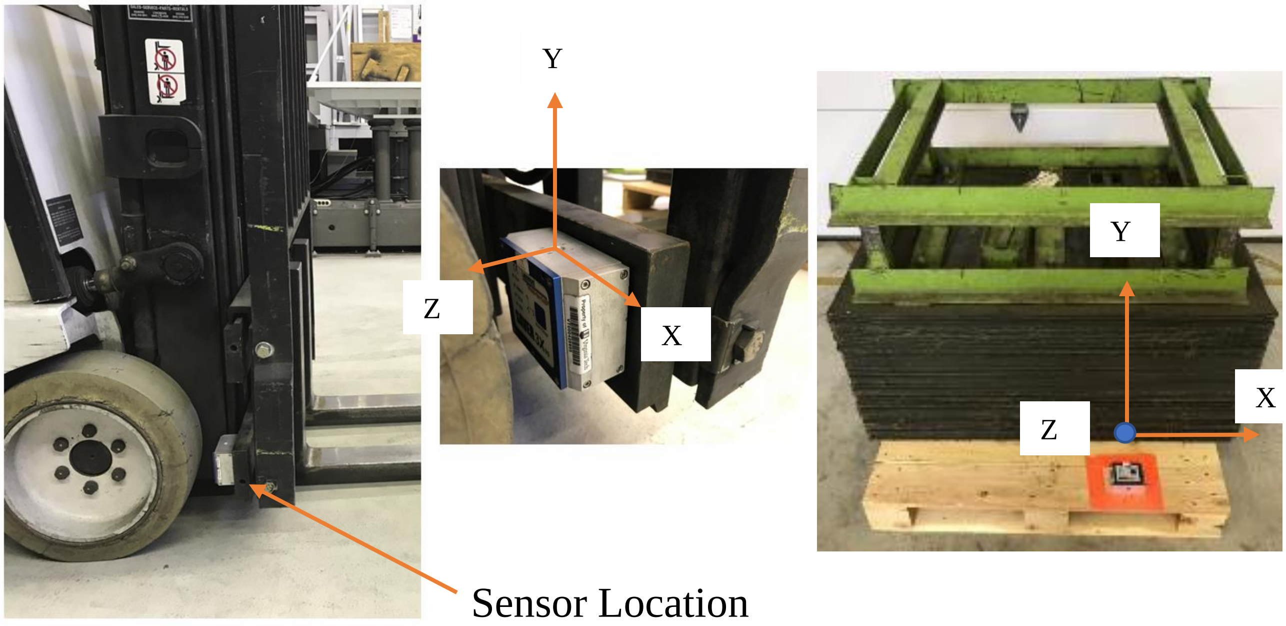


Figure 3.3. Sensor location on forklift and pallet

The SAVER 3X90 located in the back of the forktine carriage (Figure 3.3, left) was oriented with the Z axis parallel to the direction of impact (Figure 3.3, middle). In this orientation, the X axis recorded movement to the left and right. The Y axis recorded the vertical motion of the forklift. On the pallet, the SAVER 3D15 was oriented with the Y axis parallel to the direction of impact (Figure 3.3, right). Similar to the sensor on the forklift, the X axis recorded information about the sideways motion of the pallet. The Z axis recorded the vertical movement of the pallet.

3.4.4 Forklift Impact test

The pallets were impacted by the forklift in a single movement. To ensure the entry speed remained constant among repetitions, marks were drawn on the forktines. The marks reflected the distance at which the entry speed was 0.5 mph and 1 mph. To ensure that there was no disturbance in the data collection, impacts were repeated after the forklift remained idle for one minute. The condition of the pallet was monitored to avoid bias in the measurements due to pallet fatigue. The pallets were loaded with three different payloads: 500 lbs., 1,500 lbs., and 2,500 lbs. The payload was offset from the sensor to avoid the payload contacting the sensor during impact.

3.4.5 Experimental Design

The experimental design is shown in Table 3.3. The experimental design was set up as a full factorial design with acceleration as the main response. An analysis of variance (ANOVA) was used to test the effect of forklift type (3 levels), top load (3 levels), pallet design (2 levels), and entry speed (2 levels). All combinations were replicated 10 times.

Table 3.3. Specifications for experimental circumstances

			Replicates by Forklift Type		
Pallet Design	**Entry Speed (mph)**	**Payload (lbs)**	**Gas Forklift**	**Electric Forklift**	**Reach Truck**
Wood	0.5	500	10	10	10
		1500	10	10	10
		2500	10	10	10
	1	500	10	10	10
		1500	10	10	10
		2500	10	10	10
Plastic	0.5	500	10	10	10
		1500	10	10	10
		2500	10	10	10
	1	500	10	10	10
		1500	10	10	10
		2500	10	10	10

3.5 Statistical Methods

Results were analyzed with the Minitab Statistical Software (Minitab LLC, State College, PA) as well as Microsoft Excel (Microsoft Corporation, Redmond, WA). To compare the effects over the main response, an ANOVA was conducted with a significance level of 0.05. Peak G force, duration, and delta velocity were manually selected for each event using the SaverXWare software (Lansmont Corporation, Monterrey, CA).

A statistical model is used to test the effect of the factors on the peak acceleration values:

$$Y_{ijkl} = \mu + F_i + T_j + P_k + E_l + F_iE_l + F_iP_k + P_kE_l + T_jP_k + T_jE_l + F_iT_jP_k + \varepsilon_{ijkl} \tag{11}$$

Where Y_{ijkl} = the response of interest (acceleration), μ = overall mean, F_i = effect of the i^th^ forklift, T_j = effect of the j^th^ top load, P_k = effect of the k^th^ pallet design, E_l = effect of the l^th^ entry speed, F_iE_l = interaction effect between i^th^ forklift and l^th^ entry speed, F_iP_k = effect of the interaction between i^th^ forklift and k^th^ pallet design, P_kE_l = effect of the interaction between k^th^ pallet design and l^th^ entry speed, T_jP_k = effect of the interaction between the j^th^ top load and k^th^ pallet design, T_jE_l = effect of the interaction between j^th^ top load and l^th^ entry speed, $F_iT_jP_k$ = effect of the interaction between i^th^ forklift, j^th^ top load and k^th^ pallet design, and ε_{ijkl} = random error with expectations (0, σ^2)

The Tukey pairwise comparison test at a significance level of 0.05 was used to compare the factors in the study.

3.6 Results and Discussion

3.6.1 Forklift behavior

The acceleration, duration, and delta velocity response registered for each forklift is shown in Table 3.4. The average acceleration measured on the forklifts was 2.98 G. The coefficient of variation obtained for these measurements was 37%, reflecting values as low as 1.38 G (for the reach truck) or as high as 5.1 G (for the gas forklift). The event duration recorded was 13.6 ms. However, durations recorded in the reach truck were 50% higher than the durations of the gas and electric forklift. Durations in the gas and electric forklift averaged 10.2 ms. The increase in event duration for the reach truck is due to the reach mechanism being fully extended for the impacts conducted with this forklift. The coefficient of variation obtained for that event duration was 23%. While high, the variations found in this study are considered acceptable as shock is traditionally considered a difficult parameter to characterize (Ostrem & Godshall, 1979). The relationship between pallet peak acceleration and delta velocity is presented in Appendix 7.7.

Table 3.4. Acceleration, Duration and Delta Velocity response by factor configuration[f]

Forklift	Pallet Design	Entry Speed (mph)	Payload (lbs)	Peak Acceleration (G)	Duration (ms)	Delta V (in/s)
Reach	**Plastic**	**0.5**	500	1.38 (16.4)	15.40 (31.8)	4.87 (44.8)
			1500	1.51 (9.4)	25.20 (8.53)	8.30 (6.05)
			2500	1.90 (7.7)	25.60 (9.60)	10.93 (14.6)
		1	500	2.74 (31.4)	18.60 (52.6)	11.07 (55.6)
			1500	2.95 (23.8)	24.40 (25.2)	15.05 (14.4)
			2500	3.30 (11.1)	24.60 (28.1)	16.58 (22.0)
	Wood	**0.5**	500	2.02 (12.3)	23.00 (13.1)	9.63 (19.3)
			1500	1.90 (16.2)	26.20 (8.40)	10.47 (15.0)
			2500	3.03 (14.9)	23.00 (23.2)	13.26 (16.5)
		1	500	3.35 (27.2)	13.40 (10.0)	10.49 (33.5)
			1500	4.48 (19.5)	15.80 (26.3)	13.74 (26.9)
			2500	5.10 (18.5)	9.20 (15.2)	9.51 (15.3)
Electric	**Plastic**	**0.5**	500	1.84 (22.1)	8.60 (24.6)	4.00 (29.3)
			1500	1.97 (12.2)	10.60 (9.11)	4.85 (15.3)
			2500	2.61 (17.0)	9.40 (26.6)	5.63 (16.3)
		1	500	2.48 (20.3)	12.20 (41.2)	7.01 (41.3)
			1500	2.36 (37.7)	10.00 (28.2)	6.12 (46.3)
			2500	3.02 (14.9)	7.80 (18.9)	5.56 (30.3)
	Wood	**0.5**	500	2.10 (26.6)	13.00 (16.6)	5.85 (27.3)
			1500	2.06 (26.0)	12.60 (7.67)	5.34 (21.3)
			2500	3.13 (12.9)	12.20 (21.0)	8.82 (26.3)
		1	500	3.66 (30.1)	11.00 (17.6)	8.37 (22.3)
			1500	4.21 (19.2)	11.20 (12.4)	10.06 (20.3)
			2500	4.15 (32.6)	13.40 (18.6)	10.65 (29.3)
Gas	**Plastic**	**0.5**	500	3.34 (35.3)	7.4 (28.6)	5.46 (39.5)
			1500	2.96 (12.5)	10.4 (8.1)	5.86 (16.1)
			2500	2.86 (9.31)	10.4 (12.1)	6.38 (17.2)
		1	500	3.15 (26.4)	9.4 (10.2)	6.49 (17.5)
			1500	3.80 (11.5)	8.0 (11.7)	5.70 (21.1)
			2500	3.31 (28.4)	9.8 (6.4)	7.73 (22.2)
	Wood	**0.5**	500	2.92 (12.4)	9.4 (10.2)	5.64 (12.5)
			1500	2.29 (19.6)	10.8 (9.5)	5.46 (17.1)
			2500	3.79 (30.3)	10.2 (21.5)	7.60 (12.2)
		1	500	3.15 (26.4)	9.4 (10.2)	6.49 (17.5)
			1500	3.47 (18.0)	9.4 (14.3)	7.42 (9.1)
			2500	5.10 (18.5)	9.2 (15.2)	9.51 (15.2)

[f] Numbers in parentheses refer to coefficient of variation (%)

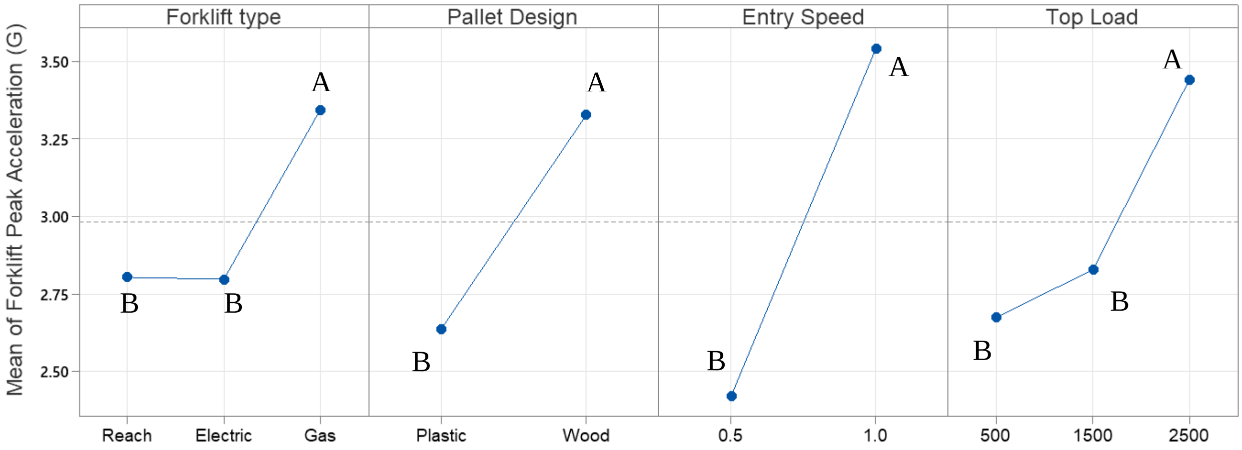
The acceleration response measured in the forklift is used as the main response for further analysis. Table 3.5 are the results of the analysis of variance:

Table 3.5. ANOVA: Acceleration response according to pallet design, entry speed, payload, and forklift.

Source	P-Value
Model	0.000
Linear	0.000
Forklift type	0.000
Pallet Design	0.000
Entry Speed	0.000
Top Load	0.000
2-Way Interactions	0.000
Forklift type*Pallet Design	0.000
Forklift type*Entry Speed	0.000
Forklift type*Top Load	0.508*
Pallet Design*Entry Speed	0.000
Pallet Design*Top Load	0.000
Entry Speed*Top Load	0.004
3-Way Interactions	0.000
Forklift type*Pallet Design*Top Load	0.000

*Factor is not significant at an alpha=0.05 level

The p-values obtained in the analysis show that all of the main factors, including forklift type, pallet design, entry speed, and top load, have significant effects on the acceleration experienced by the forklift during its interaction with the pallet. Similarly, there are two-way interactions between most variables, except between the forklift type and the top load (p = 0.508). A three-way interaction is significant in the model (p=0.000), corresponding to the forklift, pallet design, and top load.



[g] Tukey pairwise comparison indicates means that do not share a letter are significantly different at an alpha= 0.05

Figure 3.4. Main effects plot for forklift Peak Acceleration[g] response.

The effect of the main variables was further investigated using a main effects plot (Figure 3.4) and Tukey's pairwise comparison (Appendix 8.2). The measured acceleration response was significantly higher (15%) when the gas forklift was used, while the reach truck and the electric forklift were not significantly different. However, event durations in the reach truck were 45% longer than the electric forklift.

When wood pallets were used for the testing, the acceleration levels were significantly higher (20.7%). This result could be explained by the greater coefficient of friction between the pallet and the laboratory floor, which increases the resistance of the pallet to impact. The high stiffness of wood pallets could also contribute to this trend. Pallet design did not affect the duration response (Appendix 8.5).

When the impact speed was increased, the measured acceleration increased significantly (by as much as 32%). Entry speed did not affect the duration response. Comparing entry speed for pallet impact with the height when a package is dropped, higher drop heights do not have an effect on shock response durations for package drops (Goodwin & Young, 2011).

The results show that there is no significant difference in acceleration when the payload is increased from 500 lbs. to 1,500 lbs. However, when the payload was further increased to 2,500 lbs., the measured acceleration increased 22%. This result indicates that for heavy payloads, the amount of the payload needs to be tracked during data collection.

Due to the change in mean acceleration, pallet design and entry speed are the most influential factors on the acceleration measured on the forklift at the moment of impact.

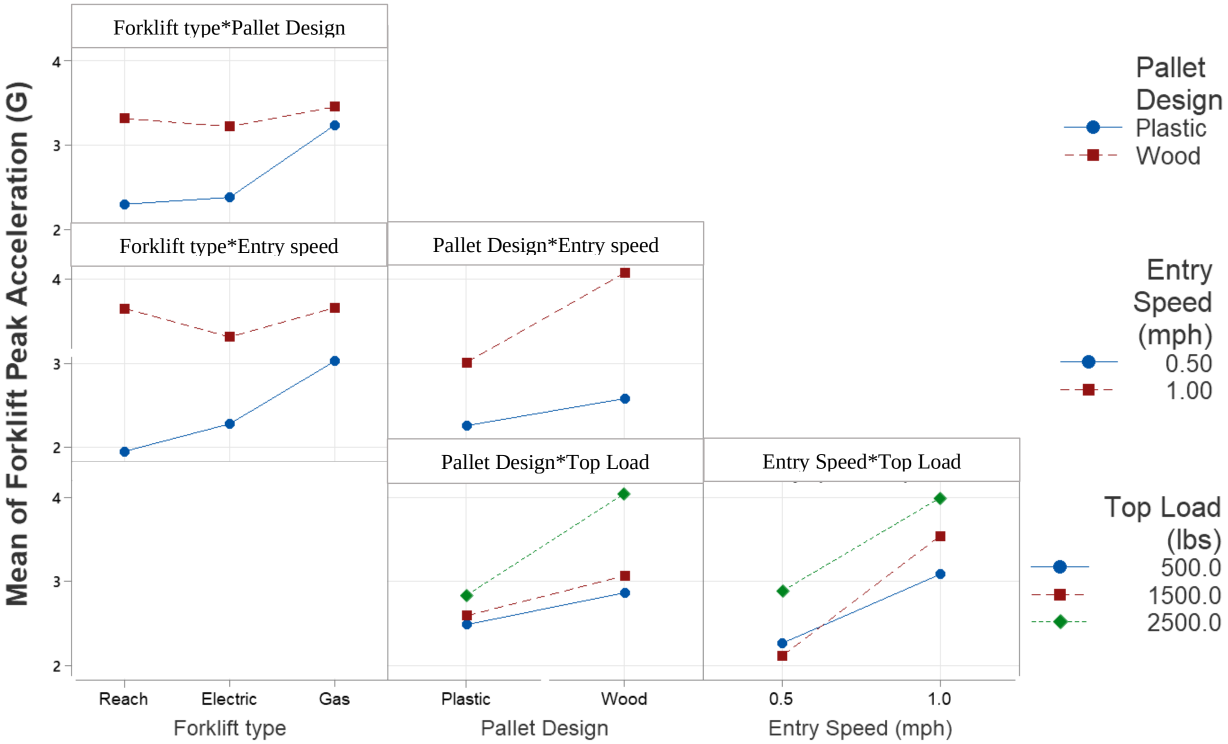


Figure 3.5. Interaction plot for Forklift Peak Acceleration response

Figure 3.5 shows the interactions between the main effects. A change in pallet design has an effect on the mean peak acceleration for the different forklifts. The change from plastic to wood design is associated with higher peak accelerations for the reach truck and the electric forklift.

Entry speed had an effect on the acceleration response for each forklift. The effect of the change in speed was greatest for the reach truck (46% increase). The changes in the behavior of the gas and the electric forklifts were similar. Pallet design is also affected in a different manner by a change in speed. The wooden design shows a greater peak acceleration response when the speed increases 0.5 mph.

Pallet design has an effect on the peak acceleration response measured for different payloads. When wood was impacted, there was a significant increase in the peak acceleration for the 2,500 lbs. top load. Although it was seen that the top load was significant, this behavior is pallet dependent. This behavior is explained by the higher weight of the pallet and the coefficient of friction, which created a greater resistance to impact.

The accelerations measured during impacts to the different top loads is also dependent on the entry speed. At higher speeds, there are significant differences between the 500 lbs., 1,500 lbs., and 2,500 lbs. payloads (12% - 14% difference). At lower speeds, the acceleration measured is the not significantly different for the 500 lbs. and 1,500 lbs top payloads.

3.6.2 Pallet Behavior

Table 3.6 shows the acceleration, duration, and delta velocity response registered in the pallet for each shock event in the study. Peak acceleration measured in the pallet is on average 13.15 G. The data have a coefficient of variation of 40%, with the lowest peak acceleration value of 3.7 G in the reach truck, and the highest acceleration value of 19.51 G measured in the gas forklift. The impact event duration was 12 ms. A coefficient of variation of 37% is associated with this data. Impacts to the pallet show an average change in speed of 28.83 in/s, with values as low as 11.1 in/s measured in the reach truck and as high as 53.1 in/s measured in the gas forklift. The coefficient of variation for delta velocity is 42%. The relationship between pallet peak acceleration and delta velocity is presented in Appendix 7.8.

Table 3.6. Pallet acceleration, duration, and delta velocity response according to factor configuration [h].

Forklift	Pallet Design	Entry Speed (mph)	Payload (lbs)	Peak Acceleration (G)	Duration (ms)	Delta V (in/s)
Reach	**Plastic**	**0.5**	500	8.00 (12.98)	10.6 (26.8)	17.8 (25.01)
			1500	5.91 (13.7)	7.80 (30.53)	9.15 (12.03)
			2500	4.72 (25.1)	12.6 (29.60)	11.1 (8.94)
		1	500	17.97 (22.96)	10.2 (14.6)	41.4 (16.3)
			1500	12.3 (35.9)	12.2 (35.2)	38.2 (30.9)
			2500	14.8 (24.6)	15.8 (18.1)	41.3 (21.4)
	Wood	**0.5**	500	8.1 (25.5)	14.6 (38.1)	14.1 (10.8)
			1500	3.7 (38.3)	20.6 (29.40)	12.9 (35.6)
			2500	10.0 (20.0)	6.80 (15.2)	15.6 (20.1)
		1	500	14.1 (37.97)	10.6 (46.0)	25.3 (37.9)
			1500	15.9 (34.2)	11.0 (35.3)	28.97 (27.99)
			2500	14.5 (14.9)	15.4 (15.2)	43.53 (10.13)
Electric	**Plastic**	**0.5**	500	11.9 (10.7)	10.2 (17.2)	27.78 (16.34)
			1500	8.54 (7.98)	12.6 (7.0)	22.93 (5.46)
			2500	9.76 (24.84)	12.4 (10.2)	33.66 (23.80)
		1	500	16.12 (16.60)	10.6 (9.5)	39.01 (10.88)
			1500	12.21 (17.76)	13.2 (23.2)	33.87 (10.16)
			2500	16.39 (12.03)	11.0 (12.1)	44.66 (6.40)
	Wood	**0.5**	500	11.9 (24.7)	15.0 (40.2)	20.69 (27.89)
			1500	10.88 (21.55)	15.4 (18.0)	21.99 (11.83)
			2500	15.08 (22.69)	7.60 (42.2)	19.90 (14.18)
		1	500	14.87 (26.40)	14.4 (41.1)	32.11 (14.82)
			1500	14.60 (19.01)	15.0 (38.1)	31.84 (18.79)
			2500	15.36 (31.65)	7.80 (35.2)	21.01 (23.29)
Gas	**Plastic**	**0.5**	500	18.99 (19.2)	11.6 (15.8)	42.79 (7.23)
			1500	10.33 (8.9)	14.0 (9.52)	23.90 (7.58)
			2500	10.02 (9.9)	13.8 (10.6)	32.48 (12.02)
		1	500	19.51 (38.3)	9.60 (61.9)	34.30 (30.73)
			1500	16.83 (10.1)	12.0 (7.86)	37.49 (6.33)
			2500	16.84 (24.6)	15.2 (11.1)	53.06 (29.20)
	Wood	**0.5**	500	17.14 (11.5)	8.40 (24.5)	25.38 (17.13)
			1500	13.57 (20.6)	10.8 (46.3)	21.86 (22.20)
			2500	11.04 (23.7)	10.6 (43.6)	19.41 (21.65)
		1	500	19.51 (38.3)	9.60 (61.9)	34.30 (30.73)
			1500	19.48 (30.8)	10.2 (40.7)	31.07 (28.12)
			2500	14.47 (14.1)	15.4 (15.0)	43.53 (10.13)

h: Numbers in parentheses refer to coefficient of variation (%)

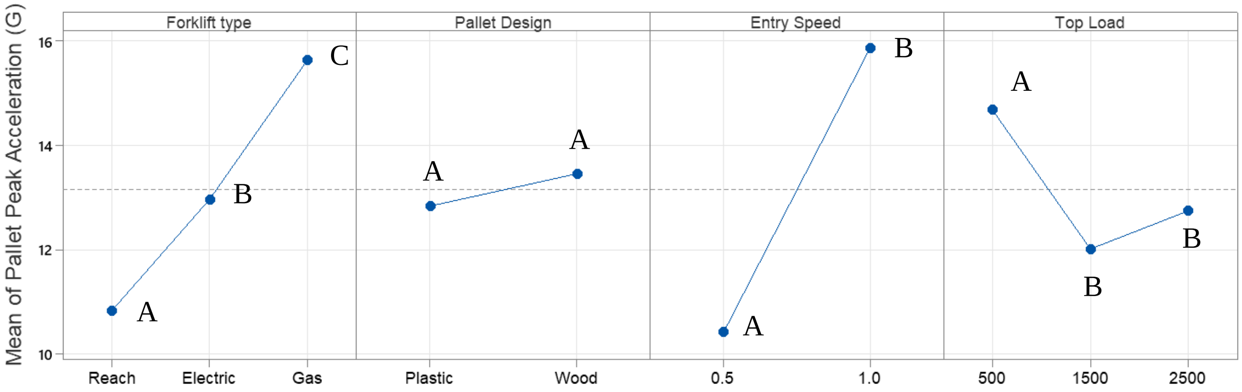
The acceleration response measured in the pallet for each impact is used as the main response for further analysis. The results from the analysis of variance are shown in Table 3.7.

Table 3.7. ANOVA for Pallet Peak Acceleration based on forklift type, pallet design, entry speed, and payload

Source	**P-Value**
Model	0.000
Linear	0.000
Forklift type	0.000
Pallet Design	0.093*
Entry Speed	0.000
Top Load	0.000
2-Way Interactions	0.000
Forklift type*Entry Speed	0.000
Forklift type*Top Load	0.000
Pallet Design*Entry Speed	0.081*
Pallet Design*Top Load	0.000
Entry Speed*Top Load	0.154*
3-Way Interactions	0.001
Pallet Design*Entry Speed*Top Load	0.001

*Factor is not significant at an alpha level=0.05

The p-values obtained in the analysis show that the main factors, including forklift type, entry speed, and top load, have a significant effect on the peak acceleration response measured on the pallet. Significant two-way interactions were found in the combinations of: forklift type and entry speed, forklift type and top load, and pallet design and top load. The interactions between pallet design, entry speed, and top load is significant in the model (p=0.001).



[i] Tukey pairwise comparison indicates means that do not share a letter are significantly different at an alpha= 0.05

Figure 3.6. Main Effects plot for Pallet Peak Acceleration[i] (G)

The effect of the main variables on the peak pallet acceleration response was investigated with the main effects plot (Figure 3.6). The forklift type plot shows an increase of 16% for a change in forklift type. The acceleration response change seems to be affected by the weight of the forklifts. No significant differences were shown in pallet duration for the different forklifts (Appendix, Table A. 10).

The entry speed plot shows a 14% peak pallet acceleration increase when the speed is 1 mph. Similar to the forklift type plot, there was no change in the duration response for increasing levels of speed. The effect of the top load shows a significant increase in peak pallet acceleration for the 500 lbs payload (13.8%). The Tukey Pairwise comparison shows no significant differences between the responses with the change of payload from 1,500 lbs. to 2,500 lbs.

Significant two-way interactions are shown in Figure 3.7. Significant differences were evaluated with the Tukey Pairwise Comparison Method (Appendix, Table A. 7).

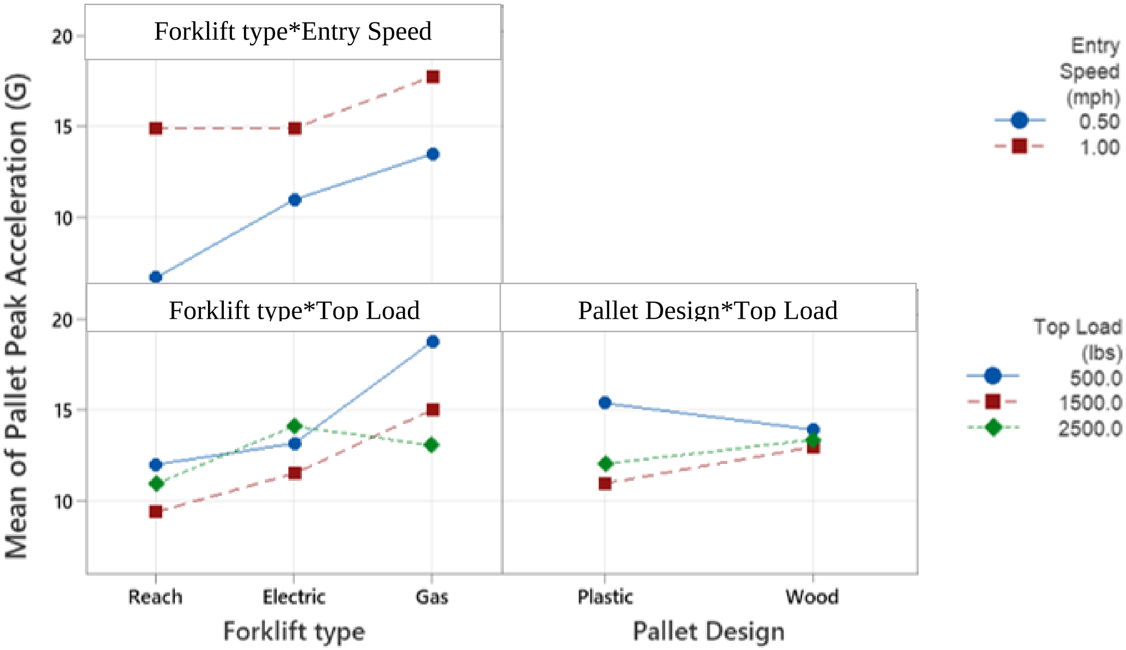


Figure 3.7. Interaction plot for Pallet Peak Acceleration response

The measured acceleration obtained by forklift type is dependent on the entry speed. At lower speeds, there are differences between forklifts. The reach truck presents the lowest acceleration response. This behavior could be explained by the reach mechanism of this forklift, which could act as a cushion during impacts. At higher speeds, the greatest acceleration was measured on the gas forklift.

The acceleration obtained with the different forklift types is also dependent on the top load of the pallet. High differences in behavior are seen for each forklift depending on the top load. The greatest acceleration was measured with the gas forklift and a 500 lbs. payload.

Pallet design affects the acceleration values obtained for each top load combination. The greatest acceleration response was recorded for the plastic design using a 500 lbs. payload. This increase in acceleration could be caused by the plastic pallet sliding when it was impacted by the forklift.

3.6.3 Pallet vs Forklift

The mean peak acceleration for the impacts measured on both the pallet and the forklift are compared with the Tukey's Pairwise Comparison. The differences were evaluated according to the main effects of the study (Table 3.8). Significant differences were found in the acceleration levels between pallet and forklift. There is an increase (17% - 21%) in pallet acceleration when heavier forklift trucks are used to impact the pallet.

Comparisons made by pallet design show significant differences between the acceleration responses measured in the pallet and the forklift. However, there is no difference between pallet designs, which show an increase of 10 G in the pallet when compared to the acceleration response measured in the forklift. The acceleration response of the forklift and pallet with the change of entry speed is significantly different. The acceleration difference ranges from 8 G – 12 G.

There are significant differences between the peak acceleration response measured in the pallet and the forklift, when varying the top loads. However, the 1,500 lb. and 2,500 lb. payloads reflect a 9 G difference when comparing pallet to forklift acceleration. There is a 12 G difference in the acceleration measured in both sources when a 500 lb. payload is used.

The acceleration in the pallet is approximately 4.4 times greater than that obtained from the forklift. However, there are deviations in the cases of the payloads and the forklift types, where this relationship is not consistent. Variations in the mass of the forklifts and operator error may explain these scenarios. The impact durations for pallet and forklift are consistent regardless of the source, ranging from 10 ms – 12 ms. Extended durations were obtained with the reach truck, which averaged 20 ms.

Table 3.8. T Pairwise Comparisons for Peak Acceleration Mean: Pallet vs Forklift [j]

		Peak Acceleration Mean (G)			
Factor	Level	Forklift	Pallet	Difference (G)	P-Value
Forklift Type	Reach	2.81 (44.5)	10.83 (50.8)	-8.03	0.000
	Electric	2.80 (37.5)	12.97 (28.9)	-10.17	0.000
	Gas	3.35 (29.6)	15.64 (33.8)	-12.30	0.000
Pallet Design	Wood	3.33 (37.2)	13.46 (39.2)	-10.13	0.000
	Plastic	2.64 (33.3)	12.84 (41.1)	-10.20	0.000
Entry Speed (mph)	0.5	2.42 (34.3)	10.42 (41.7)	-8.00	0.000
	1	3.54 (31.4)	15.87 (29.6)	-12.33	0.000
Top Load (lbs)	500	2.68 (36.6)	14.68 (39.1)	-12.00	0.000
	1500	2.83 (38.5)	12.02 (43.8)	-9.19	0.000
	2500	3.44 (33.7)	12.75 (34.6)	-9.31	0.000

j: Numbers in parentheses refer to coefficient of variation

The Pearson Correlation test was conducted on the pallet and forklift peak accelerations. The results of the test are shown in Figure 3.8. The Pearson r coefficient obtained in the test (0.451) suggests a subtle relationship between forklift peak acceleration as the predictor and pallet peak acceleration as the response. A positive coefficient supports the increasing relationship behavior seen in Table 3.8.

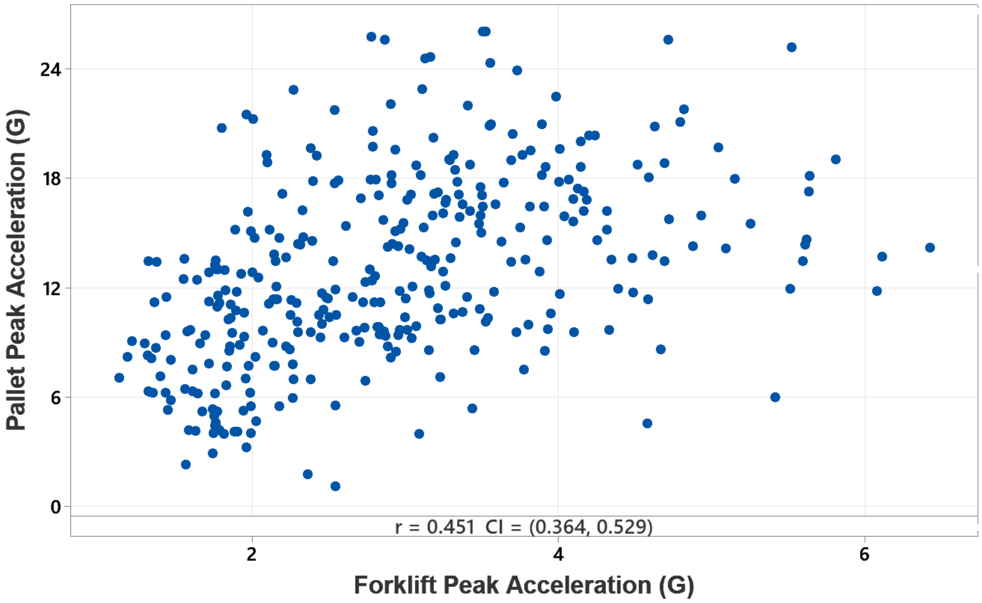


Figure 3.8. Pearson Correlation test for Peak Acceleration: Pallet vs Forklift.

A regression plot that models the relationship between the pallet and forklift is shown in Figure 3.9. The correlation test shows a linear model is a poor fit for accurately representing the relationship between the forklift and pallet peak acceleration responses. The R-squared obtained is 20%. According to the regression model, the relationship can be described as:

$$Pallet\ Peak\ Acceleration\ (G) = 2.1\ Forklift\ Acceleration\ (G) + 6.855 \qquad (12)$$

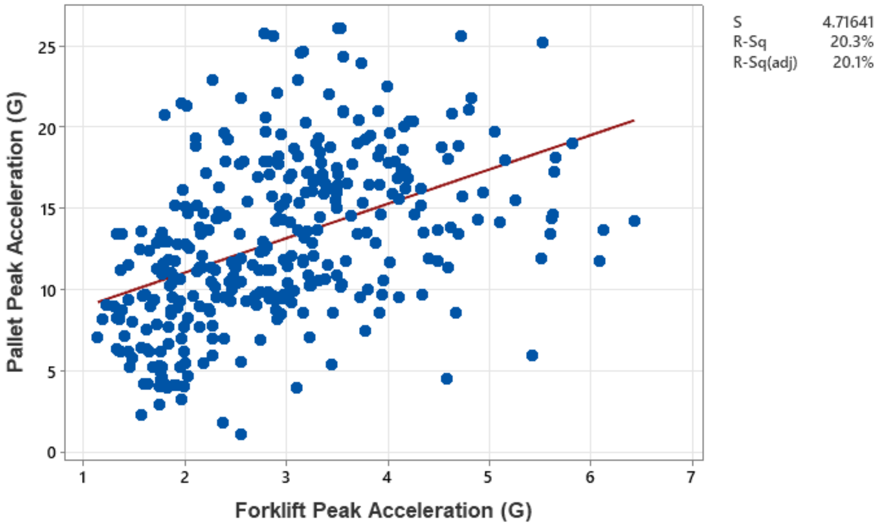
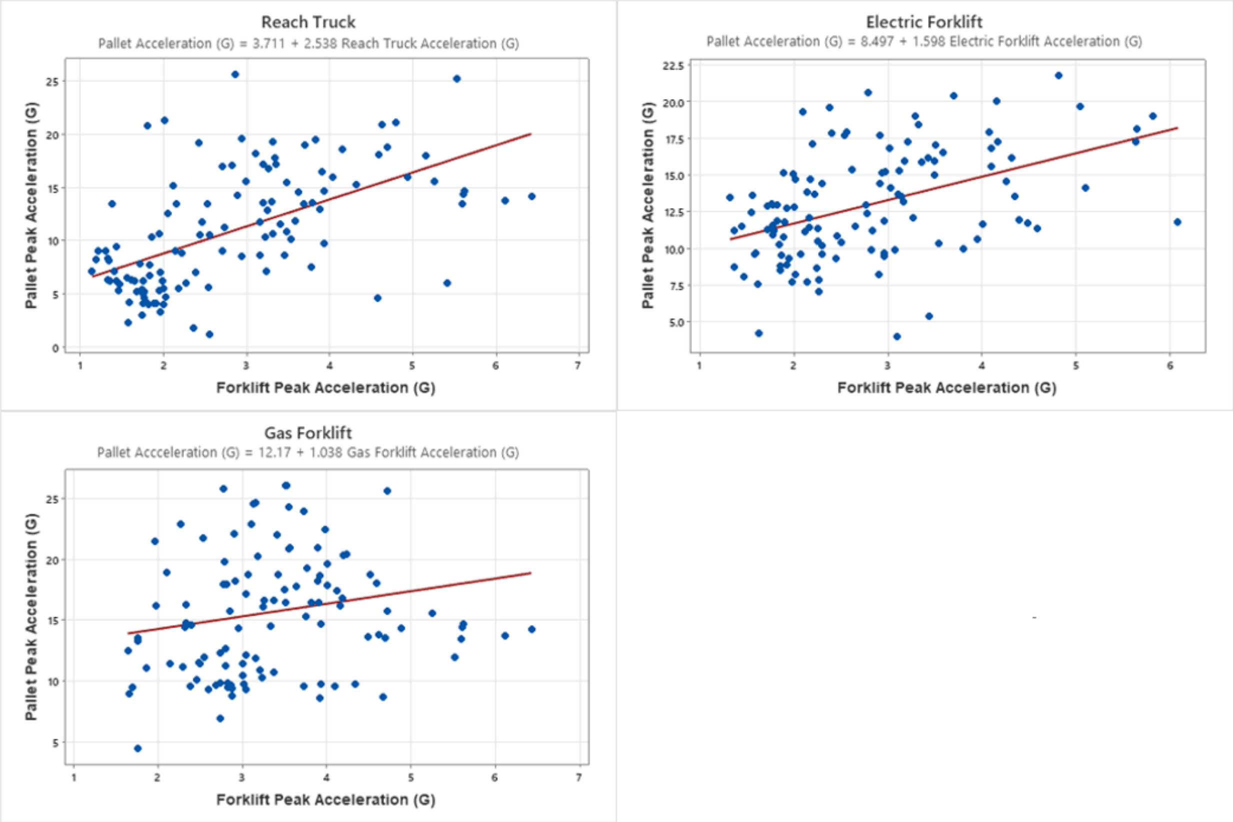


Figure 3.9. Regression plot for Pallet peak acceleration (G) vs forklift peak acceleration (G)

The relationship between the pallet and the different forklifts in terms of peak acceleration is shown in Figure 3.10. A linear regression model is presented to show the relationship between pallet designs and the different forklifts used in the study. The plot for each forklift shows no linear correlation between the acceleration measured in the pallet and the acceleration measured in the forklifts (supported by the low R^2). The best fit was obtained for the reach truck ($R^2 = 30\%$), followed by the electric forklift ($R^2 = 20\%$). As presented by the ANOVA, several factors, besides the forklift, need to be studied before being able to create a model to predict pallet acceleration. Appendix 7.6 presents the relationship of pallet peak acceleration and forklift peak acceleration for the different levels of entry speed, top load and pallet design used for this study.


Reach Truck

Electric Forklift

Gas Forklift

Figure 3.10. Regression Plot of Pallet Peak Acceleration vs Forklift Peak Acceleration

3.7 Conclusions

- The intensity of the horizontal shock response exerted on the pallet varies approximately 16% depending on the type of forklift used. It is necessary to monitor the type of forklift when comparing acceleration intensities and their effect on pallet durability.
- The plastic pallet design is associated with a 20% lower horizontal shock response in the forklift. The intensities at which wooden pallet designs are tested in the FasTrack simulation may not be adequate to test plastic pallet designs.
- A 14% higher acceleration response was obtained for the pallet when the speed was increased. Higher entry speeds could be used to simulate greater intensities for specific pallet-forklift interactions such as the ones seen in FasTrack**.**
- An increase in the acceleration response was found with the change in top load; however, this change is associated with interactions between top loads and factors such as entry speeds and forklift types**.**
- The acceleration measured in the pallet is approximately 4.4 times greater than the acceleration measured in the forklift for the same impacts. Measurements of the horizontal shock response in the forklift can be used to estimate the shock intensity when testing pallets.
- The linear correlation between pallet peak acceleration and forklift peak acceleration is poor (r=0.45). Further efforts must be done to model the pallet response and the forklift acceleration response with another model approach.

The results of this investigation show that the impact intensity of the interactions between pallets and forklifts are dependent on factors such as the load weight, the forklift type, and the entry speed. Knowing the conditions in a customer's handling environment, variations in the loads, and entry speeds could be implemented in the FasTrack simulation to improve its ability to replicate the results seen for pallets in the field. The study also showed differences between plastic and wood pallet designs, which indicate that the impacts simulated in FasTrack for wooden pallets may not be adequate for simulating plastic pallet behavior in the field.

3.8 References

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4 Overall conclusions

This study investigated 48 in. x 40 in., three-stringer, partial four-way, double-sided, non-reversible, flush, wooden pallet designs. The damage locations, damage modes, and damage severity for pallets from FasTrack and the field were quantified. The main conclusions of the investigation are:

Differences between the damage results produced with the FasTrack simulation and the field were identified. For the damage locations, FasTrack does not accurately replicate the behavior seen in the field. The simulation emphasizes damage in the stringers and the top lead deckboards of the pallet, while damages to top and bottom deckboards are underestimated. Damage to the notch is also underestimated in FasTrack. This lack of damage could be linked to the differences seen in damage modes for both data sources. Both FasTrack and field follow a close relationship for the distribution of splits and missing wood, but breaks are rarely seen in the simulation.

The damage severity inspection showed that there are no trend differences between medium and high severity damages. The damages found for FasTrack and the field were linked to the interactions with handling equipment such as forklifts and pallet jacks, and were not produced by stacking and racking conditions. While these conditions are common in warehouse environments, their presence in FasTrack is brief, and rarely produces damages. The weight and the time that the pallet remains in the loaded condition may affect the results between FasTrack and field.

A greater potential for pallet damage in the interaction with the forklift was identified for FasTrack. The effects of entry speed, top load, forklift type, and pallet design on the horizontal shock impact were investigated. The main conclusions of the investigation are presented as follows:

Modifications in entry speed and the top load of the pallet are linked to a change in the intensity of the impact between forklift and pallet. The study also showed that the intensity of the impacts was different depending on the forklift type and the pallet design. With this information, the FasTrack simulation can be customized to better meet the intensity levels expected in a customer’s handling environment.

A procedure to equip a datalogger to the forklift is presented with this research. Comparing the response measured in the pallet with the response in the forklift, the acceleration in the pallet is greater. While linear correlation is poor, the study shows that there is an opportunity to gather impact intensity information directly from the forklift, rather than the pallet. An accurate model of the relationship between pallet and forklift impact intensity could help reduce costs and ease the investigation efforts in further research, focusing on the forklift to predict pallet behavior.

5 Modification Proposal for FasTrack and Future Research

Based on the findings from both chapters of the study, there are several modifications that can be done to FasTrack to improve its performance. The results obtained during the pallet inspection showed a high level of top lead deckboard and stringer damage which often determined the end of the simulation, as FasTrack finishes when the pallet damage requires repair. The FasTrack simulation can be stopped prematurely after any repairable damage is found on lead deckboards or stringers, but this leaves the rest of the components of the pallet unaffected. As noted in Figure 2.10**,** testing repaired pallets in FasTrack yields the same top lead deckboard and stringer damage. As a modification proposal, it is recommended to run the FasTrack simulation past the point of repairable damage, until the last step of the simulation is completed and the cycle finishes.

The damage criteria used during pallet inspection for chapter two of this research was based on the standards and general guidelines followed by the industry. However, deviations from these guidelines could affect the ability of the FasTrack simulation to predict results for pallets used in the field. Additional information on the repair criteria can be gathered from companies and pallet repair facilities. With this information, an assessment of the state at which companies decide to repair pallets could be compared to the recommendations in the current standards. These criteria can be used to further improve FasTrack. The recommendation for FasTrack is to monitor for the particular damages that a customer deems as pallet failure, as well as the handling equipment that was involved. This information could be used to modify the intensity of certain steps in the simulation and adjust the failure criteria to better fit the demands of the customer.

The damages seen on the pallets tested in FasTrack are commonly generated by their interactions with the forklifts, as well as a 5 ft. drop. There are steps in FasTrack on which the damage output is low, and which are rarely featured in the damage log. These steps include static rack storage and stack storage. Similarly, the gravity flow rack seems to apply little stress to the pallets tested. Proposed modifications would include these steps being taken out of the regular FasTrack procedure and conducted as accelerated intensity tests. This could allow for an assessment of the damages associated with specific steps in the simulation. Typically, the FasTrack procedure features static rack storage as an operation that puts the pallet in said condition for approximately 30 seconds, with a 1500 lbs. payload. The accelerated intensity test would repeat this static rack condition multiple times and record the damages produced on the pallet. A similar approach would be taken with the gravity flow rack and stack storage.

As a reference, a pallet, such as a multiple-use CHEP or a GMA design, whose durability information has already been proven with the FasTrack simulation could be used for the analysis. The singular steps in FasTrack would be repeated for a representative sample. The damages seen in these repetitions would be recorded. The results of these tests would be compared in terms of damage output and/or damage modes, similar to the comparison done between FasTrack and field in this study.

The positive outcome of this assessment would be to obtain a clear characterization of the damages that specific steps in FasTrack generate. Alternatively, it could be proven that these conditions do not significantly increase the damage output of the simulation, which could be used as a base to eliminate these steps from the FasTrack procedure entirely. The pallet would instead be tested following ISO/ASTM guidelines such as ASTM-D1185 and ISO 8611 in case the client is interested in its performance for specific conditions.

The gravity flow rack is similar. Rather than the rolls, the stopper could be the only component of the flow rack that poses a threat to a pallets' integrity, but this situation is unlikely. Therefore, if no significant differences are identified in this step, its removal from the procedure could be a modification to consider.

A comparative assessment of the damages seen every ten cycles in the simulation could be used to identify whether the damages seen in pallet components, such as the lead deckboards and the stringers, are mainly caused by their interactions with forklifts during the FasTrack procedure, during entry and slueing interactions. This presents an opportunity to evaluate the implementation of controlled impacts instead of forklift usage. Controlled impacts could be implemented through the use of an incline impact tester, using a specific speed and top load. However, an assessment between FasTrack and the outcome of the incline impact tester needs to be conducted to demonstrate that there are no significant differences between both methods.

The study of the horizontal shock impact damage shows that the intensity of the horizontal shock depends on the type of forklift used. A potential modification in FasTrack could include requesting information about the forklifts used by the customer. A similar approach could be taken with the top load that the tested pallet is expected to carry. Varying levels of top loads and entry speeds could be implemented to customize the FasTrack procedure to fit the environment of specific companies or simulate harsher conditions. This proposal requires the customer to release additional information about their warehouse environment in terms of equipment and overall top load, but it provides a more accurate prediction of durability to fit their handling system.

Chapter three of this research also presents a method by which to gather shock information for the forklift. The forklift should be equipped with a datalogger before it is used for FasTrack, to measure and collect the intensity of the impacts that were conducted on the pallet. This information would be reported to the customer and could be used to monitor driver performance for the simulation with control charts. Additionally, a shock intensity study could be offered to customers, following the procedures in chapter three, so they can benchmark the intensity of their handling against the FasTrack procedures.

The study of the horizontal shock impact damage revealed differences between plastic and wooden pallets in the acceleration response measured in the forklift. FasTrack could be modified with different top loads and entry speeds to increase the intensity at which plastic pallets are tested. Additional efforts should be made to determine if a different simulation should be conducted for plastic pallets. An increase in the severity of the simulation could reduce processing time for plastic pallets and could also be better at predicting the failure modes for pallets made of this material.

This research focused on the investigation of damage modes, damage locations, and severity for 48 in. x 40 in., stringer, GMA-style pallets. There is a need for future research to be conducted on popular pallet designs such as block and winged pallets. Particularly within the block pallet class, reusable pallets such as CHEP, should be investigated to identify potential differences in terms of FasTrack output versus results from the field. An extensive investigation into how different pallet designs behave in the field could help improve FasTrack or even develop a standard method that could be applied to predict durability for a wider variety of pallet designs.

Within the FasTrack comparison, plastic pallets could be a potential path for additional research. While wooden pallets are still predominant in the field, plastic pallets are consistently increasing their market share. Plastic pallets commonly feature specialized designs, which lead to potentially different damage modes than those found on stringer and block class wooden pallets. Additionally, plastic pallets are known to have increased survivability in the FasTrack simulation, which should be studied to evaluate if a different simulation should be conducted for this specific material.

The investigation of horizontal shock damage due to the interactions between pallets and forklifts should also be expanded to cover a wider variety of pallet designs. Additionally, shock transmissibility for both the pallet and the forklift could help further understand how the energy is passed from the forklift to the pallet, and what potential design ideas could be implemented to improve top lead deckboards and stringers to withstand harsher impacts from the handling equipment. Similar to this study, collaboration with the industry, especially automated warehouses, could help us reach a better understanding about how modern equipment such as AGVs affect pallet durability.

The experimental design of this research did not find a model that could effectively predict pallet acceleration response based on forklift acceleration. Further studies should be conducted to evaluate if these variables share a relationship that could be modeled with other techniques, such as finite element analysis. A model to gain insight about pallet circumstances based on handling equipment would be beneficial not only to improving the FasTrack simulation, but also to assessing the severity of the handling environment and its relation to damage frequency and severity in pallets

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7 Appendix

7.1 Raw data for shock horizontal impacts measured in the study

Table A. 1. Horizontal shock impact damage measured in the forklift (Raw Data)

Forklift type	Pallet Design	Entry Speed (Mph)	Top Load (lbs)	Forklift Response				Pallet Response			
				Accel. (g)	Duration (ms)	Delta (in/s)	RMS (G)	Accel (g)	Duration (ms)	Delta (in/s)	RMS (G)
Reach	Plastic	0.5	500	1.13	20.00	5.00	0.17	7.07	14.00	18.21	0.40
Reach	Plastic	0.5	500	1.72	22.00	9.84	0.24	7.84	14.00	19.27	0.43
Reach	Plastic	0.5	500	1.21	10.00	2.69	0.18	9.06	10.00	21.39	0.48
Reach	Plastic	0.5	500	1.83	16.00	6.55	0.18	6.66	6.00	8.60	0.45
Reach	Plastic	0.5	500	1.34	14.00	3.83	0.18	8.16	10.00	19.91	0.46
Reach	Plastic	0.5	500	1.18	12.00	3.16	0.18	8.22	12.00	19.86	0.46
Reach	Plastic	0.5	500	1.43	12.00	3.70	0.18	9.42	12.00	22.89	0.50
Reach	Plastic	0.5	500	1.32	12.00	3.72	0.17	8.31	6.00	12.48	0.50
Reach	Plastic	0.5	500	1.32	12.00	3.70	0.16	6.33	12.00	14.82	0.42
Reach	Plastic	0.5	500	1.30	24.00	6.46	0.17	8.98	10.00	20.22	0.45
Electric	Plastic	0.5	500	1.44	8.00	2.69	0.16	11.50	10.00	30.13	0.62
Electric	Plastic	0.5	500	1.72	8.00	3.20	0.18	11.25	12.00	32.66	0.68
Electric	Plastic	0.5	500	1.93	8.00	3.74	0.17	12.77	10.00	28.89	0.66
Electric	Plastic	0.5	500	1.32	6.00	2.33	0.15	13.44	10.00	27.74	0.64
Electric	Plastic	0.5	500	1.78	8.00	3.59	0.16	11.18	10.00	28.49	0.63
Electric	Plastic	0.5	500	1.78	8.00	3.95	0.18	12.99	10.00	26.18	0.62
Electric	Plastic	0.5	500	1.36	14.00	5.24	0.18	11.21	12.00	28.99	0.48
Electric	Plastic	0.5	500	2.30	8.00	4.37	0.18	10.15	12.00	29.96	0.64
Electric	Plastic	0.5	500	2.51	10.00	6.19	0.19	10.39	6.00	15.78	0.65
Electric	Plastic	0.5	500	2.22	8.00	4.69	0.19	13.68	10.00	29.02	0.62
Gas	Plastic	0.5	500	1.76	12.00	5.78	0.29	13.27	12.00	38.66	0.80
Gas	Plastic	0.5	500	2.27	6.00	3.56	0.32	22.85	12.00	48.87	1.00
Gas	Plastic	0.5	500	2.10	6.00	3.23	0.29	18.87	12.00	43.93	0.93
Gas	Plastic	0.5	500	4.61	8.00	6.26	0.39	13.80	12.00	40.35	0.78
Gas	Plastic	0.5	500	4.20	8.00	5.73	0.32	20.32	10.00	40.88	0.93
Gas	Plastic	0.5	500	4.72	8.00	8.40	0.38	15.75	14.00	41.26	0.74
Gas	Plastic	0.5	500	3.77	6.00	4.95	0.40	19.27	8.00	39.99	1.51
Gas	Plastic	0.5	500	4.24	8.00	8.92	0.32	20.36	14.00	45.22	0.99
Gas	Plastic	0.5	500	3.73	8.00	5.74	0.38	23.90	10.00	44.66	1.10
Gas	Plastic	0.5	500	1.96	4.00	2.06	0.37	21.49	12.00	44.08	0.94
Reach	Wood	0.5	500	2.26	26.00	11.79	0.28	5.99	14.00	13.35	0.32
Reach	Wood	0.5	500	2.13	22.00	9.02	0.25	8.99	12.00	14.27	0.36
Reach	Wood	0.5	500	2.03	22.00	10.32	0.27	4.71	30.00	16.61	0.27
Reach	Wood	0.5	500	1.96	16.00	6.75	0.22	7.02	14.00	15.26	0.34
Reach	Wood	0.5	500	1.95	24.00	8.34	0.23	10.64	12.00	14.55	0.40

Reach	Wood	0.5	500	1.56	26.00	9.28	0.23	6.45	16.00	11.09	0.29
Reach	Wood	0.5	500	2.22	26.00	12.29	0.26	8.81	10.00	12.61	0.34
Reach	Wood	0.5	500	2.44	22.00	11.87	0.31	10.53	12.00	15.15	0.41
Reach	Wood	0.5	500	1.86	22.00	8.27	0.23	10.33	14.00	14.21	0.41
Reach	Wood	0.5	500	1.83	24.00	8.37	0.22	7.68	12.00	13.93	0.37
Electric	Wood	0.5	500	1.90	14.00	5.57	0.19	11.78	16.00	24.72	0.47
Electric	Wood	0.5	500	1.84	12.00	5.22	0.22	10.29	16.00	21.05	0.47
Electric	Wood	0.5	500	1.89	14.00	5.46	0.20	10.74	8.00	17.74	0.46
Electric	Wood	0.5	500	1.58	16.00	5.17	0.16	9.60	18.00	23.79	0.42
Electric	Wood	0.5	500	2.96	14.00	8.86	0.23	9.69	26.00	24.45	0.40
Electric	Wood	0.5	500	2.44	16.00	7.63	0.21	9.28	18.00	20.55	0.37
Electric	Wood	0.5	500	1.60	12.00	3.95	0.17	9.68	8.00	18.31	0.46
Electric	Wood	0.5	500	1.56	12.00	4.11	0.17	13.60	18.00	27.76	0.52
Electric	Wood	0.5	500	3.09	10.00	7.47	0.26	3.98	6.00	6.76	0.42
Electric	Wood	0.5	500	2.11	10.00	5.03	0.20	11.14	16.00	21.75	0.45
Gas	Wood	0.5	500	2.91	8.00	4.37	0.25	18.17	8.00	24.13	0.65
Gas	Wood	0.5	500	3.42	10.00	6.63	0.26	18.75	8.00	27.68	0.70
Gas	Wood	0.5	500	2.33	10.00	5.14	0.26	16.25	6.00	26.24	0.71
Gas	Wood	0.5	500	3.18	8.00	5.50	0.22	20.23	8.00	27.86	0.71
Gas	Wood	0.5	500	3.04	10.00	6.25	0.25	17.12	8.00	18.22	0.64
Gas	Wood	0.5	500	2.95	10.00	6.20	0.23	14.29	8.00	22.91	0.56
Gas	Wood	0.5	500	2.79	10.00	5.65	0.22	19.74	8.00	27.62	0.70
Gas	Wood	0.5	500	2.39	10.00	4.93	0.21	14.58	8.00	22.05	0.58
Gas	Wood	0.5	500	2.85	10.00	6.15	0.22	15.72	14.00	34.16	0.64
Gas	Wood	0.5	500	3.38	8.00	5.57	0.22	16.56	8.00	22.97	0.59
Reach	Plastic	1	500	3.31	10.00	7.28	0.34	19.29	10.00	43.24	1.07
Reach	Plastic	1	500	3.26	28.00	18.63	0.39	16.80	10.00	42.75	0.91
Reach	Plastic	1	500	1.80	8.00	3.83	0.30	20.74	8.00	42.08	1.03
Reach	Plastic	1	500	3.69	22.00	22.15	0.49	13.41	10.00	32.85	0.80
Reach	Plastic	1	500	3.82	10.00	7.46	0.37	19.50	10.00	46.81	1.16
Reach	Plastic	1	500	1.37	28.00	11.82	0.23	13.43	10.00	29.99	0.70
Reach	Plastic	1	500	2.01	10.00	4.12	0.27	21.25	10.00	38.67	0.94
Reach	Plastic	1	500	2.87	28.00	13.90	0.35	25.59	10.00	48.64	0.98
Reach	Plastic	1	500	2.04	32.00	14.22	0.24	12.58	14.00	37.61	0.60
Reach	Plastic	1	500	3.19	10.00	7.27	0.33	17.13	10.00	51.36	1.18
Electric	Plastic	1	500	2.65	22.00	11.62	0.29	11.50	12.00	33.20	0.64
Electric	Plastic	1	500	2.10	8.00	3.98	0.22	19.29	10.00	40.14	0.94
Electric	Plastic	1	500	2.20	8.00	3.97	0.24	17.14	10.00	41.28	0.91
Electric	Plastic	1	500	2.40	10.00	4.85	0.23	17.85	10.00	38.84	0.90
Electric	Plastic	1	500	1.89	18.00	9.71	0.25	15.16	12.00	34.21	0.64
Electric	Plastic	1	500	1.99	8.00	3.55	0.28	15.09	10.00	45.38	1.00
Electric	Plastic	1	500	2.30	16.00	10.16	0.28	14.41	10.00	32.67	0.67
Electric	Plastic	1	500	3.03	14.00	8.44	0.28	14.13	12.00	41.78	0.70

Electric	Plastic	1	500	2.79	10.00	6.87	0.26	20.61	10.00	41.01	1.03
Electric	Plastic	1	500	3.49	8.00	6.94	0.24	15.97	10.00	41.59	1.18
Gas	Plastic	1	500	2.78	10.00	6.41	0.25	25.76	8.00	36.57	0.95
Gas	Plastic	1	500	1.76	10.00	4.95	0.19	4.44	6.00	7.96	0.51
Gas	Plastic	1	500	1.66	10.00	4.88	0.24	8.95	26.00	50.39	0.58
Gas	Plastic	1	500	3.16	8.00	6.04	0.29	24.63	8.00	38.14	0.98
Gas	Plastic	1	500	3.64	8.00	6.63	0.25	17.75	10.00	35.81	0.78
Gas	Plastic	1	500	3.89	10.00	8.32	0.30	18.19	10.00	32.42	0.81
Gas	Plastic	1	500	3.51	10.00	7.46	0.24	26.03	8.00	37.73	0.98
Gas	Plastic	1	500	3.53	8.00	5.95	0.28	26.02	8.00	37.11	1.18
Gas	Plastic	1	500	3.55	10.00	6.29	0.23	20.88	6.00	33.18	0.81
Gas	Plastic	1	500	3.99	10.00	8.02	0.27	22.47	6.00	33.66	0.86
Reach	Wood	1	500	1.74	12.00	5.10	0.26	5.36	6.00	8.97	0.55
Reach	Wood	1	500	3.69	12.00	11.24	0.42	18.98	6.00	34.47	0.83
Reach	Wood	1	500	3.35	14.00	9.95	0.40	17.12	8.00	28.72	0.72
Reach	Wood	1	500	2.53	12.00	7.16	0.33	13.46	18.00	33.93	0.58
Reach	Wood	1	500	2.83	14.00	8.39	0.34	17.07	6.00	29.29	0.76
Reach	Wood	1	500	4.63	14.00	13.97	0.44	20.85	10.00	31.76	0.85
Reach	Wood	1	500	2.89	14.00	9.96	0.36	14.26	16.00	22.69	0.54
Reach	Wood	1	500	4.58	14.00	16.22	0.50	4.57	10.00	7.84	0.48
Reach	Wood	1	500	3.19	12.00	8.37	0.44	13.56	18.00	29.88	0.60
Reach	Wood	1	500	4.04	16.00	14.57	0.46	15.91	8.00	25.67	0.68
Electric	Wood	1	500	2.54	12.00	7.18	0.31	17.70	12.00	33.69	0.74
Electric	Wood	1	500	3.29	10.00	8.22	0.28	19.00	8.00	28.75	0.77
Electric	Wood	1	500	3.95	12.00	9.18	0.33	10.61	12.00	24.41	0.55
Electric	Wood	1	500	4.10	10.00	10.76	0.39	15.61	6.00	31.06	0.73
Electric	Wood	1	500	4.07	8.00	7.07	0.35	17.91	12.00	33.28	0.77
Electric	Wood	1	500	3.50	10.00	6.70	0.30	17.05	10.00	27.64	0.76
Electric	Wood	1	500	4.25	10.00	8.49	0.33	14.60	20.00	31.53	0.63
Electric	Wood	1	500	5.64	10.00	11.00	0.39	18.15	20.00	34.66	0.73
Electric	Wood	1	500	1.47	14.00	5.26	0.19	8.07	22.00	34.09	0.49
Electric	Wood	1	500	3.80	14.00	9.84	0.31	9.99	22.00	41.98	0.67
Gas	Wood	1	500	2.78	10.00	6.41	0.25	25.76	8.00	36.57	0.95
Gas	Wood	1	500	1.76	10.00	4.95	0.19	4.44	6.00	7.96	0.51
Gas	Wood	1	500	1.66	10.00	4.88	0.24	8.95	26.00	50.39	0.58
Gas	Wood	1	500	3.16	8.00	6.04	0.29	24.63	8.00	38.14	0.98
Gas	Wood	1	500	3.64	8.00	6.63	0.25	17.75	10.00	35.81	0.78
Gas	Wood	1	500	3.89	10.00	8.32	0.30	18.19	10.00	32.42	0.81
Gas	Wood	1	500	3.51	10.00	7.46	0.24	26.03	8.00	37.73	0.98
Gas	Wood	1	500	3.53	8.00	5.95	0.28	26.02	8.00	37.11	1.18
Gas	Wood	1	500	3.55	10.00	6.29	0.23	20.88	6.00	33.18	0.81
Gas	Wood	1	500	3.99	10.00	8.02	0.27	22.47	6.00	33.66	0.86
Reach	Plastic	0.5	1500	1.43	24.00	7.89	0.17	6.24	8.00	8.60	0.49

Reach	Plastic	0.5	1500	1.59	26.00	8.41	0.18	4.22	6.00	7.34	0.38
Reach	Plastic	0.5	1500	1.35	26.00	8.14	0.18	6.24	12.00	10.78	0.31
Reach	Plastic	0.5	1500	1.33	30.00	8.89	0.19	6.29	12.00	10.07	0.46
Reach	Plastic	0.5	1500	1.47	24.00	8.19	0.19	5.85	6.00	9.08	1.02
Reach	Plastic	0.5	1500	1.76	26.00	8.74	0.17	6.23	6.00	8.46	1.08
Reach	Plastic	0.5	1500	1.40	22.00	7.24	0.19	7.15	8.00	10.44	0.38
Reach	Plastic	0.5	1500	1.61	24.00	8.71	0.17	6.34	8.00	9.90	0.47
Reach	Plastic	0.5	1500	1.68	26.00	8.73	0.20	5.24	6.00	8.31	0.42
Reach	Plastic	0.5	1500	1.45	24.00	8.12	0.18	5.30	6.00	8.50	0.51
Electric	Plastic	0.5	1500	2.24	12.00	5.85	0.19	8.65	14.00	23.74	0.84
Electric	Plastic	0.5	1500	2.14	10.00	4.87	0.17	7.71	12.00	23.84	0.48
Electric	Plastic	0.5	1500	1.37	10.00	3.09	0.15	8.73	14.00	24.57	0.54
Electric	Plastic	0.5	1500	2.15	10.00	4.65	0.20	7.71	12.00	23.10	1.29
Electric	Plastic	0.5	1500	1.98	10.00	5.14	0.17	7.71	12.00	23.22	0.50
Electric	Plastic	0.5	1500	1.95	10.00	5.09	0.18	9.33	14.00	23.31	0.71
Electric	Plastic	0.5	1500	1.85	10.00	4.28	0.16	8.78	12.00	22.71	0.49
Electric	Plastic	0.5	1500	1.92	12.00	4.99	0.18	8.88	12.00	21.22	0.86
Electric	Plastic	0.5	1500	2.07	10.00	5.16	0.18	9.63	12.00	23.21	0.74
Electric	Plastic	0.5	1500	2.02	12.00	5.37	0.17	8.24	12.00	20.35	0.66
Gas	Plastic	0.5	1500	3.72	10.00	7.88	0.26	9.58	16.00	21.43	1.40
Gas	Plastic	0.5	1500	3.00	10.00	6.09	0.23	11.43	16.00	26.72	1.16
Gas	Plastic	0.5	1500	2.49	10.00	5.05	0.20	11.41	14.00	23.60	0.51
Gas	Plastic	0.5	1500	2.87	10.00	5.53	0.22	9.36	12.00	24.15	0.55
Gas	Plastic	0.5	1500	3.01	12.00	5.75	0.21	9.69	14.00	21.49	1.10
Gas	Plastic	0.5	1500	3.23	12.00	6.33	0.22	10.25	14.00	23.73	0.87
Gas	Plastic	0.5	1500	2.45	10.00	4.21	0.19	10.04	12.00	23.38	0.49
Gas	Plastic	0.5	1500	2.83	10.00	5.59	0.22	9.44	14.00	23.14	0.77
Gas	Plastic	0.5	1500	3.21	10.00	6.51	0.25	10.90	14.00	26.75	0.52
Gas	Plastic	0.5	1500	2.80	10.00	5.64	0.24	11.21	14.00	24.64	0.80
Reach	Wood	0.5	1500	1.75	28.00	10.73	0.20	4.04	26.00	16.50	0.27
Reach	Wood	0.5	1500	1.75	28.00	8.56	0.18	4.98	22.00	14.18	0.26
Reach	Wood	0.5	1500	1.79	28.00	10.17	0.20	4.22	24.00	15.30	0.27
Reach	Wood	0.5	1500	1.99	28.00	11.30	0.23	4.03	22.00	15.70	0.29
Reach	Wood	0.5	1500	1.76	28.00	9.26	0.20	4.55	20.00	14.43	0.26
Reach	Wood	0.5	1500	1.77	26.00	8.15	0.20	5.22	10.00	12.37	0.29
Reach	Wood	0.5	1500	1.76	26.00	10.22	0.20	4.62	22.00	15.67	0.26
Reach	Wood	0.5	1500	1.57	24.00	10.92	0.22	2.33	30.00	15.83	0.23
Reach	Wood	0.5	1500	2.36	24.00	13.35	0.27	1.81	12.00	5.26	0.25
Reach	Wood	0.5	1500	2.54	22.00	12.08	0.25	1.15	18.00	3.73	0.20
Electric	Wood	0.5	1500	1.85	14.00	4.85	0.18	8.54	18.00	22.43	0.41
Electric	Wood	0.5	1500	1.55	12.00	4.06	0.19	12.47	14.00	22.42	0.49
Electric	Wood	0.5	1500	1.77	12.00	4.69	0.19	10.95	16.00	21.46	0.45
Electric	Wood	0.5	1500	1.77	14.00	5.01	0.18	11.60	16.00	22.57	0.46

Electric	Wood	0.5	1500	1.77	12.00	4.66	0.19	13.00	16.00	24.96	0.50
Electric	Wood	0.5	1500	1.82	12.00	4.93	0.18	12.99	16.00	22.82	0.49
Electric	Wood	0.5	1500	2.16	12.00	5.36	0.18	12.07	16.00	24.85	0.48
Electric	Wood	0.5	1500	2.25	12.00	5.58	0.20	10.50	16.00	23.40	0.47
Electric	Wood	0.5	1500	3.44	14.00	8.33	0.23	5.38	8.00	17.80	0.30
Electric	Wood	0.5	1500	2.26	12.00	5.89	0.18	11.35	18.00	17.24	0.44
Gas	Wood	0.5	1500	2.81	10.00	6.71	0.22	17.91	8.00	21.15	0.64
Gas	Wood	0.5	1500	2.77	10.00	6.27	0.26	17.91	8.00	19.15	0.65
Gas	Wood	0.5	1500	2.33	12.00	5.19	0.19	14.75	8.00	18.14	0.54
Gas	Wood	0.5	1500	2.54	12.00	5.94	0.19	11.90	8.00	17.93	0.51
Gas	Wood	0.5	1500	2.31	12.00	5.92	0.19	14.36	6.00	19.28	0.58
Gas	Wood	0.5	1500	2.74	10.00	6.42	0.21	12.31	8.00	18.77	0.53
Gas	Wood	0.5	1500	2.29	10.00	5.58	0.18	11.17	8.00	18.42	0.52
Gas	Wood	0.5	1500	1.76	10.00	4.14	0.18	13.49	18.00	31.16	0.56
Gas	Wood	0.5	1500	1.64	12.00	4.34	0.17	12.43	18.00	28.02	0.50
Gas	Wood	0.5	1500	1.69	10.00	4.08	0.18	9.42	18.00	26.59	0.49
Reach	Plastic	1	1500	4.15	14.00	11.87	0.33	18.60	14.00	41.73	1.02
Reach	Plastic	1	1500	3.52	26.00	18.42	0.35	10.16	10.00	23.19	1.42
Reach	Plastic	1	1500	3.15	18.00	12.13	0.32	8.57	8.00	13.98	1.68
Reach	Plastic	1	1500	2.46	28.00	17.87	0.33	11.71	12.00	31.06	1.48
Reach	Plastic	1	1500	2.11	32.00	14.50	0.29	15.19	10.00	35.26	1.84
Reach	Plastic	1	1500	2.54	26.00	14.81	0.30	5.57	8.00	9.99	1.20
Reach	Plastic	1	1500	2.15	28.00	16.02	0.33	13.46	10.00	37.95	1.58
Reach	Plastic	1	1500	3.58	16.00	13.51	0.33	11.79	8.00	16.68	0.72
Reach	Plastic	1	1500	2.42	30.00	15.83	0.27	19.21	8.00	43.21	1.19
Reach	Plastic	1	1500	3.45	26.00	15.51	0.32	8.60	8.00	23.49	1.32
Electric	Plastic	1	1500	2.18	8.00	4.89	0.20	14.72	10.00	34.69	1.57
Electric	Plastic	1	1500	2.16	16.00	8.89	0.23	11.39	18.00	30.84	0.59
Electric	Plastic	1	1500	3.54	10.00	8.55	0.26	10.34	12.00	34.99	1.38
Electric	Plastic	1	1500	1.61	14.00	7.23	0.23	7.52	16.00	25.70	1.76
Electric	Plastic	1	1500	1.82	8.00	3.55	0.20	11.88	12.00	32.57	0.84
Electric	Plastic	1	1500	1.72	8.00	3.22	0.20	12.86	12.00	36.98	1.11
Electric	Plastic	1	1500	4.39	10.00	11.68	0.37	11.96	18.00	36.71	0.62
Electric	Plastic	1	1500	2.00	8.00	4.94	0.21	12.83	14.00	35.56	0.77
Electric	Plastic	1	1500	2.02	8.00	3.45	0.25	14.71	10.00	34.32	1.45
Electric	Plastic	1	1500	2.14	10.00	4.85	0.28	13.83	10.00	36.34	2.30
Gas	Plastic	1	1500	4.16	8.00	5.88	0.31	16.20	12.00	40.25	1.21
Gas	Plastic	1	1500	3.49	8.00	4.77	0.29	17.52	12.00	40.85	0.94
Gas	Plastic	1	1500	3.51	8.00	5.34	0.26	16.45	12.00	36.26	1.12
Gas	Plastic	1	1500	3.81	8.00	5.25	0.32	16.45	12.00	37.33	1.65
Gas	Plastic	1	1500	3.07	6.00	4.37	0.28	18.69	10.00	39.52	1.57
Gas	Plastic	1	1500	4.48	10.00	8.84	0.34	13.64	14.00	34.70	1.28
Gas	Plastic	1	1500	4.00	8.00	5.38	0.28	17.80	12.00	36.16	0.91

Gas	Plastic	1	1500	3.33	8.00	6.23	0.26	14.49	12.00	34.24	0.76
Gas	Plastic	1	1500	4.12	8.00	5.72	0.29	17.42	12.00	36.06	0.91
Gas	Plastic	1	1500	4.01	8.00	5.27	0.29	19.61	12.00	39.50	1.55
Reach	Wood	1	1500	5.41	20.00	16.30	0.36	5.99	8.00	10.52	0.46
Reach	Wood	1	1500	4.69	14.00	12.83	0.41	18.81	14.00	37.08	0.81
Reach	Wood	1	1500	4.32	26.00	20.26	0.42	15.20	8.00	24.41	0.69
Reach	Wood	1	1500	3.25	14.00	8.64	0.30	12.88	16.00	34.25	0.67
Reach	Wood	1	1500	3.23	12.00	8.11	0.31	10.27	16.00	34.97	0.64
Reach	Wood	1	1500	4.79	14.00	13.46	0.38	21.08	8.00	32.45	0.83
Reach	Wood	1	1500	5.52	14.00	16.18	0.41	25.17	8.00	36.68	0.96
Reach	Wood	1	1500	5.15	14.00	15.20	0.39	17.96	8.00	28.86	0.74
Reach	Wood	1	1500	4.93	16.00	15.12	0.35	15.98	8.00	26.20	0.67
Reach	Wood	1	1500	3.48	14.00	11.33	0.26	15.49	16.00	24.31	0.57
Electric	Wood	1	1500	4.15	10.00	8.61	0.26	20.03	18.00	42.10	0.76
Electric	Wood	1	1500	3.17	14.00	9.03	0.22	13.16	18.00	32.21	0.56
Electric	Wood	1	1500	4.32	12.00	10.43	0.33	16.19	8.00	23.53	0.64
Electric	Wood	1	1500	5.09	12.00	12.21	0.38	14.16	6.00	22.15	0.65
Electric	Wood	1	1500	4.01	10.00	8.68	0.26	11.67	18.00	35.49	0.58
Electric	Wood	1	1500	5.63	10.00	12.93	0.37	17.27	8.00	30.41	0.77
Electric	Wood	1	1500	4.59	12.00	12.16	0.30	11.38	18.00	28.96	0.52
Electric	Wood	1	1500	4.48	12.00	11.68	0.33	11.74	24.00	36.55	0.56
Electric	Wood	1	1500	3.49	10.00	7.04	0.25	15.03	16.00	32.42	0.63
Electric	Wood	1	1500	3.12	10.00	7.85	0.26	15.31	16.00	34.60	0.70
Gas	Wood	1	1500	2.74	12.00	7.30	0.23	6.90	8.00	12.64	0.53
Gas	Wood	1	1500	2.91	10.00	7.13	0.29	22.06	8.00	29.86	0.89
Gas	Wood	1	1500	3.11	8.00	6.96	0.28	22.86	14.00	42.52	0.91
Gas	Wood	1	1500	3.41	10.00	7.32	0.26	21.98	8.00	27.41	0.83
Gas	Wood	1	1500	4.72	8.00	7.62	0.32	25.59	6.00	33.03	0.97
Gas	Wood	1	1500	3.89	8.00	7.66	0.32	20.94	8.00	30.80	0.82
Gas	Wood	1	1500	3.05	10.00	6.30	0.26	12.08	18.00	39.02	0.69
Gas	Wood	1	1500	3.13	10.00	7.85	0.28	24.57	16.00	41.20	0.90
Gas	Wood	1	1500	4.19	8.00	7.13	0.33	16.81	8.00	26.64	0.82
Gas	Wood	1	1500	3.56	10.00	8.93	0.33	20.97	8.00	27.57	0.83
Reach	Plastic	0.5	2500	1.90	24.00	10.35	0.22	4.13	14.00	10.21	0.33
Reach	Plastic	0.5	2500	1.88	24.00	10.21	0.22	4.11	12.00	10.04	0.32
Reach	Plastic	0.5	2500	1.82	26.00	10.04	0.21	4.01	14.00	10.76	0.30
Reach	Plastic	0.5	2500	1.94	24.00	10.61	0.21	5.27	10.00	10.93	0.37
Reach	Plastic	0.5	2500	1.99	24.00	11.03	0.22	5.50	10.00	12.11	0.40
Reach	Plastic	0.5	2500	2.18	24.00	10.18	0.23	5.50	10.00	12.42	0.42
Reach	Plastic	0.5	2500	1.64	30.00	10.90	0.19	6.21	10.00	11.95	0.45
Reach	Plastic	0.5	2500	1.99	26.00	12.06	0.23	6.24	10.00	9.41	0.48
Reach	Plastic	0.5	2500	1.96	30.00	14.90	0.27	3.25	22.00	11.74	0.28
Reach	Plastic	0.5	2500	1.74	24.00	9.00	0.20	2.93	14.00	11.00	0.36

Electric	Plastic	0.5	2500	1.63	16.00	7.74	0.16	4.19	14.00	12.88	0.35
Electric	Plastic	0.5	2500	2.30	10.00	5.35	0.22	9.57	12.00	33.96	0.61
Electric	Plastic	0.5	2500	2.26	10.00	5.37	0.22	7.83	12.00	30.91	0.57
Electric	Plastic	0.5	2500	2.83	8.00	5.19	0.24	11.22	14.00	37.35	0.63
Electric	Plastic	0.5	2500	2.77	8.00	5.00	0.25	12.99	12.00	41.66	0.72
Electric	Plastic	0.5	2500	2.46	8.00	4.91	0.23	10.81	10.00	31.86	0.66
Electric	Plastic	0.5	2500	2.96	10.00	6.75	0.25	11.83	14.00	39.37	0.68
Electric	Plastic	0.5	2500	2.95	8.00	5.33	0.24	9.43	12.00	34.73	0.64
Electric	Plastic	0.5	2500	3.07	8.00	5.61	0.25	9.91	12.00	35.98	0.64
Electric	Plastic	0.5	2500	2.82	8.00	5.05	0.25	9.88	12.00	37.90	0.67
Gas	Plastic	0.5	2500	3.37	12.00	8.02	0.15	10.68	14.00	33.78	0.56
Gas	Plastic	0.5	2500	3.15	10.00	7.46	0.31	11.87	10.00	22.68	0.60
Gas	Plastic	0.5	2500	3.04	10.00	7.00	0.23	9.24	14.00	31.20	0.53
Gas	Plastic	0.5	2500	2.60	10.00	6.21	0.27	9.27	14.00	33.84	0.67
Gas	Plastic	0.5	2500	2.86	12.00	7.38	0.26	9.61	16.00	32.35	0.56
Gas	Plastic	0.5	2500	2.88	8.00	5.02	0.24	8.79	14.00	31.71	0.62
Gas	Plastic	0.5	2500	2.82	10.00	5.78	0.24	9.84	14.00	36.67	0.70
Gas	Plastic	0.5	2500	2.73	10.00	6.00	0.24	9.82	14.00	35.79	0.68
Gas	Plastic	0.5	2500	2.68	12.00	6.49	0.23	9.65	14.00	31.79	0.61
Gas	Plastic	0.5	2500	2.48	10.00	4.42	0.22	11.47	14.00	35.00	0.82
Reach	Wood	0.5	2500	2.72	28.00	13.73	0.23	11.20	8.00	17.50	0.41
Reach	Wood	0.5	2500	2.70	24.00	13.19	0.23	9.03	8.00	16.20	0.40
Reach	Wood	0.5	2500	2.38	20.00	8.28	0.22	7.00	6.00	10.50	0.33
Reach	Wood	0.5	2500	2.94	26.00	14.65	0.27	8.50	6.00	16.40	0.40
Reach	Wood	0.5	2500	3.31	12.00	11.17	0.02	10.60	6.00	20.90	0.46
Reach	Wood	0.5	2500	2.55	28.00	12.94	0.24	10.50	6.00	14.70	0.40
Reach	Wood	0.5	2500	3.40	20.00	14.60	0.30	11.50	8.00	15.70	0.42
Reach	Wood	0.5	2500	3.88	20.00	14.07	0.30	12.90	8.00	15.50	0.47
Reach	Wood	0.5	2500	3.16	22.00	13.78	0.07	11.70	6.00	17.80	0.43
Reach	Wood	0.5	2500	3.23	30.00	16.24	0.10	7.12	6.00	10.70	0.33
Electric	Wood	0.5	2500	2.56	10.00	6.60	0.23	17.90	6.00	15.42	0.61
Electric	Wood	0.5	2500	2.27	6.00	2.90	0.23	7.01	16.00	15.47	0.32
Electric	Wood	0.5	2500	3.42	14.00	10.21	0.29	16.19	6.00	17.32	0.54
Electric	Wood	0.5	2500	3.59	12.00	9.61	0.26	16.56	6.00	21.00	0.56
Electric	Wood	0.5	2500	3.26	14.00	10.30	0.27	12.11	6.00	21.41	0.50
Electric	Wood	0.5	2500	3.32	12.00	9.68	0.25	18.47	10.00	21.47	0.61
Electric	Wood	0.5	2500	3.21	14.00	9.85	0.25	17.24	8.00	19.68	0.57
Electric	Wood	0.5	2500	3.14	14.00	9.71	0.24	13.51	6.00	21.87	0.52
Electric	Wood	0.5	2500	3.18	14.00	9.61	0.26	15.95	6.00	22.39	0.56
Electric	Wood	0.5	2500	3.36	12.00	9.69	0.27	15.87	6.00	22.94	0.55
Gas	Wood	0.5	2500	3.91	8.00	6.92	0.26	8.55	18.00	26.38	0.45
Gas	Wood	0.5	2500	4.10	8.00	7.92	0.29	9.56	8.00	16.57	0.47
Gas	Wood	0.5	2500	4.33	10.00	8.92	0.30	9.69	8.00	18.83	0.53

Gas	Wood	0.5	2500	4.67	10.00	7.41	0.26	8.63	18.00	21.38	0.42
Gas	Wood	0.5	2500	3.26	12.00	7.51	0.25	16.65	6.00	15.13	0.58
Gas	Wood	0.5	2500	2.38	12.00	7.13	0.21	9.57	12.00	17.70	0.41
Gas	Wood	0.5	2500	3.00	12.00	8.55	0.29	10.38	6.00	14.06	0.48
Gas	Wood	0.5	2500	5.51	8.00	8.08	0.29	11.96	8.00	16.64	0.55
Gas	Wood	0.5	2500	1.86	14.00	5.66	0.16	11.07	14.00	25.01	0.48
Gas	Wood	0.5	2500	4.88	8.00	7.94	0.29	14.28	8.00	22.45	0.66
Reach	Plastic	1	2500	2.71	28.00	17.82	0.33	16.92	16.00	49.30	1.12
Reach	Plastic	1	2500	3.48	26.00	21.92	0.40	10.86	22.00	35.46	0.62
Reach	Plastic	1	2500	3.77	26.00	20.35	0.40	7.51	14.00	21.56	0.69
Reach	Plastic	1	2500	3.63	14.00	11.26	0.29	14.51	18.00	40.44	0.77
Reach	Plastic	1	2500	2.94	30.00	18.22	0.32	19.56	14.00	42.83	1.15
Reach	Plastic	1	2500	3.78	20.00	14.81	0.34	13.55	18.00	52.95	0.71
Reach	Plastic	1	2500	2.99	32.00	17.62	0.30	15.54	16.00	37.27	0.88
Reach	Plastic	1	2500	3.30	12.00	10.17	0.31	13.64	14.00	48.70	1.02
Reach	Plastic	1	2500	3.10	30.00	16.99	0.34	18.16	12.00	41.82	1.04
Reach	Plastic	1	2500	3.34	28.00	16.63	0.34	17.80	14.00	42.41	0.96
Electric	Plastic	1	2500	3.29	10.00	7.57	0.22	19.03	12.00	42.58	0.87
Electric	Plastic	1	2500	2.91	6.00	3.92	0.31	17.74	10.00	44.03	1.32
Electric	Plastic	1	2500	2.38	6.00	3.68	0.29	19.64	10.00	47.98	1.23
Electric	Plastic	1	2500	3.11	8.00	5.35	0.28	13.70	10.00	40.91	0.97
Electric	Plastic	1	2500	2.93	8.00	5.40	0.30	15.12	10.00	46.05	1.06
Electric	Plastic	1	2500	3.01	8.00	5.41	0.28	16.83	12.00	47.69	1.02
Electric	Plastic	1	2500	2.97	8.00	5.92	0.29	15.22	10.00	41.84	0.88
Electric	Plastic	1	2500	2.61	6.00	3.59	0.29	15.38	10.00	43.53	0.86
Electric	Plastic	1	2500	4.09	10.00	8.99	0.31	16.86	14.00	49.14	0.81
Electric	Plastic	1	2500	2.92	8.00	5.73	0.30	14.39	12.00	42.86	0.86
Gas	Plastic	1	2500	2.14	10.00	5.17	0.30	11.37	16.00	47.22	0.70
Gas	Plastic	1	2500	2.80	8.00	5.90	0.25	12.63	16.00	47.97	0.71
Gas	Plastic	1	2500	3.24	10.00	7.56	0.35	16.08	18.00	50.94	0.84
Gas	Plastic	1	2500	1.97	10.00	7.44	0.24	16.16	14.00	44.23	0.83
Gas	Plastic	1	2500	3.92	10.00	8.05	0.37	18.60	16.00	64.51	0.90
Gas	Plastic	1	2500	3.75	10.00	8.66	0.30	15.31	16.00	41.73	0.76
Gas	Plastic	1	2500	4.69	10.00	10.36	0.32	13.47	14.00	42.20	0.80
Gas	Plastic	1	2500	2.54	10.00	6.13	0.26	21.73	12.00	44.10	0.86
Gas	Plastic	1	2500	4.52	10.00	10.11	0.33	18.76	14.00	55.21	1.04
Gas	Plastic	1	2500	3.55	10.00	7.88	0.41	24.31	16.00	92.51	1.22
Reach	Wood	1	2500	6.11	8.00	8.72	0.34	13.70	14.00	42.81	0.71
Reach	Wood	1	2500	5.59	10.00	10.78	0.35	13.45	16.00	45.92	0.73
Reach	Wood	1	2500	5.26	8.00	9.36	0.32	15.52	16.00	40.74	0.77
Reach	Wood	1	2500	3.93	12.00	10.77	0.38	9.72	18.00	34.76	0.61
Reach	Wood	1	2500	6.42	8.00	11.76	0.47	14.19	20.00	49.30	0.72
Reach	Wood	1	2500	5.61	8.00	7.57	0.32	14.37	14.00	46.79	0.78

Reach	Wood	1	2500	3.92	8.00	7.25	0.26	14.62	16.00	43.43	0.69
Reach	Wood	1	2500	3.91	10.00	8.81	0.30	16.45	14.00	46.70	0.81
Reach	Wood	1	2500	4.59	10.00	9.71	0.17	18.03	14.00	46.16	0.86
Reach	Wood	1	2500	5.62	10.00	10.40	0.39	14.64	12.00	38.71	0.77
Electric	Wood	1	2500	6.08	14.00	15.06	0.41	11.80	10.00	20.51	0.52
Electric	Wood	1	2500	2.91	16.00	7.93	0.21	8.20	6.00	11.99	0.36
Electric	Wood	1	2500	4.35	12.00	10.06	0.28	13.54	12.00	29.52	0.63
Electric	Wood	1	2500	5.81	12.00	12.82	0.37	19.02	6.00	18.86	0.66
Electric	Wood	1	2500	3.70	8.00	6.79	0.22	20.40	4.00	18.18	0.72
Electric	Wood	1	2500	4.82	12.00	11.59	0.37	21.78	10.00	25.35	0.73
Electric	Wood	1	2500	5.04	14.00	15.19	0.37	19.67	4.00	20.98	0.70
Electric	Wood	1	2500	1.87	16.00	6.48	0.19	9.51	10.00	17.78	0.62
Electric	Wood	1	2500	2.78	14.00	9.10	0.28	12.39	8.00	21.49	0.52
Electric	Wood	1	2500	4.16	16.00	11.51	0.30	17.28	8.00	25.43	0.60
Gas	Wood	1	2500	6.11	8.00	8.72	0.34	13.70	14.00	42.81	0.71
Gas	Wood	1	2500	5.59	10.00	10.78	0.35	13.45	16.00	45.92	0.73
Gas	Wood	1	2500	5.26	8.00	9.36	0.32	15.52	16.00	40.74	0.77
Gas	Wood	1	2500	3.93	12.00	10.77	0.38	9.72	18.00	34.76	0.61
Gas	Wood	1	2500	6.42	8.00	11.76	0.47	14.19	20.00	49.30	0.72
Gas	Wood	1	2500	5.61	8.00	7.57	0.32	14.37	14.00	46.79	0.78
Gas	Wood	1	2500	3.92	8.00	7.25	0.26	14.62	16.00	43.43	0.69
Gas	Wood	1	2500	3.91	10.00	8.81	0.30	16.45	14.00	46.70	0.81
Gas	Wood	1	2500	4.59	10.00	9.71	0.17	18.03	14.00	46.16	0.86
Gas	Wood	1	2500	5.62	10.00	10.40	0.39	14.64	12.00	38.71	0.77

7.2 ANOVA and Tukey Pairwise Comparison Results for Forklift Acceleration

Table A. 2. ANOVA for Forklift acceleration according to Forklift type, pallet design, entry speed and top load

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	23	289.599	12.591	25.39	0.000
Linear	6	218.592	36.432	73.46	0.000
Forklift type	2	23.567	11.784	23.76	0.000
Pallet Design	1	42.873	42.873	86.45	0.000
Entry Speed	1	112.727	112.727	227.31	0.000
Top Load	2	39.425	19.712	39.75	0.000
2-Way Interactions	13	59.747	4.596	9.27	0.000
Forklift type*Pallet Design	2	10.588	5.294	10.67	0.000
Forklift type*Entry Speed	2	17.242	8.621	17.38	0.000
Forklift type*Top Load	4	1.643	0.411	0.83	0.508
Pallet Design*Entry Speed	1	12.265	12.265	24.73	0.000
Pallet Design*Top Load	2	12.467	6.234	12.57	0.000
Entry Speed*Top Load	2	5.543	2.771	5.59	0.004
3-Way Interactions	4	11.260	2.815	5.68	0.000
Forklift type*Pallet Design*Top Load	4	11.260	2.815	5.68	0.000
Error	336	166.628	0.496		
Lack-of-Fit	12	9.395	0.783	1.61	0.086
Pure Error	324	157.233	0.485		
Total	359	456.227			

Table A. 3. Tukey Pairwise comparison for forklift acceleration response (Main effects)

Factor	Level	N	Mean	Grouping	
Forklift type	Gas	120	3.34458	A	
	Reach	120	2.80506		B
	Electric	120	2.79862		B
Pallet design	Wood	180	3.32785	A	
	Plastic	180	2.63766		B
Entry speed	1.0	180	3.54233	A	
	0.5	180	2.42317		B
Top Load	2500	120	3.44224	A	
	1500	120	2.82996		B
	500	120	2.67606		B

Means that do not share a letter are significantly different.

Table A. 4. Tukey Pairwise comparison for forklift acceleration response (two-way interactions)

Interaction	**Level**	**N**	**Mean**	**Grouping**			
Forklift type*Pallet Design	Gas Wood	60	3.45253	A			
	Reach Wood	60	3.31274	A			
	Gas Plastic	60	3.23663	A			
	Electric Wood	60	3.21828	A			
	Electric Plastic	60	2.37896		B		
	Reach Plastic	60	2.29739		B		
Forklift type*Entry Speed	Gas 1.0	60	3.66138	A			
	Reach 1.0	60	3.65228	A			
	Electric 1.0	60	3.31334	A	B		
	Gas 0.5	60	3.02777		B		
	Electric 0.5	60	2.28390			C	
	Reach 0.5	60	1.95785			C	
Forklift type*Top Load	Gas 2500	40	3.76583	A			
	Reach 2500	40	3.33312	A	B		
	Electric 2500	40	3.22778		B		
	Gas 500	40	3.13775		B	C	
	Gas 1500	40	3.13015		B	C	
	Reach 1500	40	2.71052			C	D
	Electric 1500	40	2.64921			C	D
	Electric 500	40	2.51888				D
	Reach 500	40	2.37155				D
Pallet Design*Entry Speed	Wood 1.0	90	4.07201	A			
	Plastic 1.0	90	3.01266		B		
	Wood 0.5	90	2.58369			C	
	Plastic 0.5	90	2.26266				D
Pallet Design*Top Load	Wood 2500	60	4.04906	A			
	Wood 1500	60	3.06815		B		
	Wood 500	60	2.86634		B	C	
	Plastic 2500	60	2.83543		B	C	D
	Plastic 1500	60	2.59176			C	D
	Plastic 500	60	2.48578				D
Entry Speed*Top Load	1.0 2500	60	3.99722	A			
	1.0 1500	60	3.54376		B		
	1.0 500	60	3.08602			C	
	0.5 2500	60	2.88727			C	
	0.5 500	60	2.26609				D
	0.5 1500	60	2.11616				D

Means that do not share a letter are significantly different.

7.3 ANOVA and Tukey Pairwise Comparison Results for Pallet Acceleration

Table A. 5. ANOVA for Pallet acceleration according to Forklift type, pallet design, entry speed and top load

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	19	5852.82	308.04	25.29	0.000
Linear	6	4557.03	759.50	62.36	0.000
Forklift type	2	1395.28	697.64	57.28	0.000
Pallet Design	1	34.58	34.58	2.84	0.093
Entry Speed	1	2671.87	2671.87	219.36	0.000
Top Load	2	455.30	227.65	18.69	0.000
2-Way Interactions	11	1111.49	101.04	8.30	0.000
Forklift type*Entry Speed	2	337.77	168.89	13.87	0.000
Forklift type*Top Load	4	490.23	122.56	10.06	0.000
Pallet Design*Entry Speed	1	37.26	37.26	3.06	0.081
Pallet Design*Top Load	2	200.48	100.24	8.23	0.000
Entry Speed*Top Load	2	45.75	22.88	1.88	0.154
3-Way Interactions	2	184.30	92.15	7.57	0.001
Pallet Design*Entry Speed*Top Load	2	184.30	92.15	7.57	0.001
Error	340	4141.29	12.18		
Lack-of-Fit	16	319.76	19.99	1.69	0.046
Pure Error	324	3821.53	11.79		
Total	359	9994.11			

Table A. 6. Tukey Pairwise comparison for pallet acceleration response (Main effects)

Factor	**Level**	**N**	**Mean**	**Grouping**
Forklift type	Gas	120	15.6434	A
	Reach	120	12.9698	B
	Electric	120	10.8310	C
Pallet design	Wood	180	13.4580	A
	Plastic	180	12.8381	A
Entry speed	1.0	180	15.8724	A
	0.5	180	10.4238	B
Top Load	500	120	14.6815	A
	2500	120	12.7468	B
	1500	120	12.0159	B

Means that do not share a letter are significantly different.

Table A. 7.Tukey Pairwise comparison for Pallet acceleration response (two-way interactions)

Interaction	Level	N	Mean	Grouping				
Forklift type*Entry Speed	Gas 1.0	60	17.7730	A				
	Reach 1.0	60	14.9228		B			
	Electric 1.0	60	14.9214		B			
	Gas 0.5	60	13.5138		B			
	Electric 0.5	60	11.0169			C		
	Reach 0.5	60	6.7406				D	
Forklift type*Top Load	Gas 500	40	18.7881	A				
	Gas 1500	40	15.0492		B			
	Electric 2500	40	14.1493		B	C		
	Electric 500	40	13.2047		B	C	D	
	Gas 2500	40	13.0929		B	C	D	
	Reach 500	40	12.0517			C	D	
	Electric 1500	40	11.5555				D	E
	Reach 2500	40	10.9982				D	E
	Reach 1500	40	9.4431					E
Pallet Design*Entry Speed	Wood 1.0	90	15.8842	A				
	Plastic 1.0	90	15.8606	A				
	Wood 0.5	90	11.0554		B			
	Plastic 0.5	90	9.7921		B			
Pallet Design*Top Load	Plastic 500	60	15.4081	A				
	Wood 500	60	13.9550	A	B			
	Wood 2500	60	13.4029		B	C		
	Wood 1500	60	13.0162		B	C		
	Plastic 2500	60	12.0907			C	D	
	Plastic 1500	60	11.0157				D	
Entry Speed*Top Load	1.0 500	60	17.0159	A				
	1.0 2500	60	15.3892	A				
	1.0 1500	60	15.2120	A				
	0.5 500	60	12.3471		B			
	0.5 2500	60	10.1044			C		
	0.5 1500	60	8.8199			C		

Means that do not share a letter are significantly different.

7.4 Tukey Pairwise Comparison Results for Forklift Duration

Table A. 8. Tukey Pairwise comparison for forklift duration response (Main effects)

Factor	Level	N	Mean	Grouping		
Forklift type	Gas		20.3667	A		
	Reach		11.0000		B	
	Electric		9.4833			C
Pallet design	Plastic		13.7667	A		
	Wood		13.4667	A		
Entry speed	0.5		14.6333	A		
	1.0		12.6000		B	
Top Load	1500		14.5500	A		
	2500		13.7333	A		
	500		12.5667		B	

Means that do not share a letter are significantly different.

Table A. 9. Tukey Pairwise comparison for forklift duration response (two-way interactions)

Interaction	Level	N	Mean	Grouping				
Forklift type*Entry Speed	Reach 0.5	60	23.0667	A				
	Reach 1.0	60	17.6667		B			
	Electric 0.5	60	11.0667			C		
	Electric 1.0	60	10.9333			C		
	Gas 0.5	60	9.7667			C	D	
	Gas 1.0	60	9.2000				D	
Forklift type*Top Load	Reach 1500	40	22.90	A				
	Reach 2500	40	20.60		B			
	Reach 500	40	17.60			C		
	Electric 500	40	11.20				D	
	Electric 1500	40	11.10				D	E
	Electric 2500	40	10.70				D	E
	Gas 2500	40	9.90				D	E
	Gas 1500	40	9.65				D	E
	Gas 500	40	8.90					E
Pallet Design*Entry Speed	Wood 0.5	90	15.6000	A				
	Plastic 1.0	90	13.8667		B			
	Plastic 0.5	90	13.6667		B			
	Wood 1.0	90	11.3333			C		
Pallet Design*Top Load	Plastic 1500	60	14.7667	A				
	Plastic 2500	60	14.6000	A				
	Wood 1500	60	14.3333	A	B			
	Wood 500	60	13.2000	A	B	C		
	Wood 2500	60	12.8667		B	C		
	Plastic 500	60	11.9333			C		
Entry Speed*Top Load	0.5 1500	60	15.9667	A				
	0.5 2500	60	15.1333	A				
	1.0 1500	60	13.1333		B			
	0.5 500	60	12.8000		B			
	1.0 500	60	12.3333		B			
	1.0 2500	60	12.3333		B			
Forklift type*Pallet Design	Reach Plastic	60	22.3000	A				
	Reach Wood	60	18.4333		B			
	Electric Wood	60	12.2333			C		
	Electric Plastic	60	9.7667				D	
	Gas Wood	60	9.7333				D	
	Gas Plastic	60	9.2333				D	

Means that do not share a letter are significantly different.

7.5 Tukey Pairwise Comparison Results for Pallet Duration

Table A. 10. Tukey Pairwise comparison for pallet duration response (Main effects)

Factor	**Level**	**N**	**Mean**	**Grouping**
Forklift type	Reach		12.1333	A
	Electric		12.1000	A
	Gas		11.7667	A
Pallet design	Wood		12.1778	A
	Plastic		11.8222	A
Entry speed	1.0		12.0333	A
	0.5		11.9667	A
Top Load	1500		12.6833	A
	2500		12.0333	A B
	500		11.2833	B

Means that do not share a letter are significantly different.

Table A. 11. Tukey Pairwise comparison for pallet duration response (two-way interactions)

Interaction	Level	N	Mean	Grouping			
Forklift type*Entry Speed	Electric 0.5	60	12.2000	A			
	Reach 0.5	60	12.1667	A			
	Reach 1.0	60	12.1000	A			
	Electric 1.0	60	12.0000	A			
	Gas 1.0	60	12.0000	A			
	Gas 0.5	60	11.5333	A			
Forklift type*Top Load	Electric 1500	40	14.05	A			
	Gas 2500	40	13.75	A	B		
	Reach 2500	40	12.65	A	B		
	Electric 500	40	12.55	A	B		
	Reach 1500	40	12.25	A	B	C	
	Gas 1500	40	11.75	A	B	C	D
	Reach 500	40	11.50		B	C	D
	Gas 500	40	9.80			C	D
	Electric 2500	40	9.70				D
Pallet Design*Entry Speed	Wood 0.5	90	12.2000	A			
	Wood 1.0	90	12.1556	A			
	Plastic 1.0	90	11.9111	A			
	Plastic 0.5	90	11.7333	A			
Pallet Design*Top Load	Wood 1500	60	13.8333	A			
	Plastic 1500	60	13.4667	A			
	Wood 500	60	12.1000	A	B		
	Plastic 1500	60	11.5333		B		
	Wood 2500	60	10.6000		B		
	Plastic 500	60	10.4667		B		
Entry Speed*Top Load	0.5 1500	60	13.5333	A			
	1.0 2500	60	13.4333	A			
	1.0 1500	60	11.8333	A	B		
	0.5 500	60	11.7333	A	B		
	1.0 500	60	10.8333		B		
	0.5 2500	60	10.6333		B		
Forklift type*Pallet Design	Reach Wood	60	13.1667	A			
	Gas Plastic	60	12.7000	A	B		
	Electric Wood	60	12.5333	A	B	C	
	Electric Plastic	60	11.6667	A	B	C	
	Reach Plastic	60	11.1000		B	C	
	Gas Wood	60	10.8333			C	

Means that do not share a letter are significantly different.

7.6 Scatterplot of Pallet Peak Acceleration vs Forklift Peak Acceleration at different levels of pallet design, entry speed, and top load.

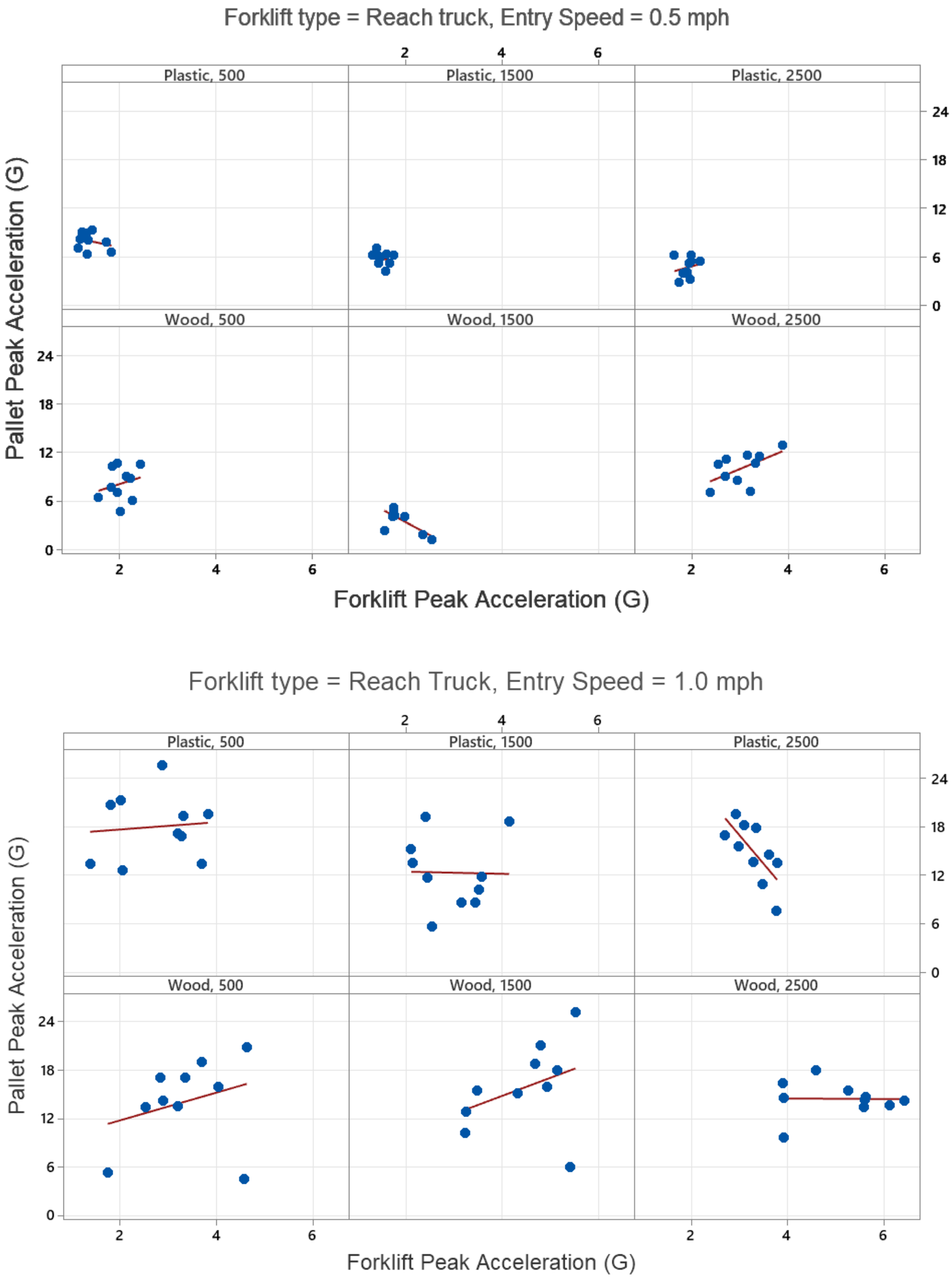

Figure A. 1 Scatterplot of Pallet Peak Acceleration vs Forklift Peak Acceleration for different levels of entry speed, pallet design, and top load (Reach Truck)

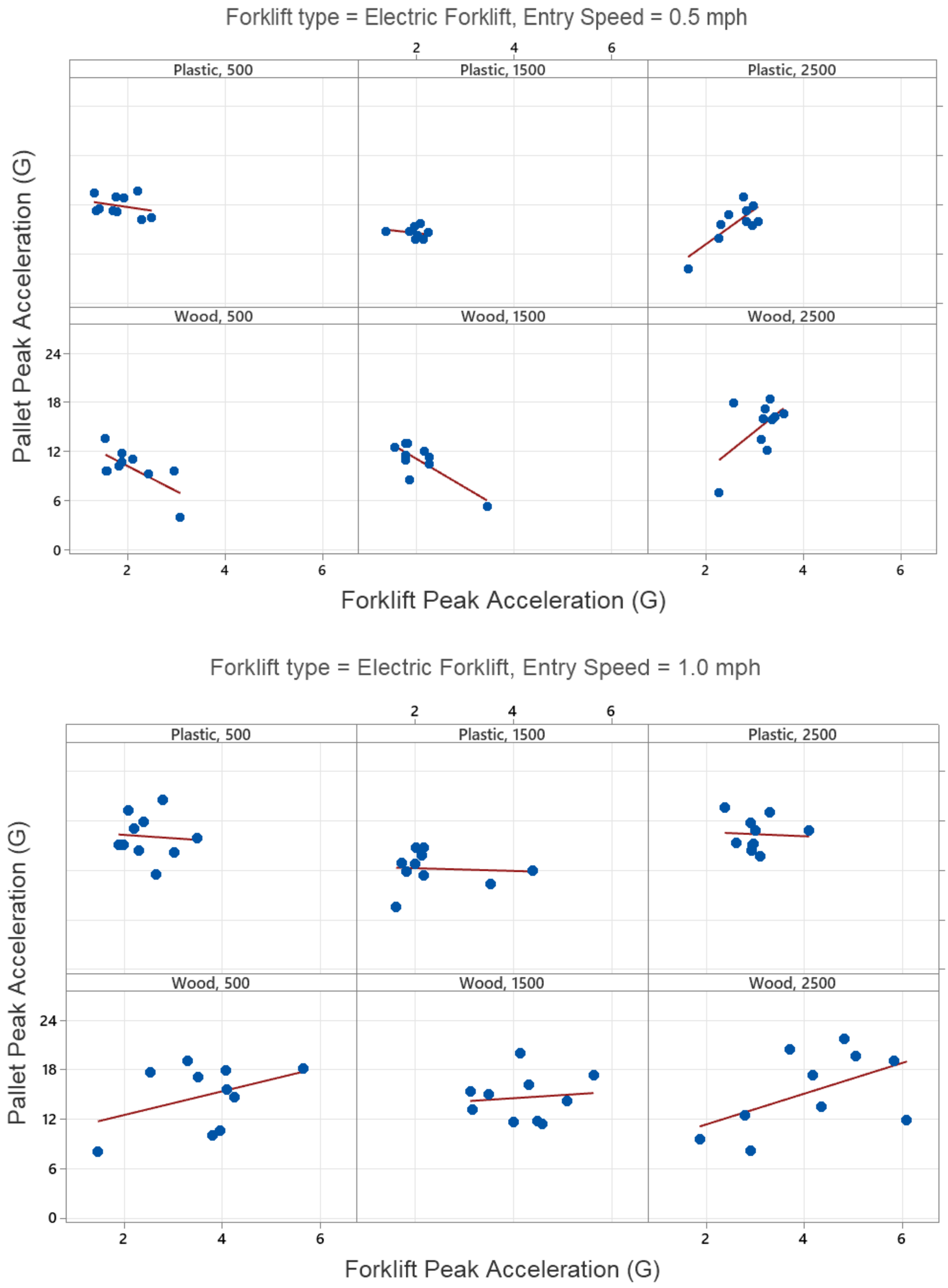

Figure A. 2. Scatterplot of Pallet Peak Acceleration vs Forklift Peak Acceleration for different levels of entry speed, pallet design, and top load (Electric Forklift)

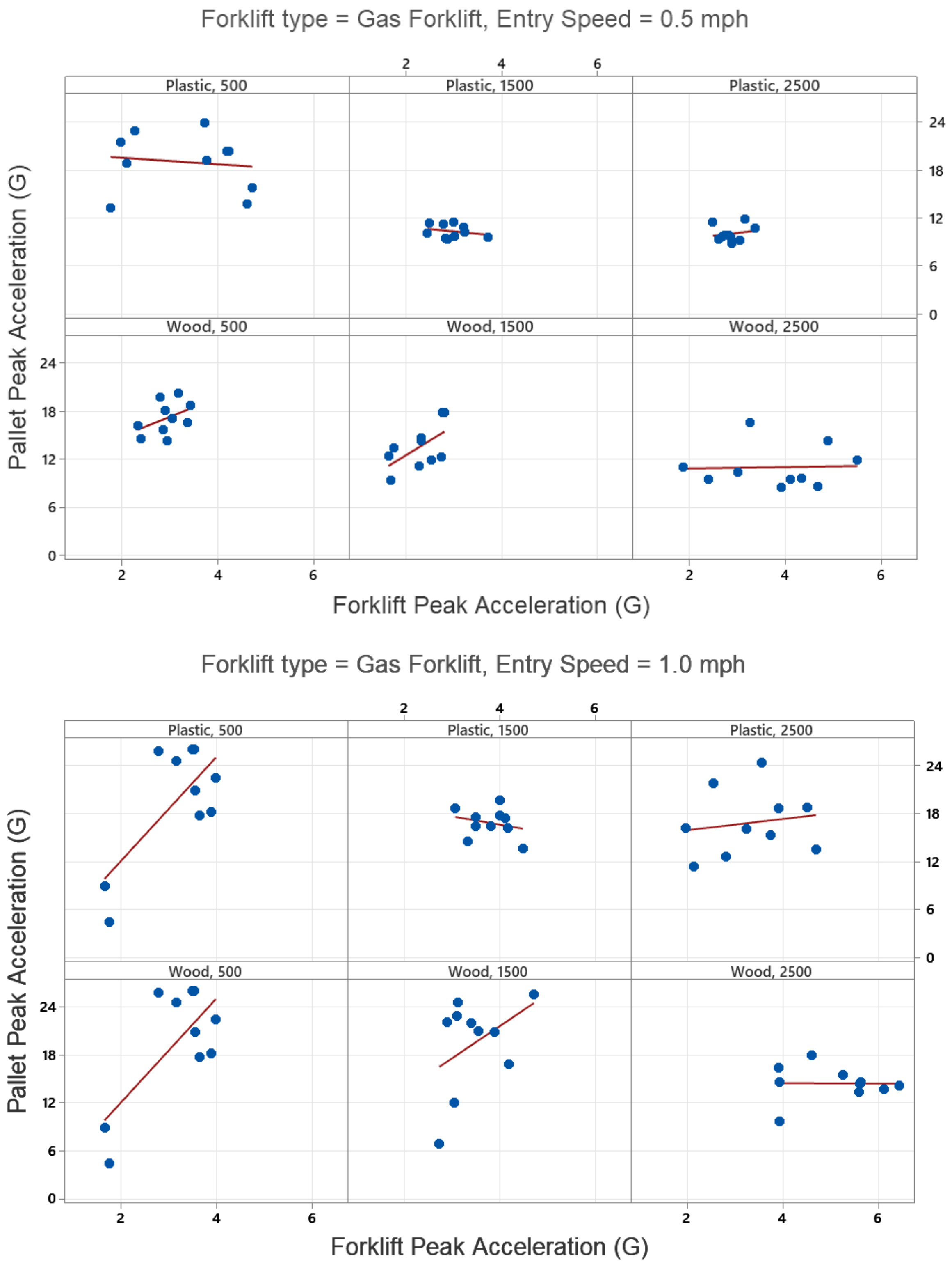

Figure A. 3. Scatterplot of Pallet Peak Acceleration vs Forklift Peak Acceleration for different levels of entry speed, pallet design, and top load (Gas Forklift)

7.7 Relationship between Forklift Peak Acceleration (G) and Delta Velocity (in/s)

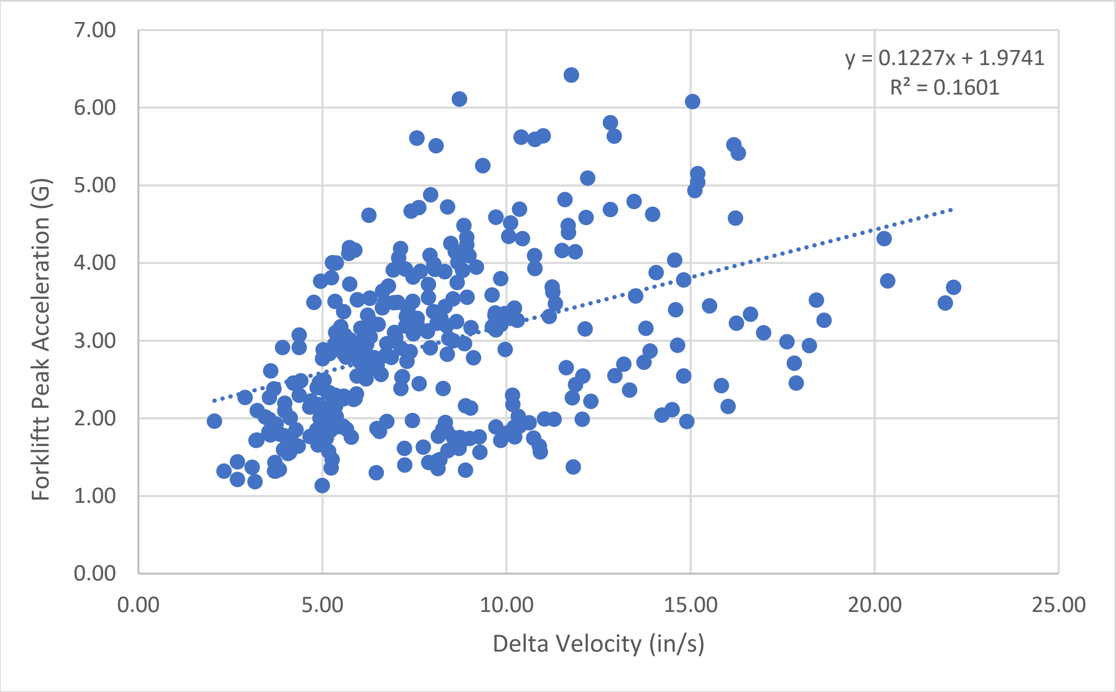

Figure A. 4. Relationship between Forklift Peak Acceleration and Delta Velocity

7.8 Relationship between Pallet Peak Acceleration (G) and Delta Velocity (in/s)

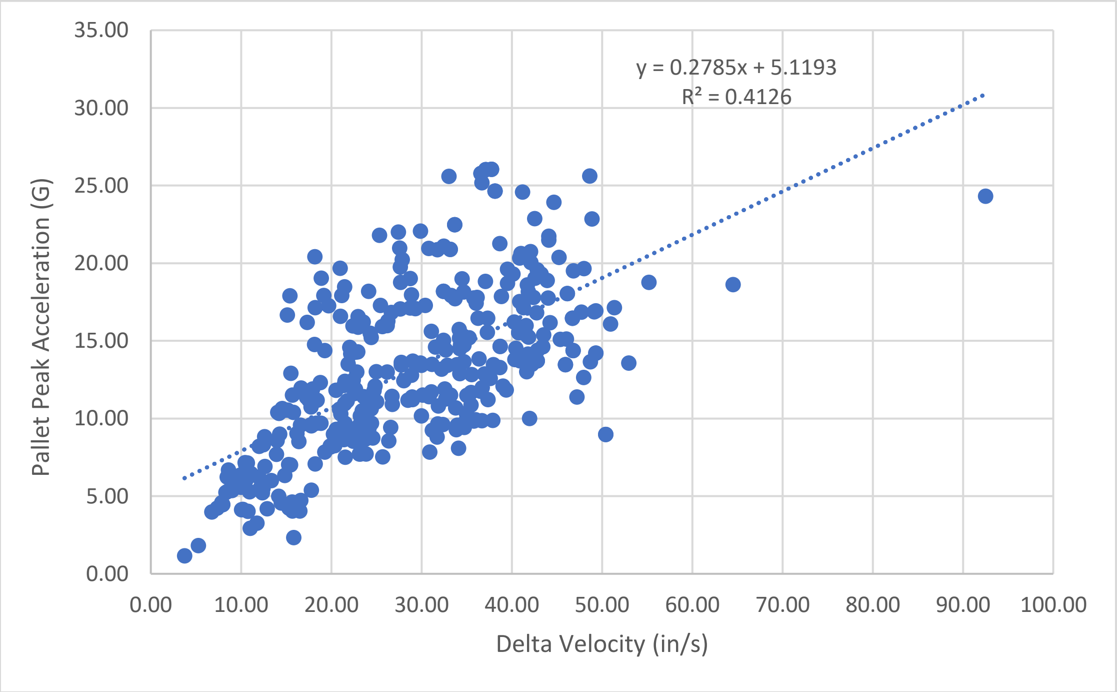

Figure A. 5. Relationship between Pallet Peak Acceleration and Delta Velocity