BACHELOR THESIS

To investigate whether it is advantageous to grant cyclists more priority during rain at the N737/N342 intersection

ROBIN MINK

FACULTY OF ENGINEERING & TECHNOLOGY
UNIVERSITY OF TWENTE

25th JULY 2021

Strukton Civiel

UNIVERSITY OF TWENTE.

Bachelor Thesis Civil Engineering

Date:	25-6-2021
Version:	Final Version

Student:

Name:	Robin Mink
Study:	Bachelor Civil Engineering
Institution:	The University of Twente
Student Number	s2159597
Email:	r.p.c.mink@student.utwente.nl

Internal Supervisor:

Name:	Prof. Dr. Ir. E.C. Van Berkum
Email:	e.c.vanberkum@utwente.nl

Internship Location:

Name:	Strukton Civiel
Address:	Westkanaaldijk 2, 3542 DA Utrecht

External Supervisor:

Name:	Annemarie Boereboom
Email:	annemarie.boereboom@strukton.com

Preface

Dear reader,

This report has been made as my graduation assignment for the Bachelor of Civil Engineering at the University of Twente. I have conducted this assignment between the 12th of April and the 25th of June 2021.

I have investigated whether cyclists could be given more priority during rain at one signalized intersection on the "Innovationroute". The assignment was performed for the company Strukton Civiel. It was my goal to give them the best advice possible about such an installation. My internship was mostly compromised, like most things, by Covid-19. I have therefore spent the vast majority of the time in my bedroom. Fortunately, I was able to work one day a week on location in Utrecht. It was nice to experience the company and meet my colleagues in person as well.

At my internship, I became a member of a group who were busy working on a new platform called WeCity. The ambition of this project is to contribute to the development of Smart Cities by establishing better cooperation. It provides an open platform where interested parties, both suppliers and customers of smart solutions, are welcome. WeCity makes it easier, more reliable and more quality-assured to apply these solutions to make cities smarter. WeCity was launched during my period at the company. I was informed about the project by being on location and participate in weekly online meetings. It was really nice to be included in these meetings to experience how certain aspects work *in real life*.

Next, I did really enjoy conducting deeper research into traffic-related matters like Intelligent traffic control systems, traffic modelling, talking traffic and much more. Further, I have also investigated topics that I did not expect to do beforehand. For example, I have been looking into meteorology to better understand radar systems and nowcasting. I have also learned about some programming in Python. This was quite a challenge since I have never programmed in this language before. I did really enjoy reading and learning about these different topics which are not entirely related to my study.

Firstly, I would like to thank my supervisor from Strukton Civiel, Annemarie Boereboom for the time and effort she has spent to help me during my assignment. Her influence has really helped me a lot during my time at the company. I would also like to thank my supervisor from the University, Mr. van Berkum for his time and useful advice about traffic modelling, the assignment itself and other related matters. Next, I would thank my family for their interest and support. I lastly would like to thank the Notebook Service Centre for lending me a laptop, since I destroyed mine just before starting this project.

I hope you will enjoy this report.

Robin Mink

Anna Paulowna, 25-6-2021

Samenvatting

De fiets is het meest gebruikte vervoerstype in Nederland. Fietsen kan een oplossing zijn voor verschillende problemen in het land. Ten eerste moet uitstoot van broeikasgassen verminderd worden. Een manier om dit te bereiken is door de fiets, in plaats van de auto nemen. Ten tweede is er veel sprake filevorming op de Nederlandse wegen. Het constant bouwen en uitbreiden van het wegennet is niet altijd mogelijk wegens de beperkte ruimte. Voor fietsers is veel minder ruimte voor nodig per persoon dan voor gemotoriseerd vervoer. Het stimuleren van fietsen kan daarom helpen om dit probleem op te lossen. Eén van het grootste nadeel van fietsen zijn de effecten van slechte weer. Mensen vinden regen de meest vervelende weersomstandigheid om doorheen te fietsers. Het wachten in de regen voor een rood stoplicht is helemaal hinderlijk. Het aantal fietsers daalt daarom ook sterk tijdens regen. Ook wordt er vaker door rood gereden, wat niet bevorderend is voor de veiligheid. Regengroen kan hier een oplossing voor zijn. Met regengroen wordt er gebruikt gemaakt van een regensensor om fietsers meer voorrang tijdens regen te geven. Hierdoor zal de veiligheid verbeteren en hoopt men dat mensen blijven fietsen tijdens regen om bij te dragen aan de benoemde doelen. In dit verslag wordt er onderzocht of het voordelig is om regengroen toe te passen op de kruising tussen de N737 en N342. Hiervoor zijn meerder aspecten onderzocht worden welke in de volgende alinea's zijn besproken.

Regengroen is niet een nieuwe uitvinding, het is al meerder keren in het laatste decennium toegepast. Deze soortgelijke toepassingen zijn eerst onderzocht om uit te zoeken hoe ze werken, waarom ze geplaatst zijn en wat de effecten ervan waren. Uit dit onderzoek blijkt ten eerste dat regengroen beter functioneert tijdens lage verkeersintensiteiten in vergelijking met hoge. Verder zijn ze allemaal op kruispunten in de bebouwde kom geïnstalleerd. Het blijkt wel dat het op verschillende manieren is toegepast. De meest voorkomende toepassing is dat twee keer per cyclus van het stoplicht voorrang is gegeven, in plaats van de gebruikelijke één. Hierom is er gekozen om het ook op deze manier in dit onderzoek te testen.

Ook is er in dit onderzoek gebruikt gemaakt van een verkeerskundig model om de effecten van regengroen te berekenen op de kruising N737/N342. Uit de resultaten blijkt dat het beter functioneert tijdens rustigere omstandigheden, net als eerder geconcludeerd. Het implementeren van regengroen is niet zonder gevolgen. Het gemotoriseerd verkeer wordt bewust vertraagd door fietsers meer voorrang te geven. Hierdoor neemt te wachttijd en CO_2 uitstoot toe. De uitstoot wordt gecompenseerd wanneer mensen de fiets boven de auto verkiezen. Critici zeggen dat als het extra voorrang geven werkt tijdens natte omstandigheden, wanneer het drukker op de weg is, moet dat ook kunnen tijdens droge omstandigheden. Het installeren en implementeren van een regensensor, wat geld kost, is dan overbodig. Dit is met het model getest. De resultaten laten dezelfde zien. Ook wordt regengroen maar 7.3 % van de tijd gebruikt (hoe vaak het regent per jaar). Het kan veel vaker gebruikt worden wanneer het in elke weersomstandigheid wordt gebruikt. Hierdoor worden nog steeds de vermelde doelstellingen tijdens nat weer behaald. Daarbovenop wordt het fietsen ook in droge omstandigheden gestimuleerd waardoor er vaker bijgedragen wordt aan de doelen. Wegens de beschreven redenen was het besloten dat het voordelig is om het tijdens elke weersomstandigheid te gebruiken waardoor het overbodig is om een regensensor te plaatsen. Verder is het alleen effectief tijdens daluren, als eerder besproken. Het is uitgerekend dat ten minste 2 mensen per uur meer de fiets moet nemen om de uitstoot te verlagen. Het is reëel dat dit gehaald wordt. Het nieuwe systeem is ook goedkoper en minder gecompliceerd omdat er geen regensensor geïntegreerd hoeft te worden. Ook kan het snel uitgeschakeld worden wanneer het tegen de verwachting in niet werkt. Het is verwacht dat de verloren tijd door automobilisten ongeveer 2351.70 euro per jaar extra kost door het nieuwe systeem, wat maar 0.83% van de totale kosten is door tijdverlies.

Summary

Cycling is the most commonly used means of transport in the Netherlands. Cycling can be a part of the solution to several problems in the country. First, greenhouse gas emissions must be reduced because of global warming. One way to achieve this is by cycling, rather than using the car. Second, there is a lot of traffic and congestion on Dutch roads. Constantly building and expanding the road network is not always possible due to limited space. Cyclists require much less space per person than motorized transport. Encouraging cycling can therefore help to solve this problem. One of the biggest disadvantages of cycling are the effects of bad weather. People consider rain the most unpleasant weather condition to cycle through. Waiting in the rain for a red traffic light is then even more annoying. The number of cyclists therefore drops sharply during rain. In addition, red lights are ignored more often, which does not enhance safety. A new arrangement can be a solution for this. With this arrangement, more priority is granted to cyclists during rain. This improves safety and encourages people to continue cycling during rain, contributing to the mentioned goals. The rain is detected by a special sensor. This report examines whether it is advantageous to apply such an arrangement at the intersection between the N737 and the N342. Several aspects were examined for this purpose which are discussed in the following paragraphs.

The discussed arrangement is not a new idea, it has already been applied several times in the last decade. These have first been studied to find out how they work, why they were installed and what their effects were. It was first concluded that they perform better during low traffic intensities compared to high ones. Furthermore, they were all installed at intersections in built-up areas. Next, it appears that they were applied in different ways. The most common application is that priority is given to cyclists twice per traffic light cycle, instead of the usual one. It was therefore decided to integrate it this way as well in this study.

A traffic model is also used in this study to calculate the effects of the proposed system on the intersection N737/N342. The results show that it indeed performs better during quieter conditions, as stated earlier. The implementation is not without consequences. Motorized traffic is deliberately slowed down by granting cyclists more priority. This causes the waiting times and CO_2 emissions to increase. The additional emissions are compensated when people choose the bicycle over the car. Critics state that if giving additional priority is advantageous during wet conditions when it is busier on the road, it should also be beneficial during dry conditions. A rain sensor is then redundant. This has been tested by using the model. The results confirm the statement. Also, it is only used 7.3% of the time (how often it rains per year). It can be used more often when used in any weather condition. As a result, the stated objectives are still achieved during wet weather. In addition, cycling is also encouraged in dry conditions, thus contributing to the goals more often. Due to the reasons described, it was decided that it is advantageous to use it during all weather conditions, making it unnecessary to install a rain sensor. Furthermore, it is only effective during off-peak hours, as discussed earlier. It has been calculated that at least 2 more people per hour need to switch to the bicycle to reduce emissions. It is realistic that this will be achieved. The new system is also cheaper and less complicated because it does not require a rain sensor to be integrated. It can also be quickly switched off when it does not work as expected. It is expected that the additional waiting time for motorized traffic costs approximately €2351.70 per year, which is only 0.83% of the total cost of lost time.

Table of contents

1. Introduction

1.1 Innovationroute

This project is executed on the innovationroute N737. This road is one of the most innovative roads in the Netherlands because of safety, technology and sustainability. It is a connection between Enschede and Deurningen. There were many problems before this route was named the innovationroute. The N737 was a dangerous road. Many accidents occurred, which were caused by multiple reasons. The most prominent reasons are that the road is narrow and has many bends. The intersections were also unclear due to the many trees along the road. Furthermore, many trucks use the road because of a nearby located truck stop. Lastly, many tractors are present because of the surrounding pastures. This creates a lot of mixing between slow and fast traffic, which is not favourable for safety (Provincie Overijssel, 2017b).

1.2 Motivation

The first motive for the innovationroute is to improve safety, or rather the lack of safety, as described in the previous section. The second reason is the location of the road. There are many locations around it where a lot of high-quality activity takes place like the Technology Base Twente and the University of Twente. However, the accessibility of these two locations is considered a bottleneck. The province also considers this route an extension of the innovative knowledge in the area. It has therefore been decided to use various new technologies and knowledge along the route to showcase them. Sustainability is also taken into account. The province hopes to realise a road that can cope with an uncertain future (Provincie Overijssel, 2017b). The province had specified a few minimum achievements for the implementation of the project. Firstly, traffic flow and safety had to be improved. The project should also contribute to CO_2 reduction and circularity. Furthermore, many desired performances were listed on which interested companies could distinguish themselves.

1.3 Selection process

Many sessions were organised by the province in which interested companies could exchange ideas about new technologies that could be realised on the innovationroute. Simply listing ideas was not enough, as these had to be largely developed and ready for deployment. In this way, the province hopes to become the first customers of these innovative companies. Many ideas were noted by the province which came out of these discussions. For example, there were ideas to capture CO_2 with biomaterial, plants that could generate energy, Wi-Fi in the road, smart traffic signs and much more (Provincie Overijssel, 2017a). The province aimed to select the best team of companies for the innovationroute. As a result, they held a selection phase between 2017 and 2018. In the end, it was decided that a partnership led by Strukton offered the best project. Several companies like Ko Hartog, Innovadis and Sorama were included in this partnership (Strukton, 2019).

1.4 The innovations on the route

Five main innovations are realised on the innovationroute project, as proposed by the contractor Strukton. Each of these innovations is shortly explained in the following paragraphs.

The first innovation is the use of an interactive traffic control installation (iVRI). This installation makes use of all kinds of novelties. Firstly, there are sound cameras. These cameras can detect sounds around the intersection. This allows the iVRI to detect traffic earlier than using detection loops alone (Tissink, 2020). These cameras can distinguish between different types of traffic such as trucks and personal cars. This is achieved by an algorithm that interprets sounds based on decibel, tone, duration and pitch. When the sound cameras hear a crash, they can immediately inform the emergency services. Cameras are also aimed at the source of the sound, making it possible to immediately identify this source. The iVRI is part of a programme called Talking Traffic on which is further elaborated upon in the theory part of this report.

Next, the layout of the intersection between the N737 and N342 can be altered by using dynamic lanes. These lanes can direct traffic in different directions, based on time. These lanes were established for 2 out of the 4 branches at the intersection. Currently, different scenarios have been established for rush hours. Therefore, the pre-sorting lanes are different in the morning compared to the afternoon. For example, two pre-sorting lanes are provided for traffic from Oldenzaal to drive to Enschede, while there is only one in the afternoon. Also, there are traffic lights 150 meters before the intersection, whose purpose is to stop the traffic so that a lane switch could be safely executed. The main advantage of these lanes is that more traffic can be processed and that the capacity of the intersection is increased. Lastly, traffic had to get used to the switching lanes since it confused some drivers. Cars took a wrong turn on some occasions because of this confusion (Hasselerharm, 2020). The system was therefore disabled for a certain time.

The next innovation is adaptive lighting. Road-side lampposts have been installed that can be switched on and dimmed individually (Innovadis, 2020). This innovation has several purposes. The first is that the sensors that detect accidents, as described in the previous section, could be used. When the system detects an accident, the lighting around the intersection is switched to maximum intensity (Innovadis, 2020). The second purpose is that the network knows with the help of an app and sound sensors, where cyclists are. This allows the lights to be switched on when a cyclist passes by. This innovation has the name Motis visible, which has several advantages. The first advantage is that energy is saved because the lights are only switched on when needed. The second is that social safety is increased. The final advantage is that nightlife in the woods around the road is not disturbed (Tissink, 2020).

Another innovation is the use of Greenfalt. Greenfalt is a special kind of asphalt that consists of 97% recycled materials. The first substance of these recycled materials is railroad ballast, the material that lies under rails. The second material is recycled asphalt from highways. Less CO_2 is emitted for the construction of the new road by using these materials (RTL Z how it's done, 2020). Greenfalt has been used in all asphalt layers, including the covering layer. New material was also used for widening the road. This new material consists of geopolymer concrete, which is reinforced with a plastic composite. This new combination can potentially cut the thickness of roads by half (Tissink, 2020). The same type of concrete has also already been used for the roundabout near the airport, which was constructed in 2017. Ridges have been placed in the asphalt in some places, which should alert inattentive drivers.

An intelligent passing lane has also been constructed. This lane can be used by tractors to let other traffic pass. The lanes are controlled by a program named Motis Passeerhaven which can alert tractor drivers when a line of cars forms behind them. Then, the tractors could enter a passing lane to let the other traffic pass. The program also informs cars behind when the tractors will let them pass (Innovadis, 2020).

1.5 Current situation

The construction of the discussed innovations took place during 2019 (Van Willigen, 2019). Most innovations are currently in use. However, the project is not finished yet. Several studies are still being conducted about the optimisation of the constructed infrastructure. For example, information obtained from the innovationroute is being studied in a Living Lab so that the programs can be refined. This allows the road to be better adapted to its users (Strukton, 2019). I am one of those people who attempt to optimize the route. I am focussing on the intersection between the N737 and the N342. A schematic overview of this intersection is shown in Figure 1. Information about the dynamic lanes is also shown. An extra lane is available during the evening rush hour for left-turning traffic from Enschede. The layout of the intersection also changes during the morning rush hour from Oldenzaal. The middle lane is then available for left-turning instead of straight through traffic. The right lane is subsequently for both straight through as right-turning traffic. The bicycle paths are indicated by the red lines.

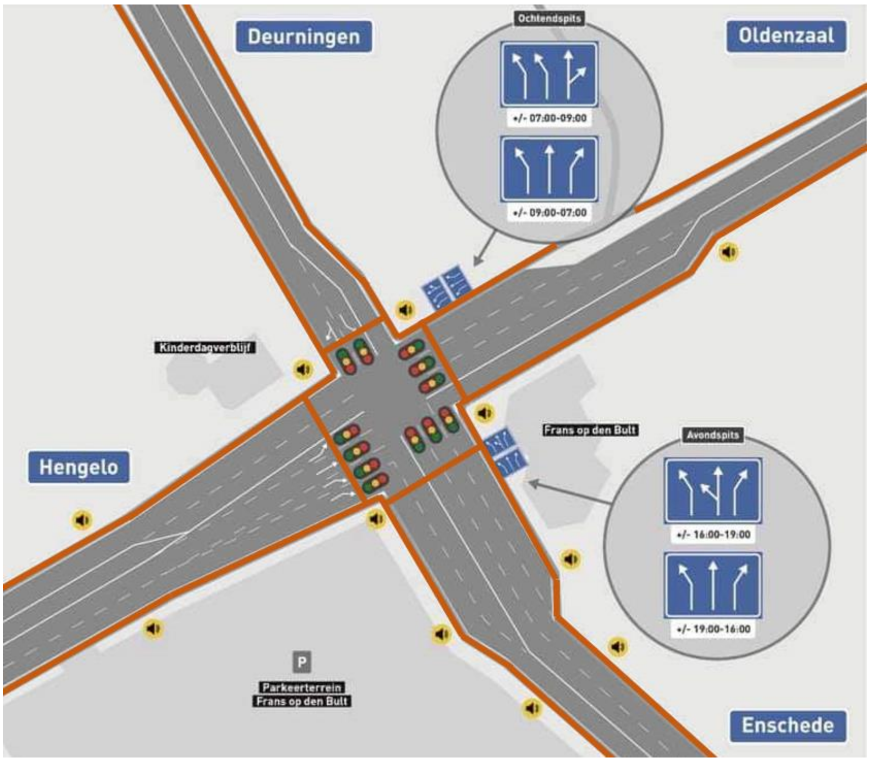

Figure 1: An overview of the intersection (Strukton Civiel [@struktonciviel], 2020).

1.6 Problem statement

The Netherlands is currently dealing or will deal in the future with major problems. The innovationroute was created to offer a solution to some of these problems. This project is not any different. It is discussed in this section what problems are present in the Netherlands and how they could be solved. Here, particular attention is paid to the effect of cycling.

First, this country is a very built-up area. There is already a lot of traffic and congestion on the Dutch traffic network. It is expected that the traffic volume will further increase by 8 percent until 2024. Further, it is expected that the time lost in traffic because of congestion will increase by 23 % by 2024 (Kennisinstituut voor mobiliteitsbeleid, 2019). There is not much space in the Netherlands to counter these changes by continually constructing and extending roads. Therefore, the government stimulates alternative transportation methods which use less space. Such methods are walking, cycling and public transport. How much space each transport type uses is shown in Figure 2. It is indicated that cyclists use 25 times less space than cars. Promoting cycling should stimulate people to cycle more instead of taking the car. This can be a part of the solution.

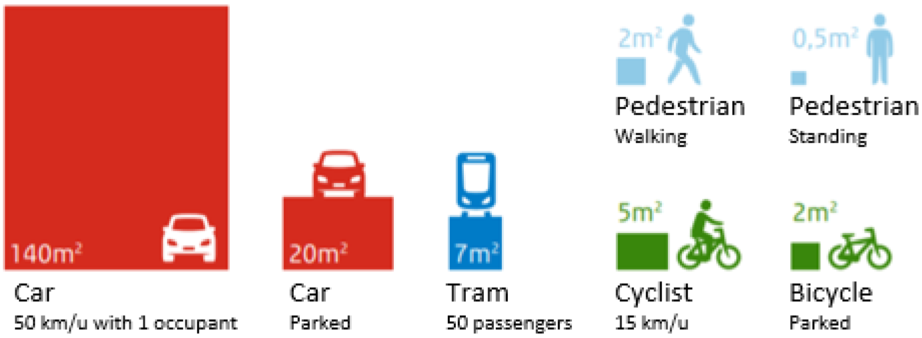

Figure 2: Used space for different types of transport (Harms & Kansen, 2018, p.14)

1.6.1 Global warming

Next, the greenhouse effect causes that human life is possible on Earth. It is a natural process that warms the surface of the earth. Sunlight is firstly emitted on the surface of the earth, which is partially absorbed. This heats warms up the earth itself. The heat radiates from earth towards space. Some of the heat is trapped by greenhouse gasses which keeps the Earth warm enough to sustain life (Australian Government, 2021). These greenhouse gasses are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and Ozone (O_3). However, human activity has caused that more of these greenhouse gasses are emitted since the industrial revolution. This causes that more heat is trapped in the atmosphere which warms up the earth further. This effect is called the enhanced greenhouse effect, or global warming. Global warming has several negative consequences like increased droughts, the melting of polar caps and rising sea levels (Jackson, 2021). Multiple agreements have been signed to combat global warming. The most important agreement is the Paris agreement. In which is stated that global warming should be limited to an increase of 2°C above pre-industrial levels and pursue an increase of 1.5 °C (Denchak, 2021). This should bound the aforementioned negative effects as much as possible.

The transport sector is responsible for 16.2 % of the global greenhouse gas emissions, from which 73.5% by road transport. (Ritchie & Roser, n.d.). The emissions are mostly caused by the combustion of fossil fuels that release large amounts of greenhouse gases such as CO_2 and NO_x. Cutbacks must therefore be made in the traffic sector just as in other sectors. These can be achieved by using new technologies like electric cars. But also by promoting alternative transportation methods which cause fewer emissions. Cycling is such a method. Substituting the car for cycling saves 150 grams of CO_2 every kilometre (Harms & Kansen, 2018)

1.6.2 Health & safety

People find rain the most annoying weather condition to cycle through, even more than heavy winds and colds (Harms, 2008). Waiting for a red light during rain is especially unpleasant. Cyclists are more likely to run a red light because of this, which can cause dangerous situations. It can be counteracted however by giving cyclists more priority. A study showed that such implementations could reduce the number of red light negations by 23 to 78% (Harms, 2008). This would naturally increase the safety of the intersection.

Furthermore, a study published in The British Medical Journal concluded that commuting and mixed-mode commuting with a cycling component were both associated with a statistically significant lower risk of all-cause mortality compared with non-active commuting (Celis-Morales et al., 2017). The health benefits of cycling are even stronger than walking according to the paper. In this research, data from 263.450 participants was used to investigate the effect of cycling on certain diseases. Confounding factors like income, ethnicity, smoking status, obesity-related markers, dietary intakes and more were considered.

1.6.3 Cycling in the Netherlands.

Cycling is a common mode of transport in the Netherlands. The Dutch cycle more than any other country in the world. More than a quarter of all the movements are made by bike (De Haas & Hamersma, 2020). An emerging trend is an electric bicycle or e-bike. Almost Half of the sold bicycles in 2020 were e-bikes. This is almost a multiplication compared to five years ago (De Haas & Hamersma, 2020). An e-bike makes it easier to cover greater distances compared to "normal" bicycles. This makes cycling also a plausible substitute for the car for longer distances. Another advantage of the e-bike is that it makes cycling easier for older people. Almost half of all e-bike trips were made by people older than 65 (Harms & Kansen, 2018)

Further, cycling is a sustainable solution for problems in the Netherlands like climate change and the increasingly overcrowded public space, as explained earlier. Cycling also improves the health of its users. The national government and municipalities have therefore developed policies to stimulate cycling even more. For example, there is a national election to select the best "fietsstad", or "cycle city", to encourage municipalities in the Netherlands to promote their cycling climate. Such an election has great effects. When you look up "fietsstad" on the internet you can find dozens of pages with policies from all kinds of municipalities like Veenendaal, Utrecht, Amsterdam, Groningen, Houten, Enschede, Haarlem, Zwolle and more. All these policies describe how municipalities are making their infrastructure more attractive for cyclists. The aimed measures are quite successful. It is expected that the number of cyclists will increase in the future (De Haas & Hamersma, 2020).

2. Research aim

One of the biggest disadvantages of cycling compared to taking the car are the effects caused by bad weather, as discussed before. The number of cyclists therefore falls sharply when it rains (Jonkeren, 2020). A way to counteract this is by installing a new sensor that is able to detect rainfall. This sensor detects when it rains and sends a signal to the traffic control system. The system switches then to a different regime in which cyclists are given more priority. This should encourage people to keep cycling during rainy conditions, contributing to the goals of reducing emissions and solving spatial scarcity. It also improves safety and the health of its users. It is investigated in this thesis whether it is worthwhile to implement such a system to the signalized intersection on the Innovationroute. The research objective of this thesis is, therefore:

"To investigate whether it is worthwhile to install a rain sensor at the signalized intersection N737/N342 to give cyclists more green time during precipitation"

Strukton Civiel is the company that maintains the discussed intersection. The goal of this thesis is thus to give them advice on whether they should implement such a system. Several factors are examined to obtain the best possible advice. These factors are carefully explained in the next chapter. How this is achieved is also specified.

3. Methodology

A traffic control system that gives cyclists more green time during rain is not a new intervention. It has already been practised several times over the last decade. Information about these other systems has firstly been gathered. The purpose is to better understand such systems. It has been researched how they work, why they were implemented and their effects on traffic. Several aspects are described. It is first described how the rain is measured. Secondly, how the regulation of the intersection is adjusted when it rains. Lastly, how these changes affected the characteristics of the traffic. Information was firstly sought on the internet via (news) articles, statements of companies and available reports. It was concluded however that the information is not complete. It lacks certain information which is required for this research. Therefore, contact was sought by e-mail with multiple municipalities, traffic engineers and companies which were involved. This has brought information to light that was not known before. All the gathered information is used to describe the other implementations in the best way possible. Comparisons between them have also been made. Criticism about rain sensors in general was also gathered. Finally, it was investigated whether the collected information could be used to claim anything about the circumstances of the intersection N737 / N342.

The weather conditions at the intersection were then investigated. Information from the last 10 years was gathered from the Royal Dutch Meteorological Institute. This information was firstly used to research how frequent precipitation occurs in the Netherlands. This has been achieved by data analysis. The precipitation is divided into several levels like slight, moderate and heavy rain. The occurrence of each category is also calculated. The purpose of this is to calculate how much percent of the time the system would be enabled. Next, precipitation could be detected in multiple different ways. These are investigated, which has been done by collecting information from the internet and by making contact with manufacturers and companies. The advantages and disadvantages of each measuring method are listed. Situations have been drawn up in which information about rain is used in different ways. You can for example give cyclists priority just before it rains, or include other properties like traffic intensities and temperature. The best measuring device has been chosen based on the different situations and the collected information.

A simulation study is thereafter performed. A traffic model of the intersection already existed. It was created by two other students. The aim is to use this model to investigate the effects of the system on traffic. The model was not yet complete. Several elements had to be calculated and altered before the model could be used.

The first element are traffic intensities. Intensities for motorized traffic, as well as cycling traffic, was gathered. The information about the motorized and cycling traffic was sent by a traffic engineer from the province of Overijssel. The data showed the intensities for each lane on the intersection in a 15-minute interval for the month of September 2020. The intensities from cycling traffic were for the month of April 2021 after a special request. All the intensities were measured by detection loops in the road. It had been decided to determine the intensities for three scenarios. This has been done because of two reasons. Firstly, it appeared that the success of similar systems was dependant on traffic intensity. They seem to perform worse during high intensities. This is tested by introducing different traffic scenarios. Secondly, because the layout of the intersection changes during the day because of the dynamic lanes, as discussed in section 1.5. These lanes route traffic in different directions during rush hours. This also causes the traffic light control to be different. The three scenarios are; morning rush hour, afternoon rush hour and off-peak hours. The intensities for motorized traffic as well as cycling traffic has been determined for each scenario by using data analysis.

Some critics say that if prioritising cyclists works in wet weather, it certainly works in dry weather. A rain sensor is then completely unnecessary. It has therefore been decided to simulate the model during dry as well as wet conditions. A traffic model is mostly run for dry conditions. It has therefore been researched how certain parameters differ between dry and wet conditions. This has firstly been done by investigating which parameters can be changed in the model. One of these parameters is traffic intensity. The earlier collected weather data and traffic data have been linked together. It has been researched if traffic intensities during the dry are different compared to the wet. A check was conducted to see if there is a relation between them. The change of all parameters were studied by conducting a literature study. The found information from both the literature study and the check has been used to calculate how much percent each parameter changes from dry to wet conditions. It is for example expected that the deceleration ability of vehicles decreases in wet circumstances.

The main goal of the model is to calculate the effects of the proposed cycle-friendly system. This can be achieved by simulating the current situation, without the system, and a situation in which the system is integrated. Comparisons can then be made to assess the effects. The model is run for all different scenarios which were discussed in the sections above. Each of these scenarios has been put in Table 1. The effect of the different scenarios is related to each other.   So there are in total $3 * 3 * 2 = 12$ different simulations.

Table 1: Scenarios

Type of Scenario	Condition 1	Condition 2	Condition 3
Traffic conditions	Morning rush hour	Afternoon rush hour.	Off-peak hours
Weather Condition	Dry	Wet	
System	Off (default)	On: 2 times priority	

The results which emerge from the model for the 12 different simulations should be compared to each other. A comparison should be made based on certain criteria. These criteria were established by creating a framework and were divided into three major groups. The first group are the legally binding criteria, which have to be met in any condition at any time. The second group are traffic-related criteria. These are criteria that indicate the effects on the traffic flows and conditions. Properties that are taken into account are average travel times, lost time and more. One of the goals of the intervention is to contribute to reducing greenhouse gas emissions. Climate-related properties are therefore taken into account in the last group.

All the gathered information during this research is used to advise on the rain friendly system. The advice consists of two parts. The first part is about such a system in general. What things should be considered when implementing such a system? The second part is about implementing the system at the intersection N737/N342. First, it is reasoned whether it is worthwhile to do so or not. Second, if it is worthwhile, how it should be implemented.

4. Theory

Related theory is elaborated on in this chapter. Three main sections are identified. Traffic engineering concepts and traffic control systems are explained in the first one. Five similar projects are explained in the second section. This section discusses how and why these projects are implemented and what their effects are. A conclusion is made based on the gathered information. The results are then related to the intersection N737/N342, which is under discussion in this report. Not everybody is positive about similar projects. Criticism has therefore been discussed in the last section. The gathered criticism can be used to create a more effective, objective advice.

4.1 Terms

Some traffic engineering terms are used in this report. They are therefore explained in this section to make the report easier to understand. A traffic control system is the focus of this research. It is therefore explained how such a control system operates. Important terms are also explained. Moreover, not just any traffic control system is located on the intersection, but an iVRI is used as introduced in section 1.4. The iVRI is part of the talking traffic partnership, which attempts to modernize traffic. This partnership and the iVRI are further elaborated upon in this chapter.

4.1.1 Traffic engineering terms

Intensity: The average number of vehicles passing a junction or stretch of road over a given time. The intensity can be expressed per minute, hour or day. The most common expression is an intensity per hour.

Congestion: Congestion is a bottleneck of traffic that causes drivers to drive slower than in ideal conditions. Congestion can occur when the capacity of a roadway is exceeded.

Travel time: The time it takes for a vehicle to get from point A to point B.

Desired travel time: The fastest possible time to get from point A to point B (at the given maximum speed). It is possible to calculate the delay at an intersection by subtracting the desired travel time from the average travel time. The desired travel time is also known as the **Free flow time.**

4.1.2 Traffic control systems

Traffic light controllers are systems that regulate traffic flows at intersections. They regulate them according to time. It uses traffic lights to indicate when a certain movement is allowed to pass. A **movement** is a combination of one origin-destination pair. Traffic arriving on the west side of the intersection and driving towards to north is one movement for example. A combination of movements that are given priority at the same time is called a **phase**. These movements do not conflict most of the time. A traffic control system has a certain sequence of phases which is called a **cycle**. The duration of one cycle is called the **cycle time**. A **realisation** is how many times per cycle a movement has received a green light. Each movement receives at least one realisation per cycle. It is however possible that multiple realisations are implemented. Vehicles are measured by detection loops in the road surface. A **gap** occurs when the time between two measurements is larger than 2 seconds.

A traffic control system is very complex. The parameters of each system are defined in a document called the "specificatie verkeerslichtenregeling", or "Traffic light control specification" in English (Huijskes, 2015). Hundreds of values are included in this document. These values are fed into the system which regulates the intersection. Relevant ones for this study are discussed now.

The duration of the **green time** of each phase is adaptable (Huijskes, 2015). The green time is how long each phase is prioritised. A minimum green time is firstly implemented based on two factors. Firstly, to ensure safety. Road users tend to not look at the traffic light right after turning green. If the **minimum green time** is too short, there is a risk that road users unknowingly drive through a red light. The second factor is that the green time should be sufficient so that traffic between the stop line and the detection loop can drive away. A **maximum green time** is also established to ensure that traffic on conflicting roads does not have to wait too long. People are more likely to drive through a red light when they are waiting for a long time. The green time may be extended starting from the minimum time when a gap has not occurred. In other words, the green time is extended when a vehicle is detected. This process can continue until the maximum green time is reached. The green time of the same phase in the next cycle is partially based on the previous one.

Next, Minimal **yellow times** are defined to make sure that all vehicles have left the intersection before the next phase is started (Huijskes, 2015). The yellow times should also not be too high to prevent drivers from continuing who could have stopped. Lastly, **minimum red times** have also been defined, which regulates the time that a phase is at least red. This time is intended to prevent an uncomfortable situation for road users.

4.1.3 Talking traffic and Intelligent traffic control systems.

Technology is constantly evolving, which is no different in the traffic sector. More and more data is being collected, exchanged and transmitted. The Talking Traffic Partnership was therefore established to stimulate this process (CROW, 2019). Talking Traffic is a partnership between the Ministry of Infrastructure and Water Management, the business community and decentralised authorities. The parties cooperate in the development of innovative traffic applications. The partnership must also ensure that the available data is exchanged more effectively between its members. The partnership is divided into three clusters. Efforts are being made within cluster 1 to ensure the availability of data by making traffic light data available. This is achieved by introducing a new interactive traffic control system (iVRI), which is the most important development within the Talking traffic partnership. The iVRI is discussed in more detail in a second. The common goal within cluster 2 is to process, enrich and distribute different data and to transform them into customised, real-time datasets and information. Data from both public and private sources are combined in this cluster. In addition to data from traffic lights, this includes all kind of different data like information about the weather, road works, accidents, parking data and many more (CROW, 2019). Most data is send using cellular communication, or 4G/5G in short. A server called TLEX (Traffic Light EXchange) is used to connect the iVRI with cluster 2. Both information to and from the iVRI is routed through the TLEX server. Lastly, the information is distributed to traffic users in cluster 3. This is achieved by for example smartphones and navigation systems. It shows road users, for example, in how many seconds they will receive a green light.

The interactive traffic control system (iVRI) was introduced a few years ago and is an upgrade to the current existing traffic control systems (CROW, 2019). An iVRI can communicate with approaching vehicles. The obtained data makes it possible to regulate the intersection more efficiently. This allows that the traffic flows could be optimized toward various goals like traffic flow, safety and sustainability. Further, rules can be developed which prioritise specific target groups like cyclists, trams and busses. Drivers themselves can also be personally informed about current traffic conditions. Lastly, the iVRI has a modular construction, which makes it possible to integrate different components in the future. This makes the system future-proof.

An iVRI is also present on the intersection N737/N343, which is investigated in this report. A system called MOTIS is used to combine relevant data and send it towards cluster 2. The goal of this research is to give cyclists more priority when it rains. Weather information must therefore be gathered, processed and then send to the iVRI. The talking traffic partnership is used for this purpose. Information about rain is firstly measured by some sensor. Which sensor is used is elaborated upon further in this report. The gathered information is then sent to the MOTIS-server, preferably with cellular communication. The data is then processed. It is assessed whether it rains to give cyclists extra priority. If so, a signal is sent towards cluster 2. The signal is subsequently sent to the iVRI via the TLEX server. The iVRI then switches to a different regulation to give cyclists more priority. A schematic overview of the described process is shown in Figure 3.

Figure 3: Schematic overview showing the implementation of a rain sensor

4.2 Priority for cyclists during precipitation at other intersections

The goal is to give cyclists more green time when it rains. However, this is not a revolutionary idea since it has already been tried or implemented before at multiple intersections in the Netherlands. These are elaborated upon in this section. Information has first been gathered by using sources on the internet. Second, by making contact with people, municipalities and companies which were involved by the different project. An overarching conclusion is made at the end of this section.

4.2.1 Other implementations

Apeldoorn

Firstly, it has already been applied at an intersection in Apeldoorn. The rain is detected by a rain radar. (Rottier, 2017). Then, the information from the radar is processed by nowcasting before the data has been fed to the traffic control system. Nowcasting is explained in more detail later in this report. The information from the radar can be used to predict when it is going to rain. This is used to give cyclists twice as much green time just before it is going to rain which could assure that cyclists arrive at their destination without getting wet. Also, cyclists are given twice as much green time during precipitation (Cleantech Regio, 2017).

The goal of the municipality of Apeldoorn is to stimulate bicycle usage. Giving people more priority just before and during rain is a method to achieve this. It is the intention of the municipality that people continue cycling during (light) rain, as stated by a traffic consultant of the municipality. However, he states that this is not really possible during heavy rain. Further, it has been attempted to investigate how the waiting times for motorized traffic has been affected by the application. This is however difficult because of multiple reasons. Firstly, people are more likely to take the car during rain, which automatically increases the traffic intensities and most probably the waiting times. This occurs already without installing any rain sensor. This makes it difficult to assess the individual effect of such measures. Also, rain showers are very capricious which makes it difficult to make comparisons.

Grave

A bicycle-friendly traffic light has been installed at an intersection in Grave (Harms, 2008). Normally, cyclists are given a green light once per cycle at traffic lights. In Grave, however, more realisations are granted depending on weather conditions and traffic intensity. First, cyclists receive more realisations during adverse weather conditions. Not only rain is considered for the adverse conditions, but also the temperature. A weather station is installed at the intersection to measure both conditions. Second, cyclists receive fewer realisations during high traffic intensities. Table 2 shows how many realisations are provided per cycle based on the described factors.

Table 2: Number of realisations per cycle for cyclists at Grave dependent on traffic intensity and weather conditions (Harms, 2008 table 1)

	high intensity	Average intensity	Low intensity
Temp > 10℃ & no rain	1	1	2
Temp < 10℃ & no rain	1	2	3
Temp > 10℃ & rain	1	2	3
Temp < 10℃ & rain	2	3	3

The purpose of the regulation is to increase safety during adverse weather conditions (Harms, 2008). People tend to run a red light more often during rain than during dry weather, which can cause dangerous circumstances. Therefore increasing the number of realisations would cause fewer red-light runners and thus creates more safety. A study has been carried out to investigate the effects of the new implementation (Harms, 2008). Firstly, it had been concluded that the new bicycle-friendly traffic light did not hurt motorized traffic. Next, the waiting times for the cyclists did sharply decrease, which has led to fewer red-light running at the intersection. A survey has also been conducted which gathered the opinions of cyclists. It was concluded from this survey that cyclists appreciate the new installation. Lastly, it was concluded that rain is seen as the most annoying weather condition. Some other remarks were given in the evaluation report as well. They expect that the effectiveness of the application is very dependent on its circumstances. Also, it is expected that the waiting times strongly increases when the traffic intensity becomes too high.

Oosterhout

Next, a bicycle-friendly traffic light was tested at the intersection between Holtroplaan and Europaweg in Oosterhout in 2007. This intersection is used by 17.000 vehicles per day. It is expected that this intersection will become more important in the future[1] (CROW Fietsberaad [powerpoint], 2007). All branches of the intersection have an important function for bicycle traffic. During the reconstruction of the intersection, it was doubtful whether a roundabout or a traffic light should be used. A roundabout is more favourable for cyclists. However, a traffic light had been chosen. To compensate for the cyclists, a system was integrated which should give cyclists more green time during precipitation. Cyclists receive more green time in the same way busses receive it. This works as follows: detected cyclists receive green in the next phase. Traffic that does not conflict with the cyclists also receives green. Busses keep the priority on cyclists during rain. Besides, cyclists cannot receive an extra green light when the maximum cycle time is reached.

A similar system was applied near a school. Here, however, cyclists no longer received more priority when it was cold, but at the start and end of school hours. Precipitation is detected differently than in Apeldoorn since it is detected by a sensor installed at the intersection. This sensor is in the form of a U and emits infrared radiation. Precipitation is detected when raindrops interrupt this radiation (CROW Fietsberaad [powerpoint], 2007). These two intersections were part of an experiment that was to be evacuated a year later (CROW Fietsberaad, 2007). Results are still not available currently. Therefore, the effects on the waiting times for cyclists and the other traffic is unknown.

Rotterdam

The municipality of Rotterdam aims to make the city more attractive for cyclists. They want to achieve this by creating more space, comfort and speed for cyclists (Klemann & Simons, 2017). One way to accomplish this is to give cyclists more priority at intersections during precipitation. At first, such a

[1] Article is from 2007, so "future" is a relative concept

system was installed at the intersection between the Boezemlaan and Bosdreef. Cyclists were initially given two times more priority during rain (Rubio, 2015). The system caused the queues for motorized traffic to increase significantly. This evoked a lot of criticism. One city counsellor states that the intersection was already very busy. Decreasing the green time for motorized traffic would logically increase the queues. He states that it is really a very wrong choice (Rubio, 2015). Also, he pointed out that fewer people choose to cycle during rain. Instead, they take the car or public transport. It is, therefore unnecessary to give the reduced number of cyclists more priority. The local residents were also unhappy about it. They were concerned about waiting cars for their homes which emit harmful exhaust gasses. The municipality decided to investigate the effects of the system. For this test, they investigated the length of the queues and the lost travel time. They compared the values between a dry day when the system was disabled and a wet day when the system was enabled (Tijssen, 2016a). Firstly, it was concluded that the average length of the queues almost tripled in size. The longest queue, on the south side, increased from 266 to 726 meters. Further, the travel times loss of traffic increased by 140-300 %. The waiting time for cyclists did, logically, decrease. The municipality changed the system after the investigation. The extra priority for cyclists was reduced. The situation was thereafter investigated again in the same way as before. It was concluded that the length of the queues did significantly decrease compared to the first implementation(Tijssen, 2016b). They were still longer however compared to the situation in which the system is disabled. The average length of the queues during the three scenarios is shown in Figure 4. The blue lines are the queues in which the system is disabled, the red lines are the queues in the first implementation and the orange lines in the improved one.

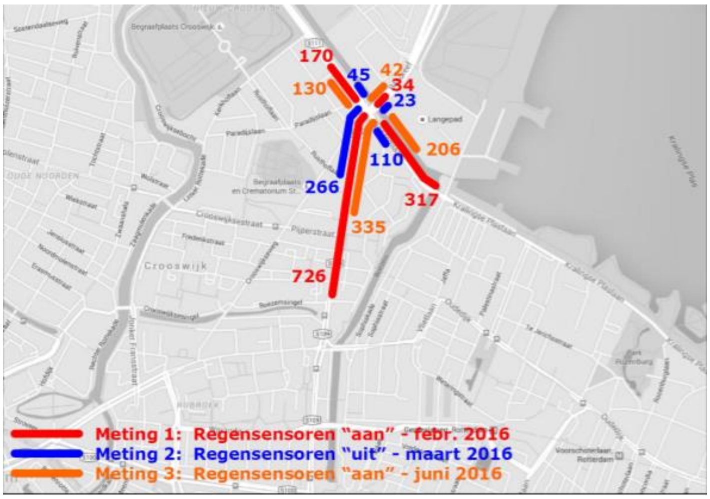

Figure 4: Average queue lengths in Rotterdam (Tijssen, 2016b, p. 12)

Groningen

Subsequently, another similar system was installed in Groningen at an intersection near the Oosterbrug, due to the success of earlier experiments in the country. An evaluation of this research is available. Firstly, it concludes that the experiment resulted in many positive reactions from cyclists, whereas there were no negative reactions from car drivers (Gemeente Groningen, 2012). Secondly, it was concluded that the implementation did not cause longer waiting times for car traffic. It is reported however that the installation cannot be part of a coordinated system in which several traffic lights are connected. This is because the influence of one light also influences the others. Finally, it was concluded that the costs of the experiment are minimal if the application is integrated during the construction of the intersection. The costs are higher when the application has to be installed afterwards (10.000 €). The municipality was positive about the experiment and is therefore upscaled to other intersections in Groningen (Gemeente Groningen 2012).

4.2.2 Location of the intersections

The success of a cycle-friendly traffic installation is heavily dependant on the circumstances where it is applied. Therefore, the traffic-related circumstances for all the implementations as discussed above are elaborated upon in this section. Firstly, all five systems have been applied within the build-up area. From which three are implemented in the centre of a big city, these are Apeldoorn, Rotterdam and Groningen. The other two are implemented in smaller villages which are Grave and Oosterhout. It is expected that the traffic intensity for cyclists as well as the other traffic is higher in the big cities. Secondly, the sizes of the intersection and the priority of the roads also differs. The biggest intersection is the one in Rotterdam, in which two main inner-city roads are connected. The intersection itself has a combined total of 13 pre-sorting lanes. Next, the intersection in Grave is the only one that connects a provincial route with inner-city routes. All the other intersections connect inner-city routes. All the cycle-friendly systems have been applied to four-way intersections, except for the one in Apeldoorn, which is a three-way intersection. The smallest two intersections are located in Apeldoorn and Groningen, which only have seven pre-sorting lanes.

4.2.3 Conclusions other implementations

Five different implementations of cycle-friendly traffic systems which take precipitation into account were explained in the previous sections. Each of these systems has its characteristics and results. An overview has therefore been made which shows the key differences and similarities between them. This overview shows the purpose of implementation, how the rain is measured, what the effects are on other traffic, how much more priory cyclists receive compared to a normal scenario and if extra additions have been made. The overview is shown in Table 3.

Table 3: Characteristics of different cycle-friendly traffic installations

	Apeldoorn	**Oosterhout**	**Rotterdam**	**Groningen**	**Grave**
Purpose	Keep same cycling intensity during rain	Compensate cyclists	Make cycling more attractive	Make cycling more attractive	Increase safety
Used rain sensor	Radar system & Nowcasting	Infrared sensor	Infrared sensor	Infrared sensor	Weather station
Effect on cyclists	Less waiting time	Probably less waiting time	Less waiting time	Less waiting time	Less waiting time
Effect on other traffic	Potential longer queues	Unknown	Longer queues and waiting times	No negative effect	No negative effect
How much priority	2 times	As much as possible	First 2 times, then less	2 times	2-3: dependant on the situation
Extra additions	Priority just before rain	Temperature and school hours.	No	No	Temperature & Traffic intensities

It can firstly be concluded that the chosen rain sensor determines what options are possible. So is an online radar able to inform the traffic control system in that it is going to rain soon, like in Apeldoorn. In Grave, a weather station is used to measure other properties like temperature. Cyclists are given two times more priority during precipitation compared to a normal dry scenario in most situations. However, more complex mechanisms are used in Grave and Oosterhout. Cyclists also received 2 times more priority in Rotterdam. But was changed to a more complex system when the results were not that great. Next, the table shows that all implementations did reduce the waiting times for cyclists. However, the effects on the rest of the traffic are mixed. So did the waiting times not increase Groningen and Grave while they did in Rotterdam and potentially in Apeldoorn.

Further, it seems that such a system works better at lower traffic intensities than higher ones. Firstly, because the same was concluded in the report which evaluated the implementation at Grave. Next, the traffic intensities at the intersection in Rotterdam were quite high. The queues increased considerably when cyclists were given priority for a second time. This also shows that such a system does not perform well during high intensities. Finally, the aim is not the same everywhere. For instance, the aim at some places is to make cycling during rain more attractive. But in Grave, efforts are being made to increase safety.

4.2.4 Relation to intersection N737/N342

Figure 5 shows the area around the intersection N737/N342. The intersection itself is indicated by a red dot. Travel distances between the intersection and the centres of nearby cities are indicated. The travel distance to the airfield is also shown. The environment around the intersection is quite different compared to the 5 intersections discussed in the sections above. Firstly because the intersection N737/N342 is located outside the built-up area, while the others are all right within it. The intersection is a connection between multiple cities and the airfield. It is therefore expected that it is used by cyclists travelling between these places. At least two places have to be connected to represent one complete trip. The indicated distances in the figure show that the cycling distances of these people must therefore be quite large. They could on average be around 9 kilometres. The average cycling distance in the Netherlands is 3.2 km (Es & Slütter, 2019). The cycling distances within cities, which is the case at the other intersections, should be much closer to this average. It is therefore expected that the cycling distances of people using the intersection is significantly larger than the average distances at the other intersections.

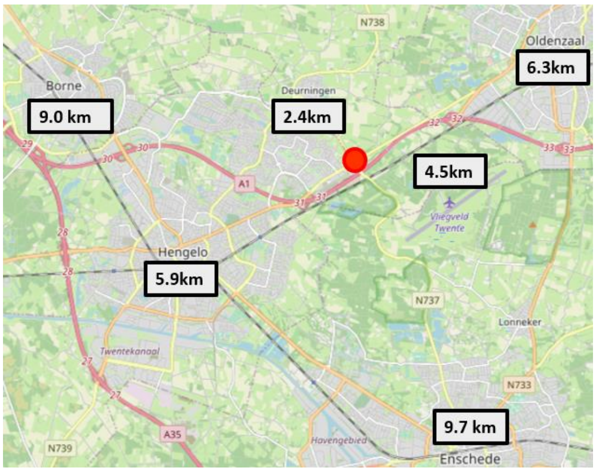

Figure 5: Surroundings of the intersection N737/N342 (OpenStreetMaps.org, 2021)

The intersection N737/N342 is quite large since two provincial roads are connected. All the other intersections connect inner-city routes on most occasions. It is expected that the intensities of motorized traffic are larger on provincial than inner-city routes. Traffic intensities at the N737/N342 intersection are therefore likely to be higher than at the other intersections. the only intersection that comes close in size is the one in Rotterdam. It is also expected that more trucks use the intersection N737/N343 compared to the other intersections. Firstly because there are more trucks on provincial roads than in built-up areas. Second, because a rest area for trucks is located right next to the intersection.

4.3 Criticism

Some people have been critical about installing rain sensors. This research aims to write unbiased advice. It is therefore important that criticism is also considered. Critical opinions have therefore been gathered and outlined in this section.

Luc Prinsen (Prinsen, 2012), who is a traffic management advisor at Goudappel Coffeng does believe that such systems are not useful. He argues that if cyclists could be given more priory during wet, which are busier conditions, then it is certainly possible during dry weather. So, a rain sensor is thus redundant. This mostly happens at a traffic control system with a lot of spare capacity or a system that has not been optimally configured. Optimizing would be way more effective than installing a rain sensor. This could for example be the case for the situation in Grave, which was explained in 4.2.1. Here a bicycle-friendly traffic light was installed which also uses a rain sensor. It was concluded that the waiting times for cyclists decreased while it did not increase for other traffic. This shows according to Prinsen that the situation is not optimal. The waiting times could then also be decreased during dry weather which makes a rain sensor redundant.

Another choice is to hinder other traffic on purpose to promote cycling, which is more a political choice. He explains that such measures fit in the current spirit of sustainable accessibility. However, there are better options to achieve this than installing a rain sensor. He explains further that such sensors are popular with the media. There is always interest when a new rain sensor is installed. However, the media overlooks how such a system actually works and the consequences of it. He advises municipalities to keep their money in their pockets and spend it on something actually useful. He says that there are better solutions to encourage cycling. Like optimizing traffic lights for example.

Next, in Trouw (Keuning, 2014) a traffic engineer who was involved in the bicycle-friendly implementation in Oosterhout was questioned about rain sensors. He says that he was first very enthusiastic about rain sensors, however, he has become more sceptical currently. He explains that rain sensors only work under very specific circumstances. Most of the time, there are better solutions. Further, he said: “It sounds nice, but it is only useful in some cases. Many intersections become too crowded with waiting cars, while cyclists could already be given more green time, even when it is dry”. Although, motorized traffic is more likely to accept the longer waiting times during wet compared to dry conditions. He lastly states that such systems are more related to political choices than traffic-related ones.

Furthermore, it was concluded by de Rekenkamer Metropool Amsterdam (Ridder et al., 2020) that the usage of a rain sensor is just a minor part of a cycle-friendly traffic light. Some aspects are way more important. It was further concluded that the usage of rain sensors does not fit in the current traffic light policy, moreover, that the use of such sensors is decreasing in other cities.

5. Weather

The aim is to give cyclists more priority during rain. The weather-related information required for this purpose is discussed in this chapter. The chapter consists of two main parts. It is calculated in the first part how often precipitation occurs. This information is processed to calculate how much percentage of the time the system is used. Next, extra priority is given when it rains. The traffic control system should therefore know when it rains. A special detection system should be used for this. It is discussed in the second part of this chapter which system performs the best for this purpose. Different systems are first introduced. Their strengths and weaknesses are elaborated upon. The systems are compared based on certain criteria and scenarios. The best device is chosen based on the gathered information.

5.1 Bad weather

The concept of bad weather brings unpleasant associations to most of us. But what does bad weather exactly entail? It has different definitions for different purposes. Most of the time it refers to conditions with unfavourable temperatures, wind speeds or precipitation. It is investigated in this thesis how cyclists could be given more priory during rain. It is therefore logical that the concept of bad weather is referred to as precipitation in this report. The table below shows different levels of precipitation. In this report, bad weather is defined as precipitation larger than the category of slight rain. Thus, with a rate of 0.5 mm per hour or higher.

Table 4: precipitation categories

Rain	Precipitation rate in mm/hour
Slight rain	<0.5
Moderate rain	0.5-4
Heavy rain	4-8
Very heavy rain	>8

Next, it is determined how much percent of the time it rains at the intersection. Data from the nearest KNMI weather station has been used, which is the Twenthe weather station (KNMI, 2020). Firstly, the time is divided into four categories based on the precipitation rates which are shown in Table 4. How this has exactly been done is discussed in Appendix A. Figure 6 shows how much percent of the time each category occurs over the last 10 years. It shows that on average, it rains 7.324 % of the time at the intersection. From which 35.5 % is light rain, 60.0% moderate rain, 3.5% heavy rain and 1.0% very heavy rain. As discussed above, bad weather is defined as rain with a rate higher than 0.5 mm/hour. This means that the weather is considered bad 4.7% of the time.

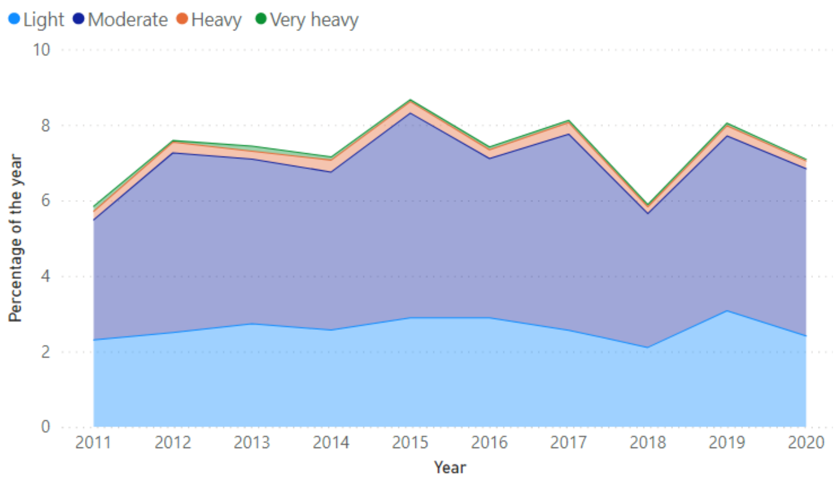

Figure 6: Occurrence of different precipitation categories over the last 10 years

However, the categories which were used in the last figure are quite coarse. They have therefore been divided into smaller categories, each with a range of 0.5 mm/hour. The cumulative values have been put in Figure 7. For example, the first bar shows how much time per year it rains. The second bar shows how much percent of the time it rains with an intensity higher than 0.5 mm/year and so on. A trendline has been put in the graph. The equation can be used to calculate how much percent per year precipitation occurs with an intensity higher than x mm/hour. This equation is useful for this report, but also for future policymakers to assess how much percent of the time the rain sensor would be active if a certain threshold is chosen. The equation is reliable for a precipitation intensity up to 5 mm/hour. The calculations are also shown in Appendix A.

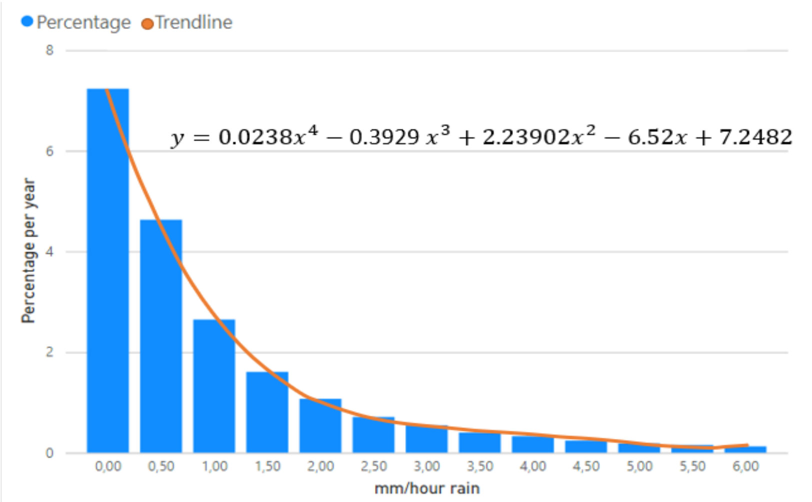

Figure 7: Cumulative occurrence of precipitation

5.2 Studying measuring devices

Rain should be detected when priority is given to cyclists during wet conditions. Multiple detection systems could be used to achieve this. A study has been conducted to determine which system is the most appropriate for the conditions at the N737/N342 intersection. This study consists of multiple parts. The systems are introduced in the first part. It is explained how they work, what should be done to integrate them and their strengths and weaknesses. Six important criteria were taken into account. A total of three systems were considered. The first one is nowcasting. With nowcasting, precipitation predictions are made by processing data from a rain radar with complex algorithms. The second one is an infrared sensor, which detects rain by using infrared radiation. The last one is a weather station, which is not only able to detect rain, but also other weather-related properties like temperature and humidity. Next, information about precipitation could be used in several ways. For example, priority can be given when a certain precipitation intensity has been reached. But priority can also be given just before it rains to make sure cyclists get less wet. The three measuring devices are compared for each of these scenarios in the second part. The six introduced criteria are used for this purpose. The most fitting device is chosen for each scenario. Lastly, the best measuring device is chosen by assessing the different scenarios. The complete study can be found in Appendix B. The conclusions are elaborated upon in the next section.

5.3 Conclusions

Firstly, multiple scenarios were discussed. A total of four were considered. The first scenario is the most simple one. In this scenario, cyclists are given more priority when a certain threshold is reached. This threshold is defined by a certain rain intensity in millimetres per hour. All three measuring systems can provide the necessary information. Therefore, a multi-criteria analysis was held to conclude which system is the most suitable. It was concluded that the infrared sensor scored the best and is thus the most suitable. The weather station was a close second. The only difference was caused by price. In the next scenario, cyclists also receive priority when it rains, just as in the previous one. Additionally, they are also given priority just before it is going to rain. This should ensure that people can arrive at their destination faster, which hopefully will mean that they will get less wet. Information about precipitation in the future must be available to implement this. Nowcasting is the only device that can do this, which makes it automatically the most viable option. The other two can only measure the actual situation. It was concluded in section 4.2.3 that similar systems perform worse during high traffic intensities. A scenario was therefore created in which the additional priority for cyclists is dependent on traffic intensities. In the last scenario, not only information about precipitation is taken into account, but also other variables related to the weather. For instance, more priority for cyclists may be applied during low temperatures. The weather station is the only device that is able to detect other parameters, it is therefore the best measuring device for this scenario. Four scenarios were thus introduced. Different rain measuring devices are more suitable than others, depending on the situation. However, it is still unclear which measuring device should be installed at the intersection. This was assessed hereafter.

It was first concluded that giving cyclists priority just before it rains by using nowcasting, as used in the second scenario was not viable. Firstly because the intersection is located outside the built-up area, as shown in section 4.2.4. Cycling distances are therefore larger. It is then unlikely that people arrive at their destination less wet. Further, it was found that nowcasting is quite expensive and difficult to implement. It seems therefore that the costs outweigh the benefits. So, it was not recommended to execute this scenario. Further, it was concluded that similar systems perform better under low traffic intensities than high intensities, as mentioned before. It is therefore important that intensities are taken into account. This is going to be done later in this research. The system is investigated during busy as well as quiet conditions. Advise is then given based on the gathered information. Two scenarios remain: the one where priority is given after a certain threshold is reached, and the one where other weather factors are taken into account. The precipitation sensor was the most viable in the first one, while the weather station was second. The only difference was caused by the cost. The weather station was the best option for the other scenario. So in conclusion, the weather station is more expensive but opens the way for potential new projects in the future. Like giving more priority based on temperature for example. The infrared sensor is also a bit outdated, it originates from 2008. This makes it a bit awkward and difficult to implement in a modern system, like an iVRI. A weather station is way more modern which makes the integration easier. It was concluded that the weather station should be used. It is a bit more expensive, but for the price difference, you get the opportunity to establish new projects and a more modern device. The price difference is, as I believe, worth it. Lastly, it was concluded that the radar system is simply too difficult and expensive to implement for one intersection.

6. Traffic

The cycle-friendly traffic system is going to be evaluated by using a traffic model. Multiple scenarios were introduced in the last chapters to achieve this. Firstly, it was concluded in section 4.2.3 that the success of the system is dependent on traffic intensities. The layout of the intersection also changes during the day because of the dynamic lanes, as discussed in section 1.5. It has therefore been decided to test the system during multiple traffic scenarios with different intensities. These scenarios are firstly defined in this chapter. Traffic conditions of the intersection N737/N342 are then assessed. This has been done to estimate the intensities during each scenario. The process to achieve this is described. The first step was to collect the traffic data. It is elaborated upon what data is needed and what conditions it must meet. The origin of the data is also described.

Next, some critics argue that if giving more priority to cyclists works in wet weather, it certainly works in dry weather. A rain sensor is then completely unnecessary. This hypothesis was tested by using the model. It is therefore run during dry as well as wet conditions. Traffic conditions are vastly different in the wet compared to the dry. A default traffic model simulates dry conditions most of the time. It is therefore investigated in the second part of this chapter how the model should be altered to mimic wet conditions as accurately as possible. In doing so, use was made of a literature study as well as data analysis. Both processes are described.

6.1 Scenarios

As mentioned before, the traffic model is run for scenarios with different traffic intensities. Firstly, to test the system during different intensities. Secondly, because of the changing intersection. Traffic is fundamentally different over the day and the week. This effect is enhanced at this intersection because of the dynamic lanes. These lanes direct traffic to other directions dependent on the time. Moreover, the sequence of the traffic light changes when the dynamic lanes change. The three changes in intensity, the layout of the intersection and the sequence of the traffic light make it impossible to represent the intersection in one scenario. The different scenarios are introduced in this section.

6.1.1 Rush hour.

Traffic is indeed different over the day, mostly caused by patterns in the working day of the population. Most people depart in the morning towards work and return in the afternoon. These simultaneous movements create rush hours. The term rush hour is a bit misleading since it takes longer than an hour. There are two types of rush hours per day. The first one is in the morning when people travel to work. The morning rush hour lasts from 7:00 to 9:00 in the Netherlands. The second one is in the afternoon when people travel back home and it takes from 16:00 to 18:00. The rush hour in the afternoon is generally busier than the rush hour in the morning. Two scenarios are established based on the rush hours. The first scenario captures the morning rush hour and the second one the afternoon rush hour. As discussed, the layout of the intersection changes during the day. There are in total 3 possible configurations. One “standard” one, one for the morning rush hour and one for the afternoon rush hour. These are shown in Figure 8. The direction of each lane is indicated with an arrow. The configuration during the afternoon rush hour is logically used in the scenario which represents the afternoon rush hour. The same is the case for the morning rush hour.

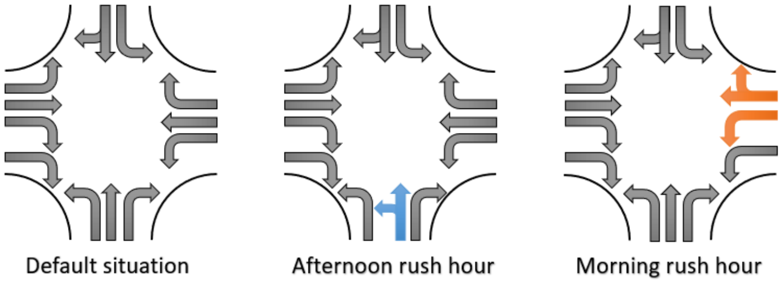

Figure 8: Lane directions at the intersection

The changes cause that different conflicts occur between movements. As a result, some movements can not be combined in one phase as before. The phases and cycles of the traffic control system are therefore different during each scenario.

6.1.2 Off-peak hours.

The time outside the rush hours are off-peak hours. Traffic intensities during off-peak hours are significantly lower than rush hours. As a result, there is generally less delay. Traffic intensities are quite similar during off-peak hours during working days and weekends. Such intensities for the intersection N737/N342 are shown in Figure 9. The intensities of motorized traffic are shown in the left graph, cycling intensities in the right one. The intensities between 9:00 and 16:00 during weekdays and weekends are for both vehicle types almost identical. It was decided to create a scenario that represents traffic during off-peak hours on weekdays as well as on weekends. The default layout of the intersection is in operation during both off-peak hours as well as during the weekend. This also makes it possible to put them together.

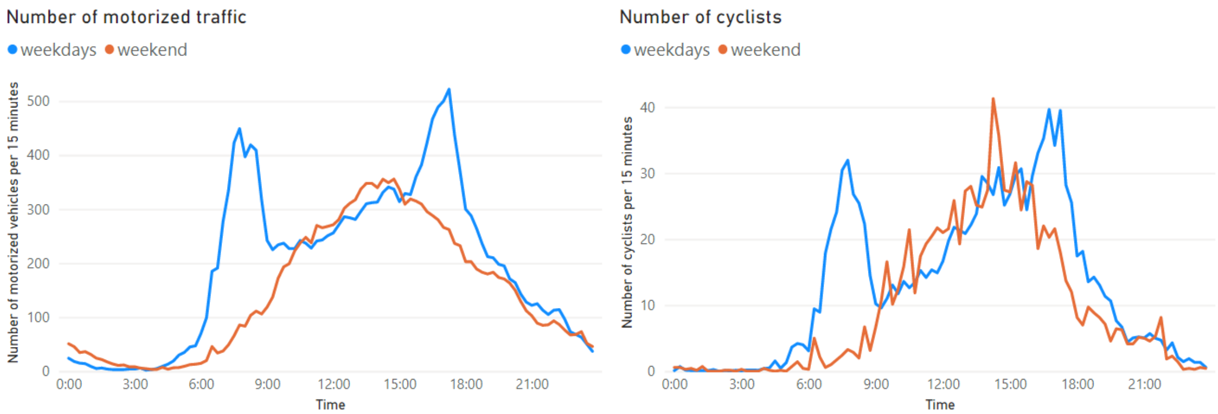

Figure 9: Number of vehicles per 15 minutes per day

Thus, in conclusion, three scenarios are established. The first one represents the morning rush hour between 7:00 and 9:00. The second one represents the afternoon rush hour between 16:00 and 18:00. The last one represents off-peak hours between 9:00-16:00 for all seven weekdays. The intensities are considerably higher during both rush hours compared to the off-peak hours. The defined scenarios can therefore nicely be used to test the effect of the system during different intensities.

6.2 Data collection

The scenarios are now established. The traffic intensities during each of them can therefore be calculated. Multiple steps are taken to achieve this. First, data about the traffic conditions have to be collected. It is described in this section what requirements the data must meet and how this has been achieved. Separation has been made between data about cyclists and motorized traffic since the processing methods are different from each other.

6.2.1 Motorized traffic data

Data about motorized traffic is used to estimate the traffic intensities for each travel direction during the three different scenarios. The data is also used to make a comparison between weather conditions and intensities. It is therefore firstly important that the data originate between 2011 and 2020 since this is the interval of the weather data. It is secondly important that the data shows the intensities of the motorized traffic into each direction, which are on a four-way intersection 4*3=12 directions. The intensities in the different scenarios are expressed in vehicles/hour. The weather data is hourly. It is therefore important that the interval of the data about the traffic intensities is at least hourly. Motorized traffic consists of multiple groups. Two main groups are included in the model, which are normal cars and trucks. Therefore, it is useful that the data also provide information on the occurrence of each group.

Data has been found which meets the above-mentioned criteria. The data was gathered by the province of Overijssel. It shows the travel intensities for each pre-sorting lane in a 15-minute interval for the month of September 2020. Each consists of two values. One absolute value with the number of vehicles and one relative value shows how much percent of these vehicles are trucks. The data has been collected by detection loops at the intersection. The different pre-sorting lanes are shown in Figure 10, in which they are indicated by a number. The figure shows that direction 7 (west to south) has two pre-sorting lanes. Data has been gathered on both of these lanes separately.

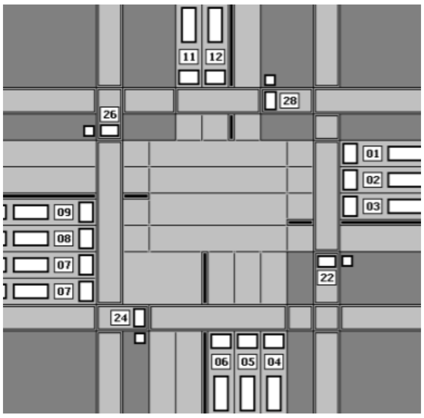

Figure 10: Detection points at the intersection N737/N342 (Fick, 2020, p. 1)

6.2.2 Cyclists data

The intensities for cycling traffic were not included in the previously mentioned data. This is certainly a problem since the goal of this thesis is to test a bicycle-friendly traffic system. A new request has therefore been made to the traffic engineer of the province to send a special file with only intensities for cycling traffic. It does not have to be from the same month since it is expected that traffic is relatively similar during each month. The data should have the same interval as the motorized traffic data.

The requested data has been received. It shows the intensities in a 15-minute interval from the month of April 2021. The intensities are defined for four bicycle lanes (22,24,26,28), as shown in figure 10. The data is also gathered by using detection loops. These loops are located just in front of the intersection, after the right-hand turn for cyclists. So, the number of detected cyclists shows how many people cross each side of the intersection.

6.3 Determining intensities

The next step is to calculate the intensities for cars, trucks and bicycles during each of the scenarios by using the gathered data. The intensities for the cars and trucks are defined for each movement. The intensities for cycling traffic are defined for each crossing, of which there are 4 in total. The calculated intensities are an average over the data's timespan. So, the intensities for cars and trucks are averaged over the month of September 2020. The intensity for cyclists is an average over the month of April 2021.

6.3.1 Motorized traffic intensities

Average values were included in the data for car and truck intensities. Thus, these do not have to be calculated anymore. The intensities are defined for each lane, as discussed in 6.2.1. The data is going to be used to estimate the intensity of each movement. This data serves as input for the traffic model. The goal is thus to create a so-called origin-destination matrix for each scenario. One with the absolute number of vehicles and one with percentages which show how many of these vehicles are trucks.

The gathered data shows the intensities for each lane. A lane represents the intensity of each movement most of the time, but not always. The difference between the lanes and movements are shown in Figure 11. A few steps should therefore be taken to translate the intensities from lanes to movements. This process could be quite difficult because of the dynamic lanes. The direction of these lanes changes over the day. As a result, different movements occur during the day on the same lane. Luckily, the dynamic lanes were not enabled during September 2020 since the new system confused drivers. This makes the translation process a bit easier.

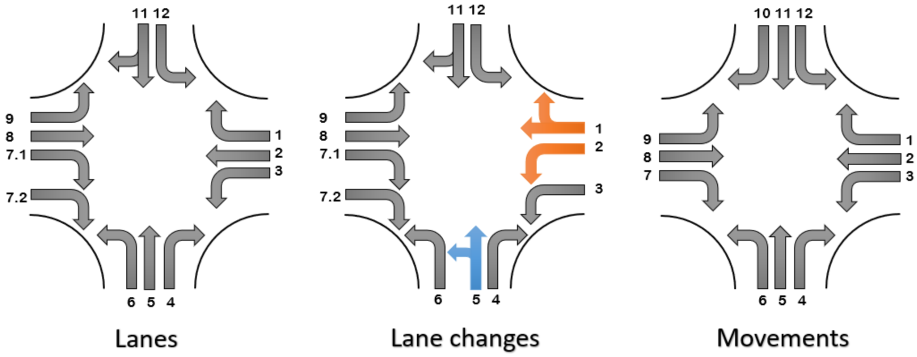

Figure 11: Movements & Lane directions at the intersection N737/N342

A few steps still have to be taken. It is firstly noticeable in figure 14 that there are 2 lanes for movement 7 (7.1 and 7.2). The intensities of these lanes have therefore been summed up. The second problem is lane 11. It directs traffic towards movement 10 as well as 11. The intensities on this lane should therefore be separated. A factor has been used for this purpose. It has been determined that 43% of vehicles on lane 11 go to the right and the other 57% goes straight on. The translation from lanes to movements is now complete and the intensities during each scenario can be calculated. For the morning rush hour, an average has been taken from 7:00 to 9:00 during weekdays. An average has been taken from 16:00 to 18:00 during weekdays for the afternoon rush hour. Lastly, an average between 9:00 and 16:00 during every day of the week is used for the off-peak hours.

6.3.2 Cycling traffic intensities

The next step is to calculate the intensities of cyclists. It was already discussed in section 6.2.2 that the detection loops for cyclists are located just in front of the intersection. Which is after the right-hand turn. So, the number of detected cyclists shows how many people cross each side of the intersection. Some cyclists may cross the intersection again. For example, if a cyclist comes from the south and goes to the west, it must first cross the intersection on the east side[2] and then on the north side[3] to reach

[2] Direction 22 as shown in figure 10 and 12

[3] Direction 28 as shown in figure 10 and 12

its destination. This cyclist therefore crosses two detection loops on its trip. This cyclist is counted twice at different locations because of this. It is not possible to determine how many cyclists cross in such a way with the available data. It has therefore been decided to simplify the movements in the model for this research. The actual situation is shown on the left side of Figure 12. Each colour represents a different travel direction. Right turning traffic has been omitted since they do not cross the intersection and are not detected by the loops. The black shapes represent the detection loops with the corresponding names. The movements have been simplified by defining four different traffic streams. The cyclists of each stream cycle in a straight direction and passes the intersection on one side. So, one steam that arrives from the west, crosses the intersection on the south side and goes to the east, one that arrives from the south, crosses on the east side and goes to the north and so on. The simplified situation is shown on the right side of Figure 12. The number of cyclists who cross the intersection, and are thus detected, at each side must be the same as in the actual situation because they influence the performance of the model. This is the case with the chosen simplifications. The number of cyclists arriving and leaving the intersection is different. But this is not a problem since they do not affect the performance of the model.

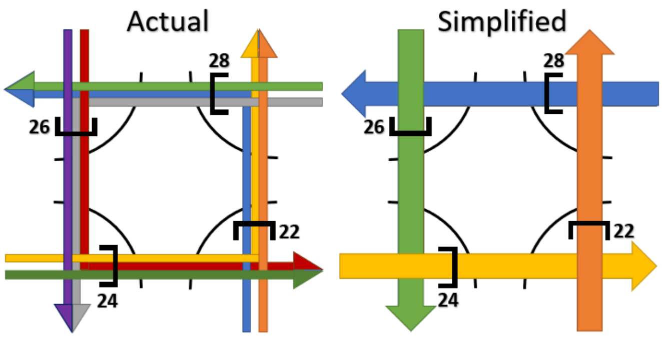

Figure 12: Simplification of cycling intensities

So, four different cycling intensities are put in the model. These correspond with the loop data and can therefore be calculated. The supplied data did not include averages. So these were calculated first. Then, the same approach as used for the motorized traffic was repeated to calculate the cycling intensities during the three different scenarios.

6.3.3 Results.

The intensities are now calculated and can be incorporated into the model. In summary, there are 28 values for each scenario. The number of motorized vehicles in each movement is defined by the first 12 of them. The next 12 show how much percent of these vehicles are trucks. The cycling intensities are defined by the last four. Figure 13 shows these values for each scenario.

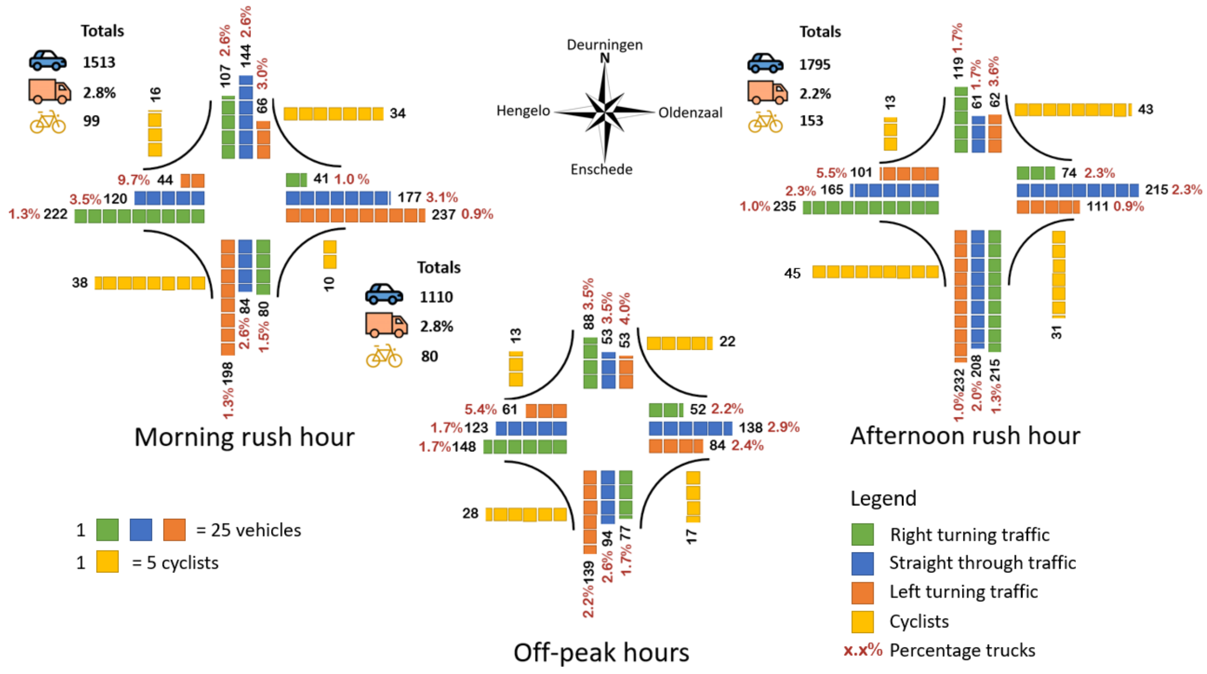

Figure 13: Traffic intensities for each scenario in vehicles/hour

6.4 Effect of precipitation on traffic

The goal of the proposed rain friendly traffic control system is to give cyclists twice a green light during one cycle, instead of the usual one. This system is enabled logically when it rains. The model should therefore be adapted to wet conditions to test the new regulation in the best possible way. Further, a traffic management consultant, as discussed in section 4.3, stated that if giving cyclists twice as much priority works in wet conditions, it would certainly work in dry conditions. Therefore, it has been decided to simulate the model not only during wet but also during dry conditions to test this argument.

The default settings in the traffic model are based on dry conditions. As mentioned earlier, traffic is fundamentally different during wet compared to dry conditions. These differences should be implemented in the model to accurately mimic wet conditions. How this is achieved is discussed in this section. This is firstly done by discussing which parameters can be changed in the model. It is investigated thereafter how these parameters change. The results are based on statistical analysis, multiple studies and physical equations.

6.4.1 Vehicle parameters.

A traffic simulation program uses a car-following model. Such a model is a complex set of equations that defines how vehicles are modelled in traffic. Things as overtaking, braking, behaviour in jams, and many more are included. The program which is used in this research is called the Krauss model. It is only important to know which parameters can be changed in this model and what their effects are. The first parameter is MinGap, which is the distance between vehicles when standing still. This could occur during dense traffic jams or before an intersection. The next two parameters are Decel and Accel which are the deceleration and acceleration abilities of vehicles under normal conditions. There is also an EmergencyDecel, or Emergency deceleration, which is the maximal physically possible deceleration of a vehicle. Such deceleration could occur when a vehicle suddenly has to stop because of the behaviour of other vehicles. The last parameter is Tau, which is the desired time headway. The headway is the time difference between two successive vehicles. Drivers attempt to maintain a gap of MinGap + headway between their front bumper and the rear bumper of the car in front. This is to ensure that they can react to the actions of the car in front.

Other parameters can also change. The first parameter is the velocity of the vehicles. This parameter is for the most part not dependent on the Krauss model or the vehicle type, but the road itself. Most roads have a maximum indicated velocity. This velocity is 80 km/h for the roads at the intersection which is investigated in this research. Vehicles may drive slower during wet conditions. The last parameters which can change are related to traffic intensities. It is possible that demand changes during wet conditions

6.4.2 Change in parameters

Dozens of studies have been performed to investigate the effects of different weather scenarios on traffic conditions. Relevant studies which relate to the earlier introduced parameters were gathered. A literature study has thus been conducted. The provided information in these studies is used to estimate how much the parameters quantitatively change. The full literature study is shown in Appendix C. A summary is given now.

Firstly, vehicles lose grip on wet surfaces because tyres cannot create the same friction as on dry surfaces. The acceleration and braking ability of vehicles decreases because of this. Further, people tend to drive more slowly in wet conditions due to the lack of grip and visibility. They also tend to keep a greater distance from the vehicles in front of them. Rainfall can also influence the intensities of motorized and cycling traffic. This relation however is more difficult to interpret. The intensities increase when people switch from slow transportation modes like cycling and walking. However, intensities can also decrease when people cancel trips because of the bad weather. A small data analysis study has therefore been conducted to study the relation between weather and intensities on the intersection N737/N342. The required data for this study was already used before. First, the traffic intensities were gathered in section 6.2.1 Data related to weather conditions was used in section 5.1. The data was combined. Statistical methods were used to conclude if intensities decrease in adverse weather conditions. The full analysis is explained and shown in appendix D. It was concluded that the available data was not reliable enough to process further in this research. The study could be improved if more data is collected. Only information during one month is taken into account. It would therefore be useful if data from a longer timespan is used. Further, information from other intersections could also be used. However, gathering and processing such an extensive amount of information takes a lot of time and effort and is therefore out of scope for this research.

My study was thus insufficient to make conclusions. Other sources have therefore been used to study the effect of rain on intensities. These are elaborated upon in the earlier mentioned literature study. The results of the complete literature study are shown in Table 5. The default values which are used in dry conditions in the model are shown in the second column. The result of the literature study has been put in the next column. The effects of these changes are shown in the last column.

Table 5: Changed parameters during a wet scenario

Parameter	Default value (dry)	Change	Adjusted value in rain
Minimal gap (m)	2.5	No change	2.5
Acceleration ability (m/s^2)	2.6	-29.7%	1.83
Deceleration ability (m/s^2)	4.5	-13.7 %	3.88
Emergency deceleration (m/s^2)	9	-40%	5.40
Average speed (km/h)	80	-7.4%	74.08
Time headway (sec)	1.5	+14.1%	1.71
Intensities	Differs	No change	

7. Assessment Framework

A traffic model is used to calculate the effects of a cycle-friendly traffic system. It is run during multiple different scenarios. These are compared to each other to make conclusions. They should be compared based on certain criteria. These criteria are discussed in this chapter. All the criteria together form an assessment framework. The framework should be used to indicate if a certain scenario performs worse or better in comparison to another. The discussed criteria have been divided into several groups.

7.1 Hard legal criteria

The first group consists of hard legal criteria. These are criteria that have been laid down in law. It is therefore important that these are never exceeded throughout the simulation. Changes must be made if they are.

Maximum cycle time

The maximum cycle time is a condition for the traffic light system itself. It is the time in which all phases in a program have been performed. So, the time in which all directions at a traffic light have received at least once a green light. It is laid down in the Netherlands how long the maximum cycle time can be. This is to ensure that the traffic does not have to wait too long. People tend to get restless when they have to wait too long and therefore more inclined to run a red light. This reduces the safety of the intersection. The maximum cycle time for the intersection N737/N342 is 120 seconds (Fick, 2020).

7.2 Traffic-related criteria

The second group of criteria are related to traffic engineering concepts. These are concepts that express the performance of an intersection.

Average travel time

The first, and most simple traffic-related criterium is the average travel time. The average travel time is the time which traffic takes on average to get from point A to point B. The travel time can be specified by traffic type, destination, arrival, etc. A situation has deteriorated when the average travel time has increased for the same route.

The average travel time should be found for every travel direction. The intersection is a four-way one. This means that there are 4*3 = 12 travel directions for motorized traffic. A simplification was implemented for cycling traffic resulting in 4 travel directions. So, 16 average travel times emerge from the model. The found values show how much time on average traffic from each direction takes to cross the intersection. It is decided to start the measurement 150 before the intersection and end it 150 meters after. The travel distances for each direction are the same by doing so. Comparisons can therefore be made between them. It is a bit bothersome and confusing to show all these 24 directions as a result. It has therefore been decided to average the values for each arrival direction, which are west, north, east and south. A total value should be calculated which shows the average travel times in one value for the complete intersection.

Vehicle hours lost/ Lost time in hours

The total time lost is a way of expressing delay. It is commonly used in the Netherlands, which is called: “voertuigverliesuren”. The total time lost is the accumulated time that has been lost by all vehicles on a certain road section. It is thus a summation. One lost hour could mean that one vehicle lost 60 minutes or that 60 vehicles lost one minute. The total time lost could be calculated for different timeframes like an entire day, during rush hour or a different one. The situation is worsened if it has increased for the same route. It could also be translated into a cost when found useful. The rule of thumb that one lost hour is equal to a cost of 10 € could be used for this purpose (Voerknecht, n.d.).

The lost time should be calculated for each travel direction, just as the average travel times. Here, the same distance of 150 meters has been used. The lengths of the queues do seldom exceed these 150 meters, which was concluded by visual inspection. This means that vehicles arrive at the designated speed when the measurement starts. So, no time is lost before the measurement is started. The values are summed for each arrival direction. A total value should also be calculated which shows the total lost time in hours over the whole intersection.

Average cycle time

The last traffic-related criterium is the average cycle time. The maximum cycle time was already discussed, which is a hard legal criterium. The average cycle time shows how long on average one cycle of the traffic control system takes. The average should off course be lower than the maximum cycle time. The average duration of the cycle time shows something about the efficiency of the traffic control system. A lower cycle time is preferred since all directions receive priority faster.

7.3 Environmental related criteria

The next group of criteria quantify the effects of traffic on the environment. Certain substances are taken into account which are emitted by vehicles. These substances are directly or indirectly harmful to humans. A situation is worsened if more harmful substances are emitted.

Greenhouse gasses

One goal of the cycle-friendly traffic system is to reduce the emission of greenhouse gasses, as discussed in section 1.7 It is therefore important to consider a criterion that tests this. Two greenhouse gasses which are emitted by traffic are carbon dioxide (CO_2) and nitrogen oxides (NO_x). Nitrous oxide does not only contribute to global warming but is also harmful to people's health. Both gasses arise when fuels are ignited within an internal combustion engine of a vehicle. Vehicles burn more fuel at an intersection if they are interrupted.

Comparing greenhouse gas emissions based on two separate substances is quite difficult. A parameter is therefore used to combine their effects. This parameter is called the global warming potential (GWP). The GWP indicates the contribution of a substance to global warming. It compares the effect of substances to carbon dioxide. The GWP for carbon dioxide is therefore 1 CO_2e. The larger the GWP, the more harmful the substance. The GWP for nitrogen oxides is around 31.5 CO_2e (Lammel & Graßl, 1995). So, one unit of Nitrogen oxides is 31.5 times more harmful than one unit of carbon dioxide. The GWP provides a common unit of measure, to add up emissions of different gasses. The emissions in GWP at the intersection can therefore be calculated by using the next equation:

$$GWP\ (CO_2e) = CO_2 + 31.5 * NO_x \tag{1}$$

CO_2 and NO_x represent the emissions of carbon dioxide and nitrogen oxides.

Most greenhouse gasses are not emitted on the intersection itself but the roads around it. Vehicles brake, wait and accelerate before and after they cross the intersection. It has been found that this mostly occurs around 75 meters from the intersection. It has therefore been decided to collect the emissions 75 meters from the intersection on each side. There are in total four sides: east, west north and south. These four values are summed up to show the total emissions emitted at the intersection.

Particulate matter

Particulate matter is the sum of all particles smaller than 10 micrometres suspended in the air. It is indicated with the acronym PM_{10} . Most of these particles are harmful to people's health. This mainly concerns the elderly and people with heart, vascular or lung diseases (RIVM, 2018). The largest portion of particulate matter is not emitted because of igniting fossil fuels but through the wear and tear of the tyres and brakes. It is estimated that 73% of the particulate matter pollution caused by cars originates from them (Evans, 2020). Tyres and brakes wear more if a car has to stop and accelerate again for a traffic light. The amount of particular matter is expressed in milligrams.

8. The model

The traffic situation on the intersection N737/N342 is simulated in a traffic simulation program. The aim of this is to investigate the effects of the proposed cycle-friendly traffic system. The simulation program which is used is called Simulation of Urban Mobility. Or SUMO, in short. SUMO is an open-source traffic simulation program and is available for free. This program has been chosen for two main reasons. The first one is that the intersection was already created in this software in an earlier performed study. This version has been used to save time. The second reason is that the software is free. This allows other people to potentially use my model without buying an expensive licence for different software.

The existing model of the intersection had to be altered in a couple of places, however. Firstly, the original model did not have cycle paths. They are quite important for this study and have therefore been added. The original traffic control system also did not take into account cyclists, since they were not present in the model. The new version has cyclists. The phases in traffic control system itself must therefore be changed to give priority to cyclists. A new logic system has therefore been added to the traffic control system. In short, this system only gives cyclists priority when they are present, like in real life. It works as follows: a phase with only movements for cars is selected when no cyclists are detected. It selects a phase that combines car and cycling movements when a cyclist is detected.

The way vehicles enter the model has also changed. Firstly, vehicles entered with equal distance to their predecessor, which is not preferable for a simulation study. Alterations have therefore been made to make sure that they arrive randomly. Other small alterations have also been made. These are elaborated upon in Appendix E. It is also explained in the appendix how SUMO works and how the model is executed. A screenshot of the model during a simulation is shown in Figure 14.

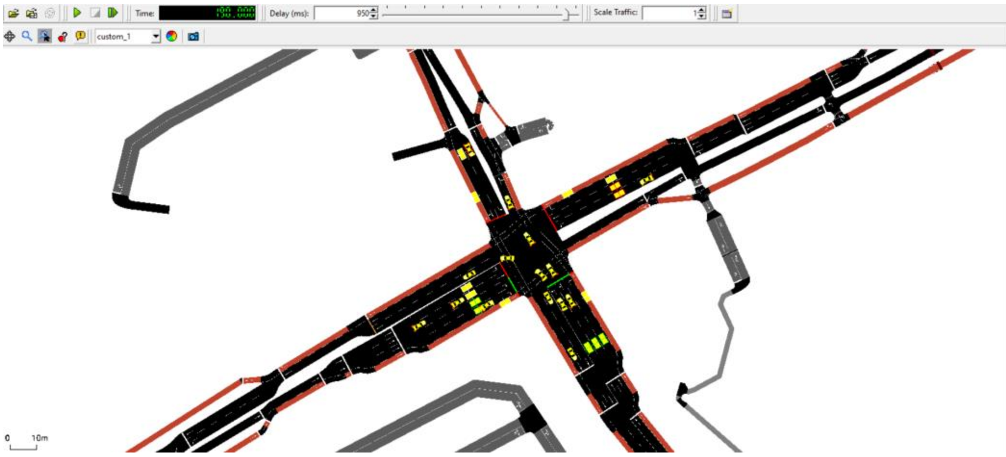

Figure 14: A screenshot during a simulation.

8.1 Scenarios

The traffic model is run for different scenarios to access the system as accurately as possible. First, multiple traffic conditions were considered, as discussed in section 6.1. There are two main reasons for this. The first one is that each scenario has different traffic intensities, which allows the system to be tested in high as well as quiet traffic conditions. Second, the dynamic lanes cause the intersection to be different during the day. The phases in the traffic control system are also different as a result. Three traffic scenarios were introduced: the morning rush hour, the afternoon rush hour and off-peak hours. A model has been created for each of these scenarios with the corresponding layout, traffic intensities and traffic control system. Next, the model is simulated during dry as well as wet conditions as discussed in section 6.4. This allows the expressions of some critics to be tested. These critics argue that if prioritizing cyclists works in wet conditions, it should most definitely work in dry conditions. The standard parameters are used for the dry conditions. The altered parameters as calculated in section 6.4.2 are used for the wet scenario. Lastly, the aim is to find the effects of the system itself. This is only possible if a situation with the proposed system is compared to the default situation. The model is, therefore, run without the system and with the system enabled. All the discussed scenarios are shown in Table 6. The model is simulated for all scenarios. So, there are in total 3*2*2=12 different simulations.

Table 6: The scenarios

Type of Scenario	**Condition 1**	**Condition 2**	**Condition 3**
Traffic conditions	Morning rush hour	Afternoon rush hour.	Off-peak hours
Weather conditions	Dry	Wet	
Rain friendly system	Off (default)	On: 2 times priority	

8.2 Traffic control system

As discussed, an intersection with a traffic control system is created in a simulation model. The traffic light control has a significant influence on the overall results. It is therefore essential that the created system in the model corresponds as closely as possible with its real-life counterpart. Different types of traffic control systems can be used in Sumo's software. A system called "actuated traffic lights" has been chosen because it most closely resembles the real system. The actuated traffic light adapts to demand dynamically. It extends the green time when a vehicle is detected until a certain maximum value, like the real system. The system in the model is configured by all kinds of parameters. The values for the different parameters have been set by using the document in which the intersection is specified (Fick, 2020). This document was elaborated upon in section 4.1.2. The traffic control system differs during each traffic scenario. Different parameters must therefore be set for each scenario.

Firstly, the defined phases in the document have been adopted. It shows which movements are combined in one phase and the order of the phases. Cyclists only receive priority if they are detected in real life. This prevents cyclists from receiving priority if they are not present. This has also been incorporated into the model. Next, minimum and maximum green times can also be specified in the model. These parameters are used in the model in the same way as in real life. Their values can thus simply be taken from the specification document. The minimum time is the same for every cycle, with 5 seconds. The maximum time differs between 10-25 seconds. The yellow times are also easily converted. Lastly, the gap is defined, which is equal to 2 seconds as discussed in section 4.1.2.

8.3 Output

The introduced criteria in the framework, as discussed in chapter 7 should be calculated for each simulation by using output values of the model. It is possible to extract gigabytes of data from SUMO during one simulation. This is a bit cumbersome of course. So, the aim is to only select suitable data which can be used to calculate the introduced criteria.

Firstly, the maximum cycle time is a legal criterium. This value can not be exceeded at any time during the simulation. The maximum cycle time is inserted as an input value in the model. The model itself makes sure that this value is not exceeded at any time. The average cycle time can also be calculated by the model, which is also useful for this research. SUMO is a traffic simulation program. Average travel times are one of the most basic output values for traffic simulation programs. These can therefore be easily extracted from the model. It is possible to gather them for all 16 travel directions for the chosen distance of 150 meters, just as requested. Also, the lost time is calculated automatically.

Next, a big advantage of SUMO is that it can calculate the emissions during the simulation. It indicates the emissions of multiple substances, under which CO_2, NO_x and PM_{10}. It is possible to gather the emissions on each road section independently. This information can be used to calculate the emissions 75 meters around the intersection, as requested.

This section is a bit brief, however. Some details have been left out. A more extensive version is therefore included in appendix F. Here, it has been explained which values are exactly extracted from the model and how they are used to calculate the values for the introduced criteria.

8.4 Run length, warmup & number of replicants

Three main aspects should be considered when performing a simulation study. The first aspect is the run length. The run length is how much time is simulated in the model. It has been chosen to use a run length of 3600 seconds or one hour. There are several reasons for this. Firstly, some statistics are calculated per hour. So, using one hour makes it way easier to compute these. Secondly, the vehicle inputs are also calculated per hour. The chosen simulation time makes it easier to put them into the model. Lastly, many different scenarios have to be performed. It is therefore wise to choose a simulation time that is not too long, otherwise, it takes hours to simulate everything. 3600 seconds is long enough to get satisfying statistics but does not take too much time to simulate.

The second aspect is the warm-up period, which is the time the model takes to reach an optimal state. The model starts empty with no cars on the roads, which is not realistic. An optimal state has been reached when a certain number of cars have entered the model so that there are realistic queues at the traffic lights. This takes time, which is thus the warmup time. Data is most of the time gathered after the warm-up period. The Marginal Standard Error Rule (MSER) rule is used to asses how long the warmup period should be for the traffic model. The calculations are explained in appendix G. The result shows that the warmup time should be 200.3 seconds. This is 5.56% of the total simulation. Implementing a warmup period in SUMO is difficult. The warmup period is quite small, so it does not have a major impact on the results. Lastly, most statistics are not measured from the first second. Take the average travel time for example. The measurement starts when the first car has left the simulation. This occurs after around 40 seconds. It has therefore been decided to not use a warmup time.

A probabilistic model is a simulation in which randomness plays a role. Running the same simulation could give different answers. A traffic simulation is also probabilistic since the arrival of vehicles is random. The precision of the results can be increased by conducting multiple replicants. The values over the different replicants are averaged to get a more precise result. It can be calculated how many runs are needed to get a satisfying result. This method and its results are also shown in Appendix G. It was concluded that each scenario should be run 5 times to achieve a satisfying outcome.

8.5 The proposed intervention

The proposed intervention of the cycle-friendly traffic system should also be inserted in the model. It had been concluded in section 4.2.3 that most similar systems gave cyclists priority on two occasions during a cycle instead of the usual one. It has therefore been decided to use this system as well. The phases in the cycle of the traffic control system are altered to mimic this system. An additional phase has been added to the scheme to give priority to cyclists for the second time. It has been decided to only give cyclists from the busiest two directions extra priority. The priority for the other two directions remains the same. This has been done to optimize the situation. People cycling from east to west and in reverse order are the busiest directions in all scenarios. So, a phase has been added which combines the two. The car movements which do not conflict with the cycle directions are also added to the new phase. This has been done to reduce the waiting times for cars during this extra phase. The extra priority is only used when cyclists are detected. It is skipped when no cyclists are present.

9. Results

All the different scenarios have been simulated. The output values are used to calculate the relevant criteria. The results are elaborated upon in this chapter. The results of the default scenario are firstly discussed. A comparison is hereafter made between wet and dry conditions. The effects of the cycle-friendly traffic system are shown in the last part of this chapter. Only the most important values are discussed. The complete results are shown in Appendix H.

9.1 Default situation

At first, the default situation for the three different traffic conditions is discussed. The results during dry weather for important criteria are shown in Table 7. The average travel time for cyclists shows how long a cyclist takes to cross the intersection, independent of its direction. The average travel time for cars shows how long a motorized vehicle takes on average to cross the intersection. This value is an average of the 12 different travel directions. The total lost time shows how much time in hours is lost on the intersection per hour due to delay. The cycle time reveals the average length of a cycle in the traffic control system. The GWP indicates how much kg CO_2e is emitted during each hour at the intersection. And lastly, how much particulate matter in grams per hour is emitted is shown in the last row. The total lost time, GWP and Particulate matter are defined per hour since the model is simulated for one hour.

Table 7: Results of the simulation in default, dry, conditions

	Unit	**Afternoon Rush hour**	**Morning Rush hour**	**Off-peak hours**
Average travel time cyclists	Seconds	91.66	93.31	86.56
Average travel time motorized vehicles	Seconds	43.37	45.39	37.07
Total time lost	Hours per hour	14.18	12.80	6.79
Cycle time (traffic light)	Seconds	61.66	61.77	47.06
Global warming potential	Kilogram $C0_2e$ per hour	223.44	192.37	126.10
Particulate matter	Grams per hour	8.15	7.06	4.96

The results show that firstly, the average travel time for cyclists as well as for motorized vehicles is the lowest during the off-peak hours. The average travel time for cars during the afternoon rush hour is lower compared to the morning rush hour. This is odd since more cars (1795/hour) are on the road in the afternoon compared to the morning (1513/hour). It is expected that more vehicles cause more delay, which seems not to be the case. The arrival direction of the cars may have an influence. In the afternoon, most traffic comes from the south. While most traffic comes from the east and west in the morning. Most time is lost in the afternoon since more vehicles are on the road. The GWP and particulate matter emissions are the highest during the afternoon for the same reason.

9.2 Wet conditions

The default situation is also simulated during wet conditions. Table 8 shows the percentual differences for certain criteria between the dry and wet conditions. A positive value means that the value for a certain criterium has increased in wet conditions.

Table 8: Changes from dry to wet conditions in percentages

	Afternoon Rush hour	**Morning Rush hour**	**Off-peak hours**
Average travel time cars	+11.42 %	+9.88 %	+14.08 %
Total time lost	+17.81 %	+15.54 %	+24.54 %
Cycle time	+4.84 %	+3.69 %	+1.36 %
GWP (kg CO2-e per hour	-5.24 %	-6.07 %	-5.65 %
Particulate matter g per hour	-1.23 %	-4.77 %	-5.11 %

Firstly, the average travel time for motorized vehicles has increased during wet conditions, and more time is lost overall. This is caused because people drive more slowly in the wet because of reduced grip and visibility. Wet conditions seem to affect traffic during off-peak hours more than during rush hours. The emissions seem to have declined as well, which does not happen in real life. The wet conditions have been mimicked in the model by lowering some parameters such as speed, acceleration and braking performance. This causes that vehicles drive more calmly in the model which results in lower fuel consumption and thus fewer emissions. In real life, however, acceleration and braking ability are decreased because vehicles have less grip in wet conditions. Fuel consumption is actually higher in wet conditions compared to dry conditions due to the reduced grip (McClusky, 2014).

9.3 Effects of the cycle-friendly traffic control system

The model is run during morning & afternoon rush and off-peak hours during wet as well as dry conditions to assess the default situation. The same 6 simulations were performed, but now with the proposed cycle-friendly enabled. The results are compared to the default conditions to access the effects of the new system. Firstly, the changes in travel times for both cycling as well as motorized traffic are visualised in Figure 15.

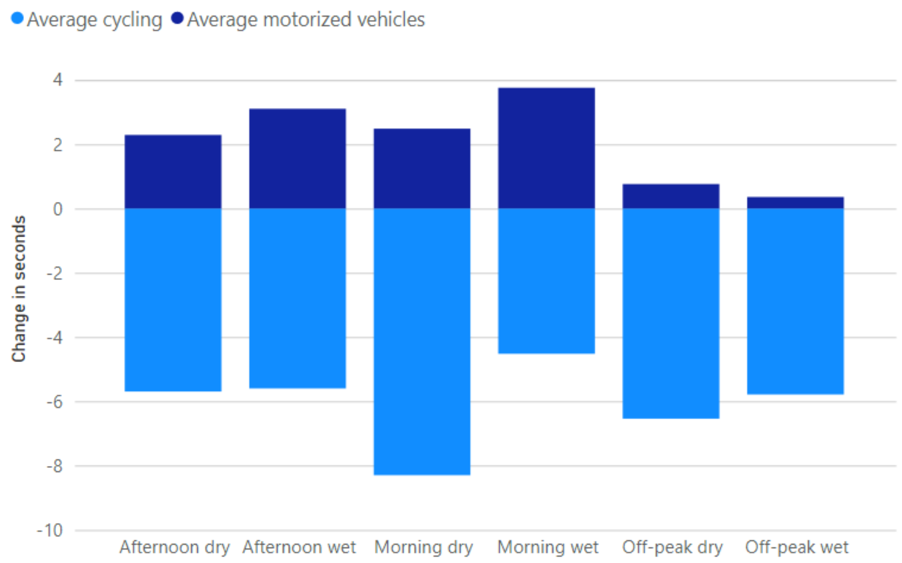

Figure 15: Changes in travel times compared to the default situation

The results show that the average travel times for motorized traffic increases the most during both rush hours, with around 2-4 seconds. The change during the off-peak hours is much smaller, less than 1 second. The average travel times for cyclists sharply decreases because of the proposed intervention. They are decreased by around 5 to 6 seconds on average. The changing travel times are translated to lost hours. The number of lost hours for cars has increased since their average travel times have increased. The lost hours for cyclists has decreased since they can cross the intersection faster. The combined change in lost hours is calculated. This value shows the complete effect of the system. The results have been put in Figure 16. The results are in lost time in hours per hour. Sounds a bit confusing perhaps. But it means that for example, 1.54 hours of time is lost each hour during the afternoon rush hour.

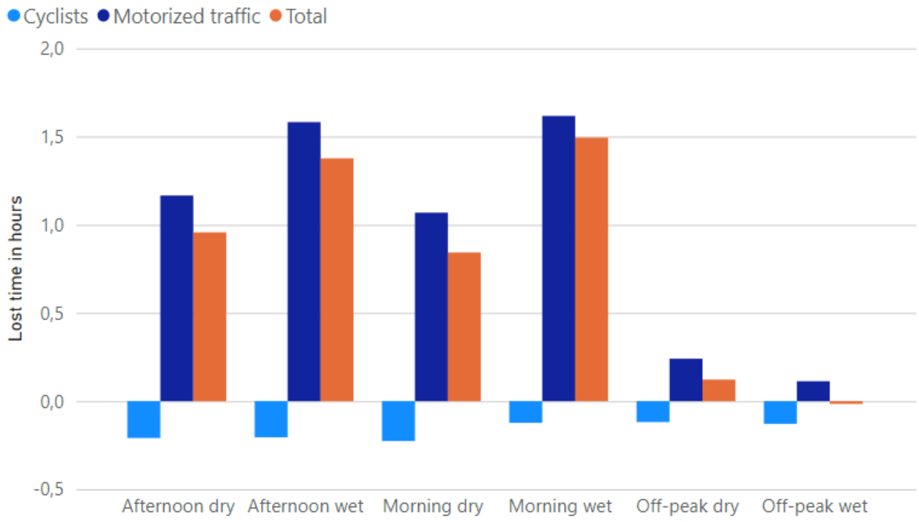

Figure 16: Change in lost hours compared to the default situation

It can first be seen that the number of lost hours has significantly increased during both rush hours. The time gained by cyclists is only a fraction of the total time lost by motorized vehicles. It can be concluded that more time is lost in wet conditions than in dry conditions during rush hours. The change during the off-peak hours is much less. Even, time is won because of the intervention during wet conditions in the off-peak hours. This is because the time gained by all cyclists combined is greater than the time lost by all cars combined. The lost hours can be translated to costs in euros. It was earlier mentioned in this report that one lost hour is equal to a cost of 10 €. This number has been used to calculate yearly costs. The results are indicated by green bars in Figure 17. Furthermore, it has been calculated how many cyclists a year pass by the intersection during the various periods. So in short, how many cyclists per year use the intersection during the afternoon rush hour, morning rush hour and off-peak hours. These results are indicated by the dark blue bar in Figure 17.

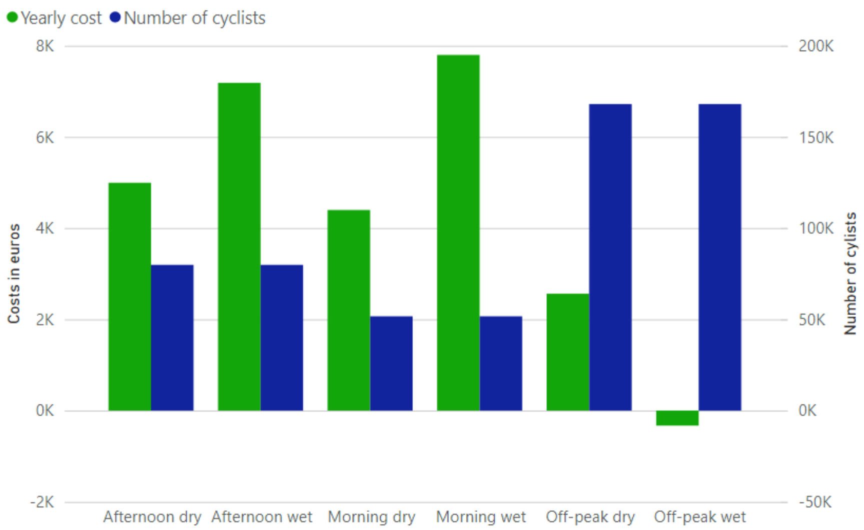

Figure 17: Yearly costs and number of cyclists

The difference in costs between rush and off-peak hours seems smaller than the difference in lost hours. This is because there are more off-peak hours than rush hours in a year. This is firstly caused because there are more off-peak hours (7) than rush hours per day (2 for each one). Furthermore, there are no rush hours during the weekend, while off-peak hours do occur. Secondly, it can be observed that there are anually many more cyclists during off-peak hours than during peak hours. This may firstly seem weird since off-peak hours are quieter than rush hours. But this is caused by the same problem as just mentioned. There are in total more off-peak hours than rush hours per year.

Vehicles have to wait longer at the intersection due to the proposed system, as previously concluded. As a result, fuel consumption and therefore greenhouse gas emissions increase. One of the goals of the cycle-friendly traffic system is to encourage people to cycle instead of taking the car, which reduces the emission of greenhouse gasses. This conflicts with what has been said before. It seems that a paradox is created: the emissions are increased around the intersection to reduce emissions. The intervention could still be successful however when the emissions reduced by people cycling instead of taking the car is higher than the extra amount emitted because vehicles have to wait longer. This problem had been anticipated in advance. A calculation method was therefore already devised to deal with this problem, which is explained in appendix F. The method calculates how many people should take the bike instead of the car to compensate for the increased emissions. The results have been put in Figure 18. The extend of the increased emissions is indicated by the blue bars. The rightmost blue bar shows how much CO_2e is saved when 1 person switches to the bike. The orange bars show how much people should take the bike instead of the car to compensate for the extra emissions for each scenario. Emissions are reduced when more people switch transport method. It fails when fewer people switch.

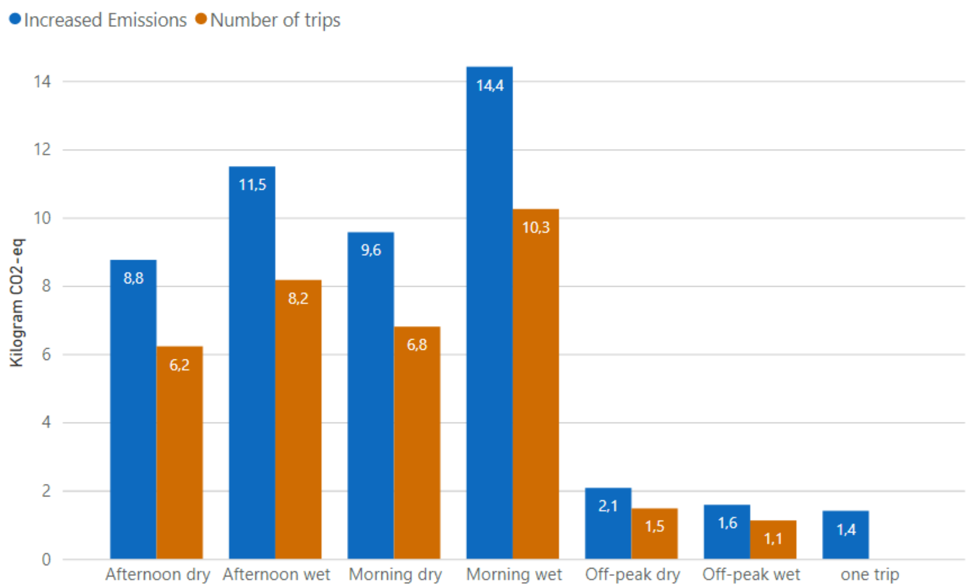

Figure 18: Increased emissions and number of trips to compensate for it

The emissions have increased more significantly during rush hours compared to off-peak hours. At least 4 times as much. More people should therefore switch to cycling to compensate. 6.23 to 8.17 people should make the switch in the afternoon, which is around 4.9 % of the total number of cyclists. So in other words, the number of cyclists should increase by 4.9 % to compensate for the emissions. This percentage is higher in the morning, with 9%. The number is the lowest during off-peak hours when it should only increase by 2.5%. Furthermore, emissions increase more rapidly in wet conditions than in dry conditions. This does not apply during off-peak hours when it is actually reduced.

Some additional parameters were calculated as well and have been put in Table 9. These also show the effect of the proposed system. The first parameter indicates how much particulate matter more has been emitted. The second one shows how often the double priority has been used. So, in how many per cent of the cycles is the phase in which cyclists are given their double priority used. The phase is skipped when no cyclists were detected. The last parameter shows how much the average duration of a cycle in the traffic control system has increased.

Table 9: changes in three other parameters

		Afternoon		Morning		Off hours	
Parameter	**Unit**	dry	wet	dry	wet	dry	wet
PMX	Grams	0.206	0.246	0.524	0.838	0.010	0.062
Priority used	Percentage	65.587	65.158	39.510	39.104	28.838	27.332
Average cycle time	Seconds	11.246	10.997	5.936	6.229	3.859	3.035

It can firstly be concluded that more particulate matter was emitted. The biggest increase is during the morning rush hour. The emission increased the least during off-peak hours. Next, the extra phase is most frequently used during the afternoon rush hour. This makes sense since most cyclists are present during this time. The last parameter depends on the second one. Adding an extra phase to a traffic control system logically increases the average duration of its cycle. It is therefore conceivable that the average duration increases more substantially when the extra phase is used more often. The difference is consequently the greatest during the afternoon rush hour.

9.4 Conclusions from the model

The effects of a cycle-friendly traffic system were tested by using a simulation model. Cyclists receive twice as much priority due to the system. Many different scenarios were therefore created to test the effects of it as well as possible. All simulation experiments were conducted. The relevant results have now be discussed and conclusions can now be made.

The model was firstly run without the system to access the default conditions. This was done first to investigate whether the model works accordingly. Second, because default conditions are needed to calculate the differences caused by the system. The results show that in general, the model behaves as expected. The average travel times and delay were higher during rush hours compared to off-peak hours. This is logical since there is way more traffic during rush hours, causing more delay. Next, the emissions were the highest during the afternoon rush hour, then comes the morning rush hour. The emissions are the lowest during the off-peak hours. This also makes sense because most vehicles are present during the same afternoon rush hour. More vehicles mean more emissions. A problem that was noticed however is that average travel times are higher during the morning compared to the afternoon rush hour, while traffic intensities are lower. The exact cause is unknown. It is possible however that the arrival pattern of the vehicles has an influence. Further, the travel times increased from dry to wet conditions, which was also expected. The emissions decrease, however, which should not happen. This is due to a problem with the model. The problem is that wet conditions were mimicked by lowering some parameters like speed, acceleration and deceleration ability. Vehicles are driving more carefully therefore and use less fuel. In real life, the same parameters decrease but the fuel consumption remains the same or rises even because tires have simply less grip. This problem should not influence the final results.

Scenarios with the system enabled were simulated after the default conditions were tested. The results were compared to each other and conclusions can be made. Firstly, it is noticeable that the proposed system works significantly worse during rush hours compared to off-peak hours. First, because considerably more time is lost as shown in Figure 16. The costs as indicated in Figure 17 are therefore also higher, while fewer cyclists use it. Further, the emissions have also increased more significantly. Because of this, more people should switch from motorized vehicles to cycling to compensate for the emissions. The results in Figure 18 indicate that 6.2 to 8.2 people per hour should switch to compensate for the emissions during the evening rush hour. Or differently put, cycling intensities should increase by 4.9 %. This number is even higher during the morning rush hour when 6.8 to 10.3 people per hour should switch, which is 9%. This is a big difference compared to off-peak hours, when only 1.4-1.6, or 2.5 % should switch. It is difficult to determine how many people will actually make the switch because this requires a special study. Such studies are quite complicated and are thus out of scope for this project. This makes it difficult to conclude whether enough people are switching to compensate for the emissions without this information. The only thing that can be said with certainty is that the chance of success is higher during off-peak hours because a smaller percentage of cyclists would have to switch. However, it is quite unrealistic that more than 6 people switch during the rush hours. It is therefore certainly possible that emissions actually increase during rush-hours because of the system, instead of decrease. It is not surprising that most parameters increase more significantly during rush hours. They are the busiest time of the day. Reducing priority during these times is asking for trouble. Even, this process is worsened since there are also more cyclists during rush hours. This means that double priority is given on more occasions, reducing priority for motorized vehicles even more.

It just seems that the system is just more suitable for quieter conditions, like off-peak hours. The results in Figure 17 showed that the extra costs caused by lost time are substantially lower during off hours whilst more people use it. Further, the additional CO_2e emissions are compensated when only two people switch modes per hour because of the system. As said, it is difficult to determine how many people will actually switch. However, Two people is quite a low amount and it seems that this should be possible.

Lastly, the results show that the system performs worse in wet conditions. The emissions have increased more in wet conditions, as well as the average travel times. The costs are therefore also higher. Further, more people should switch modes to compensate for the emissions. This also makes it less realistic. This problem only occurs during rush hours, however. The emissions and average travel times during off-peak hours have increased more in dry compared to wet conditions.

10. Conclusions

This thesis aims to investigate whether it is worthwhile to implement a system at the signalized intersection N737/N342 which gives cyclists more priority during rain. The traffic control system switches to the new regulation when precipitation is detected by some sensor. Many topics were considered to create the best possible advice.

It was first investigated how often it rains at the intersection. This information is used to calculate what percentage of the year the system would be enabled. Weather data of the last 10 years was used. It was concluded that it rains 7.3 % of the time. Some of this is light rain. The decision was made to only consider rain with an intensity higher than 0.5 mm/hour. As a result, it rains 4.7 % of the time with an intensity higher than the chosen threshold. The system is therefore enabled 4.7% of the time. However, the decision could be taken to change the chosen interval of 0.5 mm/hour. The following equation can then be used to calculate what percentage of the time the system is turned on for a given threshold.

$$T = 0.0238 * I^4 - 0.3928 * I^3 + 2.23902 * I^2 - 6.52 * I + 7.2482 \quad (2)$$

T indicates the time in percent of the year while T indicates the intensity of the rain in mm/hour. The equation is reliable up to an intensity of 5 mm/hour.

Then, multiple similar systems at other intersections in the country were investigated. It was first concluded that all of them are located within the build-up area. Some in villages, others in big cities. The intersection at issue in this thesis is located outside the build-up area. Traffic intensities are therefore different as a result. Further, it is expected that the average travel distance of people using the intersection to be about 9 kilometres. This is way longer than the average trip length in the country. This may affect the effectiveness of the proposed system. It was then found that most similar systems have implemented it by prioritizing bicyclists twice per cycle instead of the usual one. Therefore, it was decided to do it this way as well in this report. Further, it was concluded that the reasons for which the systems were introduced also differed. Some aimed to increase safety. Others aim to keep people cycling during rain, instead of switching to the car. Most agreed that cycling should be encouraged. The same applies to this thesis. More people should cycle instead of taking the car which is advantageous for the climate, safety, health and spatial scarcity.

The effects of similar systems were also researched. The average waiting time for cyclists at all intersections was logically reduced. The effect on the average waiting time of the other traffic differs. It increased at some intersections while it stayed the same at others. The success of similar systems seems to depend on traffic intensities. They do not perform great under high intensities while they perform better under lower intensities. The same conclusion can be derived from the results of the model. The results showed that the average waiting times, cycle times (of the traffic light) and emissions increased more significantly during rush hours compared to off-peak hours. Further, it was concluded that emissions most likely would increase during rush hours because of the system, instead of actually decrease. It is therefore likely that the system does not contribute to its purpose. So it was concluded because of the discussed reasons that the system should not be used during busy conditions, like rush hours.

Next, All kinds of weather measuring devices were investigated. The three most useful options appeared to be a precipitation sensor, a radar system and a weather station. The best measuring device was chosen based on certain criteria and scenarios. It was concluded that one scenario is preferred over the others. The extra priority is given in this scenario when a certain precipitation intensity has been reached. The precipitation sensor is the most suitable system for this scenario. The weather station was a close second. The only difference was caused by price. The weather station is indeed more expensive but opens the way for potential new projects in the future. The weather station is also way more modern than the sensor, which makes it easier to implement. It was therefore concluded that the benefits of this device outweigh the price difference. A weather station is thus the best choice if it is decided that a rain sensor should be installed.

The aim is to give unbiased advice. Criticism was therefore considered. The first point mentioned by critics is that similar systems are installed because of political, instead of traffic-related decisions. This is said because motorized traffic is deliberately slowed down to promote cycling. As a result, the total time lost has increased, which is not optimal from a traffic-related perspective. But there are other reasons for this, which were discussed before like climate, safety and spatial scarcity. A somewhat similar decision was to decrease the maximum velocity on highways from 120 to 100 kilometres per hour. This was not really a traffic-related decision. It was a political one. Political decisions are not only taken by me, as a student, or one company. Governmental institutions like municipalities or the province are involved in such decisions. Even, they ultimately decide whether to implement it or not. The goal of a thesis like this one is to give the deciding authorises the best information possible to base their decisions on.

This report aims to advise about a system which gives cyclists double priority during rain. More people should be encouraged to cycle instead of taking the car, which has multiple benefits. Firstly, it decreases the emission of greenhouse gasses. Secondly, cyclists tend to run a red light more often in wet conditions. Giving more priority reduces red-light running, and thus increases safety. Lastly, it lowers the pressure on the road network, which would reduce congestion and delay. Critics are not positive about this system. They argue that if prioritising cyclists works in wet weather, it certainly works in dry weather. Such a system can thus be implemented without measuring rain since it does not dependent on weather conditions. A rain sensor is then completely unnecessary and a waste of money. This hypothesis was tested by using the model. It was run during dry as well as wet conditions. The results show that the critics are right. The conditions are just as favourable in dry as well as wet conditions. Emissions of CO_2, particulate matter and delay of other traffic is the same, or lower in dry compared to wet conditions Even, sometimes it works better during dry weather. Next, it was calculated before that the system would only be active for 4.9% of the time. The impact of the system can be increased when it is used in any weather condition. Thus, 100 % of the time. As a result, the system is still enabled during wet conditions, meeting the stated goals to increase safety, reduce greenhouse gas emissions and spatial scarcity. But is also enabled in the dry, encouraging people who previously used motorized vehicles to take the bicycle in these conditions. The same goals related to reducing emissions and solving spatial scarcity are then achieved. The safety however is not likely to be increased, since people are more patient during these conditions. Implementing the system in any condition has also some other advantages. Rain has not to be detected, making a rain sensor redundant. The result is that neither the rain sensor has to be purchased nor the data processed and sent to the iVRI via the MOTIS server. Removing these operations reduces costs and makes it easier to implement. The system can also be disabled more quickly without wasting many costs when it does not work as intended due to unforeseen circumstances. Thus, in conclusion, giving cyclists more priority without a rain sensor is cheaper, easier to implement and more effective.

Still, it has not been concluded yet whether the system is an improvement to the current, default circumstances at the intersection. Firstly, it was analysed before that the system performs much better during lower intensities, like during off-peak hours. Motorized traffic is intentionally slowed down when cyclists are given more priority, as concluded from the model. Waiting times and emissions initially increase as a result. The emissions are compensated when 2 or more people change modes per hour during the off-peak hours. This is quite a low number. As discussed in section 9.4, it is difficult to determine how many people actually switch. It is likely, however, that more than two people switch. The probability of switches is lower however because cyclists using the intersection travel long distances. It was concluded before that the average travel distance is around 9 kilometres. The effect of more priority is therefore less compared to small distances. Also, cycling is not the preferred mode for such distances. Switching is then less likely. The system would therefore perform better at intersections in the build-up area where trips are shorter. Next, the waiting times cannot be compensated. It was calculated that the additional lost time costs approximately 2,351.70[4] € per year. The overall costs caused by delay are around 282,207.00[5] € per year at the intersection. This means that the costs increases by 0.83 percent, which is a small difference. For these expenses, safety is increased, one solution for spatial scarcity is provided and greenhouse gas emissions are likely to be lowered. Further, the system is also easier to implement. It can also be removed quickly with little costs. Because of the discussed reasons, it seems that implementing the system which prioritizes cyclists twice per cycle in any weather condition during off-peak hours has positive consequences.

[4] Using the values as shown in figure 20 and by assuming that it rains 7.3 % of the time, as calculated in section 5.1

[5] By using the values from the model and by taking into account delay between 7:00 and 18:00

11. Discussion

A system that gives cyclists more priority during the rain was investigated in this thesis. Many topics were considered to reach a conclusion. Different methods were used for this purpose. The validity of these methods is first elaborated upon in this chapter. Input data, mathematical processes and assumptions are considered. Some recommendations for future research are discussed in the second part of this chapter.

Much data was used in this research. It is therefore important that the input data is correct. Also referred to as garbage in, garbage out; the results are most definitely useless if the input is wrong. This is most likely not the case in this study, as almost all data was not collected personally, but by reliable sources. First, the weather data to calculate the weather conditions at the intersection was gathered by the KNMI, the Dutch national weather institute. Second, the loop data to find traffic intensities were collected and partly processed by a traffic engineer at the province of Overijssel. Further, the parameters of the traffic control system in the model were defined by using a document called "Traffic light control specification". This document was created by the designer of the intersection himself. Input data that was calculated personally were the parameters that change during rain. However, multiple reliable papers were used to establish them. Due to the discussed reasons, it is unlikely that there are major errors in the used input data.

The input data is used to calculate several aspects. Firstly, it has been calculated how often it rains at the intersection. The results showed that it rained 7.32 % of the time. Literature states that it rains around 7.5% of the time (Keuning, 2014). The used method is therefore most likely correct. The accuracy of the used traffic model is a lot harder to access due to several reasons. The main problem is that there is no data available to compare the results to. All kinds of data collected from the model, like travel times, emissions and more are not available from its real-life counterpart. The only gathered data from the real intersection is from the moment I personally visited it. Queues of waiting cars seem similar to the ones in the model. However, this data is not representative nor reliable. It is therefore difficult to validate the model. The advantage of a traffic model is that it uses software, which has been thoroughly and repeatedly validated. Therefore, the model is expected to provide accurate output when correct input data has been used. It was concluded that it is unlikely that there are major problems in the input data. The results should therefore be reliable. The situation can also be simulated in other programmes. The results should be similar. Imprecision could occur because of some simplifications. The most influential one is the simplification of the iVRI. The iVRI is a very fluid system in real life. Phases and cycles can easily be adapted corresponding to traffic demand. It is unfeasible to mimic this behaviour in a model. Simplifications have thus been applied. Firstly, the same order of phases is used. The movements in a phase are also fixed. The duration of each phase is still fluid, like in real life. The system to give cyclists priority is also fairly similar. The chosen simplifications decrease the accuracy of the model somewhat. It is expected that the difference is bigger during low intensities. This is because phases are skipped more frequently and adjusted during these low intensities. The results should still be realistic. Subsequently, I have worked for the first time with XML files, Python and SUMO during this thesis. I have learned the basics about how to use them. I did encounter multiple problems, which did delay some processes. Using more advanced processes was certainly possible with a bit more experience. This would most probably increase the precision of this research. But still, I believe that this assignment certainly meets the requested level of complexity and accuracy.

Other research has also been carried out. Similar projects were investigated. Precipitation detection methods were also studied. For both, it was concluded that information on the internet was not sufficient enough for this research. E-mails have therefore been sent to relevant parties to collect more information. Around 20 e-mails were sent during this thesis to relevant municipalities, companies and manufacturers. Most people were really helpful and shared useful knowledge, which has improved this report. Sending e-mails was also a time-consuming practice. Sometimes you get ignored, redirected or answered after 4 weeks. As a result, some processes have taken longer than planned. Conclusions and result were sometimes altered during the thesis when new information arrived. This made it sometimes a bit difficult to move on to the next stage. But in the end, there was enough time to complete this research properly. Lastly, there were some points where I did not exactly get the information as requested. As a result, some details are missing here and there. But still, I got plenty enough information to create an accurate picture.

Finally, some future research appeared during this thesis. First, data analysis was conducted to investigate how traffic intensities are affected by wet weather in The Netherlands. A reliable conclusion could not be made because of limited data. Only information during a month at one intersection was considered. Further, other sources were conflicted about the effects. It could therefore be useful to further investigate the relationship between intensities and weather conditions. This also allows the infrastructure to be more efficiently optimised for wet conditions. The conducted data analysis in this report could be expanded by using data from a larger timespan at multiple intersections in the country.

Next, some data necessary for this investigation was not available. For instance, it was assumed in section 4.2.4 that the average trip distance of people using the intersection is 9 kilometres. This number was used for further calculations, which creates inaccuracy. Accuracy could be improved if the average cycling distance was actually investigated. This could be achieved by holding a questionnaire, or by voluntary tracking GPS. Further, it is unknown how many people switch from motorized vehicles to cycling due to the proposed system. Its exact effects could therefore not be calculated. It was only assumed that it was likely that more than two people would switch per hour. This information could be acquired by using the same questionnaire as stated earlier. But now people are asked whether they would switch. A different possibility is to use a traffic demand model.

12. Advies

Het doel van deze opdracht is om advies te geven over het implementeren van regengroen op de kruising N737/N342. Met regengroen wordt er aan fietsers tijdens regen meer voorrang gegeven. Hierdoor zouden meer mensen de fiets in plaats van de auto moeten nemen wat meerder voordelen heeft. Ten eerste wordt de uitstoot van broeikasgassen verminderd. Ten tweede hebben fietsers de neiging om vaker door rood licht te rijden in natte omstandigheden. Meer voorrang verlenen vermindert het door rood licht rijden en verhoogt dus de veiligheid. Ten slotte vermindert het de druk op het wegennet, waardoor de congestie en de vertragingen afnemen. Er is geprobeerd met zo veel mogelijk aspecten rekening te houden om tot een zo goed mogelijk advies te komen. Zo is er bijvoorbeeld onderzocht hoe regengroen op 5 andere kruispunten in Nederland is toegepast. Ook is er gebruikt gemaakt van een verkeerskundig model welke de effecten ervan op het kruispunt simuleert. De resultaten en conclusies van het onderzoek zijn in dit hoofdstuk verwerkt tot advies. Het advies bestaat uit twee delen. In het eerste deel wordt er advies gegeven met betrekking tot regengroen op het kruispunt zelf. In het tweede deel wordt er advies gegeven over regengroen in het algemeen.

12.1 Plaatsgebonden advies

Regengroen is zeker niet onomstreden, sommige verkeerskundigen bekritiseren het. Deze zeggen dat als het meer voorrang geven aan fietsers werkt tijdens natte omstandigheden, wanneer het drukker is, dan moet het zeker werken tijdens droge omstandigheden. Dan is een regensensor niet nodig. Het model bevestigd dit. De uitstoot van CO_2, fijnstof en de vertraging van het overige verkeer is hetzelfde, of lager in droge omstandigheden in vergelijking tot natte. Ten tweede wordt er met regengroen maar 7.3 % (hoeveel % van het jaar het regent) van de tijd meer voorrang aan fietsers gegeven. Dit kan verhoogd worden tot 100% wanneer fietsers meer voorrang krijgen in elke weersomstandigheid. Hierdoor worden de doelen tijdens nat weer nog steeds gehaald. Bovendien wordt er nu tijdens droog weer ook bijgedragen aan de meeste doelen. Als er voorrang gegeven wordt ongeacht de weersomstandigheden hoeft een regensensor niet geïnstalleerd en geïntegreerd te worden. Er hoeft alleen een aanpassing gedaan te worden in de regelsoftware van de IVRI. Hierdoor is dit goedkoper en makkelijker te implementeren. Wegens de besproken redenen is het niet aan te raden om regengroen toe te passen op de kruising N737/N343. In plaats hiervan kunnen fietsers voorrang geven worden in elke weersomstandigheden.

Bij deze uitvoering krijgen fietsers vanaf de drukste twee richtingen twee maal voorrang per cyclus. Deze twee richtingen zijn van het westen (Hengelo) naar het oosten (Oldenzaal), en andersom. Verder blijkt dat het niet ingezet moet worden tijdens spitsuren, omdat wachttijden te veel toenemen. Fietsers meer voorrang geven verhoogd reistijden voor gemotoriseerd vervoer waardoor CO_2 uitstoot en voertuigverliesuren toenemen. De extra uitstoot wordt gecompenseerd wanneer mensen de fiets nemen in plaats van de auto. Het is uitgerekend dat twee mensen per uur de overstap moeten maken tijdens daluren om de extra emissies te compenseren. Het is realistisch dat dit gehaald wordt, waardoor het systeem bijdraagt aan verlaging van CO_2 uitstoot. Zoals gezegd neemt het aantal voertuigverliesuren iets toe. Het is verwacht dat de gemiddelde reistijd voor auto's met 0.36 tot 0.76 seconden toenemen, wat bijna niet merkbaar is. De kosten van de extra voertuigverliesuren bedraagt ongeveer € 2.351,70[6] per jaar. Dit is 0.83% van de totale kosten door vertraging op het kruispunt.

Wegens de beschreven resultaten raad ik het aan om fietsers vanaf de twee drukste richtingen twee maal voorrang te geven tijdens daluren in elke weersomstandigheid. Ten eerste is dit systeem makkelijk te implementeren omdat er enkel veranderingen in de regelsoftware van de IVRI moet

[6] Wanneer het tijdens daluren tussen 9:00-16:00 gedurende weekdagen en het weekend gebruikt wordt.

worden gedaan. Verder draagt het bij aan verlaging van CO_2 uitstoot, verhoogd het de veiligheid en vermindert het de druk op het wegennet. De kosten door vertraging is maar met 0.83% verhoogd, wat bijna niet te merken is. Als laatste kan het systeem ook heel makkelijk uitgeschakeld worden wanneer het tegen de verwachting niet werkt. Er zal dan niet geld verspilt worden aan fysieke infrastructuur, zoals een regensensor.

12.2 Algemeen advies

Regengroen kan dan wel niet nodig zijn op de kruising N737/N342, het kan wel op andere plekken van pas komen. Daarom wordt er nu advies gegeven over regengroen in het algemeen.

Het doel van regengroen is om mensen aan te sporen om te gaan fietsen. Meestal wordt het niet zelfstandig geïmplementeerd, maar maakt het deel uit van een groep maatregelen. Hierdoor is het effect groter. Verder is de slagingskans erg afhankelijk van de omstandigheden. Ook kunnen andere maatregelen beter presteren. Hierdoor is het niet aan te raden om het op een bepaalde plek in te voeren zonder van te voren onderzoek te doen. Zo werkt het bijvoorbeeld niet goed tijdens drukke omstandigheden, zoals eerder al was vermeld. Ook geeft het waarschijnlijk betere resultaten wanneer het binnen de bebouwde kom is geïmplementeerd. Dit komt omdat de reisafstanden hier lager zijn. Hierdoor zijn mensen sneller geneigd om vanaf de auto naar de fiets over te stappen. Verder is het berekend dat het ongeveer 7.3% van de tijd regent in Nederland. Dus 7.3% van de tijd kan gebruikt gemaakt worden van regengroen.

Om regengroen te implementeren moet regen op de één of andere manier gedetecteerd worden. Er zijn verschillende soorten systemen die in staat zijn om dit te doen. Zo is een infrarood sensor[7] het meest accurate en kosteneffectieve sensor. Deze is ook al op meerdere kruispunten in Nederland gebruikt. Het nadeel van de infrarood sensor is dat het vrij oud is. Hierdoor is het wat ongemakkelijk om deze voor moderne iVRI's te gebruiken. Dit komt omdat iVRI's gebruik maken van internet om gegevens te versturen en ontvangen. De uitgang van de infrarood sensor is een analoog signaal. Dit signaal moet dus verwerkt worden en gestuurd worden via 4G naar een server. Hierdoor kan er gekozen worden voor een duurdere, maar moderne regenstation, welke dit proces makkelijker maakt. Het weerstation geeft ook mogelijkheden om andere aanpassingen in de toekomst te implementeren. Bijvoorbeeld door fietsers bij een lage temperatuur meer voorrang te geven.

[7] https://www.thiesclima.com/en/Products/Precipitation-Electrical-devices/?art=794

13. Advice

This assignment aims to advise about a system that gives cyclists more priority during rain at a signalized intersection. This should cause more people to take the bike instead of the car which has multiple benefits. Firstly, it decreases the emission of greenhouse gasses. Secondly, cyclists tend to run a red light more often in wet conditions. Giving more priority reduces red-light running, and thus increases safety. Lastly, it lowers the pressure on the road network, which would reduce congestion and delay. The rain is detected by a rain sensor. It was tested at the intersection between the N737 and N342. As many things as possible were taken into account to create the best possible advice. Firstly, similar systems implemented in The Netherlands were investigated. Also, a traffic engineering model has been used to simulate the effects on the intersection. The results and conclusions have been used to create advice. This advice consists of two parts. The first part is particularly about implementing it on the intersection N737/N342. The second part is about the system in general.

13.1 Location-specific advice.

The proposed system is not undisputed. Some relevant traffic engineers criticise it. They say that if giving cyclists more priority is effective during wet conditions when it is busier, then it should certainly be effective during dry conditions. The system is then unnecessary. The model confirms this. The emissions of CO_2, particulate matter and the delay to other traffic are the same or lower in dry conditions compared to the wet. Second, cyclists are given the extra priority only 7.3 % per year. This can be increased to 100% if cyclists are given more priority in any weather condition. As a result, the targets are still met during wet weather. In addition, most goals are now also contributed to during dry weather. Cyclists are more patient in dry conditions so that no real contribution to safety is made when it is not raining. If priority is given regardless of weather conditions, no rain sensor needs to be installed and integrated. Only a modification needs to be made in the control software of the IVRI. This makes it cheaper and easier to implement. It is not advisable to apply it at the intersection N737/N343 due to the discussed reasons. Instead, cyclists may be given priority in all weather conditions.

In this implementation, cyclists from the busiest two directions receive priority twice per cycle. These two directions are from the west (Hengelo) to east (Oldenzaal), and vice versa. It further appears that it should not be used during rush hours as queues increase too much. Giving cyclists more priority increases travel times for motorized transport which results in higher CO_2 emissions and waiting times. The extra emissions are compensated when people take the bike instead of the car. It has been calculated that two people per hour must make the switch during off-peak hours to compensate for the extra emissions. Realistically, this will be achieved. So, the system contributes to reducing CO_2 emissions. As mentioned above, the number of vehicle loss hours increases slightly. It is anticipated that the average travel times increase by 0.36 to 0.76 seconds, which is hardly noticeable. The cost of the additional time lost is approximately €2,351.70 per year. This is 0.83% of the total cost due to delay at the intersection.

Because of the results described, I recommend giving cyclists priority from the two busiest directions twice during off-peak hours in any weather condition. First, this system is easy to implement because it only requires changes in the control software of the IVRI. Furthermore, it contributes to the reduction of HANS emissions, increases safety and reduces pressure on the road network. The cost due to delay is only increased by 0.83%, which is hardly noticeable. Finally, the system can also be switched off very easily if it does not work as expected. No money is then wasted on physical infrastructure, such as a rain sensor.

13.2 General advice

The system may not be necessary at the intersection N737/N342, but it can be useful at other places. General advice is therefore provided.

The purpose of the system is to encourage people to start cycling. Usually, it is not implemented independently but is part of a group of measures. The effects are therefore greater. Furthermore, the chance of success depends very much on the circumstances. Also, other measures may perform better. Therefore, it is not advisable to implement it at a certain location without doing research beforehand. For example, as mentioned earlier, it does not work well during busy conditions. It is also likely to give better results when implemented in built-up areas. This is because travel distances are lower here. As a result, people are more likely to switch from the car to the bicycle. It has also been calculated that it rains about 7.3% of the time in the Netherlands. It can thus be used 7.3 % of the time.

Rain requires to be detected in some way to implement it. Different systems are able to do this. For example, an infrared sensor is the most accurate and cost-effective sensor. It has already been used at several intersections in the Netherlands. The disadvantage of the infrared sensor is that it is quite old. This makes it somewhat awkward to use for modern iVRI's. The output of the infrared sensor is an analogue signal, while the iVRI uses a cellular network (4G). The signal must therefore be processed and sent via 4G to a server. This makes it possible to choose a more expensive, but modern rain station, which makes this process easier. The weather station also provides opportunities to implement other adjustments in the future. For example, giving cyclists more priority when the temperature is low.

14. References

Abdi Kordani, A., Rahmani, O., Abdollahzadeh Nasiri, A. S., & Boroomandrad, S. M. (2018). Effect of Adverse Weather Conditions on Vehicle Braking Distance of Highways. *Civil Engineering Journal*, *4*(1), 46. https://doi.org/10.28991/cej-030967

Australian Government. (2021, April 29). Greenhouse effect. Retrieved from https://www.environment.gov.au/climate-change/climate-science-data/climate-science/greenhouse-effect

Billot, R., El Faouzi, N. E., & De Vuyst, F. (2009). Multilevel Assessment of the Impact of Rain on Drivers' Behavior. *Transportation Research Record: Journal of the Transportation Research Board*, *2107*(1), 134–142. https://doi.org/10.3141/2107-14

Bureau of Meteorology. (2017, June 9). How does a weather radar work? - Social Media Blog - Bureau of Meteorology. Retrieved from http://media.bom.gov.au/social/blog/1459/how-does-a-weather-radar-work/

Celis-Morales, C. A., Lyall, D. M., Welsh, P., Anderson, J., Steell, L., Guo, Y., . . . Gill, J. M. R. (2017). Association between active commuting and incident cardiovascular disease, cancer, and mortality: prospective cohort study. *BMJ*, j1456. https://doi.org/10.1136/bmj.j1456

Cleantech Regio. (2017, November 1). Primeur: fietsers in de regen krijgen eerder groen - Cleantech Regio. Retrieved from https://www.cleantechregio.nl/nieuws/446-cleantech-regio-geeft-fietsers-bij-slecht-weer-vaker-voorrang

Cools, M., Moons, E., & Wets, G. (2010). Assessing the Impact of Weather on Traffic Intensity. *Weather, Climate, and Society*, *2*(1), 60–68. https://doi.org/10.1175/2009wcas1014.1

CROW. (2019, September). *Stappenplan iVRI Handreiking voor wegbeheerders*. Retrieved from https://www.crow.nl/downloads/pdf/verkeer-en-vervoer/verkeersmanagement/verkeersregelinstallaties/stappenplan-ivri

CROW Fietsberaad. (2007, November 20). Fietsers in de regen krijgen vaker groen - Fietsberaad. Retrieved from https://www.fietsberaad.nl/Kennisbank/Fietsers-in-de-regen-krijgen-vaker-groen

CROW fietsberaad. (2017, October 30). Verkeerslicht ziet de bui al hangen - Fietsberaad. Retrieved from https://www.fietsberaad.nl/Kennisbank/Verkeerslicht-ziet-de-bui-al-hangen

CROW Fietsberaad [powerpoint]. (2007). Regengevoelige VRI's Oosterhout, Holtroplaan-Europaweg. Retrieved from https://www.fietsberaad.nl/getattachment/Kennisbank/Regengevoelig-verkeerslicht/Oosterhout.pdf.aspx?lang=nl-NL&ext=.pdf

De Haas, M., & Hamersma, M. (2020, October). Fietsfeiten: nieuwe inzichten. Retrieved from https://www.fietsberaad.nl/getattachment/8eb0c037-4766-43f8-8a13-220c4acbb87e/KiM-brochure-Fietsfeiten-def.pdf.aspx?lang=nl-NL&ext=.pdf

Denchak, M. (2021, February 19). Paris Climate Agreement: Everything You Need to Know. Retrieved from https://www.nrdc.org/stories/paris-climate-agreement-everything-you-need-know

Es, M., & Slütter, M. (2019, April 24). Fietsen in cijfers. Retrieved from https://www.fietsersbond.nl/ons-werk/mobiliteit/fietsen-cijfers/

Evans, R. (2020, March 11). Pollution from tire wear 1,000 times worse than exhaust emissions. Retrieved from https://www.tiretechnologyinternational.com/news/regulations/pollution-from-tire-wear-1000-times-worse-than-exhaust-emissions.html

Fick, M. (2020, March). *Specificatie verkeerslichtenregeling*. Hengelo, Nederland: Provincie Overijssel.

Fondriest. (n.d.). Weather Stations - Weather - Products. Retrieved 10 June 2021, from https://www.fondriest.com/products/weather/weather-stations.htm

Gall, J. (2014, February 20). Where RWD, AWD, and FWD Vehicles are Sold in the U.S. [Infographic]. Retrieved from https://www.caranddriver.com/news/a15366192/differential-distribution-where-rwd-awd-and-fwd-vehicles-are-sold-in-the-u-s-infographic/

Gemeente Groningen. (2012, October 11). De leden van de raad van de gemeente Groningen te GRONINGEN. Retrieved from https://gemeenteraad.groningen.nl/Documenten/Collegebrieven/Evaluatie-regensensor-Oosterbrug.pdf

Harms, H. J. (2008, March). *Fietsvriendelijke verkeersregeling Evaluatie onderzoek*. Retrieved from https://www.fietsberaad.nl/CROWFietsberaad/media/Kennis/Bestanden/Rapportage%20evaluatie%20FieVRI_20080318.pdf?ext=.pdf

Harms, L., & Kansen, M. (2018, March). Fietsfeiten. Retrieved from https://www.kimnet.nl/binaries/kimnet/documenten/brochures/2018/03/16/fietsfeiten/Fietsfeiten_ebook.pdf

Hasselerharm, M. (2020, October 23). Het blijft wennen op supermoderne kruising van Frans op den Bult bij Hengelo. Retrieved from https://www.tubantia.nl/hengelo/het-blijft-wennen-op-supermoderne-kruising-van-frans-op-den-bult-bij-hengelo~abcc2208/

Hogema, J. H. (1996, December). *Effects of rain on daily traffic volume and on driving behaviour*. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a320664.pdf

Hoogendoorn, S. P. (2021). *Traffic Flow Theory and Simulation*. Retrieved from https://ocw.tudelft.nl/wp-content/uploads/Reader_ct4821.pdf

Hranac, R., Sterzin, E., Krechmer, D., Rakha, H., & Farzaneh, M. (2006, October). *Empirical Studies on Traffic Flow in Inclement Weather*. Retrieved from https://ops.fhwa.dot.gov/publications/weatherempirical/weatherempirical.pdf

Huang, L. X., Isaac, G. A., & Sheng, G. (2012). Integrating NWP Forecasts and Observation Data to Improve Nowcasting Accuracy. *Weather and Forecasting*, *27*(4), 938–953. https://doi.org/10.1175/waf-d-11-00125.1

Huijskes, P. N. M. S. (2015, November). *Standaard applicatie specificatie verkeersregelinstallaties*. Retrieved from https://www.tenderned.nl/tenderned-web/aankondiging/detail/documenten/document/92828f630ab0fdb1aefbdc7d744abb67/pageId/D909C/huidigemenu/aankondigingen/map/a07276e21d21f0aa1f17d8c8878733d0/akid/6e356515dc1c1adf1a13f231b781caae/da/false/actie/aa274b487977199c90ed89bf7fb5b3adf319e66f5d0d86ee89d634f7ec8ea825b560366cc6cb9e9ed68ee310df42c04f1cc1862341c2128997415317b39e2617b100d520d07b4e25519806451311da19/cid/746147;jsessionid=B43BDDD1A5389A9AFEF3AFF64131438C.node7

Innovadis. (2020, October 8). N737: De slimste weg van Nederland loopt door Twente. Retrieved from https://www.twente.com/global-goals/9-industry-innovation-and-infrastructure/n737-de-slimste-weg-van-nederland-loopt-door-twente

Janssen, W. (2019, October 15). Hoe werkt de neerslagradar? Retrieved from https://www.weerplaza.nl/weerinhetnieuws/weerweetjes/hoe-werkt-de-neerslagradar/5657/

Jonkeren, O. (2020, March). *De invloed van het weer op de personenmobiliteit*. Retrieved from https://www.kimnet.nl/publicaties/rapporten/2020/03/02/de-invloed-van-het-weer-op-de-personenmobiliteit

Kennisinstituut voor Mobiliteitsbeleid. (2019, November). *Mobiliteitsbeeld 2019*. Retrieved from https://www.kimnet.nl/publicaties/rapporten/2019/11/12/mobiliteitsbeeld-2019-vooral-het-gebruik-van-de-trein-neemt-toe

Keuning, M. (2014, April 22). In de regen vaker groen voor fietsers. Retrieved from https://www.trouw.nl/nieuws/in-de-regen-vaker-groen-voor-fietsers~bab523de/?referrer=https%3A%2F%2Fwww.google.com%2F

Klemann, B., & Simons, M. (2017, January 30). Regelkundig beheer: Hoe bereik je je doelgroep? Retrieved from https://www.vialis.nl/dynamics/modules/SFIL0200/view.php?fil_Id=6349

KNMI. (2020). KNMI - Uurgegevens van het weer in Nederland. Retrieved from https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens

KNMI. (n.d.). KNMI - Hoe werkt de neerslagradar van het KNMI? Retrieved 17 May 2021, from https://www.knmi.nl/kennis-en-datacentrum/achtergrond/neerslagradar-knmi-uitgebreide-toelichting

Kyte, M., Khatib, Z., Shannon, P., & Kitchener, F. (2001). Effect of Weather on Free-Flow Speed. *Transportation Research Record: Journal of the Transportation Research Board*, *1776*(1), 60–68. https://doi.org/10.3141/1776-08

Lammel, G., & Graßl, H. (1995). Greenhouse effect of NOX. *Environmental Science and Pollution Research*, *2*(1), 40–45. https://doi.org/10.1007/bf02987512

McClusky, B. (2014, December 24). How Adverse Weather Affects Fuel Economy | Freightliner Trucks. Retrieved from https://freightliner.com/blog-and-newsletters/how-adverse-weather-affects-fuel-economy/

Ministerie van Economische Zaken en Klimaat. (2019, June 27). Partnership Talking Traffic voor slimmer verkeer met behulp van data. Retrieved from https://www.nederlanddigitaal.nl/initiatieven/partnership-talking-traffic

mobiliteitsplatform.nl. (2020, September 12). Maakt iVRI de verwachtingen waar? Retrieved from https://www.mobiliteitsplatform.nl/artikel/maakt-ivri-de-verwachtingen-waar

Nationale Regenradar. (n.d.). Nationale Regenradar. Retrieved 14 June 2021, from https://nationaleregenradar.nl/

Openstreetmap.org. (2021). Openstreetmap. Retrieved from https://www.openstreetmap.org/#map=12/52.2500/6.8395

Polizeiliche verkehrsunfallaufnahme. (2012, June 22). Geschwindigkeiten und Bremswege. Retrieved from https://web.archive.org/web/20120622045505/http:/www.unfallaufnahme.info/uebersichten-listen-und-tabellen/geschwindigkeiten-und-bremswege/index.html

Prinsen, L. (2012, October 30). Regensensoren: van de regen in de drup? Retrieved from https://www.verkeerskunde.nl/blog/regensensoren-van-de-regen-in-de-drup

Provincie Overijssel. (2017a, December 13). Uitwerking Innovatiesessie van 13 december 2017 in Enschede. Retrieved from http://docplayer.nl/126596445-Uitwerking-innovatiesessie-van-13-december-2017-in-enschede.html

Provincie Overijssel. (2017b, December 21). Ambitie Document. N737: De innovatieroute. Retrieved from http://docplayer.nl/105977577-Ambitie-document-n737-de-innovatieroute.html

Rakha, H., Zohdy, I., Park, S., & Krechmer, D. (2010, December). *Microscopic Analysis of Traffic Flow in Inclement Weather*. Retrieved from https://vtechworks.lib.vt.edu/bitstream/handle/10919/55094/matfiw.pdf?sequence=1

Ridder, J., Kok Ra, D. A., Heldring, T., Rooijen, D. L., Zon, D. C., & Veer, D. A. (2020, June 30). Fietsvriendelijke kruispuntenOnderzoeksrapport. Retrieved from https://publicaties.rekenkamer.amsterdam.nl/fietsvriendelijke-kruispuntenonderzoeksrapport/

Ritchie, H., & Roser, M. (n.d.). Emissions by sector. Retrieved 22 March 2021, from https://ourworldindata.org/emissions-by-sector

RIVM. (2018, November 19). Fijnstof | RIVM. Retrieved from https://www.rivm.nl/fijn-stof

Rottier, J. P. (2017, October 31). Verkeerslicht ziet wanneer slecht weer nadert. Retrieved from https://www.verkeersnet.nl/fiets/24705/verkeerslicht-geeft-fietser-eerder-groen-slecht-weer/?gdpr=accept

RTL Z How it's done. (2020, January 21). RTL Z How it's Done - Innovatieroute N737 - Strukton Civiel. Retrieved from https://www.youtube.com/watch?v=_5tPat4-ix8

Rubio, A. I. (2015, December 2). Lange files door regensensor voor fietsers. Retrieved from https://www.ad.nl/rotterdam/lange-files-door-regensensor-voor-fietsers~ada42c0f/

Smith, B. L., Byrne, K. G., Copperman, R. B., Hennessy, S. M., & Goodall, N. J. (2003, July). *An investigation into the impact of rainfall on freeway traffic flow*. Retrieved from https://engrxiv.org/9xnzc/download?format=pdf

Strukton. (2019). Aan de slag op de Innovatieroute N737. Retrieved 10 March 2021, from https://strukton.maglr.nl/strukton_s_world_q3_2019/n737

Strukton Civiel [@struktonciviel]. (2020, October 24). Het is nu nog even wennen, maar in een drukke ochtend- en avondspits biedt het vooral voordelen. [Facebook Post]. Retrieved from https://nl-nl.facebook.com/struktonciviel/photos/pb.181090435254529.-2207520000../3675208352509369

Thies Clima. (2008a, June 27). Precipitation monitor. Retrieved from https://www.biral.com/wp-content/uploads/2014/09/5.4103.10.xxx_.pdf

Thies Clima. (2008b, June 27). Precipitation Sensor. Retrieved from https://www.biral.com/wp-content/uploads/2014/09/5.4103.20.xxx_.pdf

Tijssen, B. (2016a, March). *Wachtrij- en verliestijdmeting Boezemlaan-Paradijsbrug*. Rotterdam, Nederland: Groen licht verkeersadviezen.

Tijssen, B. (2016b, June). *Wachtrijmeting Boezemlaan-Paradijsbrug*. Rotterdam, Nederland: Groen licht verkeersadviezen.

Tissink, A. (2020, November 11). Zelflerende wereldprimeur voor Twentse weg. Retrieved from https://www.cobouw.nl/infra/nieuws/2020/10/op-de-n737-hoort-de-kruising-het-verkeer-al-lang-van-te-voren-aankomen-101280973?_login=1

Treiber, M., Kesting, A., & Thiemann, C. (2012). *Traffic Flow Dynamics*. New York, United States: Springer Publishing.

Van Willigen, R. (2019, July 30). Nieuwe N737 tussen Enschede en Deurningen begint vorm te krijgen. Retrieved from https://www.tubantia.nl/enschede/nieuwe-n737-tussen-enschede-en-deurningen-begint-vorm-te-krijgen~a26d2c244/

Voerknecht, H. (n.d.). De wegen slibben dicht. Hoe komt CROW tot die conclusie? Retrieved 22 March 2021, from https://www.crow.nl/kennis/bibliotheek-verkeer-en-vervoer/kennisdocumenten/de-wegen-slibben-dicht,-hoe-komt-crow-aan-die-info

Wapstra, L. (2016, June). *The performance of rainfall nowcasts from the Nationale Regenradar for extreme-event rainfall and runoff prediction : A quantitative analysis using FEWS and 3Di* (Master thesis). Retrieved from http://dspace.library.uu.nl/handle/1874/346401

What-when-how.com/. (n.d.). Calculation of Maximum Acceleration, Maximum Tractive Effort and Reactions for Different Drives (Automobile). Retrieved 6 May 2021, from http://what-when-how.com/automobile/calculation-of-maximum-acceleration-maximum-tractive-effort-and-reactions-for-different-drives-automobile/

Wikipedia. (2021, May 28). Weather radar. Retrieved 10 June 2021, from https://en.wikipedia.org/wiki/Weather_radar

Xu, F., He, Z., Sha, Z., Zhuang, L., & Sun, W. (2013). Survey the impact of different rainfall intensities on urban road traffic operations using Macroscopic Fundamental Diagram. *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, 664–669. https://doi.org/10.1109/itsc.2013.6728307

Appendix

Appendix A: rain intensity calculations

The KNMI, which is the Dutch meteorological institute, provides data about the weather in the Netherlands. This information can be downloaded from their website. They provide measurements from 39 stations in the country. It has been chosen for this project to use data from the Twenthe station since it is the closest to the intersection. It is located around 2-3 kilometres away from the intersection. Data can be downloaded in 10-year timespans. It has been chosen to use the timespan 2011-2020 since it provides the most recent data. The data is provided in a text file, which has been transferred to an Excel document. The information is provided on an hourly basis. This means that there are around 24*365*10=87600 rows of data. All kinds of factors, like wind direction, atmospheric pressure, humidity, solar radiation and many more are issued per hour. There are 22 factors in total. Most of these factors are not important for this study and have been removed from the document. Only information related to precipitation has been kept, which are two factors:

The first one shows the duration of the precipitation, which is indicated per 0.1 hours. For example, a value of 4 means that it has been raining for 40% of the time during that hour. This parameter is identified in this section by DP_f

The second one is the hourly sum of the precipitation in 0.1 mm/hour. A value of 4 means that a sum of 0.4 mm of precipitation has fallen during that hour. This parameter is identified in this section by SP_f.

This data has been processed in multiple ways. Firstly, the information about the duration of precipitation has been translated to minutes, which has been done by using the next equation:

$$DP_m = DP_f * 6 \tag{3}$$

This parameter shows how many minutes it has been raining each hour. This causes for example that a value of 3 (which shows that it has been raining for 30%) is translated to 18 minutes. The found value can easily be used to calculate how many minutes it has been dry by subtracting it from 60. This value is indicated by DD_m.

The intensity of the precipitation is essential for this research. The SP_f does not show the average intensity, only the summed amount. It has rained for example for 30 minutes ($DP_f = 5$) with a summed intensity of 1.5 mm (SP_f =15). This means that 1.5 mm of precipitation fell in these 30 minutes. The intensity in mm/hour during these 30 minutes can be calculated by using the next formula:

$$I_{mm} = \frac{DP_f}{SP_f} \tag{4}$$

This would mean that it rains with an intensity of 15/5 =3 mm/hour during these 30 minutes. The two calculated variables I_{mm} and DP_m can be used to state the following: It has rained during hour x for DP_m minutes with an intensity of I_{mm} mm/hour.

Table 10 shows the different precipitation levels again. The aim is to calculate how many % of the time each level occurs per year.

Table 10: Precipitation categories

Rain	Precipitation rate in mm/hour
Light rain	<0.5
Moderate rain	0.5-4
Heavy rain	4-8
Very heavy rain	>8

This is firstly be achieved by adding a column for each precipitation level. Each of these columns shows how many minutes it has rained within that level per hour. Using the previous example: it rained for 30 minutes with an intensity of 3 mm/hour. This means that the number 30 is filled in the column with the level of moderate rain. The other three columns show 0. Only one of the four columns can show a number higher than 0 per row. The other 3 show 0. The values in the columns are calculated by using the next equations:

$$if\ I_{mm} \leq 0.5, \text{ then } T_{light\ rain} = DP_m\ , else{:}\ T_{light\ rain} = 0 \tag{5}$$
$$if\ 0.5 < I_{mm} \leq 4, \text{ then } T_{moderate\ rain} = DP_m\ , else{:}\ T_{moderate\ rain} = 0 \tag{6}$$
$$if\ 4 < I_{mm} \leq 8, \text{ then } T_{heavy\ rain} = DP_m\ , else{:}\ T_{heavy\ rain} = 0 \tag{7}$$
$$if\ I_{mm} > 8, \text{ then } T_{very\ heavy\ rain} = DP_m\ , else{:}\ T_{very\ heavy\ rain} = 0 \tag{8}$$

The values in each column can be summed up per year to see how many minutes each level occurred. These values can then be used to calculate how many percent each category occurs per year. The equation for this is shown below. The total number of minutes in a year is $\sum T_{minutes}$.

$$P_{level} = \frac{\sum T_{level}}{\sum T_{minutes}} * 100 \tag{9}$$

The results per year are shown in Table 11. The values for each year can be summed up to find out how much percent of the time it rains per year, which is shown in the last column. The yearly values are also averaged over the last decade, which is shown in the last row. Literature shows that it rains on average 7.5% of the time in the Netherlands (Keuning, 2014). The value calculated in this report (7.32) is very close to this number. It can therefore be concluded that the described method in this section is likely to be correct.

Table 11: Occurrence frequency of each precipitation category over the last decade

Year	Light	Moderate	Heavy	Very heavy	Sum
2011	2.30	3.18	0.23	0.13	5.84
2012	2.50	4.76	0.28	0.04	7.58
2013	2.73	4.36	0.21	0.13	7.43
2014	2.57	4.18	0.32	0.08	7.15
2015	2.89	5.42	0.31	0.05	8.67
2016	2.89	4.22	0.23	0.08	7.42
2017	2.56	5.19	0.31	0.06	8.12
2018	2.10	3.54	0.18	0.06	5.89
2019	3.08	4.63	0.27	0.07	8.05
2020	2.41	4.43	0.21	0.04	7.09
Average	2.60	4.39	0.25	0.08	7.32

One last step is taken. The goal of this step is to create a formula that can be used to calculate how much percent per year precipitation occurs with an intensity higher than x mm/hour. So, you can say: it rains with an intensity higher than *y* mm/year x % of the time. Logically, the higher the intensity, the lower the probability gets.

The process to achieve this is firstly the same as before but now with equal intervals of 0.5 mm/hour instead of the 4 levels. The first interval is 0-0.5 mm/h, the second one 0.5-1 etc, until 6.5 There are 13 intervals in total. The last interval is for intensities higher than 6.5 mm/h. How much percent per year each interval occurs could be calculated with the same process as used before. So, there are 13 columns now, but there can still only be a number higher than 0 in one column per row. All the other columns show 0. The equations are:

$$For: x = [0, 0.5, 1 ,, \ldots,, 6] \tag{10}$$

$$if\ x < I_{mm} \leq x + 0.5, \text{ then } T_x = DP_m, else:\ T_x = 0 \tag{11}$$

And:

$$if\ I_{mm} > 6.5, \text{ then } T_{6.5} = DP_m, else:\ T_{6.5} = 0 \tag{12}$$

Then again, equation 7 can be used to calculate how many percent each category occurs per year. The results are shown in Table 12. The cumulative values show how much percent of the time it rains with an intensity equal to or higher than the indicated intervals. So, the first value sums up the averages 0+, the second one 0.5+ and so on. The first cumulative value in the interval 0-0.5 also shows how much percent of the time it rains on average since it takes all intervals into account. It can be seen that the average is different from before (7.23 vs 7,32) which suggests that somewhere something does not go entirely right. I have failed however to detect where this occurs. The difference between both values is minimal (1.2 %) and therefore believe that this is not a big problem.

Table 12: Occurrence frequency of each interval over the last decade

Intensity	**0-0.5**	**0.5-1**	**1-1.5**	**1.5-2**	**2-2.5**	**2.5-3**	**3-3.5**	**3.5-4**	**4-4.5**	**4.5-5**	**5-5.5**	**5.5-6**	**6-6.5**	**6.5+**
2011	2.30	1.51	0.67	0.40	0.25	0.12	0.14	0.03	0.04	0.08	0.05	0.01	0.03	0.15
2012	2.50	2.17	1.16	0.51	0.44	0.13	0.18	0.07	0.06	0.09	0.05	0.02	0.02	0.09
2013	2.73	1.96	1.07	0.55	0.28	0.20	0.14	0.07	0.06	0.09	0.02	0.01	0.01	0.14
2014	2.57	1.68	0.98	0.51	0.39	0.17	0.18	0.12	0.16	0.04	0.03	0.07	0.00	0.11
2015	2.89	2.27	1.46	0.65	0.49	0.26	0.13	0.09	0.08	0.06	0.04	0.04	0.00	0.13
2016	2.89	1.98	0.98	0.48	0.40	0.12	0.12	0.06	0.09	0.04	0.04	0.02	0.02	0.10
2017	2.56	2.46	1.09	0.70	0.45	0.22	0.17	0.05	0.12	0.05	0.03	0.04	0.01	0.10
2018	2.10	1.68	0.71	0.45	0.30	0.11	0.10	0.08	0.09	0.05	0.03	0.01	0.00	0.07
2019	3.08	2.24	1.13	0.52	0.30	0.15	0.14	0.08	0.10	0.02	0.03	0.04	0.02	0.14
2020	2.41	1.89	1.13	0.57	0.31	0.17	0.15	0.08	0.07	0.04	0.02	0.02	0.01	0.09
Average	2.60	1.98	1.04	0.53	0.36	0.16	0.15	0.07	0.09	0.05	0.03	0.03	0.01	0.11
Cumulative	7.23	4.63	2.64	1.61	1.07	0.71	0.55	0.40	0.33	0.24	0.19	0.15	0.13	0.11

Lastly, a trendline is put through the cumulative values. It has firstly been decided to use a polynomial trendline since it is not a linear relationship. A polynomial trendline with 4 orders has been chosen since it offers the best trade-off between precision and complexity. The cumulative values with the trendline are shown in Figure 19. It is visible that the trendline has an upward slope between 5.5-6. This is not desirable since the values go down as shown in Table 12 above. The trendline is therefore not reliable anymore after an intensity of around 5 mm/hour.

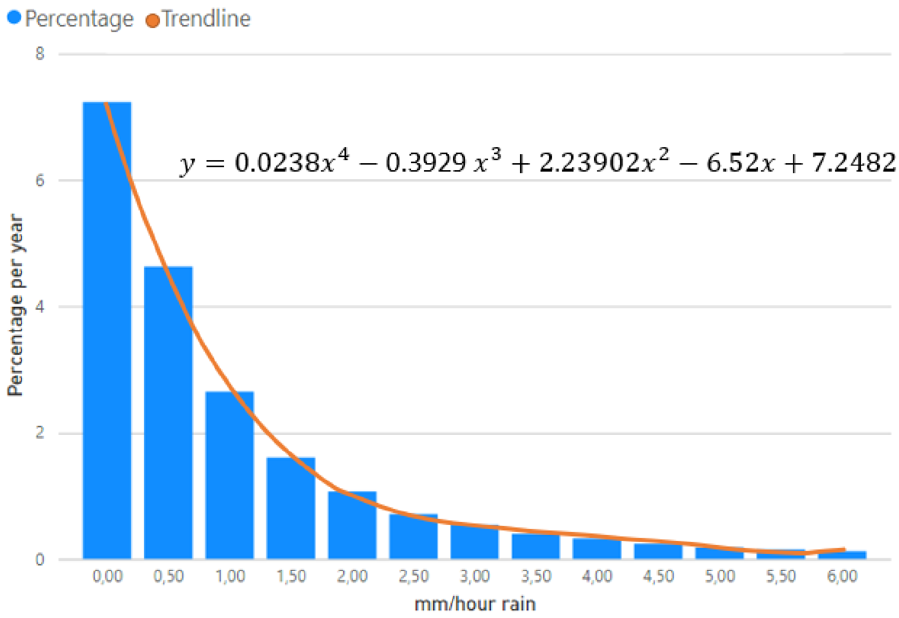

Figure 19: Occurrence of different precipitation categories over the last 10 years

Appendix B: weather detection devices.

The different detection devices are first introduced. It is explained how they work, their strengths and weaknesses and how they could be implemented.

B.1.1 A radar system & Nowcast

The first way to measure rain is by using radar. A radar is a system that sends out electromagnetic waves and detects objects by reflected radiation. A rain radar sends out bursts of radio waves with the speed of light. Most services use a wavelength of 3.75-7.5 cm with a frequency of 4-8 GHz (Wapstra, 2016). Water droplets in the air reflect these waves back to the radar. The radar collects the characteristics of the returning waves which can be transferred into information about the precipitation. The difference in time between the outgoing and incoming wave indicates the position of the precipitation. The strength of the returning waves indicates the type and strength of the precipitation. The gathered information can be fed into models and algorithms to make forecasts (Bureau of Meteorology, 2017). A forecast is a prediction of what the weather will be like in the future. The accuracy of radar systems is affected by noise caused by aeroplanes, birds, windmills smoke and more. Complex algorithms are therefore used to filter this noise. The range is also limited because of the curvature of the Earth. The gathered information is also calibrated by using rainfall stations on the surface.

Figure 20: A typical rain radar. (Wikipedia, 2021)

The information from radar systems can also be used to make Nowcasts. Nowcasting is a technique in which the current movement of meteorological phenomena is extrapolated for a few hours in the future. It is based on current and recent weather observations (Wapstra, 2016). They are reliable for lead times up to 6 hours, and already lose accuracy after three hours (Huang et al., 2012). The lead time is the difference in time between when the nowcast is released and the time for which it is given. The nowcast images are solely based on radar images. They are thus not calibrated by the aforementioned ground level rainfall stations. The output of a precipitation Nowcast is a map with intensities in millimetres per timeframe. It has the same or a lower resolution than the radar system.

The radar system which is used in the Netherlands is called the Nationale Regenradar (NRR). It uses 6 different radar systems, of which 2 located in the Netherlands, 2 in Belgium and 2 in Germany. Each one of them has a radius of 150 kilometres and has a resolution of 1 km^2 (KNMI n.d.). Information is available every 5 minutes. It is calibrated by using 35 automatic rainfall stations from which hourly information is used. The 24-hour radar images are calibrated by using 330 rainfall gauges which are operated by volunteer work. Nowcasting is also performed in the Netherlands by the NRR. Nowcasts are made every 5 minutes for two hours in the future. Detailed information about nowcasts currently and from the past can be obtained by using the platform Lizard (Nationale Regenrada, n.d.). Wapstra (2016) studied the accuracy of these Nowcasts. It was concluded that the performance of nowcasting decreases for longer lead times. Extreme precipitation events were also underestimated. Further, nowcasting is more accurate for bigger precipitation areas than smaller ones (Janssen, 2019). This is because smaller ones move more erratically which makes it harder to predict their path.

The information from nowcasts is integrated into one traffic control system in The Netherlands, which is located in Apeldoorn. A partnership with multiple parties was created to achieve this. The involved companies were the municipality of Apeldoorn, Royal HaskoningDHV, Infoplaza, and Nelen & Schuurmans (CROW Fietsberaad 2017). This shows that creating a system that can transfer information from a rain radar to a traffic control system is quite complicated and thus expensive. This makes the system also depends on the outside connections. Interruptions may occur which can paralyze a part of the system.

The gathered data about the most recent nowcast must be sent to the iVRI at the intersection N737/N342 when the radar system is chosen. It was discussed in section 4.1.3 that the data should be sent to the MOTIS server to achieve this. A partnership similar to the one discussed above must therefore be established. Some of these partners create the nowcast, the others process the information and send it to the intersection. The companies which regulate the intersection and MOTIS server should be included in the partnership.

B.1.2 An infrared U-shaped sensor

Next, an infrared sensor could be used to detect the precipitation. This sensor in the shape of a U, as shown in Figure 21. Infrared radiation is emitted within the U. The radiation is interrupted when water drops fall through it. There are two different versions of the system. The first one is called: "the precipitation monitor". This system is able to detect when it rains. It works as a kind of light switch. It only gives a signal when rain is detected. It transmits a signal when a certain number of incidences occur. An incidence is when a rain droplet or other matter falls through the sensor and are detected. It can be set manually by how many incidents between 1 and 15 it is going to transmit (Thies Clima, 2008a). Other stuff like bird droppings can cause incidences. It is recommended to use a higher number of incidences to avoid that the system transmits while it does not rain. Another parameter that is manually set is the switch-off delay. The switch-off delay is how long it takes before the system shuts down after the last incidence. It has a range of 25 to 375 seconds, with steps of 25. The sensor cannot measure the intensity of the rain. (Thies Clima, 2008a).

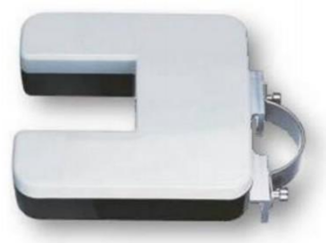

Figure 21: An infrared sensor (CROW Fietsberaad [powerpoint], 2007)

The second system is able to do this, which is the precipitation sensor. This sensor looks almost identical but behaves differently. It does not work as a switch like the precipitation monitor. Instead, it has an electrical output. The electrical current of the output is dependant on the intensity of the rain. The output ranges from 4 to 20 mA. It has a quasi-logarithmic scale (Thies Clima, 2008b). The sensor does thus not calculate the intensity itself. An external appliance, like a Programmable Logic Controller (PLC), could be used for this. The PLC should be physically connected to the sensor. It was discussed in section 4.1.3 that weather information must be sent to the MOTIS server to implement it at the discussed intersection. Preferably through 4G. So, a module should be integrated into the PLC which sends out information by using 4G.

The precipitation monitor and sensor are less complex than the radar system. It can be installed at the intersection itself. A limited number or no external parties at all are involved, which also makes it a cheaper solution. The sensor could be susceptible to fraud. People could make the sensor detect water when it is not raining. Therefore, these sensor is located on a high place when it is used to combat such fraud. But also, which cyclists are really going to take a bucket of water with them to get some extra green time? A weakness is that the sensor could only detect precipitation when it is already happening. So it does not know if it is going to precipitate in the future, as the radar system. It is expected that the precipitation sensor is more accurate than the radar system. This is because the precipitation sensor gathers information on the intersection itself. With nowcasting, information is extrapolated with a resolution of at least 1 km^2. A local shower may not be detected. The precipitation sensor also measures the intensity of the precipitation more accurately for the same reason.

The chosen rain sensors are applied to several intersections, like the one in Oosterhout (CROW Fietsberaad [powerpoint], 2007) These sensors are quite old, however, since they originate from 2008. Applying such an old system to a brand new modern traffic control system may not be the way to go. This is further elaborated upon when different systems are compared to each other.

B.1.3 A weather station

A weather station could also be used to measure precipitation. A weather station is a system that does not only detect precipitation but also other properties. Such properties could be the temperature, wind speed, humidity and more, dependent on the system. The precipitation is most of the time measured by a rain gauge, which is a cylinder that catches rain. A weather station mostly consists of two parts. The station itself with all the sensors and devices is the first part. This one is placed outside in a suitable place. The second part is the receiver unit, which collects and processes the collected data. There are currently weather stations on the market which are able to send out data by using 4G. These are a lot more modern than the earlier mentioned infrared sensors. The only problem is that these send their data towards designated weather databases and websites. An alteration should therefore be made to make sure it sends information to the MOTIS server.

Figure 22: A weather station (Fondriest, n.d.)

The weather station can only detect when it rains and the intensity of it. It can not detect if it is going to precipitate in the future, like the radar. The station is not susceptible to fraud if it is placed in an inaccessible place. A weather station could be installed at the intersection itself, for maximum accuracy. Information from a nearby station could also be used because it could be cheaper. Using a different station makes it a bit more complicated since it belongs to a different party. The gathered data is also more imprecise since there is some distance between the intersection and the weather station. A weather station has been installed at an intersection at Grave. Cyclist also receive more green time when the temperature is below 10 degrees at this location (Harms, 2008).

B.2 An overview

Three different ways to measure rain have been elaborated upon in the previous sections. Each method has its strengths and weaknesses. These have been put in Table 13.

The accuracy condition shows how accurate the systems can measure the location and intensity of the precipitation. The complexness shows how difficult it is to gather and implement the data in the traffic control system. The more complex the system, the lower the score it gets. The costs show approximately how expensive each system is. The lower the price the higher the score. The nowcasting capability shows if a system could detect if it is going to rain in the future. This information could be used to give cyclists more green time just before it is going to rain. Lastly, the other parameters conditions show if the system can measure other parameters like wind speed and temperature. The first four conditions have been indicated with symbols. The sequence of the symbols is from positive to negative: ++,+.+-,-,--. The last two conditions are yes/no questions.

Table 13: Strength and weaknesses of different weather detection methods

Condition	**Radar system**	**Infrared sensor**		**Weather station**	
		Sensor	Monitor	At location	Other location
Accuracy (more +, better accuracy)	+	+ +	- -	+ +	+ -
Fraud (more +, less fraud)	+	+-	+-	+-	+-
Complexness (more +, less complex)	- -	+	+	+	+ -
Cost (more +, less cost)	- -	+-	+	-	+-
Use nowcasts	Yes	No	No	No	No
Other parameters	Not directly	No	No	Yes	Yes

Some systems are better than others, regardless of how they are going to be used. They must be able to measure the intensity of the precipitation because the system is enabled above 0.5 mm/hour. The precipitation monitor is not able to measure this and is thus not useful. Next, it was shown that the weather station could be used in two different ways; installing a new one at the intersection itself or using an already existing one nearby. Using an existing one is less accurate and more complex. However, it is cheaper since you do not have to buy a new one. It is however expected that the difference in cost does not outweigh the negatives. The weather station on location is therefore a better solution compared to using an existing one.

So, only three possibilities remain; the radar system, the weather station at the intersection and the precipitation sensor. Each of these devices has their strength and weaknesses. No option is clearly superior. Multiple scenarios are therefore investigated to discuss which device is the best in what conditions

B.3 Scenarios

Giving people more priority during rain at an intersection is a concept that could be implemented in various ways. These are elaborated upon in this section. It is also discussed which weather measuring systems is the most suitable for each scenario. This is based on the established criteria in the previous section. These criteria are also shown in table 5 with the corresponding scores for each system.

B.3.1 the switch

First, the easiest way is a switch principle. In this scenario, cyclists are given more priority when a certain threshold is reached. This threshold is defined by a certain rain intensity in millimetres per hour. It was defined in section 5.1 that this threshold is 0.5 mm/hour in this research. The best three precipitation measuring systems as concluded before can provide the necessary information. Therefore, a small multi-criteria analysis is held to conclude which system is the most suitable. Some of the criteria which were introduced in appendix B.2 are considered. The most important criterium is that the system should be able to accurately measure the intensity of the precipitation. The next category is complexness, why would you make it more complex than necessary? The last criterium is the cost, which is always important in most decisions. How each device scores according to the introduced criteria is shown in Table 14. The precipitation sensor scores the best, the difference is small however. The only distinction is caused by costs. Nevertheless, the infrared sensor is the best measuring device for the switch scenario. The switch scenario is already applied to the intersections in Rotterdam and Groningen, where the infrared sensor is also used.

Table 14: Multi-criteria analysis switch scenario

Condition	**Radar system**	**Infrared sensor**	**Weather station**
Accuracy	+	+ +	+ +
Complexness	--	+	+
Cost	--	+-	-
Total	**3-**	**5+**	**4+**

B.3.2 The predictor

In the next scenario, cyclists are also given priority when it rains just as in the "switch" scenario. Additionally, they are also given priority just before it is going to rain. This should ensure that people can arrive at their destination faster, which hopefully will mean that they will get less wet. The scenario which takes these two things into account is named "the predictor". Still, a certain threshold is needed to access when it rains enough. The same threshold of 0.5 mm/hour as used previously is used to activate the system. This scenario needs more information than the previous one. The previous one only needed one-dimensional data which shows if the threshold is currently reached yes/no. Now, the same data is needed, but over time. Thus, if the threshold is predicted to be exceeded in the next interval. This can only be achieved by nowcasting, which makes it automatically the best solution.

B.3.3 Intensity.

Giving cyclists more priority at regulated intersections influences the rest of the traffic. Logically, increasing green time for cyclists should reduce the green time for motorized traffic. This could increase the waiting times. It was shown in section 4.2.3 that this does not always happen. It mostly tends to occur during high intensities of motorized traffic. Therefore, it could be useful to take the intensity of this traffic into account when a rain friendly installation for cyclists is implemented. Such an extra parameter related to the intensity can be applied to both scenarios which were described before. This is because it is not important for this scenario how the weather is measured. The information which is necessary to estimate the intensities are already present in the traffic control system, which is based on detection loop data. Therefore, no additional systems have to be installed. Only a new programme has to be implemented in the traffic control system.

B.3.4 Multi-functional weather

The next scenario is the multifunctional one in which not only information about precipitation is taken into account, but also other variables related to the weather. Such variables could for example be the temperature. Such a system has already been implemented at an intersection in Grave. Here, cyclists receive more green time during colder conditions. The weather station would be the best weather measuring device for this scenario since it is the only one that is able to measure other weather-related factors like temperature, humidity etc. This scenario however is out of the scope of this project in which the focus is only on rain intensity. It would therefore be logical that the less expensive infrared sensor is preferred over the weather station, which is the only difference between them, as established in appendix B.3.1 However, other researches in the future may focus on the other properties. This is not a crazy thought, since the intersection is located on the innovationroute after all. Therefore, it could be useful that a device is placed at the intersection which has the capabilities to measure this. It costs a bit more money but could open the way for other projects in the future.

B.4 Conclusions

Four scenarios were introduced during the last section. Different rain measuring devices are more suitable than others, depending on the situation. This is because every device has its strength and weaknesses. The precipitation sensor is the most suitable when priority is given above a certain threshold. The radar system is the most convenient when priority is given just before it rains. Lastly, a weather station could be useful when other properties, like temperature are going to be considered in the future.

However, it is still unclear which measuring device should be installed at the intersection, as it has not yet been concluded which scenario is the most advantageous. This is going to be done now. Firstly, it was concluded in section 4.2.4 that the average travelling distance of cyclists using the intersection is around 9 kilometres. Cyclists take on average 30 to 45 minutes to cover this distance. The closest destination is on the left of the intersection, which is the north side of Hengelo. Still, the city centre of Hengelo is 5.9 kilometres away. The closest destination from the other three sides is at least 2.4 to 6.3 kilometres. The goal of the second scenario is to give cyclists priority just before it rains to ensure that they arrive at their destination before it rains. The long distances make this less plausible. Further, the radar system was quite expensive and difficult to implement. It seems therefore that the costs outweigh the benefits. It is therefore not recommended to use this scenario.

Further, it was concluded in section 4.2.3 that similar systems perform better under low traffic intensities than high intensities. It is useful to consider using the scenario which takes intensities into account. This is going to be done in this research. The system is going to be investigated during busy as well as quiet conditions. Advice is given based on the gathered information. This is elaborated upon further in this report.

Two scenarios remain: the one where priority is given after a certain threshold is reached, and the one where other weather factors are taken into account. It was concluded that the precipitation monitor is the best solution for the first scenario. The weather station was a close second. The only difference was caused by price. The weather station is the best solution for the second scenario. So, the weather station is more expensive but opens the way for potential new projects in the future. As discussed earlier, the intersection is placed on the innovationroute. This place is full of new exciting interventions. Maybe someone will investigate the effect of temperature or humidity on traffic. The weather station is then already there. The weather station is also way more modern than the sensor. I therefore believe that the weather station should be used because of the earlier mentioned reasons, even though it is more expensive. The difference in price does likely not exceed 1500 euros.

Lastly, it was concluded that the radar system is simply too difficult and expensive to implement for one intersection. However, the project may be scaled up. It is then applied to all intersections in, for example, the municipality, or province. If so, it may well be advantageous to use radar to send information to all these intersections instead of installing a physical sensor at each intersection. But this is out of scope for this research. It is also not practical to follow the advice of 1 student for such a large project.

Appendix C: Literature study Rain vs traffic

The literature study to investigate how certain parameters change in wet circumstances Is shown in this section.

It is first assumed that the MinGap does not change. It is therefore expected that people keep the same distance between the car in front while standing still for a traffic light for example. It is however likely that vehicles retain more distance to their predecessor whilst driving in the wet, which is also advised. This reduces the probability of crashes. As discussed, this gap between cars is defined by the MinGap + the headway. It is thus likely that the headway increases. This has also been confirmed by multiple studies. Firstly, a road section in Rotterdam was investigated during dry and rainy weather conditions. It was found that the average headway increased from 1.46 to 1.71 s, which is an increase of 14.62 % (Hoogendoorn, 2021, p. 97-98) Further, Rakha et al. (2010) researched the effect of all kinds of weather scenarios on traffic using data and models in America. The headways were also investigated. It was found that the headways on a three-lane road increased in a wet scenario increased with 9.7-17.6 %.

It is expected that the deceleration ability of vehicles decreases in the wet since there is less traction between the tyres and the surface of the road. It is firstly stated by the Polizeiliche verkehrsunfallaufnahme (2012) that the deceleration ability of a car on tarmac decreases from 7.5 to 6 m/s^2 in wet circumstances. This is a decrease of 20%. This source was also used by the simulation program SUMO, which is used in my study, to set the default variables for certain parameters. Next, Abdi Kordani et al. (2018) investigated the effect of adverse weather conditions on the safety of vehicles. They used a simulation process to calculate the braking distances of certain vehicles dependent on road conditions. It was concluded that the braking distances for normal cars increased by around 8.2 meters. This is a reduction in deceleration of 7.2-7.4 %. Treiber et al. (2012) state that the emergency braking capabilities of vehicles decrease from 10 to 6 m/s^2 in wet circumstances. This is a decrease of 40%. Logically, the acceleration ability of vehicles also decreases like the deceleration ability in wet circumstances. This is also caused by the reduction in grip between the tyres and the surface of the road. Next, the acceleration ability of a vehicle can be calculated by using equations. The used equation is dependant on the layout of the vehicle. It consists of multiple parameters related to the characteristics of a car and one other factor. This other factor is the coefficient of adhesion which quantifies the grip between the tires and the road surface. This factor decreases during rainy conditions from 0.6 to 0.4 (Abdi Kordani et al., 2018). It is expected that the other parameters remain constant. The change causes that the acceleration ability of a car decreases on average by 29.7 %. The exact calculations are shown hereafter.

Calculating the change in acceleration

The calculations in this section are based on what-when-how.com (n.d.).

The forces acting on a car are shown in the sketch below.

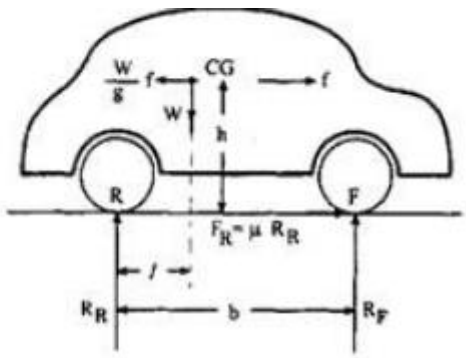

Figure 23: Forces acting on a car (what-when-how.com, n.d.)

In which:

μ	=	The coefficient of adhesion between the tyres and the road surface
f	=	The acceleration in m/s^2
R_f and R_r	=	The normal reactions at the front and rear wheels in N
b	=	The length of the wheelbase in m
h	=	The height of the centre of gravity from the road surface in m
l	=	The distance between the centre of gravity and the rear wheels in m

The acceleration of a front-wheel-drive car can be calculated by using the next formula:

$$f = \frac{\mu * l * g}{b - \mu * h} \tag{13}$$

The acceleration of a rear-wheel-drive car can be calculated by using the next formula:

$$f = \frac{\mu(b - l)g}{b - \mu * h} \tag{14}$$

The acceleration of an all-wheel-drive car can be calculated by using the next formula:

$$f = \frac{2 * \mu * l * g}{b - 2 * \mu * h} \tag{15}$$

The aim is to calculate by how much the acceleration changes between a wet and a dry scenario. The coefficient of adhesion is 0.6 on dry tarmac. It decreases to 0.4 during rainy conditions (Kordani et al 2018). All the other parameters in the formulas remain constant. The change in acceleration is calculated by changing the μ while keeping all the others constant. The values for these parameters are based on a random car and are as follows: $b = 2.75\ m$, $l = 1.6\ m, h = 0.85\ m$.

The three equations above are used to calculate the acceleration of all three types of vehicles for a dry and wet scenario. The results have been put in Table 15. The difference between them has also been calculated.

Table 15: Acceleration abilities in dry and wet conditions

	Dry: $\boldsymbol{\mu = 0.6}$	**Rain:** $\boldsymbol{\mu = 0.4}$	**Difference**
Front wheel drive	2.89	2.03	-29.7%
Rear wheel drive	3.02	1.87	-28.0%
All wheel drive	5	3.66	-26.7%

The goal is to obtain one number instead of 3. So, the differences have been multiplied by the occurrence probability of each vehicle type. In America[8], 54 % of all cars have front-wheel drive, 34 % all-wheel and 12 % rear wheel (Gall, 2014). This results in the following:

$$Total\ change = P_{rear\ wheel} * D_{rear\ wheel} + P_{front\ wheel} * D_{Front\ wheel} + P_{all\ wheel} * D_{all\ wheel} \quad (16)$$

$$= 0.12 * 0.280 + 0.54 * 0.297 + 0.34 * 0.267 = 0.285$$

Thus, the acceleration of a vehicle is 28.5% less in a rainy scenario compared to a dry scenario.

The literature study is continued.

Many studies have been performed which investigate the effect of weather conditions on traffic velocity. Almost all conclude that the velocity is negatively affected by rain. A first study which was performed in China combined traffic data with weather data to study said relation (Xu et al., 2013). It was concluded that rain reduced the speed by 9.7 %. Another study used the same approach to investigate the effects on a highway in Idaho, USA. Here, the speed decreased by 7.9% (Kyte et al., 2001). Next, a study was conducted which aimed to develop a better understanding of the impacts of weather on traffic flow (Hranac et al, 2006). The effects in Minneapolis, Saint Paul and Baltimore were examined. A distinction was made between all kinds of weather scenarios including heavy and light rain. Light rain decreased the velocity on the roads by -2 to -3.6 % while heavy rain decreased it by -6 to -9%. A study in France also investigated the effect of adverse weather conditions to make a step to better weather-responsive traffic management strategies (Billot et al., 2009). The information has been gathered from roads near Paris. Multiple parameters were investigated, including the velocity. It was found that the velocity decreases by 5.1 % in light rain and 10.88 % in moderate rain. Smith et al. (2003) studied the effect of rainfall at varying levels of intensity on capacity and speeds. Traffic and weather data were collected in Virginia, United States. It was concluded that the presence of rain decreased the speeds by 5-6.5 %, regardless of intensity.

Rainfall can also influence the intensities of motorized and cycling traffic. This relation however is more difficult to interpret. Motorized traffic can increase when people switch from slow transportation modes like cycling and walking. However, intensities can also decrease when people cancel trips because of the bad weather. A study carried out in Belgium investigated the effect of rainfall on traffic intensity (Cools et al., 2010). Data was gathered on three locations: a highway near the cities of Brussel and Hasselt and a road near the coastline. The relations were identified by using statistical correlation methods and a comprehensive model. It was concluded that weather conditions like cloudiness, wind speed and precipitation decreased the traffic intensity on all three locations. The intensities near the coast were more strongly affected by bad weather than the other two locations. It was therefore concluded that the impact of weather has a greater impact on leisure related traffic than on commuting traffic. Next, a traffic engineer of the municipality of Apeldoorn stated in an e-mail conversation that it was visible that traffic intensities increase during precipitation. He states that this occurs because people switch from cycling to motorized traffic data. Another study also investigated the same relationship (Hogema, 1996). Here, data was gathered from a highway in the Netherlands. The data showed that there was no significant relationship between traffic intensity and weather conditions. It was therefore concluded that rain does not cause a major shit towards the car. The above describes studies do not agree on the effect of rainfall on traffic intensities. One argues that it increases, another states that it decreases. Others see no significant correlation. This makes it not

[8] Unfortunately, a similar source about Europe, or The Netherlands could not be found.

possible to conclude how the intensities of motorized traffic change and by how much. These intensities are therefore not be changed in the model.

A study conducted by the Kennisinstuut voor Mobiliteitsbeleid (Dutch institute of knowledge for mobility policy) compiled all the available knowledge about traffic intensities in the Netherlands and Flanders by the means of a literature study (Jonkeren, 2020). Almost 20 relevant studies were brought together. All kinds of different factors were considered. It was first concluded that all 9 studies which investigated the effect of weather conditions on cycling agree that precipitation decreases bicycle traffic. Bicycle traffic is also dependant on other factors. It was noticeable that precipitation had a greater effect on intensities in coastal areas than inland areas. This is because the proportion of trips with a recreational purpose is higher near the coast than inland. Further, older people react more to adverse weather conditions than younger people.

Conclusions

The effect of precipitation on the relevant parameters was discussed in the last two sections. An overview has been shown in Table 16. All the discussed studies have been included.

Table 16: A literature review on the change of certain parameters during rain

Parameter	Source	Effect
Deceleration	Polizeiliche verkehrsunfallaufnahme, 2012	-20%
	Abdi Kordani et al., 2018	-7.2 to -7.4 %
Emergency Deceleration	Treiber et al., 2012	-40%
Acceleration	Equations	-28.5%
Time headway	Hoogendoorn, 2021	+14.62 %
	Rakha et al., 2010	+9.7 to +17.6 %.
Speed	Xu et al., 2013	-9.7%
	Kyte et al., 2001	-7.9%
	Billot et al., 2009	-5.1 to -10.9%
	Hranac et al., 2006	-2 to -9%
	Smith et al., 2003	-5.0 to -6.5%
Motorized traffic Intensity	This study	Inconclusive
	Cools et al., 2010	Decreased
	E-mail contact	Increased
	Hogema, 1996	No effect
Bicycle traffic intensity	Jonkeren, 2020	Negative

It has been decided to average the effects found for every parameter. This has firstly been done because all studies are not conducted in the same circumstances as those at the intersection which is investigated in this report. Thus no study is in particular better than any other. So averaging would give a better approximation of reality. Most studies have defined effects for multiple levels of precipitation. These levels are defined differently in every study. The model is only simulated for two weather scenarios; dry and wet. So, averaging all the different levels of precipitation would give a nice approximation of this one wet scenario. The averages have been shown in Table 17. The default values have also been put in that table. The found averages and default values are used to calculate the adjusted values for the parameters during precipitation.

Table 17: Changed parameters during a wet scenario

Attribute	Default value	Change	Adjusted value in rain
Minimal gap (m)	2.5	No change	2.5
Acceleration ability (m/s^2)	2.6	-29.7%	1.83
Deceleration ability (m/s^2)	4.5	-13.7 %	3.88
Emergency deceleration (m/s^2)	9	-40%	5.40
Average speed (km/h)	80	-7.4%	74.08
Time headway (sec)	1.5	+14.1%	1.71
Intensities	Differs	No change	

Appendix D: Data analysis to investigate the effect of rain on traffic intensities

Information about precipitation events and traffic intensities were used independently before. Now, a connection is made between both types of information. The aim of this is to investigate if traffic intensities are different when it rains compared to when it does not. Then, if a relation is noted, use the results for the simulation process.

Two operations must be taken before the data can be combined. First, the traffic data is from September 2020 while the weather data is from 2011-2020. The range of the comparison can therefore only be for September 2020. So, the information from this month is extracted from the extensive weather data file. Second, the weather data has an hourly interval while the traffic data has a 15-minute interval. The traffic data of 4 intervals have been summed up to solve this. The traffic intensities over all the lanes have been summed up. So, this one intensity number shows the intensity of the whole intersection.

The data has thereafter been separated for different scenarios, which are: weekend, weekdays and combined. This has been done since traffic is fundamentally different between the weekend and weekdays. The differences are mostly caused by the various reasons why people travel. The movements during the weekdays are mostly because of work. These movements are most of the time routine in which people have already pre-determined which mode of transport they are going to use. Weather conditions may not have a big influence on that. Movements at the weekends are mostly for recreational purpose. These trips may be more susceptible to weather conditions.

It is not possible to express the difference between the intensities during the dry and wet in absolute terms like vehicles/hour. This is because intensities are different over the day. This causes that differences during rush hours have a bigger impact on the results than differences during other times, which is not desirable. It is the intention that data from each hour of the day has the same impact on the results. So, the differences are expresses in relative terms by using percentages. How these relative values are calculated is shown in the equation below.

$$I_{relative} = \frac{I_{absolute} * 100}{I_{average}} - 100 \qquad (17)$$

Data between 1 and 5 a.m. is omitted since there is very little traffic during this time which makes the data unreliable. A comparison is made between the average intensities at each hour and the actual intensities. The average was established by averaging data from the whole month for each hour.

Then, the data has been divided in each scenario into two groups: relative intensities during the wet and relative intensities during the dry. This has been done by adding two columns to the sheet. The first one shows the intensity if it is dry, the second one when it is wet. There can thus only be one value in these two columns per row. The other does not show a value. Further, no data is filled in any column during 1-5 am since data is omitted between these times.

The following equations were used for this:

For the wet intensities:

$$if\ Hour > 5\ \&\ rain\ intensity > 0\ then{:}\ value = I_{relative}. \quad \text{Else: value} = \text{“ ”} \tag{18}$$

For the dry intensities:

$$if\ Hour > 5\ \&\ rain\ intensity = 0\ then{:}\ value = I_{relative}. \quad \text{Else: value} = \text{“ ”} \tag{19}$$

The values for both columns are then averaged. The first value shows the persentual change in intensities during dry weather. The second one shows the change in intensities during wet weather. These groups are compared to each other by a statistical method. Firstly, there is substantially more data during dry weather than wet weather since it rains only 7.32% of the time as concluded in section 5.1. Also, the variances of both groups are different. This causes that a normal T-test could not be conducted. Therefore, a special t-test is used, which is Welch's t-test. This test is more reliably in the described circumstances. The null hypothesis is that there is no significant difference between the intensities in the wet and the dry. The null hypothesis is rejected when a significant difference is found.

The t-test itself is performed using Matlab by using the next statement:

Result=ttest2(data1, data2, 'Vartype', 'unequal')

The results are shown in Table 18.

Table 18: Results of Welch's t-test

	Average	*StDev*	*Count*	*Test*
Weekdays				
WET	+0.73%	6.62	31	H0 not rejected
DRY	-0.06%	8.06	387	
Weekend				
WET	+13.16%	16.88	12	H0 rejected
DRY	-1.13%	23.96	140	
Combined				
WET	+4.20%	11.73	43	H0 rejected
DRY	-0.34%	14.13	527	

The table shows firstly that the null hypothesis is not rejected for the scenario that takes the weekdays into account. So, there is no significant difference between intensities in the wet compared to the dry. Next, the null hypothesis is rejected for the other two scenarios. This means that there is a significant difference between the intensities.

The results should be taken with a grain of salt, however. Firstly because there is not a lot of data. It only rained for 12 hours in the weekend scenario. This makes the test more susceptible to outliers, of which there are quite a few. Welch's t-test was used to detect if there is a significant difference. A few conditions must be met before this T-test can be used. The first one is that the data should be standardly distributed. The datasets with wet hours for the three different scenarios have been put in a histogram in Figure 24. It is visible that the dataset with wet hours during the weekend is certainly not standardly distributed. It is also questionable if the other two datasets with 31 and 43 point of data are standardly distributed.

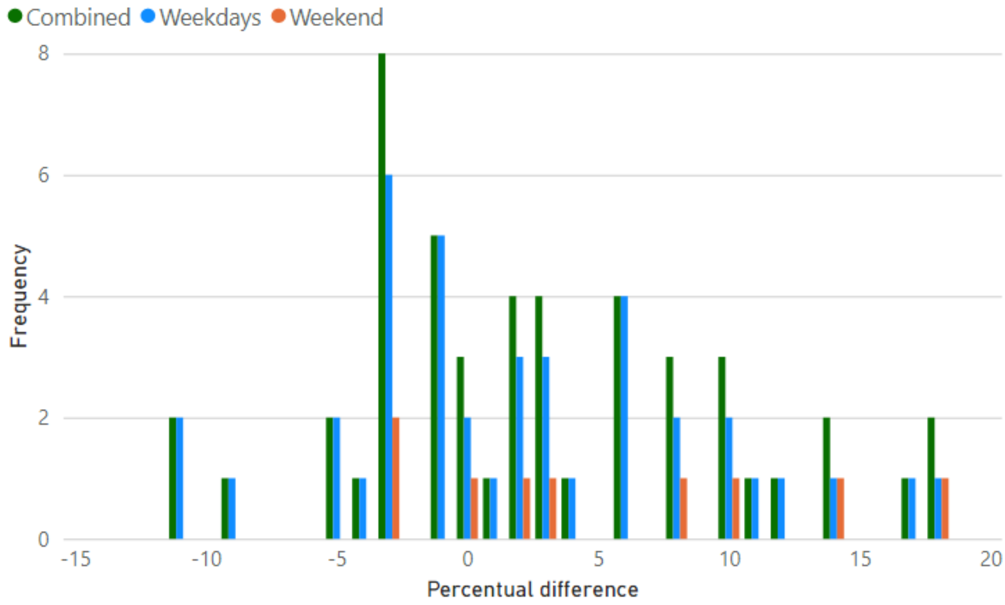

Figure 24: Spread of the percentual differences

Another condition is that the data should independent. It is also questionable if this is the case because the information from consecutive hours has been used. The circumstances from the last hour could influence the next.

Because of the discussed reasons, it has therefore be decided that the results are not reliable enough to process further in this research.

Appendix E: the model

The intersection N737/N342 has been modelled in SUMO. This model already existing before this project. It was created by other students. This version is used as a baseline for this project. A lot of parts had to be altered though. Two alterations were already discussed in the main report.

Multiple files are necessary to perform a simulation in SUMO. All files are written in XML. At first, is the route file. The road network itself is defined in this file. Traffic light systems, intersections, roads, and links between roads are considered. A network can be created in multiple ways. The first way is by using Netedit, which is a part of SUMO. Road networks can be manually created, customized and adjusted. The second way is by using OsmWebWizard, which allows downloading a certain network by using Open street maps.

The route file is the second one. Traffic which occurs in the model is defined in this file. First, vehicles are specified which appear in the model. The vehicles included in this study are cyclists, cars and trucks. Additional parameters could be assigned to each vehicle. An example of a vehicle definition is shown below.

```
<vType id="VrachtW" minGap="3.00" vClass="truck" color="red"/>
```

Now that the vehicles are defined, they can be placed in the model. There are multiple ways to achieve this. It has been done in this project by creating flows. A flow is a stream of vehicles. An example of a flow is shown below.

```
<flow id="ON" type="VrachtW" begin="0.00" departSpeed="22.20" end="3600.00"
number="52" from="-546921342" to="-6666901#3"/>
```

The name of the flow is firstly defined with “id”. Which vehicles appear in the flow is shown by type. The indicated type should match with the earlier mentioned vehicle definitions. Then, the time is defined with “begin” and “end”. This is the time between which the flow appears. The departure speed of vehicles in meters/second is shown by “departspeed”. Lastly, the travel direction of the flows is defined by the last two statements. The “from” reveals the origin of the flow and refers to the name of an edge. An edge is a section of road in the model. So, the flow starts at the beginning of this road. The end of the flow is defined by “to”, which also refers to the name of an edge. So basically it is stated for example that the vehicles in the flow ON travel from edge -546921342 to edge -6666901#3. The names are a bit awkward, but this does not matter much. The “from” and “to” roads do not have to be connected. The program automatically searches for the quickest possible route. There is one big problem with a flow, however, which is that the distance between cars in the flow is always the same. This is not realistic, since the distances differ in real life. An extra step has therefore been taken. A python script was used for this step which is automatically provided by SUMO. This script is called “Duarouter” and simply put, creates randomness in the flows.

Next, additional files are also available. All kinds of stuff could be defined in them. Only things that have been used are discussed here. The additional file in this study is only used to set up data collection. Detectors are defined in this file. Detectors collect data about vehicles like mean speed travel time etc. These are further elaborated upon in Appendix F.

The last file is the configuration file, which combines the earlier mentioned files. It also acts as the launcher of the simulation. The file is used to select which route, network and additional files are used for the simulation. The length of the simulation is also defined. An example of a configuration file is shown below.

```
<configuration>
    <input>
        <net-file value="network.net.xml"/>
        <route-files value="route.rou.xml"/>
         <additional-files value="detectors.add.xml"/>
    </input>
    <time>
        <begin value="0"/>
        <end value="3600"/>
        <step-length value="0.1"/>
    </time>
</configuration>
```

The simulation can then be started in multiple ways. The easiest way is by double-clicking on the file itself in a directory. It can also be called by using the command prompt. However, a third option is also possible which is used in this study. Here, the simulation is started by a python file. This option was chosen because it offers useful features which others do not have. One of these features is that it is used to collect important data, which is elaborated upon in Appendix F. The simulation is performed in a program called sumo-gui. The individual vehicles physically move through the network in this program.

An important thing to consider in a traffic simulation is randomness. Results could be different, depending on the arrival pattern of vehicles. The pattern is random and could be different with the same input values. The randomness is defined by a random number generator, which generates a sequence of random numbers. The value of a number is independent of the previous one and therefore cannot be predicted. A random seed is used to ensure that results are reproducible. In other words, using this parameter makes sure that anyone who re-runs the simulation gets the same outputs. One scenario is going to be simulated multiple times with different seeds. Seed 1 is used for the first simulation, seed 2 for the second one and so on.

Appendix F: Processing output of the model

As said, gigabytes of data can be extracted from the model. Take for example a look at the following website, in which all the possible output is listed:
https://sumo.dlr.de/docs/Simulation/Output/index.html.

The output should be used to calculate the introduced criteria as discussed in chapter 7. This section describes what data is used for this purpose and how it is processed. A section is created for each criterium

Travel times & time lost

First, multi-entry-exit detectors can be placed in the network. Such detectors consist of two main parts: the entry point and the exit point. These detectors gather all kinds of information about vehicles travelling between the entry and exit point. 16 detectors in total have been placed in the model for this study. 12 to gather information about each possible travelling direction of motorized traffic and 4 to gather information about cyclists. Both the entry and exit points are placed 150 meters from the intersection. So, each detector calculates the data for a travel distance of 300 m. The average travel times are calculated by the detectors. How much time on average is lost is also calculated. So, the average travel times and lost time is calculated for every travel direction. It was stated in section 7.2 that the aim is to summarize this information to provide a clearer overview

Therefore, averages have been calculated. Firstly, data about each arrival direction has been averaged. For example, vehicles arriving from the north can travel in 3 different directions: the east, west and south. Data from each of these directions are separately collected by 3 different detectors. Data of these 3 directions can be averaged to find information about vehicles arriving from the north, regardless of their direction. The next equation is used to achieve this:

$$F_t = \frac{F_1 * N_1 + F_2 * N_2 + F_3 * N_3}{N_1 + N_2 + N_3} \quad (20)$$

Were: F_t is the average from arrival point t. F_1, F_2 and F_3 the values for each destination. N_1, N_2 and N_3 the number of vehicles driving in each direction. There are 4 arrival points in total since it is a 4-way intersection. So, four averages are calculated. Lastly, these four values are used to calculate an overall average for motorized traffic over the complete intersection. The following equation is used for this purpose:

$$F_{intersection} = \frac{F_{west} * N_{west} + F_{east} * N_{east} + F_{north} * N_{north} + F_{south} * N_{south}}{N_{west} + N_{east} + N_{north} + N_{south}} \quad (21)$$

The values for F are the earlier calculated averages. The values for N are the total number of vehicles arriving to each direction. The same equation is also used to calculate the average for cycling traffic. The calculation of the average travel times is now complete. The calculations for lost time are not.

The calculated values for lost time are averages. So now it can be stated: on average, a vehicle travelling from the north to the east loses x seconds at the intersection. The goal however is to calculate how much time is lost in total. So, the average values are multiplied by the number of the vehicles, as shown in the equation below.

$$T_{lost\ total} = T_{average\ lost} * N_{vehicles} \quad (22)$$

The values for the total time lost are currently in seconds and are quite large. They are therefore translated to hours by dividing them by 3600.

The lost time is translated to costs. One lost hour is equal to a cost of 10 euros (Voerknecht, n.d.). The costs are firstly calculated per hour since the simulation also takes one hour. Then, they are calculated per year. The rush hours both last two hours a day. So the values are firstly multiplied by two. Rush hours only occur during working days. There are 261 working days per year. So, the values are multiplied by 261.

The off-peak hours last 7 hours per day. So, they are firstly multiplied by 7. The off-hours are both during weekends and weekdays excluding holidays, which are around 300 days. So, they are finally multiplied by 300.

Emissions

How much of certain substances is emitted at the intersection has also been calculated. The process to achieve this is elaborated upon in this section.

The raw data is firstly collected, which can be achieved by adding a new line to the 'additional file'. This line is as follows:

```
</e3Detector>
    <edgeData id="emissiondata" type="emissions" freq="4000"
file="data/edgeData.xml"/>
```

The frequency value defines how often data is calculated. A frequency of 4000 seconds is used to ensure that the data is calculated only once. This makes it easier to process the data. The "file" defines where the data is saved.

Data is collected for each edge. An edge is a piece of road in the network. An example of collected information is shown in Table 19.

Table 19: An example of emission output

begin	end	id	id2	SampledSeconds	CO2_abs	CO2_normed	CO2_perVeh
0	3600	emissiondata	R6554	8412.11	32920390	65152	80506.83

The first id is the name of the file. The second id (id2) is the name of the road section. The SampledSeconds shows the number of vehicles that are present on the edge/lane in each second summed up over the measurement interval. The co2_abs shows how much milligrams of $CO_2$is emitted on this edge during the complete simulation. The CO2_normed shows the CO_2 emissions during this interval normed by time and edge length in gram/kilometre/hour. Lastly, the CO2_perVeh shows the assumed CO_2 emissions in milligrams a vehicle would produce when passing the edge. The same values are calculated for fuel consumption, CO, HC, PM_x and NO_x.

The raw data has been processed. The aim is to calculate the emissions on the roads 75 m from the intersection. These roads consist of several edges. The edges on the east side or shown in Figure 25.

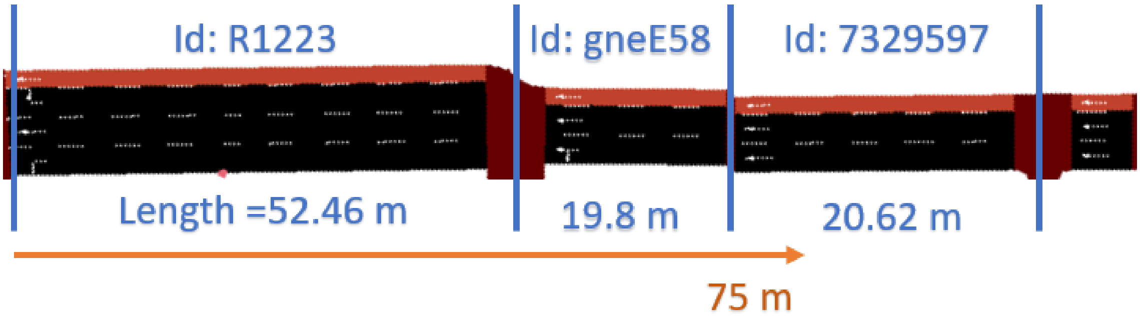

Figure 25: Edges on the east side of the intersection

Data from several edges should be used to calculate the emissions 75 meters from the intersection. First, the data from the first two edges can be summed up. The absolute values are used for this purpose. As shown in the figure, a bit of the last edge should be included to complete the 75m. This can be achieved by using the normed values. The normed values are indicated in g/km/h, while they should be in mg to add them to the other 2 values. g/km is the same as mg/m. So no correction should be conducted for this change. Then, the remaining distance should be multiplied by the normed value. This distance is calculated by subtracting the length of the other two edges from 75. The total emission on the east side of the intersection is thus:

$$CO2_{\,east} = CO2\_abs_{R1223} + CO2\_abs_{gneE58} + (75 - L_{R1223} - L_{gneE58}) * \, CO2\_normed_{7329597} \qquad (23)$$

The equation is also used to calculate the CO, HC, PM_x and NO_x emissions. Each road section is different, however. So, the equation is altered based on the characteristics of each one.

The emissions are calculated for the road sections to and from each side of the intersection, which are 8 different sections. This is visualised in Figure 26. Then, the values on each side of the intersection are summed up to create 4 values. Lastly, all the values are summed to show how much is emitted at the complete intersection.

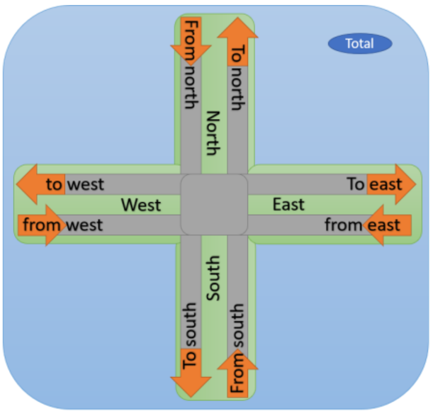

Figure 26: The summation of calculated emission values

Next, the global warming potential (GWP) is calculated. The equation introduced in section 7.3 is used for this:

$$GWP\ (CO_2e) = CO_2 + 31.5 * NO_x \tag{24}$$

The GWP is calculated to show the total amount of greenhouse gas emissions per hour on the intersection.

One of the goals of the cycle-friendly traffic system is to encourage people to cycle instead of taking the car. This should reduce the amount of emitted greenhouse gasses. However, motorized traffic has to wait longer at the intersection, because their green time has been cut to give more priority to cyclists. Longer waiting times ensure that emissions are increased. So, the emissions reduced by people cycling instead of taking the car should be higher than the amount emitted because vehicles have to wait longer to ensure that the proposed innovation is successful. This has been investigated. It has been calculated how much people should take the bike instead of the car to reduce the overall emissions.

To achieve this, it was first calculated how much $C0_2$ is saved by taking the bike instead of the car for one trip. Equation 24 is used for this. It was established in 4.2.4 that on average, one trip is around 9 kilometres long. Next, 150 grams of CO_2 and 0.2 grams NO_x are saved each kilometre (Harms & Kansen, 2018). So, the saved amount for each switch is:

$$= 9 * (150 + 31.5 * 0.2) = 1406.7\ g\ CO_2e$$

Lastly, the amount of extra emissions is divided by this number to calculate the number of trips necessary to compensate it:

$$n_{trips} = E_{extra}/1406.7 \tag{25}$$

Average Cycle time.

The average cycle time is how long each cycle of the traffic control system takes on average. It is ensured in the python script that the simulation time is saved when the end of a cycle is reached. This is achieved by the next statement:

```
if traci.trafficlight.getPhase("gneJ7") == 9:
    print(traci.simulation.getTime())
```

Phase 9 is the last phase. All the gathered values have been put in a file. The duration of each cycle can be calculated by subtracting the simulation time when the cycle finished from the simulation time when the previous cycle finished. This is indicated in the next equation. CT is the cycle time and ST is the simulation time.

$$CT_t = ST_t - ST_{t-1} \tag{26}$$

The duration of each cycle during the simulation is now calculated. The values are averaged to calculate the average cycle time.

Finally, the number of cycles in which the extra priority was used is calculated. This is achieved by introducing a counter in the python script. 1 is added to the counter when the extra priority is enabled. The python script used to achieve this looks like this:

```
count=0
…
```

```
if  traci.trafficlight.getPhase("gneJ7") == 31:
    count=count+1
```

Phase 31 is the phase in which the extra priority for cyclists is integrated.

The last step is to divide the count from the total number of cycles to see how much percent of the cycles the extra priority is used.

Comparisons

The previously explained parameters are calculated for many scenarios. These scenarios are shown again in Table 20.

Table 20: Scenarios

Type of Scenario	Condition 1	Condition 2	Condition 3
Traffic conditions	Morning rush hour	Afternoon rush hour.	Off-peak hours
Weather conditions	Dry	Wet	
Rain friendly system	Off (default)	On: 2 times priority	

The model was first used to calculate the default conditions. The default conditions are the three traffic conditions during dry weather. The same three traffic conditions were run hereafter but then in wet conditions. The results are compared to each other to investigate the effect of wet weather on traffic conditions. Relative changes are calculated. Thus, it can for example be stated that the waiting time for cars has increased by 5 % from dry to wet conditions. The next formula is used to calculate the relative changes:

$$C = \frac{100 * V_{wet}}{V_{dry}} - 100 \qquad (27)$$

C is the percentual change and V_{dry} is a parameter during dry conditions while V_{wet} is the same parameter but during wet conditions.

The same scenarios are run with the proposed system enabled to calculate its effect. The results are compared to the default scenarios. Absolute as well as relative changes are calculated. The absolute values are calculated by subtracting the value with the system enabled from the value when the system was not enabled. The relative values are calculated by the next equation:

$$C = \frac{100 * V_{enabled}}{V_{disabled}} - 100 \qquad (28)$$

Appendix G: Warmup-time and number of replicants

First, the warmup time is calculated. The Marginal standard error rule (MSER) has been used for this purpose. This rule calculates when a steady-state condition has been reached in the model. Steady-state conditions have been reached when the results are around the same average. The MSER aims to minimize the width of the confidence interval around the mean after the warm-up period. The formulas to calculate the warmup time are shown below.

$$MSER(i) = \frac{1}{(m-i)^2} \sum_{i=d+1}^{m} \left(Y_i - \bar{Y}(m,i)\right)^2 \qquad (30)$$

$$d = min(MSER(i)) \qquad (31)$$

Where:

- i = the current timestep
- m = total number of timesteps taken into account;
- Yi = mean of 5 replications of the average waiting time of one timestep;
- Y(m,i) = mean of the average waiting time data.

The MSER(i) is calculated for every time step (i). The timestep with the lowest value for the MSER(ii) defines the length of the warmup time. For example, the MSER is the lowest at timestep 500. The warmup length is then 500 seconds.

It has been decided to use the average velocity of all vehicles in the model to calculate the MSER. This is because the average velocity is initially high when vehicles are approaching the intersection. Then, the average velocity reaches a steady-state condition when the queues have become realistic at the traffic lights. A time step of 0.1 seconds is used. The results of the MSER are shown in Figure 27. The average velocity is indicated by the blue line. The MSER is indicated by the red line.

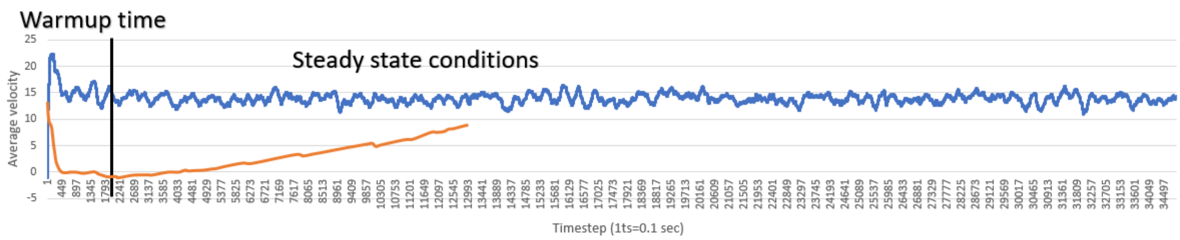

Figure 27: Calculating the warm-up time by using the MSER rule

The MSER is the lowest at timestep 2003, indicated by the black line. One timestep was equal to 0.1 seconds. So, the warm-up time is 0.1*2003=200.3 seconds. The total simulation lasts 3600 seconds. The warmup time is thus 200.3/3600*100 = 5.56 % of the simulation.

Now, the number of replications is calculated. The equation to do this is shown below.

$$n = \left(\frac{100 * S * t_{n-1,\frac{a}{2}}}{d * X}\right)^2 \quad (32)$$

<u>Where:</u>

n = The number of replications
S = The standard deviation
X = The mean
d = The percentage deviation of the confidence interval about the mean
$t_{n-1,\frac{a}{2}}$ = The value from the Students t-distribution
a = The confidence interval
n = The degrees of freedom

The values for the mean and standard deviation can be found by simulating the model a few times. Ideally, between 5-10 times. The degrees of freedom is equal to the number of simulations. The $t_{n-1,\frac{a}{2}}$ can be determined by using the confidence interval and degrees of freedom.

It has been decided to use the average travel times to calculate the number of replicants. The confidence interval is assumed to be 97.5%. Next, a d of 5% is assumed. This means that the true mean is within 95 and 105 % of the mean of the measurements. the model is simulated 10 times to estimate the mean and standard deviation of the travel times. $t_{n-1,\frac{a}{2}}$ is equal to 2.26 because of the chosen confidence level of 97.5 % and an n of 10. The results are shown in Table 21. The number of replicants is calculated for every travel direction.

Table 21: Number of replicants for each movement

	AVERAGE	ST DEV	d	$t_{n-1,\frac{a}{2}}$	n
CycleEW	82.78	3.96	5.00	2.26	4.70
CycleNS	86.60	2.56	5.00	2.26	1.79
CycleSN	84.71	2.53	5.00	2.26	1.83
CycleWE	90.20	3.04	5.00	2.26	2.32
EN	31.01	1.22	5.00	2.26	3.15
ES	39.17	1.13	5.00	2.26	1.71
EW	38.96	1.32	5.00	2.26	2.34
NE	42.38	1.64	5.00	2.26	3.06
NS	40.07	1.96	5.00	2.26	4.92
NW	40.60	0.97	5.00	2.26	1.16
SE	29.31	0.90	5.00	2.26	1.93
SN	40.56	1.22	5.00	2.26	1.85
SW	39.86	1.85	5.00	2.26	4.41
WE	39.71	1.23	5.00	2.26	1.96
WN	43.05	1.09	5.00	2.26	1.30
WS	30.49	0.67	5.00	2.26	0.98

It has been decided to chose the highest n to make sure that every outcome has the desired precision. The highest value is 4.92 for the direction NS. The number of replicants is therefore rounded up to 5.

Appendix H: Results

A quick note to avoid confusion; the point (.) in the numbers indicate decimals instead of thousands. So, the first value is 91.664, or 91.65 rounded up.

DEFAULT CONDITIONS

	Afternoon		**Morning**		**Off hours**	
	Dry	Wet	Dry	Wet	Dry	Wet
TRAVEL TIME	**Seconds**					
Average cycling	91.664	92.835	93.309	92.030	86.563	85.477
Average east	43.910	49.517	47.026	51.765	36.991	42.125
Average north	47.171	52.764	49.731	54.169	38.984	44.625
Average south	41.370	46.036	43.621	48.054	36.551	42.268
Average west	43.709	48.203	41.604	45.881	36.491	41.063
Average total	43.373	48.324	45.389	49.875	37.071	42.289
TIME LOST	**Seconds**					
Average cycling	27.518	28.688	29.163	27.883	21.210	21.330
Average east	28.815	34.421	31.621	36.669	21.918	27.029
Average north	32.001	37.592	34.663	38.997	23.821	29.453
Average south	26.067	30.732	28.043	32.750	21.081	26.964
Average west	27.234	31.732	25.136	29.410	19.997	24.592
Average total	27.805	32.757	29.740	34.362	21.447	26.711
TIME LOST	**Hours**					
Total cycling	1.009	1.052	0.794	0.759	0.471	0.474
Total east	3.274	3.911	4.076	4.726	1.711	2.110
Total north	2.196	2.579	3.091	3.477	1.330	1.644
Total south	4.815	5.677	2.867	3.348	1.856	2.374
Total west	3.896	4.539	2.772	3.243	1.889	2.323
Total sum	14.180	16.706	12.805	14.795	6.786	8.451
CYCLE TIME	**Seconds**					
Average	61.660	64.646	61.772	64.050	47.055	47.694
Maximum	107.300	104.300	95.300	95.300	70.300	76.300
Minimum	44.300	44.300	44.300	44.300	40.300	40.300
GWP	**Kilogram CO2-eq**					
West	61.799	58.400	50.572	46.323	36.652	33.825
North	42.149	39.678	34.596	34.246	24.637	23.725
East	60.137	56.715	50.642	48.819	31.993	30.143
South	59.359	56.952	56.557	51.306	32.818	31.288
Sum	223.444	211.745	192.367	180.693	126.100	118.981

PMX	Grams					
West	2.242	2.353	1.900	1.744	1.420	1.283
North	1.699	1.566	1.466	1.512	1.090	1.050
East	2.325	2.219	1.912	1.848	1.189	1.170
South	1.882	1.909	1.784	1.621	1.256	1.200
Sum	8.148	8.047	7.063	6.725	4.956	4.702
FUEL	**Litres**					
West	25.578	24.007	20.858	19.074	15.080	13.908
North	17.276	16.259	14.161	13.974	10.035	9.651
East	24.752	23.298	20.901	20.130	13.186	12.379
South	24.731	23.648	23.555	21.334	13.520	12.872
Sum	92.338	87.212	79.475	74.513	51.821	48.811

Note: This table shows the circumstances of the intersection without the system enabled. So, in default conditions.

Percentual change from dry to wet in default conditions

	Afternoon	Morning	Off hours
TRAVEL TIME	**Percentage**		
Average cycling	1.277	-1.371	-1.255
Average east	12.769	10.079	13.877
Average north	11.857	8.924	14.470
Average south	11.277	10.161	15.641
Average west	10.280	10.280	12.529
Average total	11.417	9.883	14.075
TIME LOST	**Afternoon**	**Morning**	**Off hours**
Average cycling	4.253	-4.387	0.570
Average east	19.458	15.966	23.318
Average north	17.469	12.504	23.646
Average south	17.894	16.784	27.911
Average west	16.516	17.007	22.978
Average total	17.811	15.539	24.544
TIME LOST	**Afternoon**	**Morning**	**Off hours**
Total cycling	4.253	-4.387	0.570
Total east	19.458	15.966	23.318
Total north	17.469	12.504	23.646
Total south	17.894	16.784	27.911
Total west	16.516	17.007	22.978
Total sum	17.811	15.539	24.544

CYCLE TIME	**Afternoon**	**Morning**	**Off hours**
Average	4.843	3.688	1.356
Maximum	-2.796	0.000	8.535
Minimum	0.000	0.000	0.000
GWP	**Afternoon**	**Morning**	**Off hours**
West	-5.501	-8.403	-7.712
North	-5.861	-1.012	-3.705
East	-5.691	-3.601	-5.781
South	-4.054	-9.285	-4.662
Sum	-5.236	-6.069	-5.646
PMX	**Afternoon**	**Morning**	**Off hours**
West	4.957	-8.218	-9.680
North	-7.845	3.129	-3.698
East	-4.554	-3.318	-1.601
South	1.459	-9.152	-4.500
Sum	-1.234	-4.772	-5.113
FUEL	**Afternoon**	**Morning**	**Off hours**
West	-6.141	-8.552	-7.772
North	-5.891	-1.319	-3.828
East	-5.875	-3.690	-6.117
South	-4.382	-9.428	-4.788
Sum	-5.552	-6.244	-5.809

Note: This table shows the percentual change from dry to wet conditions in default conditions. So, when the system is not enabled. A decrease means that the value is lower in wet conditions. A increase means that it is higher in wet conditions .

SYSTEM ENABLED

	Afternoon		**Morning**		**Off hours**	
	Dry	Wet	Dry	Wet	Dry	Wet
TRAVEL TIME	**Seconds**					
Average cycling	85.968	87.235	85.010	87.508	80.022	79.689
Average east	40.002	45.817	49.997	56.545	36.736	41.608
Average north	52.463	58.892	53.932	60.762	41.878	46.909
Average south	48.628	55.509	46.626	52.195	38.850	44.099
Average west	43.056	47.028	41.642	45.787	35.393	39.629
Average total	45.659	51.426	47.872	53.630	37.831	42.646
TIME LOST	**Seconds**					
Average cycling	21.821	23.088	20.863	23.362	15.876	15.543
Average east	24.904	30.721	34.595	41.449	21.660	26.512

Average north	37.291	43.720	38.863	45.590	26.717	31.737
Average south	33.324	40.205	31.046	36.891	23.380	28.795
Average west	26.581	30.557	25.170	29.316	18.901	23.159
Average total	30.090	35.859	32.222	38.117	22.208	27.068
TIME LOST	**Hours**					
Total cycling	0.800	0.847	0.568	0.636	0.353	0.345
Total east	2.829	3.490	4.459	5.342	1.691	2.069
Total north	2.559	3.000	3.465	4.065	1.492	1.772
Total south	6.156	7.427	3.174	3.771	2.059	2.536
Total west	3.803	4.371	2.776	3.233	1.785	2.187
Total sum	15.346	18.288	13.873	16.411	7.026	8.564
CYCLE TIME	**Seconds**					
Average	72.906	75.642	67.708	70.279	50.914	50.728
Maximum	110.400	115.400	104.400	103.400	80.400	85.400
Minimum	44.300	44.300	44.300	44.300	40.300	40.300
GWP	**Kilogram CO2-eq**					
West	61.835	57.660	50.766	46.991	35.817	32.960
North	44.905	43.342	37.948	38.638	25.763	24.829
East	55.826	52.512	53.989	54.542	32.195	30.147
South	69.637	69.726	59.234	54.940	34.403	32.626
Sum	232.204	223.240	201.937	195.112	128.178	120.563
PMX	**Grams**					
West	2.308	2.314	1.978	1.908	1.370	1.258
North	1.719	1.723	1.649	1.740	1.130	1.111
East	2.057	1.976	2.009	2.138	1.208	1.181
South	2.269	2.281	1.950	1.777	1.258	1.215
Sum	8.354	8.293	7.587	7.563	4.966	4.764
FUEL	**Litres**					
West	25.557	23.706	20.896	19.269	14.743	13.544
North	18.469	17.769	15.520	15.766	10.505	10.099
East	23.023	21.600	22.309	22.465	13.263	12.375
South	28.997	29.017	24.630	22.832	14.212	13.449
Sum	96.046	92.091	83.355	80.332	52.723	49.468
PART ENABLED	**Percent**					
average	65.587	65.158	39.510	39.104	28.838	27.332

Note: This table shows the new circumstances of the intersection with the system enabled.

PERCENTUAL CHANGE DEFAULT TO ENABLED

	Afternoon		Morning		Off hours	
	Dry	Wet	Dry	Wet	Dry	Wet
TRAVEL TIME	**Percentage**					
Average cycling	-6.214	-6.032	-8.895	-4.913	-7.556	-6.771
Average east	-8.901	-7.473	6.318	9.232	-0.692	-1.228
Average north	11.220	11.614	8.448	12.171	7.422	5.117
Average south	17.542	20.578	6.888	8.618	6.289	4.331
Average west	-1.494	-2.438	0.090	-0.206	-3.009	-3.491
Average total	5.272	6.419	5.469	7.529	2.049	0.844
TIME LOST	**Percentage**					
Average cycling	-20.700	-19.520	-28.460	-16.216	-25.149	-27.134
Average east	-13.572	-10.751	9.404	13.033	-1.175	-1.914
Average north	16.530	16.302	12.117	16.906	12.161	7.754
Average south	27.839	30.826	10.707	12.645	10.909	6.789
Average west	-2.399	-3.703	0.136	-0.321	-5.484	-5.830
Average total	8.220	9.469	8.344	10.928	3.545	1.336
TIME LOST	**Percentage**					
Total cycling	-20.700	-19.520	-28.460	-16.216	-25.149	-27.134
Total east	-13.572	-10.751	9.404	13.033	-1.175	-1.914
Total north	16.530	16.302	12.117	16.906	12.161	7.754
Total south	27.839	30.826	10.707	12.645	10.909	6.789
Total west	-2.399	-3.703	0.136	-0.321	-5.484	-5.830
Total sum	8.220	9.469	8.344	10.928	3.545	1.336
CYCLE TIME	**Percentage**					
Average	18.239	17.011	9.610	9.725	8.201	6.363
Maximum	2.889	10.642	9.549	8.499	14.367	11.927
Minimum	0.000	0.000	0.000	0.000	0.000	0.000
GWP	**Percentage**					
West	0.059	-1.266	0.383	1.443	-2.278	-2.556
North	6.539	9.234	9.689	12.827	4.569	4.655
East	-7.169	-7.412	6.609	11.724	0.631	0.013
South	17.316	22.429	4.734	7.085	4.830	4.278
Sum	3.920	5.429	4.975	7.980	1.648	1.330
PMX	**Percentage**					
West	2.948	-1.691	4.108	9.390	-3.517	-1.963
North	1.195	10.043	12.522	15.090	3.708	5.855
East	-11.509	-10.954	5.090	15.677	1.549	0.919
South	20.587	19.477	9.259	9.631	0.121	1.275

Sum	2.531	3.059	7.422	12.457	0.210	1.325
FUEL	**Percentage**					
West	-0.081	-1.257	0.181	1.022	-2.241	-2.620
North	6.906	9.290	9.596	12.818	4.685	4.642
East	-6.988	-7.290	6.738	11.600	0.588	-0.030
South	17.247	22.703	4.563	7.023	5.119	4.483
Sum	4.015	5.595	4.882	7.810	1.740	1.346

Note: This table shows the percentual change between an enabled system to default conditions.

ABSOLUTE CHANGE SYSTEM ENABLED TO DEFAULT

	Afternoon		**Morning**		**Off hours**	
	Dry	Wet	Dry	Wet	Dry	Wet
TRAVEL TIME	**Seconds**					
Average cycling	-5.696	-5.600	-8.300	-4.522	-6.541	-5.788
Average east	-3.908	-3.701	2.971	4.779	-0.256	-0.517
Average north	5.293	6.128	4.201	6.593	2.894	2.284
Average south	7.257	9.473	3.005	4.141	2.299	1.831
Average west	-0.653	-1.175	0.037	-0.094	-1.098	-1.434
Average total	2.287	3.102	2.482	3.755	0.759	0.357
TIME LOST	**Seconds**					
Average cycling	-5.696	-5.600	-8.300	-4.522	-5.334	-5.788
Average east	-3.911	-3.701	2.974	4.779	-0.258	-0.517
Average north	5.290	6.128	4.200	6.593	2.897	2.284
Average south	7.257	9.473	3.003	4.141	2.300	1.831
Average west	-0.653	-1.175	0.034	-0.094	-1.097	-1.434
Average total	2.286	3.102	2.482	3.755	0.760	0.357
TIME LOST	**Hours**					
Total cycling	-0.209	-0.205	-0.226	-0.123	-0.119	-0.129
Total east	-0.444	-0.420	0.383	0.616	-0.020	-0.040
Total north	0.363	0.420	0.375	0.588	0.162	0.128
Total south	1.340	1.750	0.307	0.423	0.203	0.161
Total west	-0.093	-0.168	0.004	-0.010	-0.104	-0.135
Total sum	1.166	1.582	1.068	1.617	0.241	0.113
CYCLE TIME	**Seconds**					
Average	11.246	10.997	5.936	6.229	3.859	3.035
Maximum	3.100	11.100	9.100	8.100	10.100	9.100
Minimum	0.000	0.000	0.000	0.000	0.000	0.000
GWP	**Kilogram CO2-eq**					

West	0.036	-0.739	0.194	0.668	-0.835	-0.865
North	2.756	3.664	3.352	4.393	1.126	1.104
East	-4.311	-4.203	3.347	5.724	0.202	0.004
South	10.278	12.774	2.677	3.635	1.585	1.338
Sum	8.760	11.495	9.570	14.419	2.078	1.582
PMX	**Grams**					
West	0.066	-0.040	0.078	0.164	-0.050	-0.025
North	0.020	0.157	0.184	0.228	0.040	0.061
East	-0.268	-0.243	0.097	0.290	0.018	0.011
South	0.387	0.372	0.165	0.156	0.002	0.015
Sum	0.206	0.246	0.524	0.838	0.010	0.062
FUEL	**Litres**					
West	-0.021	-0.302	0.038	0.195	-0.338	-0.364
North	1.193	1.510	1.359	1.791	0.470	0.448
East	-1.730	-1.698	1.408	2.335	0.077	-0.004
South	4.265	5.369	1.075	1.498	0.692	0.577
Sum	3.708	4.879	3.880	5.819	0.902	0.657

COMPENSATING INCREASED EMISSIONS

	Afternoon		**Morning**		**Off hours**		**1 trip**
	Dry	Wet	Dry	Wet	Dry	Wet	
GWP	**Kilogram CO2-eq**						
Increased emissions	8.760	11.495	9.570	14.419	2.078	1.582	1.407
	Number						
Number of trips	6.23	8.17	6.80	10.25	1.48	1.12	1

Note: this table shows how much people should take the bike instead of the car to compensate for the increased emissions caused by the new system.

COSTS OF EXTRA TRAVEL TIME

	Afternoon		**Morning**		**Off hours**	
	Dry	Wet	Dry	Wet	Dry	Wet
COSTS	**Euros**					
Hourly	9.57	13.77	8.43	14.94	1.22	-0.16
Daily	19.14	27.53	16.85	29.87	8.54	-1.10
Yearly	4994.51	7185.49	4398.13	7796.86	2562.56	-329.35

Note: The extra lost time caused by the system are translated to costs. 1 lost hour costs 10 euros. The results are shown in the table.