FAILURE RATE STUDIES AND DESIGN ALTERNATIVES FOR STANDUP FORKLIFT TRUCKS

Srinivas Jagarlamudi
University of Kentucky, sjaga0@engr.uky.edu

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ABSTRACT OF THESIS

FAILURE RATE STUDIES AND DESIGN ALTERNATIVES FOR STANDUP FORKLIFT TRUCKS

Standup forklift trucks are extensively used primarily for material handling in high density warehouses. These forklifts over the years have been involved in severe accidents causing injuries and taking lives of the operator and that of people on the floor. The major accidents involving these trucks are tip-over, off the dock accidents, compartment intrusions and under the rack injuries. The objective of the work is to analyze the accident data and to provide a conceptual design to ensure safety of the operator riding the standup forklift trucks. The operator is assumed to be safe when retained within the compartment similar to that of the safe space environment of a sit down forklift truck or tractors. Thus a door on the standup forklift would provide a safer compartment. This design would help in preventing severe injuries to the operator in case of any accidents. The important criterion of this design is to provide a door with latch and slide mechanism to ensure easy egress and ingress of the operator. The compartment is designed ergonomically for 95th percentile industrial male population. The accident data is studied by performing statistical and failure analysis. Weibull plots are fitted for life time distribution data and are found to be of increasing rate. This suggests that present safety precautions are increasingly ineffective.

Keywords: Standup Forklift, Workplace design, Door design, Ergonomics, Operator safety, Operator comfort, Failure rates

Srinivas Jagarlamudi

Date: 12/09/2004

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FAILURE RATE STUDIES AND DESIGN ALTERNATIVES
FOR STANDUP FORKLIFT TRUCKS

By

Srinivas Jagarlamudi

Dr. Ottfried J. Hahn
(Director of Thesis)

Dr. George Huang
(Director of Graduate Studies)

Date: 12/09/2004
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THESIS

Srinivas Jagarlamudi

The Graduate School
University of Kentucky
2004
FAILURE RATE STUDIES AND DESIGN ALTERNATIVES FOR STANDUP FORKLIFT TRUCKS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering in the College of Engineering at the University of Kentucky

By
Srinivas Jagarlamudi
Lexington, Kentucky

Director: Dr Ottfried J. Hahn
(Professor of Mechanical engineering)
Lexington, Kentucky
2004

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TO MY SISTER AND TO MY PARENTS.
ACKNOWLEDGMENTS

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Since the advent of mechanization, manual handling has been replaced by the use of mechanized lifting and transport equipment. The most successful workhorse for materials handling is the forklift truck. It was invented by Clark material handling about a hundred years ago. These Forklift trucks also popularly known as industrial trucks are frequently used in manufacturing industry on shop floors for material handling and storage and are individually operated by an operator. The need to operate and maneuver in narrow aisles on shop floors led to the introduction of standup narrow aisle trucks into the material handling industry. Narrow aisle trucks are designed to use less floor space by stacking products vertically along aisles 5 to 10 feet wide [1]. These Standup forklift trucks have been through lots of design changes over a period of time for ease of operation, superior visibility, to maximize the operator safety and for controllability to avoid accidents. The latest standup forklift trucks in the industry are manufactured with operator side stance to create new market share and improve productivity of operator. In these types of trucks, the operator faces the left side of the truck thus having maximum visibility in forward direction with forks leading and in backward direction with forks trailing.

The operator in standup forklift truck with side stance position uses his back to rest on the right side of the truck for good forward and backward vision. Control of these forklift trucks is by means of break pedal located under the left foot, a steering wheel controlled by left hand and control lever operated by right hand.
Forward and reverse motion of the truck is controlled by control lever and braking is done by lifting the left foot or reversing the drive motor called plugging. The operator uses his left leg to control the motion of forklift truck. So, the forklift moves when the operator presses his left leg against the brake pedal and forklift comes to rest when the foot is lifted of the brake pedal.

Figure 1.1: Types of standup forklift trucks
1.2 FORKLIFT TRUCK CLASSIFICATION

Fork lift trucks in general are classified accordingly by operator stance as sit-down forklift truck and stand-up forklift trucks. These Forklift trucks are further classified according to the driving power, lifting capacity, operator stance, and type of tires used and the mode of offsetting the weight of payload. The type of driving power depends on service for which truck is intended. For outdoor operations trucks with internal combustion engines gasoline, diesel, propane or compressed natural gas are used. These internal combustion engine trucks are used when length of operation is extended and heavy duty operations are required. Forklifts that operate on electric power uses a battery to supply electricity and are limited to use in indoor operations because of their low material handling efficiency and the time required for recharging and replacing the battery.

Forklift trucks classified with respect to the mode of offsetting the weight of payload are counterbalanced trucks and trucks with forks extending forward of the truck. In the counterbalanced trucks a counter weight is generally attached to the rear of the truck. Generally, batteries are used as counterweight system for electrically powered forklift trucks. These counterbalanced rider trucks are widely used during operations requiring great mobility. The order-picker trucks with forward facing arms are used in warehouses to take goods to and from shelves with operator platform on the forks. Side loader truck carries load from the side and are used for carrying and staking bulky and heavy items. Turret trucks have a rotating fork and can be used for stacking at right angles to the forklift and these trucks generally have a high lift capacity [1].
The industrial truck association, US industry’s primary trade classified the forklifts into seven different classes and are shown in the table provided below.

Table 1.1.a: Industrial Truck Association Classification System

<table>
<thead>
<tr>
<th>Class</th>
<th>Motive power</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>Electric</td>
<td>Counterbalanced rider: Stand-up or Three-wheel sit-down</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 2</td>
<td>Electric</td>
<td>Narrow-aisle: High-lift straddle, Order picker, Reach-type outrigger, Side-loaders, turret trucks, swing mast and convertible turret/stock picker Low-lift pallet and platform(rider)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3</td>
<td>Electric</td>
<td>Hand trucks: Low-lift platform Low-lift walkie pallet Low-lift walkie/center control Reach-type outrigger High-lift straddle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1.1.b: Industrial Truck Association Classification System

<table>
<thead>
<tr>
<th>Class</th>
<th>Engine Type</th>
<th>Tire Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 4</td>
<td>Internal Combustion Engine</td>
<td>Fork, cushion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tire</td>
</tr>
<tr>
<td>Class 5</td>
<td>Internal Combustion Engine</td>
<td>Fork, pneumatic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tire</td>
</tr>
<tr>
<td>Class 6</td>
<td>Electric or Internal Combustion Engine</td>
<td>Tractor, sit-down rider, drawbar pull over 999lbs.</td>
</tr>
<tr>
<td>Class 7</td>
<td>Electric or Internal Combustion Engine</td>
<td>Rough terrain forklift truck</td>
</tr>
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Source: Industry and Trade Summary: Forklift trucks and related vehicles

1.3 OBJECTIVE

The primary objective of the work is to analyze the safety of the operator’s compartment, design rear post and to conceptually design a door to protect the operator without compromising on rapid egress from the forklift as per standard ASME B56.1 [2]. Then ergonomic design of operator compartment for 95th percentile industrial male population, design alternatives for standup forklifts is done to achieve target. Statistical and failure analysis of the forklifts accident data is performed in support of the design for standup forklift trucks.
CHAPTER 2
LITERATURE REVIEW

The safety of the operator associated with forklift trucks has been a major cause for material handling industry over a period of time. Many safety guidelines have been incorporated by Occupational Safety and Health Administration (OSHA). OSHA proposed those operator training guidelines in OSHA 1910.178 [3]. The applicable standard ASME B56.1 [2] for low lift and high lift industrial trucks suggests a compartment design facilitating easy egress and ingress and operator restraints to retain the operator within the compartment in case of a tip-over or off the dock accidents. In the sit down forklift trucks the operator can be restrained in the seat without falling by means of a seat belt in case of a tip-over or off the dock accident. Thus a person operating sit down forklift trucks is safer in the case when tip-over or off the dock accidents occur.

Crockett and Miller [4] performed simulations on tip-over and off the dock accidents of standup forklift trucks with and without door with the help of three operators in order to determine the injury potential and to calculate the egress time. These experiments suggested an average additional egress time of 0.83 seconds that would severely compromise the safety of operator in a situation where in the operator has to egress rapidly. These studies did not consider improved step height and planned door action in their studies to reduce the egress time. These rapid egress situations generally arise when tip-over or off the dock accidents occur. Operator can easily exit the forklift with forks leading but his ability to jump clear off the forklift with forks trailing in an off the dock accident leading to fatal injuries or even causing death of
the operator. These injuries usually occur when the operator in the standup forklift is not retained within the operator compartment [5].

Mohamad, Watkins, Sadegh and Dunlap [6] investigated potential injury to operators of standup forklift trucks with operator confined in the compartment by means of door using computer simulations with biodynamic model and experimental setup with an Hybrid III, 50th percentile male anthropometric test device. They calculated head impact velocity and proposed not to implement doors on standup forklift trucks. This is in stark contrast with the sit down forklift where the safest place is the seat. The study also did not consider restraint of person in falling by hand hold and operator with helmet.

Harris & DeRosia [7] investigated loss of stability and falling of the operator during normal operations in warehouses. The paper performed simulations and concluded that operator often loses stability due to unanticipated accelerations and decelerations causing the operator to fall. This study further supported the use of door to retain the operator and to prevent serious lower body injuries.

Carlin & Sances, Jr. [8] discussed forklift overturns and head injuries with the help of hybrid II dummies, side impact dummies and stunt men on forklifts of different manufacturers. The investigation concluded that dummy lacked ability to hold on to the truck during accidents. The operator was either crushed or death occurred when jumped or was thrown out by an overturning truck. The work supported the idea of retaining the operator within the compartment by means of restraints. The operator would sustain fewer injuries by remaining in the forklift. The study also showed that
the head of the operator always struck the ground regardless of restraint systems and thus means to prevent head injuries has to be addressed.

Failure analysis associates [9] performed a comparative analysis of accidents involving forklift trucks and analyzed in terms of accident type and type of injury. These accident categories were applied to the data compiled by California’s department of industrial relations, mine safety and health administration and Clark Equipment Company. Comparison of accident reports provided information for forklift truck designers as to the accident patterns and frequencies of industrial truck accidents to incorporate necessary design changes in order to prevent the accidents and to incorporate necessary design alternatives. No changes in the workspace were proposed in the paper as has been seen in many other industrial operators work stations such as tractors, dozers etc.
CHAPTER 3

DESIGN ALTERNATIVES FOR STANDUP FORKLIFT TRUCKS

3.1 INTRODUCTION

Ergonomics is the application of scientific principles, methods, and data drawn from a variety of disciplines to the development of engineering systems in which people play a significant role. These engineering systems vary from use of simple tool by a consumer to multiperson sociotechnical systems [10]. An ergonomics approach to the design of workstations attempts to achieve balance between the worker capabilities and work requirements to optimize worker productivity and the total system [11]. The standup forklift truck operator compartment has to be designed ergonomically for better performance, operator comfort and safety of the operator.

3.2 DESIGN TO FIT BODY POSTURE

Often in industry the workstations are designed in an arbitrary fashion giving little consideration to anthropometric measurements of the user. The physical dimensions of operator are significantly important in the design of workstation for safety and productivity. Inadequate postures due to improperly designed work place can result into static muscle efforts resulting in muscle fatigue and aggravating operator related health hazards. So, in designing an operator compartment it is necessary to obtain information on task performance, equipment and working posture. Thus it is appropriate to design primarily by considering effects of anthropometry and locations of the machine elements on posture, reach, vision and interference of the body with the machine.
3.2.1 Human Physical Dimensions

Figure 3.1: Anthropometric Data in Standing Position

Source: SAE J833 May 1989
Figure 3.1 gives the detailed dimensions of human body for small human representing 5\textsuperscript{th} percentile family, medium human representing 50\textsuperscript{th} percentile family and large human representing 95\textsuperscript{th} percentile population. These dimensions include an allowance for shoe height and light clothing [12].

3.2.2 Operator Space Envelope Dimensions

SAE J54 standard defines the dimensions for minimum normal operating space envelope around the clothed standing operator for operator enclosures.

![Figure 3.2: Operator space envelope dimensions](source: SAE J54 Jun1992)
According to the standard [13] the operator enclosure minimum space envelope may be smaller than specified in the figure 2.2 in condition where the reduced operator space envelope for a particular machine application allows for adequate operator performance. The internal operator space envelope width may be reduced to a minimum of 670mm to accommodate a 95\textsuperscript{th} percentile operator with heavy clothing. But it cannot accommodate 95\textsuperscript{th} percentile operator if the width is reduced less than 670mm.

**3.3 DESIGN OF STANDUP FORKLIFT OPERATOR COMPARTMENT AND DOOR**

The standup forklift compartment is designed with respect to the guidelines provided by the SAE standards. Since many tip over, and most off dock accidents are emergent events, the primary goal for protection in tip over and off the dock accidents should be to prevent the operator from being thrown out of the compartment. In order to prevent death or serious injuries due to the crushing of the operator by the forklift, the operator and all body parts has to be retained within the compartment. According to ASME B56.1, the operator protection means shall be designed so as not to interfere with the normal operation of the controls and to allow getting on and off the truck easily and permitting rapid exit in case of an emergency.

The issue of providing the door for standup forklift trucks has been a major debate in the industry over the last several decades. The procedure for sit down forklifts in case of accidents is to stay with the machine. Standup trucks with forks leading and with no door allow exit in case of an off the dock accident by stepping off the forklift by sensing the impending accident. But the operator ability to clear off the truck can be
seriously compromised when the truck is operated with forks trailing. In the case of a lateral tip-over the operator can exit from the truck by stepping backward, but the inability of the operator to be clear of the truck may lead to severe amputations or even lead to death. Injuries to operators left legs form the major percentage of accidents involving standup forklift trucks. OSHA in its safety guideline mandates the need for operator left leg to remain within the compartment while operating. The operator while braking is in a single limb stance posture [7]. So, in the process of deceleration the operator momentum is directed towards the entry of forklift. Deceleration of forklift results in loss of postural stability of the operator and thus it is important to arrest the loss of balance, falling and injuries during operation of standup forklift truck. The above mentioned safety issues are addressed by providing the operator restraint in the form of door to standup forklift trucks.

3.3.1 Introduction to Pro/Engineer

Pro/engineer is a 3D feature-based parametric solid modeler enabling to create true 3D solid models of the designs. Pro/engineer enables to work with feature based modeling, parametric relationships and associativity. Objects designed in pro/engineer can be shared with many applications.

3.3.1.1 Feature based modeling

Parametric modeling systems are often referred to as feature based modelers. A feature is a primary component that can be created or used to build a three dimensional part. Pro/engineer models are feature based, which means they are composed of one or many features. These features may comprise either a positive space or negative space. Positive space features are composed with actual mass and
negative space feature is where a part has a segment cut away or subtracted. During the sketching of the feature, design intent is developed in the model by adding dimensions and constraints to the sketch.

Some examples of features are

- **Datum planes**, which are two dimensional invisible flat planes usually used for referencing to create other features.
- **Datum axes and curves**, which are basically two and three dimensional lines, used for referencing during modeling.
- **Protrusions**, which create solid material either from sketched sections or from existing features within the model.
- **Cuts**, which are similar to protrusions except that they remove material from the model.

### 3.3.1.2 Design Intent

Design intent is the capability unique to parametric modeling packages compared to other forms of CAD. Most CAD packages have the ability to display the design but fail to hold the actual vector data required for construction. Design intent is the intellectual arrangement of assemblies, parts, features and dimensions to solve the design problem. Tools for incorporating design intent are

- **Assembly constraints** used to form relationships between components of a design.
- **Dimensional relationships** capture the design intent between features in a part and in between parts of an assembly. A dimensional relationship is an explicit way to relate features in a design.
Dimensioning scheme is extremely important for design intent. The placement of dimensions within the section or feature should match the intent of design.

References are created within part and assembly modeling there by creating a parent-child relationship. An example of reference within part mode is to use edges of existing features. Thus changes in edge of parent feature results in corresponding change in child feature.

Feature constraints are used, if design requires a feature element be constrained to other element. Examples of feature constraints are perpendicular, parallel, tangent and equal length.

3.3.1.3 Parametric Features

Design created with pro/engineer can be parametric. Parametric models use dimensions and other parameters within the model to control the physical shape of the model. This controlling happens by means of using rules or equations called relationships.

3.3.1.4 Associativity

Pro/engineer is an integrated, fully associative computer aided mechanical design package. Pro/engineer is the fundamental application in a powerful suite of tools capable of an integrated and concurrent environment. Objects created in one module of pro/engineer and can used with other applications. Due to associativity, changes made to an object in one mode reflects in other modes,
Basic modules in Pro/engineer are

- **Sketch Mode**: Sketch mode uses two-dimensional approach where feature entities are sketched and then three-dimensional construction operators such as extrude, revolve can be invoked. Sketches can be created separately from part and assembly environments and can be saved for future use.

- **Part Mode**: Part mode is used to create solid and surface models. This is the primary design environment and objects created in this mode can be subsequently used in for drawing and manufacturing modes.

- **Drawing Mode**: drawing mode is used to create engineering drawings of models created. Drawing mode takes existing part or an assembly to produce an orthographic drawing. It is also used to produce detailed drawings with section and auxiliary views.

- **Assembly Mode**: Assembly module is used to create assembly of design components into a final design solution.
Figure 3.3: Orthogonal view of standup forklift truck design
Figure 3.4: Wire frame model of standup forklift truck.

The standup forklift truck in the above figure is an ergonomic design of operator compartment with respect to the guidelines provided by SAE standards and conceptual design of providing a door to restraint operator within the compartment without compromising on rapid ingress and egress as stressed by industrial trucks standard.
3.4 OPERATOR COMPARTMENT

Figure 3.5: Orthographic view of operator compartment

All dimensions in millimeters.
Table 3.1: Design parameters of the compartment:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension in millimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Height</td>
<td>180</td>
</tr>
<tr>
<td>Entrance width</td>
<td>500</td>
</tr>
<tr>
<td>Height of the cab</td>
<td>1200</td>
</tr>
<tr>
<td>Width of the cab</td>
<td>1200</td>
</tr>
<tr>
<td>Length of the cab</td>
<td>1000</td>
</tr>
<tr>
<td>Width of back rest</td>
<td>400</td>
</tr>
<tr>
<td>Knee cap</td>
<td>150</td>
</tr>
<tr>
<td>Counter weight width</td>
<td>600</td>
</tr>
</tbody>
</table>

The step height is reduced from normal height of 11 inches used by forklift manufacturers to reduce the time taken to ingress and egress. The standard step height of 180mm or approximately seven and quarter of an inch is considered. In a side stance forklift truck, back rest plays an important role by providing cushion to the back of the operator and enhancing operator stability. A knee cap is provided to reduce the fatigue on operator knee. Due to the absence of suspension system in present day forklift trucks, floor padding is provided to protect operator from vibrations caused due to uneven floors. Posts are provided to prevent injuries to the operator caused when the trucks accidentally pass below the racks while traveling in backward direction. Hand rails are provided for the operator to hold on to the forklift and to avoid being thrown out of the compartment.
3.5 DESIGN OF DOOR

The design of door plays a crucial role. It should have the advantages of low cost, easy in construction and high acceptance to the operator. The primary objective when providing a door is that it should not hamper the ability of the operator to easily enter the forklift and exit the forklift in case of an emergency. The material used is 1/4 inch steel having strength enough to hold the operator within the compartment and also to protect the operator from compartment intrusions. The door here is designed to slide and then latch to the hook. The hook disengages on pressing the handle provided and the door slides by slightest effort. The bearings have to be lubricated for easy sliding. The operator upon boarding pulls the door to slide and latch on to the hook. The door is held at three locations and is provided with a bend for strength and to protect operator from sharp edges.

Figure 3.6: Front view of door
3.6 DESIGN ALTERNATIVES AND BENCHMARKING

The safety and comfort of the operator of standup forklift trucks has to be improved to protect and improve the stability in case of accidents. These design changes can be achieved by a method known as benchmarking. Benchmarking is a continuous improvement process measuring products, services and practices against competitors of companies recognized as industry leaders [14]. Benchmarking provides a way to improve products and methods to achieve the desired targets.

Design features of race car interiors and restraints for the safety of the operator during collisions can be incorporated. Head and neck support (HANS) to prevent the head from snapping forward or to the side during collisions is attached to the helmet. This restraint would avoid serious head and neck injuries. Window openings are covered by mesh made from nylon webbing. This webbing helps keep the drivers arms from flailing out during accidents.

Safety factor associated with tractors, dozers and sit down forklifts is to protect the operator in roll over accidents. The operator compartment is provided with a rollover protective structure (ROPS) and compartment of some trucks are enclosed to prevent operator from being pinned by over head guard.

Severe and permanent head injuries can result from falling onto a hard surface from a height of just two feet. Standard dock heights are generally four feet and the equivalent impact on operator head in an off dock accident can be similar to that of rodeo barrel hit by a bull weighing 3000 to 4000 pounds. The barrel material is made out of aluminum and some made out of steel or fiberglass with rubber or nylon.
padding to protect the clown. Helmet made out of rodeo barrel material has to be mandated to prevent head injuries due to the impact with ground.

Atlet Inc. a Swedish forklift truck manufacturer designed narrow aisle trucks with operator seat eliminating standup postures. The industry has solutions for the safety associated with operator in sit down postures. Schaeff Inc. manufacturing w-series warehouse forklifts and echo series forklifts have operator compartment door as an optional and safety feature.
CHAPTER 4

ANALYSIS OF ACCIDENT DATA

4.1 INTRODUCTION

A comparative analysis of reported accidents involving standup forklift trucks was performed. Analysis and comparison of the accident data from accident reports provides information to the equipment designer so that design attention can be focused onto most frequent and serious accidents. Thus accident data can also be used as guide by designer in the process of any design modifications involving the equipment to avoid major and severe accidents [9]. The data from Table 4.1 provides the information of all the accidents involving standup forklift trucks over the years spanning from 1978 to 2002, the number of hours of operation per year and also the number of accidents that were serious in nature [5]. This data is further classified according to the type of accidents involving standup forklift trucks that posed severe threat to operator safety such as off the dock accidents, tip over accidents and accidents occurring with forks trailing. These forks trailing collisions are further divided into accidents involving left leg injuries and accidents without left leg injuries. The other types of accidents are beyond the consideration of this study.
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<th>Accidents for year</th>
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<td>Forks Trailing Collisions/ Left Leg Injuries</td>
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<td>69</td>
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</table>
4.2 COMPARISON OF ACCIDENT DATA

According to [9], the accident frequency is defined by the ratio of the number of times an accident occurs during a certain activity divided by the total number of opportunities that accident occurs during that activity. The choice of the denominator allows the comparison of accident frequencies of different events. The accident fraction used in this comparison is in terms of the percentage of total number of accidents. Table 4.2 illustrates the comparison of accident types in terms of total number of accidents. It can be noted that forks trailing collisions form major percentage of accidents followed by tip-over and off the dock accidents respectively.

Table 4.2: Comparison of Total Number of Accidents

<table>
<thead>
<tr>
<th>Type of Accident</th>
<th>Number of Accidents</th>
<th>Percentage of Accidents</th>
</tr>
</thead>
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<tr>
<td>Forks trailing collisions</td>
<td>1158</td>
<td>46.26</td>
</tr>
<tr>
<td>Off Dock Accidents</td>
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<td>7.99</td>
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<tr>
<td>Tip over Accidents</td>
<td>358</td>
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<td>Other Accidents</td>
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<td>31.44</td>
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<td>Total Accidents</td>
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Table 4.3 provides the comparison of accident types in terms of the percentage of total number of accidents per every year. Figure 4.1 is the graph plotted with percentage of accidents per year on y-axis and the percentage of accident types per year on x-axis. From the graph, it is imperative that forks trailing collisions form major percentage of total number of accidents involving standup forklift trucks. The graph also illustrates that the tip over accidents, off the dock accidents, and forks
trailing collisions combined forming major percentage of accidents and following a constant rate starting from the early nineties.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage of Tip Over Accidents</th>
<th>Percentage of Off the Dock Accidents</th>
<th>Percentage of collisions with forks trailing</th>
<th>Percentage of Leg injuries with forks trailing</th>
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<td>42.86</td>
<td>28.57</td>
</tr>
<tr>
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<td>6.25</td>
<td>50.00</td>
<td>25.00</td>
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<td>1981</td>
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<td>20.00</td>
<td>50.00</td>
<td>40.00</td>
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<td>16.67</td>
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<td>42.59</td>
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</table>
4.3 Incident Rates of Accidents:

US Department of labor, bureau of labor statistics [15] defined an equation to calculate the incident rates of accidents and work related injuries. These incident rates can be used to show relative level of injuries and illnesses among different industries or incidents within one organization. The equation to determine the incident rate is given by

\[
Incident rate = \frac{\text{Number of Accidents} \times 200,000}{\text{Employee hours worked}}
\]  

(4.1)

The number of hours worked did not include any non working time and it is calculated based on eight hours per day. The value 200,000 providing standard base is calculated taking into consideration the equivalent of 100 employees working for 40 hours per week and 50 weeks per year. Table 4.4 shows the incident rates of accidents per year, tip over accidents, off the dock accidents, forks trailing collisions, and forks trailing collisions with left leg injuries.
Table 4.4: Incident rate of accidents

<table>
<thead>
<tr>
<th>Year</th>
<th>Hour/Year</th>
<th>Incident rate of accidents per year</th>
<th>Incident rate of off dock accidents</th>
<th>Incident rate of tip over accidents</th>
<th>Incident rate of forks trailing collisions</th>
<th>Incident rate of forks trailing leg injuries</th>
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<td>0.12</td>
<td>0.20</td>
<td>0.85</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Incident rates in the table are calculated using the equation 4.1. The number of accidents provided in table 4.1 and the hours per year of forklift truck operation is
used to determine the incident rates. A sample incident rate calculation is shown below.

Incident rate of accidents per year during 1978:

Number of accidents = 6
Hours of operation per year = 52000 hrs
Incident rate = \frac{(6*200,000)}{52000} = 2.31

Figure 4.2: Incident rates of accidents per year
The plot of incident rates in the figure 4.2 is plotted with year of accident on x-axis and incident rate on y-axis. A trend line for the incident rates is added. The trend of incident rates is of increasing order for all the type of accidents stressing the importance of design changes in order to protect the operator in case of the above accidents. This analysis further supports the idea of providing operator restraint in the form of door and other restraints such as hand hold to retain arms and the head in the compartment.
CHAPTER 5

FAILURE RATE MODELS OF FORKLIFT TRUCK ACCIDENTS

5.1 INTRODUCTION

The accident data is used in order to determine the failure rate models of the accident types involving standup forklift trucks. The above analysis is performed on tip over accidents, off the dock accidents, forks trailing collisions and forks trailing collisions causing left leg injuries while operating standup forklift trucks. The data is tested for the goodness-of-fit and a best lifetime distribution model is fitted using a statistical software MINITAB.

5.2 RELIABILITY, LIFETIME DISTRIBUTIONS, LIFETIME DISTRIBUTION MODELS

5.2.1 Reliability

Reliability is the probability that a system, vehicle, machine, device, and so on, will perform its intended function under encountered operating conditions, for a specified period of time. However the product is considered to have failed if it fails to meet the specifications over a given period of time. Unreliability can be defined as the probability that the product fails to meet the specifications over given time period [16].

5.2.2 Lifetime Distributions

Lifetime distribution representation is helpful in determining the risk associated with the item over a period of time. Three types of representation of lifetime distribution are the survivor function, probability density function and the hazard function.
5.2.2.1 Survivor Function

Survivor function is defined as probability of an item functioning at any time $t$:

$$S(t) = P[T \geq t] \quad t \geq 0$$

The survivor function is also known as reliability function and a complimentary cumulative distribution function. It is assumed that $S(t) = 1$ for all $t < 0$ [16].

5.2.2.2 Probability Density Function

Probability density function is defined by $f(t) = -S'(t)$ and is used to indicate the likelihood of failure at any time, $t$. The probability density function also illustrates the relationship between cumulative distribution function $F(t)$ and the survivor function $S(t)$ for a lifetime. The probability of failure between time interval $[a, b]$ is calculated by

$$p[a \leq T \leq b] = \int_{a}^{b} f(t) \, dt.$$

5.2.2.3 Hazard Function

Hazard rate function or failure rate function is the best representation indicating the risk associated with an item at any given time $t$. The hazard rate representation is useful in comparing the way risks change over time for several populations of items by plotting the hazard function on a single axis [17]. Hazard rate function is defined by the ratio of probability density function to the survivor function.

$$h(t) = \frac{f(t)}{s(t)}; t \geq 0$$

5.2.3 Lifetime Distribution Models

The theoretical population models used to describe unit lifetimes are known as Lifetime Distribution Models. The population is generally considered to be the entire possible unit lifetimes for all of the units that are in use. A random sample of size $n$
from this population is the collection of failure times observed for a randomly selected group of \( n \) units.

5.2.3.1 The Exponential Distribution

The constant failure rate model for continuously operating systems leads to an exponential distribution. Replacing the time-dependent failure rate \( \lambda(t) \) by a constant \( \lambda \) in probability density function, \( f(t) = \lambda e^{-\lambda t} \).

Similarly, the cumulative distribution function is given by \( F(t) = 1 - e^{-\lambda t} \)

And the reliability is given by \( R(t) = e^{-\lambda t} \).

5.2.3.2 The Normal Distribution

To describe the time dependence of reliability problems, the PDF for the normal distribution is given by \( f(t) = \frac{1}{\sqrt{2\pi\sigma}} \exp[-\frac{(t-\mu)^2}{2\sigma^2}] \); where \( \mu \) is the mean time to fail.

The corresponding cumulative distribution function is given by

\[
F(t) = \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(t'-\mu)^2}{2\sigma^2}\right] dt'
\]

The normal distributions are used to describe the reliability of equipment that is quite different from that to which constant failure rates are applicable. It is useful in describing reliability in situations in which there is a reasonably well-defined wear out time, \( \mu \). This may be the case for example, in describing the life of a tread on a tire or the cutting edge on a machine tool. In these situations the life may be given as
a mean value and an uncertainty. Uncertainty in the life of unit is measured in terms of intervals in time in the case of normal distribution.

5.2.3.3 The Lognormal Distribution

The lognormal is a related distribution that has been found to be useful in describing failure distributions for a variety of situations. It is particularly appropriate when the time of failure is associated with a large uncertainty therefore the variance of the distribution will be a large function of the mean time to failure (MTTF). However, it is still possible to state a failure and to estimate with it the probability that the time to failure lies within some factor say $n$, and also if it is known that 90% of the failures are within a factor of $n$ of some time $t_0$, then

$$\Pr\left\{\frac{t_0}{n} \leq t \leq nt_0\right\} = 0.9$$

The PDF for the time to failure is then given by

$$f(t) = \frac{1}{\sqrt{2\pi\omega t}} \exp\left\{-\frac{1}{2\omega^2} \left[\ln\left(\frac{t}{t_0}\right)\right]^2\right\}$$

and the corresponding cumulative distribution function is given by

$$F(t) = \Phi\left[\frac{1}{\omega} \ln\left(\frac{t}{t_0}\right)\right].$$

In lognormal distribution model the failure rate can be either increasing or decreasing depending on the value of $\omega$. The log normal distribution is frequently used to describe fatigue and other phenomenon caused by aging or wear in failure rates that increase with time.

5.2.3.4 The Weibull Distribution

The weibull distribution is one of the most widely used in reliability calculations and with an appropriate choice of parameters can be used to model variety of failure rate
behaviors. These include, as special case, the constant failure rate, in addition to modeling increasing failure rates. The Weibull distribution may be formulated in either a two or three parameter form.

The two-parameter Weibull distribution, assumes that the failure rate is in the form of a power law given by

$$\lambda(t) = \frac{\beta}{\theta} \left(\frac{t}{\theta}\right)^{\beta-1}$$

where $\beta$ is the shape parameter or Weibull slope and $\theta$ is the scale parameter or characteristic life.

The equation for probability density function is given by

$$F(t) = m \left(\frac{t}{\theta}\right)^{m-1} \exp\left[-\left(\frac{t}{\theta}\right)^m\right].$$

and the cumulative distribution function is given by

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\theta}\right)^m\right].$$

5.3 MINITAB ANALYSIS

Numerous calculations involved in theoretical analysis of failure data can be eliminated by using statistical analysis software like MINITAB. MINITAB is an easy to use statistical analysis software tool that provides wide range of data analysis capabilities. It can be used to analyze data and present in graphical representation.

The steps involved in performing analysis using MINITAB are

- Feeding the data into MINITAB excel sheet.
- Performing reliability/survival distribution analysis to check for goodness of fit.
- Lifetime distribution plot.
The spread sheet of the accident data of standup forklift trucks is imported into MINITAB in order to perform the analysis. The frequencies used in analyzing the data are the number of hours the trucks were operated per year. After importing the data, the following commands are selected from the drop down menu to perform the reliability distribution analysis of the data.

The sequence of the selection is Stat > Reliability/Survival > Distribution Analysis (Right Censoring) > Distribution ID Plot. Distribution ID Plot (Right Censoring) is used in order to determine the distribution that fits best to the data by comparing how closely the plot points lie to the best-fit lines of a probability plot and providing goodness-fit measures to help determine the best distribution.

5.3.1 Goodness – of – Fit
MINITAB provides two types of goodness of fit measures to determine the best fit.
They are

- Anderson – Darling test for maximum likelihood and least square estimation methods
- Pearson correlation coefficient for least square estimation method.

The Anderson-Darling statistic is the measure of how far the plot points fall from the fitted line in a probability plot. The statistic is a weighted squared distance from the plot points to the fitted line with larger weights in the tails of the distribution. MINITAB uses an adjusted Anderson-Darling statistic, because the statistic changes when a different plot point method is used. The Pearson correlation measures the strength of the linear relationship between the X and Y variables on a probability plot [18].
A smaller Anderson-Darling statistic indicates that the distribution fits the data better. The correlation ranges between 0 and 1, with higher values indicating a better fitting distribution [18].

### 5.3.2 Lifetime Distribution Plots

Once the best lifetime distribution model is determined from the Anderson-Darling goodness of fit test, the lifetime distribution representations and the lifetime distribution model is plotted. The following commands are selected from the drop down menu.

**Stat > Reliability/Survival > Distribution Analysis (Right Censoring) > Distribution Overview Plot.**

Distribution Overview Plot is used to generate a layout of plots that allows viewing the life data in different ways on one graph. A parametric overview plot of the best distribution of the data includes a probability plot for the selected distribution, a survival or reliability plot, a probability density function, and a hazard plot.

### 5.4 RESULTS AND DISCUSSION

The Anderson-Darling coefficient for goodness of fit from the post processor of the MINITAB for all the accident data resulted in a minimum value for weibull distribution showing it to be the best fit and those values are tabulated in table 5.1. The Pearson correlation coefficient is neglected as the method used for distribution analysis is of maximum likelihood estimation. The distribution overview plots of the accident types are shown in the Figures 5.1 to 5.5. The weibull distribution plots for the total number of accidents per year, tip over accidents, off the dock accidents, forks trailing collisions and forks trailing collisions with left leg injuries are of
increasing rate as the values of the shape parameters from table 5.1 are greater than one. The hazard plots are of increasing rate with time and reliability and the survivor plot is that of a decreasing order. Thus the accidents involving standup forklift trucks are of increasing rate with the time.

Table 5.1: Results from MINITAB Analysis

<table>
<thead>
<tr>
<th>Type of Accident</th>
<th>Anderson-Darling coefficient</th>
<th>Shape Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of accidents per year</td>
<td>47.017</td>
<td>2.54</td>
</tr>
<tr>
<td>Tip over accidents</td>
<td>7.437</td>
<td>2.67</td>
</tr>
<tr>
<td>Off the dock accidents</td>
<td>3.478</td>
<td>2.19</td>
</tr>
<tr>
<td>Forks trailing collisions</td>
<td>22.755</td>
<td>2.50</td>
</tr>
<tr>
<td>Forks trailing collisions with left leg injuries</td>
<td>13.503</td>
<td>2.48</td>
</tr>
</tbody>
</table>
Figure 5.1: Weibull plot of total number of accidents

Figure 5.2: Weibull plot of tip over accidents
Figure 5.3: Weibull plot of off the dock accidents

Figure 5.4: Weibull plot of forks trailing collisions
Figure 5.5: Weibull plot of forks trailing collisions with leg injuries
CHAPTER 6
CONCLUSIONS

6.1 INTRODUCTION
Accidents involving standup forklift trucks have been a major concern for the material handling and storage industry over the past years. The safety of the operator associated with these trucks is seriously jeopardized in the case of a tip over or off the dock accidents, compartment intrusions, under the rack collisions, arms or head out of the compartment and also leg injuries due to the loss of stability. These accidents can lead to death or cause severe injuries to the operator such as broken bones and amputations. This work included alternatives to be made to the standup forklift trucks, detailed accident and failure rate analysis of the accidents.

6.2 CONCLUSIONS

6.2.1 Design Options
The safety of the operator can be improved by providing alternatives to the existing design of the standup forklift trucks. One such alternative is to provide a door to protect the operator. Since the industry standard mandates productivity vs. safety, easy ingress and egress of the forklift trucks, the proposal of door for standup forklift trucks is seriously opposed. The reason for opposing is that a door would increase the time to ingress and egress. This can be overcome by reducing the step height to seven and a quarter inch from the ground thereby reducing the time delay by one-third to two-thirds of a second. The sliding mechanism of the door also aids in reducing the time delay. More over doors to the standup forklift trucks would prevent lower body injuries caused due to the compartment intrusions. Door to the forklift truck would
arrest loss of balance of the operator while braking and there by preventing left leg injuries. While applying braking the operator loses stability and may result in the crushing of left leg. Figure B.3 shows the pictures of forklifts with hits on the step thus stressing the importance of restraint in the form of door to arrest loss of balance. It is important to provide posts to protect the operator when hit by the racks in a situation where the trucks accidentally slide below the racks. Hand rails are provided in posts so that operator can hold on to the forklift. The pictures of forklifts hit by the racks are shown in figure B.2 of appendix B.

The operator compartment is designed to fit 95th percentile population. The ergonomics of the compartment is addressed by providing back rest, knee pad and padding to the floor to protect the operator from shocks and vibrations resulting from uneven floors.

**6.2.2 Data Analysis**

The accident data of standup forklift trucks is statistically analyzed and failure rates of the accidents are computed according to the accident type. The accident types considered were tip over and off the dock accidents, forks trailing collisions and collisions involving left leg injuries. The incident rate of the accidents involving standup forklift trucks is found to be of increasing order for all the accident types. The forks trailing collisions constituted major percentage of accidents followed by tip over and off the dock accidents respectively.

The accident data is also analyzed using Minitab software to determine the failure rates. The data is best fitted by checking Anderson-Darling and Pearson correlation coefficient tests. The goodness of fit from above tests showed weibull distribution to
be the best lifetime distribution for all the accident types being considered. The shape parameter from the weibull distribution for all the accident types had a value greater than one indicating increasing failure rate.

6.3 REMARKS

- The accidents involving standup forklift trucks found to be of increasing order.
- The training of the operators as per recommended standards failed to reduce the accidents.
- Operator safety warrants necessary design changes to the standup forklift trucks.
- Design changes had to be made to prevent accidents and to protect the operator in case of an accident.
- Bench marking results in getting the desired objectives.
- The safety features similar to that of tractors and race cars can be incorporated into the standup forklift trucks.
- Door would protect operator in case of a tip over, off the dock accidents and forks trailing collisions. If door used would arrest loss of balance and prevent leg injuries. Ford used 100 forklift trucks with doors and reported no injuries.
- Posts would protect the operator from under the rack hits.
- Padding results in ergonomic comfort and more stability to the operator.
- The injury severity to the operator head in case of a tip over or off the dock accidents is reduced by mandating helmet that would absorb the impact energy of collision with ground.
APPENDIX A

MINITAB ANALYSIS

Reliability Distribution Analysis of Total Number of Accidents

Distribution ID Plot: Hour/Year

Using frequencies in Accidents per year

Goodness-of-Fit

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Anderson-Darling (adj)</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull</td>
<td>47.017</td>
<td>0.970</td>
</tr>
<tr>
<td>Lognormal</td>
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<td>Exponential</td>
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<tr>
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Table of Percentiles

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| Weibull                        | 10      | 5026104    | 94855.0        | 4843588             | 5215497             |
| Lognormal                      | 10      | 5254804    | 64839.5        | 5129245             | 5383436             |
| Exponential                    | 10      | 777416     | 12831.4        | 752669              | 802976              |
| Loglogistic                    | 10      | 5412502    | 76649.2        | 5264338             | 5564836             |
Table of MTTF

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Distribution Overview Plot: Hour/Year

Using frequencies in Accidents per year

Goodness-of-Fit

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Anderson-Darling Correlation</th>
<th>(adj) Coefficient</th>
</tr>
</thead>
<tbody>
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<td>Weibull</td>
<td>47.017</td>
<td>0.970</td>
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</tbody>
</table>
### Reliability Distribution Analysis of Tip-Over Accidents

#### Distribution ID Plot: Hour/Year

Using frequencies in Tip-Over Accidents

#### Goodness-of-Fit

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Anderson-Darling (adj)</th>
<th>Correlation Coefficient</th>
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**Distribution Overview Plot: Hour/Year**

Using frequencies in Tip Over Accidents

**Goodness-of-Fit**

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Reliability Distribution Analysis of Off the Dock Accidents

Distribution ID Plot: Hour/Year

Using frequencies in Off the dock accidents

Goodness-of-Fit

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**Distribution Overview Plot: Hour/Year**

Using frequencies in Off the dock accidents

**Goodness-of-Fit**

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Reliability Distribution Analysis of Forks Trailing Collisions

Distribution ID Plot: Hour/Year

Using frequencies in Forks Trailing Collisions

Goodness-of-Fit

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### Distribution Overview Plot: Hour/Year

Using frequencies in Forks Trailing Collisions

#### Goodness-of-Fit

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Reliability Distribution Analysis of Forks Trailing Collisions with Left Leg Injuries

Distribution ID Plot: Hour/Year

Using frequencies in Forks Trailing Collisions with left leg injuries

Goodness-of-Fit

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Distribution Overview Plot: Hour/Year

Using frequencies in Forks Trailing Collisions with left leg injuries

Goodness-of-Fit

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APPENDIX B

STANDUP FORKLIFT TRUCK PICTURES

Figure B.1: Side-stance stand-up forklift truck
Figure B.2: Hit by racks
Figure B.3: Hits on step
# APPENDIX C

## STANDUP FORKLIFT TRUCKS DATA

Table C.1.a: Standup electric forklifts prior to 2002

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Source: Lambert Coffin

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### Table C.1.b: Standup electric forklifts prior to 2002

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Source: Lambert Coffin

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60
Table C.2.a: Latest standup forklifts

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REFERENCES

1. Peder A. Anderson “Industry & Trade Summary: Forklift Trucks and Related Vehicles” USITC Publication 2954, April 1996.


18. MINITAB Help Documentation.
VITA

Date and Place of Birth

- January 16th, 1980 at Hyderabad, India

Education

- Bachelor of Engineering from Vasavi College of Engineering affiliated to Osmania University, India (2002)

Work Experience

- Teaching Assistant at University of Kentucky, Department of Mechanical Engineering (October 2002 – May 2003)

Activities

- Student member, American Society of Mechanical Engineers (ASME)
- Member, Child Relief and Youth (CRY)