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Autonomous compaction roller

Temporarily convert a non-autonomous compaction machine to become autonomous during endurance testing

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis at any other institution to obtain a degree.

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Abstract

How can a non-autonomous compaction roller be converted to become temporarily autonomous while it performs a 500 hours endurance test? Particularly since the compaction rollers in question is not built to be autonomous and shall not be autonomous after the endurance test is completed. The autonomous system shall also be adaptable to all compaction rollers which Dynapac is developing and shall be moved to another machine when the endurance test is completed.
In this thesis a concept is engineered of how the whole autonomous system will work and a prototype is fabricated of how to convert the current manual mechanical steering to be performed by a computer. The steering prototype has been tested on a Dynapac CC4200 double drum asphalt compaction roller and worked as intended. To develop this, an extensive risk analysis is also established and with it a requirements list of what's needed to be fulfilled when performing autonomous testing of a compaction roller. The work has been done using the method “design thinking” which is a collection of multiple methods to create new concepts and ideas. The final concept resulted in a navigation system which uses GNSS for path planning and limitation of the operation area. It also uses radar to detect foreign objects in its path to prevent a collision. Multiple systems are also proposed to be used for malfunction detection of the roller, which is a major part of a human operator’s job when testing out new machines. The test track for the machine was undefined and also had to be engineered as part of the concept. It resulted in closing the area of operation with a mesh fence to prevent access to the area from unauthorised personnel and geo-fence to prevent the machine from escaping. Access to the area is only granted to authorized personnel and only when the autonomous roller is shut off. Due to the machines in question isn’t fully developed, they can’t be trusted enough to have people inside the area of operation as the autonomous machine is operating.

Keywords: Autonomous system, Compaction machine, Endurance testing, Risk assessment, Self-driving

Sammanfattning

Hur kan en icke-autonom vägvält omvandlas till att bli tillfälligt autonom medan den utför ett 500 timmar långttidsprov? Särskilt sedan vägvälten ifråga inte är byggd för att vara autonom och ska inte vara autonom efter att långtidsprovet är slutfört. Det autonoma systemet ska även kunna anpassas till alla vältar som Dynapac utvecklar och ska flyttas till en annan maskin när långtidsprovet är klart. I denna avhandling konstrueras ett koncept för hur hela det autonoma systemet kommer att fungera och en prototyp tillverkas på hur man konverterar den nuvarande manuella mekaniska styrningen till att styras av en dator. Styrprototypen testades på en Dynapac CC4200 asfaltsvält med dubbla valsar och fungerade bra. En omfattande riskanalys utvecklades och lika så en kravlista över vad som behöver uppnås vid autonom testning av en vägvält. Arbetet har gjorts med hjälp av metoden “design thinking”, vilket är en samling av flera metoder för att skapa nya koncept och idéer. Det slutgiltiga konceptet resulterade i ett navigationssystem som använder GNSS för navigering och begränsning av körområdet. Den använder också radar för att upptäcka främmande föremål i sin väg vilket förhindrar kollision. Flera system föreslås användas för funktionsfelsdetektering på välten, vilket är en viktig del av en mänsklig operatörs arbete vid provning av nya maskiner. Maskinen kommer att vara i ett slutet område som är avskilt med ett nätstängsel. Tillträde till området ges endast till behörig personal och endast när den autonoma välten är avstängd. På grund av maskinerna ifråga inte är fullt utvecklade, kan de inte litas på tillräckligt för att ha personer inom körområdet medan det autonoma systemet är i drift.

Nyckelord: Autonomt system , Kompakteringsmaskin, Långtidsprov, Riskanalys, Självkörande

Contents

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Abbreviations

Abbreviation	Description
AOZ	Autonomous operation zone
ASAM	Autonomous or semi-autonomous machine
CAD	Computer aided design
CCTV	Closed-circuit television
DC	Direct current
FOV	Field of view
GNSS	Global navigation satellite system
GPS	Global positioning system
HMW	How might we
ISO	International organization for standardization
LiDAR	Light detection and ranging
LPS	Local positioning system
POSE	Positioning and orientation
RA	Risk assessment
RADAR	Radio detection and ranging
RPM	Revolutions per minute
RTK	Real time kinematic
SAE	Society of automotive engineers

1 INTRODUCTION

1.1 Background

Autonomation technology is an area that is hot today, partly due to the hype provided by the automotive industries where a lot of resources are currently invested in the research and development of commercial autonomous cars. While the big companies like Tesla and Google is racing to be the first ones to develop an autonomous car that can handle the complexity of the real-world traffic and all of its surroundings, big progress in autonomation is being done in other areas. The autonomous technology can be found in many places of society, from smaller innovations like autonomous lawn mower in your backyard to big autonomous trucks operating on mining sites. In areas such as mining, autonomous vehicles offer higher productivity, efficiency and safety. This by removing the human operator and thus removing the need for breaks, lunch and shift changes which saves time. The autonomous system will perform all task with the same level of precision, not affected by individual skill level. Higher safety is ensured by completely removing any human personnel from the site [1] [2].

New areas of implementation of the autonomous technology is discovered continuously and one such area is vehicle durability testing. Most vehicles in its late development phases exposed to various durability tests, that often means driving the vehicles for a certain number of miles, to ensure the products durability. These long lasting, monotone and dull tasks, that in some cases also include uncomfortable tasks, is autotomized spare the driver. It also allows the test to be conducted without breaks, speeding up the process [3].

In the late developing phases of a Dynapac compaction roller, a 500 hours endurance test is done to find design flaws that must be corrected before the machine is taken into production. The test is a time consuming, monotone and dull task that exposes the operator for unwanted working conditions from vibration and shock. To be able to spare the operator as well as saving time and resources, Dynapac is planning for the autonomation of the endurance test. The problem assigned from Dynapac is to investigate the requirements needed to fulfill the current laws and regulations around the topic and to guarantee a safe environment. While the problem has a lot of similarities with other autonomous systems it has some characteristics that is quite specific for this problem. The first being that since the endurance test is part of the developing phase, the machine being tested is still just a prototype. The prototype cannot be expected to work flawlessly, and should be expected to malfunction in some way at some time. The second characteristic is that the compaction roller in question is not and will not be designed for autonomous driving. The endurance test is a onetime thing. Equipment for autonomous driving has to be mounted on the roller in the beginning of the test and will then be dismounted when the test is completed. The machines that is then set into production will never be driven autonomously.

1.2 Objectives

Engineer a concept of how to conduct endurance testing of a non-autonomous compaction roller autonomously. This involves specifying specific requirements that are set on the testing area for an autonomous roller to work in this area, as well as obtaining the requirements on the roller for it to be operated autonomously for several hours in a row. A selection of these requirements is occupational safety rules, rules for how autonomous vehicles may operate, safety stop functions, amount of supervision the roller requires, how to refuel the machine, methods for autonomous operation and steering of the roller. Extra important is the safety aspect, since it is a prototype machine and not a fully developed and complete machine that is to be tested autonomously. Therefore, it is not possible to assume that the machine is functioning properly, both in terms of its physical properties and its software. Therefore, safety precautions must ensure that the machine stops if something goes wrong.

1.3 Today's Solution

In today's position, when developing new compaction rollers on Dynapac, an endurance test of the new machine prototype is performed. The endurance test consists of about 500 hours of driving on a test track. In this test, you try to expose the machine to the worst possible scenarios that the machine is designed to cope with. The main result of the endurance test is revealed first after the test is done, when the machine is disassembled and all the components is analyzed into detail. It is important that the test simulate how the machine is being used in its natural working environment. This is done by dividing the test into the different phases; compaction, transportation and idle driving.

The compaction phase is performed by driving back and forth with vibration to simulate how the machine is working on the asphalt or other surfaces that is designed to compact. The ground surface that the machine drives on in this phase is relatively 'soft' to represent the warm asphalt and the vibration frequency switches between high and low amplitudes. The transportation phase is supposed to represent and simulate the time the machine spends on transporting itself between working areas. The driver is mostly free to drive the roller how he/she pleases during this phase. However, the driver is asked to perform a number of specified maneuvers during this phase. The driver must perform an 8-like driving pattern with the machine to test the machines turning capacity to its limit and to later see if something is taking damage from the maximal turning e.g. hoes or joints. The driver also must test the machines acceleration and retardation in this phase to put some pressure on the machines engine, gearing and breaks. Another part of the transportation phase is driving over cones (see Figure 1). The cones are small bumps that will tilt the machine in a way that strains and test the articulated joint. The transportation phase is often performed on somewhat more rugged and harder ground surface, but ultimately depends somewhat on the type of machine. The third phase, idle driving, is mostly for the smaller machines. The smaller machines are mostly used for smaller road repairs where it spends a large portion of time waiting in idle drive, hence this phase. The time each machine spends in each phase depend on what size and type of machine is being tested. The time spent in each phase should represent the proportion of time the machine spends on that phase in its working life. The larger CC machines will therefore spend about equal time in the transport phase as in the compaction phase and little to non- time in idle drive. The smaller machines would on the contrary spend less time in the compaction phase and more time in idle and transportation phase.

As it is a person (or two who takes turns) who performs the test, labor protection rules reduce the ability for Dynapac to perform tougher tests on the machine. The current working environment of the machine operator is not ideal, just like the machine the operator is also being exposed to the different scenarios. This means that the operator is being exposed to both the noise and vibration that the machine produces and thus provides a risk to the operator's health. Small obstacles like small rocks will generate high shocks that will have a large negative effect on the operator comfort. Especially in the smaller machine where the operator is located directly over the drum and the shock propagates directly to the operator without sufficient damping. The endurance test is done regardless of the weather conditions, as long as the track is cleared from snow and ice. Some of the machines lack a closed cabin for the driver, who then have to endure the cold weather, wind and rain that might occur during the test.

Figure 1, Two metal cones which the roller drives over in the endurance test. On the left and right in the picture are five compaction rollers with a single drum displayed.

1.3.1 What is a compaction roller

A compaction roller is a machine used to compact different types of surfaces on the ground, for instance, gravel, soil or asphalt. This is done by either one or two large heavy cylinders which rolls over the surface. The cylinders are also vibrating to increase the compaction rate compared to only use the weight of the machine to compact the ground. Dynapac's compaction rollers have a diesel engine for propulsion which is electrically controlled, and a water tank to lubricate the cylinder. Most of the machines have articulated steering and this system is totally mechanical. When the steering wheel is turned, a valve to a hydraulic pump adjusts the amount of hydraulic oil which goes to the piston. This leads to a change in pressure and the piston will either go out or in, and this turns the machine [4].

1.3.2 What is Dynapac

Dynapac is a company that develop and produce road construction equipment, in particular compaction rollers, were the assembly facility is located in Karlskrona. Dynapac also exists in countries as the United States, Germany, Brazil and China. It is currently a part of the bigger French company Fayat Group, which is large company in the construction, civil works and industrial sectors.

Figure 2, Compaction roller with two drums.

1.4 Research Questions

The main purpose of this thesis work is to develop a concept of how to perform endurance test autonomously with a compaction roller, in this case a Dynapac roller, which are not designed for autonomous control. A big part of this concept is the steering, of which a prototype was constructed. The research question for this thesis are the following:

> *How can the endurance test of a compaction roller be performed autonomously on a machine that isn't designed for autonomous control?*

Two additional sub questions are also raised in the thesis to give further focus on the safety aspects of conducting autonomous endurance test and on the equipment needed to perform it. The sub questions are as follows:

> *SQ1: What solutions shall be deployed to guarantee safety for people and property?*
> *SQ2: What equipment is needed on the machine to be able to perform autonomous endurance test?*

1.5 Community Benefits

Today's society is developing ever faster and great progress can be seen everywhere when it comes to automation of vehicles. There are already cars equipped with autonomous braking, parking and even control. This technology has extremely great potential, not just in the automotive industry but everywhere in society. Autonomous technology can be used in society to make the heavy and dull work that nobody wants to do. This allows time to be spent on more significant work that can benefit society's development. The technology studied in this work has a wide application area and the work is therefore not only relevant to Dynapac but also to other companies. The autonomous tests will also enable the machine to be exposed to tougher tests without compromising the well-being of any driver. This means that you can get more optimized machines that simultaneously save on society's resources.

1.6 Ethics, Community- and Sustainability Aspects

By switching to autonomous control, the personnel that would otherwise have suffered from the monotonous, dull and uncomfortable task (driving these 500 hours), could be put to better use. Dynapac will also be able to perform tougher tests, leading to machines that are better adapted to the tasks they are designed for. This leads to more optimized products that do not need to be over dimensioned to last, saving the resources of the planet. The more aggressive tests could also lead to a reduction in the test period, which means that the total fuel consumption of the endurance test would decrease.

1.7 Limitations

The work will be based upon the rollers from Dynapac and the information collected regarding endurance test will reflect how it is performed at Dynapac. Another delimitation for the work is that economic aspects will not be analyzed in detail, but only in rough terms. The work will only consider Swedish laws and regulations. The scope of this thesis will not include any contribution in the fields of AI-technology and other software areas, as it will mainly focus on the functionalities of the autonomous endurance testing and the required technologies and safety precautions. No FEM or strength of material calculations has been done on the solutions and concepts developed in this thesis.

2 METHOD

2.1 Design thinking

The “design thinking” process is the main method to execute this thesis. This method is separated in 4 different phases (initiation, inspiration, ideation and implementation) which all interconnect with each other. First phase is the initiation phase where the framing and planning of the work is done. Second phase is where a need finding process is carried out to determine the issues which needs to be solved. Tech, trend and market watching is also carried out to discover current and future solutions from other companies which fulfils the needs from the need finding. In the ideation phase new solutions are made to fulfill the needs from the need finding. This is carried out by converging and diverging ideas in multiple cycles, where the converging generates the quantity of the ideas and diverging creates the quality on the most promising ideas. Last phase is the implementation phase and here are prototypes developed and tested. Since all phases interconnect and overlap, it is possible to jump back and forth between the different phases as much as needed to develop a good solution.

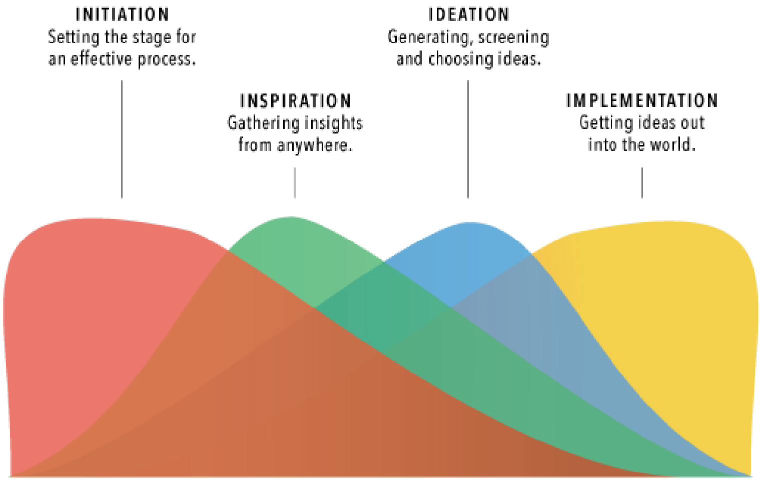

Figure 3, Illustration of how the four different stages of design thinking interconnect. [5]

2.2 Market watching

It is used to establish an understanding of the current market and how companies have adopted to new technology. It can also be of interest to review old products to get a histogram of how the trends have evolved over time. Then it is also possible to see what have been tested in the past and why it worked or didn’t work. Sometimes it is possible to find solutions which was implemented before its time and was neglected because of its futuristic approach or it needed technology which didn't exist at the time. These solutions can be reassessed to determine if the technology exist today and if it is still an upgrade from the current product on the market. The market watching has mainly been focused on the road construction equipment market to see what has already been done and how far the autonomous technology has been implemented. This has brought us an insight of what has been done in this area, both the good aspects that can be used and/or further developed as well as the bad aspects that will have to be improved.

2.3 Trend Watching

Trend watching is a tool to determine trends in products using new technology. By analyzing the trends, an understanding of how the consumers expectation on products are changing alongside with the raise of new technology. It is also about how trends are spreading over the world and how it will affect certain companies and sectors. The trends can be both technical and social trends and as a company it is important to follow these trends to survive the competition on the market. A trend is evolved from a need from a customer. The need is changing over time as the customer influences by new products [6].

2.4 Tech Watching

While conducting tech watching you look into what new technologies which are upcoming and will be hot in the future. The chosen tool for this is “Hype Cycles” [7]. This tool is used to display new and upcoming technology in a graph which is separated in 5 different phases, then the technology is plotted in the graph with an assumption of when it is mainstream.

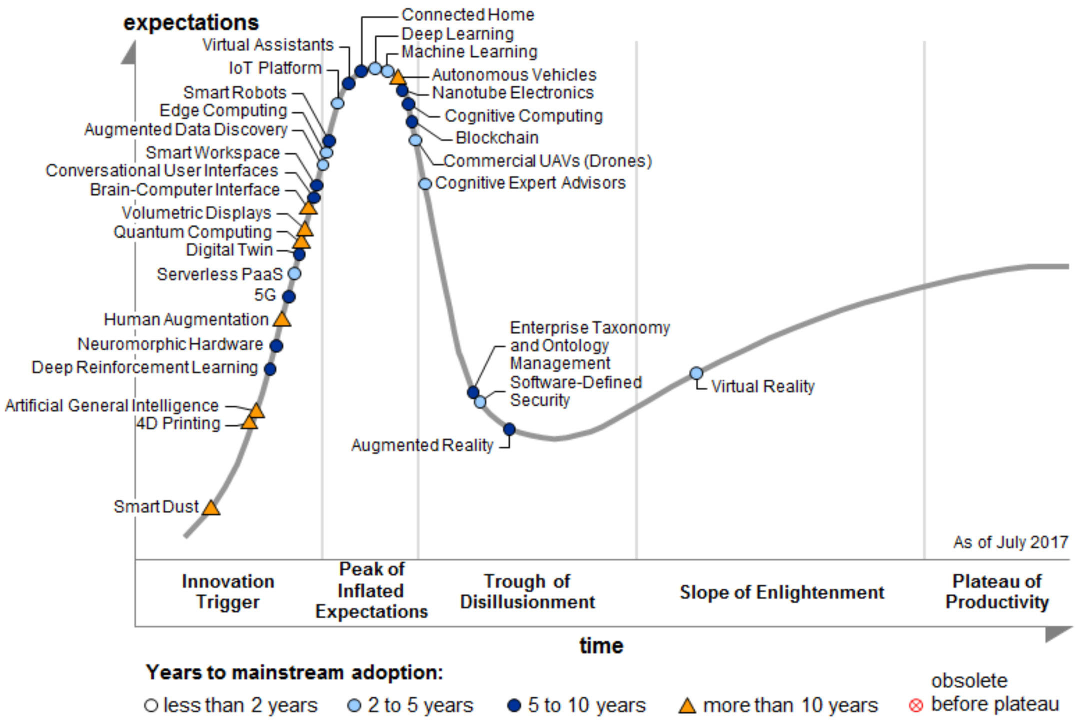

Figure 4, Hype cycle from July 2017 by Gartner [8]. As seen in the graph Autonomous vehicles is in the “peak of inflated expectation” which makes it relevant as a research area.

2.5 Need finding

To understand which needs that exists a need finding process is conducted. The main objective with need finding is to make a list of everything that is needed for the solution to work as expected. By analyzing the risk assessment some of the needs is gathered, a portion comes from analyzing laws and restriction which are affecting system, and the rest comes from interviews with Bo Svilling at Dynapac. All the findings were evaluated and then categorized before put into a list. The result from the need finding was used in two different ways. The first to aid the creation of the “how might we questions", and the second to make a specific requirements list of what conditions is required to conduct the autonomous endurance test with a compaction roller.

2.6 How Might We

The How Might We-method is a way of listing all the needs in the project and formulate them as possibilities instead of challenges. This generates a more positive approach to the challenges and opens up for creative and innovative thinking. The method is simple, as mentioned the problem and challenges is reformulated into questions that opens with the phrase "How might we…". The HMW-question shouldn't be answerable by one answer, it shall remain open for many different solutions to enhance the creativeness and boost the coming ideation. It shall however not be to open, widening the questions too much will give a negative effect [9]. This tool was used to create a good structure in the ideation phase, where all HMW-questions was used to generate ideas through brainstorming.

2.7 Risk Assessment

The risk assessment is done to identify possible hazards early in the design process so that they can either be eliminated or at the least minimized. The risk assessment is based on information provided by Dynapac about the rollers and their previous conducted endurance tests. It is important that the risk assessment covers all potential hazards from the manual operated endurance test, as these hazards won't disappear. On the contrary they are more important to identify and mitigate early when the most important troubleshooter on the machine, the operator, is taken away. The risk assessment will also consider information from other autonomous systems that is relevant for this setup. Eventual hazards surrounding the autonomous system is also of great importance though it is the autonomy part that is the unexplored ground and in that way, contributes to a lot of unidentified hazards and grey areas that has to be explored and mitigated. Doing this early will provide a better base for when generating and selecting ideas and concepts to work within the ideation phase. The risk assessment was also used when generating the requirement specifics for how to autonomously conduct the endurance test with a non-autonomous compaction roller.

The hazards identified is categorized in classes and subclasses according to what area of the system the hazard can be connected to. The hazard is explained and connected to what potential consequence that might emerge if the hazard occurs. The severity of the consequence is evaluated on a scale 1-5, where 5 represent a hazard with a potential fatal outcome or critical injury. The severity then scales down through minor injury, large material damage, small material damage and lastly a '1' if the hazard is negligible. A similar 1-5 scale is also done for the probability of the consequence starting with a 5 for 'almost certain' and then continues down with 'likely', 'moderate', 'unlikely' and lastly 'rare'. The severity times the probability will then provide a combined score of the magnitude of the hazard, 'risk', that is scaled 1-25. This way a clear priority list can be made of which hazards is most critical and is in most need of mitigation and which hazard that isn't in need of as much attention.

2.8 Mitigation Plan

For the hazard with a higher risk needs a mitigation to lower the risk. A mitigation plan is a quick and simple way of stating potential mitigation actions to either eliminate or minimize the risk of the hazard. While the mitigation plan will offer solutions to mitigate each risk it does not offer a complete picture of the system, only focusing on one single hazard. It was therefore only used as a preliminary plan and work as a launchpad for the ideation of more complex and extensive solutions. The mitigation plan will only be relevant for the hazards with higher risk score. The lower risks could be good to include but is not a necessity.

2.9 Idea generation

Brainstorming has been the main tool used to generate ideas. By generating ideas to one or two selected needs at the time from the how might we question, the brainstorming went through the whole list of needs. Ideas that was created was written on a whiteboard and later into a digital document. From this the ideas were put at random into different complete concepts, to create an understanding of how the whole system could look like.

2.10 Pugh

Pugh matrixes was conducted to evaluate the ideas from the idea generation. A Pugh matrix is built of many characteristics which helps you evaluated the different ideas by comparing them towards a single idea which you set as a baseline. This idea is scored 0 for all characteristics and the rest of the ideas are scored either 0, for a similar fulfillment of the characteristics or get the score of 1 or 2 for a little/ much better fulfillment of the characteristics and vice versa, for -1 or -2. There are some characteristics which are more important than others, so the matrix weighted by applying a multiplying factor to those characteristics which are more important. All values are later summarized and compared with each other to find those ideas which scored the highest [10]. These are either used as they are or combined with each other to create the final concept.

2.11 Prototyping

A delving into one specific area of the general concept were a prototype has been constructed to prove the solutions functionality. The area of the general solution that is focused upon is the steering mechanism of the autonomous compactor. Thus, the steering on the compactor is physically done by regulating hydraulic pumps when turning the steering wheel, that in its turn controls the articulated joint and steers the machine, there is a need for a mechanism that can perform the operators job of controlling the steering wheel. Prototyping is an efficient and priceworthy way of determining if a solution is valid before it is put into reality. To build the prototype a brushed electrical DC motor from a height adjustable table was used and controlled by Arduino UNO via a driver/controller. Two different types of drivers were used; the L298n [11] and later the VNH3P30 [12]. For the transmission from the DC motor to the steering wheel, bicycle sprockets and chain is used. The tools used for the construction of the prototype is mainly metal and wood processing tools of various types but also 3D-printing, welding and soldering has also been conducted. Programming was done in Arduinos own software.

2.12 Conversations with Dynapac

During the whole thesis empirical discussions have been done with the supervisor from Dynapac. With these conversations, ideas and risks have been discussed to validate the work. Information in the risk assessment have been sent back and forth multiple times to Dynapac to get a valid risk assessment. During the meetings with Dynapac information which concerns the performance of the machine and how the machine behaves have been gathered.

3 RESULTS

3.1 Trend, Tech and Market Watching Result

The trend, tech and market watching has been conducted on three main areas of interests beyond road construction. These areas include the automotive and mining industry as well as industrial robotics, were autonomous technology is used and developed. Different technologies have also been studied to give a better insight of the sensors and equipment is being used in different autonomous solutions.

3.1.1 Compaction Roller

Hamm, a compaction roller manufacturer, have created a small test track for the purpose of conducting endurance testing autonomously [13]. At this track an autonomous prototype compaction roller is being tested on various different scenarios which the roller will endure during its life. The track is about 70 m long and is in the shape of a slightly curved s. It is not described how the compaction roller navigate the track, but by analyzing the pictures and the given information, it looks like the machine navigates through multiple light sensor which measure the reflected light from the ground. The edge of the track is bright white and the rest of the ground is dark grey. The track also got track obstacles in the shape of half cones which the machine drives over to test its durability. The track ends with a large slope for the machine to drive as high as possible. The machine drives back and forth the track around the clock when the conditions are favorable. Seen from google maps there are large spotlights which would enable the machine to drive at night [14]. In the beginning of the track there are a refueling point where the machine park itself after a test is completed. Around the whole track there are a fence to prevent people from accessing the area. This testing facility is however quite limited, it does covers a lot of the task that is wanted in a Dynapac endurance test but far from all. All the task it performs is done in a small scale which misses vital parts that is sought-after in a Dynapac endurance test. One such thing is the inability to perform sharp turns as there isn't sufficient space. It also eliminates the randomness that gives some variation to the test and simulates how a human driver would use the machine, and it doesn't have an area where the vibration for the compaction is tested.

Hamm have also made a driverless compaction roller concept which do its work while it follows a road paver. There is however no information about how this works or which type of sensors the machine is using or how far this is from being a reality. Hamm have also designed how an autonomous roller will look like and work in a real-life environment. The description is rough and the only usable information for us is that they will use GNSS to understand the amount a certain area has been driven on [13].

3.1.2 Automotive Industry

In the automotive industry there exists 6 different levels of automation according to the standard J3016 from the Society of automotive engineers (SAE), from 0-5, were 0 represents no automation and a 5 is an indication of full automation [15], see

Table *1*. This 0-5 scale of automation is something that is used merely in the automotive industry, when it comes to manufacturing and other industries there exists other scales to describe the automation level [16]. "A Model for Types and Levels of Human Interaction with Automation" describes level of automation on a scale 1-10, were 1 represents operations conducted by a human without any assistance from any computer and 10 stands for a fully automated process where the human is totally excluded [17].

Table 1, 6 levels of automation, standard J3016, from SAE international [15]

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/deceleration	Monitoring of driving environment	Fallback Performance of Dynamic Driving Task	System Capability (driving modes)
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	System	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	System	Human driver	Some driving modes
4	High Automation	the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	System	Some driving modes
5	Full Automation	the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver	System	System	System	All driving modes

For several decades automation of cars has been taken place and car manufacturers has been working their way up through the levels of automation (the levels presented by SAE). Various types of lane assists, cruise control, emergency braking and automatic parking are some examples of automation features commercialized by several different manufacturers and are located in the first and second level of automation. The jump from the second to the third level is considered the hardest step to make and currently it is only Tesla that is considered (depending on who you speak to) to have reached this level. Other car manufacturers are planning to jump directly to level 4 from level 2, this referring to the safety issue of having shared responsibility between the car and driver (level 3). A process with high autonomy that isn't perfect and still needs some supervision is in risk of being totally trusted over time by its supervisor. If an accident then occurs the supervisor won't be able to respond as stated in "*A Model for Types and Levels of Human Interaction with Automation*" from 2000 [17]. The autonomous compaction machine concept will be equivalent to SAEs 4th level of automation. This is considered the hardest step to fulfill in the automotive industry, but for a compaction roller in an enclosed area it is much easier.

Google's Waymo project had in February 2018 logged 5 million miles (ca 8 million km) of autonomous driving on the public roads in various location (mostly urban) throughout the US [18]. Just as many other big actors in the business, the data collected from these logged miles is being used as experience to the computer that drives the cars so that an autonomous car of level 4 can be commercialized. The Waymo cars uses a combination of LiDAR, radar and cameras in an integrated way to map and detect its surroundings. The LiDAR (Light Detection And Ranging) creates a 360-degree 3D-map of anything around the car, effectively keeping track of pedestrians and other vehicles around the car. It can even be used to determine and predict the movement of other road users. The cameras are used to scan signs and other traffic signals that the car needs to follow. The radar sensors are used as a complement to the other sensors as it is the best alternative in bad weather conditions [19]. The Waymo car doesn't rely on GNSS to find its way in the world, the cars sensors create a highly accurate map that is used to locate the car's position. GNSS is however used to determine the car's route [20].

One of the biggest problem for all autonomous cars is the weather. Big companies have logged millions of autonomous miles, all in clear weather because of the fact that autonomous system does work poorly in bad weather. The radars, LiDARs, cameras that is being used to collect information of the cars surroundings can't function at the minimum required level for the cars to handle bad weather in form of rain, fog and snow [21]. The equipment will also have problem with dust.

Toyota is testing their type "Avalon" for rough road durability by driving over a lot of potholes on a track in Michigan in speeds of up to 100 km/h. This endurance test is performed by an Avalon which is converted to become autonomous on that specific track. The car from the factory have advanced navigation and driver assist sensors like, LiDAR and cameras but they are not used in the test. The car navigates the track using a high precision GNSS with an accuracy of about 20 mm. The track is restricted from other activates and no human is allowed on the track meanwhile the autonomous car is driving. Toyota have supervisors which keeping an eye on the car at all time using cameras placed at different locations on the track. To turn the steering wheel, apply brakes/gas and gear shifting, Toyota's engineers have made a couple of unique robots to perform these tasks. By replacing humans to perform this test they save the health of the test drivers which needs to perform these rough and exhausting tests, but they also increase the amount of testing which can be done since the autonomous car only needs to stop for refueling meanwhile if performed by humans, a driver change is necessary every 30-40 minutes to not hurt the test drivers. Another advantage of using autonomous system is the continuity of where and how the car is driven on the track, this results in better test data with less noise. [3].

3.1.3 Mining Industry

A typical mining site, both underground or open pit, is a hostile environment for any human worker. With trucks, excavators, loaders and bulldozer in the same size of a smaller houses, constantly moving around the mining site, as well as rock falls and explosions, there is a considerable risk of accidents with injuries or even fatality as outcome. In especially the underground mines the workers are also exposed to the noxious exhausts which the machines emit and constitutes a health risk for the workers.

Autonomous technology has for the past decade been implemented in the mining industry on different levels to move the workers from the mining site to a control room. Prominent actors in the business include companies like Caterpillar [22, 1], Komatsu [23], Sandvik [24] and Epiroc [25] who offers solutions on different levels of autonomy. From semi-autonomous machines that allow one single operator to remotely manage several machines to the fully autonomous machines that operates without any operator. This trend does result in workers no longer has to be exposed for unnecessary risks and in that way, raise the safety on the sites. It also has a positive impact on the mining efficiency. Autonomous vehicles will operate tirelessly with the same pace around the clock, only stopping for refueling and maintenance, which means that the vehicle will work both faster and more hours per day than a manned vehicle would [2]. The fully autonomous trucks provided by Caterpillar achieve 20% higher productivity than the manned vehicles did on the same site, according to Caterpillars own technology manager Craig Watkins [1].

When designing for autonomy it is important to be able to predict different situations that might occur and design in such a way that the situation can be handled in a safe way. A mining site is an enclosed area were all vehicles and workers can be controlled and regulated. This means that the different situations that occur is limited and can therefore be predicted more easily. In contrast, autonomous vehicles/machines that is operating in more public accessible areas, such as cars, will have seemingly infinite unpredictable situations which needs to be managed and will therefore need a more robust system. Separating human and machine also terminates the risk connected to the human factor but isn’t always an option. Today's modern mines are often operated by both autonomous or semi-autonomous machines (ASAM) and manual operated machines. This is possible by sharing information like positioning, velocity and direction between the machines. The machines operating in open pit mines usually uses a highly accurate global navigation satellite system, GNSS, that provides coordinates of the machine in real time that has an accuracy of a couple of centimeters [26].

There are many different mining machines that operates a mine, and these machines has reached different stages of automation. Bulldozer, load-haul-dump trucks (LHDs) and blast hole drills is examples of machines that is on a semi-autonomous stage were the operator still remotely manages key-operations and then let the machine autonomously carry out simpler tasks. This allow one operator to manage multiple machines. Dump trucks that operate surface or open pit mines are the machines that currently reach the status of fully automation. They carry out all tasks autonomously from the loading to the dumping. Even refueling has been automated and is carried out by a specially designed robot. The autonomous dump truck relies on its highly accurate GNSS as mentioned before as well as various combinations of different detection instruments and advanced sensors in order to navigate safely around the mining site. Human operators task is to monitor the process [1] [23].

3.1.4 Robotics

Industrial robots have been taking over manufacturing for the last decades and the development of these machines are extensive. Major progress has been done of how to control the robot and to improve its precision [27], But more relevant is how they prevent people from getting too close to the robot and get injured. Depending on the location and the tasks assigned to the robot it requires different safety layers. Most often there are a fence separating people from the machine and a door to enter the area, which is hooked up with non-contact sensor, which will put the machine to an emergency stop if the contact is broken. The door can also be locked with electromagnetic force or a lock to prevent people from opening the door. For open spaces in the fence where goods are transported light curtains is used to prevent anybody from accessing the area unnoticeably. The placement of emergency stops is crucial to prevent anybody from getting hurt and needs to be placed where they are easy to reach. If the machine needs to be operated by hand from the inside of the fence the controls are in a safe distance away from the robot and have 2 or 3 touch points which needs to be pressed and hold to operate the machine, this prevents the operator from approaching the machine while its moving [28].

Robot lawn mowers are designed to cut your grass in a random pattern and the more advanced machines will track its position using GNSS to cover the assigned area as evenly as possible. Some lawn mowers also have ultrasonic sensors to detect object in its path [29]. To prevent the machine from escaping the area, a cable is dug down in the ground which the lawn mower senses and chooses another direction. To guide the machine back to the charging area a similar method exists, but this time the machine follows another cable in the ground until its back in the charger [30].

3.1.5 Sensors

3.1.5.1 Positioning and Orientation Sensors

GNSS is a common and well used technology for positioning determination. By measuring the distance to (at least) four satellites via radio signals, it is possible to determine the location of receivers on earth. The GNSS is commonly used in many types of vehicles, from cars to airplanes and ships, most cellphones are also today equipped with an GNSS receiver. The accuracy is normally within a few meters, but using RTK (Real Time kinematic) a boosted accuracy of just a few centimeters can be reached [31]. The GNSS receiver needs to be in range of the satellites radio signals, which means it works best outside. When using RTK two receivers is needed, one mobile and one stationary that acts as a sort of reference [32]. The two receivers have to be within a certain range of a few kilometers which limits the area of operation. Local positioning system (LPS) can be described as a downsized GNSS and instead of providing coordinates globally it is focused on a smaller limited area. Instead of satellites as the GNSS uses, LPS measures the distance to a beacon or tower located on earth, three to four of these beacons are needed to determine the position of the receiver.

3.1.5.2 Vision sensor

Vision sensors are used to not only measure distances but more importantly to identify objects and/or signs. Cameras in combination with computer vision software can be highly effective to identifying both objects of different shapes and signs on a range of up to 120 m, the maximum range for detecting pedestrians is however set to 60 m [33]. It is a proven technology that is used on several of the autonomous prototypes that is being developed and used commercially in functions as collision warning systems and lane assist. Cameras can be used to predict an object's movement. Cameras does, however, have some drawbacks, their vision is limited in bad weather conditions and is also sensitive to various optical conditions (day/night, sun interference).

3D-LiDAR is a technology were several laser beams measures the distance to over a million different points in its surroundings per second. When all the points are combined they create an advanced 3D-map of the surrounding which is then used to identifying different objects and predict the object's movement (speed and direction). The technology is very modern and has a quite high price tag. A Velodyne LiDAR puck have a range of up to 200 m and a 360-degree vision. The 360-degree vision is possible by rotating the lasers at high speed and in that way acquiring data points all around the sensor. The LiDAR has an accuracy of up to 20 mm according to its manufacturer [34].

3.1.5.3 Distance sensors

Distance sensors are used to determine the range between the sensor and an object, it can also be used to determine if the object is in motion or not. In contrast to the vision sensors, the distance sensors are unable to identify different objects and distinguish them from each other’s.

A proven distance sensor is radar, were the sensor sends out radio waves and measures the time it takes for them to hit an obstacle and bounce back. It has a long range that depends a lot on the type and purpose of the radar. The waves of the radar spread in like a cone and therefore has a slightly inferior accuracy then other technology [35]. A good radar from Bosch has an accuracy of 120 mm and a range of 250 m. The radar also has angular range of about 12 degrees [36]. Another benefit of the radar is that it is operational in all weather conditions, as long as it is not covered by e.g. snow, mud or dust.

Another distance sensor technology is LiDAR who also exists in a simpler version, “2D-LiDAR”, that measures the distance in similar way of the radar but using light instead of radio waves. By using light, the LiDAR is considerably more restrained by weather than the radar. It compensates in accuracy but has to be place in the right height and angle thus it only registers object in a straight line in front of it. This makes a benefit in terms of accuracy but it also allows for blind spots due to the lack of coverage area. Its simplicity makes much cheaper than 3D-LiDAR [35].

Ultrasonic sensor is another type of distance sensor, instead of radio waves or light, it measures the time for ultrasonic waves (sound) to bounce back from an object. Relying on sound brings both benefits and drawbacks, sound waves is not affected by the weather such as snow or rain or by any optical conditions (night/day, sun interference, etc.), sound waves are however affected by the temperature and thus the software needs to be adjusted accordingly to current temperature. Vapor do change the change speed of sound in the air and makes the sensor inaccurate, which could be a problem in heavy fog. Different sensors have different range, but generally the ultrasonic sensors can’t compete with the radar or 2D-LiDAR when it comes to range, having a range of about 20 meters. The accuracy depends on the range of the object, and is defined as better than 1% of the distance to the obstacle [37].

3.1.6 Motors

3.1.6.1 Stepper motor

The stepper motor is a simple and robust motor that ensures low maintenance cost at a relatively low price. It is good for positioning and doesn’t need any external equipment to track its angle. The stepper motor also offers a high momentum at low rpms. At higher rpms the motor loses its momentum. The stepper motor might also get some problem with resonance which might lead to lose in momentum and track of position [38].

3.1.6.2 Brushed DC motor

The brushed DC motor runs very smooth and has a high efficiency. The motor can be produced on a large scale and is therefore a cheap motor alternative. The motor uses coal brushes which is worn out and raises the maintenance of the motor. The brushes might also generate sparks that will make the motor unsuitable for some applications. This motor can’t however be set to a specific angle without implementing external sensors. [38].

3.1.6.3 Brushless DC motor (Servomotor)

The brushless DC motor has a very high efficiency and the lack of any coal brushes makes it suitable for any application. Special magnetic materials and an expensive manufacturing process places the brushless DC motor in a high price class [38].

3.2 Risk assessment

The risk assessment (see Appendix A - Risk) resulted in just under 80 identified hazards for autonomous testing of a compaction roller. The risk assessment reevaluates the hazards that existed for previous conducted endurance tests as well as newly acquired hazards that appears when the test is made autonomous. The hazards are identified by analyzing data and information provided by Dynapac as well as analyzing other similar autonomous systems. A lot of information has been provided by the ISO 17757:2017 standard about “Autonomous and semi-autonomous machine system safety” [39] in the mining industry.

There were four hazards that scored a 10 (on a 1-25 scale) in total risk value and these hazards was therefore put into focus when developing the requirements on the autonomous system. The four hazards with the highest risk, number 60, 61, 72 and 74, reached a risk score of 10, all with the combination of a high severity of 5 and a relatively low probability of 2. Hazard No. 60, inability to deal with blind spots or objects obscured by other objects, can have devastating and even fatal effect for any human in the machines present. The limited access to the machine however decreases the probability of the hazard occurring. The best way to mitigate this hazard further is to either eliminate the blind spots or not allowing any persons in the AOZ when the machine is active at all. Hazard No. 61, switching from idle driving when a human is present, is closely related to the previous hazard. This hazard might appear when the machine is stopping for maintenance or inspection and human personnel is in the machines present. If the machine should switch from idle driving in such a case the nearby person would be in danger of being hit or squeezed by the machine. This hazard can be mitigated by various safety measures to not allowing the machine to leave idle drive mode or/and by completely shut down the machine when allowing persons access to the machine. Hazard No. 72, if the machine drives into the wrong section of the track while maintenance is being performed, this also constitutes a risk for the people working there. Having humans in the presence of a machine in autonomous mode is always a hazard and should be avoided if possible. To mitigate this hazard maintenance should only be conducted while the machine is not operational. If hazard No. 74, the machine escapes the AOZ, occurs there is a big risk of damaging its surrounding or even injuring nearby persons. This risk has a low probability because of that it is only possible if several malfunctions occur at the same time. There should be several levels of safety measurements that work to prevent this situation. Multiple systems should be installed to be able to hinder this scenario from ever happening or/and to be able to stop it if it ever should occur.

Table 2, cut out from the risk assessment showing hazard No. 60, 61, 72 & 74.

No.	Class	Subclass	Hazard	Potential consequences	Severity (1-5)	Probability (1-5)	Risk
60	Sensor/ Detect object	Blind spot	Blind spots, objects obscured by other objects	Unable to detect objects in that spot	5	2	10
61	Sensor/ Detect object	Blind spot	Switch from idle to driving when a human is present	Injure human	5	2	10
72	Software	Driving cycle	Drives wrong test section, while personnel are working in that section	Injure the personnel in that section	5	2	10
74	Track	Area	Machine escapes from area	Machine out of control	5	2	10

3.3 Requirement specifics

The risk assessment is compiled together in a requirement specification list with a linking reference to either one or several hazards in the risk assessment (RA) or another relevant reference. The requirement specifics are meant to act as guidelines for what minimum of requirements that must be fulfilled to perform autonomous endurance tests on a compaction roller. It is required by Swedish working environment law (Arbetsmiljölagen, AML) to change or replace any condition that is a risk of accidents or the health of the worker [40].

3.3.1 Requirement specific list:

1. Area limitation- Physical barrier {RA: 60-69, 72, also in “Fordonsförordningen & Fordonslagen” (Swedish law & regulation) [41] and ISO 17757 [39]}
   a. During autonomous operation the machine shall be separated from all other activities. Safety precautions shall be taken so that the machine can’t or won’t start when a person is located within the AOZ and so that the machine is inaccessible during operation.
   b. Unauthorized personnel shall not be able to access the area in any situation.
2. Distance/vision sensor {RA: 37–39, 43–56, 59–70, 76}
   a. The machine shall be able to detect objects and hinders in its driving path at a distance equal to 2 times the braking distance.
   b. The machine shall be able to detect objects and hinders that is located in an area that departs 40 degrees from its driving path.
3. Positioning sensor {RA: 40, 41}
   a. The Machine must be able to locate itself on the track and with enough precision to be able to maneuver within the area without ramming the physical barrier.
4. Which weather it can operate in {RA: 43–56}

    a. The equipment of the autonomous system must be operational during bad weather conditions such as rain and fog. (Extreme weather as well as snowy and icy weather is not included.
5. Failure detection {RA: 1–17, 22–58 and ISO 17757}, [39]
    a. Critical failures must be detected immediately and result in an instant machine stop.
    b. Not critical failures shall be detected within 24 hours.
    c. If power is lost or a sensor cannot fulfill minimum requirements, the machine shall brake and stop.
6. Prevent machine from escaping {RA: 74}
    a. Machine shall not be able to escape from the area when in autonomous mode and shall have multiple safety system to prevent this from happening.
7. Blind Spots {RA: 60, 61}
    a. The solution shall ensure that no person is able to enter a blind spot while the machine in operation and/or located in a blind spot while the machine is being started.
8. Autonomous mode {ISO 17757} [39]
    a. Switching from manual operation to autonomous mode shall be done only by authorized personnel and from a location outside of the AOZ.
9. Emergency stop {ISO 17757} [39]
    a. The autonomous machine shall be able to put a halt remotely by any personnel that is located within the machines surrounding. Intervention by an authorized operator would then be required to continue in autonomous mode.
    b. The autonomous machine shall be equipped with emergency stops that is easily accessible from both outside and inside the machine.
10. Warnings {ISO 17757} [39]
    a. The machine shall be able to indicate to its surroundings that it is in autonomous mode.
    b. Warning signs must be placed around the perimeter and at every entry point to the AOZ to inform about the activity and danger within the closed area.

It should be noted that there are several ways of fulfilling the requirements stated above. The requirements are primarily guidelines that shall be followed to guarantee a safe performance of the endurance test autonomously. The requirements are a result of the risk assessment that has been conducted of the scenario were the compaction roller performs the endurance test autonomously in an area separated from other activities. Some of the requirements do also partially or completely originate in other sources, the main one being ISO 17757:2017, “Earth-moving machinery and mining - Autonomous and semi-autonomous machine system safety”. The mining industry has reached far when it comes to autonomous systems and has many things that is directly applicable to the compaction roller. The need for emergency stops, warning signs and indications is pretty much the same as in the standard.

3.4 Concept

The final concept will be of autonomy level 4 (see Table 1) and will be in a closed area. To become temporarily autonomous while the endurance test is carried out it has multiple systems which can be mounted and dismounted on a variety of Dynapac roller. Navigation of the roller will mainly be handled by GNSS which both choses path and define the perimeter of the track. As a safety feature a radar is used in the front and the rear, to enable the machine detecting foreign objects in its path. The machine will stop at a safe distance from the object and will not move until it is gone. Both the steering and the propulsion needs to be regulated using an onboard computer. The propulsion can today be regulated using electricity meanwhile the steering needs an additional system which uses a servomotor connected to the steering wheel to adjust the correct steering angle. To simplify dismounting of the steering system, the steering wheel and the motor is connected by screws and of a design which can be adjusted to fit a variety of Dynapac roller. To identify malfunctions, the most hazardous faults is monitored all the time using sensors meanwhile the other, less vital hazards, are analyzed by a person daily. Everything shall also be monitored with CCTV and be remotely stoppable if necessary. Since the autonomous roller can't be trusted enough to operate alongside humans, the perimeter is sealed by a meshed fence to prohibit interactions between the machine and unauthored personnel. To enter the AOZ the machine needs to be remotely shutdown before an authorized person enters the area through a gate. This person will look for malfunctions and also refuel the machine daily. A more detailed description of the system is found in the subchapters 3.4.1 - 3.4.7.

3.4.1 Steering

When the steering wheel is turned, a valve to a hydraulic pump adjusts the amount of hydraulic oil which goes to the piston. This leads to a change in pressure and the piston will either go out or in, and this turns the machine [4]. This makes the steering system only mechanical and not adjustable through the use of a computer. In order to perform autonomous steering by the machine this needs to be controlled by a computer. The solution needs to be reliable and able to steer the machine with the same or better precision as a human operator. It is also important to not fully remove the ability to operate the machine manually, since the machine will be transported and moved at rare occasions outside of the track. At these occasions it will be operated by a human. Considering the compaction roller will not use the autonomous steering system on the customer product, it is important that it isn't too complex and can be adaptable to other compaction roller prototypes.

Figure 5, Steering on a conventional compaction roller.

This can be addressed in multiple ways. One solution was to manipulate the pressure valve to the pump by removing the steering axis and put an electric motor on the valve which is controllable through a processor. The motor can also be controlled manually by a regulator on the control panel to allow a human to steer the machine. This solution is not feasible since it changes major components on the final product and the main objective with the endurance test is to find out which parts which will break and needs to be modified before the product goes to market. A further way of controlling the steering wheel is with the use of friction. One friction solution is to have a smaller ductile wheel of rubber connected to the steering wheel. The rubber wheel is connected to a servo motor which is connected to a computer. To gain manual control of the machine the rubber wheel will slide along a rail to the degree when the connection between the two wheels are lost. One more friction solution was to use four spools connected to the rim of the steering wheel in a rectangular pattern. All the spools were connected with a chain, too turn at the same time and with the same speed. The chain was also connected to a servo motor using a sprocket which generates the speed and angle of the system. By pressing a new button on the dashboard which turns of the stall torque on the motor, manual control is gain and the steering wheel will be turned using the conventional steering knob. The steering shaft is splined in the end where it connects to the steering wheel. This could be used to connect a splined gear instead of the steering wheel to rotate the shaft. The gear will then be connected to another gear on a servo motor. Manual control is achieved by regulating the servo motor using a potentiometer. A different idea of using the steering wheel was to connect it with a gear which is locked into place by hooking it up by the three spokes on the steering wheel, and manual control is gain in the same way as the previous idea.

The solution which was chosen to build a prototype of, was the idea where a gear is connected to the steering wheel by hooking it up to the three spokes. Compared to the others, this idea is simpler to build with a low budget and the equipment which we have. To our disposal we had an Arduino kit, metal/ wood processing tools, 2 sprockets with chain from a bicycle and a 50W brushed motor with a gear box. The idea is also simple to adapt to the other compaction rollers at Dynapac, since all use the same steering wheel and the same dimensions on the steering shaft. The prototype was further developed to adapt it to our resources. The connection between motor and the steering wheel was built of two sprockets with a chain to rotate the wheel. A wooden plate is created to attach the sprockets to the assigned equipment. The sprocket on the steering wheel is connected by two cable ties and a bent threaded rod. (Intent was to use three pipe clamps to hook the gear to the steering wheel but they were not available at the time of the build). By creating a custom bracket using square steel pipes and pipe clamps the motor got a stable connection to the frame. The gearbox on the motor creates a sufficient gearing for the system, unfortunately it doesn't have a good joint to connect the sprocket to. This is solved by attaching the sprocket to a rod with hexagon socket which fits the gearbox. Sadly, the rod makes the system wobble since the hexagon joint on the gearbox is not fully fixed in radial direction and allows movement to some degree. This is solved by designing a "anti-wobbling bracket" which is 3D printed and fitted around the rod. This bracket also prevents axial movement of the rod (This anti-wobbling bracket is not part of the final solution and is only in the prototype since it is need to make current parts work together). To determine the angle of the steering, a hall effect sensor is used to track magnets attached to the steering wheel. The hall effect sensor is placed on the top of the "anti-wobbling bracket". The intention is to use a servo motor or a step motor, but due to our low budget we couldn't afford one of these motors. (With these motors an angle can be coded and given to the motor, which makes the hall effect sensor system redundant). All electronics are connected to an Arduino UNO board, and is coded to turn the steering wheel when a handheld joystick is used or when you set a specific angle in the code. The prototype ended up being only manually controlled through a joystick to decide the steering angle, since the hall effect sensors didn't detect all pulses which resulted in inaccurate angle on the steering wheel. Since the hall effect sensor is not part of the final concept of the steering it was decided to terminate this part of the prototype. The prototype of the steering was tested on a Dynapac CC4200 machine and worked as intended. The steering wheel turned when the joystick was adjusted and stopped when the joystick was in the "zero" position. A couple of different speeds on the motor was tested to try out how fast and how responsive the steering was. The prototype could rotate the steering wheel more than enough and at the highest tested speed the machine turned so fast that people on the machine would have been thrown of it, if they hadn't held on to the safety cage around the roller. Since this prototype consists of inferior equipment than what is need for a final autonomous compaction roller, was this only a proof of concept and further development of controlling the speed on the motor to make smooth turns was not done.

Figure 6, Prototype of steering with motor, gearbox, "anti-wobbling bracket" (green and black), sprockets, chain and connection bracket is visible.

Figure 7, Prototype of steering with motor, gearbox, "anti-wobbling bracket" (green and black), sprockets, chain and connection bracket is visible.

Figure 8, Prototype of steering with sprockets, sprockets connections and chain visible.

Figure 9, Successful test of the prototype on a moving Dynapac CC4200 compaction machine.

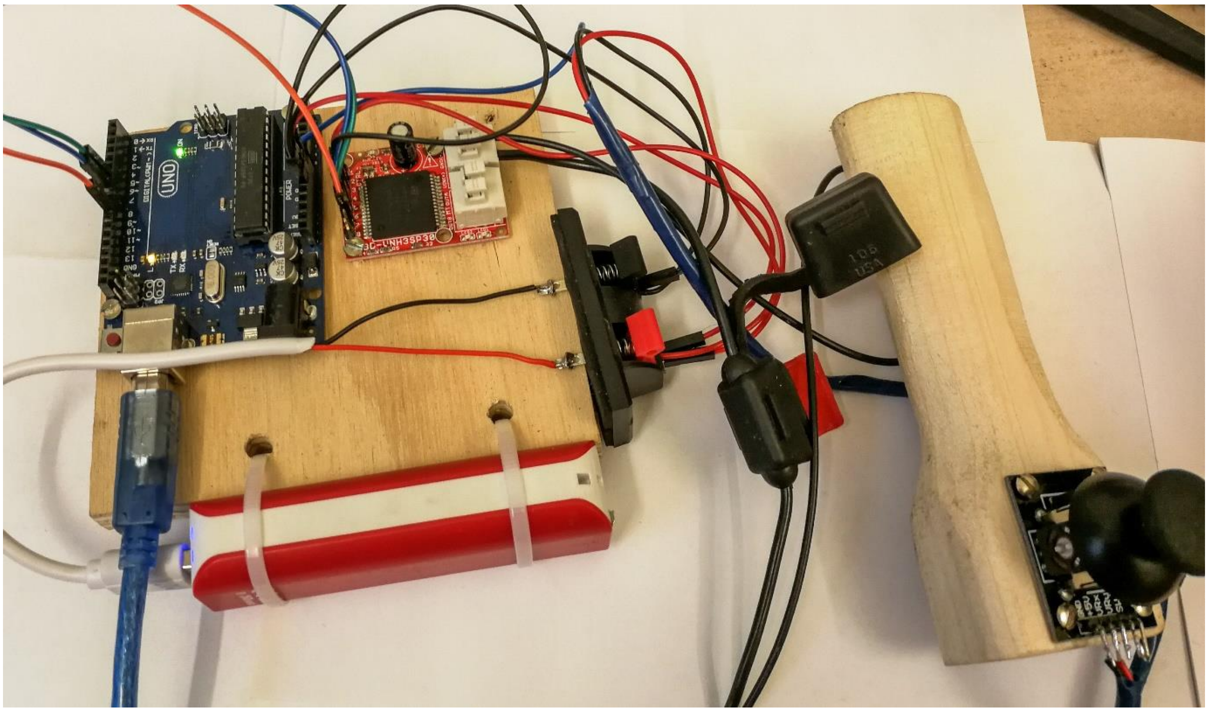

Figure 10, To the left is the Arduino UNO board and the VNH3SP30 motor driver. To the right is the controller with the joystick.

The prototype turned out to be successful and gave valuable information of how to refine the concept for the final solution. It was decided to keep the idea of attaching a gear to the steering wheel but instead of hooking it up to the three spokes using pipe clamps, will the gear be connected on the steering wheel using splines. The gears which are between motor and steering wheel will be of the model helical to ensure a good connection when the roller is operating and not decrease in performance when the machine is vibrating. The motor should be of the type servo, since these motors can be used to set a specific angle when controlled by a computer. It was discovered in the test on a real machine that the pipe around the steering shaft is sufficiently attached to the frame and can be used to attach the motor on. This will be done by a custom bracket which is bolted to the pipe around the steering shaft and the motor, using pipe clamps. The steering angle will be determined by GNSS coordinates and processed by a computer, which will control the motor to turn the proper amount. When the steering system for the autonomous compaction roller shall be moved to another machine the easiest way is to move the whole steering wheel with its connected gear to the next machine along with the motor and its bracket. Since the same steering wheel is used on all machines and only connected with one nut, the change will be quick and easy.

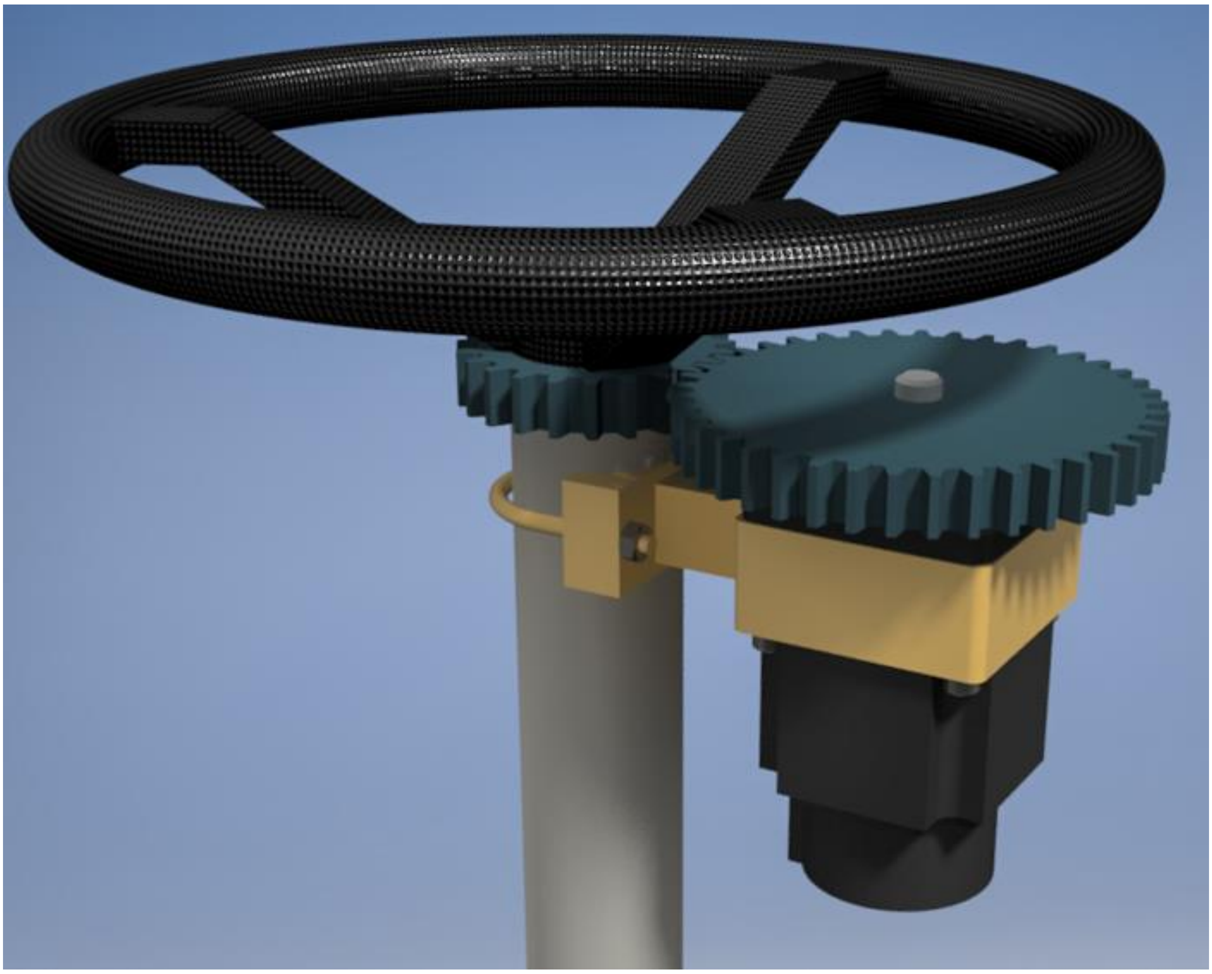

Figure 11, CAD model of the final concept of the steering.

3.4.2 Propulsion

Regulating the speed of the machine is also a vital part of the automation. The propulsion of the machine is however mostly managed electronically with a potentiometer and a lever, and can in these cases be managed electronically directly by the computer when in autonomous mode. In some of the smaller machines the propulsion is regulated by a lever connected to the throttle by a wire. In this case there will have to be a solution for doing the manual work of pulling that lever. Two main ideas of how to do this was generated to solve the problem. The first idea is built around controlling the throttle lever, which would be best done by rotating the axis where it is fixed. The easiest way to do this would be by a servomotor to get high precision. The second idea would be to disconnect the lever and instead pull the wire directly with either a motor or a hydraulic arm and control the throttle this way. Disconnecting the throttle lever would however disallow manual control of the machine which is needed when transporting the machine to and from the test track. The selected solution for our concept and most effective way of controlling the throttle is electronically by a computer, but in those cases, were that isn’t possible the solution would instead be to control the throttle lever by a servomotor around its pivot axis.

Figure 12, Control panel of the propulsion of the existing machine. As seen is everything electronical controlled and thereby easy to convert to autonomous control.

3.4.3 Human Safety

Conducting experimental autonomous tests has to be done in an enclosed private area by Swedish law, if not having any permit for such activity [41]. Area limitation is important for preventing unauthorized people to come in touch with the autonomous compaction roller. By driving the compaction roller in a closed area, unauthorized people will not get subjected to hazardous situations with potential devastating consequences, as it is stated in the requirement specifics list (requirements 1a & 1b). The machine will also be allowed to work continuously without interruptions and interference, which will raise the efficiency of test performance. Since the machine is still a prototype machine when conducting the endurance test, it can be taken for granted that parts and components will, sooner or later break, which in some occasions will affect the machines operability (see Appendix A - Risk Assessment) and hence human presence would always be subjected to the risk of a malfunctioning machine. Removing all other activity around the autonomous machine will also simplify autonomous system significantly, since there will be fewer factors to take into consideration and predict.

One of the greatest risk of autonomous endurance test is injuring a human (see Appendix A - Risk Assessment) but human contact with the machine cannot be excluded totally. Contact between machine and service personnel cannot be avoided, since the machine still needs refueling, eventual maintenance and close up inspection. Since the machine shall be kept separated from all other activities during autonomous operation (requirement 1a) the machine must be switched out of autonomous mode and/or shut down completely, so that personnel can enter the area and perform the refueling or maintenance. This is estimated to be done at least once a day. Autonomous mode shall then only be able to reactivate by an authorized operator.

The best way of limiting the area to keep out unauthorized visits is by enclosing the area with meshed fences. It is an efficient solution that is considerably cheaper than for example a wooden fence or a wall. A meshed fence will also offer visibility into the enclosed area which will ease supervision of the machine. Every entry to the AOZ must be equipped with an access control system to guarantee that no one is able to enter when the machine is operational in autonomous mode. Warning signs must be placed around the perimeter to inform of the activity inside the enclosure and the potential hazard of the area, as required by requirement 10b. To indicate that the machine is currently operating in autonomous mode a rotating light on top flash in a color that differs from the rollers own waring light so it can't be mistaken for the usual warning light. To further alert the machines surroundings of that the machine is entering autonomous mode, the machine will give of a sound signal with machines horn. If any person is near the machine in this moment, they will not be totally surprised when the machine is set in motion.

If any accident should ever, despite all safety measures, occur it is important to easily be able to shut down the machine quickly. As stated in the ISO 17577 [39], an autonomous machine shall be able to be stopped from a safe remote distance, for the compaction roller this translates into installing emergency stops on the fence surrounding the AOZ, especially at every entrance of the area. The ability to stop the machine shall also be possible from the surveillance room were the system operator can monitor the machine. Emergency stops shall also be placed on the machines body, easily accessible for anyone that is too close to the machine (requirement 9b). When the machine is stopped, it shall only be possible to restart it into autonomous mode by a system operator (requirement 8a and 9a).

3.4.4 Navigation

The compaction roller performs several different tasks within the endurance test that all have their own requirements on how they should be performed that require different levels of advanced technology. The easiest way to perform the test would be to have totally predefined paths that the machine just follows. This is however not the most efficient way of conducting the endurance test thus it removes the randomness that is provided by a human operator and it would therefore give an unjust simulation of the machines real working environment.

The compacting phase is to simulate the machines working phase on a road construction site and were the machine drives back and forth while changing lateral lane. It is a repetitive task which allow for a predefined path. Continuity and a smooth driving is sought-after in this phase and is something that an autonomous machine will do better than an operator. Some distance variations in the different back and forth routes is still needed to mimic an operator's driving behavior. It is enough to just have a few meters variation that is randomized. In the transportation phase there is a need for both predefined and random driving pattern. The random driving pattern is here wanted to again mimic how the machine is used in its real working environment were its transportation distances always will differ from each other. The predefined pattern is wanted to spread the wearing on the ground that the machine causes equally around the area to reduce maintenance. The transportation phase also includes the tasks of driving in an 8-like pattern, drive over "cones" and test the machine acceleration and retardation. This additional task would also need predefined conditions. Another parameter to take into consideration for this problem is the precision needed to perform autonomous endurance test. The high level of accuracy in determining the position is needed, as the machines ability to "see" is limited because of the choice to use radar, that only measure the distance to an object. The positioning and orientation system will be the main system for making sure that the machine stays within its perimeter by creating a so called geo-fence, as its required (see requirement 6a). The geo-fence will define an area within the fence, that the machine is allowed to drive within. If the machine should ever be located outside the geo-fence, the machine shall immediately shut down and inform the supervisor. The area defined by the geo-fence has to be smaller than the fenced area so that a safety distance to the fence is established. Relying on the positioning system to keep the machine within the perimeter, sets high requirements on the system in terms of precision, availability and reliability.

To meet the requirements on the positioning system stated above, the machine will rely on a high precision GNSS or LPS. The high precision will ensure that will be able to locate itself and maneuver within the AOZ (requirement 3a). Ideas of how to define the driving path in different way were ideated, among the ideas were the use of GPS drawing to spread the utilization equal around the test area. GPS drawing is a method to track the locations a machine has been at in the past. By analyzing the past coordinates a future path can be determined which optimizes the use of the designated area. This would be used when driving in a random path pattern to prevent uneven wearing on the track that otherwise could appear. Other ideas of how to define the driving path was also ideated in the early stages of the ideation phase. Ideas of having the machine following a predefined path, that is in some way outlined physically in the test track, e.g. following a line in the ground using sensors to identify it. With these types of ideas there wouldn't be the same need for the GNSS. However, these ideas were deemed to be too inflexible to rearrange and wouldn't give the "randomness" sought-after to simulate a human operator's driving path and was therefore abandoned in favor of the use of GPS drawing. The use of GPS drawing would however only be used for the transportation phase were the demand for a random driving path existed most. For the other phases and tasks, the path would have to be predefined by GNSS coordinates, with some variation factors as described above when it comes to the compaction phase.

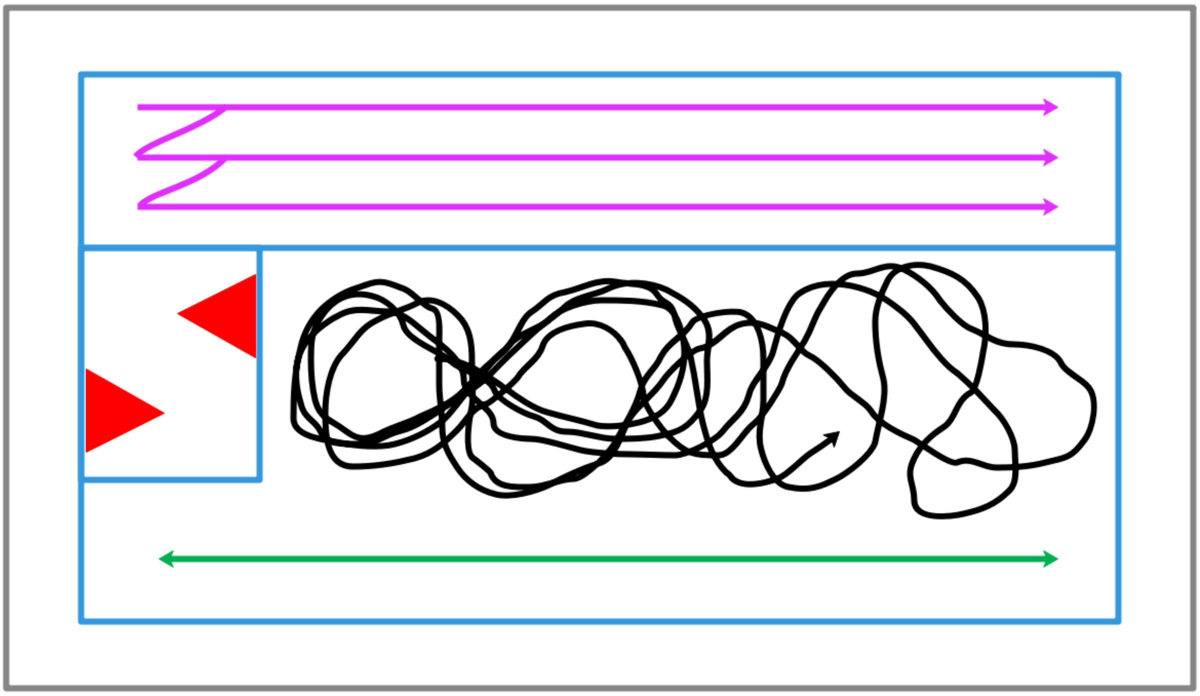

Figure 13, Track layout where purple demonstrates the compaction zone, black the random section, green the acceleration and breaking section and the red demonstrates the cones which shall be driven over. Blue demonstrates the geo-fence and grey is the meshed fence.

3.4.5 Malfunction Detection

Detecting failures of the machine is an important part of a human operator's job during the endurance test. Since the compaction rollers in question only are prototypes, it is certain that faults will occur. Unfortunately, it is close to impossible to predict what specific fault will occur and when. Faults which has occurred with earlier tested prototypes are the following: frame collapse, articulated joint collapse, wear on hoses, leaking hoses, loose hose connection which results in leakage, loose oil filters, indicators failures, door/ hatch locks failures, external components like mirrors which have fallen of, loose screws on various places [4]. It is problematic to detect these when driving autonomously since the characteristics of the different faults is widely spread and need multiple solutions for detection. It is suggested that the faults are categorized by how emergent a fault is for the operation of the roller. Where critical failures need to be detected rapidly to shut down the machine instantly, as required by requirement 5a, and faults which doesn’t prohibit the performance of the test can be detected hours later (requirement 5b). Analyzing the historical faults; frame collapse, articulated joint collapse and leakage of oil/ fuel is categorized to be critical faults and the rest is not that vital to be detected right away. The machine will be checked on at least once every day by the operator to gather test data and refuel the machine. The less urgent faults will be detected by this person and written down. Meanwhile the critical faults need different specific solutions to be detected. Leakage will be detected by measuring the pressure on the fluid and compare it to reference values. By comparing the engine output value with the GNSS coordinates change, serious malfunction on the machine can be detected. If for example the machine is register a speed of 10 km/h but the GNSS can’t register any positioning change that will be an indication of that something is wrong on the machine and the system should shut down. Similar fault detection can also be done between the steering and the gyroscopic sensor and/or GNSS, if the machine is turning but no indication is registered on either the gyroscope or the GNSS a similar conclusion can be made. Frame collapse, articulated joint collapse and similar malfunction will be detected by this kind of comparisons. This method will also work to detect if there is anything wrong with the sensors, as it could be either a sensor malfunction or a machine malfunction. In any of those cases the machine should stop and be shut down, as both are too serious for continued testing (requirement 5a & 5b).

Monitoring the compaction rollers domestic values that is already registered in the rollers computer is a way of detecting if something is wrong with the machine. Continuously comparing these values to predefined reference values would give status on engine systems. Deflecting values should be dealt with an appropriate response. The autonomous roller shall also be monitored by surveillance cameras to allow responsible system operator to quickly be able to check in on the machine and if necessary be able to remotely shut down the machine. The camera surveillance is meant to be a tool for the system operator to check in with machine without needing to physically visit the testing area every time. It can be used to spot less critical failures like minor components that has detached.

This solution is a combination of several different methods that was ideated to identify malfunctions on the machine. There was also an idea of recording the sound of the machine and to register major irregularities. The complexity of such a solution would however be of major proportion. As there exists large amounts of irregular noises that is created by the machine and its surroundings when the machine is working fine, it would be extremely hard to detect noise that indicate that something is wrong, especially as you do not know what it will sound like

3.4.6 Detect and Identify Objects

There are examples of autonomous vehicles with similar task to ours that relies only on its GNSS to maneuver, without any sensors to detect what is in the machines close surroundings [3]. The rough-road durability testing that Toyota perform autonomous is similar to the endurance test that the Dynapac compaction machine will perform. However, Toyotas rough-road durability test is being constantly monitored by human personnel that could intervene and abort the testing if a hazardous situation would appear e.g. if something should enter the test track. The autonomous endurance test of the Dynapac compaction machine will on the contrary not be under constant supervision from human personnel. Therefore, a need for enhanced safety measures and stricter requirements on the machines ability to detect these hazardous situations occurs. The biggest hazard of not constantly monitoring the machine is if human comes in contact with the machine (which shouldn't be possible in the first place), and risk being squashed under the roller. By giving the machine its own eyes, in form of sensors, it will be able to detect foreign objects in its path and stop before any accident occurs. The requirements list created from the risk assessment states three requirements (requirement 2a, 2b & 7a).

There are substantially four sensor technology types to choose from for this purpose; LiDAR (3D and 2D), camera, radar or ultrasonic sensor. The sensors strengths and weaknesses were compared between the different solutions in a Pugh matrix. The characteristics were selected and weighted based upon the needs and requirements acquired by the risk assessment and from Dynapac. Other solutions were also taken into account when selecting and weighting the characteristics, as some characteristics already were solved and therefore didn't need to be prioritized.

Table 3, Pugh matrix of vision and distance sensors for detection of foreign objects.

	Characteristics	Weight	Vision sensors		Distance sensors		
			Camera	3D-LiDAR	2D-LiDAR	Radar	Ultrasonic
Weather	Fog	1	0	1	1	2	0
	Rain	1	0	1	1	2	1
Performance	Range (Distance)	2	0	1	1	1	−2
	Range (Agular)	2	0	2	−2	−1	−1
	Accuracy	1	0	1	1	−1	−2
	Detail	1	0	0	−2	−2	−2
Implementation	Cost	3	0	−2	0	1	2
	Software development difficulty	2	0	1	2	2	2
Total score			0	5	3	8	1

From the Pugh matrix in Table 3; the camera solution was set as the reference and all its values is therefore set to zero. The characteristics are weighted according to how important they are considered to the overall solution. For instance, the need for perfect accuracy and highly detailed information is not weighted high due to the fact that the machine will be operating in an enclosed environment were there shouldn't be any other objects in its surrounding. The sensors main purpose is only to detect if a foreign object has entered the area despite the enclosure and then it will stop the machine. Greater accuracy and detailed information would be necessary if the machine was working in an environment where it had to take other road users and a changing environment into account. Also, the machine will be navigating mainly by the GNSS and doesn't need the detection /vision sensors for that purpose.

The range of the sensors is important up to a certain distance, it must be long enough to be able to detect a foreign object and stop before any collision is possible. Max speed of the machine is about 13 km/h so the maximum braking distance will be below 5 m and with an added safety distance the sensor should at least have a range of 10 m. The different weathers that the machine might be operating in is limited down to foggy and rainy weather (requirement 4a). Snow and ice is not taken into consideration due to the fact that the machine is inoperable in these conditions, were the roller won't get grip on the slippery ground surface. The best scoring sensor according to the Pugh matrix is the radar that scores higher than the LiDAR, mainly due to the high cost of the LiDAR technology. In the accuracy, angular range and information details the radar does score worse than both LiDAR and camera, however this does not mean that it is not good enough for the task. The final solution, for giving the machine a second safety precaution and the ability detect object in its driving path, is to mount radars on the machine. Multiple radars must be placed to cover both the front and rear of the compaction machine. The radars must be placed so that they cover the area that departs 40 degrees from the driving path so that the compactor can turn without risking colliding with an obstacle that was out of the FOV. The radar has a long range and thus the requirement of detection within the distance of 2 times the breaking distance should not be a problem.

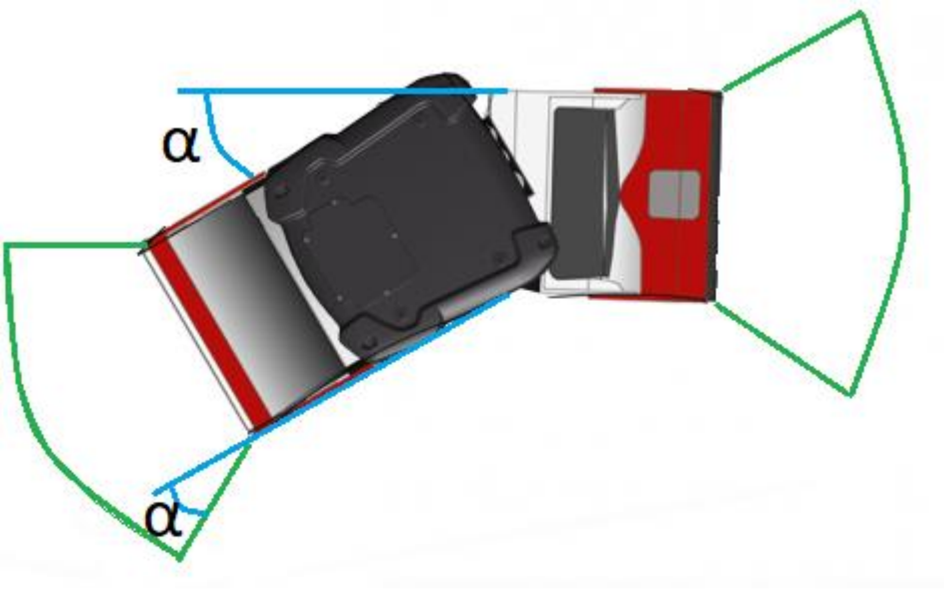

Figure 14, FOV angle is displayed in green with angle alpha and describes how it was estimated. Alpha is equivalent to the maximum turning angle which is about 40 degrees depending on the machine type.

3.4.7 Refueling

The compaction roller need diesel to run and this needs to be refueled once every 8h. One option of completing this task is to build an automatic refueling station, which the autonomous roller will use by itself when it needs to fill up the tank. By discussing this option with Dynapac it was considered to become too expensive and was by that mean neglected [4]. The option left is to complete the refueling manually. This can be handled by either having the system operator of the machine refueling the machine, other authorized person in the area, rent a security firm to perform the task or employ a neighbor which live close to the test track (if the test track is at another place than at Dynapac). The first option seemed most logical since the system operator will be looking for faults with the machine and gather test data once every day. In order to perform a safe refueling the machine will drive itself to the refueling area meanwhile the human is standing outside of the track perimeter. When the machine is parked and shut off in the assigned area, then the system operator is granted access to the area and can perform its tasks. The test will for safety reasons only continue after the system operator has left the AOZ and restarted the autonomous system from the outside of the area.

4 ANALYSIS AND DISCUSSION

4.1 Trend, Tech and Market Watching

Relevant information regarding autonomous compactors and other autonomous vehicles for that matter is not as easy to find as one might think at first. There is a lot of commercially based information to promote the own company and its products, but other than that companies in these businesses tend to keep their cards close to the chest. Much information has been acquired by analysing the limited information that is actually given. The information that is handed out in commercial purpose has a tendency to be biased and therefore it is important to not be too naive when interpreting the information that companies markets with.

An autonomous compaction machine endurance test was actually found and it is performed by the German company “Hamm”. Their test is however, very simplified, as the machine only drives back and forth on a slightly curved track of around 70 meters. As understood from the pictures and from analysing google maps overview of the track, this 70-meter distance include different surfaces that is assumed to be for the compacting part of the test. The track also includes bumps, similar to the cones (see Figure 1), for tilting the machine to test and strain its articulated joint. This is a solution that is being used by Hamm and has been used since 2014 and have over 10 000 hours of autonomous test performed according to their homepage [13]. It is however not specified if they are conducting additional test as it is unlikely that the small track that they use for autonomous testing is sufficient enough to cover all the aspects of a complete endurance test. The test is very repetitive and has no space for the machine to take out its turn to its full potential. A larger AOZ would be needed for a better simulation of how a human operator would use the machine with a more random driving pattern and to be able to perform larger manoeuvres as is provided by the solution presented by this thesis. The thing you trade for a better and more comprehensive test is that while the machine is given more freedom in what it can do by itself, more steps must be taken to ensure that the machine won’t or cannot overstep its new and wider boundaries.

When talking about autonomous technology today it is almost impossible to not mention what is done in the automotive industry. Of all systems that is being made autonomous a car that shall be able to handle public traffic, is probably one of the hardest and most complex system to do so. The computer that would replace the human driver in a car would be exposed to an internal variation of different situations that is must, on life and death, be able to handle. As a result, the equipment used on these cars and the software in its computers is of top quality. By looking on the automotive industry and the level of advanced both hardware and software that is needed in that environment has given us a confirmation of that keeping human and autonomous machine apart at all time is the best way to ensure safety without skyrocketing the expenses for the system. The automotive industry has also been a big source of inspiration and information to what technology actually exists and are being used, e.g. LiDAR, ultrasonic sensors, radar, etc. and how they are being used to get the best out of them. The automotive industry has also started to use the autonomous technology to perform their equivalent to the endurance test. Toyota has recently started to perform their durability test autonomously and this without all the complex equipment, like sensors, LiDAR and similar, to navigate the durability test track, it only uses GNSS. The biggest difference from their test and the solution presented in this thesis is that the car is being monitored during the whole test and can be aborted if necessary by the engineers that monitor the process and therefore additional safety precautions is needed for the compaction machine.

The compaction roller concept reaches the 4th level of SAEs automation levels if to compare it with cars. The SAE levels of automation are however developed for on-road vehicles and which make the comparison somewhat unfair. It is much easier to reach this level as this machine always operates in an enclosed area with no humans to take into consideration.

The mining industry and the environment that its machines operate in is more similar to the testing grounds of the compaction roller then the automotive industry is. The mines area more enclosed and more controllable then the public roads is. Being able to control the area were the autonomous machines is operating and how it can be done to promote safety is something that the mining industry has provided a lot of information about. Autonomous machines do however in many cases share the mining site with other non-autonomous machines and the safety measurements and precautions taken is shaped after this. The autonomous compactor does not have to share its operational area and therefore the solutions might be too advanced for direct implementation to the compaction machine.

4.2 Risk assessment

From the risk assessment it was discovered that the most severe scenario which could happen is if a human would be hurt. Thereby is it of the greatest importance to prohibit humans to interfere with the autonomous compaction roller since it can’t be fully trusted considering all test rollers have had faults in different occasions. Considering this, two main aspects needs to be solved. The first is to prohibit humans from entering the AOZ and the second is to prohibit the machine form exiting the AOZ. It was decided that multiple system is needed for the autonomous compaction roller, were geo-fence is prohibiting the machine from exiting the AOZ, and complemented with radar to detect unrecognized objects in its pathway. If the GNSS system would fail and the machine drives out of control, the radar will act as a backup to stop the machine when it starts to drive towards an object. Meanwhile a fence and signs prohibits humans from entering the area. It is never for certain that no one will get hurt since dealing with heavy machinery always needs some common sense to avoid getting hurt when dealt with. Main difference is the amount of mass which the machine possesses and thereby a large momentum when set into motion, these machines often have long braking distances even at low speed. Which makes them dangerous for people which thinks they can stop on a dime. Through a deeper analysis of the risk assessment an engineer could find why certain risks are more important than others and why they need to be dealt with differently. It will also create a deeper understanding of the risks of performing autonomous endurance testing. To avoid the high risks there are suggested mitigation plans for all the highest risks. If the mitigation is followed it result in a system which is reliable and don’t exposing anything or anyone to unnecessary damage.

The risk assessment is developed in cooperation with Dynapac that has both contributed with vital information about the compaction rollers and the endurance test, as well as with verification of the risk assessment. The requirements and solutions that has been engineered in throughout the thesis can be traced back to the result of the risk assessment.

4.3 Requirement specifics

The requirements which is made for the compaction roller is to simplify the process when adapting to autonomous endurance testing. Through an analysis of the risk assessment the requirement list was created and displays the information in a simpler way than just looking at all the risks. With this list an engineer can adapt to autonomous endurance testing in an easier manner than before. By studying the list, the engineer can see how different parts interact with each other and which risks exist for certain entities. The requirements specificities could be used as a check-list in order to create an autonomous endurance test system which is robust to failures and can be used on a variety of compaction machines even other machines which is tested under similar conditions. With a reevaluation of a few parts it could be adapted to almost every moving vehicle which will perform an endurance test where it drives around on a test track in a similar fashion.

4.4 Steering

Converting the steering mechanism to become adapted for autonomous operation of the roller is possible and the prototype turned out successful and is a proof of concept that it will work. By analyzing the prototype, it is found the importance of having a good alignment between the gears to have a reliable system which don't fail. The prototype was mainly built with hand tools which resulted in small errors on especially the parts in wood. All small faults ended up in gear alignment which wasn't good enough and one wood panel which was used to connect the sprocket to the motor shaft, had to be redone with a higher precision. Due to budget limitations of an early prototype, is this build only for testing purposes. The motor comes from an old height adjustable table which was donated to us. These tables are expensive when they are purchased and we hoped they used stepper motors. Unfortunately, we found out when taking everything apart that the motors are cheap brushed motors with hall effect sensors to control the position of the table. It was tested to use these sensors with Arduino but they behaved strangely and gave varying data. It was also tested to put magnets on the steering wheel and a hall effect sensor beneath it to detect the angle. Unfortunately, it was discovered that the hall effect sensors need to be within 2 mm from the magnet otherwise it doesn't work. It also gave variating results when the speed of the steering wheel was too slow or too high and only worked good at medium speed. Because of this the hall effect sensors were never tested on the real compaction machine. Hall effect sensor is a common sensor to measure speed and number of rotations on spinning axis and since we tested 3 different hall effect sensors and all gave data which varied, it is probably the Arduino board which can't handle these kinds of sensors properly. The low budget also resulted in buying cheap electronics (L298n) which barely was supposed to handle the power output, but it didn't fulfill its own requirements and we had two motor drivers which was destroyed due to overheating when we increase the voltage to the needed amount. It was then decided to buy a more advanced circuit (VNH3SP30) which was more expensive, but it got the job done. Why we choose to use chain when connecting the motor and steering wheel, is only because we got the sprockets and chain for free from an old bicycle. Chain worked good in the prototype phase but the chain will jump of when used with vibration mode on the machine in the long run, since the chain is positioned horizontally and not vertically which a chain is supposed to be, and therefore are gears a safer and more reliable option.

4.5 Propulsion

The need for a device to manually move the throttle lever is predicted to fade away as Dynapac is moving towards machines that is more electronically controlled. Most of the machine models is already controlled electronically and do not need a device to manually move the throttle lever. However, a problem arises when controlling the throttle of the machine electronically, the machines throttle lever and transmission controls isn't being used as it would by a human operator. Controlling the throttle electronically would therefore mean that eventual design flaws and/or production defects wouldn't be detected and make it out in the final product. One could argue that the solution, to move the throttle lever with a servo, on the smaller roller also could work on the electronically controlled rollers as well. However, that is not the case as the control panel on the bigger rollers is much more complex as it has additional potentiometers and transmission settings that would require to be adjusted manually with some device as well. To sum up the propulsion there is a simple solution that will work but it is discussable if it is the best.

4.6 Human Safety

Total separation of human and autonomous machine seems like a completely foolproof solution that will ensure that no human ever comes in harm's way because of the autonomous roller. The solution is easy to design in theory but to make it actually work in reality is something completely else. It isn't possible to lock the machine in for all of the 500 hours it has to drive, maintenance and refueling has to be done by a human operator. This leaves a small possibility for mistakes to be made and it has to be reduced to a minimum. That is where all emergency stops, access control systems, warning signs and signals come in to the picture. The question now becomes when can we be sure that the adequate level of safety precautions has been taken? "Enough" is a hard level to pinpoint with certainty, as we lack experience from working with this kind of problem before. Instead we have been forced to analyze other similar setups and draw conclusions based on that. To our help we have had access to some ISO standards, as the ISO 17577, that is based on the mining industry and at the ISO 13849 [28] from the robotics industry. The evidence of that the safety precautions used works is that they are being used in those areas with great success.

4.7 Navigation

The navigation uses high precision GNSS as the main tool to navigate and from our research it was found that this method is tested and being used today [3]. Alongside GNSS, radar will be used to prohibit the compaction roller from hitting any foreign objects in its path. The radar will also act as a backup system to prevent the machine from driving out of the AOZ if the GNSS system would fail. Since the autonomous compaction roller will be in a closed area with non-changing objects, there are no need for a super advanced autonomous system which scans the area and can determine the difference between a road sign and a pedestrian. The system will however be of a certain level of advancement, since in the suggested system the random section will be optimised by a GPS drawing technology and optimize the usage of the track to not always drive in the same area and thereby decrease the wear these areas. Geo-fence feature will set the perimeter for the machine and makes physical barriers redundant for the machine to operate from. With Geo-fencing instead of a conventional wall, the track can be modified faster and less costly than moving walls. If the machine would get outside of the Geo-fence, the system will be shut down and the operator will be noticed. The machine is not supposed to cross this line and if it does, it is possibly because of a malfunction on the tested machine which needs to be analysed.

4.8 Malfunction detection

Malfunction detection is a tough nut to crack, since faults vary and aren't predictable. It would be too expensive to monitor all possible scenarios and therefore is a person which observes the system a necessity. But the system doesn't need to be analyzed by a human all the time. It was decided to have a detection sensor on the parts which are a high risk to the environment or for the safety of the machine if they fail, and the rest is a human's job to spot. By analyzing the high-risk areas major faults on the machine which will damage other components on the machine can be avoided. When a high-risk fault is detected the machine will stop working and be set to a halted stage. To prevent further damage, an inspection by the operator is needed before the system can continue with the endurance test. With today's technology is it not economical defendable to let computers detect all faults and totally replace the human in the testing phase. But with an autonomous compaction roller there will be large savings in the amount of time a human need to put into the testing. The tests are also rough to endure by existing human drivers which needs multiple brakes every day to not get hurt by simply driving the machine trough the endurance course.

4.9 Detect and Identify Objects

There are many different solutions that include different combinations of sensors and technology to complete this task. To sort out what way that would work best for our case is not an easy task, the different factors that has to be taken into account is many. The advanced technologies like LiDAR and camera vision that offers a highly detailed picture of the compactors surround is of course the absolute best way to detect and identify objects surrounding the compactor. However, the equipment for this is not easy nor cheap to implement. It is not worth it when the compactor is to operate in its own area anyway. The detection function is supposed to act as a backup system that will prevent accidents from happening if one of the primal safety systems would fail. Because of this is the high level of detail deemed unnecessary as it only needs to the detect a hazard and without having to handle the situation more than to stop and alert the system operator. The Pugh matrix that was created, was mainly for the purpose of giving an overview of the different options for the task. The fact we picked the radar for our solution isn't solely based on the fact that it scored best in the matrix, but the main arguments that speaks for the radar can be visualized in the Pugh matrix and compared to the LiDAR. What the Pugh matrix doesn't show is that even though the LiDAR scores better in all of the performance categories, it doesn't show that the radar actually also meets up with the requirements needed.

4.10 Refueling

It was discussed to make a system which automatically refuels the machine but in the end, it was determined to be too expensive to build, especially since the machine will be checked for faults every day by a system operator. It is thereby most economical to have this person refuelling the machine. Considering the person needs to enter the area to refuel the machine a "refuelling sequence" will be made for the autonomous machine, where it drives by itself to the refuelling station and shuts down, from the press on a button by the system operator outside of the AOZ.

4.11 Ethic and Environment

Automation of human jobs can be quite controversial as the former workers is replaced by machines and computer as they often can perform the job faster, with more precision and at a lower cost. In this case however the machine is taking over the dull, monotone, repetitive and unconfutable work that is of low attraction for any worker. As operator of the compaction roller during the endurance test you are exposed to vibration and shock that make an unpleasant ride. Many of the compaction roller doesn't have a closed cabin to sit in and the operator is exposed to whatever weather they are driving in, cold or hot, rain and wind. This is a work task that no one will miss when it is gone.

As mentioned a computer will perform better than a human operator and this will have a positive impact on the environment. Smoother driving will burn less fuel and harder and better testing might shorten the period needed for endurance testing. The harder and better endurance testing of the machine could also lead to better machines which lasts longer.

5 CONCLUSIONS AND FUTURE WORK

There already exists solutions for autonomous endurance or durability testing for both cars and compaction rollers that work and are being used. The concept presented in this thesis is however more comprehensive and covers more aspects of a compaction roller endurance test than other solutions that was found and does not require permanent supervision form operators. There is infinite amount of different ways to complete the task of autonomous endurance testing a compaction roller. Choosing solution for the task should be determined by what is expected of the endurance test and with resources that can be put into it. An autonomous machine as the compaction roller could operate only on its GNSS navigation system, if a detailed enough map is provided. To guarantee safety when performing autonomous operations, the requirements increases on the system. The best way to guarantee safety is to separate human and machine completely, if this is not fully possible, additional safety precautions has to be established. The largest hardware impaction on the roller is to create a system which temporarily can control the steering wheel without rebuilding the steering and then move it to another machine. It was proven with our prototype that this is possible and it is also easy to mount on another compaction machine from Dynapac. The prototype could probably work on more machines than Dynapac's compaction rollers, but this is not investigated. Making tasks as the endurance test autonomous will benefit company, society and environment. It will raise efficiency and lower expenses for the company and it will release people from boring and health wearing working conditions. With smoother execution of the tasks, energy consumption will decrease and the environment will benefit.

The main findings of this thesis work can be summed up in 4 points:

- An autonomous compaction roller needs a high precision navigation system to be able to perform endurance tests in an efficient and safe way.
- To guarantee peoples safety when conducting autonomous endurance testing, no one can be allowed in the autonomous operating zone while the machine is in autonomous mode.
- If the autonomous machine is to be operating without constant surveillance, the machine must be equipped with instruments to detect hazardous situations and stop.
- If the autonomous machine is to be operating without constant surveillance, the machine must be equipped with the means to detect domestic malfunctioning of critical level.

For future work it is required to determine the size of the area that is needed for this concept. Exactly how big this testing facility needs to be is still not answered and it is something that Dynapac has to decide, with this concept and previous endurance testing in mind. A more extensive concept of the propulsion solution needs to be further developed for those machines were the electronic control is not an option.

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Appendix

Appendix A - Risk Assessment

Motivations for Severity and Probability Values

Severity	Motivation
1	Negligible
2	Small material damage & disturbing & loss of time
3	Large material damage and kill animals
4	Minor injuries on humans
5	Fatally or badly injure humans

Probability	Motivation
1	Rare
2	Unlikely
3	Moderate
4	Likely
5	Almost Certain

Risk Calculating Matrix

		Consequence severity				
		1 Insignificant	2 Minor	3 Significant	4 Major	5 Severe
Probability	5 Almost Certain	5 Medium	10 High	15 Very High	20 Extreme	25 Extreme
	4 Likely	4 Medium	8 Medium	12 High	16 Very High	20 Extreme
	3 Moderate	3 Low	6 Medium	9 Medium	12 High	15 Very High
	2 Unlikely	2 Very Low	4 Low	6 Medium	8 Medium	10 High
	1 Rare	1 Very Low	2 Very Low	3 Low	4 Medium	5 Medium

Risk Assessment, Part 1; Class, Subclass, Hazard, Potential Consequence, Severity, Probability and Risk

No.	Class	Subclass	Hazard	Potential consequences	Severity (1-5)	Probability (1-5)	Risk
1	Control system	Cables	Cables not properly installed	Machines electrical components can't function	2	4	8
2	Control system	Cables	Loose cables from installation	Machines electrical components can't function	2	4	8
3	Control system	Cables	Loosen cables from vibration/shock	Machines electrical components can't function	2	3	6
4	Control system	Cables	Cables detaches	Machines electrical components can't function	2	3	6
5	Control system	Cables	Cable damage	Machines electrical components can't function	2	2	4
6	Machine	Component	External components detach	Destroyed parts	2	3	6
7	Machine	Component	Screws detaches	Increased risk for machine breakdown	2	3	6
8	Machine	Components	Machine crush detached object	Loss of valuable equipment	2	2	4
9	Machine	Components	Hatchet open and obscure the sensors FOV	Incapable of properly detecting surroundings	2	1	2
10	Machine	Damage	Scuffed hoses	Leakage, low pressure	2	3	6
11	Machine	Damage	Lamps/indicators failure	No light/no indications	1	2	2
12	Machine	Damage	Hatch and door lock failure	Hatches and doors swings out of control	1	2	2
13	Machine	Damage	Articulated joint collapse	Machine breakdown	3	1	3
14	Machine	Leakage	Hose connections detaches	Leakage into environment	3	2	6
15	Machine	Leakage	Loose hydraulic oil filter	Leakage of oil into environment	3	2	6
16	Machine	Leakage	Loose oil filter	Engine breakdown, leakage of oil into environment	3	2	6
17	Machine	Leakage	Fuel tank leakage	Shortened driving time, leakage of fuel into environment	3	2	6

18	Machine	Refuelling	Misses refuelling hole	Fuel leakage	2	1	2
19	Machine	Refuelling	Not refuelling enough	Increased amount of refuelling times	2	1	2
20	Machine	Refuelling	Refuelling too much	Fuel leakage	2	1	2
21	Machine	Security	Stealing the machine	Loss of machine	3	1	3
22	Machine/Fracture	Components	Components break due to stress or shock	Machine damaged, loss of component	2	2	4
23	Machine/Fracture	Frame	Frame break due to stress or shock	Machine do not handle as normal, machine is damaged or machine breakdown	3	1	3
24	Manoeuvring	Brake	Service brake stops to function	Longer braking distance or machine incapable of stopping without emergency brake	2	2	4
25	Manoeuvring	Brake	Both service and emergency brakes stops to function	Machine unable to stop	3	1	3
26	Manoeuvring	Brake	Service brakes wear down	Longer braking distance	2	1	2
27	Manoeuvring	Driving	Interference in driving control system	Machine incapable of manoeuvring properly	2	1	2
28	Manoeuvring	Steering	Over-manoeuvre the steering wheel	Steering breakdown	2	1	2
29	Manoeuvring	Steering	Under-manoeuvre the steering wheel	Machine steers to little	2	1	2
30	Manoeuvring	Steering	Steering instrument detaches	No manoeuvrability	2	1	2
31	Manoeuvring	Steering	Steering instrument loosening	Manoeuvring is delayed	2	1	2
32	Manoeuvring	Steering	Hydraulic oil to the steering mechanism leak	Incapable of manoeuvring properly	2	3	6
33	Manoeuvring	Steering	Articulated joint jamming	incapable of manoeuvring properly, Unable to tilt properly	2	1	2
34	Manoeuvring	Steering	Unable to steer according to defined path	Task isn't performed as instructed, test won't be as valid	2	1	2
35	Manoeuvring	Speed	Throttle wire loosen	Unable to adjust speed of machine properly	2	2	4

36	Manoeuvring	Speed	Throttle wire detaches	Unable to adjust speed of machine	2	1	2
37	Sensor	Damage	Sensors detaches	Machine operates on false data	3	1	3
38	Sensor	Damage	Sensor loosen	Machine operates on false data	3	2	6
39	Sensor	Damage	Sensor break down	Machine operates on false data	2	2	4
40	Sensor	Damage	Orientation sensor malfunction	Machine is unable to determine its orientation	2	3	6
41	Sensor	Damage	Position sensor malfunction	Machine is unable to determine its position	2	1	2
42	Sensor	Damage	Speed sensor malfunction	Machine is unable to determine its speed	2	1	2
43	Sensor	Environment	Night restrains vision (relevant if camera)	Incapable of properly detecting surroundings	2	2	4
44	Sensor	Environment	EMC- interference from high voltage equipment	Sensor error/ failure	2	1	2
45	Sensor	Environment	Sensors gets covered with mud or dirt	Incapable of properly detecting surroundings	2	1	2
46	Sensor	Environment	Fog obscure the sensor	Incapable of properly detecting surroundings	2	3	6
47	Sensor	Environment	Fog obscure the sensors FOV	Incapable of properly detecting surroundings	2	2	4
48	Sensor	Environment	Dew obscure the sensor	Incapable of properly detecting surroundings	2	3	6
49	Sensor	Environment	Rain obscure the sensor	Incapable of properly detecting surroundings	2	3	6
50	Sensor	Environment	Rain obscure the sensors FOV	Incapable of properly detecting surroundings	2	3	6
51	Sensor	Environment	Snow obscure the sensor	Incapable of properly detecting surroundings	2	1	2
52	Sensor	Environment	Snow obscure the sensors FOV	Incapable of properly detecting surroundings	2	1	2
53	Sensor	Environment	Ice cover the sensor and obscure the sensors FOV	Incapable of properly detecting surroundings	2	1	2

54	Sensor	Environment	Dust cover the sensor	Incapable of properly detecting surroundings	2	3	6
55	Sensor	Environment	Dust cover sensors the FOV	Incapable of properly detecting surroundings	2	1	2
56	Sensor	Environment	Dust penetrates the sensor	Sensor malfunction	2	1	2
57	Sensor	Measurement	Measurement equipment failure	Inaccurate data collection	2	2	4
58	Sensor	Measurement	Measurement equipment detaches	Data collection becomes incomplete	2	2	4
59	Sensor/ Detect object	Animal	Fail to detect animal	Injure or fatal injure animal	3	1	3
60	Sensor/ Detect object	Blind spot	Blind spots, objects obscured by other objects	Unable to detect objects in that spot	5	2	10
61	Sensor/ Detect object	Blind spot	Switch from idle to driving when a human is present	Injure human	5	2	10
62	Sensor/ Detect object	Movement	Fail to predict object's movement	Crash into object	3	2	6
63	Sensor/ Detect object	Object	Fail to detect other machines	Material damage	3	2	6
64	Sensor/ Detect object	Object	Unable to distinguish soft objects from hard ones, e.g. paper ball from a rock	Machine makes unnecessary stops	2	2	4
65	Sensor/ Detect object	Object	Failing to detect minor unidentified objects	Damage to object and/or on machine	2	2	4
66	Sensor/ Detect object	Movement	Difficulty in detecting objects which approaching the roller from behind	Crash into object	5	1	5
67	Sensor/ Detect object	Person	Fail to detect authorised personnel	Injure or fatal injure person	5	1	5
68	Sensor/ detect objects	Person	Fail to detect unauthorised person	Injure or fatal injure person	5	1	5
69	Software	Code	Not programmed for unexpected scenario	Unpredictable consequence	2	2	4
70	Software	Code	Bugs	Unpredictable consequence	2	3	6
71	Software	Driving cycle	Drives wrong test section	Wrong test data is acquired	2	2	4

72	Software	Driving cycle	Drives wrong test section, while personnel are working in that section	Injure the personnel in that section	5	2	10
73	Software	Security	Hacking	Hacker taking control of systems which is connected to internet, i.e. webcams and such	2	1	2
74	Track	Area	Machine escapes from area	Machine out of control	5	2	10
75	Track	Location	Disturb surrounding area	Complaints from eventual neighbours	2	3	6
76	Track	Objects	Unable to register object that is part of the track, e.g. fence, wall, cones, pylon, etc.	Makes unnecessary stops instead of avoiding the object	2	2	4
77	Track	Obstacle	Machine get caught on a cone	Machine is unable to continue endurance test	2	2	4

Risk Assessment, Part 2; Comments, Eventual References and Possible Mitigation

No.	Comments	Eventual reference	Possible Mitigation
1	Most machines consist of numerous different electrical components. This includes the engine that in most cases is highly dependent on electrical components		Test the electronics, trouble shot to see if you can find a fail spot
2	Most machines consist of numerous different electrical components. This includes the engine that in most cases is highly dependent on electrical components		Test the electronics, trouble shot to see if you can find a fail spot
3	Most machines consist of numerous different electrical components. This includes the engine that in most cases is highly dependent on electrical components		Test the electronics, trouble shot to see if you can find a fail spot
4	Most machines consist of numerous different electrical components. This includes the engine that in most cases is highly dependent on electrical components		Test the electronics, troubleshoot to see if you can find a fail spot
5	Most machines consist of numerous different electrical components. This includes the engine that in most cases is highly dependent on electrical components		

6	Example of external components is mirrors, windscreen wiper, etc. The might be destroyed either in the fall or crushed by the compactor if they are not picked up directly	Dynapac failure/ breakdown history	Inspection before every shift and/or while refuelling
7	Screws might detach but won't necessary mean direct material damage on the machine. It all comes down to how many and vital screw that actually detaches. The more screw the less probability it is for it to happen.	Dynapac failure/ breakdown history	Inspection before every shift and/or while refuelling
8	Components that detaches from the machine runs a risk of being crushed if not detected by the machine.		
9	Depending on where the sensors is mounted there is a possibility that their FOV will be blocked when the hatchets is opened. If mounted on a hatchet, the sensors FOV will be changed completely		
10	Leakage will of substances like oil or fuel will affect the nature and environment	Dynapac failure/ breakdown history	Inspection before every shift and/or while refuelling
11		Dynapac failure/ breakdown history	
12		Dynapac failure/ breakdown history	
13	Depending on how severe the collapse is the machine will have trouble to manoeuvre or in worst case suffer a complete breakdown.	Dynapac failure/ breakdown history	
14	Leakage will of substances like oil or fuel will affect the nature and environment	Dynapac failure/ breakdown history	Inspection before test. Measure the pressure and safety shutdown if pressure is lost
15	Leakage will of substances like oil or fuel will affect the nature and environment	Dynapac failure/ breakdown history	Inspection before test. Measure the pressure and safety shutdown if pressure is lost
16	Leakage will of substances like oil or fuel will affect the nature and environment	Dynapac failure/ breakdown history	Inspection before test. Measure the pressure and safety shutdown if pressure is lost
17	Leakage will of substances like oil or fuel will affect the nature and environment.		Inspection before test. Measure the pressure and safety shutdown if pressure is lost
18	Leakage will of substances like oil or fuel will affect the nature and environment.		
19	Will lower the efficiency of the autonomous system. Mostly relevant for automatic refuelling system		

20	Leakage will of substances like oil or fuel will affect the nature and environment.		
21	If the machine is without any human supervision it will be easier to steal the machine without anyone noticing it		
22	There is a lot of different components that could break with different consequences. Loss of vital components will increase risk of further malfunctions		
23	The consequence will depend on where and how severe the fracture of the frame is.	Dynapac failure/ breakdown history	
24	Uncertain of how the emergency brake system function and under what circumstances it will activate itself.		
25	If both brakes fail the machine won't be able to stop by itself		
26			
27			
28	Turns the steering wheel over its limit. The steering of the machine is not hydraulic and therefore needs a device to physically turn the steering wheel. Here is a risk of overdoing that	ISO 26262	
29	Same as over manoeuvring but on the contrary	ISO 26262	
30	Loss of the steering instrument mounted on the steering wheel will mean complete loss of steering control of the machine	ISO 26262	
31		ISO 26262	
32	Loss of pressure for the hydraulic oil to the steering mechanism will decrease the force used to angle the articulated joint and in that way slow down or prevent the turning of the machine.		Regular inspections, monitor pressure
33	If the articulated joint is jamming or not functioning properly it will obstruct the turning process. The machine might not be able to tilt properly when for example driving over the cones		

34	This can be for example if the program isn't adjusted to the machines individual steering capabilities		
35	Machine drives in the wrong speed which can result in the machine thinks it standing still but it is actually moving		
36	Machine drives in the wrong speed which can result in the machine thinks it standing still but it is actually moving		
37	If the sensor detaches it might get angled in a way so that it won't detect any objects and the machine will believe it has a clear way ahead	ISO 26262	
38			Mount it properly, inspect if mounting is secure
39	If the sensor does not operate as it should it might lead to that it registers a clear way ahead when there are objects in the way		
40	Machine drives with the wrong angle		Calibrate sensors at regular intervals
41	Machine can’t perform the test since it doesn’t know its position		
42	Machine drives in the wrong speed which can result in the machine thinks it standing still but it is actually moving		
43	If driving on night and using a camera		
44	The EMC field needs to be quite strong to interfere with the sensors		
45	Dirt on sensor		
46	Small water particles get stuck to the sensor	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	Weather resistant sensors, complementary sensors, don't drive in very harsh weather
47	The fog is so thick that sensor think it is an object	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	
48	Dew in the morning decreases the functionality of sensors	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	Weather resistant sensors, complementary sensors, don't drive in very harsh weather

49	Water sticks to the sensor	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	Weather resistant sensors, complementary sensors, don't drive in very harsh weather
50	The rain is so thick that sensor think it is an object	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	Weather resistant sensors, complementary sensors, don't drive in very harsh weather
51	Depending on season. Probability is low due to the fact that you do not drive when there is snow on the track.	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	
52	The snow is so thick that sensor think it is an object. Probability is low due to the fact that you do not drive when there is snow on the track.	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7795565/?reload=true	
53	The Ice is so thick that the sensor thinks it is an object. If it is minus degrees and a slippery driving surface you can't drive		
54	Dust sticks to the sensor		Wipe the sensors at regular intervals
55	The dust is so thick that sensor think it is an object		
56	Large problem in dusty area, and leads to additional wear		
57	Test maybe needs to be redone	Dynapac failure/ breakdown history	
58	Measurement equipment might be destroyed	Dynapac failure/ breakdown history	
59	Complex problem of how to identify and treat moving objects		
60	Depending on design and FOV		Eliminate blind spots,
61	The machine goes in to a simulated idle mode, and then a curious human approach the machine and stands in a blind spot. Then the machine goes in to drive mode and thinks the cost is clear	http://ieeexplore.ieee.org.miman.bib.bth.se/document/7934783/?reload=true	Shut down completely when human is present.
62	Can be all living things and machines. Complex problem of how to identify and treat moving objects		No other machines are allowed in the area
63	Complex problem of how to identify and treat moving objects		No other machines are allowed in the area
64	Machine don’t know what objects that can be over run		

65	Damage is depending on the size and density of the object		
66	Complex problem of how to identify and treat moving objects		Safety shutdown of the machine if authorised personnel access the area. Like a safety cage around an industrial robot
67	Complex problem of how to identify and treat moving objects		Safety shutdown of the machine if authorised personnel access the area. Like a safety cage around an industrial robot. Sensors on the machine to stop if something unidentified is in its path
68	Complex problem of how to identify and treat moving objects, unauthorised persons should not be on the track		Physical barrier to prevent unauthorised personnel to access the area. Sensors on the machine to stop if something unidentified is in its path
69	Can result in multiple different failures.		
70	Can result in multiple different failures		Test the program for as many possible scenarios as possible
71	Test maybe needs to be redone		
72	Possible hazard if track maintenance is performed mean while the machine is running		No maintenance on the track is allowed when the machine is active
73	If the compactor is connected online it will also be exposed to online threats like hacking		
74	This is only possible if several of the other risks occur and is not fixed at once. Many systems must be coordinated to prevent this from ever happening		Multiple systems to stop the machine if it escapes the area. Physical barriers to stop the machine, sensors to stop the machine when it interacts with an object or location defined test track (GNSS) and stop it if the machine is outside of the track
75	Depending on geographical position		Track location is remote from any nearby neighbours. Dirt piles around the area to absorb sound
76	The machine needs to treat these track objects differently compared to non-track objects. if it does not it might come to a permanent stop		
77	One test which the machine performs is driving over cones, and there is a potential risk that the machine gets stuck with the cone in the middle of the drums		

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