

Static Analysis of a Forklift

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Abstract

Forklifts are versatile machines used in most material handling applications. They are often seen used for moving raw materials from transport vehicles onto the factory floor, repositioning objects inside the factory, or placing finished products back onto transport vehicles to be shipped to customers. There are various forklift models commercially available on the market; however, this static tipping analysis was conducted on one specific model of forklift machine, namely the *Hyster Model H50*. Depending on work space availability (warehouse or in the street), larger and heavier forklifts are less likely to tip while lifting up or lowering down in materials handlings. Static forces on the tires of forklift machine when the forklift was unloaded as well as when standard loads were being lifted, have been determined. Furthermore, the maximum load that could be lifted before tipping was determined for several configurations depending on the forks positioning. Note that only the tipping force and the normal forces created by the forklift and the load it carried were analyzed using the basic governing equations of static equilibrium. It was found that the tipping point of the forklift was reached when the back two tires of the machine started to leave the ground, i.e. when there were no other static forces keeping them affixed to the surface. This resulted in two types of calculations. First, the maximum weight that could be lifted in the air by the forks before the unit tipped was found. Second, a fixed load was added and the normal force on each pair of tires was found. Backward, vertical, and forward mast angles were used for analysis. It was found that forks tilted backwards could lift more weight and provide better static stability. In addition, an increase in size to the boxes, but not the weight, caused a faster tipping point because the center of gravity of the box was farther away from the front two wheels.

This work was completed as a semester project to fulfill partial course requirement for *MAE 241 Statics*.

Introduction

Forklifts are the machines of choice in most material handling applications. Forklifts are used in most industries because they can quickly transport just about anything from bags of sand, breakfast cereal to heavier loads like machine parts and construction materials. Often forklifts are used to

move raw material from transport vehicles onto the factory floor, reposition objects inside the factory, or place finished products back onto transport vehicles to be shipped to customers. There are many different styles and models of forklifts on the market today. However, this report will focus only on one specific model, namely the Hyster H50 (See **Figures 1 through 8** and the specific model in operation is shown in **Figure 10**). An online presentation compiled by *Bruce Mayer, a professional engineer and statics instructor*, was used as the basis of our analysis³. *Hyster, the manufacturer of the popular H50 forklift*, published a technical operating manual that was used to gather data about the dimensions and mass of the lift⁵. Furthermore, the standard weight of an operator was taken into consideration. According to the United States Coast Guard, the average weight of an American person is 185 pounds¹. Using this information, a scenario was created and the forklift was analyzed in six different configurations as explained further below.

Problem Statement

Two types of boxes needed to be moved from a transport vehicle onto the top shelf of a warehouse rack. Some of the boxes are 42 in. × 42 in. × 42 in. (all dimensions are in inches) while others are longer at 84 in. × 42 in. × 42 in. (all dimensions are in inches). Assume that the forklift operator will lift the boxes from their width, meaning they will always be lifted from a side that is 42 in. × 42 in. (all dimensions are in inches). The mast, which is the portion of the forklift that extends to lift the load⁴, will need to be raised to its maximum height of 170 in. and may need to tilt forward or backward by five degrees (**Figures 1 through 8**). These two configurations as well as a configuration with no tilt will need to be analyzed for both types of boxes. First, determine the normal force for axle A and axle B if the forklift is in static equilibrium for all six configurations as well as when the forks do not bear any load. Assume that all boxes weigh 5,000 lbf (in pounds). Finally, find the true maximum load the forklift can handle for each of the six configurations. **Figures 1 through 8** show each configuration and include dimensions. The mass at the forklift’s center of gravity (CG) was then taken 7,903 lb. This also includes the weight of an operator.

Procedure/Plan

The equations of equilibrium were used to solve for each scenario. The three equations (See **Equations 1 to 3**) of equilibrium in two dimensional plane, obtained from Hibbeler’s textbook on Statics and Dynamics⁴, are shown below.

$$\Sigma F_x = 0 \dots\dots\dots(1)$$

$$\Sigma F_y = 0 \dots\dots\dots(2)$$

$$\Sigma M_A = 0 \dots\dots\dots(3)$$

Where, ΣF_x is the summation of all the forces in the x direction (i.e., horizontal). ΣF_y is the summation of all the forces in the y direction (i.e., vertical). ΣM_A is the summation of all the moments about any point A. Note that only the tipping force and the normal forces created by the

forklift and the load it carried were analyzed. When there were no significant forces in the x direction, the horizontal force equation $\Sigma F_x = 0$ was applied. **Figure 9** of the appendix shows a flowchart outlining how these equations were used as well as the procedure used to compile this report. Trigonometry was used to calculate the horizontal distance from N_A to the center of gravity of the load for configurations that involved a tilted mast.

Results and Discussion

The table below shows the results that were obtained. The figure numbers refer to the AutoCAD drawings in the appendix of this report. The table shows that the most stable load is the small box tilted back. The least stable load is the large rectangular load tilted forward. This makes sense intuitively because the center of gravity of the forklift is closest to the fulcrum (N_A) in the configuration depicted in **Figure 3** and is the furthest away in the configuration depicted in **Figure 8**. It is somewhat surprising that the longer, rectangular load tilted back is more stable than the smaller, square load tilted forward. However, upon further consideration, this also makes sense intuitively since the center of gravity of the longer, rectangular load tilted back is closer to the fulcrum (N_A) than the smaller, square load tilted forward.

Table 1: Equilibrium Analysis of a forklift							
Figures	Load Dimensions (L x W x H) (in.)	Mast Angle (deg.)	Carriage Height (in.)	Weight of Load (lbf)	N_A (lbf)	N_B (lbf)	Maximum Load (lbf)
1 & 2	No Load	0.0	NA	NA	2,493.5	5,409.5	NA
3	42 x 42 x 42	5.0 (Back)	170.0	5,000.0	9,183.2	3,719.8	16,007.6
4	42 x 42 x 42	0.0	NA	5,000.0	10,622.8	2,280.2	8,643.2
5	84 x 42 x 42	5.0 (Back)	170.0	5,000.0	10,678.0	2,225.0	7,746.9
6	42 x 42 x 42	-5.0 (Forward)	170.0	5,000.0	12,053.9	849.1	5,931.0
7*	84 x 42 x 42	0.0	NA	5,000.0	12,433.2	469.8	5,475.6
8	84 x 42 x 42	-5.0 (Forward)	170.0	5,000.0	TIPPED	TIPPED	4,251.3

*See **Figure 11** for sample calculations.

Appropriate assumptions were made while calculating the data in **Table 1**. The forklift has several irregular components that make difficult, in some cases, to calculate the precise center of gravity. The center of gravity of each component would need to be calculated, and many of them are irregular as well. Therefore, it was assumed that the center of gravity was located 55 in. from the base of the carriage. This is slightly closer to the back of the forklift than it is to the front. This

seems logical since the designers placed heavier components at the back of the forklift. In addition, it was assumed that the forks are weightless. When compared to the weight of the forklift and the load the weight of the forks themselves are not very significant. It was assumed that the forklift is on a perfectly level surface. In addition, the small excess width created by the fixture for the carriage was not taken into consideration. Furthermore, it was assumed that the forklift is perfectly perpendicular to the warehouse shelf that it is placing the load on and the load is centered on the forks. It is also assumed that the load does not slip off the forks. It was assumed that the forklift would lift the rectangular load by placing the forks under its width. If the forks were placed under its length, the load would be less likely to cause the forklift to tip forward, but more likely to slip off or cause the forklift to tip to the side. This scenario is beyond the scope of this report.

While the analysis of all six scenarios may seem superfluous, they are all valid scenarios. When **Figure 11** is examined in detail one can see that the warehouse shelving is not leveled. It is also noticeable that the operator in the figure has tilted the mast back while moving the load into position. One can assume that the operator is about to tilt the mast forward and sit the load onto the shelf. Therefore, this figure is an example of at least three of the scenarios that were analyzed. Forklifts are a readily available piece of equipment and are often used to handle objects that extend past the end of the forks. Even if the center of gravity were over the edge of the forks, the friction created by the forks in the slit in the pallet would likely be enough to hold the load in place. This is a dangerous situation because, as one can see from the table and the corresponding figures, the longer load moves the center of gravity away from the fulcrum and causes more moment. This can significantly lower the maximum load the forklift can lift. As visible in the data based on **Figure 5**, it is possible for an operator to be able to lift a long rectangular load that is above the published maximum weight of the forklift (5,000 lbf) by tilting the mast back, however when it is raised and tilted forward to place onto a shelf it would tip. This is a highly dangerous scenario and one that all forklift operators should be aware of.

Several concepts about the statics and the reason behind the design of forklifts have been uncovered. First, the heavier the forklift is and the further away the center of gravity is from the fulcrum (N_A) the heavier the load (L) can be before the forklift tips. In addition, when the load is lifted while the mast is tilted forward it moves the center of gravity away from the fulcrum (N_A) and increases the likelihood of it tipping. When the load is lifted vertically, the moment is not altered, therefore from a statics perspective the forklift is not any more or less likely to tip when it is raised very high or when it is barely off the ground. This is why the carriage height is not applicable for static analyses when there is no tilt. Finally, when the mast is tilted back and the load is raised it moves the center of gravity closer to the fulcrum and makes the load less likely to tip.

Conclusion

Depending on space availability in a particular warehouse, larger and heavier forklifts are less likely to tip when used to lift items. An increase in the angle that the forks could tilt back would allow heavier items to be handled by moving the center of gravity between axle A and axle B. In addition, a heavier weight overall for the body of the forklift would help to counteract the weight that was being lifted. If space were an issue in certain warehouses, a feasible solution to allow larger load lifting would be to add more counterweight to the rear of the forklift. This would increase the overall weight and alter the center of gravity of the forklift, but it may also put more stress on the mast or other parts of the forklift. Future work could potentially include analyzing the forklift in three dimensions and taking into consideration loads that may not be balanced along its width. Materials properties such as tensile and compressive strength of the components of the forklift should be analyzed. A factor of safety of 2.0 or more is considered for best practice and the maximum load that the forklift components can handle while maintaining this factor of safety should be determined. The dynamic equilibrium could also be analyzed, as forklifts often are accelerating and decelerating, as well as traveling over uneven and rough surfaces.

Bibliography

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Appendix

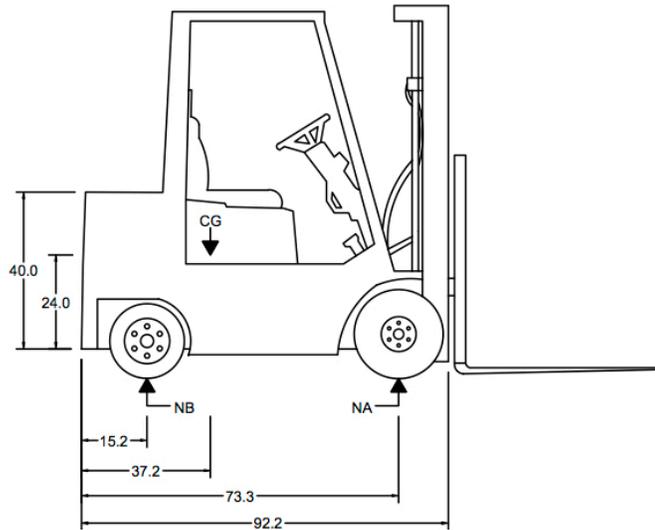


Figure 1 Forklift Mast contracted (No tilt, no load)

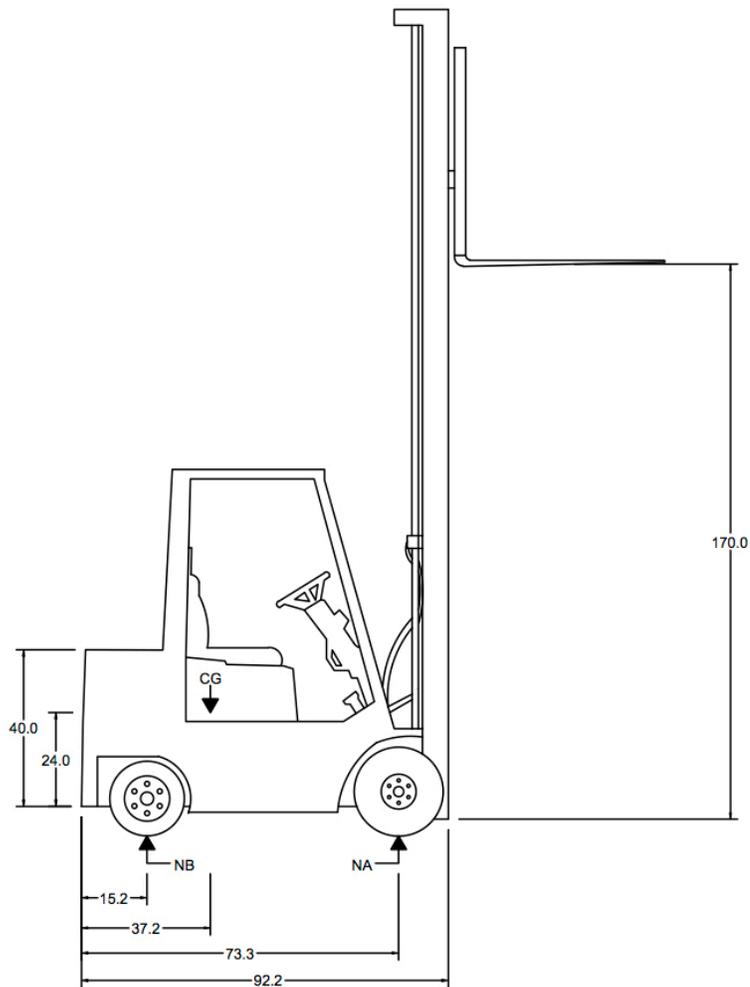


Figure 2 Forklift Mast extended (No tilt, no load)

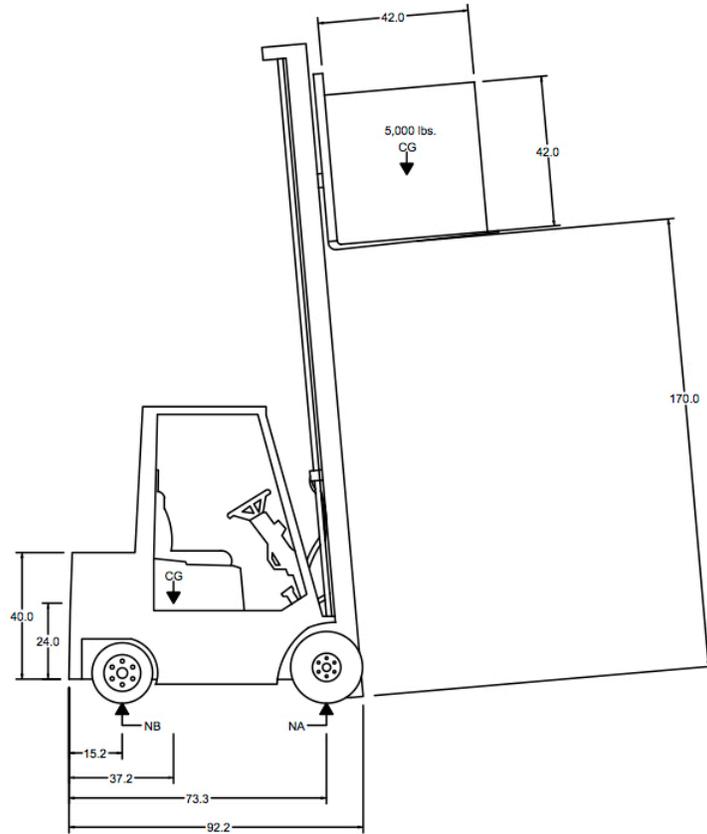


Figure 3 Forklift Mast extended (Tilted 5° back, small square shaped load)

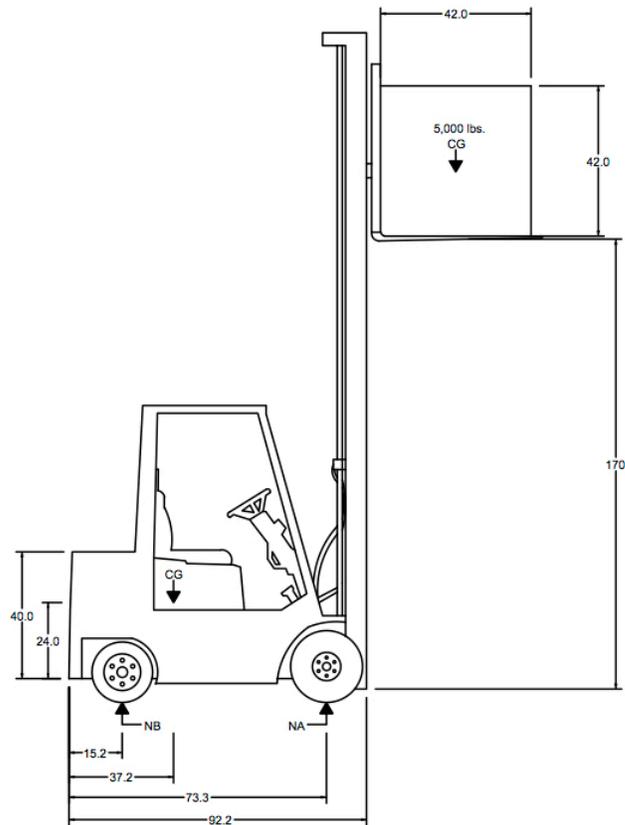


Figure 4 Forklift Mast extended (No tilt, small square shaped load)

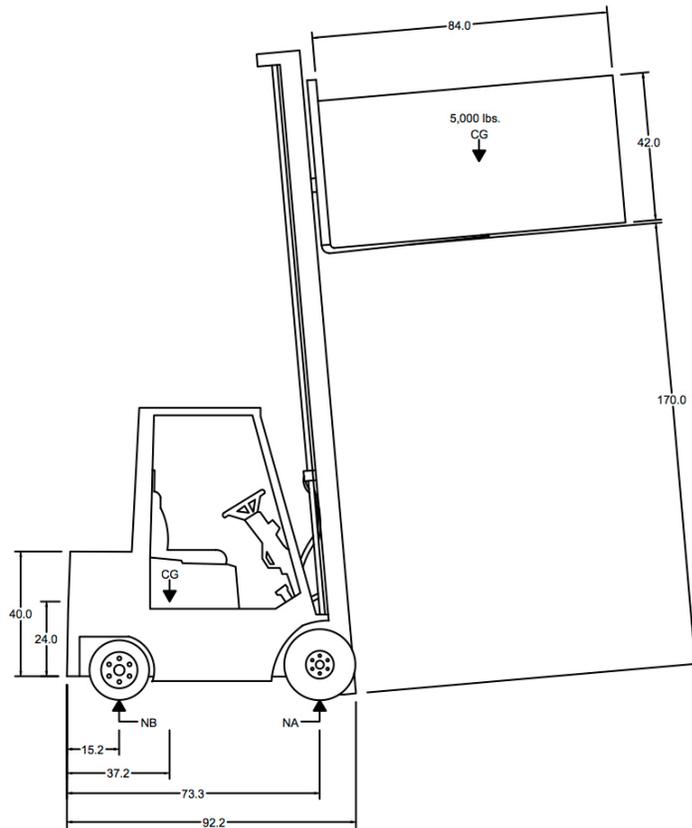


Figure 5 Forklift Mast extended (Tilted 5° back, large rectangular shaped load)

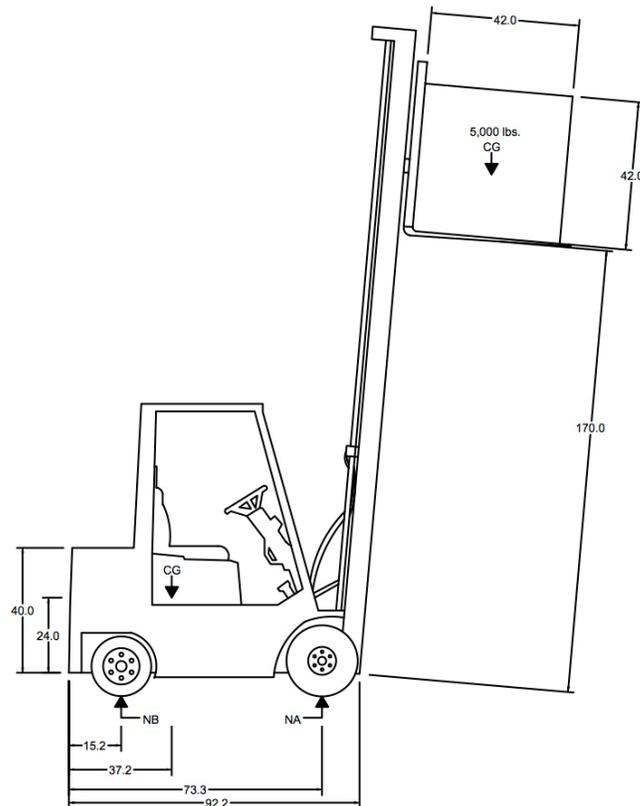


Figure 6 Forklift Mast extended (Tilted 5° forward, small square shaped load)

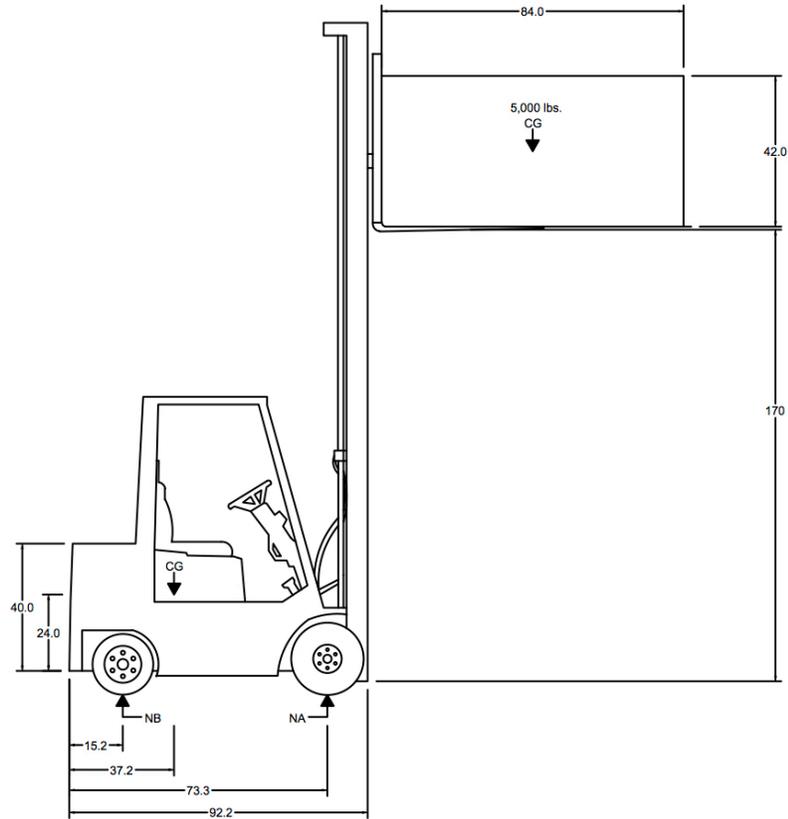


Figure 7 Forklift Mast extended (No tilt, large rectangular load)

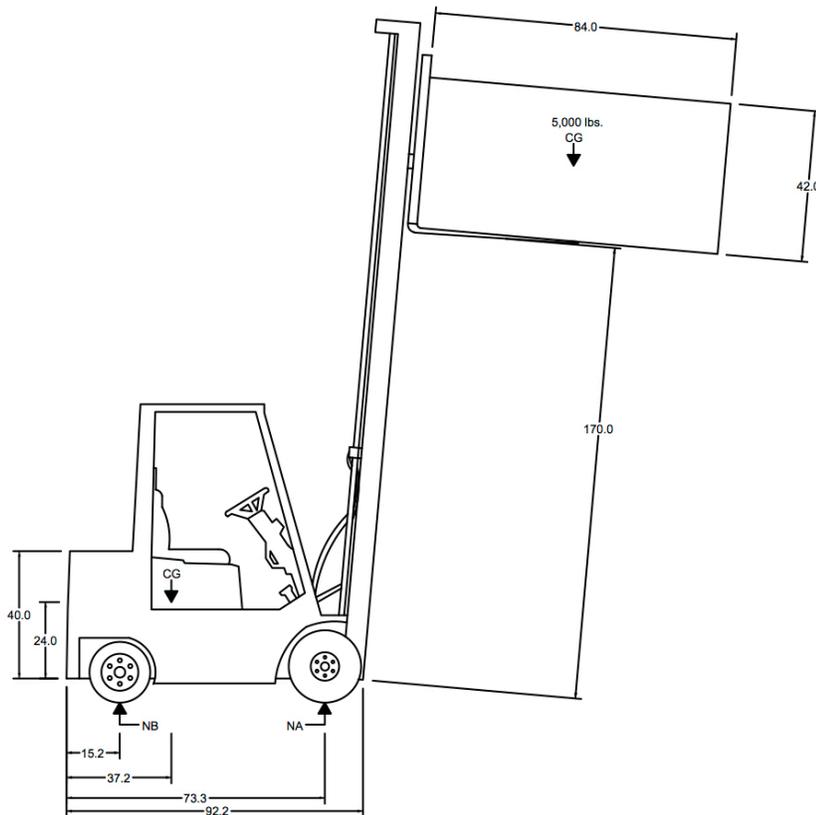


Figure 8 Forklift Mast extended (Tilted 5° forward, large rectangular load)

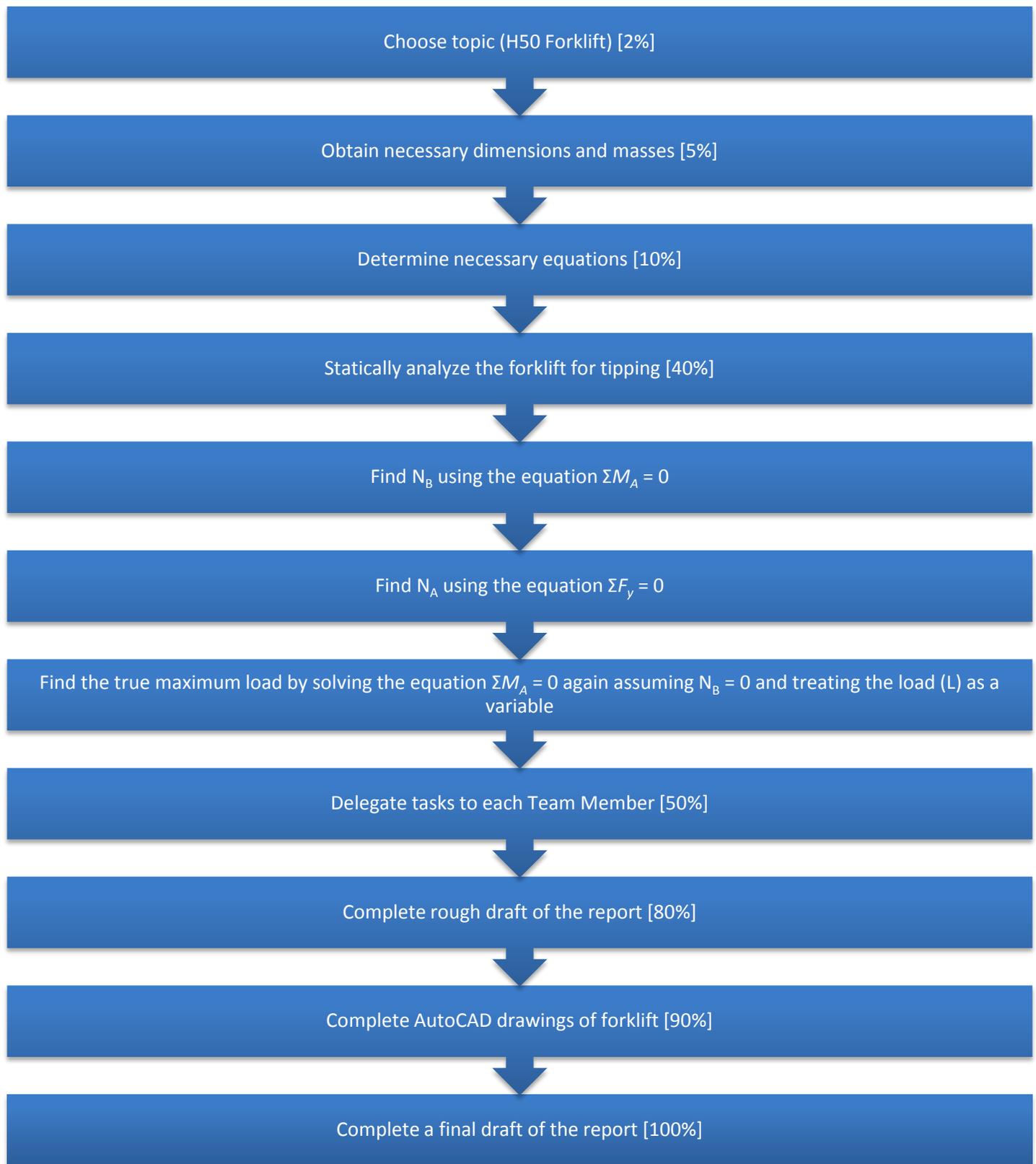


Figure 9 Flowchart of semester project work



Figure 10 Hyster forklift in operation similar to **Figure 5** Tilted 5° back with large rectangular shaped load

The mass of the forklift is 7903 lb

See Fig. 7 for all other dimensions and masses

Solve for the normal force on the rear wheels (N_B) by applying the moment equation about point A.

$$\oplus \sum M_A = 0$$

$$N_B(58) + (5,000)(57.3) - (7,903)(39.7) = 0$$

$$N_B(58) - 27,249.1 = 0$$

$$N_B(58) = 27,249.1$$

$$N_B = 469.8 \text{ lb}$$

Solve for the normal force on the front wheels (N_A) by summing forces in the y direction.

$$\uparrow + \sum F_y = 0$$

$$N_A - 5,000 - 7,903 + 469.8 = 0$$

$$N_A - 12,433.2 = 0$$

$$N_A = 12,433.2 \text{ lb}$$

Solve for the maximum load (L) by re-applying the moment equation about point A while assuming that tipping occurs when there are no normal forces on the rear wheels (N_B).

$$\oplus \sum M_A = 0$$

$$(0)(58) + (L)(57.3) - (7,903)(39.7) = 0$$

$$(L)(57.3) = 31,374.1$$

$$L = 5,475.6 \text{ lb}$$

Figure 11 Sample calculations for Forklift Mast extended (No tilt, large rectangular load)