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Industrial Electrical Engineering and Automation

Algorithm for Anti-Tip Over Function

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Master Thesis
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Abstract

The main focus of this thesis is to present an algorithm that, given a certain set of measured factors, keeps the electric forklift truck ECG160-12, developed by Cargotec, stable at all times. The forklift truck has a lifting capacity of 16 tons and a lift height of 5 m. In order to design the anti-tip over function, the dynamics of the forklift truck was evaluated. By dividing the forklift truck into separate centers of gravity (CoG) and setting up a coordinate system, equations that calculates a tipping threshold could be computed. The sensor measurements that are needed as input to produce the desired output is presented and a sensor evaluation of the sensors that is already implemented on the forklift truck has been carried out. Given that the anti-tip over function is a safety feature, the components of a safety evaluation has been studied. Lastly, a proposition of how the anti-tip over function could be implemented is presented.

Acknowledgements

I would like to thank my supervisor Hampus Lavin for all the help and support I received during this master thesis. He has always been there for discussions and feedback and has done his utmost to answer my questions in the best way possible. I would also like to thank my colleagues at Cargotec that in any way have had a part of this master thesis for taking their time to help. Lastly, I extend an extra thanks to my academic supervisor Gunnar Lindstedt for always being available for meetings and discussions.

Abbreviations

PLC	Programmable logic controller
CoG	Center of gravity
DOF	Degrees of freedom
HIL *simulator*	Hardware-in-the-loop simulator
$MTTF_D$	Mean time to dangerous failure
DC	Diagnostic coverage
PFH_D	Probability of dangerous failure per hour
PL	Performance level

Contents

1 Introduction

1.1 Background

As the world becomes more intelligent, the customer expectations on machines developed by companies to become smarter also increase. As an effect of this, driver assistance functions are becoming more common across many different vehicle types in all industries. These functions not only enhances the driving experience but also the safety for people in the environment in which the machine is running. In Sweden, forklift truck accidents make up the largest category of work accident reports, almost eight hundred injuries associated with trucks occur every year [2]. One of the main reasons of the accidents is the driver losing control of the truck while driving.

1.2 Company description of Cargotec

Cargotec is a leading provider of cargo and load handling solutions. The company operates in more than 100 countries and has employees working in 43 of them. In the end of 2018, Cargotec had around 12000 employees [3]. This master thesis was conducted at Kalmar in Ljungy. Kalmar is a part of Cargotec and provides cargo handling solutions and services to ports, terminals, distribution centres and heavy industry. One in four container moves around the world is being handled by a Kalmar solution. At the end of 2018, Kalmar had more than 5700 employees in 30 countries [4].

Figure 1: Cargotec electric forklift truck

1.3 Problem statement

Because of its elevated centre of gravity while lifting, forklift trucks run the risk of tipping over. One way to counteract the tipping risk is to make the forklift heavier or/and bigger, but from a marketing view this solution is not profitable. A more advantageous solution is to add functions in the programmable software of the truck. With help from different types of sensors, the magnitude of different parameters can be identified and with these parameters, programmable limitations can be calculated. That leads to the question; how should the function be designed and implemented? The problems that this project will focus on are the following:

- How should the anti-tip over function be designed?
- Which sensors are needed to implement the function?

1.4 Purpose

The main purpose of designing an anti-tip over function is to improve the safety of employees working in the environment in which the trucks are running. As Cargotec's future vision is to develop autonomous cargo handling machines, features as the anti-tip over function reduces the gap of development to the final product. Additionally, the anti-tip over functions enhances the driving experience and is a feature that can be used to promote the product to customers.

1.5 Goal

The goal of this master thesis is to develop an anti-tip over function for Cargotec's forklift trucks. To achieve a complete solution the following tasks have to be executed:

- Find an algorithm for the anti-tip over function
- Present the supporting calculations
- Identify sensors needed to implement the anti-tip over function
- Do a preliminary safety evaluation to ensure system robustness

1.6 Disposition of the report

- **Chapter 2 - Theory**
  In the theory section, all parameters and equations that are used in the project are presented. The dynamics of the truck are described and the ISO standards that are relevant to the anti-tip over function are introduced. Lastly, the tools for doing a safety analysis are described.
- **Chapter 3 - Implementation**
  The implementation of the anti-tip over function is presented. The section presents all the equations and supporting calculations. It also covers the limitations of the project as well as sensor evaluations.
- **Chapter 4 - Results and discussion**
  In chapter 4, the results are presented mostly as graphs with supporting discussion texts. The dilemmas of the problem are also presented.
- **Chapter 5 - Conclusion**
  The last chapter of the report illustrates the conclusions of the project. An implementation proposition of the anti-tip over function is also presented.

2 Theory

This project is carried out on Cargotec's electric forklift truck ECG160-12 [1] with a maximal lift height of 5 m and a lifting capacity of 16 tons at the load center, 1.2 m from the base of the forks. If the anti tip-over function works as desired, it can be implemented on several models of Cargotec's trucks. A machine that is even more prone to tip over is the Empty Container Handler, DCG80-100. The EC truck has a maximal lift height of 21 m and lifting capacity of 10 tons. To develop the anti tip-over function, calculations of forces on the truck will be carried out. The calculations will first be divided into partial centers of gravity, one for each part of the truck. The partial centers of gravity will then be combined into a total center of gravity. Depending on where the summarized center of gravity is positioned, the stability of the forklift truck can be determined.

Change of forces on the forklift:

- Accelerating
- Decelerating (braking)
- Turning
- Loading/unloading forks
- Raising/lowering forks
- Moving forks laterally
- Tilting the mast
- Change of ground inclination

2.1 Assumptions

In order to find an algorithm for the anti-tip over function the following assumptions were made:

- Maximal friction between tires and ground
- Tire pressure neglected
- Driver weight neglected
- No impact from wind
- A maximal of 3.5% ground inclination in the forward direction and 6% lateral ground inclination in the sideways direction.

2.2 Tip over causes

The main directions that the forklift truck can tip over is either forward or sideways. Since the velocity limit is calculated with maximal deceleration, the tires can be assumed to be almost locked in place, so the forward tip over is located along the intersection of where the two front wheels meet the ground. The axes for the sideways tip over are located along the intersection of the outer left front- and back wheel and the intersection of the outer right front- and back wheel. Another factor to take into count is that the chassis is connected to the tire axes in the form of a triangle, two connections in over the front wheels and one connection over the back wheels. In order for the forklift truck to remain stable, the force from breaking or the centripetal force from turning must not exceed the gravitational force of the truck. The most thinkable causes of tipping over are:

- Braking hard ⟶ forklift truck tips forward
- Making a strong turn ⟶ forklift truck tips sideways

In each case the risk of tipping increase with increasing load elevation, load weight, steering angle and velocity.

2.3 Special cases with risk of tipping over

There are several special cases in which the forklift truck is at risk of tipping over. These cases are not taken into account because of their complexity and/or low chance of occurring.

- Lowering the carriage fast and making an abrupt stop with a heavy load ⟶ forklift truck tips forward
- High acceleration in reverse while carrying an elevated, heavy load ⟶ forklift truck tips forward

2.4 Force equations [11]

2.4.1 Newton's first law

If the vector sum of all forces on an object is zero, the velocity of the object is constant.

$$\sum F = 0 \Longleftrightarrow \frac{dv}{dt} = a = 0 \tag{1}$$

2.4.2 Newton's second law

The rate of change of momentum of a body is directly proportional to the force applied and the change of momentum takes place in the same direction as the force applied.

$$F = \frac{d(m \cdot v)}{dt} = m \cdot a \qquad [Nm] \tag{2}$$

2.4.3 Centripetal force

$$F_c = m\frac{v^2}{r} = m \cdot r \cdot w^2 \qquad [Nm] \tag{3}$$

$$a_c = \frac{v^2}{r} = r \cdot w^2 \qquad [m/s^2] \tag{4}$$

2.4.4 Torque

Torque is the rotational equivalent of linear force.

$$\tau = r \times F = r \cdot F \cdot sin\theta \qquad [Nm] \tag{5}$$

where r is the distance from the axis of rotation to the center of gravity och the object and θ is the angle between the position and force vector.

2.4.5 Center of gravity

The center of gravity (CoG) is the unique point where the weighted relative position of a distributed mass sums to zero. CoG calculations will have a critical part of the calculations needed to design the anti-tip over function. To simplify the problem, the truck, the mast, carriage, forks and the load will each have their own CoG. Combining these will then result in a summarized CoG.

2.5 Dynamics

The calculations will be carried out with the axis directions illustrated in figure 2. The origin is placed on ground level between the front wheels.

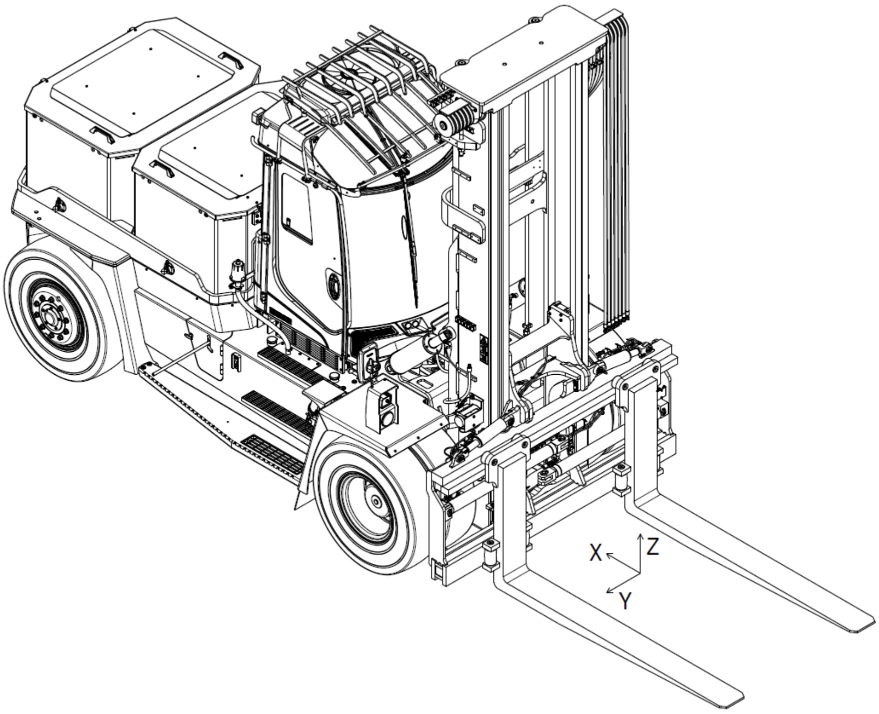

Figure 2: Placement of coordinate system

The truck is divided into five parts with different CoG; the truck, the mast, the carriage, the forks and the load, see figure 3. The CoG for the load is not possible to determine without knowing the dimensions of the load and how the load is packed. In the calculations, the CoG of the load is therefore placed at the load center (1.2 m from fork base) with a height 1 m above the CoG of the forks.

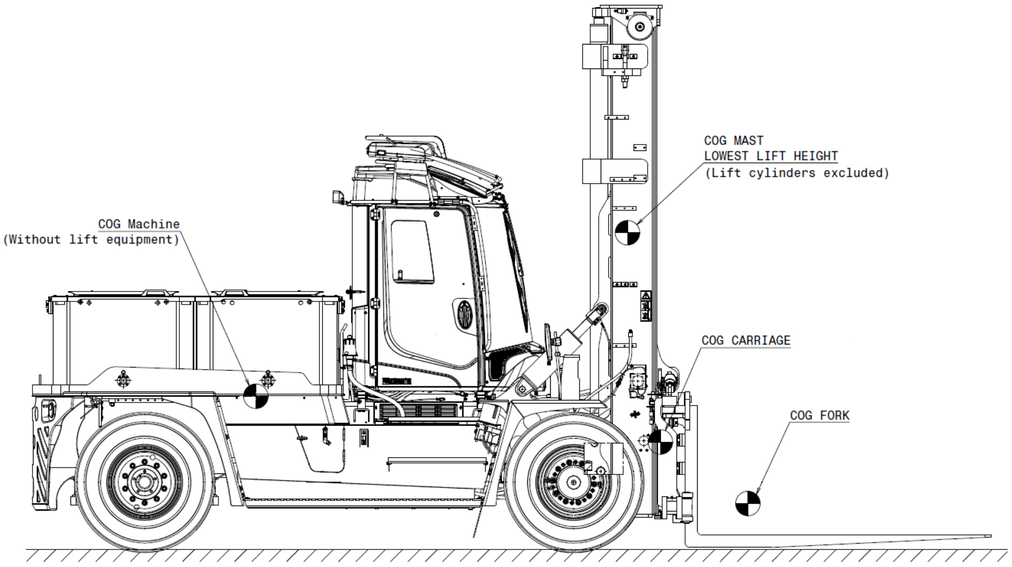

Figure 3: Placements of CoGs

Cargotec's electric forklift trucks are customized by customer's choice. The customer can choose between different batteries, a range of different masts, lifting capacity and attachments. Depending on the customer's choice of design, the dynamics of the forklift truck will differ. In the calculations, the different weights and dimensions for the actual setup must be specified in order to achieve a well working anti tip-over function. Therefore, it is important that the Matlab code is modular and easy to configure for different setups.

2.5.1 Truck dynamics

The forklift truck's chassis has three connections to the wheel axes, one on the back and two on the front. On the back wheel axis, the connection is placed in at the center of the axis and on the front wheel the frontal connections are places above the left- and right wheel. This placement of connections will reduce the magnitude of shaking when driving over uneven ground but will ultimately decrease the sideways stability of the truck. The three connections form a stability triangle that is used when calculating the sideways stability, see figure 4.

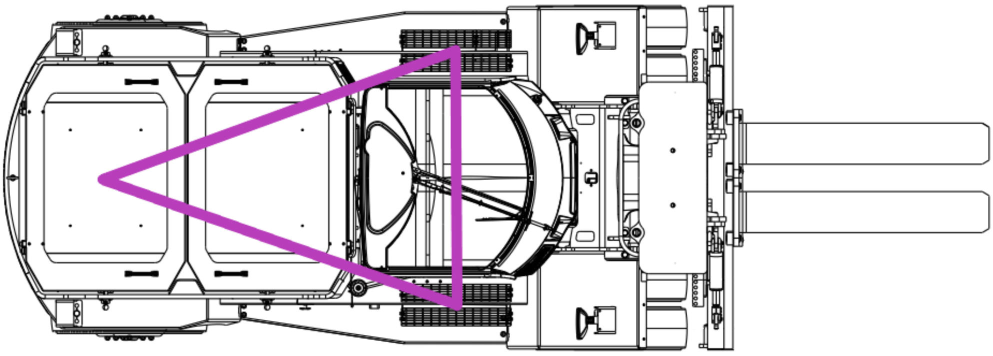

Figure 4: Stability triangle

2.5.2 Mast dynamics

The forklift trucks can be customized with different masts. The mast can tilt 14° forwards and 9° backwards. To calculate the change of CoG due to mast tilting, a separate coordinate system which has its origin in the mast's point of rotation is used. The new coordinates for a rotation of α is given by calculating the rotational matrix

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{6}$$

2.5.3 Fork dynamics

The carriage has two degrees of freedom (DOF). The carriage can move vertically and the forks can move laterally in either a simultaneous or separately motion. If the forks are not placed on each side with the same distance from the center, a lateral move will result in a change of CoG.

2.5.4 Steering dynamics

The forklift has Ackermann steering which means that all wheels have their axis arranged as radii of circles with a common centre point, i.e. the turning wheels have different angles while turning, see figure 5. The inner wheel has a maximal turning angle of 75,5° and the outer wheel 54,2°. The use of Ackermann steering helps avoiding the tires to slip sideways when following a path around a curve.

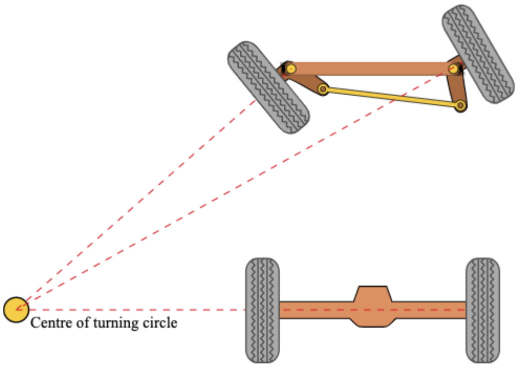

Figure 5: Ackermann steering [5]

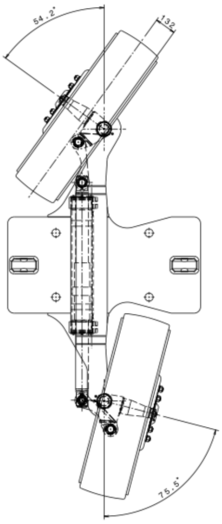

Figure 6: Wheel angles

2.6 Tire compression

Depending on the tire pressure, dimension of the tires and the characteristics of the tire material, the tires will be more or less compressed with the change of load, altering it's effective radius. The compression results in a lateral change of the rolling axes of the truck, which in it's turn has an affect on the stability. Like putting down a balloon filled with water on the ground, the tires will compress towards its sides and the different CoGs of the truck will be displaced from their initial positions. An experiment was carried out, measuring the vertical offset due to tire compression at maximal load mass. The offset of 2,2 cm had a negligible impact on the CoGs, therefore the tire compression is not taken into count in the anti tip-over calculations.

2.7 ISO Standards

Standards are a way of facilitating cooperation between companies by developing common solutions to recurring problems. The International Organization of Standardization provides over 20000 standards and has 164 member countries. Apart from promoting the companies, the standards also ensure the end-user that the certified products hold a certain level of quality.

2.7.1 Standard SS-ISO 22915-2:2018

Standard SS-ISO 22915-2:2018 [6] verifies the stability of the forklift truck. For this standard to be fulfilled, the forklift truck has to remain stable in different ground inclinations and scenarios.

2.7.2 Standard SS-ISO 6292:2008

Standard SS-ISO 6292:2008 [7] covers the breaking distance s_0 at different velocities v that the truck has to fulfill. The braking distance calculations for different velocity intervals can be seen in table 1.

v [km/h]	$v \leq 5$	$5 < v \leq 13,4$	$v > 13,4$
s_0 [m]	$s_0 < 0,15 \cdot \text{v} + \frac{v^2}{19,1}$	$s_0 < 0,15 \cdot v + \frac{v}{3,8}$	$s_0 < 0,15 \cdot v + \frac{v^2}{50,9}$

Table 1: Braking standard calculations

2.7.3 Standard SS-EN ISO 13849-1:2016

Standard SS-EN ISO 13849-1:2016 [8] covers general principles of design for machine safety and how the design is validated. A more thorough description is presented in the safety evaluation in chapter 3.

2.8 Safety evaluation

For the anti-tip over function to be implemented, a safety evaluation must be done. When a safety evaluation is carried out, a performance level of the function is achieved. Depending on which performance level is desired, certain requirements needs to be satisfied. If the anti tip-over function is going to perform controlling actions, the performance level needs to be higher than if the anti tip-over function only would work as a warning system.

2.8.1 Mean Time To dangerous Failure - $MTTF_D$

All the components have a $MTTF_D$ value which measures the mean time to dangerous failure. This value is given by the manufacturer of the component and is measured in years.

Denotation of each channel	Mean time to dangerous failure $MTTF_D$
Low	$3\ years \leq MTTF_D < 10\ years$
Medium	$10\ years \leq MTTF_D < 30\ years$
High	$33\ years \leq MTTF_D < 100\ years$

Table 2: MTTF Categories

2.8.2 Diagnostic Coverage - DC

The Diagnostic Coverage is a measure of detectable faults. The DC is divided into four different categories; none, low, medium and high. The categories has different ranges, see table 3. The DC can be used for either single components and subsystems.

$$DC = \frac{The\ failure\ rate\ of\ detected\ dangerous\ failures}{The\ failure\ rate\ of\ total\ dangerous\ failures}$$

Denotion	Range
None	DC $<$ 60%
Low	60% $\leq$ DC $<$ 90%
Medium	90% $\leq$ DC $<$ 99%
High	99% $\leq$ DC

Table 3: DC Categories

The average Diagnostic Coverage for a system, DC_{avg}, is calculated through

$$DC_{avg} = \frac{\frac{DC_1}{MTTF_{D1}} + \frac{DC_2}{MTTF_{D2}} + ... + \frac{DC_N}{MTTF_{DN}}}{\frac{1}{MTTF_{D1}} + \frac{1}{MTTF_{D2}} + ... + \frac{1}{MTTF_{DN}}}$$

2.8.3 Probability of dangerous Failure per Hour - PFH_D

The PFH_D is the average probability of dangerous failure taking place during one hour for a system, subsystem or component. As the value of $MTTF_D$, the value of PFH_D is usually provided by the manufacturer. The total PFH_D for the system is calculated through

$$PFH_D = PFH_{D1} + PFH_{D2} + ... + PFH_{DN}$$

2.8.4 Architectures

There are five different categories of architecture; B, 1, 2, 3 and 4, see table 4. Each category has requirements on the DC, $MTTF_D$ and system behaviour. Depending on the components that are used and the design of the system, it will fit into a certain category.

Category	System behaviour	$MTTF_D$	DC_{avg}
B	The occurrence of a fault can lead to the loss of the safety function.	Low to medium	None
1	The occurrence of a fault can lead to the loss of the safety function but the probability of occurrence is lower than for category B.	High	None
2	The occurrence of a fault can lead to the loss of the safety function between the checks. The loss of safety function is detected by the check.	Low to high	Low to medium
3	When a single fault occurs, the safety function is always performed. Some, but not all, faults will be detected. Accumulation of undetected faults can lead to the loss of the safety function.	Low to high	Low to medium
4	When a single fault occurs the safety function is always performed. Detection of accumulated faults reduces the probability of the loss of the safety function (high DC). The faults will be detected in time to prevent the loss of the safety function.	High	High

Table 4: Architectures

2.8.5 PL - Performance level

Through the values attained from the different parts of the safety analysis, a performance level is achieved. The performance level specifies the ability of the safety related parts of the control system to perform a safety function under foreseeable conditions. There are five different performance levels; a, b, c, d and e.

PL	PFH_D	Architecture category
a	$\geq 10^{-5} < 10^{-4}$	B, 2, 3
b	$\geq 3 \cdot 10^{-6} < 10^{-5}$	B, 1, 2, 3
c	$\geq 10^{-6} < 3 \cdot 10^{-6}$	1, 2, 3
d	$\geq 10^{-7} < 10^{-6}$	2, 3
e	$\geq 10^{-8} < 10^{-7}$	3, 4

Table 5: Performance levels

3 Implementation

3.1 Design

The anti-tip over function could be designed in various ways i.g limiting the velocity, limiting the steering angle or moving weights that change the CoG of the forklift. The latter would not only have to be implemented in the programmable software of the forklift truck but would also result in big changes of the forklift's physical design, which isn't an option for this master thesis project. Because of the forklift trucks run in an environment where there also are people present, neither limiting the steering angle is an option. To ensure safety for other people, the driver must always have the option to swerve. Therefore, the design of the anti-tip over function will operate in the following hierarchy:

1. Velocity limit calculated on the current load weight and load height.
2. Additional velocity limit calculated on the current steering angle.

The thresholds are calculated from the equilibrium or forces around the tipping axes. In practice, this means that the threshold for each case is when the summarized CoG is above the tipping axis. Exceeding the threshold doesn't necessarily mean that the truck will tip over. In the forward tipping case, releasing the brake right after the tipping motion has started, i.e the threshold just has been exceeded, will stabilize the truck. Likewise, in the sideways tipping case, steering the truck in the tipping direction when the tipping motion has started will stabilize the truck even though the threshold has been exceeded.

3.2 Calculations

3.2.1 Tipping forward

To maintain stability in forward direction while standing still, the summarized CoG of the forklift truck must be behind the axis of frontal rotation i.e. behind the axis of the front wheels. To maintain stability while the truck is moving and a brake is performed, the torque force generated cannot exceed the truck's potential energy. The following equation therefore needs to be fulfilled:

$$m_t \cdot a \cdot d_{tz} + m_m(a \cdot d_{mz} + g \cdot d_{mx}) + m_c(a \cdot d_{cz} + g \cdot d_{cx}) + m_f(a \cdot d_{fz} + g \cdot d_{fx}) + m_l(a \cdot d_{lz} + g \cdot d_{lx}) \leq m_t \cdot g \cdot d_{tx}$$

$$\iff a \leq \frac{g \cdot ((m_t \cdot d_{tx}) + (m_m \cdot d_{mx}) + (m_c \cdot d_{cx}) + (m_f \cdot d_{fx}) + (m_l \cdot d_{lx}))}{(m_t \cdot d_{tz}) + (m_m \cdot d_{mz}) + (m_c \cdot d_{cz}) + (m_f \cdot d_{fz}) + (m_l \cdot d_{lz})} \tag{7}$$

where a represents the deceleration when braking, g is the gravity constant. The other parameters of the equations is for mass m_x and distance d_{xy}. The x in these parameters denotes the different parts of the forklift truck; truck, mast, carriage, forks and load. The y in the distance parameters denotes the direction of the axis in the local coordinate system.

The velocity limit can be determined in different ways. As of today, there is no way of controlling the brake force of the truck other than the driver pushing the brake pedal with varying force. As this is a very unreliable way of controlling the brake force, the anti tip-over function must be designed to maintain stability even if the driver is braking with full force. In an internal technical report, braking tests performed on the truck shows the maximal deceleration of the truck is 3.1 m/s^2. If an external brake controller is implemented, e.g. brake-by-wire, the brake force can be limited to a specific value to guarantee a certain deceleration. The velocity limit can then be calculated from the reduced deceleration, allowing the truck to run at higher velocities.

$$E_k = \frac{1}{2}mv^2 \tag{8}$$

$$a = \frac{E_k}{m}s_0 = \frac{1}{2}v^2 s_0 \Longleftrightarrow v = \sqrt{2as_o} \tag{9}$$

From equation 7 the maximal deceleration is calculated. From table 1 we can calculate the velocity limit. The velocity limit can also be determined graphically by plotting the minimal deceleration for several velocities and finding the intersection between the tipping threshold and velocity, see figure 11.

3.2.2 Tipping sideways

To maintain stability in sideways direction, the total CoG of the forklift truck must be inside the axes of sideways rotation i.e. inside the outer side of the front and back wheel on both sides. Because of the different trackwidth of the front and the back tire pairs The following equation needs to be fulfilled:

$$\frac{v^2}{r}(m_t \cdot d_{tz} + m_m \cdot d_{mz} + m_c \cdot d_{cz} + m_f \cdot d_{fz} + m_l \cdot d_{lz}) \leq g(m_t \cdot d_{ty} + m_m \cdot d_{my} + m_c \cdot d_{cy} + m_f \cdot d_{fy} + m_l \cdot d_{ly})$$

$$\Longleftrightarrow v \leq \sqrt{\frac{r \cdot g(m_t \cdot d_{ty} + m_m \cdot d_{my} + m_c \cdot d_{cy} + m_f \cdot d_{fy} + m_l \cdot d_{ly})}{(m_t \cdot d_{tz} + m_m \cdot d_{mz} + m_c \cdot d_{cz} + m_f \cdot d_{fz} + m_l \cdot d_{lz})}} \tag{10}$$

$$r = \frac{d_{wheelbase}}{\cos(90^\circ - \alpha)} \tag{11}$$

where v is the velocity, r is the inner turning radius and α is the steering angle of the inner wheel. As described in the forward tipping calculations, m_x denotes the masses and d_{xy} denotes the distances.

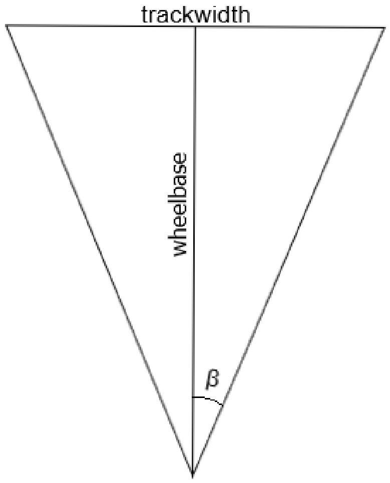

Figure 7: Stability triangle

The angle from the back connection point to the front connection point on the stability triangle seen in figure 7 is $\beta = 17.43°$ from the x axis.

Depending on where the summarized CoG is placed along the x axis, $CoGx$, and along the y axis, $CoGy$, the distance to the stability triangle $d_y tip$ varies.

$$CoGx = \frac{m_t \cdot d_{tx} + m_m \cdot d_{mx} + m_c \cdot d_{cx} + m_f \cdot d_{fx} + m_l \cdot d_{lx}}{m_t + m_m + m_c + m_f + m_l}$$

$$CoGy = \frac{m_t \cdot d_{ty} + m_m \cdot d_{my} + m_c \cdot d_{cy} + m_f \cdot d_{fy} + m_l \cdot d_{ly}}{m_t + m_m + m_c + m_f + m_l}$$

To compensate for an eventual y axis offset if the summarized CoG is not centered laterally, the angle ϕ is calculated through

$$\phi = \tan^{-1} \cdot \frac{CoGy}{(d_{wheelbase} - d_{CoGx})}$$

The distance to the sideways tipping axis is calculated by

$$d_{ytip} = \tan(\beta) \cdot (d_{wheelbase} - CoGx) - \tan(\phi) \cdot (d_{wheelbase} - CoGx)$$

Because of the centripetal force from turning is pointed perpendicular to the x axis, the force perpendicular to the stability triangle tipping axis is $\cos(\beta)$. The velocity limit equation is therefore

$$v \leq \sqrt{\frac{\frac{d_{wheelbase}}{\cos{(90° - \alpha)}} \cdot d_{ytip} \cdot \frac{1}{\cos(\beta)} \cdot g(m_t \cdot d_{ty} + m_m \cdot d_{my} + m_c \cdot d_{cy} + m_f \cdot d_{fy} + m_l \cdot d_{ly})}{(m_t \cdot d_{tz} + m_m \cdot d_{mz} + m_c \cdot d_{cz} + m_f \cdot d_{fz} + m_l \cdot d_{lz})}} \tag{12}$$

3.2.3 Load placement

Today, the truck has no detection of where the load is placed. To evaluate if the placement of the load has a contributing factor in the case of tipping sideways, calculations on a maximal load placed on one fork can be seen in figure 19.

As can be seen, the placement of the load plays a big part of the resulting allowed velocity in the case with an elevated heavy load. This is a strong argument of implementing a sensor to detect load placement. To find the location of the load on the forklift, pressure sensors could be implemented in the carriage. To calculate the lateral position of the load's centre of mass, the difference of the measured pressure is used.

$$F_l = m_l \cdot g = F_{f1} \cdot d_1 + F_{f2} \cdot d_2 \iff d_1 = \frac{m_l \cdot g - F_{f2} \cdot d_2}{F_{f1}} \iff d_2 = \frac{m_l \cdot g - F_{f1} \cdot d_1}{F_{f2}} \tag{13}$$

$$\text{load offset} = \frac{d_1 + d_2}{2} - d_1 \tag{14}$$

where F_l is the gravitational force of the load, F_{f1} is the pressure measured in fork one and F_{f2} the pressure in fork two. The distances d_1 and d_2 denotes the lateral distance from the center to each fork.

3.2.4 Mast tilt

Tilting the mast results in a change of CoG for the mast, carriage, fork and load. The change for each part can be calculated through

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x - d_{mrotx} \\ y - d_{mroty} \end{bmatrix} + \begin{bmatrix} d_{mrotx} \\ d_{mroty} \end{bmatrix} \tag{15}$$

where x' is the horizontal component and y' is the vertical component of the new CoG, d_{mrotx} is the horizontal distance and d_{mroty} is the vertical distance from the mast's point of rotation to the tipping axis (see figure 8) and α is the mast tilting angle. To calculate the mast rotation around the rotational point of the mast, the distance from the tipping axis to the mast rotational point is subtracted from the rotational matrix while the rotational calculations are carried out and then added again.

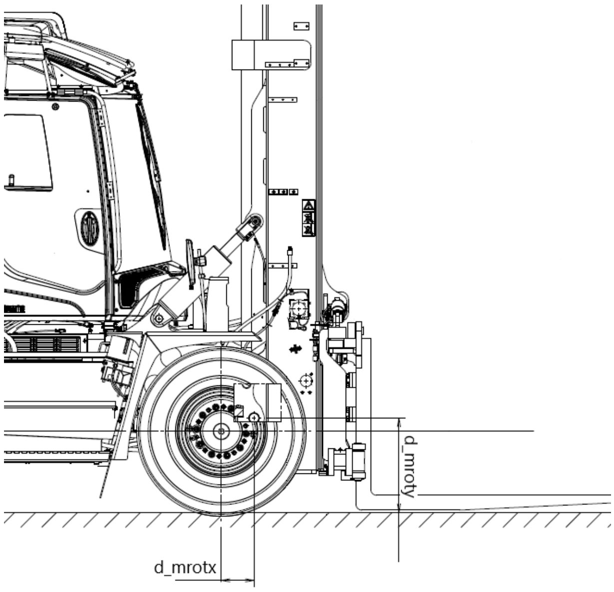

Figure 8: Mast rotational point

3.2.5 Ground inclination

According to standard 22915:2-2018 [6], the truck must remain stable in a 3.5 % longitudinal and a 6 % lateral inclination when the load is placed at maximal lift height and the truck is standing still.

In the same manner as calculating the mast tilt, CoGs affected by the ground inclination are calculated through a rotational matrix. An forward inclination is calculated through a rotation around the y axis. The rotational point is positioned at the origin of the coordinate system. A sideways inclination is calculated through a rotation around the x axis with the same rotational point as the forward inclination.

3.3 Testing

Cargotec has an enclosed testing site with different testing loads and slopes. There is also a tipping table to verify the stability of the truck while standing still but there is no testing environment that are meant for testing stability while driving. Before implementing the anti tip-over function, testing should instead be carried out in a hardware-in-the-loop (HIL) simulation environment that also allows unstable processes to be tested.

3.4 Sensors

The truck has several sensors implemented but some features of the anti tip-over function will need additional sensors to operate. Some sensors also needs to be upgraded before the anti tip-over function can be implemented.

3.4.1 Implemented sensors

- Velocity
  The velocity is determined with an encoder placed on the front wheel axle.
- Turning angle
  A steering angle sensor is placed on the rear wheels and is used to determine the turning angle.
- Ground inclination
  A fluid based inclination sensor is used to determine the ground inclination.
- Lift height
  To determine the lifting height, draw-wire displacement sensors are used [9]. They are optimal for measuring distances and positions between 50-50000 mm and have a resolution towards infinity.
- Load weight
  The load is weighted through a pressure sensor in the valve controlling the lift cylinder.
- Load placement
  There is currently no sensor to determine the load placement.
- Fork placement
  The forks lateral positions are, like the lifting height, determined through draw-wire displacement sensors. Because of individual movement of the forks is possible, each fork has a sensor.
- Mast tilt
  Today there are two ways of measuring the mast tilt; through a potentiometer in the base of the mast and through an inclinometer placed in one of the forks.

3.5 Limitations

As neither the sensors that the anti tip-over function will need to be implemented are specified nor the exact functionality of the function is determined, a safety analysis could not be carried out in this project. It can only be done when all components and functionality are specified.

4 Result and discussion

4.1 Tipping forward

In figure 9 the tipping thresholds of a minimal (green) and maximal (red) load at different heights are represented. The black line represents the deceleration of a maximal brake. When carrying a maximal load, the truck is very prone to tipping. When unloaded, the truck is stable at all times.

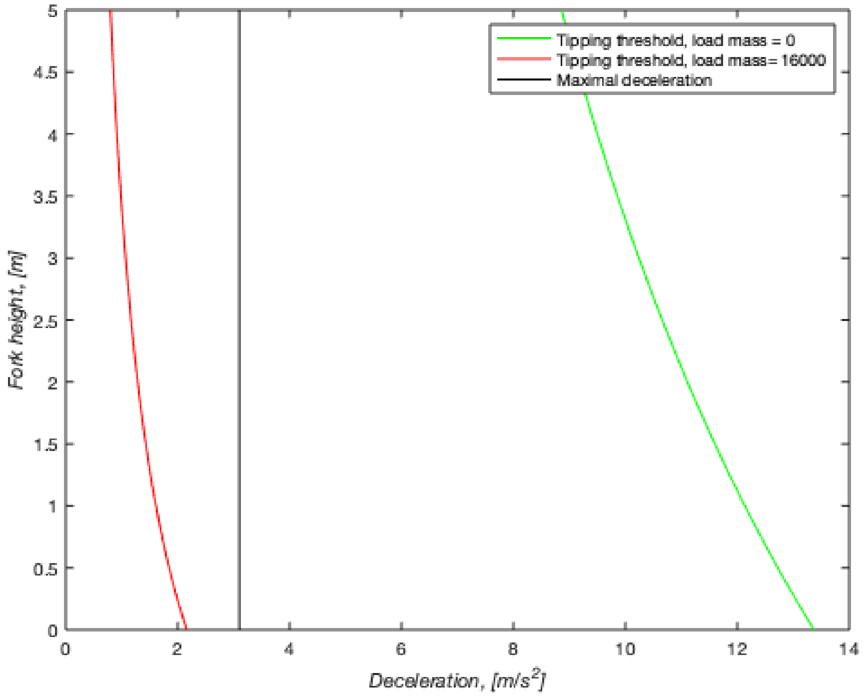

Figure 9: Threshold for tipping forward

Figure 10 represents the deceleration threshold without load at different heights. The colored lines represent the minimal deceleration to fulfill standard SS-ISO 6292:2008[7] at different velocities. From the plot, it can be concluded that the forklift truck can't tip over without load.

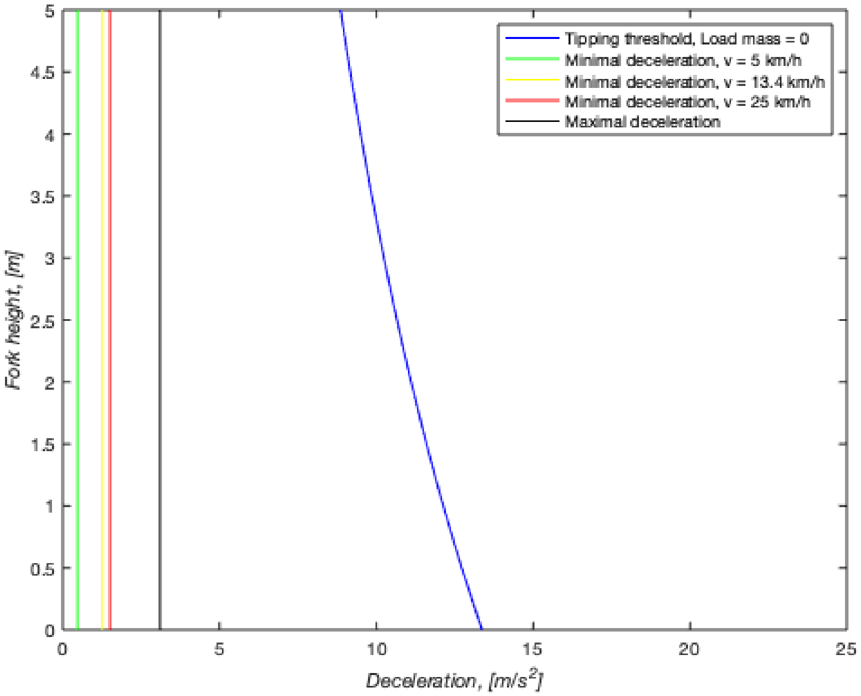

Figure 10: Threshold for tipping forward without load. Braking standards at 5, 13.4 and 25 km/h.

Figure 11 represents the deceleration threshold with maximal load at different heights. As in figure 10, the colored lines represent the minimal deceleration to fulfill standard SS-ISO 6292:2008 [7] at different velocities. The tipping motion will be initiated for all fork heights if a maximal brake is applied. The optimal deceleration is found right to the left of the intersection of the tipping threshold and the current lift height. If brake-by-wire is implemented, the velocity limit should be set to the corresponding velocity from the braking standard. For instance, with a load mass of 16000 kg and a fork height of 2 m, the velocity limit should be set to 13.4 km/h. If brake-by-wire is not implemented, the truck should always remain stable if maximal brake is performed. According to the plot this is an impossible outcome, but as mentioned before, the tipping threshold represent the force that initiate the tipping motion. It doesn't necessarily mean that the truck will tip over if the threshold is exceeded. Therefore, there should be a limitation on both the fork height and velocity that keeps the truck stable even in a maximal brake is performed. These limitations must be determined through testing in the HIL simulation environment.

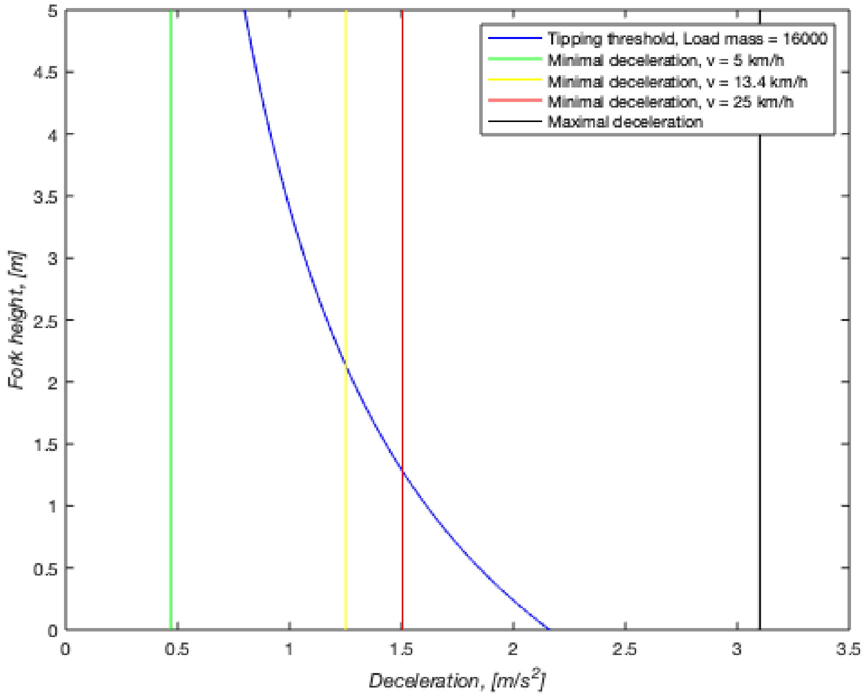

Figure 11: Threshold for tipping forward with maximal load. Braking standards at 5, 13.4 and 25 km/h.

In figure 12 the load is placed on three different points; at load center (blue), at fork base (green) and at fork tip (red). As can be seen, the placement of the load along the x-axis has a great impact on the stability. Even if the lifting capacity is specified when the load is placed at the load center, the case when the load is placed at the fork tip can still occur in reality, making the truck even more prone to tipping over. When the load is placed at the base of the forks it can be concluded that the truck is stable at all times if fork heights $< 1.5\ m$, even with a maximal load.

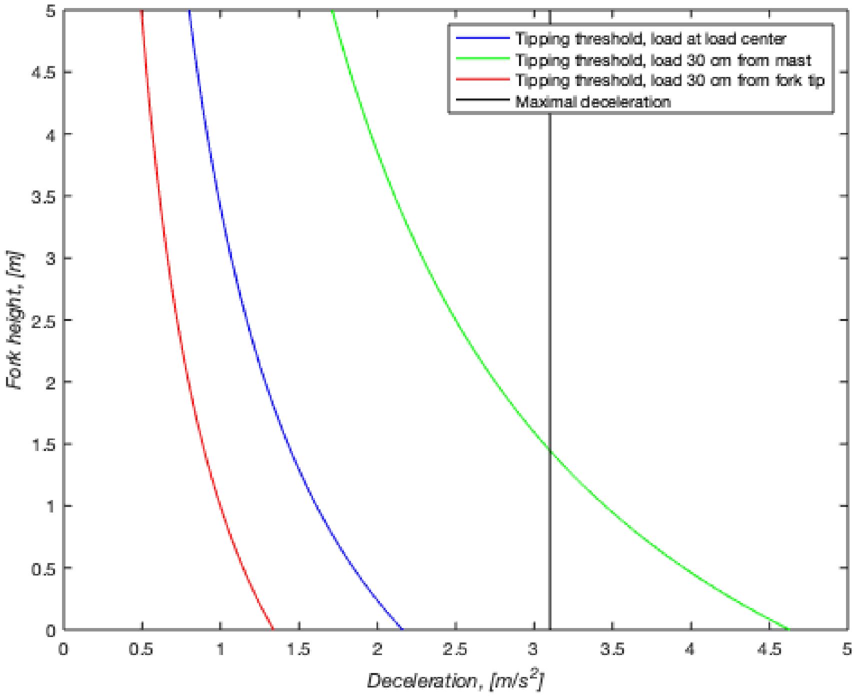

Figure 12: Threshold for tipping forward with different load placements. Load mass 16000 kg.

As can be seen in figure 13, the velocity limit is strongly impacted by the load weight. A difference of approximately 1 ton entails a difference of 11.6 km/h for the preferred velocity limit. It can be concluded that with a load weight < 7500 kg, the truck is stable at all times in the forward direction.

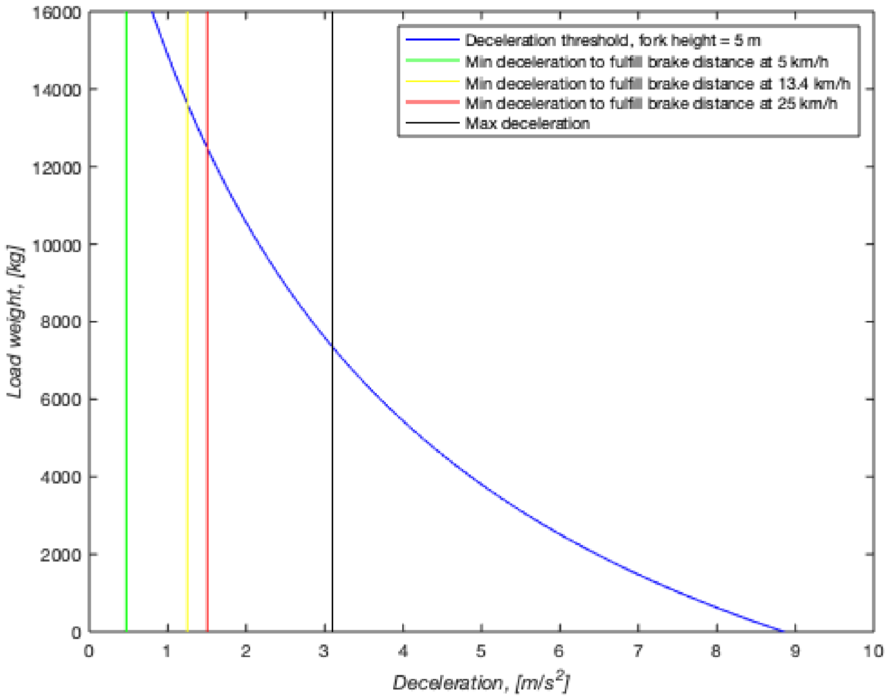

Figure 13: Threshold for tipping forward with varied load weight at maximal fork height. Braking standards at 5, 13.4 and 25 km/h.

In figure 14 and 15, the stability thresholds at different mast tilts are shown. The truck is most stable when the mast is fully tilted backwards at lowest fork heights and most unstable when the mast is fully tilted forward at maximal fork height. The maximal difference in allowed deceleration is approximately 5.5 m/s^2. For the case when the truck is unloaded with the forks at a maximal height, the mast tilts uttermost positions contributes to a difference of approximately 1.8 m/s^2 of allowed deceleration. The forks have a length of 1.8 m which means the lowest height that a full forward tilt is possible is at

$$\sin(14°) = \frac{x}{1.8\ m} \Longleftrightarrow x = \sin(14°) \cdot 1.8\ m = 0.44\ m$$

The maximal forward tilt reduces from 14° at 0.43646 m to 0° at 0 m fork height, which means that the red curve should enclose to the blue curve at fork heights < 0.43646 m. However, for an unloaded truck the difference is so small that it wouldn't make a noticeable change the resulting thresholds.

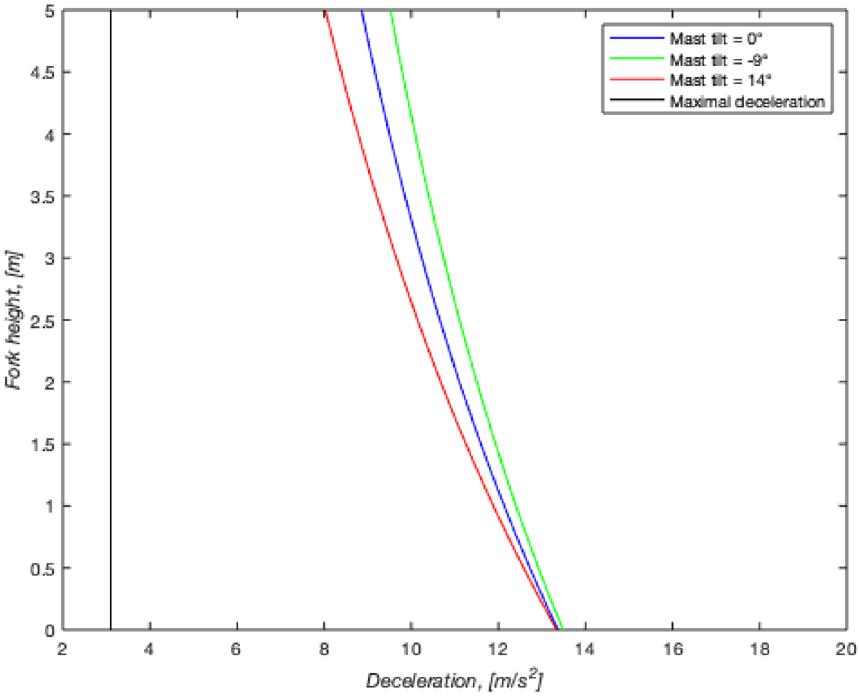

Figure 14: Threshold for tipping forward with at maximal forwards and backwards mast tilt. Load mass 0 kg.

The mast tilt when carrying a load has a big impact on the stability. In figure 15 we can see that a maximal load elevated higher than 2 m initiates the tipping motion. Unlike the case of the unloaded truck, fully tilting the mast forward on a maximal loaded truck yields a noticeable difference in allowed deceleration even for fork heights below 0.43646 m. However, as the red curve represents the worst case scenario, following the incorrectly calculated threshold won't affect the stability.

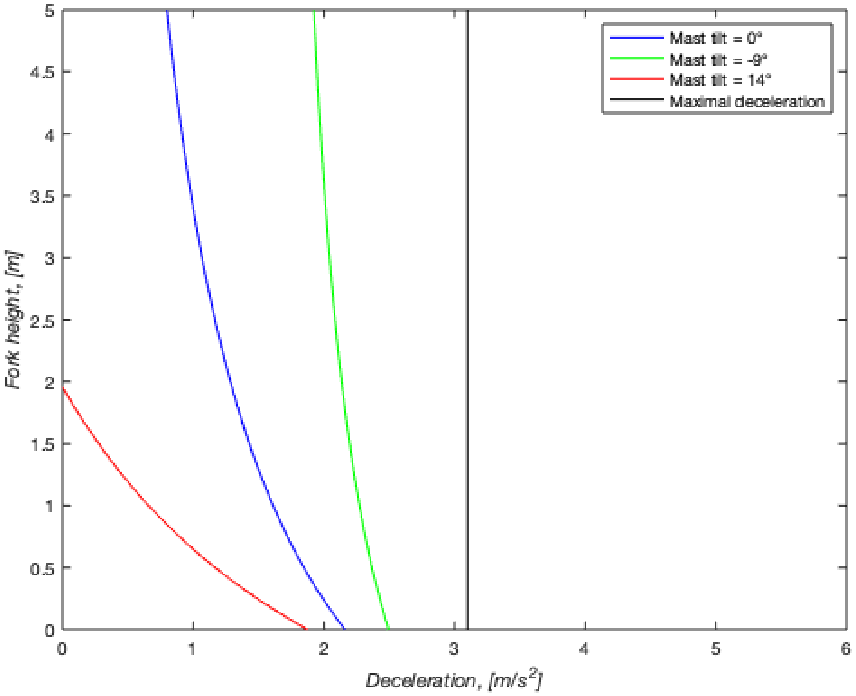

Figure 15: Threshold for tipping forward with at maximal forward and backwards mast tilt. Load mass 16000 kg.

Standard SS-ISO 22915-2:2018 [6] requires that the truck maintain stability in a 3.5% longitudinal ground inclination. As can be seen in figure 16, an uphill inclination increases the forward stability while a downhill inclination decreases forward stability of the truck. Therefore, it is important that the direction of the inclination is determined before the velocity limit is set.

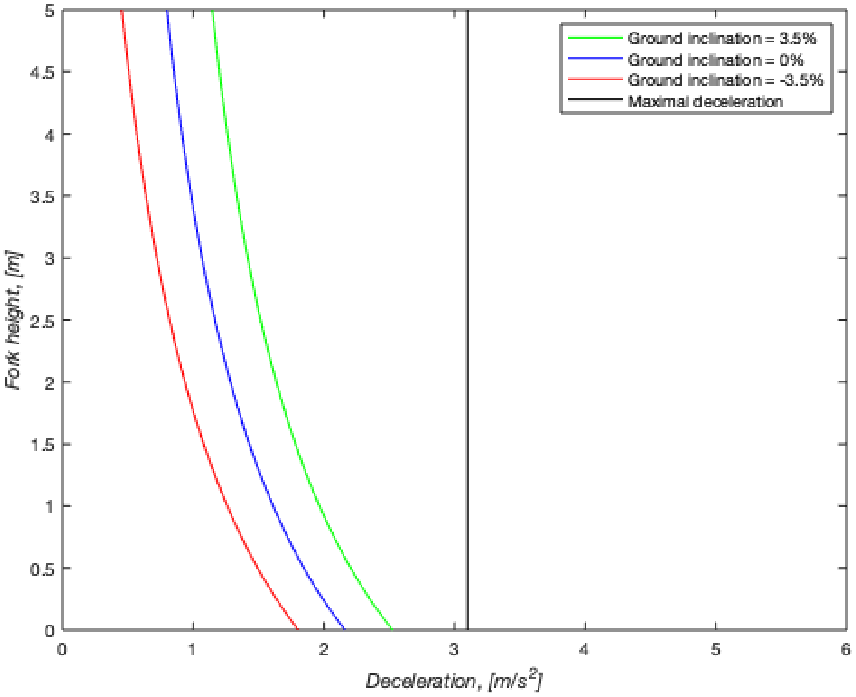

Figure 16: Threshold for tipping forward with ground inclination.

4.2 Tipping sideways

The sideways tipping thresholds while carrying a minimal (green) and a maximal (red) load can be seen in figure 17. The steering angle is fixed at 45° and the load height is varied. From the plot, it can be determined that the forklift truck can't tip if $v < 12.5$ km/h. An interesting observation is that the truck is always more stable when carrying a load.

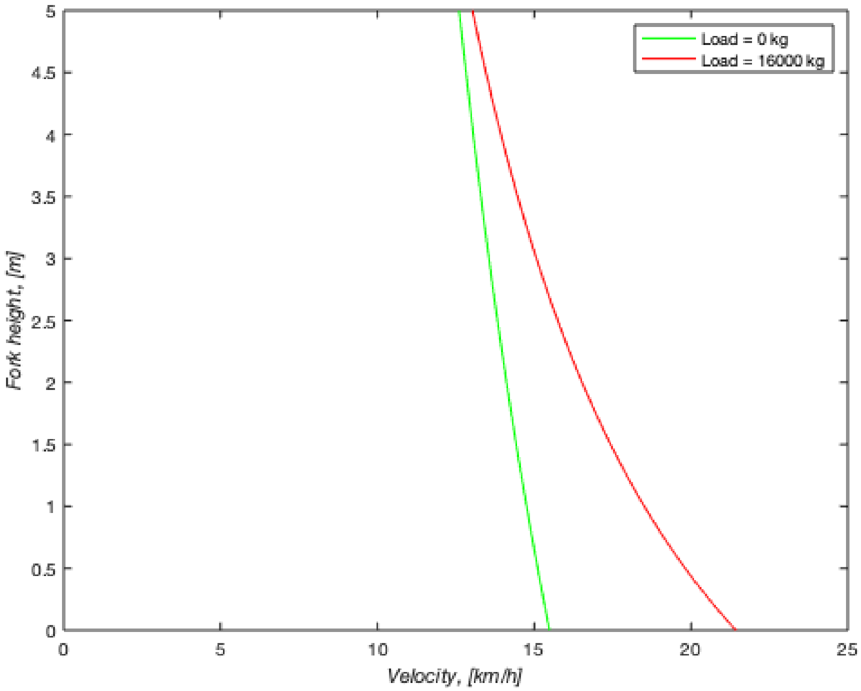

Figure 17: Threshold for tipping sideways with minimal and maximal load, steering angle at 45°

In figure 18, four combinations of minimal and maximal load and height at different steering angles are plotted. The steering angle axis goes from 0° to the maximal steering angle of 68°. The truck is most stable while carrying a maximal load at minimal height. The truck is most prone to tipping over when carrying a minimal load at maximal height but the difference yielded from fork height at a constant load mass is greater when carrying a maximal load. From the plot it can also be determined that the truck can't tip sideways if the steering angle $< 9°$.

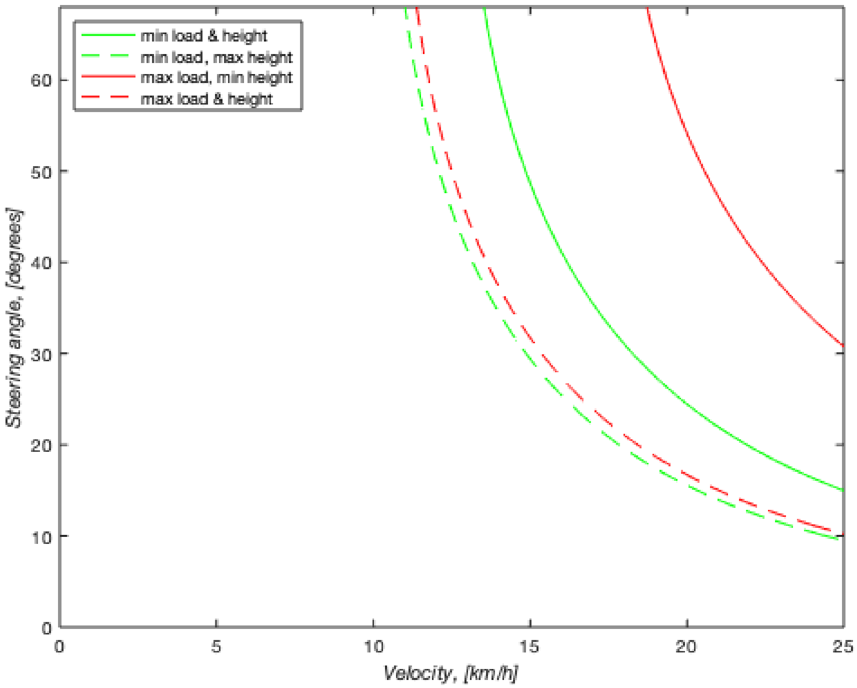

Figure 18: Threshold for tipping sideways with minimal and maximal load and height at different steering angles.

Some companies might only use one fork while lifting i.e. heavy cable rolls. All the weight will then be distributed on one side, which decreases sideways stability. Figure 19 illustrates the case when a maximal weight is placed as far out on one side as possible. The stability decreases when load mass or lifting height increases.

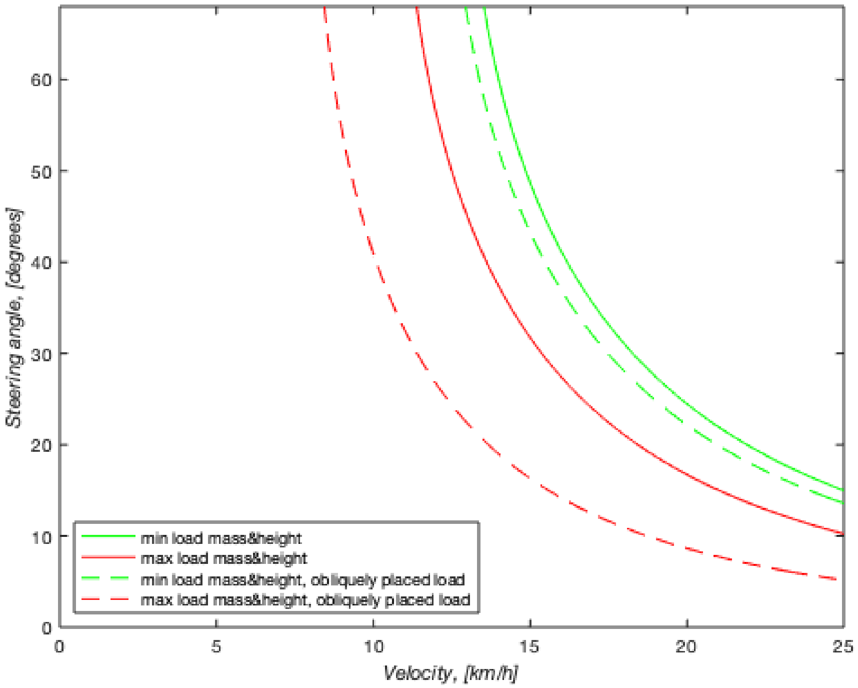

Figure 19: Threshold for tipping sideways with minimal and maximal load when load is placed obliquely.

To fulfill standard SS-ISO 22915-2:2018 [6], the maximal lateral ground inclination in which the truck has to maintain stability is 6%. In figure 20, the velocity thresholds for tipping sideways while making a turn on inclined ground are plotted. Depending on the direction of the turn the truck will gain or lose stability. Steering uphill yields a lower stability and steering downhill yields a higher stability. Since the direction of the turn is unknown, the velocity limit should always be calculated from an uphill turn.

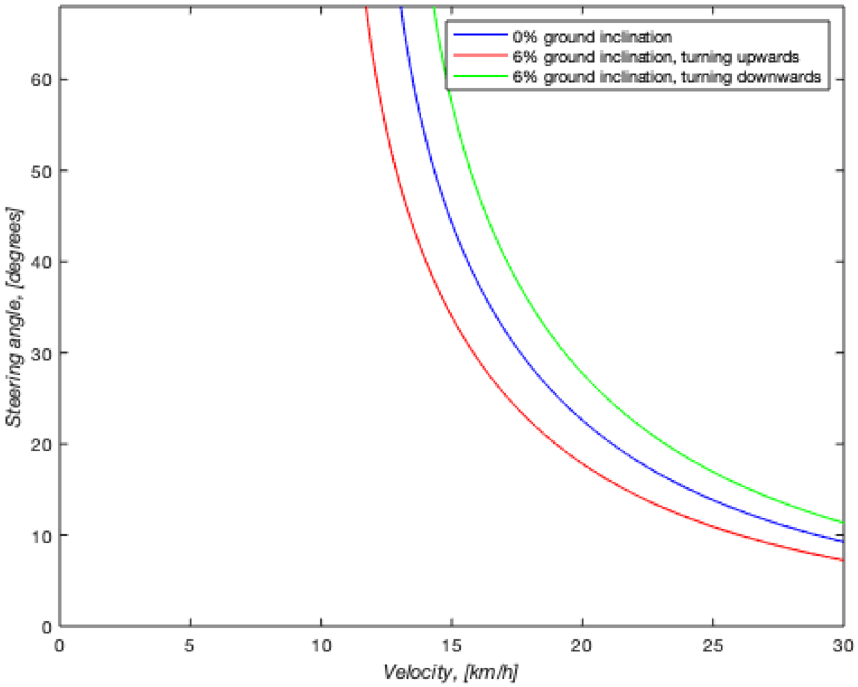

Figure 20: Threshold for tipping sideways with ground inclination.

4.3 Sensor evaluation

The priority when performing the sensor evaluation is to ensure a high safety for the anti-tip over function. This means that the sensors that has a big impact in the calculations needs to have a high resolution and accuracy. The sensors also needs to be fail-safe.

- Velocity
  The current method for measuring the velocity of the truck satisfies the resolution needed.
- Turning angle
  The steering angle sensor is precise. The resolution doesn't need to be high, a small change in steering angle does not have a big impact on the velocity limit.
- Ground inclination
  A major disadvantage of fluid based inclination sensor is that it is very sensitive to noise. If the truck is driving over an uneven ground, the inclination could be very difficult to determine. The truck would almost have to stand still for the sensor to

give a reliable value. Instead, an IMU (Inertial measurement unit) could be used. An IMU is a combination of an accelerometer and a gyroscope.

- Lift height
  The draw-wire displacement sensors are cheap and easy to maintenance but due to their exposed positioning makes them prone to measurement fault. If a wire comes in contact with an object, the length is increased and the measurement becomes incorrect. Instead of using multiple draw-wire sensors to detect faults, a cylinder sensor from Liebherr [10] could be used. With a resolution of 100 μm, the sensor is placed inside the cylinder and measures the position of the cylinder through radio-frequency measurement, which ultimately can be used to determine the lift height. This method is very fault-safe and due to its protected placing, the sensor will have a long life time.
- Load weight
  The implemented sensor has an error range of several hundred kilograms. As mentioned earlier, the load weight has a large impact on the calculated tipping thresholds. Therefore, the current sensor may need to be replaced. To determine the weight of the load with a higher resolution, pressure sensors in the carriage could be implemented.
- Load placement
  By having one pressure sensor for each fork in the carriage, the lateral position of the CoG of the load could be determined through calculations on the difference in pressure. The position along the x-axis could be determined in several ways. For example, a sensor measuring the pulling force of the mast could be implemented. The calculation would have to take both the load weight and the mast tilt into count.
- Fork placement
  In the same manner as measuring the lift height, cylinder sensors from Liebherr could be used to determine the placement of the forks.
- Mast tilt The sensors that are currently used gives a value that satisfies the needed resolution.

4.4 Active choices

An important point to mention is the dilemmic situations that can occur while driving a truck. In some situations the driver may have to chose between scenarios that will all have a more or less disastrous outcome. The driver may have to swerve to avoid running someone or something over with the result of the truck tipping over. Limitations on the truck might prohibit the driver from actively making the less disastrous choice. A simple solution to this question would be to eliminate the risk of anyone or anything that should not be the running environment of the trucks to be there in the first place, but in practice this can not be treated as a guarantee. In a future where the machines are autonomous, these kind of questions are very important. How should a computer prioritize situations where every outcome is more or less negative?

5 Conclusion

Implementing a function such as the anti-tip over function is a bigger task than one can predict. Not only are there many inputs that needs to be processed, but also multiple factors that plays a big part in how the function should be designed. When new sensors needs to be implemented, a thorough evaluation needs to be carried out before the sensors can be installed and tested. For a machine that runs in an environment where it can cause harm to people, animals or expensive cargo, a safety analysis is a vital part of the function implementation. To achieve the required performance level can apart from being a time consuming task, cost a lot of money in terms of components and material. The anti-tip over function will need a lot of testing before it can be implemented.
By conducting this master thesis the gap in development to autonomous machines reduces. Additionally, a modular Matlab code simplifies the anti-tip over function to be implemented in Cargotec's other machines.

5.1 Implementation proposition

To determine the procedure of the anti-tip over function implementation a meeting with employees from the development unit was held. Their insight in the customer needs was a big help to distinguish the most common tipping scenarios and which parts of the function that was most important to implement. There was also discussions about in which order the anti-tip over partial functions should be implemented.

My suggestion is to do the implementation of the anti-tip over function in several steps. In figure 21 the schematics of these three phases are illustrated.

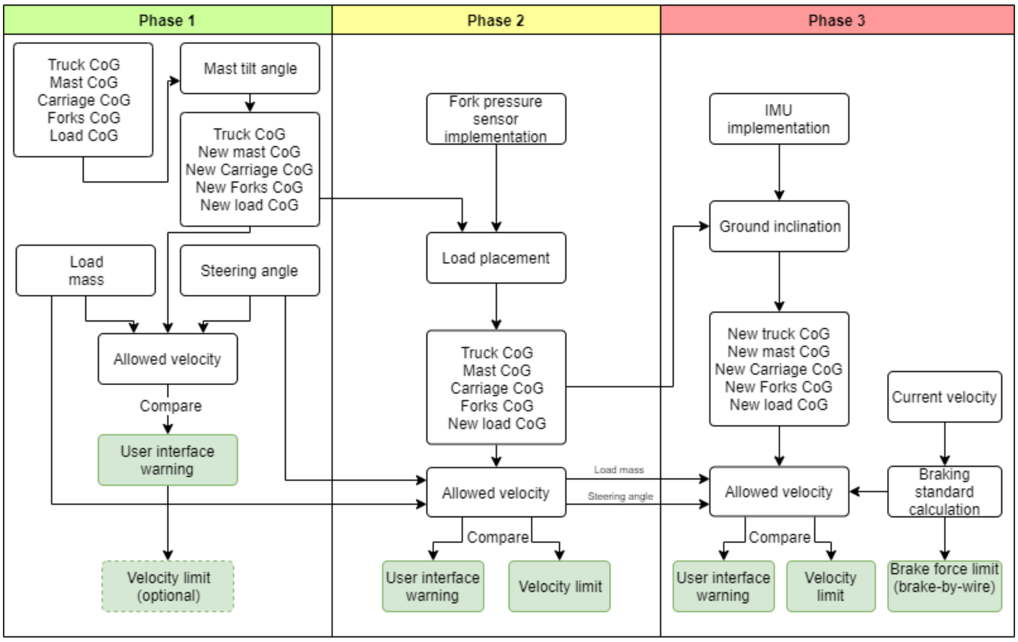

Figure 21: Implementation chart.

The outcome of the different phases is described below:

1. A visual implementation, giving warnings to the user
2. Implement fork pressure sensor which can calculate the load's lateral placement. Furthermore, instead of just giving a visual warning, also taking action, limiting the allowed velocity of the forklift truck.
3. Implement an IMU which can calculate the ground inclination, taking it into count in the tipping calculations. Also implement break-by-wire which will result in a higher allowed velocity.

A strong argument for implementing the anti tip-over function in steps is that before the function takes over actions from the user, a new safety analysis must be done. This is a very complex and time consuming task to perform. If the functions gives a visual warning but lets the user make all the actions, the current performance level will be withheld. It would also be interesting to see if only using a visual warning would lower the number of accidents occurring. In figure 21, a visual representation of the different phases is illustrated.

Phase 1 could be implemented without having to implement new sensors.

The fork pressure sensor implementation is done in phase 2, which means that the load placement can be determined. Before this sensor implementation, the anti tip-over function will have to assume the worst case scenario, that the load is placed obliquely. With a maximal load mass and lift height, it can be seen in figure 19 that the difference in allowed velocity > 5 between an obliquely placed load and a load that is placed in the center.

In phase 3, the brake-by-wire is implemented. This means that the allowed velocity is no longer calculated from the maximal brake force. Instead, depending on the lift height and load mass, the velocity limit will be calculated on the minimal brake force that fulfills the braking standard. As can be seen in figure 11, this will make a huge difference.

6 References

[1] `https://www.kalmarglobal.com/4a8251/globalassets/equipment/forklift-trucks/forklift-trucks-9-18-ton/electric-forklift-trucks-9-18-ton-brochure.pdf`
(Accessed 20190923)

[2] `https://www.av.se/produktion-industri-och-logistik/fordon/truckar/`
(Accessed 20191218)

[3] `https://www.cargotec.com/en/about-Cargotec/cargotec-corporation/`
(Accessed 20190923)

[4] `https://www.kalmarglobal.com/about-us/kalmar-in-brief/`
(Accessed 20190923)

[5] `https://upload.wikimedia.org/wikipedia/commons/a/a0/Ackermann_turning.svg`
(Accessed 20200115)

[6] Swedish Standards Institute. (2018). *Industrial trucks – Verification of stability – Part 2: Counterbalanced trucks with mast* (ISO 22915-2:2018, IDT)

[7] Swedish Standards Institute. (2008). *Powered industrial trucks and tractors – Brake performance and component strength* (ISO 6292:2008, IDT)

[8] Swedish Standards Institute. (2015). *Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design* (ISO 13849-1:2015)

[9] `https://www.micro-epsilon.com/displacement-position-sensors/draw-wire-sensor/`
(Accessed 20200122)

[10] `https://www.liebherr.com/en/usa/products/components/control-technology-electronics/sensor-technology/liview-position-transducer.html`
(Accessed 20200122)

[11] Tipler, Paul A.; Mosca, Gene. *Physics for Scientists and Engineers.* New York, 2008.