Quantification of leaf fall near railway level crossings

In particular, in what order to take precautions in the signalling system for level crossings on the basis of the leaf fall situation.

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QUANTIFICATION OF LEAF FALL NEAR RAILWAY LEVEL CROSSINGS

A thesis submitted to the University of Twente in fulfillment of the requirements for the degree of

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by

Evelien Gosenshuis

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Evelien Gosenshuis: *Quantification of leaf fall near railway level crossings* (2020)

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MANAGEMENT SUMMARY

Every year problems arise due to leaf fall near the railway. The leaf fall can cause adhesion problems and detection loss of trains. Especially near level crossings where the signalling system is activated by the detection of a train through wheel/rail contact. Some leaves form a new layer on the rail head preventing detection of the train. This can result in deactivation of signalling systems. The detection loss, which is also called Loss of Shunt (LOS), can cause major collisions if it occurs near level crossings.

Research is conducted for ProRail B.V., which is the owner of the Dutch rail network and manages 7000 km of railway with 2300 level crossings. Their goal is to replace the current detection system by another detection system, the axle counters. The improved detection system uses a magnetic field to detect the train and is not reliant on the wheel/rail contact. Currently the decision on the locations of replacing the detection system, is based on knowledge and experience from experts.

The goal of this research is to develop a model that can quantify the amount of leaf biomass near each level crossing. Hereby answering the following central research question: "How to design a reliable and user-friendly method to quantify leaf fall influencing LOS? In particular, in what order to take precautions in the signalling system for level crossings, based on the leaf fall situation."

There are multiple factors that can influence the wheel/rail contact. These factors are related to either the condition of the rail or to the pollution on the rail head. The complexity of detection loss is mainly caused by the inability of directly measuring and monitoring the influential factors. A literature review is executed for quantifying the influence of leaf fall on LOS. The most suitable equation is worked out for quantification of the leaf area and biomass. The vegetation data available from ProRail, on the trees near the rails, includes the height of the tree and crown diameter. The species of the trees are unknown. For this research we use the most common species in the Netherlands the *Quercus Robur*.

Methods combining dispersal of leaves with the leaf area and biomass are found through literature research. One of these methods calculates leaf biomass per m^2, using wind direction as influential factor. A dominant wind direction can have a great influence on the dispersal of leaves in an area.

We developed our own method by combining dispersal of leaves with amount of leaf biomass of a tree. For the dispersal we use the segment of a cone. In this method we multiplied by two the amount of leaves of trees with an angle of the predominant wind direction. Through researching the last 20 years

of wind directions in the Netherlands we found a predominant southwest wind direction.

Using the volume of a cone shape is a new approach for calculating leaf fall. The approach is flexible and user friendly, because any additional information that comes available can be easily implemented by adding or extending the cone segment method.

The method found in literature and our newly developed method were both used to calculate the amount of biomass near each level crossing with an automatic protected level crossing system. Both methods provide similar results with only small ranking differences for some level crossings.

The level crossings are categorised by a risk assessment into critical, high, medium, low and no risk. The categories are grouped based on the percentage of total leaf biomass of the cone method. Each category has a colour and a symbol shown in table 0.1. A map of the Dutch railway network including the locations of the level crossings, based on the categorisation of the risk assessment, is illustrated in figure 0.1.

Table 0.1: Risk categorisation of the level crossings

colour	Symbol	Percentage of total biomass	Number of level crossings	Risk
	□	1.57%	3	Critical
	◇	32.39%	143	High
	○	34.38%	295	Medium
	×	31.66%	951	Low
	+	0%	126	No risk (or no data)

The critical level crossings and the calculated leaf biomass are listed in table 0.2. The highest ranking level crossing is located in Enschede. We recommend to start looking into the signalling system of this level crossing first. Then the other critical level crossings can be reviewed to see if axle counters can be implemented.

Table 0.2: Critical level crossings

	Level Crossing	City	Staelens et al. method leaf biomass in gram per m2	# of trees per level crossing sections	Cone segment method leaf biomass in gram per m2	# of trees used in cone segment method
1	028 / 056.959	ENSCHEDE	22327.90	1267	19459.11	973
2	021 / 082.673	HOOG SOEREN	18657.47	1694	17285.49	1038
3	309 / 002.061	EYGELSHOVEN	16668.80	1072	16086.96	818

For further research we recommend to look at other factors influencing LOS. Additional parameters can be added to the developed model. Certain level crossings already have additional measures installed, but this is not included in this research. We recommend to include this information first, to prevent taking unnecessary precautions at a level crossing.

The developed model can provide ProRail with insight into which level crossing is of higher risk of having LOS caused by leaf fall. Leaf fall is often the cause of adhesion problems too. Since the quantification of the leaf biomass can be performed for any location on the tracks, the model might also provide insight into high risk locations for adhesion problems.

Figure 0.1: Overview level crossing map

GLOSSARY

APLC Automatic protected level crossing (in Dutch "Active beveiligde overwegen") is a level crossing that has automatic signalling. This signalling can include barriers, bells or lights that are activated when a train is approaching the intersection. (Section 2.3)

DBH Diameter at Breast Height is a measurement system for measuring the tree stem diameter. This is done on breast height, which is generally at 1.3 meter from the ground. (Section 3.1)

GRS General Railway Signal is the current main detection system used in the Netherlands. (Section 1.2)

LAI Leaf Area Index is the most used quantification of leaf area. It is defined as the projected area of leaves over a unit of land. (Section 3.1)

LOS Loss of Shunt is a failure of detecting a train by the track-citcuit, as a result of poor wheel/rail contact. This failure may lead to inadequate functioning of the level crossing system. (Section 1.2)

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1 INTRODUCTION

1.1 PRORAIL

ProRail B.V. is the owner of the Dutch rail network and manages around 7000 km of railway, 2300 level crossings and 399 stations across the Netherlands. ProRail is responsible for the safety, reliability, security, maintenance and control of the railway. This involves distributing the capacity of the tracks and managing train traffic, signalling systems, crossings, switches, rail tracks and stations. For the maintenance of the rail, different companies are contracted by ProRail, like BAM Rail, Strukton Rail and Volker Rail. These companies maintain certain parts of the rail network. (ProRail, 2019b)

ProRail has 4400 employees and is 100% owned by the Dutch government under the ministry of Infrastructure and Water Management (ProRail, 2019b). The main office is in Utrecht with 4 more regional offices in Amsterdam, Eindhoven, Rotterdam and Zwolle. The operations part of ProRail consist of four departments, namely asset management, projects, ICT and traffic control.(ProRail, 2019b)

For this research the focus is on Asset Management (AM), which is responsible for the reliability and safety of the rail network. Part of AM is the department Railway Signalling (Treinbeveiliging), which is the main stakeholder and instigator of this research paper. The department of Railway Signalling (Treinbeveiliging) consist of three separate sub departments. These sub departments are conventional technology, new technology and interlocking. For an overview of the interconnections between the departments, see figure 1.1.

The focus for this research is in the conventional technology area, namely the train detection track circuits. This track circuit detection system has one main disadvantage that under specific circumstances train detection can fail, caused by poor wheel/rail contact. This problem will be discussed in the next section.

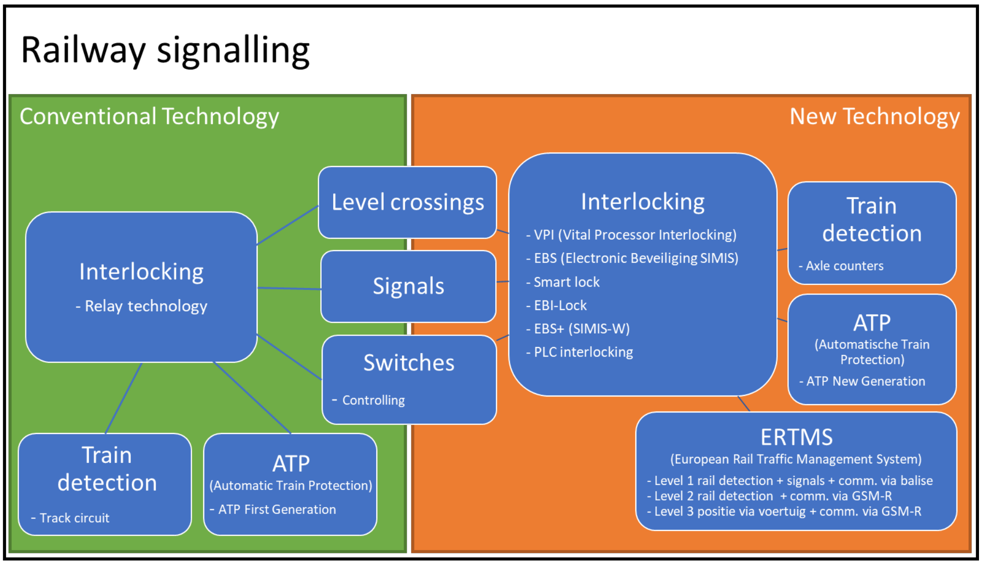

Figure 1.1: Railway signalling department

1.2 PROBLEM DESCRIPTION

Every year around 2.2 million passenger trains make use of the rail network. This accounts for around 165 million kilometer each year. The track safety systems (signalling systems) are dependent on the exact locations of all trains on the tracks. The train detection system detects if a train is on a specific section of the track. Train detection information can be relayed directly to the lamp circuits of the signals, to the level crossings or to the interlocking systems.

There are different train detection systems in use in the Netherlands. Here the focus will be on the General Railway Signal (GRS) track circuit detection system. This system uses the principle of short circuiting the two rails of the track by the wheelsets of the trains. These circuits allow for automatic detection of the trains within a specific section of the track and consist of 3 elements. These elements are an emitter, transmission line and a receiver. If there is no train present, the current produced by the emitter is able to reach the receiver. In the case that a train enters the track, the wheels and axle will cause a short-circuit, which ensures that the current is not transmitted to the receiver. This short-circuit is called a shunt. The drop in current in the receiver causes the section to be occupied by the train. How this works is visualised by figure 1.2. Here a train is occupying a track section by the short-circuit, this information is send to the lamp circuits causing the signalling light to turn red. (CER, 2019) (Hardwick et al., 2014)

Under unfavourable conditions the wheel/rail contact is diminished and causes loss of detection or also called Loss of Shunt (LOS). The probability of this failure mode is very low, but this loss of detection can eventually result in collisions at level crossings.

One of the reasons a poor wheel/rail contact occurs is leaves on the track. These leaves are pressed on the rail by the wheels of the train. The components of the leaves merge with the components of the rail and form a substantial black layer that can prevent detection of trains. The LOS occurring during October, November and December can be explained by leaf fall on the track. Other known causes of LOS is major rust formation, pollution of the rail head in combination with rolling stock characteristics.

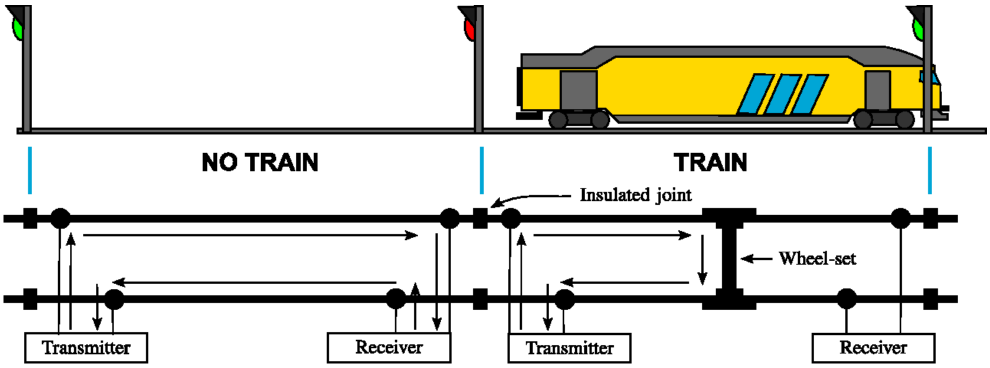

Figure 1.2: Track circuit (Bruin et al., 2016)

The phenomenon loss of shunt can only occur at detection systems based on short circuit by the train axles. For other detection systems such as axle counters, there is no problem of having LOS. The axle counters, as the name reveals, counts the number of axles within a section. This counting is based on disturbance of a magnetic field between two sensors on each side of the rail during passage of a wheel. Therefore axle counters are an effective solution to the LOS problem. (Lorang et al., 2018)

Currently the largest part of the tracks in the Netherlands have the GRS detection systems. The map in figure 1.3 shows the different detection systems in the Netherlands. The dark blue lines in figure 1.3 are the tracks where the GRS system is present. This also means that the largest part of the Dutch railway is vulnerable to LOS.

Only a few locations are known where LOS has happened caused by leaf fall. Additional measures were taken, at these locations, to mitigate the effect of LOS. Currently a small part of the Dutch railway is protected by axle counters. The goal is to have the whole rail network covered by the axle counter detection system. Installing this new detection system is expensive and time consuming.

In this research we will design a method to calculate the amount of leaf biomass. Then the locations with the highest risk of detection loss caused by leaf fall can be found. Eventually this will result in recommending for which level crossings to take precaution in the signalling system.

Figure 1.3: Train detection systems map 2020 (ProRail, 2019a)

Problem cluster

For a clear overview of the problem and relations within this research, a problem cluster is made in figure 1.4. The problem of LOS can be solved by axle counters, but this takes huge investments and years to implement. The locations that require additional measures are decided on expert judgement and unquantified data. What is missing is a model providing insight on the locations that pose the highest risks of LOS, caused by leaf fall. The green parts of the problem cluster show the problems that are researched.

Figure 1.4: Problem cluster

1.3 RESEARCH APPROACH

In this part the goal of the research, the research questions and the methodology for answering the research questions are discussed.

The goal of this research is to develop a model that can help in the decision making where to take precautions in the signalling systems for level crossings to prevent deactivation of the level crossing systems. This model should quantify the parameters that influence the risk of loss of shunt caused by leaf fall. Then a categorisation can be made on the risk for the probability of LOS per level crossing. This will result in a map of all level crossing ranking the risk of LOS based on the quantification of the leaf fall.

Central research question: How to design a reliable and user-friendly method to quantify leaf fall influencing LOS? In particular, in what order to take precautions in the signalling system for level crossings, based on the leaf fall situation.

Parameter quantification

1. Which parameters should be considered for quantifying the probability of LOS?
   a) What are the causes for LOS?
   b) What type of information can be gathered on the influential factors of LOS?

Methods to quantify leaf fall

2. How to develop a good quantification for leaf fall on the track?

a) Which equations can be found in literature to quantify the leaf area and leaf biomass?

b) What indicators are present from data on the vegetation surrounding the tracks?

c) Which methods exist in literature to calculate leaf fall?

Development of quantification model

3. What kind of model can calculate the risk of having LOS caused by leaf fall?

    a) To what extent can the model predict the amount of leaves?

    b) Which parameters are of influence to the amount of leaves on the tracks?

Overview of risk

4. What type of distinction can be made in the risk categorisation on LOS caused by leaf fall?

5. Which railway lines have the most high risk level crossings?

Methodology

Currently there is no measuring system in place that monitors if or when LOS happens. Meaning that there is limited information from historic data on the locations of LOS. Occasionally information of the train driver or watchful citizens who notice strange behaviour of the level crossing installation indicate the occurrence of a LOS. Recently all vegetation around the train tracks have been mapped for ProRail. This information provides the height and distance of each tree in relation to the tracks. Next to these sources of information a literature review is conducted.

To answer the first research question information on loss of shunt is assessed. In this step all possible factors influencing the probability of LOS are gathered using common knowledge and literature. For finding all factors influencing LOS a literature review is conducted.

For the second research question the focus is on the quantification of leaf fall. Through a literature review the existing formulas for computing the amount of leaves per area are researched. Also the data from the mapped vegetation is assessed, hereby finding out what information can be used for the quantification. Multiple methods are assessed for developing a model that can quantify the leaf fall. Based on the assessment a method is developed that can estimate the amount of leaf biomass near each level crossing.

For answering the third research question the parameters relations are analysed. Then the model for quantifying the leaf fall is developed. This model is tested and validated. The validation is done by comparing the different quantification methods.

For the last question a categorisation is made of the risk of LOS caused by leaf fall. A colour coding is included per risk category and visualised into a map of the Dutch railway network. This map will show where the highest risk level crossings are located in the Netherlands.

1.4 SCOPE

For this research the area of coverage is loss of shunt caused by leaf fall. Other areas not included in this research are:

- Loss of shunt caused by different factors.
- The way of collecting the data on LOS.
- Adhesion problems on the track caused by leaf fall.
- Condition of the tracks throughout the rail network.
- The importance of frequently used level crossings to less frequently used level crossings.

1.5 DELIVERABLES

Below are the deliverables of this research paper. These deliverables will include:

- An overview of factors having influence on the probability of LOS caused by leaf fall.
- Model with quantification of leaf biomass near each level crossing.
- A map of all level crossings showing the risk for LOS caused by leaf fall.

1.6 THESIS STRUCTURE

This thesis will start by explaining what happens in a LOS. The factors influencing LOS are discussed. After this the data available is given. In the third chapter we explain the literature review. Then in the fourth chapter the quantification approach of the leaf fall is explored. The data on the vegetation and the developed formula is explained for calculating leaf biomass. In chapter 5 we research parameter relations and explain the development of the model. The model is tested and validated and the results are discussed. Also the constrains and limitations of the model are addressed. Then in chapter 6 a map of the Dutch railway network will visualise the locations with the highest risk for LOS caused by leaf fall. In chapter 7 we discuss the cone segment method. Finally chapter 8 includes the conclusion and recommendations.

2

THE INFLUENTIAL FACTORS OF LOSS OF SHUNT

In this chapter the workings of loss of shunt (LOS) are explained more clearly. First the history is given on the current detection system in the Netherlands. Then the mechanics of LOS is described. We give the factors that influence LOS and the frequency of LOS. Finally the data that is available on LOS in the Netherlands data on the influential factors and on level crossings will be addressed.

2.1 BACKGROUND

There are different detection systems in use in the Dutch railway network. The largest part consist of the GRS track circuits. As part of the Marshall Plan after world war II the GRS track circuits were introduced in the Netherlands. The General Railway Signal (GRS) is the name of the company that manufactured the track circuit. This specific detection system uses the wheel/rail contact to detect a train on the track. It consist of an emitter, transmission line and a receiver. If there is no train present, then the emitter will send a current through the rails to the receiver. In the case that a train enters the track, the wheels and axle will cause a short-circuit, which ensures that the current will not reach the receiver. This short-circuit is called a shunt. In case of poor wheel/rail contact there is loss of detection also called Loss of Shunt (LOS).

The mechanics of LOS has to do with how much current is being received. In normal conditions the wheel causes a short-circuit and the current goes to zero, shown in figure 2.1. Then a signal is given to the signalling system, that a train is present, activating the level crossing.

In case of poor wheel/rail contact, the high residual current causes the relay to rise, leading to a signal that the section is unoccupied. Figure 2.2 shows an example of excessive residual current leading to a LOS of more than 2 seconds.

In the Netherlands a B2 Track Relay is used with a Track Repeat Relay. The section is considered unoccupied when the residual current exceeds a certain

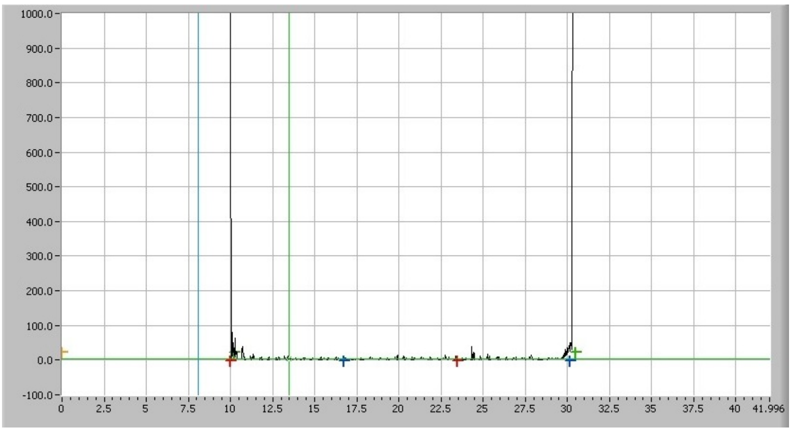

Figure 2.1: Receiving current with no residual current (ProRail, 2020)

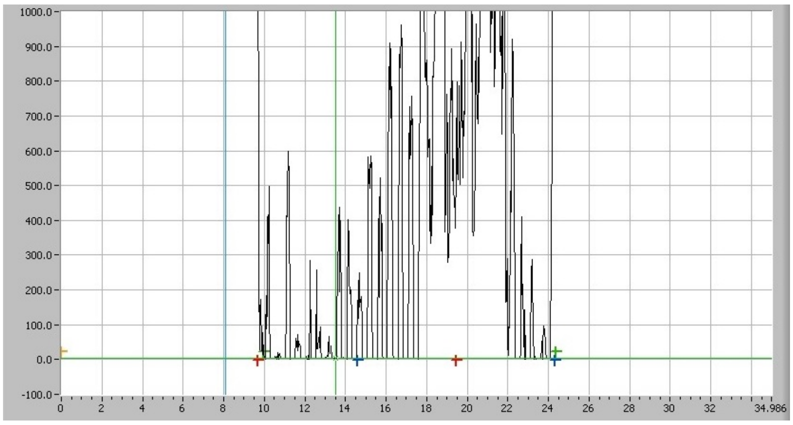

Figure 2.2: Receiving current with residual current (ProRail, 2020)

threshold, for at least 1.6 seconds. In case of LOS the B2 Track Relay will switch contacts after 300 mS and the Track Repeat Relay after 1300 mS. This explains the 1.6 seconds. The Track Repeat Relay is used as a back up to prevent the relay to rise too quickly, when residual current is present.

The track circuits are laid out per section. A section can have a length of 24 meter to 1800 meters, but on average a section has a length of 300 to 400 meter. There are specific announcement sections that signal the level crossings. Here LOS can have a greater impact on safety than at other sections. A detection failure at these sections can directly lead to a collision with road traffic. The length of these sections, signalling the level crossings, are based on the speed of the track. The general warning period of at least 21 seconds is required. If the maximum speed of a track is 130 km/h then the announcement section should be at least 760 meters. When a detection failure occurs in the announcement section the level crossing will be deactivated.

It is unclear how often this happens in the Netherlands, outside station areas, as only bystanders and the train drivers can notice deactivation of the level crossing. It is estimated that each year a few cases of deactivation will occur in the Netherlands as a result of LOS. For safety precaution it is important to mitigate the risk of LOS at announcement sections near level crossings.

2.2 KNOWN FACTORS

The focus of this research is on the influential factor of leaves contaminating the rail. To determine other factors influencing loss of shunt a systematic literature search was conducted. The steps taken to find the literature on all factors influencing LOS can be found in appendix II.

All influential factors are related to either the condition of the rail or to the pollution of the rail head. These two groups are identified as polluting or cleaning by Wybo and visualised in figure 2.3 It is different per country which factors have more influence than other.(CER, 2019) The problem of loss of detection is complex for the inability of directly measuring and monitoring of the condition of the rails and the severity of the contamination. (Hubbard et al., 2016)

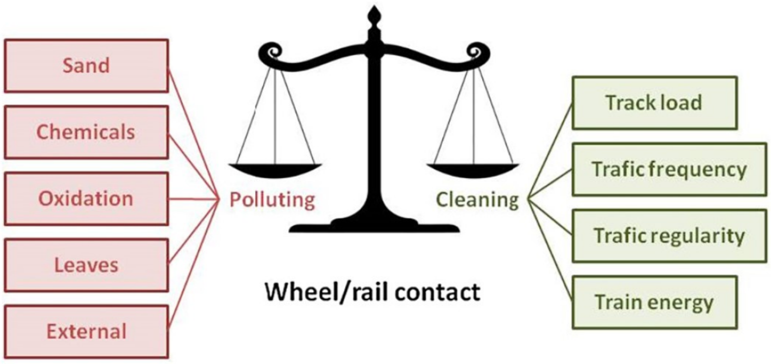

Figure 2.3: Factors influencing wheel/rail contact (Wybo, 2018)

For detection to take place the contact area of the rail head needs to be in good condition and clean of contamination. For excellent condition of the contact area there should be no rust present. The rust can be prevented by regular usage of the rails. Using different rolling stock can keep a larger part of the rail head from rusting. If only one type of rolling stock is present, then only a small part of the rail head is clean. Hereby the design of the wheels can influence the amount of wheel/rail contact.

Contamination of the rail is caused by lubricants (chemicals like oil), sand, oxidation of water, leaves and other produce falling on the rails.(Wybo, 2018) In most countries the main cause of LOS is the contamination of leaves on the rail head. (CER, 2019)

There is a new external factor observed that is not included in the two groups. This factor was found by observing detection loss in the northern part of the Netherlands. The cause is identified as a strong wind that made the wheels of the train touch the rusting part of the rail head. The locations had in common that no trees aligned the rails. The trees can withhold strong winds and might prevent the train wheels to touch the rusting part of the rail head. From this factor we might conclude that trees can also have a positive effect on preventing detection loss.

LEAF CONTAMINATION

This research focuses on leaf fall as the most problematic influential factor for loss of detection. These leaves are pressed on the rail head and form a new layer, often compared with the non-stick coating of pans. This difference is visible in figure 2.4 between a clean rail head and a leaf layered rail head. Three main components of the leaf layer are related to keeping plant cell together, these are pectin, cellulose and lignin. Other components found in the leaf layer include calcium, carbon, iron, nitrogen and oxide (Ishizaka et al., 2017). These components show that a bonding develops between the leaf components and the rail steel.

Clean rail head | Leaf layered rail head

Figure 2.4: The left picture is a clean rail head and the right picture is a leaf layered rail head(ProRail, 2020)

The bonding of the leaf layer can be quite substantial and is not easily removed. Given the right conditions through heavy rainfall and friction the layer can break down naturally. The opposite happens during low rainfall and dew, then the leaf layer becomes a problem for good adhesion. The rail head gets slippery and can cause traction and breaking problems, which result in station overruns and signal passed at danger. Measures are taken against adhesion by applying third bodies (friction modifiers, sand or lubricants) to increase adhesion during autumn. These third bodies can have a negative effect on the wheel/rail contact for detecting trains. (Hubbard et al., 2016)(Lewis et al., 2011)

There are some leaves that have a larger impact on forming a layer than others. The British Adhesion Working Group (AWG) has conducted research into adhesion and different type of tree species. An overview was made of the most common trees in the UK and the impact of each species on adhesion. Especially broad leaf species contribute more to the leaf layer than coniferous species. Another remark is the distance of the trees to the tracks. According to the research when trees are planted near the tracks it is best to plant local native species. These species tend to have insects affecting the leaves, while alien species have untouched leaves. Hereby diminishing the leaves and have a positive effect on the total amount of leaves. (Edgley, 2018)

2.3 DATA COLLECTION

Over the last years every instance of a possible LOS has been documented. When a level crossing system is inadvertently deactivated or not activated at all, a mechanic is called to the scene to search for the cause. With the amount of possible causes of detection loss, the mechanic needs sufficient knowledge on the topic to find the cause. From experience it is often unclear if the observed cause is the actual cause of LOS. In the months of October, November and December the main cause for detection loss is the leaf fall. Outside of the Netherlands this problem occurs during the same period. There are no instances where LOS is caused by leaf fall in the same location twice. In most cases extra measures are taken to prevent loss of detection from occurring again, by adding additional detection systems. The occurrence of LOS is unpredictable through the data collected of previous instances. From this data collection we learn that it is difficult to determine and predict having LOS caused by leaf fall near the track.

Other data is present on the vegetation around the tracks in the Netherlands. This vegetation differs from forest, small groups of trees or lone trees. The vegetation management of ProRail had all the trees around the rails digitised. This vegetation data consist of around 700,000 trees taken from 30 meter at each side of the tracks. The vegetation data includes the tree height, crown diameter and location parameters. The type of trees vary from coniferous to deciduous species. Additional specifications of the data are discussed in section 4.2. This vegetation data can help identify the risk of having LOS near level crossings based on the leaf area and amount of biomass.

For this research we focus on the announcement sections that signal the level crossings. Not all level crossings have active level barriers. Each type of level crossing system has its own name. The Automatic Protected Level Crossing (APLC) systems at risk of having LOS are:

- Automatische dubbele Overweg Bomen (ADOB). This system uses flashing lights, warning sounds and level barriers that span across the entire road. Blocking off any traffic from crossing the tracks.
- Automatische Halve Overweg Bomen (AHOB). The majority of level crossings in the Netherlands are AHOB. This system includes flashing lights, bell ringing and level barriers to close off half of the road, hereby still preventing oncoming traffic from crossing the tracks.
- Automatische Knipperlicht Installatie (AKI). It consists of flashing lights and warning sounds, but has no level barriers. There are only a few level crossings left with this system.
- Automatische Overpad Bomen (AOB). In many train station this is a platform crossing for pedestrians. It includes level barriers and flash-

ing lights as well as warning bells. Some barriers have extra fencing underneath, to prevent travellers from passing underneath the barriers.

- Waarschuwingsinstallatie Landelijke Overwegen (WILO). This system only uses flashing lights. It includes country fencing and is applied for crossing on private property for example on farm land.

ProRail has provided a list, including the location parameters of all the level crossings with the above mentioned level crossing systems. The list contains a total of 1518 level crossings all over the Netherlands. For each of these level crossings the leaf area and biomass is calculated.

2.4 CONCLUSION

The largest part of the Dutch railway network has a GRS system. This type of detection system can have detection loss if poor wheel/rail contact occurs. This detection loss, also called Loss of Shunt (LOS) happens when the residual current received is too high for 1.6 seconds. An LOS happening near a level crossing can cause the signalling system to deactivate an already activated level crossing. Traffic will not be stopped, which can cause a major collision. The influential factors contribution to LOS are related to either the condition of the rail or the contamination of the rail head. In the months October, November and December the most problematic factor is the falling of leaves. By forming a new layer, these leaves can cause detection loss and loss of adhesion. Broad leaf species tend to be more problematic than coniferous species.

From earlier documentation on LOS in the Netherlands we find that it is difficult to predict which level crossings have a high risk of deactivation due to LOS. There are no instances where LOS happens in the same location twice. If LOS is observed additional measures are taken.

For vegetation management all trees in 30 meter at each side of the track are digitised. This data provides the tree height, crown diameter and location parameters of each tree. Only the trees near automatic level crossings are of interest for this research. The type of level crossings taken into account are ADOB, AHOB, AKI, AOB and WILO. All these level crossings have in common that the detection of a train activates the system automatically. If LOS happens near one of these level crossings dangerous situations can occur.

3

LITERATURE REVIEW

In this chapter the scientific literature related to the knowledge problems are reviewed. For calculating the amount of leaves expected to fall near a specific section of the tracks a literature review was conducted. In this literature review the focus is on finding formulas, which are adaptable to different species of trees, to quantify the amount of leaves falling near the tracks.

3.1 LEAF AREA CALCULATION

For calculating the leaf area a lot of information can be found through the topics, forestry and the ecosystem. Over multiple decades the technology to calculate the leaves of a tree have improved significantly. From using simple linear calculations on a trees characteristics to high end laser technology. The laser technology, often referred to as the LiDAR method, uses laser light and sensors. Then the reflection of light is measured to get a three dimensional picture of the leaves and the tree.

The most common quantification in literature on the amount of foliage of a tree is the Leaf Area Index (LAI). "Leaf area index is defined as the projected area of leaves over a unit of land ($m^2\ m^{-2}$), so one unit of LAI is equivalent to 10,000 m2 of leaf area per hectare." (Waring and Running, 2007). To estimate LAI there are direct methods, through leaf litterfall or destructive sampling, or indirect methods which uses the relationship with other measurable parameters. Currently the most used methods for estimating the LAI is optical remote sensing (Fang and Liang, 2008).

For this research the parameters that are available, from the vegetation data of ProRail, consists of the tree height and crown diameter. The current methods using laser technology are not applicable in this research. Other ways of calculating the leaf area and biomass have to be reviewed. One of these calculations is based on the Diameter at Breast Height (DBH), which is the stem diameter measured at a height of 1.3 meter from the ground. The other calculations use the crown parameters or height of the tree. A systematic research was conducted using multiple databases on finding leaf area and biomass equations in literature. The steps taken in selection of search strings and criteria can be found in appendix II.

There are seven papers left for review after the systematic literature selection. Each of the papers are checked on the adaptability of the equations, findings on calculations of leaf area and biomass, the use of a single species and the use of broad leaf species. The adaptability of the equation refers to the flexibility of using the equation on different species. This analysis is developed into table 3.1.

Table 3.1: Literature review matrix

Including | Papers	1	2	3	4	5	6	7
Adaptability of equation	-	-	-	+	-	+	-
Allometric equation	+	+	+	+	+	+	+
Calculation of leaf area	+	-	+	+	+	+	-
Calculation of leaf biomass	+	+	+	+	+	+	+
Addressing a single species	+	+	+	-	+	-	-
Addressing broad leaf species	+	-	+	+	+	+	+

1.Bartelink (1997), 2. Inagaki et al. (2019), 3. Le Goff and Ottorini (1996), 4. Nowak (1996), 5. Osada et al. (2003), 6. Timilsina et al. (2017), 7. Vento et al. (2019)

In reviewing the seven papers the most important part is to find a usable equation suitable for multiple species. From information on the vegetation data provided by ProRail it is uncertain what the exact species is of the trees near the tracks. The equation should be adjustable to broad leaf species, because these species have a larger influence on the detection loss than coniferous species.

The papers focusing on a single species are 1. Bartelink (1997), 2. Inagaki et al. (2019), 3. Le Goff and Ottorini (1996) and 5. Osada et al. (2003). In these papers the characteristics of one species is integrated into the equation. Often developed through field research and leaf collection. If species become known in future vegetation data of ProRail these equations might be used.

In the paper of Vento et al. (2019) there are two broad leaf species considered in an urban area. These species are the *Morus alba* and *Plantanus hispanica*. Measurements of the DBH, crown height and crown major and minor diameter are recorded. For each parameter the linear correlation is checked through the coefficient of determination known as R^2. The R^2 indicates the proportion of the variance of a dependent variable based on an independent variable. The R^2 often ranges between 0 or 1. The higher the R^2 the better an estimation can be calculated based on the observed values being near the regression line. The highest R^2 value for both species is between the crown height and crown volume. The final equations for estimating the leaf biomass are developed by a linear equation based on the crown height. The paper explains that this is the best option for estimating the leaf biomass of these species.

Vento et al. does not include the calculation of the leaf area, but calculates the leaf biomass per m^2. This study concludes for the two species that calculating the leaf biomass by crown parameters appears to be more accurate than by DBH. The equation is solemnly based on linearity for two specific species. This is an example of finding linearity in the parameters, which could be used on the vegetation data of ProRail. Therefore we will check the relations between parameter to see if a regression equation could be developed for this research. For other equations on leaf biomass calculations the paper references Nowak (1996) for a logarithmic regression equation and to Dobbs et al. (2011) for a probabilistic methodology using only DBH and tree height.

The paper of Nowak (1996) suggest that a general model can be used to calculate the leaf area and biomass of a wide range of species. The regression equations are based on DBH or crown characteristics. All equations are developed for broad leaf species and a list of the species shading factors is included. The work in this paper is often referred to in new studies, because it can be easily adapted to calculate the leaf area and biomass for multiple species.

Table 3.2: Overestimation of leaf area and biomass. (Timilsina et al., 2017)

Models	Bias Current model	Bias Nowak (1996)	Relative Bias Current model (% of mean)	Relative Bias Nowak (1996) (% of mean)
Dbh model for leaf area (m^2)	−6.6	−113	−6	−106
Crown model for leaf area (m^2)	−6.5	−127	−5.8	−115.7
Dbh model for dry weight (g)	−8105	−69310	−98	−839
Crown model for dry weight (g)	−728	−13401	−8.8	−162.3

The paper of Timilsina et al. (2017) compares a local developed model against the general model of Nowak. The researchers collected data on the characteristics of 74 trees similarly to Nowak. The data was then used to fit two regression models and checked for linear correlation. The outcome of the calculations were compared to the outcome using Nowak's equations. It shows that the general model of Nowak overestimates the amount of leaf area and biomass in all calculations, compared to the actual leaf area and biomass. The overestimation counts for both models shown in table 3.2, which for the DBH model is 6.6 m^2 overestimated in the local model and 113 m^2 for the Nowak calculations. From this comparison it is clear that with precise values, on the selected trees parameters, a more accurate calculation can be done to estimate the leaf area and biomass. This study shows that if information is available on the exact measurements of the trees a better equation can be developed through fitting linear regression.

3.2 CONCLUSION

A systematic literature review was conducted. The steps are explained in appendix II. The result provided seven papers for review. Each paper was read and assessed on key findings in table 3.1. Most of the papers focused on one single species, which made the equations not adaptable to other type of trees. The three papers that included broad leaf species and equation for more than one type of species were Vento et al. (2019), Nowak (1996) and Timilsina et al. (2017). All of the papers include linear regression equations. A general equation developed by Nowak was mentioned by the other two papers. These researchers developed their own regression equations for calculation leaf area and biomass for the species included in their research. From this literature review we found that checking for linear correlation might provide a good estimating regression equation for calculating leaf area and biomass. The general regression equations of Nowak could be applicable for this research.

4

QUANTIFICATION APPROACH OF THE LEAF AREA

In this chapter the quantification approach to the leaf area is specified. Explained are the existing formulas and the required parameters. The vegetation data available for this research is reviewed. Finally we explain the chosen methods for calculating the leaf area and biomass are summarised and explained.

4.1 LEAF AREA CALCULATION METHODS

The leaf area and biomass of a tree can be calculated by the tree's variables. The parts of the tree referred to in this research for measurements are illustrated in figure 4.1 by Allan McInnes. (Morgenroth and Östberg, 2017)

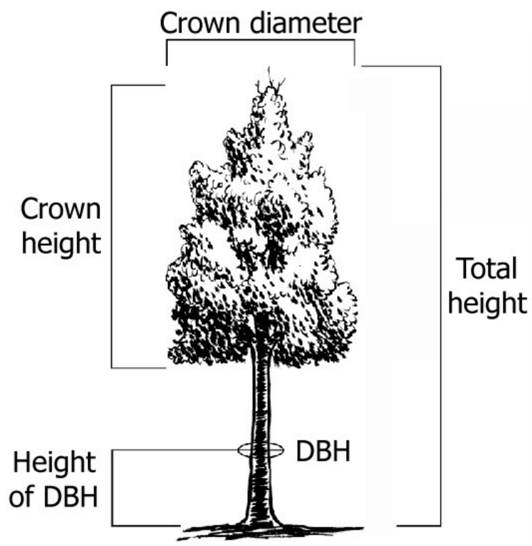

Figure 4.1: Variables of tree measurements (Morgenroth and Östberg, 2017)

The paper "Estimating leaf area and leaf biomass of open-grown deciduous urban trees."(Nowak, 1996) found in the literature review, uses the linear equation for calculating the leaf area (m^2) and leaf biomass (g) based on the crown parameters.

This linear regression equation 4.1 includes H for crown height (m), D for crown diameter (m), S for shading factor and C as the outer surface area of the tree crown. The value of C is calculated by $(\pi D(H + D)/2)$. The $b_0 - b_4$ are regression coefficients, with the corresponding values given in table 4.1. A correction is made in the form of (MSE/2) to correct for logarithmic bias.(Nowak, 1996)

$$\ln Y = b_0 + b_1 H + b_2 D + b_3 S + b_4 C \tag{4.1}$$

Equation 4.1 has a logarithmic form often used in tree allometry. (Picard et al., 2012) This form makes it possible to include different characteristic and dimensions of a tree. The Y is the outcome for either the leaf area (m^2) or the leaf biomass (g) (Nowak, 1996).

Table 4.1: Regression coefficient values (Nowak, 1996)

E	Y	b_0	b_1	b_2	b_3	b_4	R^2	MSE
Dbh	Leaf area	0.2102 (0.8368)	0.0586 (0.0085)	4.0202 (1.0711)	na	na	0.64	0.3386
Dbh	Leaf biomass	7.6109 (0.2355)	0.0643 (0.0081)	ns	na	na	0.54	0.3616
Crown	Leaf area	−4.3309 (0.7227)	0.2942 (0.0253)	0.7312 (0.0579)	5.7217 (0.8147)	−0.0148 (0.0018)	0.91	0.2317
Crown	Leaf biomass	1.9375 (0.709)	0.4184 (0.057)	0.6218 (0.0709)	3.0825 (0.7918)	−0.0133 (0.0018)	0.92	0.2145

The regression coefficients b_1 and b_2, used for the height and diameter of the crown, are the ratio of influence of these parameters. The shading factor is based on the proportion of light intercepted by the tree canopy. A list of shading factors per species is given by Nowak. The regression coefficient b_4 of the outer surface area of the tree crown is a negative value of -0.01. There is no explanation for this negative regression coefficient. (Nowak, 1996)

In equation 4.1 the only parameter that is unknown is the crown height. The vegetation data from ProRail only provides the tree height and crown diameter, therefore we researched a way to calculate the crown height.

For calculating the crown height we found equation 4.2 from DeYoung (2018) in forest measurement, which uses the crown ratio. This is the ratio of crown height to tree height. It is called a ratio by the writer, but expressed as a percentage.

$$Crown\ Ratio = 100 * \left(\frac{Crown\ Height}{Tree\ Height}\right) \tag{4.2}$$

There is another equation on the crown ratio using other variables. According to Holdaway (1986) in "Modeling tree crown ratio" the tree crown ratio can be calculated by a non-linear model. In this model the Diameter at Breast Height (DBH) and the Basal Area (BA) are the parameters. The BA is the sum of the surface area of a tree, measured at DBH, and reported on a per unit area basis (Bettinger et al., 2017).

The crown ratio is based on the shape and size of the crown. This can be determined by the space and available light seeping through the canopy. A maturing tree will have an increasing crown canopy and will let less light through to the ground. The crown ratio decreases when the competition of light increases (Holdaway, 1986).

This effect is calculated in equation 4.3. The first part $(b_1/(1 + b_2 * BA))$ produces a base curve describing the crown ratio over the basal area. The second part $(b_3 * (1 - e^{-b_4*(DBH)}))$ adds how much a tree will exceed this base curve based on the size of a tree. Here b_1 estimates the maximum ratio without competition of light and b_2 is the decrease in crown ratio when competition increases. In the second part b_3 is the maximum value that the crown ratio can increase based on an increasing DBH. The purpose of b_4 multiplied with the DBH is unexplained. (Holdaway, 1986)

In equation 4.4 the crown ratio is calculated by the crown ratio code. It is unclear how the value of 0.45 in equation 4.4 is calculated. Since the paper is frequently referenced in other studies, we trust the expertise of the writer.

$$\mathcal{CRC} = \frac{b_1}{1 + b_2 * BA} + b_3 * (1 - e^{-b_4*(DBH)}) \tag{4.3}$$

$$\mathcal{CR} = \frac{CRC - 0.45}{10} * 100 \tag{4.4}$$

To calculate the crown ratio, the DBH and BA have to be calculated first. The BA can be calculated when the DBH is known. For calculating the basal area the assumption is that the tree is cut off at the DBH. The area of a circle is πr^2, but in forest measurements the diameter is used instead of the radius. This can be seen in equation 4.5. (Bettinger et al., 2017)

$$Basal\,Area(units^2) = \pi \left(\frac{DBH}{2}\right)^2 \tag{4.5}$$

When the DBH is measured in centimeters the basal area is expressed in m^2. This is shown in equation 4.6. (Bettinger et al., 2017)

$$BA(m^2) = 0.00007854 * DBH(cm)^2 \tag{4.6}$$

If the DBH is known the basal area can be calculated. Research by Hemery et al. states that there is a relationship between crown diameter and DBH. In this study multiple linear regressions are calculated for different species, resulting in high R^2 values. Here the R^2 is the coefficient of determination. When the R^2 is close to 1 there is a positive linear relationship between two variables. If one of the variables increases it is more likely the other variables increases as well. The relationship between crown diameter (K) and the DBH (d) are referred to by Hemery et al. as the K/d ratio. Both values are expressed in meters. Figure 4.2 from Hemery et al. (2005) shows the linear regression of Beech. In table 4.2 the corresponding linear regression parameters for each species are listed. Also included in the table are the R^2 values per species. (Hemery et al., 2005)

Table 4.2: Regression parameters per species (Hemery et al., 2005)

Species	No. of observations	Predicting K from d		r^2
		Intercept (a)	Slope (b)	
Sycamore: *Acer pseudoplatanus*	52	0.69189	18.6770	89.6
Birch: *Betula* spp.	55	0.97524	16.1512	92.2
Chestnut[a]: *Castanea sativa*	43	2.79271	10.6684	76.1
Beech: *Fagus sylvatica*	58	1.13312	15.2331	92.0
Ash: *Fraxinus excelsior*	61	0.75810	20.3565	93.0
Walnut[b]: *Juglans regia*	46	2.75266	18.1646	92.9
Poplar: *Populus*	37	0.80097	18.9502	96.5
Cherry[c]: *Prunus avium*	[d]	1.7600	15.40	84.0
Oak: *Quercus robur* and *Q. petraea*	64	1.71733	15.6159	91.1
Rowan: *Sorbus aucuparia*	13	1.09576	18.4490	93.2
Lime[a]: *Tilia cordata*	33	2.25928	11.4408	90.5

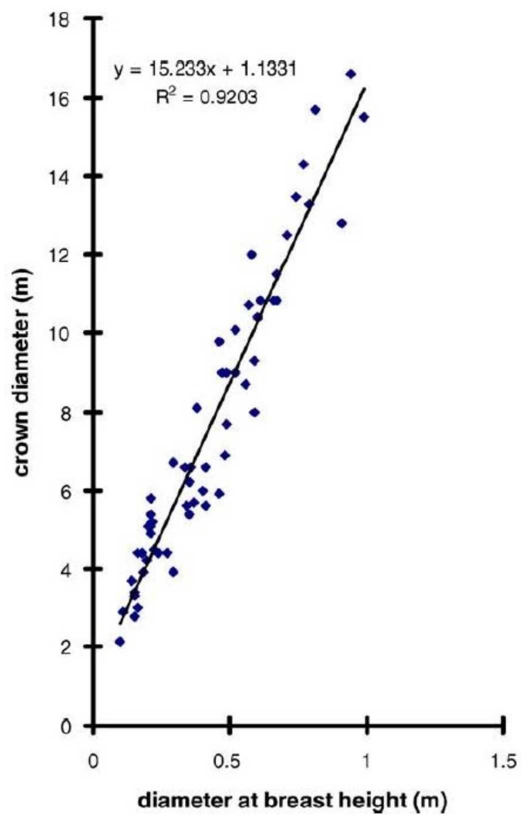

Figure 4.2: Relationship crown diameter to DBH for beech (Hemery et al., 2005)

Using a standard linear regression equation and the parameters from table 4.2, the DBH can be calculated. We show this in equation 4.7. To get the DBH using the crown diameter as input, equation 4.7 is rewritten to equation 4.8.

$$Crown\ Diameter = b * (DBH) + a \tag{4.7}$$

$$DBH = \frac{Crown\ Diameter - a}{b} \tag{4.8}$$

Calculating the crown height makes it possible to solve equation 4.1 by Nowak, to get the leaf area (m^2) and the leaf biomass (g) of a tree. By solving equation 4.8 using the crown diameter, we get the DBH of the tree. The DBH can be used to calculate the BA in equation 4.6. By having the BA and DBH known, the CRC can be calculated in equation 4.3. Then equation 4.4 can be solved using the CRC resulting in the CR. This crown ratio combined with the already known tree height can provide the crown height, by calculating equation 4.2.

Another option is to calculate only the biomass of a tree based on the DBH. By using equation 4.8 for calculating the DBH and the most used allometric equation 4.9 for calculating the biomass of a tree. (Ferrari and Sugita, 1996)

$$Foliage\ biomass = \alpha\,(DBH)^{\beta} \tag{4.9}$$

Where α is β are parameters that determine the increase of biomass to the diameter at breast height, based on the tree species. Each species has its own crown shape that influences the total biomass.

Limitations

The method of calculating the crown height in the above way might not provide the exact crown height. For each equation there are certain constraints on the characteristic of the trees. The choice is made to calculate the crown height anyway, due to the limited parameter data available for this research. The equation of Nowak is the leading equation found, to calculate the leaf area and leaf biomass through crown parameters. This equation does not need the value of the DBH. The downside is that the equation was developed based on a crown height of 3.4 to 9.1 meter and a crown diameter of 4.1 to 14 meter. (Nowak, 1996) The data available for this research include trees with a higher and lower value for the crown diameter. We found a study that compared the Nowak equation to newly developed local models. This study points out that having larger trees will conclude in an overestimation of the leaf biomass. Another remark is made that calculating the leaf biomass based on the DBH will provide a more accurate prediction on the amount of leaf fall. (Timilsina et al., 2017) Since the leaf area is based on the crown parameters, including the large crown diameter values, we can expect a major overestimation of the leaf area.

4.2 VEGETATION DATA

For different topics ProRail uses a Geographic Information Systems(GIS) framework. This type of framework uses maps for data analysis. It visualises the data by layering the information. For ProRail all the trees around the tracks are visualised using a GIS framework. This web application is called "Bomen in Beeld", literally translated into "trees in picture". This map shows the exact location of each tree from 30 meter of the nearest axis of the rail. For each tree the following characteristics are provided:

- The location in x,y-coordinates
- The location in mile marker (in Dutch "kilometrering")
- The tree height, z-coordinate (meter)
- The crown projection, horizontal diameter of the tree crown taken as the largest diameter of the crown (meter)
- The horizontal length that a tree would cover if toppled (meter)
- The angle from the tree to the track (between -180° and 180°)
- The distance from the tree to the middle of the track (meter)

In the web application each tree has a colour, based on the height of the tree. This colour represents the potential risk of a tree collapsing on the tracks. The trees that can fall on the tracks are red, the trees that can fall on the inspection path are orange and the remaining trees are green. Figure 4.3 shows the different colour of the trees in the web application of ProRail.

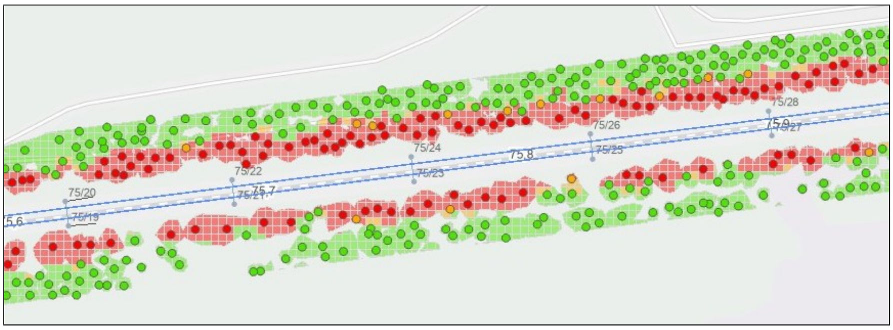

Figure 4.3: Web application "Bomen in Beeld" (ProRail, 2020)

For ProRail this is the first time that all the trees around the tracks are digitally registered. Not knowing what quality requirements needed to be requested, resulted in the received data containing a lot of observational errors.

The vegetation data includes other objects, like lampposts and transmission towers. Also the bushes near the trees are included in the diameter of the crown. Hereby generating unrealistic values for both tree height and crown diameter. The data was collected during the summer period, in which the trees are in full foliage. This made it impossible to accurately locate the stem of the tree. For the location of the stem a best-guess was made, by pinpointing the stem right below the highest points of the tree. Some trees have more than one top, which causes the data to project more trees on the same location.

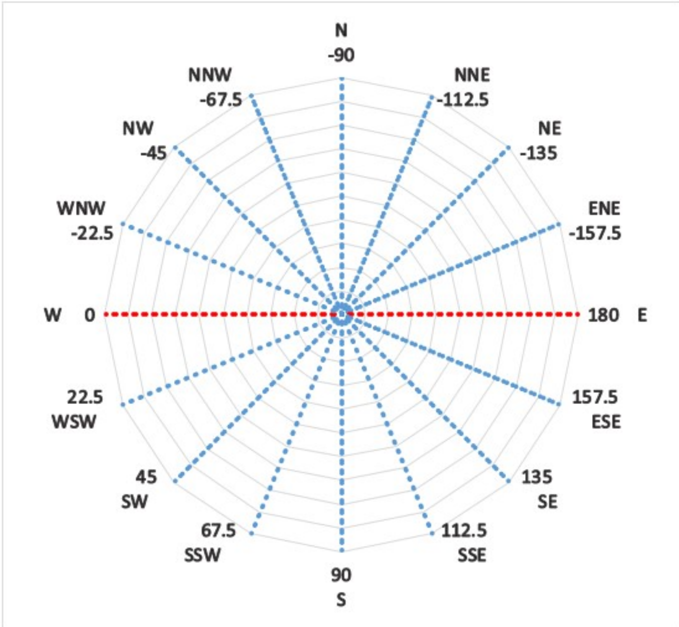

Figure 4.4: Compass rose for the angle of the tree to the tracks

Next to the characteristics and location of the tree, the vegetation data includes the angle from the tree to the tracks. This angle is registered in a range between -180° and 180°. We illustrated this range in figure 4.4. The midpoint is the location of the tracks. The red line in figure 4.4 represents a topographical line from the west to the east. A tree north of the track has a negative angle between 0° and -180° and a tree south of the track has an angle between 0° and 180°.

Two examples of the angle can be seen in figure 4.5 and figure 4.6. In figure 4.5 the angle is -139.6° following a northeast direction. In figure 4.6 the angle is 40.6° having a southwest direction.

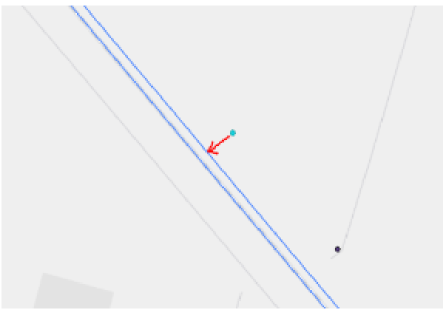

Figure 4.5: NE direction (ProRail, 2020)

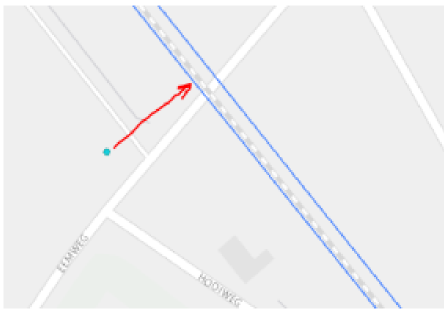

Figure 4.6: SW direction (ProRail, 2020)

The vegetation data contained information on the species of the trees. A distinction was made between deciduous trees and coniferous trees based on the density of the tree crown. To check the accuracy of this distinction a sample of trees was studied. The result provided an incorrect distinction for most trees. Thus we cannot validate which trees belong to which species, based on the vegetation data from ProRail.

For the calculations of the leaf area and biomass, we have to decide on a species for the parameter values. For calculation purposes a general tree type could be chosen. Therefore we researched the most common tree types in the Netherlands.

Due to climate change, the Dutch government is working on a forest strategy (in Dutch called "bossenstrategie") for their climate goals. For this strategy the government commissioned ProBos to research the current situation of forests in the Netherlands. ProBos took multiple samples from all over the Netherlands to make a realistic prediction of different tree types. We derived the percentage of shares per tree type in the Netherlands from the ProBos report. These percentages are summarised in table 4.3.(Schelhaas et al., 2014)

Table 4.3: List of species

Tree type	Share	Surface	Min	Max
Common oak	17.2%	64,283	59,217	69349
Birch	6.6%	24767	21620	27913
Beech	4.1%	15,410	12,928	17893
Ash	3.5%	13,099	10,810	15387
Poplar	3.3%	12,328	10,108	14549
Black ash	2.4%	8,916	7,028	10804
American oak	2.3%	8696	6831	10561
Willow	1.7%	6,274	4,690	7858
Native decideous tree	1.5%	5,614	4,115	7112
Sycamore	1.0%	3,853	2,611	5094
Foreign decideous tree	0.5%	1,981	1,091	2872
Bushes	0.4%	1,651	838	2464
Total decideous trees	**44.7%**	**166,872**	**158,720**	**175023**
Scots pine	29.9%	111,835	105,157	118513
Douglas fir	5.1%	18,933	16,181	21684
Japanese larch	4.9%	18,162	15,467	20857
European Spruce	3.4%	12,769	10509	15028
Corsican pine	2.6%	9,797	7,817	11776
Austrian pine	1.1%	4,073	2,796	5349
Other needle leaves tree	0.9%	3,412	2,244	4581
Total coniferous trees	**47.9%**	**178,980**	**170,539**	**187421**
Clearcutting	1.4%	5,284	3,830	6737
Not visited area	6.0%	22,345	19,356	25334
Total	**100%**	**373,480**		

Previous research by the British Adhesion Working Group (AWG) found that deciduous trees are more problematic to the rail surface than coniferous trees. (Edgley, 2018) AWG found that non-native trees are a greater problem than native trees. The native trees are part of the ecological system and insects will help decompose the leaves. For the non-native trees, which are not part of the ecological system, there are no insects to help decompose the leaves.

We concluded that the common oak would be most suitable, based on the data from ProBos and knowing deciduous trees are more problematic. The common oak, which is also known by its Latin name *Quercus Robur*, is chosen for all calculations that require certain parameter values related to species.

4.3 EXISTING METHODS FOR CALCULATING LEAF FALL

The first method to calculate the leaf area and biomass is from Staelens et al. (2003). This method includes the distance from tree to location and the wind direction as influential parameter. The outcome of the calculations in their study give the leaf biomass per gram per m^2. This paper is based on prior equations developed by Ferrari and Shinya (Ferrari and Sugita, 1996). Both studies use specific species to formulate the required parameters. Another study written by Jonard et al. compares the two previous methods with a newly developed ballistic approach. In all three models the same allometric equation is used to calculate the amount of leaf biomass. The difference in the models is the approach towards the dispersal of the leaves. Both models, from Staelens et al. and Jonard et al., take into account the wind direction. The approach of Jonard et al. goes further by including the wind speed, release height and leaf fall velocity. We developed an overview in table 4.4 of all the parameters included in each model.

Table 4.4: Required parameters for each model

	Models		
Parameter	Ferrari et al.	Staelens et al.	Jonard et al.
Tree species	+	+	+
Height of tree	-	-	-
Diameter at breast height	+	+	+
Crown diameter	-	-	+
Crown height	-	-	+
Distance of tree to location	+	+	+
Angle of tree to location	-	+	+
Wind direction	-	+	+
Wind speed	-	-	+
Release height of leaves	-	-	+

From the available vegetation data we known the angle from the tree to the tracks. The wind direction can be an influential parameter by using this data. The ballistic approach by Jonard et al. includes additional parameters such as release height and wind speed. There is no data on these parameters available. Based on the available data we chose the Staelens et al. model.

Equation 4.10 is developed by Staelens et al. and includes specific tree parameters, wind direction and angle from tree to tracks. The equation calculates the LLF_i which is the amount of leaf biomass in gram per m^2 per year for one tree contributing to location i. Here the summation is over all the trees j that contribute to location i. In this equation leaf fall is influenced by a predominant wind direction. The trigonometrical function of $c(\theta) = c_0 + c_1 cos(\theta - \theta_d)$ is added to indicate that more leaves would fall upwind than downwind. The θ is the angle from tree j to location i and the θ_d is the prevailing wind dispersal in degrees clockwise from north. The values of c_0 and c_1 are related to the tree species and determine the shape of the leaf fall shadow (Staelens et al., 2003). In this equation the x is the distance in meters from tree j to location i. The dispersal in equation 4.10 includes a decline of the leaves based on the distance from the tree trunk and wind direction, seen in part $Exp[-(c_0 + c_1 cos(\theta - \theta_d))x_{ij} - d * (DBH)_{ij}$. The other part of equation 4.10 calculates the leaf biomass where the parameters a and b are related to the species. The leaf biomass increases by an increasing DBH of a tree. The N is the normalisation constant calculated through integrating the dispersal over 2π and an infinite distance. The value of N can be calculated numerically, but for this research the provided value for N from Staelens et al. is used for the *Quercus Robur* species.

According to Staelens et al. previous studies have shown that a more common form, where parameter d is equal to zero, still accurately predicts biomass. When the tree diameter increases, parameter d declines the rate of increase in LLF_i. The result of the study (Staelens et al., 2003) shows that parameter d is similar to zero for the *Quercus Robur* and therefore negligible.

$$Total\ LLF_i = \frac{a}{N}\sum_{j=1}^{n}(DBH)_{ij}^{b} * Exp[-(c_0 + c_1 cos(\theta - \theta_d))\ x_{ij} - d * (DBH)_{ij}] \tag{4.10}$$

4.4 A NEW DEVELOPED METHOD FOR CALCULATING LEAF FALL

The existing methods need a lot of parameter estimations, which are based on a study area of specific species of trees. These methods are difficult to apply and adapt to the vegetation data of ProRail. We therefore developed a new approach to quantify the leaf fall. This new method should be reliable, adaptable and user friendly. In the below paragraph we explain the new method constructed by using a circular segment and the volume of a cone shape.

There are many factors that influence the motion of a leaf. To exactly predict the landing location of a falling leaf is difficult. For the new method we have chosen a circular segment, hereby assuming that the leaves will fall in a circle around the tree. A circular segment is a part of a circle where a straight line cuts a segment out. This can be seen in figure 4.7, where the green area is the circular segment. We are going to use the green segment later on for calculating the leaf fall near the tracks. (Weisstein, 2002)

Here the R represent the radius, θ the angle in radians and s the arc length. The dashed line in figure 4.7 is a the cord length. The small r is the height from the mid point to the cord length a. The height of the arced green part is h.

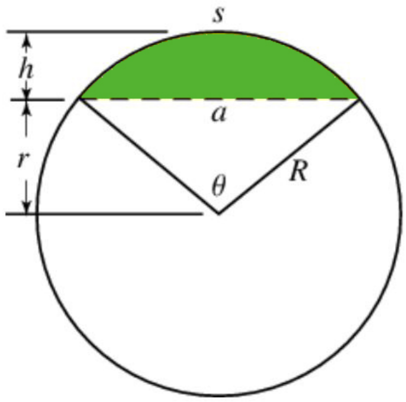

Figure 4.7: Circular segment (Weisstein, 2002)

The circular segment area is calculated by using a double integral, equation 4.11. It is the direct integration for finding the circular segment area according to Weisstein. (Weisstein, 2002)

$$Area = \int_{-R*Sin(\theta/2)}^{R*Sin(\theta/2)} \int_{R*Cos(\theta/2)}^{\sqrt{R^2-x^2}} dydx \tag{4.11}$$

Equation 4.11 can be interpreted as the estimated leaf fall for a density of 1. In general, this density can be expressed in polar coordinates as a function $f(r,\theta)$. In polar coordinates r is the radius and θ is the angle. Using polar coordinates and adding a density function equation 4.12 is developed. This equation can approximate the leaf fall in the green area. The calculations of this new double integral are given in appendix III.

$$Leaf\ Area = \int_{-\theta_0}^{\theta_0} \int_{\frac{R*Cos(\theta_0)}{Cos(\theta)}}^{R} f(r,\theta)rdrd\theta \tag{4.12}$$

According to many studies there is a negative exponential decrease in the amount of leaf fall by distance from the tree. Most leaves tend to fall close to the tree and decline by distance from the tree trunk. According to many studies there is a negative exponential decrease in the amount of leaf fall by distance from the tree, which means that $f(r,\theta)$ decreases exponentially as a function r for a fixed θ. Most leaves tend to fall close to the tree and decline in number by distance from the tree trunk. This form has been shown in multiple studies that quantified leaf litter dispersal from trees.(Spicer, 1981)(Ferguson, 1985)(Shure and Phillips, 1987) We visualised the negative exponential decrease of leaf litterfall in a simple illustration in figure 4.8.

The tracks cross the circle at a specific point. To illustrate this part of the leaf area the following drawing is shown in figure 4.9. Here the brown spot represents the tree trunk and the green striped area is the circular segment.

We looked at multiple programs for calculating the double integral formula with a negative exponential density. One program that can calculate a dou-

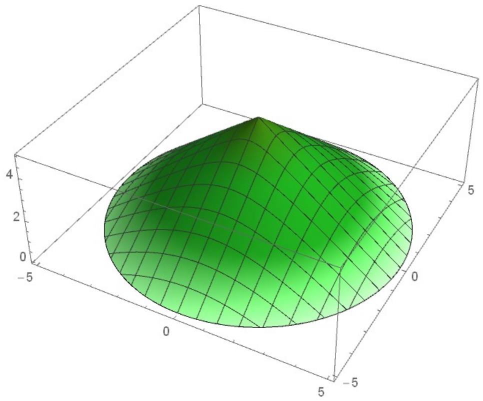

Figure 4.8: Distribution of leaf fall

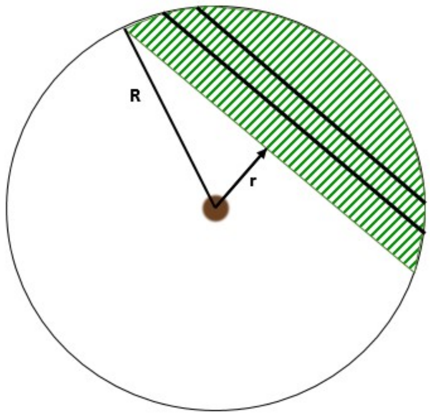

Figure 4.9: Circular segment of tracks

ble integral is Wolfram Mathematica. For this research Wolfram Mathematica was used to try different options for calculations. The program is also used to check the developed formulas mentioned in appendix III. After trying multiple options to include the double integral into Excel through the trapeziod rule or Simpson's Rule, we decided to take a different approach.

Knowing the leaves follow a negative exponential function, illustrated in figure 4.8, we looked into solid shapes. We choose the cone shape for this leaf fall situation. The circular segment is translated into a three dimensional cone shape. The cone shape represents the leaf fall. We will call the cut part of the cone shape a cone segment. The cone segment is the coloured part of the cone, illustrated in figure 4.10. By calculating the volume of the cone segment that covers the tracks, an estimation can be made on the amount of leaf biomass.

In equation 4.12 polar coordinates are used for calculating the leaf area. Using this equation as a base to calculate the volume of a cone segment changes are made. The equation is adapted by adding the height of the cone. Also different notations are used for the new equation. The translation from the equation 4.12 to equation 4.13 can be found in appendix III.

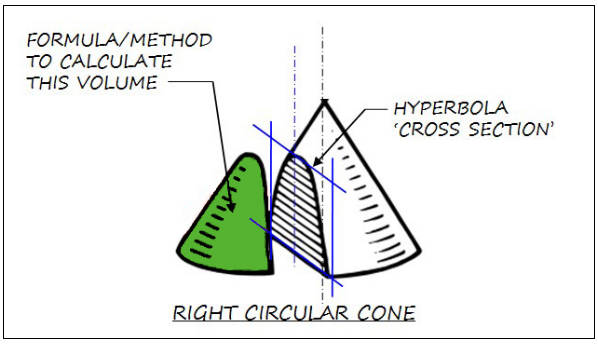

Figure 4.10: Cone segment (stackexchange, 2016)

We use formula 4.13 for calculating the cone segment volume. (Rajpoot, 2016)

$$V_{segment} = \frac{H}{3R}\left[R^3 Cos^{-1}\left(\frac{r}{R}\right) - 2Rr\sqrt{R^2 - r^2} + r^3 ln\left(\frac{R + \sqrt{R^2 - r^2}}{r}\right)\right] \quad \forall\, 0 \leq r \leq R \tag{4.13}$$

The H is the height of the cone, which is the height of the tree in this research. Then the R is the base radius of the ground surface around the tree. We chose the tree height for the radius R. The information on the trees is limited to tree height and crown diameter. Leaves can fall from the highest point of the tree, therefore we believe that the most reliable choice for R is the tree height.

The small r is the distance between the tree and the tracks. Currently the distance is taken from the tree trunk to the midpoint between the rails. This would mean that half of the tracks is not included in the segment.

To be able to calculate the segment over the whole tracks shown in figure 4.9, the distance r is reduced in the following way. The reduction is based on the clearance outline NL1, which regulates the minimum width and height of space that should be clear around the tracks. This is the most common clearance outline in the Dutch railway. The total width of the railway clearance NL1 is 3.6 meter, so a reduction of 1.8 meter is chosen. This will ensure the inclusion of the whole rail and an additional part next to the rail. By changing the r value in the above way the segment becomes larger. More trees will meet the requirement of $r \leq R$ and be included in the calculations. The segment can cover a larger area on the other side of the tracks than the 1.8 meter on the tree side. We expect that this can cause an overestimation of the leaf biomass. We choose to keep the rest of the segment, since we expect more leaves to be drawn to the tracks through aerodynamic suction. By using this formula only the trees that have a height R higher than the distance r, are used for calculation.

4.5 CONCLUSION

In this chapter the calculation methods, from the literature review, are adapted to fit the available data. Tree measurements are used to quantify the leaf area and biomass of each tree. The equation from Nowak, chosen in the literature review, is based on the crown height and crown diameter. The crown height is not included in the available data. Multiple equations from different papers are needed to calculate the crown height. The most used equation for calculating only the leaf biomass is an allometric equation using the DBH. Here two parameters, related the species of the tree, determine the increase of biomass. The available vegetation data provided by ProRail is reviewed and the species *Quercus Robur* is chosen. This species is the most common deciduous species in the Netherlands. The species is needed for specific parameter values.

There are two methods chosen to calculate the leaf area and biomass. The first method is an existing method from literature developed by Staelens et al.. This method includes the wind direction and distance from tree to the tracks to calculate the amount of leaf biomass in grams per m^2. The second method is a new approach to calculating leaf biomass. This new developed method is based on the volume of a cone shape. The cone shape represents the leaf fall. The part of the cone shape covering the tracks is called the cone segment. Using the volume of the cone segment, the leaf biomass is calculated. To include the whole track in this method the distance from the tree to the tracks is reduced by 1.8 meters. Only trees with a height higher than the distance, from the tree to the tracks, are included in the cone segment method. Both methods will be used for quantifying the leaf area and biomass near each level crossing.

5

QUANTIFICATION MODEL

The required parameters for the methods to calculate the leaf area and biomass are listed. The parameters are checked and prepared for usage in the methods. We explain the development of the quantification methods into Excel VBA. Also the data is prepared and the model is tested and validated. Finally an analysis is made of the results of the quantification methods.

5.1 PARAMETER RELATIONS

For quantification of the leaf biomass near each level crossing multiple parameters are needed. For this research the required parameters for the quantification of the leaf fall are:

- Height of tree
- Diameter of tree crown
- Location of tree
- Location of tracks
- Distance between tree and tracks
- Angle of tree to tracks
- Wind direction

The influential parameter of the tree, tree height and crown diameter, are of influence to the amount of leaf biomass. Influencing the leaf dispersal are the predominant wind direction and the distance and the angle of the tree to the tracks. Hereby meaning how far away the tracks are located from the tree, but also accounting for the wind influencing the leaf dispersal.

There are many studies that refer to linear regression functions for calculating the leaf biomass. These function often include the tree height and the DBH. The variables available from the vegetation data, provided by ProRail, are the tree height and the crown diameter. We looked at the relationship between these two tree parameters to check for any linearity.

All available data is used on the tree height and crown diameter to created the linear regression in figure 5.1. The corresponding function to this linear regression is $y = 6.8666 ln(x) + 1.1146$. The R^2 = 0.2317 shows no clear linearity between the tree height and crown diameter. In most equations in literature, simple linear regression are used for calculating leaf biomass. These linear regression equations are based on linearity between tree parameters. The resulting R^2 of figure 5.1 indicates that developing a linear regression equation, based on tree parameters, is not the best option for this research.

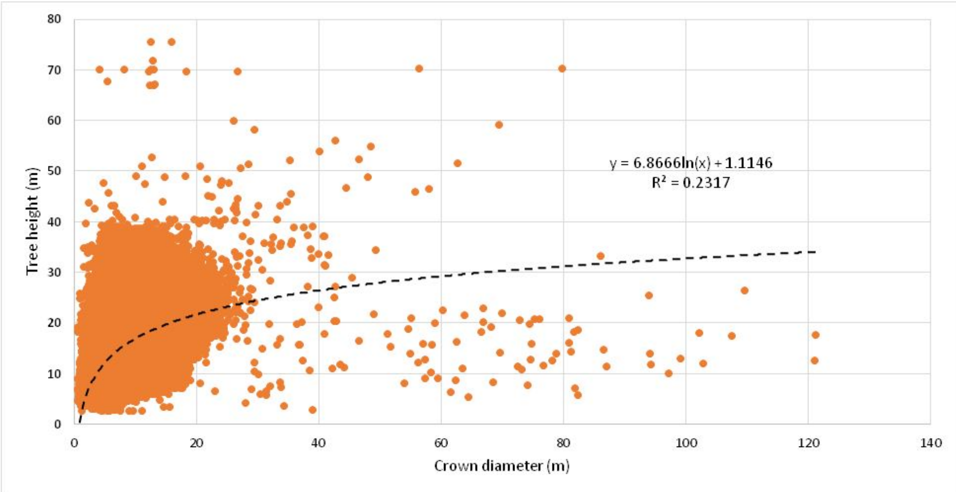

Figure 5.1: Linear regression of tree height to crown diameter

The parameters provided that are related to the location are the distance between a tree and the middle of the tracks, the angle of the tree to the tracks and the topographical mile marker system. This mile marker, in Dutch called "kilometrering", consist of a Geocode for the region and KM-Geocode for the specific location on the railway line. In addition to these parameters there is also an x, y-coordinate for each tree. For indicating a location on the tracks the mile marker is used, rather than the x,y-coordinates.

The mile marker provides the known location of the tree to the tracks. For example the nearest point of the tracks to a certain tree is the mile marker with a Geocode of 91 and a KM-Geocode of 2.722. This mile marker can be set for multiple trees, if the trees are near the same point of the tracks. The trees located near a specific announcement section of the level crossing, can be located by the corresponding mile marker from that section.

There is no list of announcement section available. Therefore we looked at the active level crossings locations to locate the announcement sections. ProRail provided a list of all active level crossings. This list contains the mile marker for each level crossing. This makes it possible to relate the trees to the announcement sections that activate the level crossings. The data on the mile marker of the trees in combination with the mile marker of the level crossings are used to collect the trees per level crossing.

The vegetation data from ProRail provides the angle of the trees to the track in a range of -180° to 180°. For calculation purposes these angles are changed to a range between 0° and 360°.

We developed two small formulas to recalculate the angle which are shown in equation 5.1. In these formulas the x is the angle from the vegetation data and the y is the new angle between 0° and 360°.

$$y = \begin{cases} -x - 90 & \text{if} \quad -180 \leq x \leq -90 \\ -x + 270 & \text{if} \quad -90 < x \leq 180 \end{cases} \tag{5.1}$$

The wind direction can influence the amount of leaf biomass near the level crossing. There can be a predominant wind direction in the months that trees shed their leaves. We know that leaves fall in the months October, November and December. For these months data was retrieved from the Royal Netherlands Meteorological Institute, in Dutch known as the KNMI. The data from the last 10 years of wind direction are grouped. For each month an overview is made of the wind rose. The wind rose for each month and a combined total is illustrated in figure 5.2. We calculated that the main wind direction is 204°, which has a southwest direction. The range of the dominant wind direction is from 202.5° to 225°. The analysis and calculations of the wind direction are found in appendix IV.

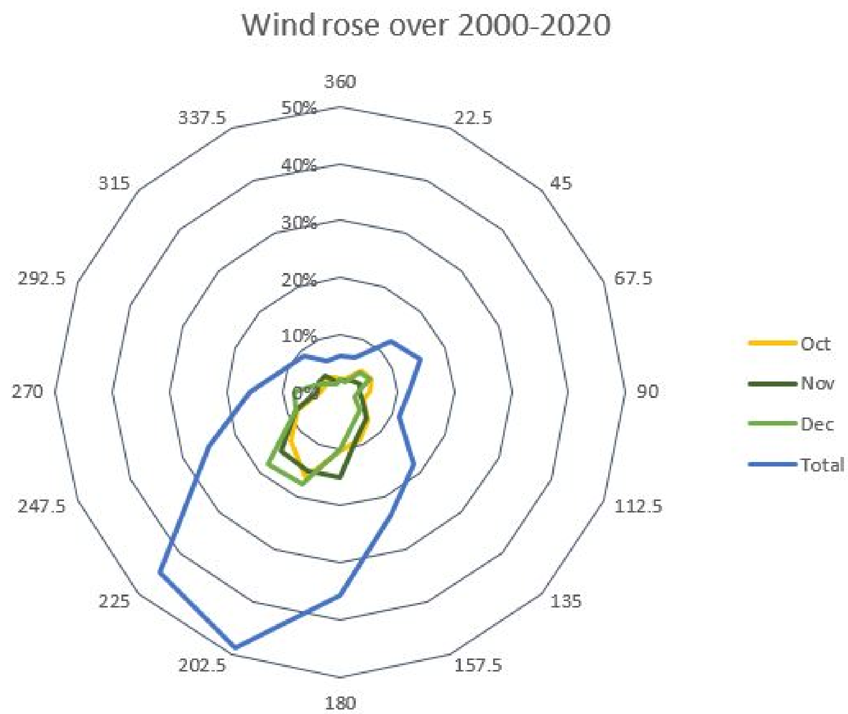

Figure 5.2: Wind rose over 2000-2020

5.2 QUANTIFICATION MODEL

The model is developed in Excel by using Visual Basic for Applications (VBA). We chose to use Excel as the employees of ProRail are familiar with the program and hereby develop a method that is user-friendly. Another reason is that changes this can easily be done in the model if new data on the vegetation comes available.

The vegetation data includes around 700.000 trees. Only the trees that are near an announcement section are included. The selected trees are written in array for the calculations of the corresponding level crossing. The moment the total tree biomass is calculated, the array will be emptied again. For the next level crossing the corresponding trees will be written again into the emptied array. The same amount of trees will not be found at each level crossings. Therefore we chose to loop through a dynamic array. This type of array can easily be resized, because it does not have a fixed size. Using this specific type of array the running time of the model can also be reduced.

For each level crossing the following actions are developed:

- Selection of the trees near the announcement section
- Calculate the DBH and the angle of the tree to the track
- Calculate the dispersal and leaf biomass
- Summarize the total leaf biomass per level crossing

The selection of trees near the announcement section is based on the mile marker system, explained in the previous paragraph. The level crossing is activated 20 seconds before the train reaches the crossing. Depending on the maximum speed on the tracks the length of the announcement sections that signal the level crossing can be calculated. For this research we chose a fixed value of 800 meters before and after each level crossing location. This is translated to a range of -800 meter and +800 meter of the KM-Geocode of the level crossing.

A restriction is implemented that if there are zero or one tree related to a level crossing the calculations are not executed.

For the selected trees the calculation of the DBH in cm is done through equation 4.8. In this equation the crown diameter of the tree from the vegetation data is used, with the parameters on the *Quercus Robur* from Hemery et al. (2005). The data on the angle from the trees to the track is changed to a 0° to 360° with equations 5.1. For calculating the influence of the wind on the leaf dispersal we use a cosine function. In VBA the cosine function only works in radians. The angle is recalculated from degrees to radians by using the general equation 5.2.

$$\text{Angle in radians} = \frac{\text{Angle in degree} * \pi}{180^\circ} \quad (5.2)$$

Now all parameters needed for calculating the leaf area and biomass with both methods are translated. For the Staelens et al. method, we use their provided parameter values related to the *Quercus Robur*. In the paper the *Quercus Robur* is called the *pedunculate oak*. The values taken from the vegetation data are the calculated DBH and angle in radians from the tree to the tracks. The predominant southwest wind direction is 204° as calculated in Appendix IV. This method from Staelens et al. is used to calculate the leaf biomass per gram per m^2 for each level crossing. The result of the calculations are written in the Excel sheet "Result". The number of trees selected per level crossing, for this method, are also included in this Excel sheet.

The developed cone segment method uses a different approach. Previously mentioned this approach has a restriction that the tree height should to be higher than the distance between the tree and the track. Only the trees that are higher than the distance are taken into account. From these trees the biomass is first calculated through the standard equation 4.9. For this equation the calculated DBH and the α and β values of Ferrari and Sugita are used. We did not use the values for α and β from Staelens et al., because the α value is integrated with the normalisation constant N. They state the ratio a/N as a single parameter. Therefore we made the choice to take the values of Ferrari and Sugita for calculating the leaf biomass of each tree in the cone segment method.

For the dispersal of the leaves the angle of the trees to the tracks is used in the cone segment method. There is a predominant wind direction in the range 202.5° and 225°. All trees that are within this range are expected to have more influence on the risk of LOS. We chose to multiply the leaf biomass of these trees by a factor of two. We assume that the trees on the southwest side of the tracks have twice as much impact than other trees.

Having calculated the leaf biomass, the next step is to calculate the cone segment volume. To find the percentage of the total volume equation 5.3 is added, to calculate the total volume of a cone. The cone segment volume is divided by the total volume, to calculate the percentage of the total.

$$\text{Total volume of a cone} = \frac{\pi}{3} * \text{Height of tree} \tag{5.3}$$

In equation 5.3 the height of the cone is the height of the tree. The percentage is multiplied by the total leaf biomass of the tree. Then the leaf area is calculated as the base of the cone segment. The cone segment volume is divided by the leaf area resulting in the leaf biomass in grams per m^2 for each tree. The total biomass of all trees per level crossing are written in the Excel sheet "Result". The number of trees selected per level crossing for the cone segment method, requiring the tree height to reach the tracks in distance, are also listed in the Excel sheet "Result".

5.3 DATA PREPARATION

The raw data is cleaned before it can be used by the quantification model. The vegetation data provided by ProRail takes into account lamppost, transmission towers and other objects. Therefore we chose to put restriction on the tree height and crown diameter. The minimum size and maximum size of these parameters are reviewed. The tree height has an average of 14.08 meter, a minimum of 2.51 meter and a maximum 75.38 meter. According to Bekaert and Philippona (2020) the top largest trees in the Netherlands are slightly above 40 meter. The average transmission towers are around 45 meter. We chose to set 40 meters as the maximum height. We checked the trees with a height of 40.03 meter and 40.05 meter and discovered that these are both transmission towers.

For the crown diameter the average is 7.22 meter, the minimum is 0.59 meter and the maximum 121.25 meter. We can explain the 121.25 meter, knowing that bushes are included as an extension of the crown. For accuracy we chose 40 meter to be the maximum of the crown diameter.

In total the vegetation data includes 717557 entries. Reducing the maximum height of the tree to 40 meter a total of 78 entries were deleted. This resulted in 717479 entries left. By reducing the maximum crown diameter to 40 meter another 79 entries were deleted. To prevent poles or lamppost next to the tracks to be counted as trees all entries with a distance lower than 5 meter were deleted. This amounted to 11606 entries. Another restriction was set to trees with a higher distance of 30 meter from the tracks, which are 235 entries. The final amount of 705559 tree entries are used for calculations.

5.4 VALIDATION

To validate that the model would perform the right calculations and select the correct trees, we manually checked one level crossing. The trees that are normally selected by the model are manually put into an Excel sheet. Then for each tree all calculations are done and checked against the VBA model. The total leaf biomass and the total number of trees selected corresponded with the outcome of the VBA model. During the calculations of this one level crossing we found that using the logarithmic regression model of Nowak for calculating the leaf biomass would generate a high result in total leaf biomass.

The validation of the result is very difficult, because no other research is done before on leaf biomass near the tracks. There is a different result using the Nowak logarithmic function for calculating biomass compared to calculating biomass based on the DBH using the Staelens et al. method. The equation from Nowak is known to overestimate the amount of biomass compared to other calculations of leaf biomass. The total amount of biomass is multiplied by the wind dispersal in the model of Staelens et al.. In case of a very large amount of biomass the wind dispersal will have little effect on the total outcome of leaf biomass. The smaller the amount of biomass the more influence the wind direction will have on the amount of biomass, expected near the level crossing. The cone segment method calculates the leaf biomass covering the tracks using the volume of a cone segment. For dispersal the leaf biomass is multiplied by two, if the angle of the tree to the tracks is in the predominant wind direction range. The multiplication of two is chosen for compensation of the small segment of the whole volume of leaf biomass of a tree. Both Staelens et al. and the cone segment method use wind as an influential factor for dispersal. The result of these methods can be compared to check for reliability of the new developed cone segment method.

It is expected that more leaves influence the risk of LOS than calculated in the cone segment method. Predicting how much more leaves fall near the tracks is difficult according to research. The exact location a leaf will fall to the ground is difficult to predict. Many researchers have tried, but an estimation seems most preferable. Thus we chose to calculate the leaf biomass per m^2 in the cone segment method, instead of calculating the leaf area separately. Hereby making it possible to compare the results of the cone segment method with the Staelens et al. method.

5.5 RESULT

The results of Nowak's equation overestimated the amount of biomass by thousands of kilograms more than the standard allometric equation 4.9. The high amount of biomass using Nowak's equation overruled the dispersal of wind in the Staelens et al. method. Thus causing the wind direction to be of no influence. The cause of this overestimation could be the parameters values related to the species are set to the *Quercus Robur* and not each species individually. Another reason can be that Nowak's equation work best for trees with a maximum crown height of 12 meter and maximum crown diameter of 14 meter. The trees included in this research can have a maximum crown diameter of 40 meters.

The equation from Nowak was also tested for the cone segment method. The result showed a similar overestimation of leaf biomass. The result of the Nowak's equation is compared to the other calculations of leaf biomass. We found two level crossings having a larger overestimation from equation. These two level crossings have in common that near the crossing a group of large trees are located. Furthermore there are less trees present at these crossings, than near other level crossings. We conclude that Nowak's equation is more effected by the tree height. The tree height does not guarantee a larger estimation of leaf biomass. We chose to calculate the leaf biomass through the DBH equation instead of using the Nowak's equation in each method.

For the Staelens et al. method the leaf biomass is calculated using their parameters and the newly calculated DBH. For the cone segment method the same equation 4.9 is used, but the parameter values are taken from Ferrari and Sugita (1996).

The results using Staelens et al. calculation method shows a measured amount below 200 gram leaf biomass per tree at a location. The estimated average biomass per tree per m^2, according to their study, is 9.6 kilogram for a *Quercus Robur*. This is a very small fraction of the expected amount of 9.6 kilogram of a *Quercus Robur*. We suspect that this is the result of the way the dispersal of the leaves is calculated. In table 5.1 the minimum, maximum and average amount of leaf biomass per $m2$, plus the total from both calculation methods are summarised.

Table 5.1: Result leaf biomass

Method	Min (g)	Max (g)	Average (g)	Total (kg)
Staelens et al.	4.79	22327.9	3996.81	5679.46
Cone segment	1.28	19459.11	2366.39	3362.63

The amount of leaf biomass depends on the included trees' characteristics and the dispersal calculations. The cone segment method includes less trees, due to the tree height restriction, than the Staelens et al. method. Using the multiplication of two on the leaf biomass of trees with an angle in the predominant wind direction compensates for using less trees. The closer trees to the tracks weigh heavier in the cone segment method than the Staelens et al. method.

Table 5.2: Critical level crossings

	Level Crossing	City	Staelens et al. method leaf biomass in gram per m2	# of trees per level crossing sections	Cone segment method leaf biomass in gram per m2	# of trees used in cone segment method
1	028 / 056.959	ENSCHEDE	22327.90	1267	19459.11	973
2	021 / 082.673	HOOG SOEREN	18657.47	1694	17285.49	1038
3	309 / 002.061	EYGELSHOVEN	16668.80	1072	16086.96	818

The highest scoring level crossings based on the leaf biomass calculations are given in table 5.2. These level crossings have the largest amount of leaf biomass in both calculation methods. The level crossing 028/056.959 in Enschede scores the highest by far to the second highest level crossing.

The results of both methods plus the amount of trees per level crossing are listed in the Excel sheet "Result". Looking at the results the ranking of the level crossings with the highest leaf biomass for each method are only slightly different. When we look at the amount of trees, the result does not show that more trees cause a higher amount of leaf biomass. This can be caused by the calculations of the dispersal of leaves, but also the distance from the trees to the tracks. Using the wind direction a smaller amount of trees can cause higher leaf biomass if located on the southwest side of the tracks.

Another difference between the methods having effect on the results is the dispersal calculations. The wind dispersal is different for both methods. The Staelens et al. method uses one wind direction at 204°. The cone segment method uses a range of dominant wind direction between 202.5° to 225°. The influence of angle from the tree to the tracks can result in a multiplication of two. If the tree angle is between the range of the dominant wind direction. This might explain the high leaf biomass in gram per m^2, while including less trees in the calculations.

5.6 conclusion

There is no linearity between the tree height and crown diameter from the vegetation data. For the location of each level crossing mile markers are used instead of x, y-coordinates. Some of the required parameters are recalculated for the quantification model. There is a predominant wind direction in the months October, November and December which come from the southwest direction. The quantification model is developed in Excel VBA to make it user friendly. Another reason is that simple recalculations can be done over the large data set. For each level crossing only the trees that are near the announcement section are selected. The DBH is calculated from parameters already available. The angle of the tree to the tracks is translated to a range between 0° and 360°. The parameters listed are used in the two methods for calculating the leaf biomass and amount of trees per level crossing.

The raw data included lamppost, transmission towers and other objects. In the crown diameter bushes were included and poles next to the tracks were seen as trees. Data cleaning was necessary for removing the irrelevant data. The restrictions were set to a maximum tree height of 40 meter and a maximum crown diameter of 40 meter. Any tree closer to the tracks than 5 meter in distance were deleted. This resulted in a deletion of 11998 entries. The final amount of 705559 trees are used for calculations.

Validation is difficult with no earlier research done on the amount of leaf biomass near the rail. The two methods of calculations use different way of calculating the dispersal. The exact location of a falling leaf seems impossible to predict, therefore an estimation of leaf biomass per m^2 is chosen.

Both the Staelens et al. method and the cone segment method result in an estimated leaf biomass in grams per m^2. The highest level crossings for both calculations differ only slightly in ranking. All results from the quantification method are listed in the Excel sheet 'Result'.

6

MAP OF LEVEL CROSSINGS

In this chapter the characteristics of the level crossings are explained. We categorised the level crossings for the risk of having LOS caused by leaf fall. The risk categories are used in developing a map of all the level crossings in the Dutch rail network.

6.1 LEVEL CROSSINGS

All the level crossings with an automatic signalling system are included in this research. The total amounts to 1518 level crossings. These level crossings can be located in a forest, near open farm land or in the middle of a city or train station. We estimated the amount of leaf biomass per m^2 that can cause LOS at a level crossing. The risk level of having LOS is solemnly based on the estimated leaf biomass. This risk level does not include any other parameter that might increase the risk of LOS. The result of this research can give an indication which level crossings have a higher risk than other level crossings. The results are based on comparison between the level crossings to allow categorisation of the risk.

6.2 THE LEVEL CROSSINGS MAP

A map is developed of the level crossings having the most risk of LOS caused by leaf fall. For this map we assess the risk based on the amount of leaf biomass near a level crossing. In table 6.1 the corresponding colour and symbol for each risk category is listed.

Table 6.1: Risk categories

colour	Symbol	Percentage of total biomass	Number of level crossings	Risk
	□	1.57%	3	Critical
	◇	32.39%	143	High
	○	34.38%	295	Medium
	×	31.66%	951	Low
	+	0%	126	No risk (or no data)

This risk categorisation is based on the results from the calculations of the cone segment method. Equation 6.1 is developed to calculate the percentage of leaf biomass per level crossing.

$$\textit{\% of total biomass} = \frac{\text{Leaf biomass of level crossing}}{\text{Total leaf biomass of all level crossings}} * 100 \tag{6.1}$$

The categorisation is executed by looking at the percentage per level crossings. The largest percentages are 0.58%, 0.51% and 0.48% of the top 3 level crossings. There are 1518 level crossings included, which explains why a 0.5% can be seen as a high percentage. These highest ranking level crossings are categorised separately as critical risk. The other level crossings have a smaller variation in percentage of total leaf biomass. Therefore we chose to cluster these level crossings into three categories. Each of these three categories is cut at a minimum to maximum percentage. The total percentage of total biomass of each of these categories should be equally distributed. In table 6.1 the percentage of total biomass for the high, medium and low categories are around 33% each.

The high risk category includes level crossings with a percentage between 0.17% to 0.40% of the total. The percentage of the total, for level crossings in the medium risk category are between 0.09% to 0.16%. The level crossings in the low risk category have a percentage between 0.01% to 0.08% of the total. The final category includes all level crossings that have 0% of the total leaf biomass calculated with the cone segment method. Some of these level crossings might have trees near the tracks in reality, but these trees are not registered in the data.

The colours and symbols from table 6.1 are used for the map showing all level crossings. We developed this map illustrated in figure 6.1 through RailMaps, a feature of ProRail including the Dutch rail network. For employees of ProRail a link to this map is given in the bibliography of this study.

The map in figure 6.1 shows the most high risk level crossings to be located in the central part of the Netherlands. The Hoge Veluwe National Park is located near most of these level crossings in the mid-east of the Netherlands. The railway line between Haarlem-Baarn-Den Dolder and the line Maarn-Rhenen show a lot of high risk level crossings as well. The areas near these railway lines are known to have high tree density.

6.3 CONCLUSION

The level crossings included in this research have automatic signalling systems. Based on the amount of leaf biomass of two methods the risk is categorised for each level crossing. The critical level crossings have a combined estimating 1.65% of the total amount of leaf biomass. The other risk categories are, high, medium, low and no risk. The category of no risk are all the level crossings with 0% of the total leaf biomass calculated by the cone segment method. It is unclear, due to inaccurate data, which level crossings might have trees that should be included in the calculations. The results of the categorisation and the corresponding map are only based on the vegetation data provided by ProRail. The railway lines with the highest risk level crossings, according to the result of this research, are known to have high tree density.

Figure 6.1: The level crossings map (Railmaps, 2020)

7

DISCUSSION

In this chapter we discuss the cone segment method. We will describe what the advantages and disadvantages are of this method.

Most methods for calculating leaf biomass need specific parameters. The available parameters from the vegetation data from ProRail made it difficult to apply these methods. To design a method that could estimate the amount of leaf biomass near each level crossing the cone segment method is developed. This model is understandable and easy to explain. The cone segment method provides reliable results and looks more critically at trees close to the tracks. The model is easily adaptable and can be made extremely precise if necessary. In the present model we deliberately overestimate the leaf biomass in the cone segment method. We expect more leaves to be drawn to the tracks through aerodynamic suction. Another reason for the overestimation is that certain trees are excluded, due to the height restriction. If required these trees can be included with a small alteration to the model.

There are other extensions that can easily be made to the cone segment method. The results of the method are in grams per m^2, but the leaf area is actually set by the choice of the cone height and radius. Changing the cone height or radius can change the leaf area. The segment calculated can become larger or smaller depending on the desired area.

Another change to the model can be a more advanced way of including the influential factor of the wind. The cone segment uses a range for the predominant wind direction. Only trees with angles in this range will have their leaf biomass multiplied by a factor of two. Trees with other angles can still have influence on the tracks at another location, than currently calculated. Additional changes can be made in the calculations for the influential factor of the wind on the dispersal of leaves. Hereby taking into account other trees that are outside of the predominant wind direction range currently used.

In other methods multiple calculations are done to get new parameter values for a different sample plot of trees. In the cone segment method only the values corresponding with the leaf biomass of a species have to be added. Using these values the cone segment method can be easily adapted for multiple different species. Especially if additional information comes available on the species of the trees near the tracks.

The disadvantage of the model is that the cone shape does not cover all leaf area of the trees. Leaves can travel long distances and fall outside of the radius of the cone segment. By changing the radius or the dispersal function in the cone segment method this loss could be compensated.

The cone segment method can only be validated on its result and lacks the ability to be validated by a study area of trees. The ranking of the level crossings only vary slightly from the results of the Staelens et al. method. Thus we can state that the results of the simplified cone method fall within the range of the well established Staelens et al. method.

8

CONCLUSION AND RECOMMENDATION

In this chapter the central research question is answered and recommendations are given. In addition the scientific contribution of this paper and the limitations are discussed. The central research question to be answered is:

"How to design a reliable and user-friendly method to quantify leaf fall influencing LOS? In particular, in what order to take precautions in the signalling system for level crossings, based on the leaf fall situation."

8.1 MAIN FINDINGS

In the months of October, November and December leaves fall from the trees. These leaves can cause loss of detection in the train signalling system. The loss of detection, also called Loss of Shunt (LOS) is the most dangerous at announcement sections near level crossings.

In this research we developed a model that can calculate the leaf biomass per gram per m^2 at a certain location. Hereby quantifying the leaf fall. The higher the amount of leaf biomass the higher the risk of having LOS. The parameters of influence to leaf fall are the tree height, diameter of tree crown, distance and angle of the tree to the tracks and a predominant wind direction. The tree characteristics, tree height and crown diameter, are of influence to the amount of leaf biomass. The distance and the angle of the tree to the tracks in combination with a predominant wind direction, influence the leaf dispersal.

The model is based on the cone segment method, which uses the volume of a segment of a cone shape to calculate the amount of leaf biomass. The cone shape represents the leaf biomass and the segment is the part of the cone that covers the tracks.

The results from the calculations of the cone segment method are used to categorise the level crossings. This categorisation is based on the percentage of each level crossing from total leaf biomass of all level crossings. The categories are critical, high, medium, low or no risk. The level crossings in the critical category have much higher amount of leaf biomass than other level crossings. These level crossings are listed in table 8.1. The next categories all include a larger number of level crossings having similar percentages of total leaf biomass.

It can be concluded that during the fall period, in the months October, November and December there is a predominate wind direction from the southwest direction. This wind direction can cause specific trees to have more influence on the amount of leaf biomass than others. There are certain species that have a greater influence on the possibility of LOS than other. According to previous studies deciduous species are more problematic than coniferous species. The most common deciduous tree in the Netherlands is the *Quercus Robur*, also called the common Oak.

The critical level crossings and the calculated leaf biomass are shown in table 8.1. We recommend to start looking into the signalling system of the level crossing in Enschede, because it ranks highest in leaf biomass per m^2. Then the other critical level crossings can be reviewed to see if axle counters can be implemented in order of the list in 8.1.

Table 8.1: Critical level crossings

	Level Crossing	City	Staelens et al. method leaf biomass in gram per m2	# of trees per level crossing sections	Cone segment method leaf biomass in gram per m2	# of trees used in cone segment method
1	028 / 056.959	ENSCHEDE	22327.90	1267	19459.11	973
2	021 / 082.673	HOOG SOEREN	18657.47	1694	17285.49	1038
3	309 / 002.061	EYGELSHOVEN	16668.80	1072	16086.96	818

For each level crossing the amount of trees are calculated and provided in the sheet 'Result' in the Excel VBA model. The methods used for calculating the leaf biomass use the wind dispersal. We expect that this causes the amount of trees to be less decisive on the amount of leaf biomass.

The detection loss map shows that the most critical level crossings in the Netherlands are located in the mid-east of the country. This is close to one of the largest National Parks, which might explain the large amount of critical and high risk level crossings. The railway lines with the highest risk level crossings are the line Haarlem-Baarn-Den Dolder and the line Maarn-Rhenen. The areas near these railway lines are known to have high tree density.

Adding the result of the leaf biomass per level crossing with the expert knowledge of ProRail, the developed model can help the decision making of where to take precaution against LOS caused by leaf fall.

For further research we recommend to look at other factors influencing LOS and hereby including more parameters in the developed model. In this research the additional measures taken at certain level crossings preventing LOS, are not taken into account. We recommend to include this information first, to prevent taking unnecessary precautions at a level crossing.

The moment that additional vegetation data becomes available at ProRail, we recommend to incorporate this data into the VBA model and recalculate the amount of leaf biomass. We expect that the new data will include the species of each tree, which can provide a more accurate calculation of the leaf biomass per level crossing.

8.2 CONTRIBUTION TO LITERATURE

In this research a model is developed to quantify the amount of leaf biomass near each level crossing in the Netherlands. This model can provide ProRail with insight into which level crossing is of higher risk of having LOS caused by leaf fall. The model is very adaptable and can be used for adding other factors influencing LOS.

This method, for quantifying the leaf biomass near the tracks, can be of interest for adhesion problems too. Often the adhesion problems are caused by leaves on the rail. The quantification of the leaf biomass can be performed for any location on the tracks. At the moment ProRail takes measures against adhesion, based on expert knowledge. Being able to quantify the expected amount of leaves anywhere on the tracks, might provide insight into high risk locations for adhesion problems.

The contribution to scientific literature is a new way of calculating leaf biomass as the volume of a cone shape. Hereby using a cone segment to calculate the leaf biomass for a specific area. Calculating the leaf biomass through the volume of a cone shape is a different approach to existing methods. The cone segment can be extended or changed easily. Additional changes to the factor of wind can be implemented. The approach is flexible and user friendly, because any additional information that comes available can be easily implemented by adding or extending the cone segment method.

8.3 LIMITATION

Due to the complexity of the problem and limited time of the research only the influential factor of leaf fall is quantified and researched. Including other influential factors could have increased the accuracy of the outcome. This might have reduced reliability, for validation of the results is difficult.

The provided data on the trees contained limited information for calculating the leaf biomass. Not knowing the species limits the possibility to include the type of trees. In the current calculations all trees are taken into account equally. In reality deciduous species have more effect on the risk of LOS than coniferous species.

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I

REFLECTION

My understanding of the rail network was very limited at the start of this research. I did not expect the high level of complexity of the rail system. Each year reports on the problem of leaf fall on the tracks are in the news. I never thought I would research this particular problem.

Working on this new subject, having no previous knowledge, finding a best practice is time-consuming. In addition to the tracks being the main new subject, the calculation of leaf area and leaf biomass was also a new topic. Finding the right terminology corresponding with the methods of calculating leaf fall was difficult.

For the first part of the research the focus was on finding all factors influencing loss of shunt. There was not enough data on most factors to make an analysis. Some literature refers to this problem as being complex due to the inability to measure and monitor the factors of influence. The vegetation data provided by ProRail made the main focus shift to the influence of leaf fall on loss of shunt.

For calculating the leaf area and biomass the most promising equation from Nowak was found in the literature review. This equation is based only on the crown parameters of the tree. Then one morning while searching on the keywords "dispersal" and "leaf" the paper of Jonard et al. was found. This study included two other studies by Staelens et al. and Ferrari and Sugita, both including methods of calculating the dispersal of leaves. Finding these methods made it possible to develop a new calculation method for ProRail. This resulted in the cone segment method.

I am very fortunate that I could research and learn a lot about so many new subjects. I got a new admiration for the rail network and how everything seems to run so smoothly, while behind the curtains many people work very hard on solving complex problems.

II

LITERATURE REVIEW

The main research topic is on Loss of Shunt (LOS). The definition of LOS is the loss of detection between the wheel/axle of the train and the rail. The used abbreviation for LOS in the UK is a Wrong Side Track Circuit Failure (WSTCF). Loss of shunt is also seen as a track circuit failure. The opposite failure of LOS is that the track is wrongfully occupied. In the UK this is called a Right Side Track Circuit Failure(RSTCF). When information is found on track circuit failures it is important to check that this information refers to LOS and not to other causes. For finding literature on the topic of LOS the search strings consist of "loss of shunt", "Wrong side track circuit failure" and "Track circuit failure".

In figure II.1 we visualize the search strings and online databases used for literature selection. We made a selection in the abstracts on the words "rail" and "detection" to only have papers that are focused on the main subject. In the last step the abstract of the nine papers are read to check relevancy. Only two papers had a clear indication toward LOS. These papers and a short description of the key findings are:

1. The effect of friction modifiers on wheel/rail isolation at low axle loads (Hardwick et al., 2014). The focus in this paper is the effect of third-body layer on shunting. A clear explanation of the workings of a shunt and the signalling system.
2. Track circuit reliability assessment for preventing railway accidents (Wybo, 2018). The paper assesses the risk factor of loss of shunt. The contributing factors to loss of shunt and the accidents that can occur are explained and grouped.

The second topic for systematic selection is the rail contamination. One of the main causes of LOS is the contamination of the rail head, which causes poor wheel/rail contact. For finding literature on this topic we use the search strings "rail contamination". To find information on the poor wheel/rail contact we set a search string with "wheel/rail contact" AND "contamination". Lastly a search string is made to find papers explicitly focused on contamination of leaves on the track, which is "rail" AND "leaves" AND "contamination". The steps are shown in table II.2.

Search string	Scope	Date of search	Data range	Nr. Of entries
Search protocol for Scopus				
"loss of shunt"	Title, keyword and abstract	Jan-20	1990 - present	13
"wrong side track circuit failure"	Title, keyword and abstract	Jan-20	1990 - present	0
"track circuit failure" OR "track circuit fault"	Title, keyword and abstract	Jan-20	1990 - present	9
Search protocol for Web of science				
"loss of shunt"	Topic	Jan-20	1990 - present	8
"wrong side track circuit failure"	Topic	Jan-20	1990 - present	1
"track circuit failure" OR "track circuit fault"	Topic	Jan-20	1990 - present	2
Search protocol for ScienceDirect				
"loss of shunt" AND "rail"	Keywords, research articles	Jan-20	1990 - present	2
"wrong side track circuit failure"	Keywords, research articles	Jan-20	1990 - present	0
"track circuit failure" OR "track circuit fault"	Keywords, research articles	Jan-20	1990 - present	24
Total in Endnote				**59**
Removing duplicates				-22 **37**
Selecting "rail" in abstract				-15 **22**
Selecting "track" in abstract				-13 **9**
Removed after reading abstract				-7
Total selected for usage				**2**

Figure II.1: Systematic literature selection for Loss of Shunt

To select articles that give information on the leaf contamination and wheel/rail contact the choice is made to select only articles that have "leaves" in the abstract. Multiple papers focus solemnly on different mechanisms to prevent adhesion, therefore the papers mentioning "performance" in the abstract are left out. Then the abstracts are read and the papers focused on adhesion and not specific on contamination are left out. We visualized the selection in II.3. A short description of the key findings of each article are given below:

1. The low adhesion problem due to leaf contamination in the wheel/rail contact: bonding and low adhesion mechanisms (Ishizaka et al., 2017). This paper discusses the bonding materials, possible preventions and mitigation of low adhesion caused by leaf fall.

2. Leaves on the Line: Low Adhesion Detection in Railways (Hubbard et al., 2016). The focus in this paper is on the contact mechanism and creep force. A simulation model is developed to test the contact force of the wheel to the track. This paper mentioned the difficulty of mea-

suring and monitoring all factors involved in this complex low adhesion problem.

3. The effect of friction modifiers on wheel/rail isolation (Lewis et al., 2011). The paper researches the effect of friction modifiers on the signalling system. The mechanism of a track circuit are explained and the causes of loss of adhesion are mentioned.

Another research into literature was done for methods to quantify the amount of leaves per area. For this specific topic the keyword "Leaf Area Index" (LAI) was used as starting point for research. LAI indicates the projected area of leaves over a unit of land (Waring & Running, 2007). Next to knowing the area the amount of leaves is often referred to as biomass. A lot of papers refer to measuring the LAI through optical remote sensing, which uses sensors and imaging of the light frequency. For this paper calculations that use the height and crown diameter of the trees are interesting, because

Search string	**Scope**	**Date of search**	**Data range**	**Nr. Of entries**
Search protocol for Scopus				
"rail contamination"	Title, keyword and abstract	Jan-23	1990 - present	6
"wheel/rail contact" AND "contamination"	Title Title, keyword and abstract	Jan-23	1990 - present	14
"rail" AND "leaves" AND "contamination"	Title Title, keyword and abstract	Jan-23	1990 - present	17
Search protocol for Web of science				
"rail contamination"	Topic	Jan-23	1990 - present	2
"wheel/rail contact" AND "contamination"	Topic	Jan-23	1990 - present	19
"rail" AND "leaves" AND "contamination"	Topic	Jan-23	1990 - present	17
Search protocol for ScienceDirect				
"rail contamination"	Keywords, research articles	Jan-23	1990 - present	15
"wheel/rail contact" AND "contamination"	Title Keywords, research articles	Jan-23	1990 - present	11
"rail" AND "leaves" AND "contamination"	Keywords, research articles	Jan-23	1990 - present	24
Total in Endnote				**125**
Removing duplicates				-84 **41**
Selecting "leaves" in abstract				-26 **15**
Selecting NO "performance" in abstract				-3 **12**
Removed after reading abstract				-9
Total selected for usage				**3**

Figure II.2: Systematic literature selection for rail contamination these are the known parameters from vegetation data present at ProRail. To discard the papers that focus on optical remote sensing, the exclusion of the words "image", "photo", "sensors" and "light" has been added to each search string. The following keywords were used for this literature selection: "leaf", "area", "biomass", "crown diameter", "tree height", "estimating" and "calculating".

For each online database the search string and resulting amount of papers are shown in table II.3. The papers and the literature review corresponding can be found in chapter 3.

For the final 14 papers the abstract was read to see which papers could be of interest for this research. Each paper that is not included after reading the abstract and the reason why are:

- This paper compares the leaf litter of different tree species against each other, but no clear calculations of leaf area or biomass. Therefore not applicable to this research. *Burnham, R. J., Wing, S. L., & Parker, G. G. (1992). The reflection of deciduous forest communities in leaf litter - implications for autochthonous litter assemblages from the fossil record. Paleobiology, 18(1), 30-49. doi:10.1017/s0094837300012203*
- Bases biomass calculations on branches of certain species. There is no need for branches to be included in this research, therefore this paper is excluded. *Dobbs, C., Hernández, J., & Escobedo, F. (2011). Above ground biomass and leaf area models based on a non destructive method for urban trees of two communes in central chile. Bosque, 32(3), 287-296. doi:10.4067/S0717-92002011000300010*
- Focuses on vegetation control for young Douglas trees. Information on vegetation control for one species is not relevant for this research. *Petersen, K. S., Ares, A., Terry, T. A., & Harrison, R. B. (2008). Vegetation competition effects on aboveground biomass and macronutrients, leaf area, and crown structure in 5-year old Douglas-fir. New Forests, 35(3), 299-311. doi:10.1007/s11056-007-9078-z*
- This study is focused on leaf biomass as food for lifestock. Not applicable for this research. *Sèwadé, C., Azihou, A. F., Fandohan, A. B., Glèlè Kakaï, R. L., Mensah, G. A., & Houinato, M. R. B. (2017). Leaf biomass modeling, carrying capacity and species-specific performance in aerial fodder production of three priority browse species Afzelia africana, Pterocarpus erinaceus and Daniellia oliveri in Benin. Livestock Research for Rural Development, 29(10).*
- Again a study on the leaf biomass (of pollarded Lebanon oak) as food for lifestock. Also looks at the pollarding impacts on the nutrient cycle in a forest. Not relevant for this research. *Shahabedini, S., Ghahramany, L., Pulido, F., Khosravi, S., & Moreno, G. (2018). Estimating leaf biomass of pollarded lebanon oak in open silvopastoral systems using allometric equations. Trees-Structure and Function, 32(1), 99-108. doi:10.1007/s00468-017-1614-7*

Search string	Scope	Date of search	Data range	Nr. Of entries
Search protocol for Scopus				
"Leaf" AND "Area" AND "biomass" AND "crown diameter" AND NOT "image", "photo", "light"	Title Title, keyword and abstract	Jan-29	1990 - present	11
"leaf" AND "crown diameter" AND "tree height" AND "estimating" OR "calculating" AND NOT "image", "photo*", "light", "sensors"	Title Title, keyword and abstract	Jan-29	1990 - present	10
"leaf" AND "biomass" AND "crown diameter" AND "estimating" OR "calculating" AND NOT "image", "photo*", "light"	Title, keyword and abstract	Jan-29	1990 - present	27
Search protocol for Web of science				
"Leaf" AND "Area" AND "biomass" AND "crown diameter" AND NOT "image", "photo", "light"	Title Topic	Jan-29	1990 - present	22
"leaf" AND "crown diameter" AND "tree height" AND "estimating" OR "calculating" AND NOT "image", "photo*", "light", "sensors"	Title Topic	Jan-29	1990 - present	18
"leaf" AND "biomass" AND "crown diameter" AND "estimating" OR "calculating" AND NOT "image", "photo*", "light"	Topic	Jan-29	1990 - present	24
Search protocol for ScienceDirect				
"Leaf" AND "Area" AND "biomass" AND "crown diameter" AND NOT "image", "photo", "light"	Keywords, research articles	Jan-29	1990 - present	36
"leaf" AND "crown diameter" AND "tree height" AND "estimating" OR "calculating" AND NOT "image", "photo*", "light", "sensors"	Title Keywords, research articles	Jan-29	1990 - present	29
"leaf" AND "biomass" AND "crown diameter" AND "estimating" OR "calculating" AND NOT "image", "photo*", "light"	Keywords, research articles	Jan-29	1990 - present	18
Total in Endnote				**185**
Removing duplicates				-56 **129**
Selecting "leaf" in title				-60 **69**
Selecting "biomass" in any field				-13 **56**
Selecting "crown" in any field				-20 **36**
Selecting NO "photo" in any field				-12 **26**
Selecting NO "light" in any field				-3 **23**
Selecting NO "pine" in any field				-9 **14**
Removed after reading abstract				-7
Total selected for review				**7**

Figure II.3: Systematic literature selection for leaf area and biomass

- Research on the effects of a snow storm on sugar bushes through leaf biomass. Not applicable to this research. *Ter-Mikaelian, M., & Lautenschlager, R. A. (2001). Predictive equations for leaf area and biomass for sugar bushes in eastern Ontario. Forestry Chronicle, 77(4), 643-649. doi:10.5558/tfc77643-4*

- Introduces sapwood area as parameter for calculations for Leaf Area Index. The sapwood area is not a parameter usable in this research therefore the paper is not included. *Turner, D. P., Acker, S. A., Means, J. E., & Garman, S. L. (2000). Assessing alternative allometric algorithms for estimating leaf area of Douglas-fir trees and stands. Forest Ecology and Management, 126(1), 61-76. doi:https://doi.org/10.1016/S0378-1127(99)00083-3*

The 7 papers selected for the literature review that include relevant information for this research are listed in Endnote II.4. The literature review can be found in 3.

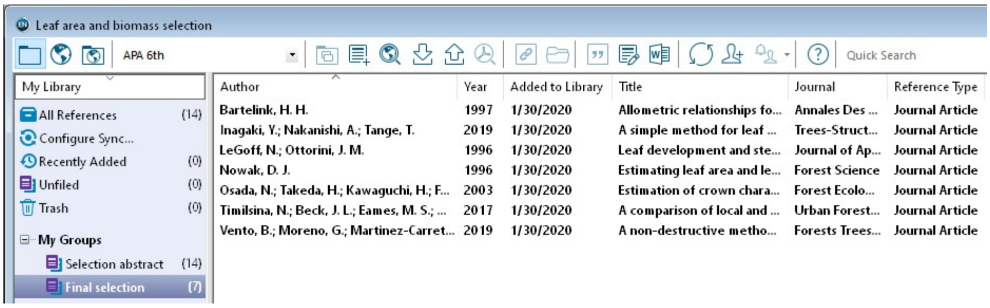

Figure II.4: Endnote list of literature selected for review

III

MATHEMATICAL CALCULATIONS

In this appendix the double integral on the circular segment is explained. The steps taken to calculate the cone segment volume can be found. We also explain the link between the double integral on the circular segment and the formula for the cone segment volume.

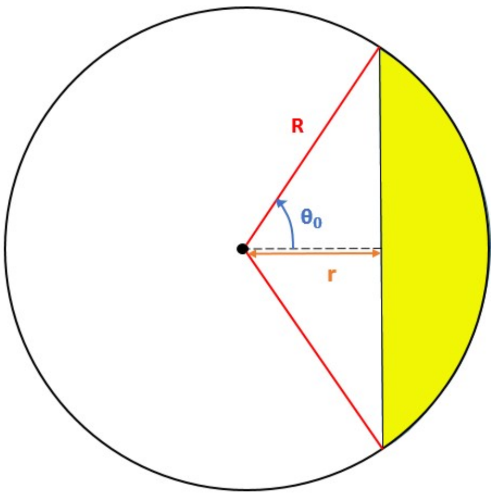

Figure III.1: Illustration circular segment polar coordinates

In figure III.1 the yellow area is the circular segment. The R is the radius, the θ_0 the angle from the dotted line to the R and the small r is the distance from the point to the segment cut. It should be noted that the angle from the dotted line to the lower red line is translated to $-\theta_0$.

The double integral for the yellow area starts with $-\theta_0$ to θ_0, which can be written as $\frac{\theta}{2}$. Then the second integral is taken from the distance of the small r to the big R. The r is translated by geometric rules into $\frac{Rcos(\theta_0)}{Cos(\theta)}$. The double integral corresponding with figure III.1 is:

$$Area = \int_{-\theta_0}^{\theta_0} \int_{\frac{R*Cos(\theta_0)}{Cos(\theta)}}^{R} f(r,\theta) r dr d\theta \tag{III.1}$$

For calculations purposes the $Rcos(\theta_0)$ is translated to x. We calculated the double integral by setting $f(r,\theta) = 1$. The steps taken are:

$$Area = \int_{-\theta_0}^{\theta_0} \int_{\frac{x}{Cos(\theta)}}^{R} 1 * rdrd\theta \tag{III.2}$$

$$= \int_{-\theta_0}^{\theta_0} \frac{1}{2} r^2 \Big|_{\frac{x}{Cos(\theta)}}^{R} d\theta \tag{III.3}$$

$$= \int_{-\theta_0}^{\theta_0} \frac{1}{2} \left(R^2 - \frac{x^2}{cos^2(\theta)} \right) d\theta \tag{III.4}$$

$$= \frac{1}{2} \int_{-\theta_0}^{\theta_0} R^2 - \frac{x^2}{cos^2(\theta)} d\theta \tag{III.5}$$

$$= \frac{1}{2} \left[\theta R^2 - x^2 tan(\theta) \right]_{-\theta_0}^{\theta_0} \tag{III.6}$$

$$= \frac{1}{2} \left((\theta_0 R^2 - (-\theta_0 R^2)) - (x^2 tan(\theta_0) - x^2 tan(-\theta_0)) \right) \tag{III.7}$$

$$= \frac{1}{2} \left((\frac{\theta}{2} R^2 + \frac{\theta}{2} R^2)) - (x^2 tan(\frac{\theta}{2}) + x^2 tan(\frac{\theta}{2})) \right) \tag{III.8}$$

$$= \frac{1}{2} \left(\theta R^2 - 2x^2 tan(\frac{\theta}{2}) \right) \tag{III.9}$$

$$= \frac{1}{2} \theta R^2 - R^2 cos^2(\frac{\theta}{2}) tan(\frac{\theta}{2}) \tag{III.10}$$

$$= \frac{1}{2} \theta R^2 - R^2 sin(\frac{\theta}{2}) cos(\frac{\theta}{2}) \tag{III.11}$$

$$= \frac{1}{2} \theta R^2 - R^2 \frac{sin(\theta)}{2} \tag{III.12}$$

$$= \frac{1}{2} R^2 (\theta - sin(\theta)) \tag{III.13}$$

In step 8 the θ_0 are changed to $\frac{\theta}{2}$. In step 10 the x is changed to $Rcos(\frac{\theta}{2})$, which is the previously mentioned as $Rcos(\theta_0)$. The final formula is the general formula for calculating a circular segment area. (Weisstein, 2002)

From the area of a circular segment we go to a right circular cone. Here we focus on the volume of a cone segment. The cone segment being the part of a right circular cone that is cut by a plane parallel to the symmetrical axis (Rajpoot, 2016). The cone segment is illustrated in figure III.2 as the blue part of the right circular cone. The height of the cone segment is z and the height of the cone is H.

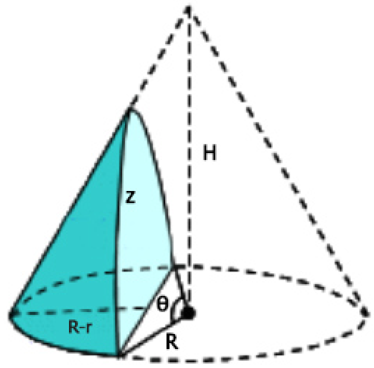

Figure III.2: Illustation of right circular cone (keisan, 2019)

The cut of the cone segment is parallel to the symmetrical axis of the cone. Following trigonometric rules both the cone and cone segment have a right angle of 90°. Meaning that the angle of $\frac{H}{R}$ of the cone is symmetrical to the cone segment angle of $\frac{z}{(R-r)}$. The height of the cone segment z, can be written as $z = \frac{H}{R}(R - r)$.

The integral for calculating the cone segment volume can be written into a triangle calculation. The integral is multiplied by 2, having two triangles visible in figure III.1. The integral will be taken from 0 to $Cos^{-1}(\frac{r}{R}) = \frac{\theta}{2} = \theta_0$ and from $xsec(\theta)$ to R. The $\frac{x}{cos(\theta)}$ used in the previously calculated double integral is rewritten into $xsec(\theta)$. The following mathematical steps show how the formula for the cone segment volume is developed:

$$
\begin{aligned}
V_{segment} &= \iint zrdrd\theta && \text{(III.14)}\\
&= 2\int_0^{Cos^{-1}\left(\frac{r}{R}\right)=\theta_0}\int_{x\sec\theta}^{R} zrdrd\theta && \text{(III.15)}\\
&= 2\int_0^{\theta_0} d\theta \int_{x\sec\theta}^{R} \frac{H}{R}(R-r)rdr && \text{(III.16)}\\
&= \frac{2H}{R}\int_0^{\theta_0} d\theta \int_{x\sec\theta}^{R} (R-r)rdr && \text{(III.17)}\\
&= \frac{2H}{R}\int_0^{\theta_0} d\theta \left[\frac{Rr^2}{2}-\frac{r^3}{3}\right]_{x\sec\theta}^{R} && \text{(III.18)}\\
&= \frac{2H}{R}\int_0^{\theta_0} \left(\frac{R^3-3Rx^2\sec^2\theta+2x^3\sec^3\theta}{6}\right)d\theta && \text{(III.19)}\\
&= \frac{H}{3R}\int_0^{\theta_0} (R^3-3Rx^2\sec^2\theta+2x^3\sec^3\theta)d\theta && \text{(III.20)}\\
&= \frac{H}{3R}[R^3\theta-3Rx^2\tan\theta+x^3(\sec\theta\tan\theta+\ln|\sec\theta+\tan\theta|)]_0^{\theta_0} && \text{(III.21)}\\
&= \frac{H}{3R}[R^3\theta_0-3Rx^2\tan\theta_0+x^3(\sec\theta_0\tan\theta_0+\ln|\sec\theta_0+\tan\theta_0|)] && \text{(III.22)}\\
&= \frac{H}{3R}\left[R^3Cos^{-1}\left(\frac{r}{R}\right)-3Rx^2\frac{\sqrt{R^2-r^2}}{x}\right.\\
&\qquad \left.+x^3\left(\frac{R}{x}\frac{\sqrt{R^2-r^2}}{x}+\ln\left|\frac{R}{x}+\frac{\sqrt{R^2-r^2}}{x}\right|\right)\right] && \text{(III.23)}\\
&= \frac{H}{3R}\left[R^3Cos^{-1}\left(\frac{r}{R}\right)-3Rx\sqrt{R^2-r^2}\right.\\
&\qquad \left.+Rx\sqrt{R^2-r^2}+x^3\ln\left|\frac{R}{x}+\frac{\sqrt{R^2-r^2}}{x}\right|\right] && \text{(III.24)}\\
&= \frac{H}{3R}\left[R^3Cos^{-1}\left(\frac{r}{R}\right)-3Rx\sqrt{R^2-r^2}\right.\\
&\qquad \left.+Rx\sqrt{R^2-r^2}+x^3\ln\left|\frac{R}{x}+\frac{\sqrt{R^2-r^2}}{x}\right|\right] && \text{(III.25)}\\
V_{segment} &= \frac{H}{3R}\left[R^3Cos^{-1}\left(\frac{r}{R}\right)-2Rr\sqrt{R^2-r^2}\right.\\
&\qquad \left.+r^3ln\left(\frac{R+\sqrt{R^2-r^2}}{r}\right)\right]\forall\ 0\le r\le R && \text{(III.26)}
\end{aligned}
$$

In part III.16 the value z is substituted into $\frac{H}{R}(R-r)$. Part III.20 is changed to part III.21 by using the program Wolfram Mathematica. In part III.23, θ_0 is replaced by $Cos^{-1}\left(\frac{r}{R}\right)$. Additionally changing the Secant and the Tangent, through trigonometric functions, to get a more basic mathematical formula. The final formula III.26 is used in this research to calculate the cone segment volume. These steps originated from "Volume & surface area of right circular cone cut by a plane parallel to its symmetrical axis" by Harish Chandra Rajpoot. (Rajpoot, 2016)

IV

WIND DIRECTION

Leaf fall happens around the months October, November and December. The wind directions in these months can have an effect on the leaf fall location. With a predominant wind direction more leaves could be expected from a certain angle. To find out if in these months in the Netherlands a predominant wind direction can be found the Dutch weather institution(KNMI) was contacted. Data was retrieved on the wind direction of each day for the last 20 years from 2000 to 2020 from the station De Bilt. This station is located in the geographical midpoint of the Netherlands. The direction is given in degree, where 1° means there is no wind. Each of the degrees is given a wind direction in ranges. These ranges are registered in table IV.1 and come from the wind rose figure IV.1 of the KNMI.

	Range		
Direction	Min.	Max.	Degree
N	348	11	360
NNO	11	33	22.5
NO	33	56	45
ONO	56	78	67.5
O	78	101	90
OZO	101	123	112.5
ZO	123	146	135
ZZO	146	168	157.5
Z	168	191	180
ZZW	191	213	202.5
ZW	213	236	225
WZW	236	258	247.5
W	258	281	270
WNW	281	303	292.5
NW	303	326	315
NNW	326	348	337.5

Table IV.1: Overview ranges per wind direction

For each months the last 20 years of wind direction is summarized. The percentage of the total of each month is given in table IV.2. We see that the ranges of 180°, 202.5° and 225° are the largest. The range of the most

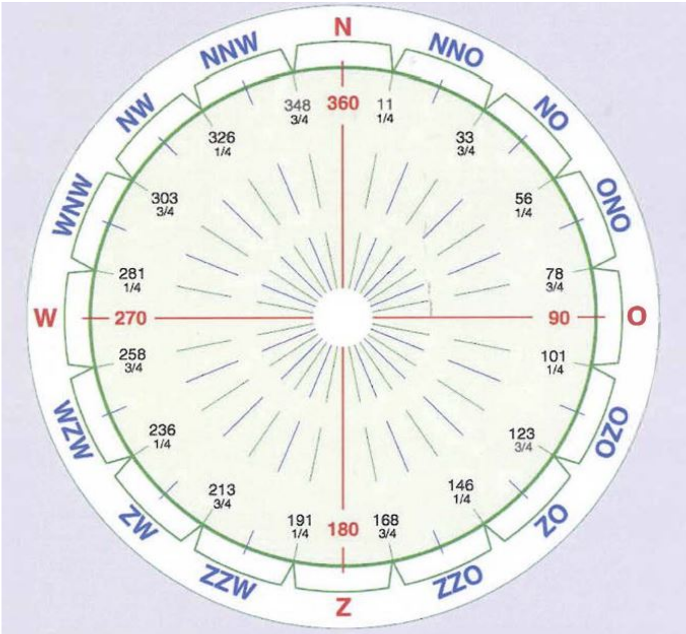

Figure IV.1: Wind rose KNMI (KNMI, 2014)

frequent wind directions in the months October, November and December can be set from 168° to 236°.

Degree ranges	Oct	Nov	Dec	Average
360	2%	2%	2%	**2%**
22.5	2%	2%	2%	**2%**
45	5%	3%	5%	**4%**
67.5	6%	4%	6%	**5%**
90	5%	4%	3%	**4%**
112.5	4%	4%	3%	**4%**
135	7%	7%	5%	**6%**
157.5	9%	8%	6%	**8%**
180	10%	15%	10%	**12%**
202.5	16%	15%	17%	**16%**
225	12%	15%	18%	**15%**
247.5	8%	8%	8%	**8%**
270	3%	4%	8%	**5%**
292.5	3%	4%	4%	**4%**
315	3%	4%	2%	**3%**
337.5	3%	2%	1%	**2%**

Table IV.2: percentage of total wind each month

The percentages of each wind direction for each month and a total of the three months are made into a wind rose. This wind rose 5.2 can be found in chapter 5. We see in table IV.2 that the range 202.5° and 225° with a south western wind direction is dominant. With a simple calculation IV.1 of the three largest percentages taken from table IV.2 we get a predominant 204°. This 204° is used in calculations for the dominant wind direction.

$$204° = \frac{180° * 0.12 + 202.5° * 0.16 + 225° * 0.15}{0.12 + 0.16 + 0.15} \tag{IV.1}$$

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