Improving and expanding the algorithms of Gouden Regelen

BSc thesis report final version

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Preface

This is the final report of my bachelor thesis *'Improving and expanding the algorithms of Gouden Regelen'*. I carried out this thesis within the department Verkeersmanagement en -Prognoses of Goudappel between April and July 2022. Within this period I learned a lot about traffic control systems and conducting research. It was interested interesting to get a glimpse of what it is like to work full-time within a company.

I would like to thank my external supervisors Niels van Gurp and Wim Pruijsers for their help and guidance during my graduation period. They helped me by getting more insight in traffic control systems in general and by understanding the code of Gouden Regelen . During the meetings they gave me useful thoughts and feedback. I also want to thank my internal supervisor from the University of Twente, Tom Thomas. His feedback and experience in the research field helped me to improve my research and report. In addition to my supervisors I would like to thank Goudappel for the opportunity to compute my bachelor assignment within the organization.

Loes Hazenberg

Enschede, July 4, 2022

Summary

In this study, algorithms are designed and evaluated to improve Gouden Regelen. Gouden Regelen is an application for traffic control systems. It uses real life data from detection loops to optimize the maximum green times and the order in which signal groups get green. In this study, this application is optimized by adding algorithms that are made to better incorporate cyclists and long vehicles (or trucks) in the application.

For the algorithm that incorporates cyclists into Gouden Regelen was found that already research for this was conducted. Therefore, the algorithm was based on this research. The algorithm designed exists of two parts, namely the part that determines the number of cyclists that pass the distant loop detector per occupation and the part that adds cyclists to the queue. The number of cyclists that pass the detector loop is determined using the follow-up time and the occupation time. The follow-up time is mainly used to determine the direction the cyclist(s) is going and the occupation time is used to determine the number of cyclists passing the detector. This number is then added to the number of cyclists in the queue.

The algorithm that is made to incorporate long vehicles, classifies whether a vehicle passing the distant loop detector is a passenger car or freight traffic. Depending on the situation, the algorithm uses different methods for this. When the queue fits within the detection field, the algorithm uses the method that bases the expected occupation time on the expected braking distance. By comparing the expected occupation time with the actual occupation time, the vehicle classification can be determined. When a vehicle is standing still on the distant loop detector, the vehicle classification is determined by comparing the distance between the end of the queue and the distant loop detector with the (expected) length of a passenger car. If the distance is much bigger, the vehicle is classified as freight traffic. Otherwise, it is classified as a passenger car. The last situation, is the situation where the queue grew outside the detection field. In that case, the classification is determined by comparing the occupation time of the current vehicle with the occupation time of the previous vehicle.

The accuracy of the algorithms is tested in order to evaluate their performance. This is done using multiple tests, such as the base scenario, a scenario where the traffic volume is increased, etc. The results from these tests are that the accuracy is high for almost all cases. However, some things stand out. Namely that the algorithm is not that good at recognizing when multiple cyclists pass the detection loop at once. This is mainly due to the fact that the occupation time is not different when only one cyclist passes the detection loop. The algorithm that classifies motor vehicles has its deficiencies as well. Firstly, from the results could be seen that especially the method which uses the braking distance to classify vehicles performs well. However, the other methods could be improved to increase the accuracy. Next to that, the algorithm is designed to only make a distinction between a truck and a passenger car. While it could be desired to make more distinctions in order to optimise Gouden Regelen even more.

Besides the accuracy, also the effects on the traffic flow, traffic safety and credibility of traffic control systems equipped with Gouden Regelen are determined. This is done by comparing the results of four different scenarios (no algorithms, both algorithms, only the cyclist algorithm and only the freight algorithm) with each other. As indicators of the effects, the waiting time and the chance that vehicles have to stop multiple times during a cycle are used. It was found that there were no significant differences between the different scenarios. Meaning that the algorithms do neither improve nor deteriorate the traffic flow, traffic safety and credibility.

From the results can be concluded that the algorithms perform in most cases like it is supposed to do. However, due to some of the deficiencies of the algorithms and the results which indicate the effects of implementing the algorithms, it is advised to conduct some more research before the algorithms are implemented. Besides that, the algorithms are only tested using simulations, in order to find all results it is desired to also test them in real life.

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1. Introduction

1.1. Context

Nowadays, traffic lights are standard features to regulate intersections. However, before 1868, when the first traffic light was installed in London at the Houses of Parliament, the principle of traffic lights was not used. Even though this traffic light was removed after one year due to an accident with a gas leak caused by the traffic light, it was the start of a new way to regulate intersections. Years later, in 1912, the first electric traffic light was designed. In 1928, the first electric traffic was installed in the Netherlands (IsGeschiedenis, n.d.). Since then, a lot has changed.

Currently, around 5500 intersections in the Netherlands are controlled by traffic control systems (in Dutch: verkeersregelinstallaties) (De IRVI uitgelegd_V7, 2021) using four different types of traffic control systems (112schade.nl, 2021):

- Pre-timed signal control: (in Dutch: Starre regeling) This control system has a repetitive cycle with a fixed pattern; the system does not respond to whether vehicles are present at the intersection (Gartner, 2013). In other words, there is a fixed cycle time, a fixed green time, and signal groups get green regardless of whether vehicles are present (so it has a set sequence).
- Vehicle-actuated control system: This system can respond to the presence of vehicles at the intersection. The presence of vehicles is determined by the occupation of the vehicle detection (mainly inductive loop detection). In contrast to the pre-timed signal control, the system can adapt the green times, order, and sequence of phases according to the signals from the vehicle detectors (Matthew, 2019)
- Semi-actuated control system: This is a combination of the previously mentioned control systems. This system has fewer options to adapt features like green time (Matthew, 2019). The big difference with the vehicle-actuated control system is that this system argues the other way around. The system is fixed (so fixed sequence, cycle time, and green time) unless certain conditions are applicable. In that case, the cycle can deviate from the repetitive cycle. This system is mainly used at intersections that work with the phenomenon ‘Progressive traffic signal system’ (in Dutch: Groene Golf) (DTV consultants, n.d.).
- Adaptive traffic control system (ATCS): The last system is the adaptive traffic control system (ATCS). ATCS optimises itself (on network level) using real-life traffic conditions. This is system is used more often due to the developments of Talking Traffic (De IRVI uitgelegd_V7, 2021).

In addition to these ‘traditional’ traffic control systems, the intelligent traffic control system (ITCS) is on the rise. This system is part of the partnership Talking Traffic. The system can communicate with arriving traffic; this aids the traffic flow. Also, this enables vehicles to receive data from the system. For example, show how long it will take before the light turns green. The ITCS is not a replacement for the four systems earlier mentioned; the system uses the same hardware as the systems earlier mentioned but it has a more advanced software system. This ensures that TCS is no longer only dependent on roadside systems (Rijkswaterstaat, n.d.).

As mentioned before, the ITCS is derived from the partnership Talking Traffic. Goudappel is not part of this partnership. However, Goudappel also created a system that uses and can support the ITCS called Gouden Regelen. This system can be compared with the methods that are part of the partnership Talking Traffic. The difference with the systems developed by the partnership Talking Traffic is that this system, called Gouden Regelen, also applies to ‘traditional’ Traffic control systems. Gouden Regelen uses the data from vehicles not as essential data but as additional data (De IRVI uitgelegd_V7, 2021).

Gouden Regelen exists out of 3 modules. One of these modules is the Omniflex module. This module calculates the maximum green times based on the current flow of traffic(using detection loops) and determines the order in which the signal groups receive green. The goal of using the current flow of traffic to calculate the maximum green time instead of using predefined maximum green times is to utilise the maximum green times better. When the order in which signal groups get green is dynamic instead of fixed, the result is that signal groups with high traffic intensities get earlier and more frequent green realisations. The module calculates this by constantly determining which signal group has the highest cumulative weighted waiting time; this signal group will get green first. This minimises road users' time loss (Krol, 2019).

Even though Gouden Regelen is already implemented on at least 100 traffic control systems (De IRVI uitgelegd_V7, 2021) and is a good working application, some parts of the application could still be improved and optimised to improve the traffic flow, traffic safety, and the credibility of traffic control systems. Among others the fact that Gouden Regelen can detect vehicles and incorporate this amount in the calculations made by the traffic control system. However, Gouden Regelen cannot make distinctions between different kinds of vehicles. But also the fact that Gouden Regelen can detect whether a cyclist is waiting for the traffic light. However, it does not know the number of cyclists waiting in front of the traffic light.

Even though the Gouden Regelen application currently does not incorporate these special target groups (the long vehicles and cyclists), it is desired that this is adjusted. By incorporating these groups in the Gouden Regelen application, the application can optimise its calculations. For example, the maximum green times can be determined more accurately, but the priority of certain signal groups could also be adapted based on the particular target groups. Therefore, this research aims to elaborate the Gouden Regelen application by creating and implementing algorithms that can incorporate these special target groups.

1.2. Research objective

As mentioned before, Gouden Regelen is already an extensive application, resulting in traffic control systems equipped with Gouden Regelen having better traffic flow, traffic safety, and increased credibility. However, parts of the Gouden Regelen could be optimised to improve these factors. Therefore, the research objective is:

"To optimise the traffic flow, traffic safety, and the credibility of the traffic control systems that are and will be equipped with Gouden Regelen by improving and expanding the algorithms of Gouden Regelen and afterwards evaluating these new algorithms. "

The credibility of the traffic control system is, in this case, stated as the fact that the TCS makes logical choices in terms of determining the sequence, maximum green time, etc. This do not necessarily have to be the best choices. For example, it should ensure that every direction gets green and that not one direction gets green every time. But also ensure that the green time is long enough (so vehicles do not have to stop multiple times for an intersection) but also ensure that the maximum green time is not too long. The credibility is increased when vehicles do not have to wait (unnecessarily) long (Bongers, 2017).

This research objective can be achieved by improving different algorithms of Gouden Regelen. Due to time constraints, this study will only focus on particular algorithms, namely the one(s) that incorporate special target groups in Gouden Regelen. These algorithms currently do not exist or are not extensive enough.

Currently, there is no distinction between the different types of vehicles that arrive at an intersection (the application assumes that all vehicles are passenger cars). However, it is desired to incorporate the 'special target group' of long vehicles (like trucks and busses) since these have a (significant) influence on the system. This applies to two things:

- Due to the length of these vehicles, the queue will pass the distant loop earlier. This will influence the method used and the accuracy of the number of vehicles in the queue. If, for example, the queue has already passed the distant loop detector, but the application does not add vehicles to the queue because only two vehicles are detected, while the application will only add vehicles when more than three vehicles are present. This causes the number of vehicles in the queue to be not calculated accurately. When long vehicles are present, the chance is higher that the queue is growing behind the distant loop detector before reaching the maximum number of vehicles that fit within the detection field.
- The acceleration of long vehicles is generally lower than for passenger cars. So if long vehicles are in the queue, the needed maximum green time for the queue to pass the traffic light needs to be higher.

The 'special target group' of cyclists is already incorporated in the application Gouden Regelen, it can already determine whether a cyclist is present at the intersection. However, the number/magnitude of cyclists crossing an intersection is not determined. Therefore, Gouden Regelen uses a fixed number for this. By broadening the algorithm for this special target group, the application has a more extensive insight into how many bikes arrive and can thus adjust the priority to this. This could increase the bike-friendliness, which is a goal of the Government (Rijksoverheid, n.d.).

When the special target groups can be recognised, the algorithm will be adapted to incorporate these two target groups to improve the traffic flow, safety and credibility of the intersection. This will be done in two ways: by optimising Gouden Regelen's calculations (such as the number of vehicles in the queue, maximum green time, etc.). If, for example, it is known how many trucks are in the queue the maximum green time can be better estimated. And by optimisation of the prioritising of the different target groups. When the number/magnitude of bikes is known, a better weight (and thus priority) can be given to this signal group.

1.2.1. Research Questions

This study focuses on incorporating special target groups in Gouden Regelen. This results in the following research question:

"How can special target groups be (better) included in Gouden Regelen to optimise the traffic flow, traffic safety, and the credibility of the traffic control systems that are and will be equipped with Gouden Regelen? "

To answer this research question, three sub-questions are formulated, which together form an answer to the research question.

The first question focuses on the working of the ITCS and on the Gouden Regelen application (in terms of how vehicles are recognised by both the traffic control system and the Gouden Regelen application). Specifically how Gouden Regelen application can distinguish different target groups:

1. How can different target groups be recognised by the Gouden Regelen application?

When it is known how different target groups can be recognised, an algorithm can be created to implement this in the Gouden Regelen application; this forms sub-question 2:

2. How can the different target groups be implemented in the Gouden Regelen application?

When an algorithm is created that incorporates the special target groups in the Gouden Regelen application, it is desired to know how this affects the Gouden Regelen application. This leads to sub-question 3:

3. What are the effects of implementing the different target groups within Gouden Regelen on the traffic flow, traffic safety, and the credibility of the traffic control systems that are and will be equipped with Gouden Regelen?

1.3. Thesis outline

In this report, first, the theoretical framework of the research study is given. The theories that support the research study's topic are explained in the theoretical framework. After the theoretical framework, the methodology of the research is given. This section describes the method used to find an answer to the research questions. After the methodology, the results are shown. The results are divided into two different sections. In the first section, the algorithm that is created is explained. In the third section, the accuracy and effects of the algorithms are described. After the results, the discussion, conclusion and recommendations are written down.

2. Theoretical Framework

In this section, the theoretical framework is given. The theoretical framework aims to support the theory of the research study. In the theoretical framework, theories are introduced (and described) that explain the research problem.

2.1. Gouden Regelen

As mentioned before, Gouden Regelen is the application studied in this research. Gouden Regelen exists out of three modules. In this study, the focus is put on the OmniFlex module. In this sub-section, an explanation is given about this module. A more elaborate description of Gouden Regelen can be found in Appendix A.

All the information stated in this sub-section originates from the report 'OmniFlex', in which this module of Gouden Regelen is explained (Omniflex)

2.1.1. The components of Gouden Regelen

As was mentioned in the Context Section, Omniflex, the module of Gouden Regelen that is used in this study, calculates both the maximum green and determines the order in which signal groups get green. The module does this based on the current traffic flow, using detection loops. The Omniflex module uses this data as input for the calculations made by the module.

To translate the input data to the maximum green time and the order of phases, the module uses multiple calculations, which are divided into components. These components are the following:

- Estimating the actual traffic volume
- Estimate the number of vehicles in the queue
- Calculate the maximum green time
- Determine the order of phases

2.1.2. Estimated actual traffic volume

The estimated actual traffic volume, translates the data from the detection loops into an estimated actual traffic volume. This calculation is based on the number of occupations of the detection loop(s) over a determined time interval.

2.1.3. Estimate the number of vehicles in the queue

The number of vehicles in the queue can be estimated using two methods. The first method, uses the raw data received from the detection loops to determine the number of vehicles. This method determines the number of vehicles that are in the queue using the data from entering the distant loop detector and exiting of the stop line detector. The difference between the number of occupations indicates the number of vehicles in the queue. When the first method cannot be used (for example due to fact that there is no distant loop detector present or it is not operating), the estimated actual traffic volume can be used to determine the estimated number of vehicles in the queue. This method is also used to determine the number of vehicles in the queue, when the queue is behind the distant loop detector (it grew out of the detection field). As the name already suggests, this method uses the estimated actual traffic volume (and the time that indicates since when this method is active) to determine the number of vehicles in the queue.

2.1.4. Calculate the maximum green time

When the number of vehicles in the queue is estimated, the maximum green time can be calculated. This calculation is based on the number of vehicles in the queue and the discharge rate. By dividing the number of vehicles by the discharge rate, the time that is needed to clear the queue is calculated, and thus the maximum green time needed is known.

2.1.5. Determine the order of phases

To determine the order in which signal groups get green, different stages are defined. A stage, is a group of signal groups which can have green at the same time without having a conflict with each other. For every stage, the cumulative waiting time is calculated. The cumulative waiting time is calculated per signal group and indicates the total waiting time of that signal group. This cumulative waiting time is multiplied by the weight of a signal group. The weight indicates the priority of a signal group. The stage with the highest cumulative waiting time, receives green first. After that, the cumulative waiting time per stage is calculated again to determine the stage which should receive green next.

2.2. Evaluate traffic control systems equipped with Gouden Regelen

To check if a traffic control system equipped with Gouden Regelen works properly, the effectiveness is evaluated. In order to do this, there is looked at the traffic flow, traffic safety and credibility of the traffic control system. The parameters are compared to other situations (e.g. the previous situation or another type of traffic control system).

To understand the principle of evaluating the traffic control system, first an explanation is given about what the different parameters to evaluate the traffic control system are. After that, the indicators that give an indication of the of these parameters are explained. Lastly, is explained how the values of the indicators can be found.

2.2.1. Parameters to evaluate effectiveness of ‘Gouden Regelen’

To evaluate traffic control systems, multiple indicators are used to determine the effectiveness of the TCS. For example, travel times, travel speeds and number of stops could be indicators to determine the effectiveness of TCS (Khattak, Magalotti, & Fontaine, 2020). These indicators can be linked to parameters that described these effects, namely the traffic flow, traffic safety and credibility of traffic control systems.

Traffic flow

The traffic flow is an indication of how many disruption vehicles experience while passing the intersection. In other words, it indicates the flow of the traffic stream arriving at the intersection. The traffic flow is optimal if vehicles can drive the maximum speed without disturbance.

Traffic safety

In this case, traffic safety is stated as not only the number of dangerous situations that occur. But also the likeliness that these occur (for example, if people tend to ignore red light faster in the current situation).

Credibility

As discussed before, the credibility of the traffic control systems equipped with Gouden Regelen is the fact whether the traffic control system makes the most logical choices.

2.2.2. Indicators to evaluate effectiveness of ‘Gouden Regelen’

In order to evaluate the traffic control system, the effect on the parameters traffic flow, traffic safety and credibility is determined using the indicators waiting times and number of (extra) stops in front of the intersection.

Waiting times

The first indicator that is used to evaluate the effectiveness of 'Gouden Regelen', are the waiting times. This indicator is used to evaluate the effect on all three parameters.

For the traffic flow applies that it can be assessed by comparing the travel times in peak hours and in so-called free flow hours (Ministerie van Infrastructuur en Milieu, 2014). This can be transformed to the loss time of a vehicle. Since the loss time is depending on the waiting times, if the waiting time increases the loss time will also increase. Therefore, applies that if the loss time is higher, the traffic flow decreases.

Research has shown that when the red times are too long (resulting in an increase in waiting times), the traffic safety decreases. In that case, more people tend to ignore the red light (Speisser, Damas, & Lab, 2018). This also applies for cyclists, there is a connection between the waiting time and the number of red light negations. If the waiting time is too high, the number of red light negations increases (Buursink et al., 2003). For cyclists applies that if the waiting time is decreased, the red light negations will also decrease (Tertoolen & Ruijs, 2015).

As mentioned earlier, the credibility of a traffic control system is the principle that a traffic control system makes logical choices. The first indicator that can be used to evaluate the credibility of a traffic control system, is the waiting times. If the waiting times have increased compared to the other situation, the credibility of the traffic control system is lower. Hence, the traffic control systems does not make the most logical choices in that case.

Number of (extra) stops in front of the intersection

The indicator 'the number of (extra) stops in front of the intersection', is used to evaluate the indicators traffic safety and credibility.

Research has shown that if the green times are too short (resulting in vehicles having to make multiple stops before they can pass the intersection), the traffic safety decreases. In those cases, more people tend to ignore the red light (Speisser, Damas, & Lab, 2018).

Besides the waiting time, the indicator 'Number of (extra) stops in front of the intersection' can also be used to evaluate the credibility of a traffic control system ('t Hoen, Vanhuysse, & Los, 2013). In this case the indicator applies the same as for the traffic safety evaluation, if the number of stops in front of the intersection have increased compared to the other situation, the credibility of the traffic control system is lower. Hence, the traffic control systems does not make the most logical choice in that case.

The operation of traffic control systems can be assessed by determining the effects on the traffic flow, traffic safety and credibility of the traffic control system. This can be done using the waiting time and the number of (extra) stops in front of the intersection as indicators. If the value of an indicator increases, the traffic flow, traffic safety and credibility of a traffic control system do not improve (but get worse).

2.2.3. Determination of the value of the indicators

To determine the effects of the Gouden Regelen application, the values of the indicators should be known. This can be done in two ways. The first one is to implement the application on a traffic control system. The values of the indicators can be determined using data received from the vehicles. Such as the GPS data, which is also done in the study conducted by Khattak et al. (2020).

The second option to determine the values of the indicator, is to conduct a (micro-) simulation study. This is a method that is used frequently to evaluate traffic control systems. However, when comparing it to a 'real-life' evaluation, the credibility is a bit lower (Robert, Gordon, & Warren Tighe, 2005). Nevertheless, research has shown that there is no significant difference between the evaluation in real-life and in micro-simulation. Especially when looking at the travel times and the number of stops (Kergaye, Stevanovic, & Martin, 201). Micro-simulations are a lot easier to utilise than 'real-life' evaluations. Also, if the evaluation is conducted in 'real-life' there will be an impact on the traffic passing the traffic control system, while for micro-simulations this is not the case.

Simulation tool

Goudappel has designed a (micro) simulation tool to evaluate traffic control systems equipped with Gouden Regelen. In Appendix B – Simulation tool + Oss 15, images of the simulation tool can be found. This simulation tool is based on a car-following Model. A car-following Model is a microscopic simulation model that describes the one-by-one following of vehicles in the same lane. Since following behaviour is an essential aspect of micro-study in traffic, this model embodies human factors and reflects the actual traffic situation better than other traffic-flow models (Weng & Wu). Multiple types of car-following models can be used in simulation tools. In the device designed by Goudappel, the Extended Intelligent Driver Model made by Treiber and Kesting is used. This model is also used in, among others, SUMO simulation (SUMO, n.d.).

2.3. Methods to determine the number of bicycles at a signalised intersection using detection loops

In the Netherlands, multiple studies are conducted on how to count cyclists using (distant) detection loops. The outcome of these studies are very similar to each other. In this sub-section the most important results are discussed.

The municipality of The Hague has conducted a study in which they investigated the reliability of bicycle detection loops. In this research, they compared different types of detection loops with each other. The conclusion of this research is that bicycle detection loops are very suitable to detect cyclists (Gorter & Vries, 2016).

However, in order to count cyclists in the correct way, two recommendations are made by Gorter & Vries (2016). The first one is to use a minimal occupation time of 0.3 seconds of the detection loop. Since cyclists mostly have a speed between 14 and 24 km/h, this can be translated to a minimal occupation time of 0.3 seconds. If motor scooters also need to be incorporated, this minimal occupation time could be lowered. The second recommendation is to raise the number of cyclists in the queue using a factor when the intensity is increased. The results of this research, and the research conducted by Veenstra et al. (2016), showed that when the volume of cyclists is high (more than 50 cyclists per 15 minutes), the detection loop systematically underestimates the number of cyclists. This is due to the fact that in that case cyclists are more likely to ride next to each other or right behind each other. This causes only one cyclist to be counted when in fact multiple cyclist passed the detection loop (Veenstra, Geurs, Thomas, & Hof, 2016).

A research is conducted on traffic jams among cyclists (in Dutch: fietsfile). This research shows that there are multiple indicators to determine whether a cyclists jam is present at a traffic light. Two of these situations are when the detection loop counts more than 25 cyclists or when the distant detection loop is occupied for more than 4 seconds. If these situations are applicable, a traffic jam among cyclists is present (Hoskam, sd.) .

For a project in Maastricht, Goudappel (van Gurp, 2019) has made an algorithm to determine the number of cyclists using a distant loop detector. This algorithm is used for situations were multiple distant loop detectors are operating. This ensures that the algorithm can make a distinction in the direction cyclists are travelling. The algorithm does this by determining the follow-up time of the detection loops. The follow up time is the time between the detection notification (in Dutch: detectie hoog) of the first loop (the one which has the largest distance to the intersection) of the pair of the distant loop detector and the detection notification of the second loop. In Figure 1 an overview of this is given.

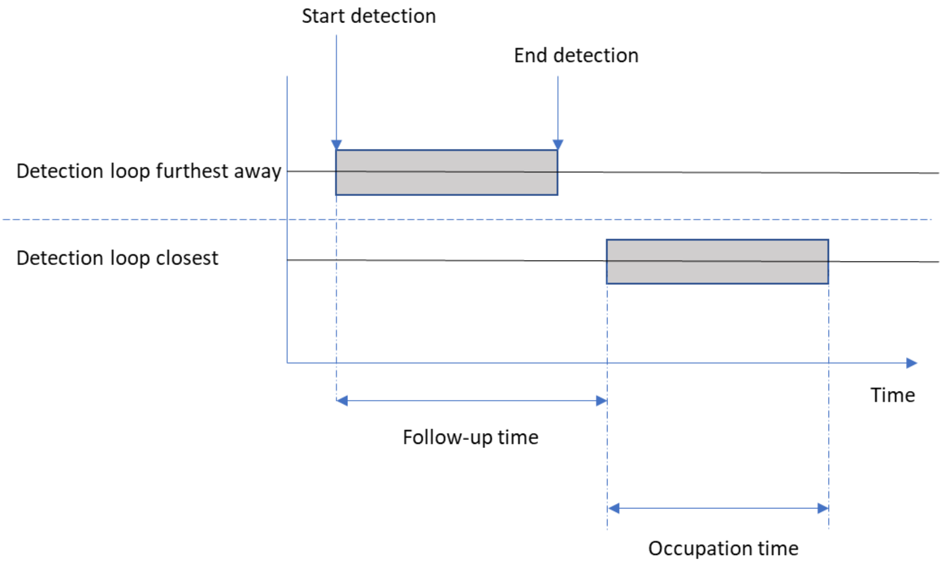

Figure 1: The follow-up time is displayed by showing the occupation of the two distant loop detectors. The grey blocks indicate that a detection is occurring. The lines indicate that the detection loop is not occupied.

If the follow up time is within the boundaries of the possible follow-up times (between 0 and the maximum follow-up time (see Figure 2 for a schematisation)), the number of cyclists can be determined using the occupation time. The maximum follow-up time can be determined by determining the length the cyclists need to be covered (the length of the detection loop plus the length between the detection loops). If the (minimal) speed of cyclists is known, the time it takes to travel can be determined.

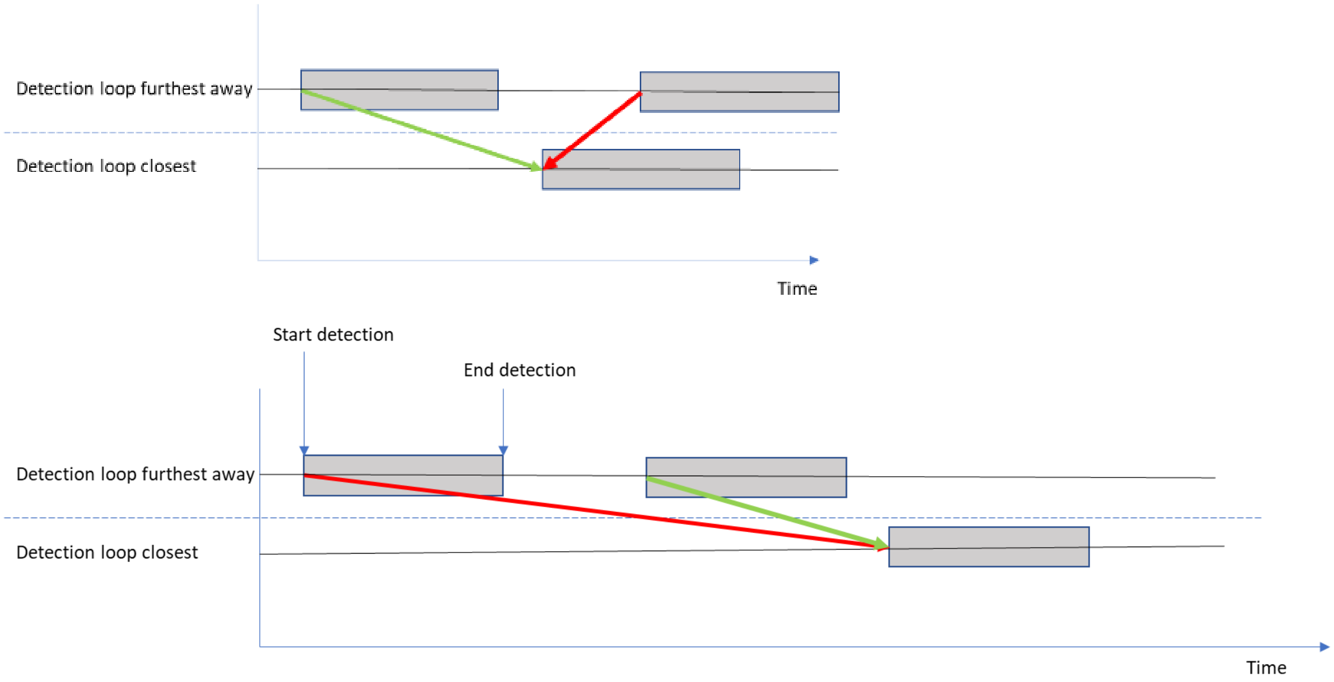

Figure 2: The arrows indicate in which cases the follow-up time falls within the boundaries and in which not. The upper image shows the situation when the follow-up time is negative. The lower image shows the situation where the follow-up time is too big. In these cases the algorithm does not incorporate the detections.

Besides the follow-up time, the algorithm also incorporates the occupation time to determine the number of cyclists that pass the (distant) detector loop(s). This algorithm makes a distinguish between three options: No bicycles, one bicycle or two bicycles pass the detection loop. To determine which of the situations is applicable, the algorithm uses the occupation time by setting boundary conditions. These boundary conditions indicate the minimal occupation time for one cyclist and the minimal occupation time for two cyclists (or the maximum occupation time for one cyclist). The value of these conditions are determined using the speed of cyclists, the length of the detection loops and the length of bicycles. In the case of Maastricht for which the algorithm was designed, these boundaries were set at 0.1 seconds for one cyclist and 0.7 seconds for two cyclists.

2.4. Methods to recognise long vehicles using detection loops

There have been multiple researches conducted on how to classify the type of vehicle that is passing the (distant loop) detector.

One of the methods that came forward in many of these researches, is the one that uses vehicle signatures created by the detection loops to determine the vehicle classification. To understand how a vehicle signature is created, the induction loop detector system needs to be explained. This system contains some principle components, namely an insulted loop (lead-in)wire which is in a shallow slot in the pavement, a Lead-in cable from the pull box to the controller Cabinet and the electronics (which are located in the Controller Cabinet) (U.S. Department of Transportation, 2006). In Figure 3, this system is displayed schematically.

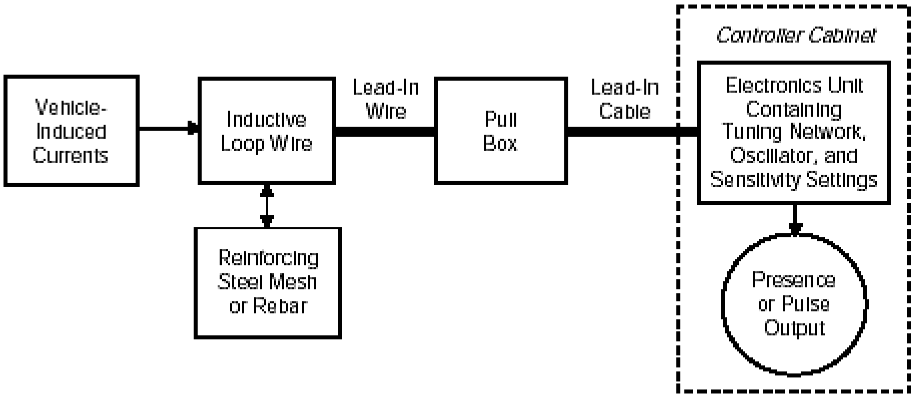

Figure 3: Schematic display of inductive loop detection (U.S. Department of Transportation, 2006)

Energy is transmitted into the wire which loops by the electronics unit in the controller cabinet. This energy creates an induction field around the wire. When a vehicle passes the loop or stops at the loop, a change in the inductance can be noted. The electronic unit detects this change since the output is different (U.S. Department of Transportation, 2006) & (Portacon, n.d.). Inductive loop detectors can detect vehicles and obtain the inductance change over the loop from the vehicle's passage. This inductance change gives a vehicle signature (Oh, Ritchie, & Oh). Research has shown that the different vehicle types can be classified under a unique vehicle signature, depending on some parameters which can be derived from the signature (Lamas-Seco, Castro , Dapena, & Vazquez-Araujo, 2016). In Figure 4, an example is given for different vehicles and their vehicle signature. In this Figure it can be seen that the different vehicle types have different signatures.

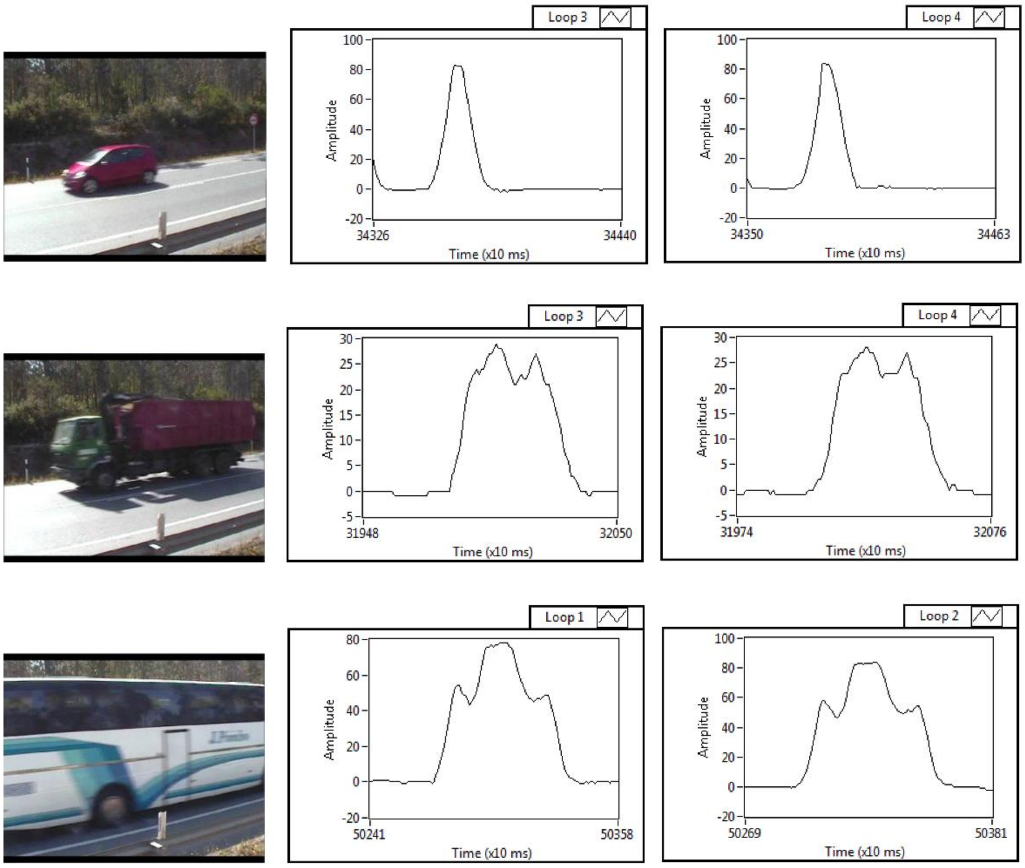

Figure 4ly cars: Different vehicle signatures for different (types of) vehicles (Lamas-Seco, Castro , Dapena, & Vazquez-Araujo, 2016)

However, the output from the detection loop used for the Gouden Regelen application send out binary signals instead of analogy signals(as seen in the image above). This binary output signal is determined using a threshold value. This threshold value indicates when a vehicle passes the detector loop. If the change in inductance is bigger than the threshold value, the binary output will change from 0 to 1, indicating that there is a vehicle passing the loop (Wilson, 2014). In Figure 5, a schematisation of this is given.

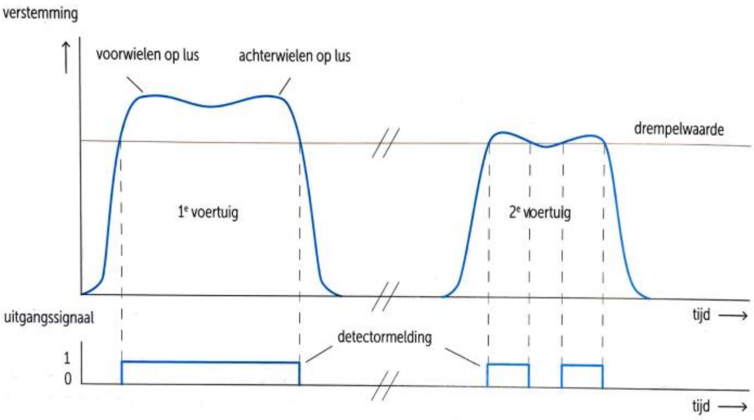

Figure 5: Transferring the relative change in inductance of detection loops to binary output (Wilson, 2014)

Because binary detection patterns do not have a profile, Coifman & Kim (2009) came up with another method to determine the vehicle classification from freeway single-loop detectors using the occupation time of the detector loop. This method is based on the following equation:

$$l = t_{on} * v$$

Equation 1

Where:
l (m) = Length of the vehicle
t_{on} (s)= Occupation time of the detector loop
v (m/s) = Speed of the vehicle

This method uses the average length of a short (or long) vehicle (and the average occupation time of the detection loop) to make an estimation of the mean speed. Using this mean speed (and the occupation time), the length of individual vehicles can be determined. The results of this study show that for some occupation times the vehicle classification can be determined. However, in some cases it is not possible to make a conclusion which vehicle type is passing the detection loop. This is due to the fact that in some cases the occupation time of the detection loop is the same, while the classification is different. For example, if a long vehicle passes the detection loop with a high speed and a passenger car with a low speed, the detection time is (approximately) the same. Since the speed of the individual vehicles is not known, the length of the vehicles (and thus the classification) cannot be determined. For freeways, this issue is less of a problem since the speeds are in general closer to each other. However, for intersection/traffic lights the speed is varying more, therefore the classification is harder to predict.

3. Methodology

In order to get answers to the research question (and its sub-questions) in a structured way and to make sure that it can be reproduced, a research methodology is set up. The research method exists out of 3 phases, which together give answers to the research question. In Figure 6, a schematisation can be found of this methodology. In this Figure, green corresponds to phase 1. The goal of this phase is to come up with algorithms to detect and incorporate cyclists and long vehicles. In phase 2, indicated with red in the schematisation, it is checked what the accuracy of the algorithms is by implementing it in the application. Yellow indicates the last phase, in that phase the effects of the algorithms is determined. To do this, multiple tests are conducted based on several scenarios. In this section, an explanation is given about the different phases (and its steps) of the methodology.

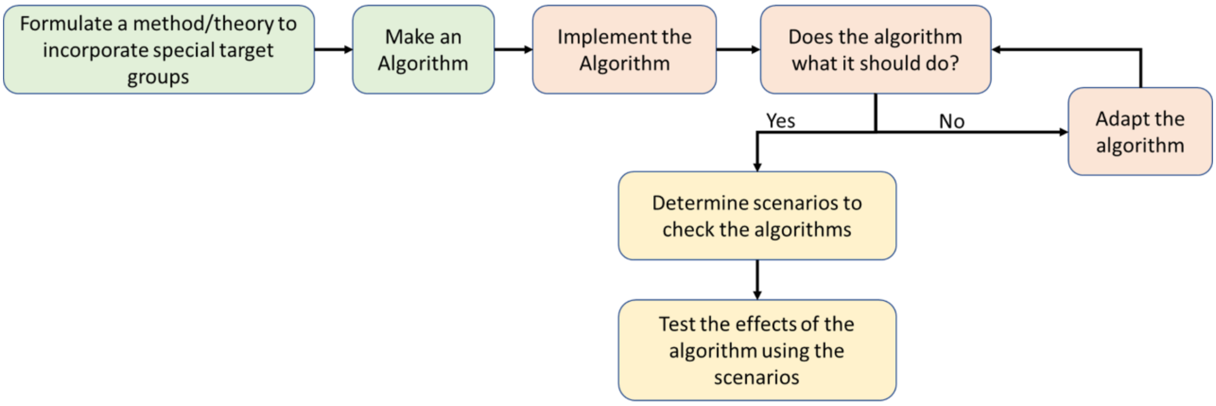

Figure 6: Schematisation of the research methodology.

3.1. Come up with an algorithm

The first phase of the study that is conducted, is to come up with algorithms that include the number of cyclists in the queue and that can detect and incorporate long vehicles in the application. The phase exists out of two steps, namely:

- Formulating a method/theory that forms the basis for the algorithms
- Make an algorithm

3.1.1. Formulating a method/theory that forms the basis for the algorithms

The first step, is aimed at developing a method or theory on how the special target groups can be implemented in the Gouden Regelen application. In order to do this it is desirable to understand the application that is used in the research-study thoroughly. In this case, the Gouden Regelen application. With understanding it thoroughly is meant understanding both the algorithm (the code) and the theories that are the basis for the algorithms of the application.

Together with theories/methods found in the literature, this is used to developing a method/theory which is the basis for the algorithm. The goal of the literature study will be to seek for other applications that can make a distinguish between different target groups and check whether this method is also suitable for the Gouden Regelen application.

3.1.2. Make an algorithm

Using the knowledge gained in previous step, an algorithm will be written. The first step for this, is transforming the theories/methods from the previous phase. If the knowledge gained in the first step is scarce or not useful, there has to be come up with an algorithm from scratch. The goal of this step is to think out the whole algorithm and to write this down before the code of the algorithm is programmed.

3.2. Check whether the algorithm does what it is supposed to

When the principle of the algorithms is known, the Algorithm can be implemented in the code of Gouden Regelen and the accuracy of the method can be determined. This phase is an iterative process, where the first step is to implement (parts of the) code and after that it is checked whether the algorithm works like it is supposed to. If this is not the case, the algorithm/code of the algorithm will be adapted to achieve that the accuracy of the algorithm increases. When the algorithm works properly/satisfactory, the iterative process is finished.

3.2.1. Implement the algorithm

The step to implement the algorithm in the code of Gouden Regelen, exists of two parts. The first part, is to make an extension to the already existing code of Gouden Regelen by implementing the code of the algorithm that is designed in the previous phase.

The second part is about incorporating the different special target groups in the Gouden Regelen application. When the special target groups can be recognised, some of the calculations can be improved. For cyclists this applies to the determination of the (cumulative) waiting time. By implementing the queue generated by the algorithm and by changing the factor that states the importance of the signal group, the algorithm that determines the queue of cyclists is incorporated.

The algorithm that determines the vehicle classification and also incorporates this in the queue, can be implemented in the Gouden Regelen application by adapting two things. The queue determined by the algorithm, can be added to the application by translating it to the PCU, passenger car unit/equivalent, of the queue. Currently, the Gouden Regelen application uses the number of vehicles in the queue. This can be replaced by the PCU of the queue. Besides this change, an additional requirement is added to determine when the application should add vehicles to the queue using the traffic volume (because the queue is behind the distant loop detector). This requirement, is the length of the queue (in meters). If the length is bigger than the detection field, this method will be activated.

3.3. Accuracy of the algorithm

When the algorithm is implemented, it can be tested whether the algorithm works like it is supposed to do. This will be done using a micro-simulation, namely the simulation tool of Goudappel. In the section Theoretical Framework, an explanation of this tool can be found.

Tests

Since the situation at the traffic control system is not always similar to the 'standard' situation, multiple tests are conducted. These tests correspond with the different situations that could be possible. With the different tests can be determined whether the accuracy is good in every situation or what the situations are in which the algorithms performs better (or worse). To test for the different situations (that are expected to have impact on the algorithm), the following parameters will be adapted:

- Different volumes of traffic
- For cyclists: different speeds
- For long vehicles: different percentages of freight traffic
- For long vehicles: the length of (long) vehicles

These parameters are chosen, since it is expected that they influence the accuracy of the Algorithm. In Appendix C – Methodology it is indicated how these different tests are performed.

Determine accuracy

Using the different tests described above, the accuracy of the algorithm can be determined (for the different situations). For both algorithms applies that the accuracy of the algorithm is determined differently.

For the algorithm that detects cyclists applies that the accuracy of the algorithm will be determined via two ways; namely by determining the accuracy of the number of vehicles that is detected and by determining the accuracy of the number of cyclists in the queue. For both applies that this is evaluated by computing the difference between what the simulation has determined and what the algorithm had determined. The smaller the difference, the more accurate the algorithm.

The accuracy of the algorithm that classifies the vehicle type (of motor vehicles) will be determined by comparing the vehicle type that is indicated by the simulation with the expected vehicle type of the algorithm. The more frequent this deviant from each other, the less accurate the algorithm is.

3.4. Determine the effects of the algorithm

When the algorithms are implemented in Gouden Regelen, the effect on the traffic flow, traffic safety, and the credibility of the traffic control systems that are and will be equipped with Gouden Regelen will be investigated. The effect will be determined using the simulation tool of Goudappel. This tool can give different data as output, such as the waiting times, travel times and the chance that during a (green) cycle vehicles have to stop multiple times before they can pass the intersection.

The effects will be tested by implementing the algorithms on the intersection called Oss 15. This is an intersection which already is equipped with Gouden Regelen. The intersection is a T-junction, where every direction has a separate lane, and cyclists can also go in every direction. In Appendix B – Simulation tool + Oss 15, an image of the intersection can be found.

To get a good indication of the effects, different tests will be conducted namely:

- Test where the algorithms are not implemented;
- Test where both algorithms are implemented;
- Test where only the algorithm of cyclists is implemented
- Test where only the algorithm of long vehicles is implemented.

To determine the effect of the algorithms, the difference in the traffic flow, traffic safety and the credibility of the tests should be determined. As mentioned in the section Theoretical Framework, the effects on the traffic flow, traffic safety and credibility of traffic control systems equipped with Gouden Regelen can be evaluated using the indicators waiting times and number of stops. These parameters (the loss time and the chance that vehicles have to stop multiple times before passing the intersection to be precise), are output from the simulation tool. Therefore, the effects are evaluated using these parameters.

4. The Algorithm(s)

As is mentioned in the Section Methodology, one of the ‘results’ of the study, are the algorithms created to incorporate the number of cyclists and to determine and incorporate the vehicle classification of motor vehicles (long vehicle or passenger car). In this section a description of these algorithms is given. In Appendix D an elaborated explanation is given, in the explanation given in Appendix B is also the principles and line of reasoning of some choices explained.

4.1. Queue of signal groups with cyclists

To determine the number of cyclists that are in the queue, different calculations are done. In Figure 7 a schematisation is given of the main principle to determine the number of cyclists that are in the queue.

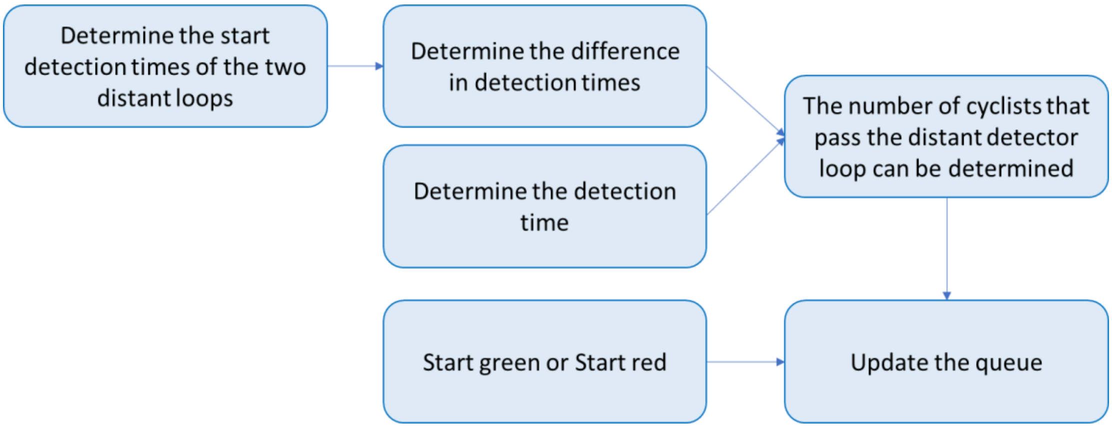

Figure 7: Schematisation of the algorithm to determine the number cyclists in the queue

As can be seen, the main output of the algorithm is the number of cyclists in the queue. In order to know this, the number of cyclists that pass the (distant) loop detector need to be determined. The follow-up time (the difference between the start detection of the two distant loop detectors) and the occupation time of the distant loop detector, is the input to determine the number of cyclists that pass the detector loop per passage. For the follow up time applies that if it is within the boundaries of going in the right direction, that the detection is taken into account. For the occupation time applies (in general) that if the occupation time is higher that the number of cyclists passing the detection loop is higher. . As can be found in Appendix D– The algorithms, there is not a hard line for which the occupation time fits to one or multiple cyclists. However, for this algorithm is assumed that if the occupation time is between 0.9 and 4.0 seconds that two vehicles pass the detection loop. If the occupation time is less than 0.9 seconds, only one vehicle passes the detection loop and if the occupation time is higher than 4.0 seconds there is a cyclists traffic jam (in other words a group of cyclists passes the detection loop). The number of cyclists that is detected by the detection loop, is added to the queue.

When the traffic light turns green, cyclists will leave the queue. Therefore the algorithm will empty the queue at start green. However, during the time that the traffic light is green cyclists will pass the distant loop detector(s) as well. Some of these cyclists are not able to reach the traffic light in time to pass the intersection while the traffic light is still green, so these will be in the queue at start red. However, there are cyclists that arrive during green that are able to pass the traffic light while it is still green. Therefore, at start red the queue is reset by determining which of the cyclists passed the intersection and which cyclists are in the queue. To determine this, the expected time it takes to travel from the distant loop detector is compared to the time the traffic light was still green or yellow when they arrived at the (nearest) distant loop detector.

4.2. Incorporating long vehicles

In the Section Theoretical Framework, the Theory of Coifman & Kim (2009), which is a theory to determine the vehicle classification based on the occupation time, is given. As described in this section, for this method it is essential to know the (average) vehicle length and the mean speed. However, due to the fact that the speed of vehicles (at the distant loop) is very dependent on the length of the queue (and thus there is a big variation in speeds), it is not possible to take an average speed at intersections. Besides that, the average length of the vehicle(s) is also not known since this is one of the outputs you want to receive from the application. Therefore, this method cannot be copied directly. However, part of the line of reasoning is used in this study.

The algorithm that is created to make a distinction between vehicle classifications (passenger cars or long vehicles), uses the occupation time of the distant loop detector to determine the type of vehicle. To determine the vehicle classification (based on the occupation time of the distant loop detector) multiple methods are applicable. Depending on the situation, it is determined which of the methods is used. The different situations with the corresponding methods are the following:

- The queue fits within the detection field: the vehicle classification is determined using the braking distance of vehicles;
- A vehicle stands still on the distant loop detector: the vehicle classification is determined using the distance between the end of the queue and the distant loop detector;
- The queue has grown behind the distant loop detector: the vehicle classification is determined using the occupation time of the previous vehicle.

In Figure 8 a schematisation of the different situations is given. The different situations can be detected using parameters that will be different in the different situations, such as the length of the queue (in meters). In Appendix D– The algorithms, all parameters can be found. Also in this appendix an explanation is given for which values the different situations are applicable.

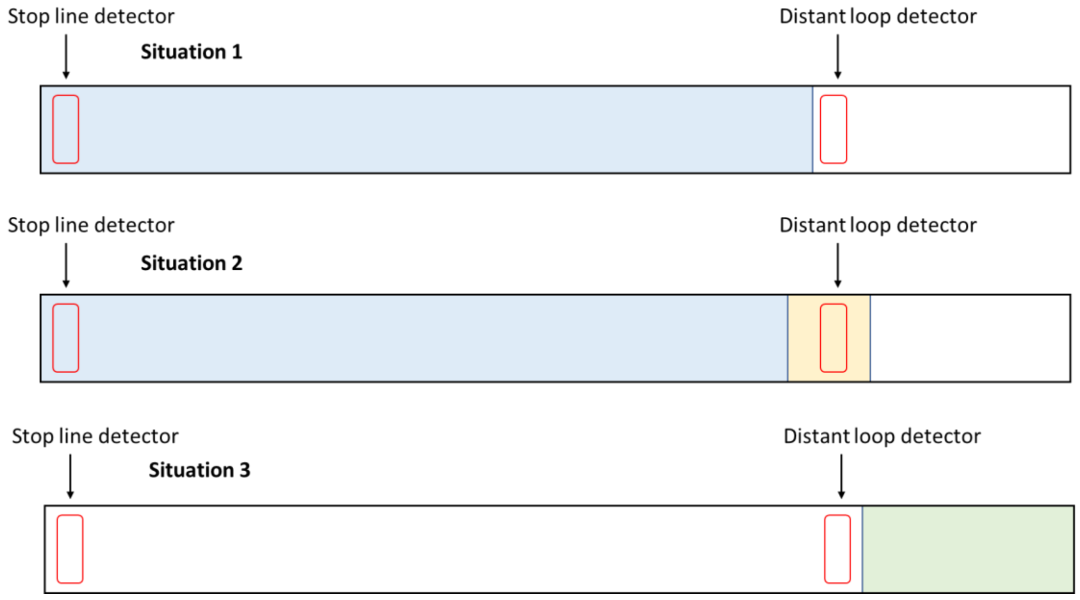

Figure 8: Different situations when different methods to determine the vehicles classification are applicable

In the following sub-sections, the methods that correspond to these situations and the main principle are explained. However, this is a global description. In Appendix B an elaborate explanation is given.

4.2.1. Different methods

As mentioned before, there are three possible situations with for each situation a different method to determine the vehicle classification. The first one is the situation where the queue is within the detection field. To classify the vehicles that pass the distant loop detector, the expected braking distance is determined. Based on the expected braking distance, the expected speed at the distant loop detector, and therefore also the expected occupation time, can be determined. By comparing the expected occupation time and the actual occupation time, the vehicle can be classified. In Figure 9 a schematisation of this method is given.

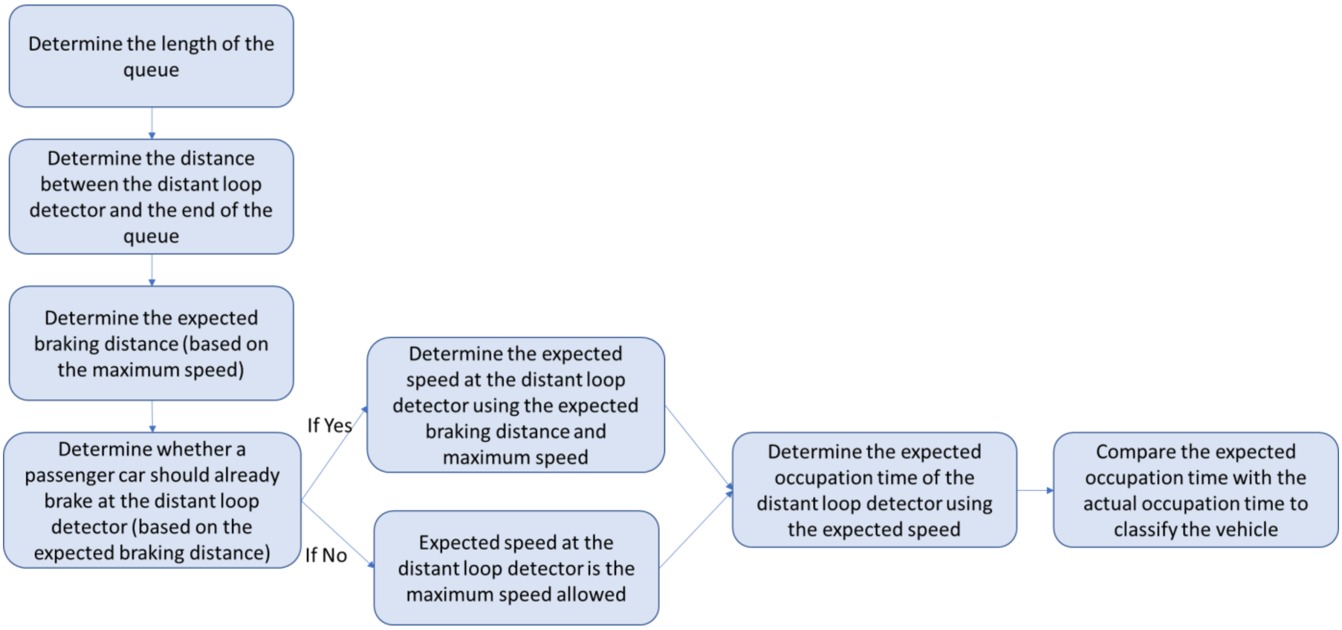

Figure 9: Schematisation of the method which determines the vehicle classification based on the expected braking distance. The method is applicable when the queue fits within the detection field.

The second situation in Figure 8, displays the situation where a vehicle is standing still on the distant loop detector. In that case, the distance between the end of the queue and the distant loop detector is compared with the (expected) length of a passenger car. If the distance is bigger than the expected length of the passenger car, it is classified as a long vehicle. Otherwise, it is classified as a passenger car. In Figure 10 a schematisation of this method can be found.

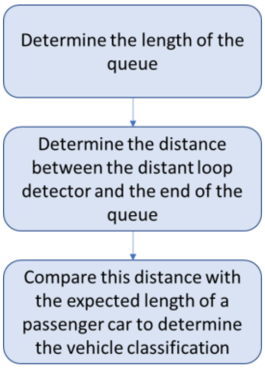

Figure 10: Schematisation of the method which determines the vehicle classification based on the expected braking distance. The method is applicable when a vehicle is standing still on the distnt loop detector.

The third method that determines the vehicle classification is used in the third situation, when the end of the queue is behind the distant loop detector. When this method is applicable, the vehicle classification is determined using the occupation time of the detector loops from the current and previous vehicle. If the occupation time of the distant detector loop of the current vehicle is comparable with the previous vehicle (falls within the accepted deviation), the vehicle classification is the same as the previous vehicle. This deviation is used to incorporate the fact that the speed of two consecutive vehicles can be different because the acceleration or deceleration is different for the vehicles. In Appendix D– The algorithms, this is explained more in depth. If the occupation time is not within the accepted deviation, the vehicle is classified the same as the previous vehicle. In Figure 11 a schematisation of this method is given.

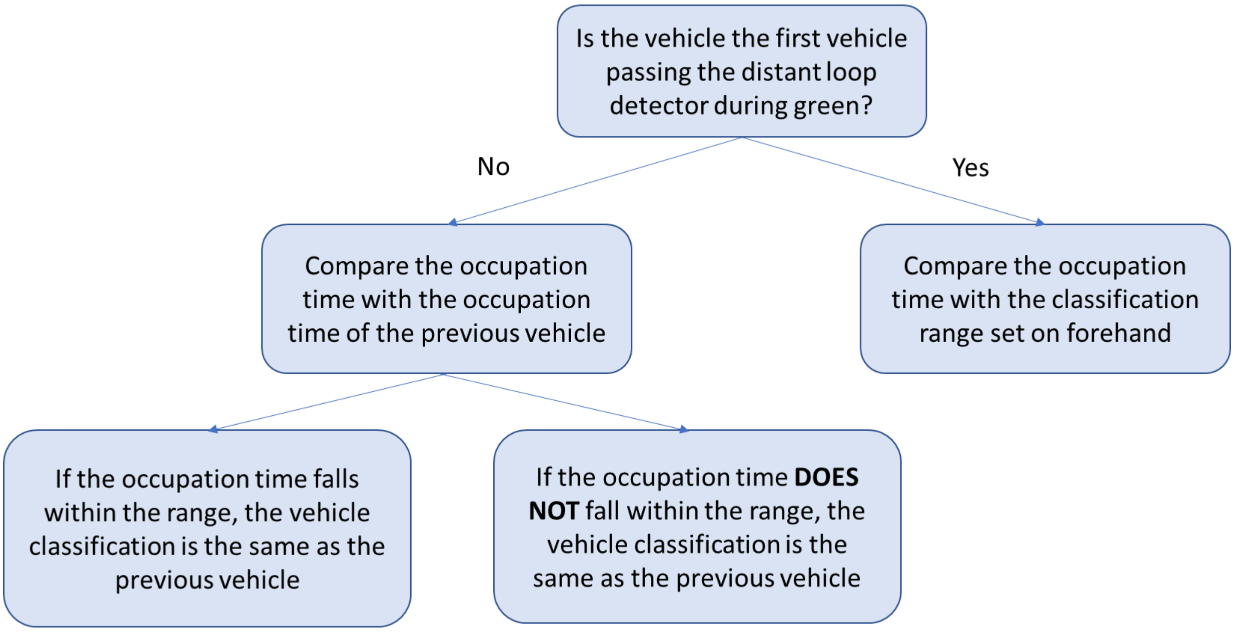

Figure 11: Schematisation of the method which determines the vehicle classification based on the occupation time of the previous vehicle. The method is applicable when a the queue is behind the distant loop detector. There is made a distinction between the first and other vehicles passing the distant loop.

4.2.2. Main principle

The methods described above, determine the vehicle classification of the vehicle that passes the distant loop detector. Even though the method to do this is different per situation, the main principle behind the algorithm is the same for all methods. In Figure 12 a schematisation of the main principle can be found.

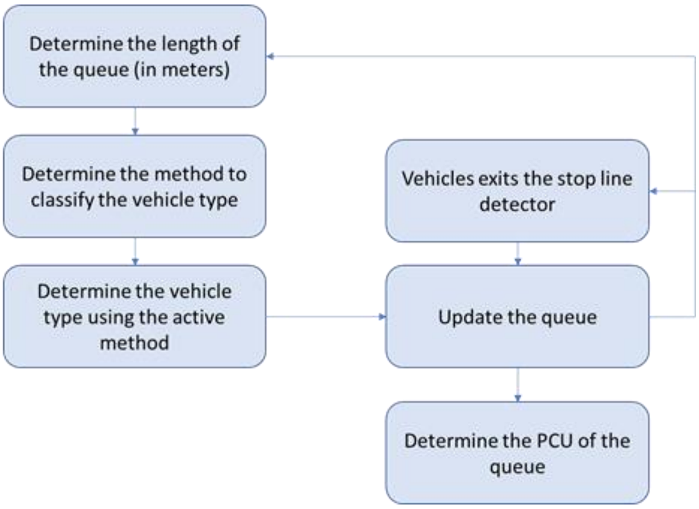

Figure 12: Main principle of the algorithm that determines the vehicle classification

All of the aspects of the main principle, that is depicted in Figure 12, are connected to the created queue. Therefore, the most important part (besides the determination of the vehicle classification) is to track the queue correctly. This is done by filling an array when vehicles pass the distant loop detector. Vehicles are removed from the array when a vehicle passes the stop line detector. Since the (expected) length and PCU per vehicle type are known, the length and the PCU of the queue can be calculated using the array.

5. Results

In this section the results are explained. This is divided in two parts. The first part shows the results that indicate the accuracy of the algorithm. The second part shows the effects on the traffic flow, traffic safety and credibility of traffic control system if the algorithm is implemented.

To determine the accuracy and effects, simulation runs for the intersection called Oss 15 (shown in Appendix B – Simulation tool + Oss 15) are done. This is done using multiple scenarios The other conditions of these tests are kept the same and correspond to the 'basic' situation of Oss 15. To generate enough data, all tests are executed in the simulation for one simulation week.

5.1. The accuracy of the algorithm

In order to determine the accuracy of the algorithm, the data made by the simulation is compared to the data that is generated by the algorithm. More specifically, for the algorithm that detects and incorporates cyclists in the application it is checked whether the number of cyclists that is detected by the algorithm corresponds to the data generated by the simulation. Besides that the number of cyclists in the waiting queue determined by the algorithm is compared to the number of cyclists in the queue according to the simulation. For the algorithm that detects and incorporates long vehicles, it is checked whether the classification corresponds with the type of vehicle that is generated by the simulation. In this sub-section, the results are shown.

5.1.1. Algorithm to detect and incorporate cyclists

To determine the accuracy of the algorithm that is generated to detect and incorporate cyclists, the results are split in two part; The number of cyclists that is detected per passage of the distant loop detector and the number of cyclists in the queue. As is mentioned in the Methodology Section, the accuracy is determined using multiple tests. Test 1 corresponds with the basic/normal situation. In test 2, the traffic volume is increased for all signal groups. In this test, signal group 22 got the smallest traffic volume and signal group 28 the highest. In the last test, test 3, the speed of the cyclists is adapted. In that test, signal group 22 got lower speeds, signal group 26 got a higher speeds and signal group 28 got a bigger spread in speeds compared to the 'basic' scenario. In the Methodology Section and in Appendix C – Methodology is explained why these tests are chosen.

5.1.2. Number of cyclists detected

The goal of the algorithm that detects and incorporates cyclists, is to have a good estimation of the number of cyclists in the queue. In order to determine this correctly, it is desired to know the number of cyclists that pass the distant loop detector per occupation as accurately as possible. Therefore, the accuracy of this is investigated.

To calculate the accuracy, it is determined in how many cases the algorithm expected the same number of cyclists to pass the detection loop as in reality (or in this case the simulation). When the number of cyclists expected by the algorithm deviates from the simulation, it is determined how much it deviates. In Figure 13 the results of this can be found for the three different tests. On the x-axis the number of cyclists that pass the distant loop detector in the simulation is plotted. The different bars indicate the deviation the algorithm displayed compared to the simulation. On the y-axis is plotted how big the percentage is that the bars correspond with.

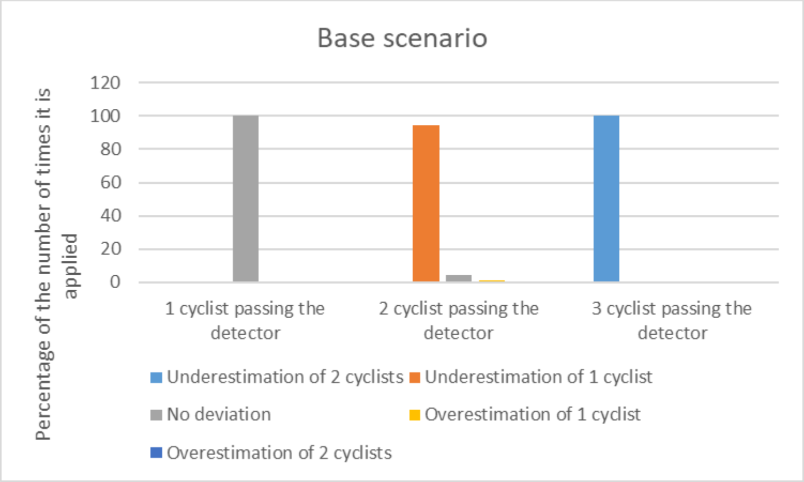

Figure 13a: The accuracy of the number of cyclists that is detected per occupation for the first test: the base scenario.

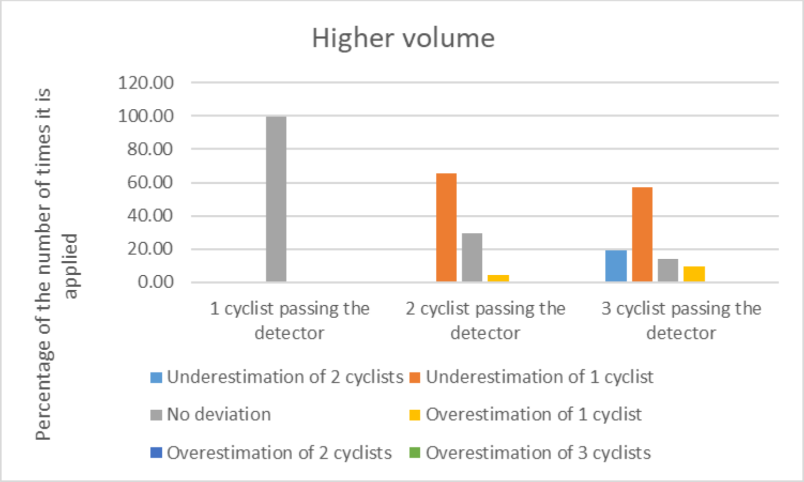

Figure13b : The accuracy of the number of cyclists that is detected per occupation for the second test: when the traffic volume is increased.

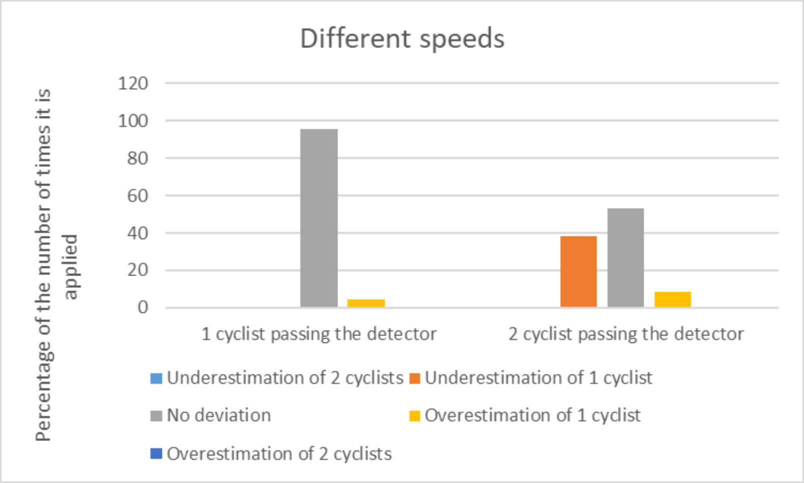

Figure 13c: The accuracy of the number of cyclists that is detected per occupation for the third test: where the speeds of the cyclists are altered.

Figure 13: The accuracy of the number of cyclists that is detected per occupation. On the x-axis the number of cyclists that pass the distant loop detector in the simulation is plotted. The different bars indicate the deviation the algorithm displayed compared to the simulation. On the y-axis is plotted how big the percentage is that the bars correspond with.

When looking at Figure 13, it can be seen that in general applies that if only 1 cyclist passes the distant loop during occupation, the algorithm can detect this in a correct way. Since, when this is the case the bar called ‘no deviation’, which indicates that there is no difference between the expected number of cyclists by the algorithm and the number of cyclists that actually pass the detection loop, is in all cases (almost) 100%. When looking at the cases where multiple cyclists (2 or 3) pass the detection loop during one occupation, the number of cyclists expected by the algorithm deviates more from the number of cyclists that actually pass the detection loop. This is shown by the fact that the bars which indicate these deviations are bigger and the fact that the bar which indicates that there is no deviation is not reaching 100%.

From this can be concluded, that the algorithm is not very accurate when multiple cyclists are passing the detection loop during one occupation. However, it should be kept in mind the Figures display the percentages. When looking at the absolute values, it is noted that in almost all cases only one cyclist passes the distant loop detector at once. In Table 1, an overview is given of the absolute values.

RMSE

Besides the deviation displayed in Figure 13, the Root Mean Square Error can be calculated for the different tests. The Root Mean Square Error (RMSE) indicates how good the algorithm ‘fits’ to the dataset of the simulation (Zach, 2020). The main difference with the results in Figure 13, is that the RMSE takes into account the number of times that the occupations happen (so the absolute values and not the percentages). If the RMSE is higher, the distribution is bigger. Meaning that the algorithm performs worse. In Table 1, the RMSE for the number of cyclists per passage is shown.

Table 1: The RMSE of determining the number of cyclists per passage

	Base scenario	Higher traffic volume	Different speeds
Total	0.0619	0.122	0.215
fc22	0.0700	0.073	0.050
fc26	0.0575	0.115	0.319
fc28	0.0574	0.138	0.193

In Table 1 can be seen that the RMSE is higher for test 2 and test 3, than for test 1. It can also be seen that within those tests, the RMSE is different per signal group. From test 2 can be determined that if the traffic volume is higher (signal group 26 and signal group 28), that the RMSE is higher. This can be explained by the fact that the deviation between the algorithm and the simulation is higher in those cases. For test 3 applies that signal group 26 has the worst RMSE. From this can be derived that if the speeds are higher, that the difference between the number of cyclists determined by the algorithm and the number of cyclists that actually pass the loop detector is higher. Also if the spread of speeds is higher, the RMSE is higher. However, it is unclear if this is due to the spread or because of the higher speeds.

The reasons why test 2 and test 3 are less accurate, is because the traffic volume is higher so the chance that cyclists cycle next to each other is also higher. It has emerged that the algorithm does not always count multiple cyclists when this is the case, because the occupation time is not always higher than the occupation time of one cyclist. The second reason, is the fact that if the speed is higher, the occupation time is lower. In that case, also the occupation time in which multiple cyclists pass the distant loop is lower. Therefore it is more likely that multiple cyclists pass the distant loop detector while the algorithm only counts them as one (since the occupation time is comparable with the occupation time of one cyclist) . This corresponds with the results shown in Figure 13.

5.1.3. Number of cyclists in the queue

As mentioned, the main goal of the algorithm is to determine the number of cyclists in the queue correctly. Therefore, it is desired to know the accuracy of this. To determine the accuracy of the number of cyclists in the queue, the queue generated by the algorithm is compared to the queue from the simulation at start green. The accuracy is expressed in the number of times (translated to percentages) that the algorithm is accurate about the number of cyclists in the queue. Besides this, it is also stated in how many times the algorithm deviates from the actual number and how big this deviation is.

In Figure 14 the results of this are given for the three different tests that are executed. The results are displayed for the different number of cyclists in the queue, which is stated on the x-axis. The y-axis, show the percentage of times that the different situations occur. These situations, in other words the magnitude of the deviation, are displayed by the bars.

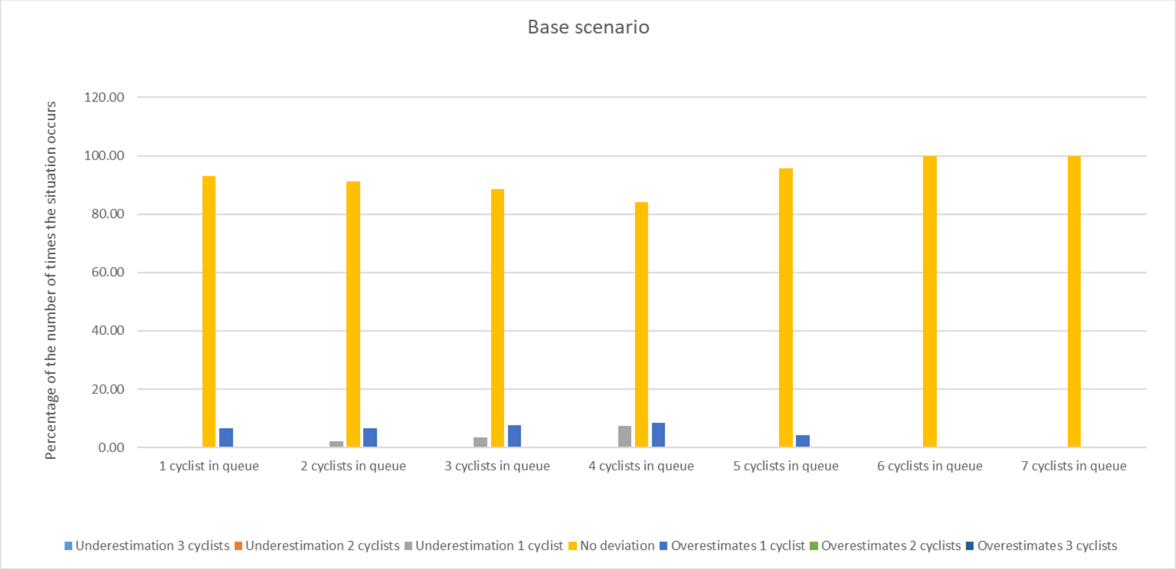

Figure 14a: The accuracy of the number of cyclists in queue for the first test: the base scenario.

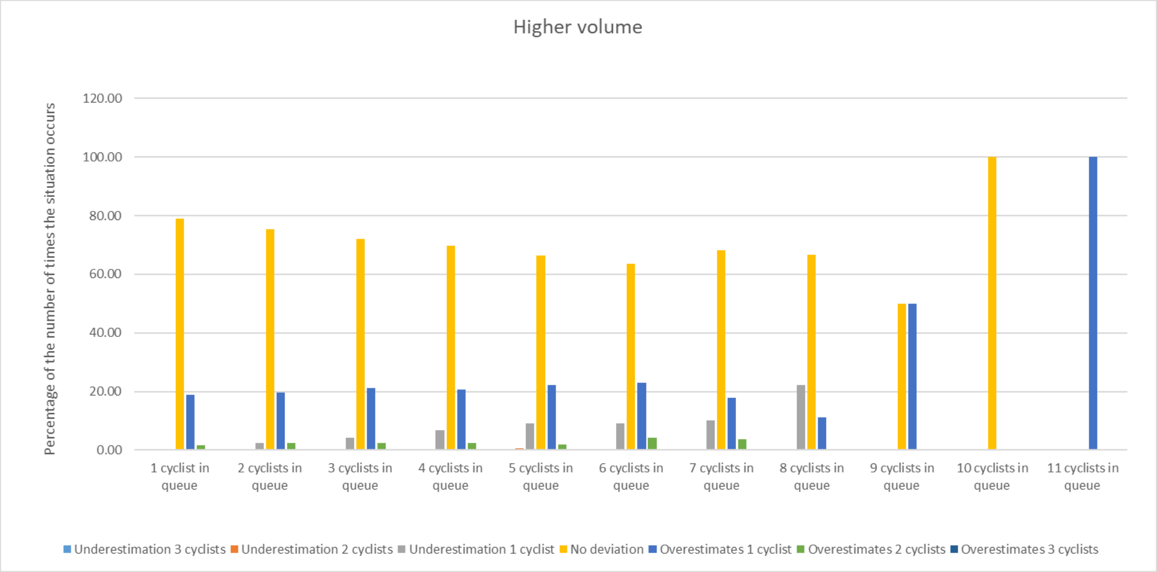

Figure 14b: The accuracy of the number of cyclists in queue for the second test: where the volume of cyclists is altered compared to the base scenario.

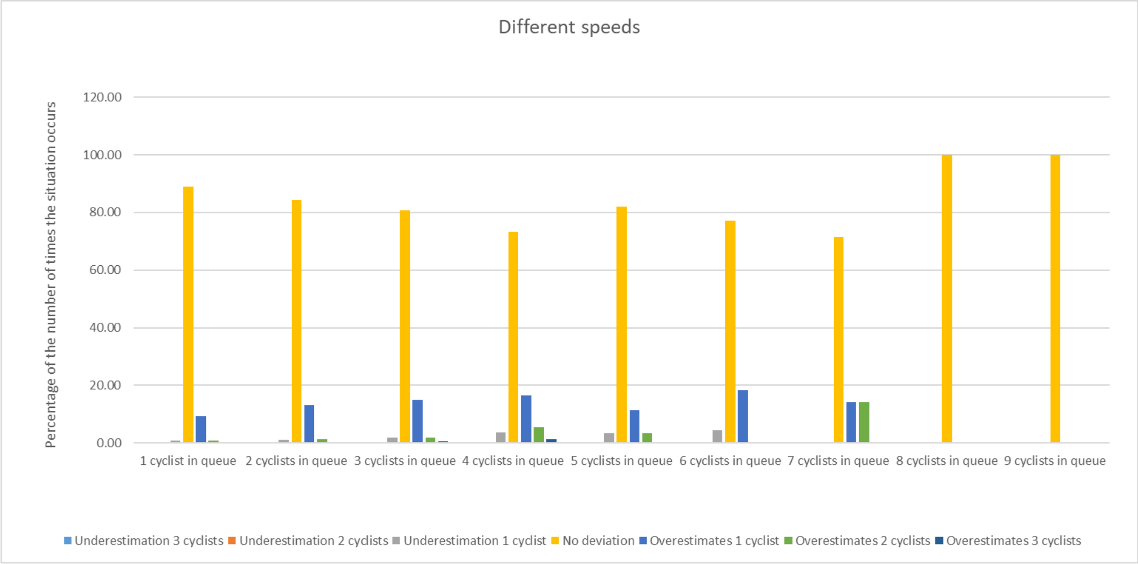

Figure14c : The accuracy of the number of cyclists in queue for the third test: where the speeds are altered compared to the base scenario.

Figure 14: The accuracy of the number of cyclists in the queue. On the x-axis the number of cyclists that are in the queue is plotted. The different bars indicate the deviation the algorithm displayed compared to the simulation. On the y-axis is plotted how big the percentage is that the bars correspond with.

As can be seen in the Figure, the algorithm determines the number of cyclists in the queue correctly in many cases. For most situations applies that in 80% of the cases the algorithm determines the number of cyclists in the queue correctly. What also can be seen is that in many of the cases in which a deviation takes place, it is only a deviation of one cyclist. One thing that should be kept in mind is the fact that the Figures displays percentages. When looking at the absolute values, it is noted that the queues with less cyclists occur more often.

Something that stands out from Figure 14, is the fact that the performance of the algorithm is better for the base scenario than for the other tests. Which is logical when looking at the RMSE score of the number of cyclists detected per occupation. The RMSE showed that the part of the algorithm that determines the number of cyclists passing per occupation was more accurate for the base scenario. The number of cyclists in the queue is mainly based on this, therefore it is logically that also in this case the algorithm performs better for the base scenario as for the other situations.

Another thing that stands out, is the fact that if the number of cyclists in the queue is higher, the deviation is in general bigger. This can be explained by the fact that the volume is in that case higher than in the case where less cyclists are in the queue. As is mentioned before, if the volume is higher the chance that cyclists cycle next/close to each other is bigger. As is shown in Figure, the algorithm is not that accurate when multiple cyclists are passing during one occupation. This could be the reason why the deviation is higher when the number of cyclists in the queue is higher.

Besides this, it should be noted that the algorithm adds cyclists to the queue earlier than the simulation. The algorithm adds cyclists to the queue after they have passed the distant loop detector, while the simulation does this when they are actually waiting for the traffic light. Therefore it is possible that at start green cyclists are taken into account by the algorithm but not by the simulation since they already passed the distant loop detector but are not waiting in the queue yet. Especially if the traffic volume increases, the chance that this happens increases.

RMSE

Also for the number of cyclists in the queue, the RMSE can be determined. In this case also applies that if the RMSE is higher, the deviation is bigger. Meaning that the accuracy of the algorithm is worse. In Table 2, the results of the RMSE can be found.

Table 2: The RMSE of determining the number of cyclists in the queue

	Base scenario	**Higher traffic volume**	**Different speeds**
Total	0.2824	0.564	0.396
fc22	0.2813	0.363	0.268
fc26	0.2779	0.536	0.471
fc28	0.2903	0.673	0.378

When comparing Table 2 to Table 1, it is noted that the RMSE is higher for the number of cyclists in the queue than for the number of cyclists per occupation. This corresponds with the results shown in Figure 13 and Figure 14. Besides this, the results show that test 2 has the highest RMSE. Also the RMSE of test 3 is higher than from test 1. This also corresponds with the results shown in Figure 14. As mentioned before, the deviation is probably higher due to the fact that multiple cyclists pass the detection loop during one occupation. The algorithm does not always incorporate this. When the volume is higher, the chance that this occurs is higher.

For the third test, the one where the speeds are altered, an explanation of the higher RMSE could be the fact that number of cyclists detected by the algorithm is different from reality due to the fact that the occupation times are different causes by the different speeds. If for example the speeds are higher the occupation time is lower, this makes it more likely that two cyclists have the occupation time of one cyclist.

5.1.4. Algorithm to detect and incorporate long vehicles

To determine the accuracy of the algorithm that classifies the different motor vehicles (passenger car or long vehicle), multiple tests are conducted. As is mentioned in the Section Methodology, The first test is the basic situation. In test 2, the percentage of freight traffic is higher (10% instead of the 4% in the 'basic' situation). In the third and fourth test, the traffic volume is altered. In test 3, the traffic volume is taken as 1.5 times the traffic volume of the 'basic' situation. In test 4 the traffic volume is 0.5 times the volume of the 'basic' situation. More explanation of these tests can be found in the Methodology Section and in Appendix C – Methodology.

To evaluate the accuracy of the algorithm, for all tests is determined in how many cases the algorithm determines the correct vehicle classification. Therefore, four situations are possible, namely:

- A car is classified as a car;
- A car is classified as freight;
- Freight is classified as freight;
- Freight is classified as a car.

The first and third situation (car as car and freight as freight), are the desired situations to occur. In those cases, the algorithms performs like it is supposed to. The result of this evaluation is shown in Figure 15. In this figure the upper part shows the accuracy of the classification car and the lower part shows the accuracy of the classification freight. On the x-axis, the different tests conducted are plotted. On the y-axis the number of times that a situation occurs is displayed. The bars indicate the different situations that are possible.

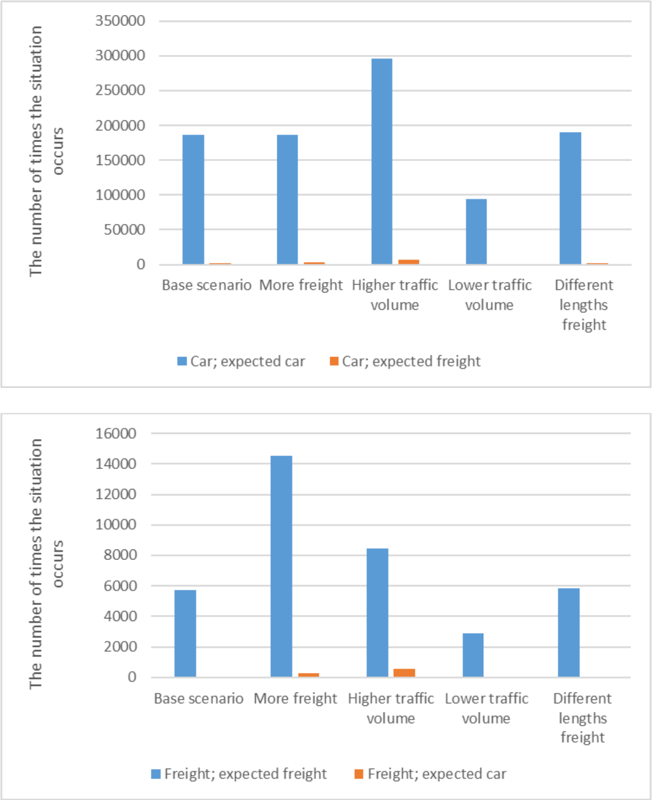

Figure 15: The results of the accuracy of the algorithm that classifies motor vehicles. On the x-axis, the different tests conducted are plotted. On the y-axis the number of times that a situation occurs is displayed. The bars indicate the different situations that are possible.

When looking at the figure, it stands out that the number of times that the algorithm determines the classification wrong is low. In other words, the algorithm has a high accuracy. Even the tests for which the algorithm was not calibrated (the test with the different lengths of freight traffic), scored a high accuracy. Besides the overall results, there are also results for the different methods. For the method that uses the braking distance to classify the vehicle, the results correspond with the overall results. These can be found in Appendix E. The results of the other methods are explained below

Results method standing still on the distant loop detector

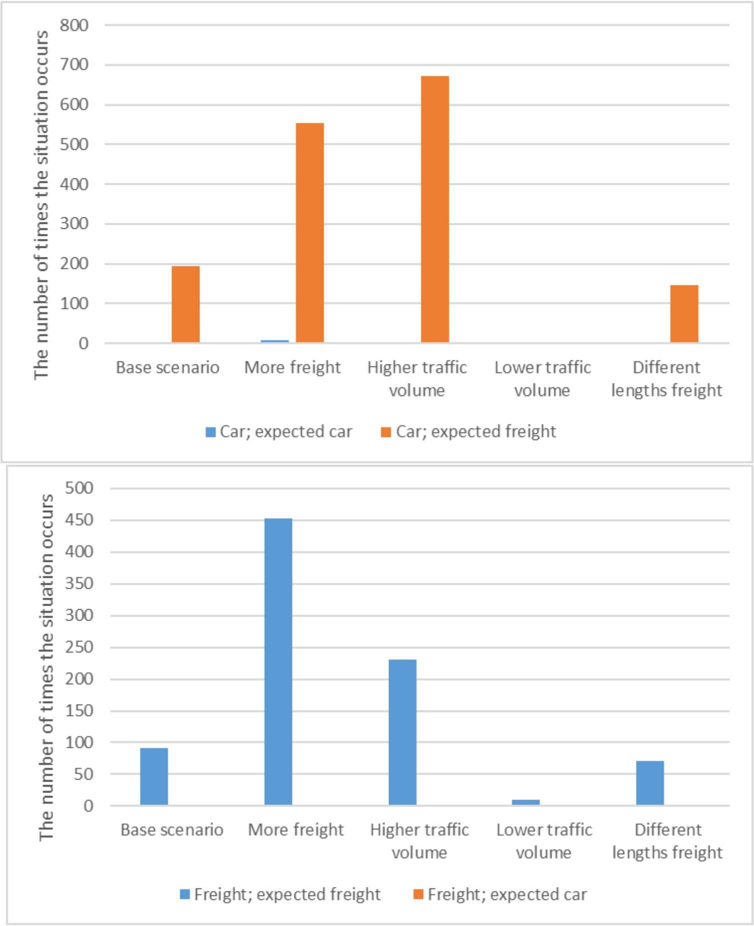

Figure 16: The results of the accuracy of the algorithm that classifies motor vehicles for the method when a vehicle is standing still on the distant loop detector. On the x-axis, the different tests conducted are plotted. On the y-axis the number of times that a situation occurs is displayed. The bars indicate the different situations that are possible.

As can be seen in the figure, the method that is used to determine the vehicle classification when a vehicle is standing still on the distant loop detector has a high accuracy for the detection of freight traffic. However, it is not good at classifying a passenger car. When looking at all the results, this outcome can be explained by the fact that in many cases a vehicle has a high occupation time (more than the boundary value for which this method becomes active). In many of those cases, the distance between the end of the queue and the distant loop detector is quite high (more than the length of a car). This results that in almost all cases the vehicles are classified as a truck, however in reality the vehicle is a passenger car.

However, classifying cars as freight is not as big as a problem as classifying freight as cars. Because if a car is classified as freight, the calculations will be altered in such a way that the green times are enhanced while this is not necessary. If it is the other way around, the green times will be too small for all vehicles to pass, resulting in extra stops and a higher waiting time for vehicles.

Results method using the occupation time of the previous vehicle

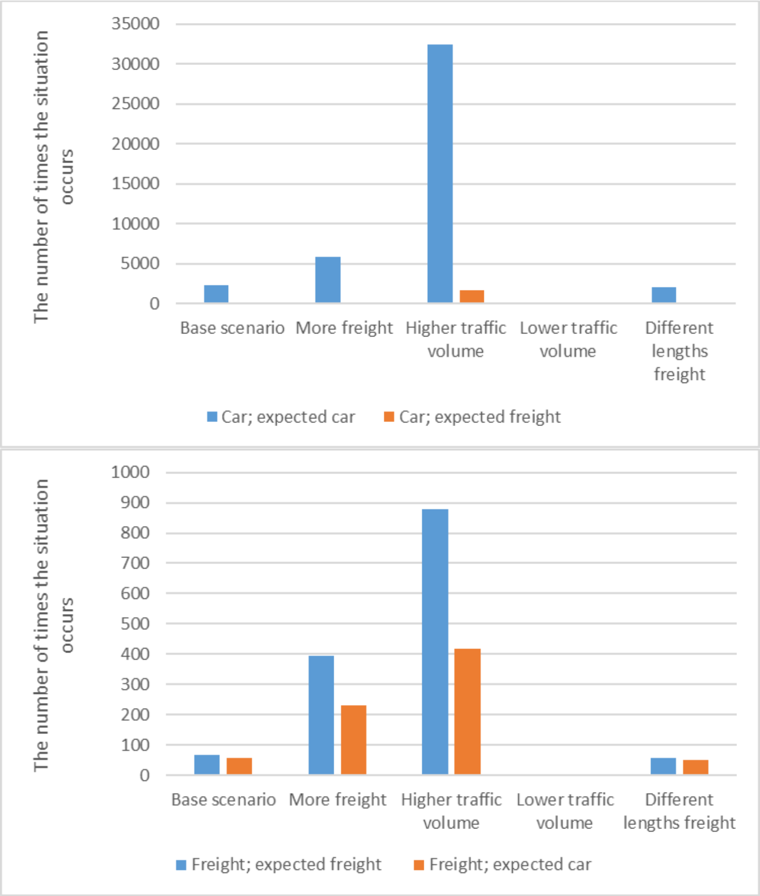

Figure 17: the results of the method which uses the occupation time of the previous vehicle

As can be seen in the figure, the method which bases the vehicle classification on the occupation time of the previous vehicle has a high accuracy for cars. However, when looking at the accuracy for classifying trucks this is significantly worse. When looking at the data, it could be seen that in some cases the occupation times of passenger cars and vehicles is not different. This results in the fact that no distinction can be made between passenger cars and freight traffic.

For some tests, there is little to no data. This is due to the fact that in those tests the queue does not grow behind the distant loop detector frequently. This is mostly the case in the situation where the traffic volume is lower. However, in the case with more freight traffic it happens frequently due to the fact that the queue is generally longer because more freight traffic is present.

5.2. The effects of implementing the algorithm

As mentioned in the Section Methodology, the effects on the traffic flow, traffic safety and the credibility of traffic control systems that are and will be equipped with Gouden Regelen can be determined using the waiting times and the number of stops for the intersection. In this study, the loss time and the chance on an extra stop in front of the intersection are used to determine the effects. These effects are determined for four different scenarios, namely:

- A scenario where the algorithms are not implemented;
- A scenario where both algorithms are implemented;
- A scenario where only the algorithm to detect and incorporate cyclists is implemented;
- A scenario where only the algorithm to classify motor vehicles is implemented.

For all these scenarios applies that all the other variables are kept the same.

The loss time per road user

The first result that is given, is the average loss time per road user (in other words the waiting time per road user). To analyse this result, a figure is made in which the loss time in seconds is plotted against the time of the day. This is depicted in Figure 9. On the x-axis, the time during the day is given. On the Y-axis, the loss time in seconds is given.

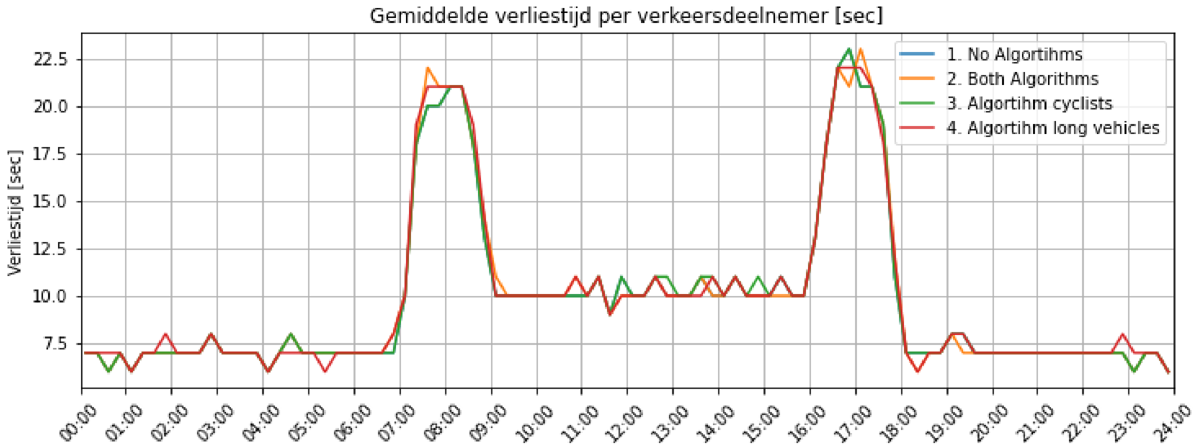

Figure 18: The average loss time for all the road users

From the Figure can be concluded that there is no significant difference between the four different tests. This applies for both the peak hours and the off-peak periods. The figure gives the results for all road users, however there is also looked at the results in which only cyclists or only motor vehicles are taken into account. From this results was concluded the same (that no significant difference is found). The results of this can be found in Appendix E.

The chance of extra stops

Besides the loss time for the vehicles, the chance that during a green cycle vehicles have to stop multiple times before the intersection is also determined. The result of this is that only during peak hours a small chance to have extra stops can be seen. However, this chance is so small and no significant differences can be spotted between the different scenarios. Therefore, this is not taken into account. Instead there is looked at the frequencies of the individual signal groups to evaluate the effects.

When looking at the frequencies of the individual signal groups some differences can be seen. Even though differences are spotted, these differences are not always in line with each other. In Figure 19 and Figure 20 the frequency that vehicles have to stop multiple times before passing the intersection for different green times is given for two signal groups (signal group 9 and 10). The results for the other signal groups can be found in Appendix E. In these figures the time is given on the X-axis in seconds, and on the Y-axis the frequency that extra stops occurred is given. As can be seen in the Figure, the number of stops for signal group 9 is smaller when both algorithms and when the algorithm for long vehicles are implemented compared to when none of the algorithms or only the algorithm to detect cyclists is implemented. However, when looking at signal group 10, this is the other way around. When looking at the two figures, it should be kept in mind that the values on the y-axis are different in both figures.

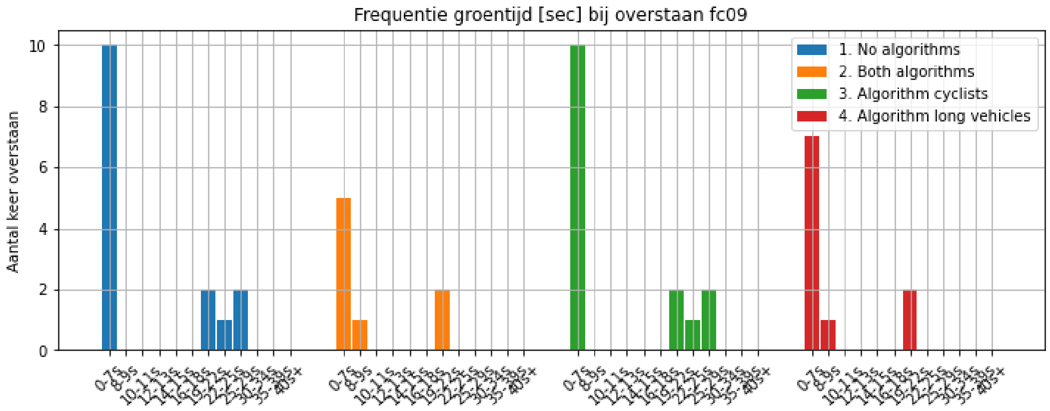

Figure 19: The number of stops for different green times for signal group 9

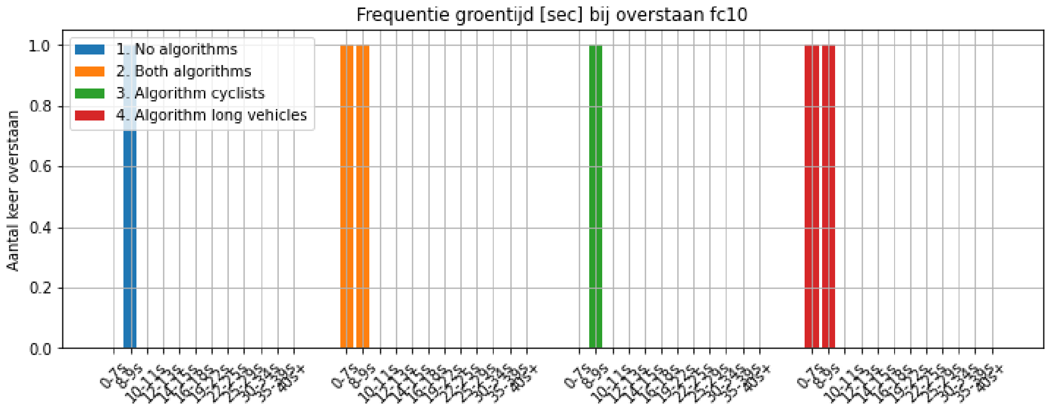

Figure 20: The number of stops for different green times for signal group 10

What can be seen in both figures is that there is a peak at the green realisations with the smallest green time. This can be explained by the fact that these green times mainly correspond with alternative green realisations. Alternative green realisations, is the principle that a signal group gets green due to the fact that they are not in conflict with the signal group that receives green because they have the highest cumulative waiting time. During alternative green realisations, there is not looked at how long the signal groups should receive green. The green time is based on the green time of the signal group that receives green in the first place. This causes that the chance that vehicles have to stop multiple times increases.

Since the number of times that extra stops happen is negligible small (the number of extra stops is very small when comparing it to the total number of green realisations), and due to the fact that no significant difference is spotted in the chance to have extra stops. It can be said that there is no significant difference between the number of extra stops for the different scenarios.

6. Discussion

The results shown in the previous section are liable for some points which are discussed in this section.

Firstly, in order to detect and incorporate cyclists into the application, the algorithm uses two methods. During red, the algorithm adds the cyclists to the queue that are detected by the distant loop detector. During green, the cyclists are stored in an array and are added to the queue at start red (if they did not pass the intersection). It is assumed that the cyclists that arrive during red time will pass the intersection during the next green phase. This assumption is plausible, since the green time is in fact always longer than the needed time to travel from the distant loop detector to the intersection. However, this is not proven in a scientific way.

For the algorithm that detects and incorporates long vehicles, also a caution should be given. The algorithm only makes a distinction between a passenger car and a truck (of 18 meters). While in reality, there are more classifications in terms of vehicles with different lengths. Even though a test is executed to check the accuracy of the algorithm when the length of long vehicles is different, it is expected that the different lengths can have an effect on the other calculations of Gouden Regelen. For example the PCU is set at a value for long vehicles, however a vehicle of 18 meters is likely to have another PCU as a vehicle of 12 meters.

For both algorithms applies that some of the parameters or methods used are not based on data or on literature. For example, the boundaries which are used to determine the range of the occupation time of the previous vehicle to compare with the current occupation time. But also the method that uses the braking distance is not based on literature. The method expects the vehicles to have a linear deceleration. For some of these parameters/methods applies that the output given by algorithm is very dependent on the value of them. For most parameters and methods applies that is plausible that they are correct, since the accuracy of the algorithms is high. However, changing them to other values could improve the algorithm.

To test the effects of the algorithm, a simulation is run for an intersection called Oss 15. This intersection is a three-arm intersection. In this study, the effects are only tested under 'normal' circumstances. However, to get a good indication of the effects it is desired to test the effects under multiple conditions. In that case it can be determined in which situations (whether) it is useful to implement the new algorithms. Also, if an intersection has more arms the degrees of freedom (for the different stages) get higher. In that case, the results will be different and possibly more/other effects can be seen.

Lastly, a point of discussion is the fact that a simulation tool is used to evaluate the accuracy and the effects of the algorithms. As is mentioned in the section Theoretical Framework, a simulation tool is a liable way to test the effects of traffic control systems. However, a simulation cannot be conveyed for 100% in a simulation tool. There will always be differences between the simulation tool and the reality. Therefore also the effects that are determined using the simulation tool could be (slightly) different in reality.

7. Conclusion

The goal of this research was to find an answer to the research question which is stated in the section Research Questions. In order to do so, three sub-questions were prepared. In this section an answer to these question is given.

7.1. How can different target groups be recognised by the Gouden Regelen application?

The answer to this question, are the algorithms which are designed to detect and incorporate cyclists and long vehicles in the Gouden Regelen application. In short applies that cyclists can be incorporated using the follow-up time and the occupation time of the distant loop detectors. Using this information it can be determined whether a cyclists is going in the right direction and to determine the amount of cyclists passing per occupation. This number of cyclists can be added to the queue.

For the algorithm that detects and incorporates long vehicles applies that depending on the situation, different methods can be used to classify the different motor vehicles. In total there are three situations, the queue fits within the detection field, a vehicle is standing still on the distant loop detector or the queue grew behind the distant loop. Respectively the method used would be based on the braking distance, distance between end of the queue and the distant loop detector or the occupation time of the previous vehicle.

7.2. How can the different target groups be implemented in the Gouden Regelen application?

The algorithms can be implemented by adapting the queues of the cyclists and the motor vehicles. For cyclists applies that it can be altered by changing the standard weight that is given to the number of cyclists in the queue. For motor vehicles applies that the number of vehicles in the queue is altered to the PCU of the queue.

7.2.1. Accuracy of the algorithms

Even though, the target groups can be implemented the question arises whether it is desired to implement the target groups. This can be answered using the accuracy of the algorithms.

When looking at the results of the accuracy of the algorithm that detects and incorporates the number of cyclists that are in the queue, it can be concluded that in general the accuracy of the algorithm is high. It is noticed that if the traffic volume increases, the algorithm is more likely to underestimate the number of cyclists. Which corresponds to earlier researches. Since the accuracy is still high, even when the traffic volume is increased, it is concluded that based on the accuracy, the algorithm could be implemented in the Gouden Regelen application. However, if it is known that an intersection has a high volume of cyclists, it could be desired to adapt the number of cyclist in the queue with a correction factor.

For the algorithm that detects and incorporates long vehicles applies that the accuracy of the algorithm is also high. This is also true for the different scenarios for which the algorithm is tested. When looking at these results, it could be concluded that the algorithm could be implemented in the application to make a distinction in vehicle classification. However, as already mentioned in the Discussion Section, the algorithm only makes a distinction between a passenger car and a truck (of 18 meters). In order to make it applicable in real life, it is desired to make more distinctions. So to conclude, the algorithm could be implemented in the application. However, it is expected that the performs is not as optimised as possible. Therefore it is desired to expand the algorithm with more vehicle classifications before it is implemented.

7.3. What are the effects of implementing the different target groups within Gouden Regelen on the traffic flow, traffic safety, and the credibility of the traffic control systems that are and will be equipped with Gouden Regelen?

When looking at the effects on the traffic flow, traffic safety and credibility of a traffic control systems that are equipped with Gouden Regelen when the two algorithms are implemented, no (significant) differences can be noticed from the tests conducted. Meaning the effects do neither improve nor deteriorate. However, to draw a conclusion based on these effects it is desired to compute more tests with different scenarios.

8. Recommendations

Because of limited time and knowledge, not all research that is desired could be conducted. Therefore further research is recommended, as is also mentioned in the Discussion and Conclusion sections. In this section is described which further research is recommended.

8.1. Deficiency algorithms

The first recommendation made, is to look at deficiency of the algorithms and to try to solve them.

For the algorithm that determines the number of cyclists in the queue, the main deficiency is the underestimation if the volume of cyclists is high. Since the occupation time is not always different when multiple vehicles pass compared to the occupation time when one vehicle passes, it is hard to solve it. However, it could be tried to decrease the problem by multiplying the number of cyclists in the queue when the volume is higher.

For the algorithm that classifies and incorporates long vehicles, multiple weaknesses are present. The first one is that for the method that is used when a vehicle is standing still on the distant loop detector and the method that is used when the queue has grown outside the detection field, the accuracy of the algorithm could be improved (compared to the other method). For the method that is used to determine the classification of a vehicle that is on the distant loop detector applies that it mainly has a deficiency to classify a car. A possible solution could be to compare the distance between the end of the queue and the detector not only with the length of a passenger car, but also with a long vehicle. If the distance is also bigger than a long vehicle, than classify it as a passenger car. For the method which uses the occupation time of the previous vehicle, it could be optimized by doing more research to the link between the occupation time of two succeeding vehicles. Currently, a range is taken. However, it could be possible that this range is not big enough/too big.

Besides this, the algorithms currently assumes that the vehicles that pass the distant loop detector do not switch lanes. However, in reality this is a principle that happens. If vehicles change lanes, this has impact on the algorithm. Because the queue that is generated by the algorithm is different and therefore calculations made by the application are not based on the real situation. Therefore it is recommended to investigate how this principle can be incorporate into the algorithm.

Lastly, as already mentioned in the Conclusion Section, in order to implement the algorithm to detect and incorporate long vehicles in the Gouden Regelen application it is desired to expand the algorithm by making a distinction between more vehicle classifications. Therefore it is recommended to investigate how more distinction in vehicle classification can be made.

8.2. Testing

The second part of recommendations exists out of conducting extra tests.

During this study, multiple tests are conducted to determine the accuracy of the algorithms. However, these tests do not incorporate all possible situations (which are expected to influence the accuracy). Firstly, the tests that are conducted are conducted by only changing one parameter. However, if multiple parameters are changed the effect on the accuracy could be different.

Besides that, some parameters are not changed yet to evaluate their effect on the accuracy. For example, for the motor vehicles the deceleration and acceleration is set at a fixed value for freight and for passenger cars. However, in reality there will also be differences within those groups.

Therefore it is recommended to conduct more tests to evaluate the accuracy of the algorithms. This also contributes to testing the accuracy for the real situation, since these tests will look more like reality.

Next to this recommendation, it is also recommended to execute more tests for different scenarios to determine the effects on the traffic flow, traffic safety and credibility of traffic control systems equipped with Gouden Regelen. By doing this, a better insight can be given on what the effects are. Different scenarios that are recommended to test, are different type of intersection (for example a four-armed intersection), different traffic volumes and different compositions of traffic (for example, different percentage of freight traffic, different speeds for cyclists, etc.).

Lastly, the tests are conducted using a simulation tool. When the tests are executed in reality, the results could be different. Therefore, it is recommended to execute the tests on real life applications (when all other tests are conducted successfully).

Based on the tests (for both the accuracy as to determine the effects), it could be desired to alternate the algorithms in order to improve them.

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Appendices

Appendix A – Theoretical framework : Gouden Regelen

In this section, an elaboration is given to the explanation about the components of the module Omniflex of the application Gouden Regelen that is given in the Section Theoretical Framework.

Estimated actual traffic volume

The first step that is determined by Gouden Regelen, is the estimated actual traffic volume of a signal group. The traffic volume indicates the number of vehicles passing a cross-section of a road per unit of time (van Berkum, Flow Characteristics and Measurement - part 3, 2020). The traffic volume is estimated based on the number of occupancies of the stop line or distant loop detector during a cycle (or multiple cycles). This data corresponds with the number of vehicles that have passed the detector (the number of occupancies is equal to the number of vehicles). With this information, the traffic volume can be calculated using the following formulae:

$$q = \frac{n}{T}$$

Equation 1 (van Berkum, Flow Characteristics and Measurement - part 3, 2020)

Where:
q (veh/min) = The traffic volume of a traffic flow
n (-) = The number of vehicles that have passed
T (min) = Time interval

In this case, a cycle is from the start red moment till the next start red moment. Thus the time interval is the length of one cycle, and the number of vehicles that have passed is calculated for this time interval.

Estimate the number of vehicles in the queue

The maximum green times can be calculated when the actual traffic volume is determined. First, the number of vehicles in the queue is estimated. In order to do this, two methods can be used. The first method uses the data received from the detection loops (both the stop line and distant loop detector) to determine the (estimated) number of vehicles in the queue. The method uses the entering of the distant loop detector (in Dutch: opkomen van de detectielus); this occurs when a vehicle arrives at the loop detector. From the stop line detector, this method uses the data of the number of vehicles that are exiting from the detection loop (in Dutch: afvallen van de detectielus). These vehicles have passed the detection loop and are now leaving the stop line (and are thus out of the queue).

By using this data, the queue can be determined using a simple equation:

$$\begin{aligned} &Number\ of\ vehicles\ in\ the\ Queue \\ &= number\ of\ occupations\ distant\ loop\ detector - number\ of\ occupations\ stop\ line\ detector \end{aligned}$$

Equation 2

To determine the number of vehicles in the queue as accurately as possible, a distinction is made between the entering and exiting from the detection loop. If, for example, the stop line detector would also use the data of the entering of the detection loop, the loop measures when a vehicle enters the stop line detector. However, if the traffic light is red, the vehicle is still waiting in line while the number of vehicles in the queue is already deducted by one vehicle.

When the counted queue is too long to fit within the two loops (so it grows behind the distant loop detector) or when method one is not applicable (for example, when one of the detection loops is not operable), the application will determine the number of vehicles in the queue based on a second method. The second method estimates the number of vehicles in the queue using the estimated actual traffic volume and the time that it is red. When rewriting Equation 3, you get the following equation with which the number of vehicles in the queue can be determined:

$$n = q * T$$

Equation 3 (van Berkum, Flow Characteristics and Measurement - part 3, 2020)

Where:
N (-) = The number of vehicles in the queue
q (veh/min)= The traffic volume of a traffic flow
T(min) = Time of red

For both methods applies that vehicles arrive at the traffic light during the green time. These vehicles are also incorporated in the number of vehicles in the queue.

As mentioned before, when the application uses the first method to estimate the number of vehicles in the queue but the queue is too long to fit within the two detection loops, the second method is used to determine the number of vehicles in the queue. In that case, the first method is used to calculate the number of vehicles in the queue between the two detection loops. The second method is used to determine the number of vehicles in the queue behind the distant loop detector. These numbers are added together to determine the number of vehicles in the queue. To determine if this second method should be used, it is determined whether the number of vehicles in the queue reached a certain number (set on forehand). This number indicates the maximum number of vehicles in the queue that fit between the two detection loops. However, this number is estimated and can be different in real life (if, for example, a long vehicle is in the queue). Therefore, the application also takes into account whether the distant loop detector is occupied for a certain time. If this time reaches a certain number, it is expected that a vehicle is standing still on the distant loop detector, and therefore that the queue is growing behind the distant loop detector.

Calculate the maximum green time

When the queue is known, the maximum green time can be calculated. The basic principle the OmniFlex-module uses for this, besides the queue, is the discharge rate of a road. The fundamental relation for this is described in Equation 4.

$$Maximum\ green\ time = \frac{Number\ of\ vehicles\ in\ queue}{Discharge\ rate}$$

Equation 4

However, the application also considers other factors influencing the maximum green time. Such as the acceleration loss, which is the loss because humans will not immediately drive when it is green. Also, to incorporate that not all vehicles will accelerate as fast as expected, the maximum green time is multiplied by a number set on forehand to ensure that the green time is enough. Besides the loss due to acceleration, also utilised yellow time, which indicates the time that it is already yellow but vehicles will still drive since they are not on time to stop anymore, is taken into account. To ensure that signal groups do not have to wait (unnecessarily) long, a maximum cycle time is predefined (mostly

100-120 seconds). When the sum of the maximum green times is bigger than this maximum cycle time, the maximum green times will be decreased.

Order of the Phases

To determine the order in which signal groups get green, the stages must first be defined. A stage exists of a number of signal groups that can receive green at the same time. When the stages are defined, the cumulative waiting time for each stage can be calculated. The cumulative waiting time for every signal group can be calculated using Equation 5.

$$Cumulative\ Waiting\ Time = \sum_{t=0}^{\infty} Number\ of\ vehicles\ in\ queue\ (t) * factor$$

Equation 5

The factor in Equation 5 indicates the weight of the signal group. For example, if bikes should get more priority, a signal group with only bicycles will have a higher factor than a signal group with only cars. In Figure 6, a graphical display is given of the cumulative waiting time. In this case, the factor is one for all vehicles and every two seconds, a vehicle arrives.

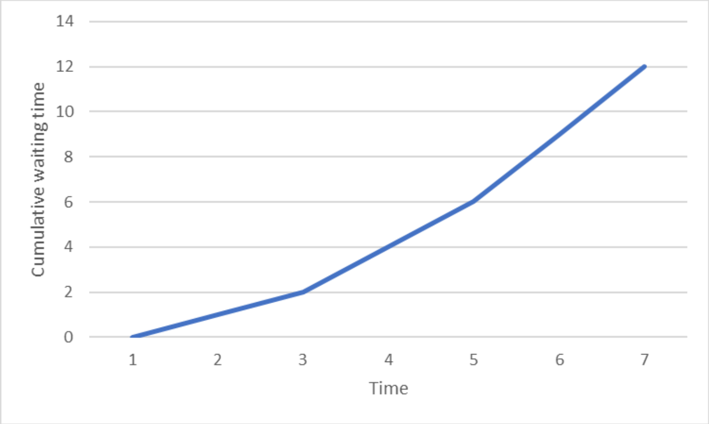

Figure 21: Example cumulative waiting time, every 2 seconds a vehicle arrives with factor 1

Based on the cumulative waiting time of every signal group, the cumulative waiting time per stage can be determined by adding the cumulative waiting time for every signal group in that stage. The stage with the highest cumulative waiting time will receive green first; then, the new cumulative waiting time is determined. The stage with the new highest cumulative waiting time will receive green next, and so on.

Gouden Regelen also has some additional ‘rules’. Such as a predefined maximum waiting time for every direction. When this waiting time is exceeded, the value (for the priority) will strongly increase. Besides this, a functionality is built in to ensure that directions do not get green more frequently than other directions. Also, the application can communicate with (among others) public transport and ambulances to ensure that they get green earlier or immediately (in the case of an ambulance).

Appendix B – Simulation tool + Oss 15

In this section, the intersection that is used to determine the effects is depicted.

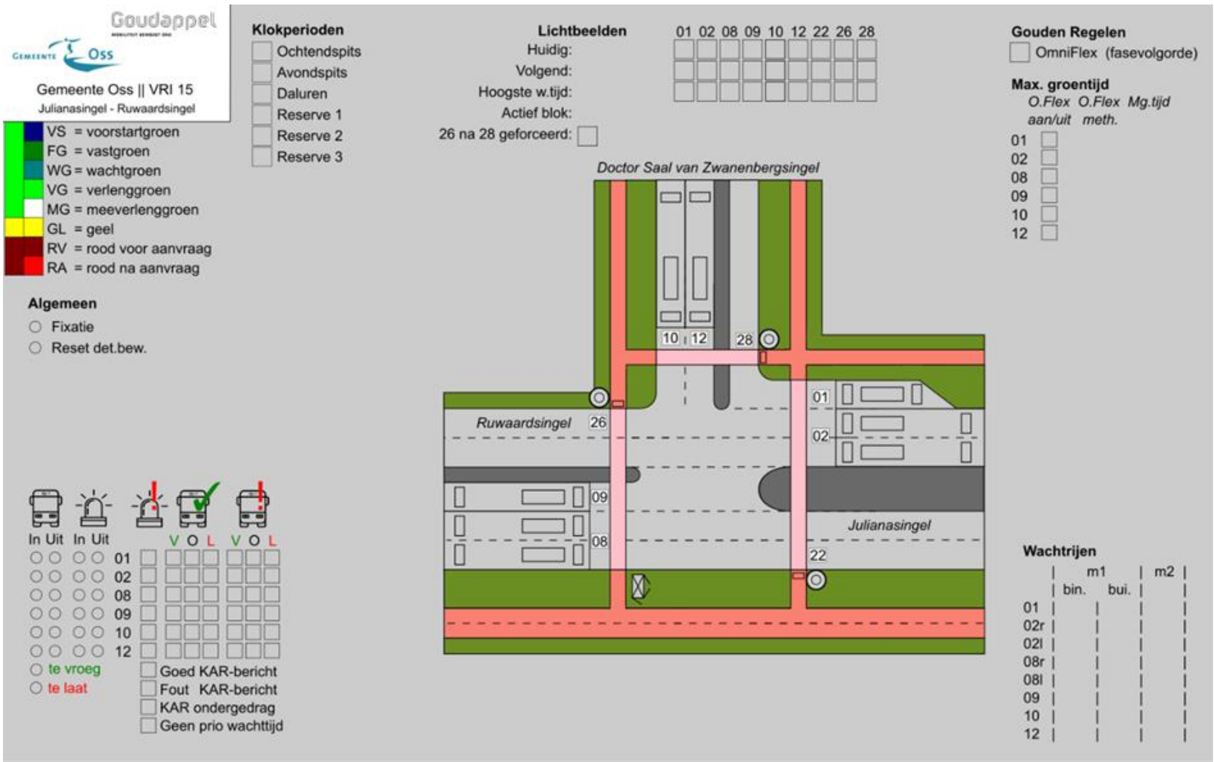

Figure 22: Overview of the simulation tool + the intersection that is used to determine the effects of the designed Algortihms

Appendix C – Methodology

As mentioned in the section Methodology, to test the accuracy of the algorithms multiple tests are conducted, namely:

- Different volumes of traffic;
- For cyclists: different speeds;
- For long vehicles: different percentages of freight traffic;
- For long vehicles: the length of (long) vehicles.

In this section is explained why these tests are chosen and what these tests withhold.

Different volumes of traffic

The first test that is conducted for both algorithms is the different volumes of traffic. This test is chosen, since it is expected that this influences the accuracy of the algorithm.

For the algorithm of cyclists applies that if the volume of cyclists increases, cyclists are more likely to cycle close/next to each other. This results in the fact that the chance that multiple cyclists pass during one occupation time is higher, as is also stated in the section Theoretical Framework. Therefore, it is tested whether the algorithm is also accurate if the number of cyclists increases.

For the algorithm of recognizing and incorporating long vehicles applies that the speed of vehicles and thus the occupation time of the distant loop detector, is subject to the length of the queue. One of the variables that influences this, is the traffic volume. Therefore two tests are conducted to incorporate this in order to have a good indication of the accuracy, namely one where the traffic volume is set at 0.5 times the traffic volume of the base scenario and one where the traffic volume is set at 1.5 times the traffic volume of the base scenario.

For cyclists: different speeds

In the base scenario, the speed of cyclists is set at a range between 13 and 16 kilometres per hour. However, the speed will have an influence on the occupation time. To determine the influence of this on the accuracy of the algorithm, the speeds are altered. For this, one signal group gets a lower speed, one gets a higher speed and one gets a wider range.

For long vehicles: different percentages of freight traffic

Besides the traffic volume, also the percentage of freight traffic has a big influence on the length of the queue (and therefore on the occupation times). If the percentage of freight increases, the chance that a long vehicle is in the queue is bigger. In that case, the length of the queue is higher. To incorporate this in the accuracy, a test is conducted in which the percentage of freight is altered to 10% instead of the 4% of the base scenario.

For long vehicles: the length of (long) vehicles

In the base scenario, the length of long vehicles is set at 18 meters. However, in reality the length of long vehicles is not always the same. To test the accuracy of the algorithm for a situation which corresponds more with reality, this test is conducted. Within the test, the length of long vehicles varies between 12 and 18.75 meters (which is the maximal length of a truck in the Netherlands).

Appendix D– The algorithms

In this section an elaborated explanation is given on the algorithms that detect and incorporate cyclists and long vehicles. Also the line of reasoning for some choices is explained.

Determining the waiting queue for signal groups with cyclists

This algorithm consists of two parts. The first part is about the detection of a cyclists (or the number of cyclists). The second part indicates the number of cyclists that are waiting in the queue.

Number of cyclists

To determine the number of cyclists that are arriving at the queue, data from the distant loop detector is needed. For this, there are two possible types of distant loop detectors. The first one is the direction-sensitive loop detector couple. These are two distant loop detectors which lay on a certain distance from each other. Since the distance is known, the direction of cyclists can be determined. The second possibility is a single distant loop detector. The algorithm that is created is aimed to be used with a direction-sensitive loop detector couple, however it is also applicable for a single distant loop detector. In that case, some parameters are set on a fixed value.

The part of the algorithm that estimates the number of cyclists that pass the (distant loop) detector, is divided into multiple components. All these components are discussed in this section.

Calculating the follow up time

To ensure that only cyclists that cycle in the right direction, towards the intersection, are counted, the follow up time of the distant loops need to be determined. The follow up time is the time between the start of the detection of distant loop detector that is furthest away and the start of the detection of distant loop detector that is closest to the intersection. If the follow up time falls within certain boundaries (higher than 0 and less than 2 seconds) the cyclist(s) is/are counted. In the other cases it is expected that for example the cyclists is cycling in the wrong direction (if the follow up time is smaller than 0) or that a cyclist is standing still on the detection loop/has turned off.

As mentioned, the follow up time is calculated using the start detection of both distant loop detectors. So the first step of the algorithm is to determine the time at which the start detection of a detector takes place. When this is determined for both the loop detectors, the follow up time can be calculated by determining the difference between the start detection times. Equation 1 shows the calculation for this:

$$\begin{aligned} & \mathit{Follow\ up\ time} \\ & = \mathit{start\ detection\ time\ distant\ loop\ detector\ closest\ to\ the\ intersection} \\ & -\ \mathit{start\ detection\ time\ distant\ loop\ detector\ furthest\ away\ from\ the\ intersection} \end{aligned}$$

Equation 1

The above mentioned method is of course only applicable when an intersection only has multiple distant loop detectors. However, it is also possible that a cycle signal group only has a single distant loop detector. In that case the follow up time is set at 0. This ensures that the follow up time is not taken into account in the other calculations and thus the calculations can be done for a signal group with only one distant loop detector.

Determine the occupation time

The number of cyclists that pass the detection loop (per detection) is determined using the occupation time of the distant loop detector. In case of multiple distant loop detectors, the distant loop detector closest to the intersection is used to determine the occupation time. However, it is expected that it does not make a difference when the other distant loop detector (the distant loop detector that is further away from the intersection) is used to determine the occupation time.

Determine the number of cyclists passing the detection loop

When the follow up time is within the boundaries, the number of cyclists passing the detection loops can be determined. Due to the fact that cyclists can cycle close to each other (for example next to each other of right behind each other), it is possible that in one detection multiple cycles pass the distant loop detector. To incorporate this, the number of cyclists that is determined by the algorithm is dependent on the detection time. A distinction is made between 1,2 or a group of cyclists. To determine the distribution between the number of cyclists and the detection times, data received from the simulation tool is used. For the 'normal' situation of 'Oss 15', the detection times are plotted against the number of cyclists passing the detection loop. The results from this can be found in Table 3.

Table 3: The number of cyclists that pass the distant loop detector per detection time

Occupation time	1 cyclist	2 cyclists	Percentage 1 cyclist	Percentage 2 cyclists
0.4	434	0	100.00%	0.00%
0.5	2822	8	99.72%	0.28%
0.6	3448	64	98.18%	1.82%
0.7	1433	114	92.63%	7.37%
0.8	330	101	76.57%	23.43%
0.9	42	93	31.11%	68.89%
1	22	60	26.83%	73.17%
1.1	19	75	20.21%	79.79%
1.2	15	58	20.55%	79.45%

In the Table can be seen that there is not a hard line between the detection times for one and two cyclists. However it can be seen that at 0.9 seconds, the majority of the detections is from two cyclists. Therefore, it is decided to take an occupation time of 0.9 seconds as the boundary between 1 and 2 cyclists. One thing that should be kept in mind, is that this data is received from a simulation generated for the 'normal' situation of this intersection. It is likely that this data is different for other situations.

The research of Simone Hoskam (sd.) is used as basis for the detection time of a group of cyclists. In this research is stated that if the detection times is 4 seconds or higher a cyclists jam is present. In the algorithm this is translated by calculating 3 cyclists at a detection time of 4 seconds. This is based on data (on which also Table 3 is based), which indicates that it is almost never occurring that more than 3 cyclists pass the distant loop detector at during one occupation.

Determine the number of cyclists in the queue.

For the application of Gouden Regelen it is required to transform the number of cyclists that pass the distant loop detector(s) into a number of cyclists that is in the queue. This is done via two ways, depending on the situation that is applicable. The first method, is based on adding the number of cyclists detected by the distant loop detector(s) to the queue. In that case, the current number of cyclists in the queue is increased by the number of cyclists that pass the distant loop detector(s).

When the traffic light turns green, the queue will be emptied. To incorporate this process, a second method is developed. In the algorithm, the queue is reset (the number of cyclists in the queue is set at 0) at start green. However, during the time that the signal group has green, some cyclists will pass the distant loop detector(s) that will not join the queue (because they arrive at the traffic light when it is still green). To incorporate this, the cyclists that are detected by the distant loop detector(s) when the traffic light of that signal group is not red (so yellow or green), are stored in an array. In this array, it is also stored how long ago the cyclist(s) passed the distant loop detector(s). At start red, it is determined which of the cyclists that passed the distant loop detector, are still in the queue. This is determined by the time since the cyclist has passed the distant loop detector. If the time that indicates how long ago the cyclists passed the distant loop detector is higher than the expected travel time (the time that it is expected to take from the distant loop detector to the intersection based on an average speed of 15 km/h), than it is assumed that the cyclists have passed the intersection. The other cyclists are added to the (number of cyclists in the) queue.

Incorporating the number of cyclists in the queue

When the number of cyclists in the queue is known, this queue can be implemented into the Gouden Regelen application. This can be done by using the knowledge of the queue for the determination of the (cumulative) waiting time of the signal group. Since in most cases cycling is promoted, the default of the factor that is multiplied with the cumulative waiting time is set at 2.

Detection of long vehicles/freight traffic

The algorithm that is designed to make a distinction between passenger cars and long vehicles (mainly trucks), consists of multiple methods to do so. Depending on the situation that is applicable, the method is different. Based on the expected length of the queue (in meters), the occupation time of the distant loop detector and the previous method used, is determined which method is used to determine the classification of the vehicle (passenger car or long vehicle/truck) passing the distant loop detector. In total 3 methods are possible, namely:

- Method based on braking distance;
- Method when a vehicle is standing still on the distant loop detector;
- Method based on detection time of previous vehicle, where a distinction is made between the first vehicle passing the distant loop detector and the other vehicles.

In Figure 23 a schematisation can be found for the different situations for which different methods are applicable. As can be seen in this Figure, the method which bases the vehicle classification on the braking distance, is used in the situation where the queue fits within the detection field. As the name already suggest, the second method (the method when a vehicle is standing still on the distant loop detector) is used in the situation where a vehicle is standing still on the distant loop detector. The third method, the method which bases the vehicle classification on the detection time of the previous vehicle, is used when the queue is behind the distant loop detector (so the length of the queue is higher than the length of the detection field).

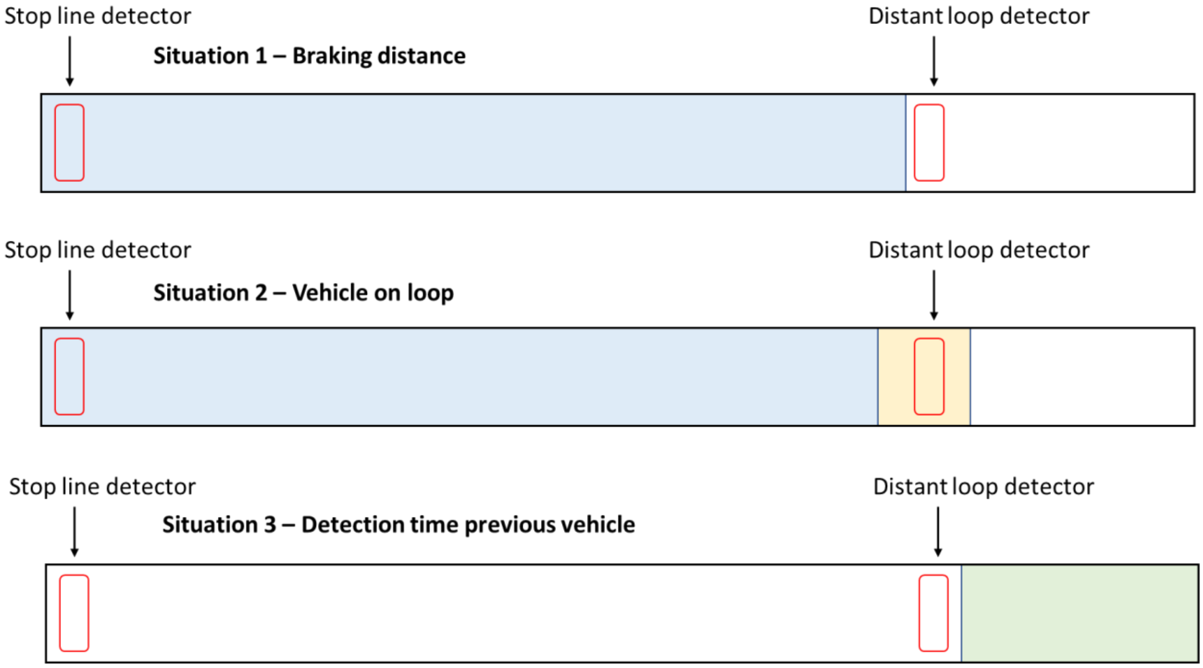

Figure 23: The situations in which the different methods are applicable

In the rest of this section, the different steps of the algorithm are explained. Also an elaborated explanation of the different methods is given.

Main principle of the algorithm

The main goal of the algorithm is not only to use the different methods to determine the classification of the vehicle, but also to store this in the correct way so different properties of the queue are known/can be determined.

The queue is 'stored' in an array. In this array, the vehicle classification, (expected) length of the vehicle and the occupation time of the vehicles in the queue is given. When a new vehicle passes the distant loop, the vehicle is added to the array. When a vehicle exits the stop line detector (the stop line detector is 'end detection'), this vehicle (and its properties) is removed from the array.

Determine the length of the queue

In order to both determine which method should be used to classify the vehicle and to determine the classification of the vehicle, the length of the queue (in meters) needs to be known. The length of the queue is calculated by adding up the lengths of the vehicles in the queue. Next to that, also the distance between the vehicles in the queue is added to the length of the queue.

Determine the active method

As mentioned before, depending on the situation, the method to determine the vehicle classification will be different. In order to determine which method should be used, the value of different parameters is checked. The parameters that influence the active method, are the length of the queue (compared to the length of the detection field), the gap at the distant loop detector (in Dutch Hiaat), the fact that the traffic light is green, the active method for the previous classification and the occupation time of the distant loop detector. An overview is given under which circumstances which method is applicable:

- Method based on braking distance: Length of the queue is smaller than the length of the detection field;
- Vehicle is standing on loop: Length of the queue is smaller than the length of the detection field, the occupation time of the distant loop detector is higher than the threshold value whether a vehicle is standing still on the distant loop and the previous method was the method based on braking distance;
- Method based on the previous vehicle: The length of the queue is smaller than the length of the detection field, the vehicle before was also determined using this method and the traffic light is green (or was just green);
    - First vehicle that passes the loop: If no vehicle has passed the distant loop detector since it was green.

Vehicle classification

When it is determined which method should be used to determine the classification of a vehicle, this method can be executed.

Method using the braking distance

As the name already states, this method is based on the (expected) braking distance of a passenger car. It is in this case assumed that a vehicle drives with the maximum speed that is allowed. Using the formulae of the braking distance in a 'normal' situation (so not an emergency stop), which is given at Equation 6, the expected braking distance of a passenger car is calculated.

$$Braking\ distance\ (m) = \frac{Maximum\ speed\ \left(\frac{km}{h}\right)}{10} * \frac{Maximum\ speed\ \left(\frac{km}{h}\right)}{10}$$

Equation 6 (ADAC, 2021)

Since the length of the queue is also known, the expected speed of a passenger car at the distant loop detector can be determined. To do this, two situations are possible:

- Expected braking distance > distance from end of queue to distant loop detector
- Expected braking distance < distance from end of queue to distant loop detector

In the first situation, the expected speed is set at the maximum speed. Since in that case passenger cars do not need to brake yet. In the second situation, the expected speed can be calculated using the following equation:

$$(Expected)\ speed\ \left(\frac{m}{s}\right) = \frac{Maximum\ speed\ (\frac{m}{s})}{Braking\ distance\ (m)} * distance\ between\ end\ of\ queue\ and\ the\ distant\ loop\ detector$$

Equation 7

As can be seen in the equation, it is in this case expected that the speed decelerates linear over the braking distance.

When the expected speed of a passenger car at the distant loop detector is determined, this speed can be translated into the expected occupation time of the distant loop detector. If the actual occupation time of the distant loop detector falls within the range from the expected occupation time, it is classified as a passenger car. In the other situation, it is classified as a long vehicle/truck.

Method when a vehicle is standing still on the distant loop detector

When the distant loop detector is occupied longer than a threshold value, which indicates that a vehicle is standing still on the detection loop, it is expected that a vehicle is standing still on the distant loop detector. If this is the case, it is determined what the distance is between the end of the queue and the distant loop detector. If this distance is more than the length of a passenger car (including the distance between vehicles), the vehicle is classified as a long vehicle/truck. In the other situations, it is classified as a passenger car.

Method using the detection time of the previous vehicle

This method is divided into two parts, namely the detection of the first vehicle that passes the distant loop detector (when the signal group gets a green traffic light) and the other vehicles. For the first vehicle that passes the distant loop detector when the traffic light is green, the classification of the vehicle is based on a boundary occupation time. If the occupation time is smaller than this boundary it is classified as a passenger car, otherwise it is classified as a long vehicle/truck.

For the other vehicles applies, that the vehicle classification is based on the occupation time of the current vehicle and the occupation time of the previous vehicle. In Table 4 an overview is given in which situation which classification is given.

Table 4: Determination classification based on occupation time previous vehicle

Previous vehicle	**Passenger car**	**Truck**
Passenger car	Occupation time < 2 times the occupation time of the previous vehicle	Occupation time > 2 times the occupation time of the previous vehicle
Truck	Occupation time < 0.5 times the occupation time of the previous vehicle	Occupation time > 0.5 times the occupation time of the previous vehicle

This range is chosen, since the speed of two succeeding vehicles will not be exactly the same. This is due to the fact that vehicles will accelerate when the vehicle turns green. Not all vehicles will accelerate with the same magnitude, which causes differences in speed. Besides that, the distance between the two vehicles and the distant loop detector is different. The first vehicle is standing closer to the distant loop detector, resulting in that the speed of this vehicle would be lower (if the acceleration is the same). When the traffic light turns red and vehicles are still in line, the reverse happens. The first vehicle will have to brake later since the length of the queue is smaller for him than for the vehicle behind him. Also the deceleration of the different vehicles could be different, resulting in different speeds at the distant loop detector. Since the speed is different, the occupation time will also be different. To incorporate this a range is used. It is assumed that the speeds of the succeeding vehicles (and therefore the occupation time) can differ a bit, but are roughly the same.

PCU of the queue

To incorporate the queue that is generated by the algorithm into the Gouden Regelen application, the passenger car unit, PCU, of the queue is determined. The PCU, is a measure to express the traffic load in an traffic system. This is done by expressing all vehicles in the weight of a passenger car. In this way heterogenous data is transformed into homogeneous data (Islam, Sadeek, Miah, & Hossain, n.d.). In this case, for freight a PCU of 2.3 is taken, and for passenger cars the PCU is set at 1. In the Gouden Regelen application, the number of vehicles in the queue can be substituted by the PCU of the queue.

Appendix E – Results

Accuracy of the Algorithm

Cyclists

Table 5: Absolute values of the deviation of the number of cyclists passing the detection loop at once for the base scenario

Base scenario	Underestimation of 2 cyclists	Underestimation of 1 cyclist	No deviation	Overestimation of 1 cyclist
1 cyclist passing the detector	0	0	18924	0
2 cyclist passing the detector	0	68	3	1
3 cyclist passing the detector	1	0	0	0

Table 6: Absolute values of the deviation of the number of cyclists passing the detection loop at once for the scenario with a higher volume of cyclists

Higher volume	Underestimation of 2 cyclists	Underestimation of 1 cyclist	No deviation	Overestimation of 1 cyclist	Overestimation of 2 cyclists	Overestimation of 3 cyclists
1 cyclist passing the detector	8	8	67752	51	1	6
2 cyclist passing the detector	3	838	379	56	0	0
3 cyclist passing the detector	4	12	3	2	0	0

Table 7: Absolute values of the deviation of the number of cyclists passing the detection loop at once for the scenario in which speeds of cyclists are altered

Different speeds	Underestimation of 1 cyclist	No deviation	Overestimation of 1 cyclist
1 cyclist passing the detector	0	18353	861
2 cyclist passing the detector	31	43	7
3 cyclist passing the detector	0	0	0

Long vehicles

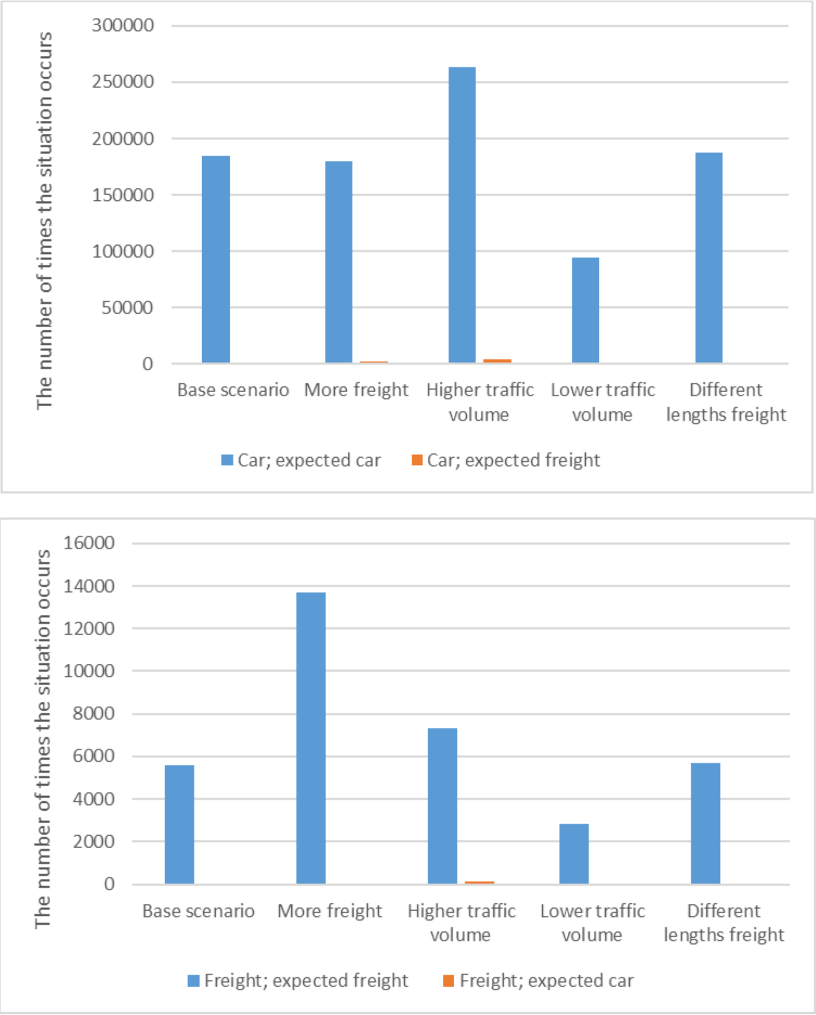

Figure 24: The results of the accuracy of the algorithm that classifies motor vehicles using the method which is based on the braking distance of vehicles. On the x-axis, the different tests conducted are plotted. On the y-axis the number of times that a situation occurs is displayed. The bars indicate the different outcomes.

Effects of the Algorithm

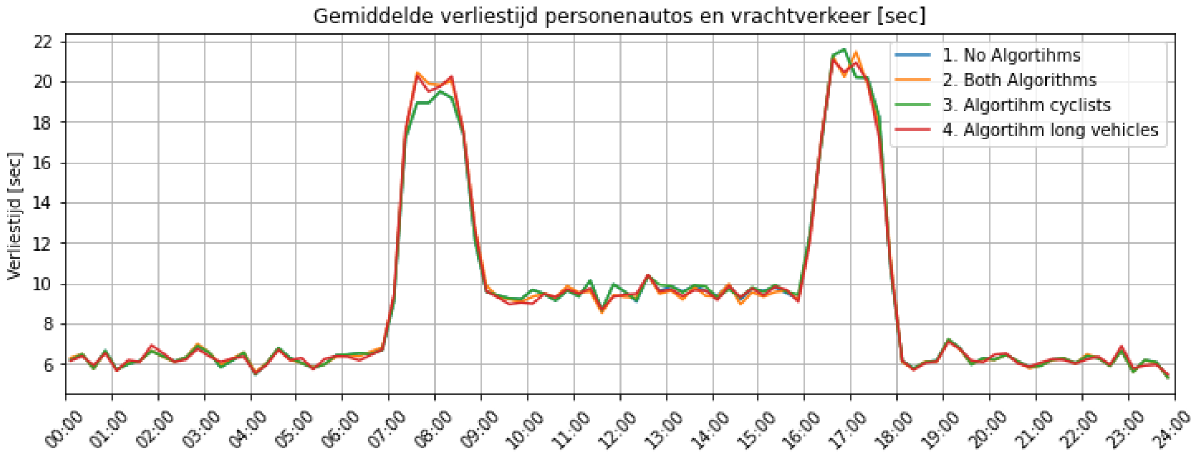

Figure 25: The average loss time for passenger cars and freight traffic

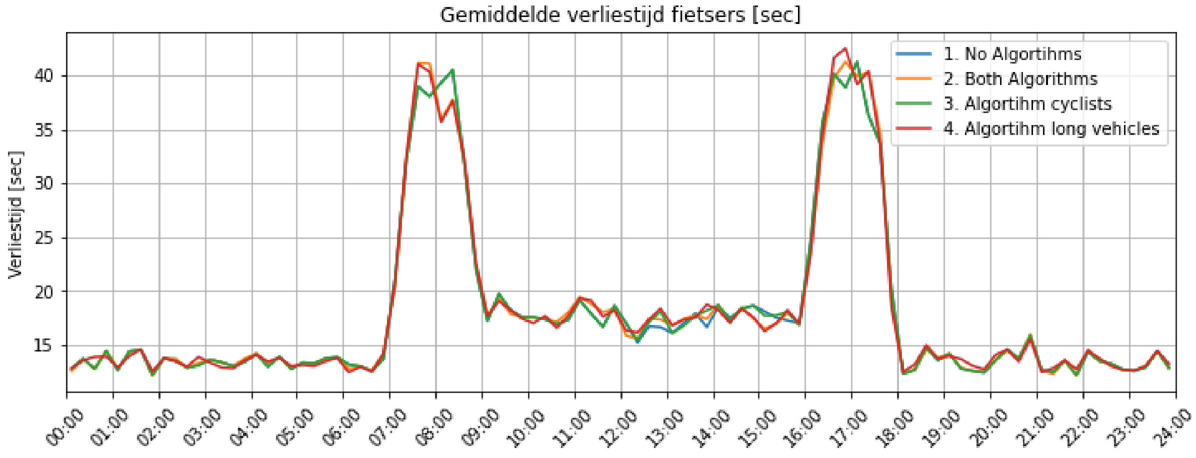

Figure 26: The average loss time for cyclists

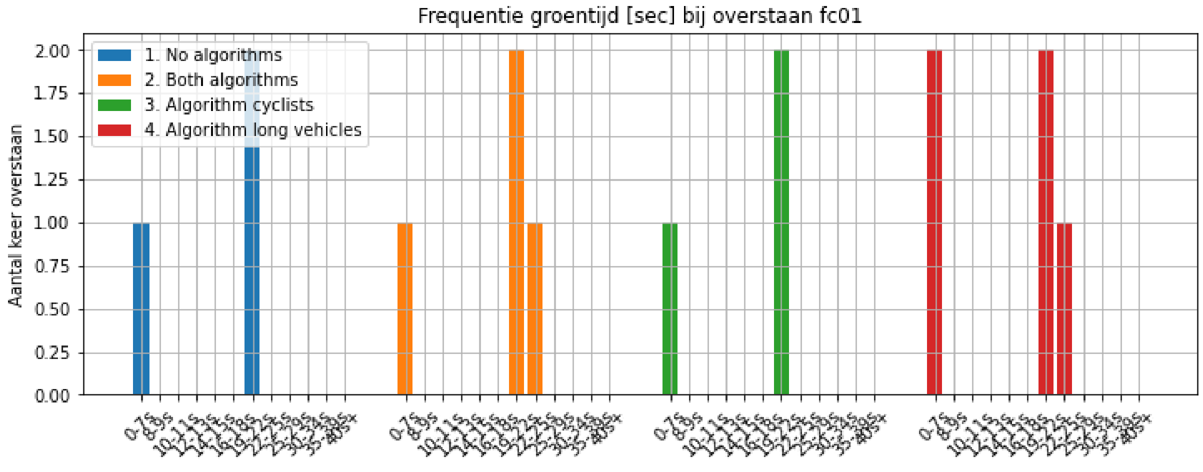

Figure 27: The number of stops for different green times for signal group 01

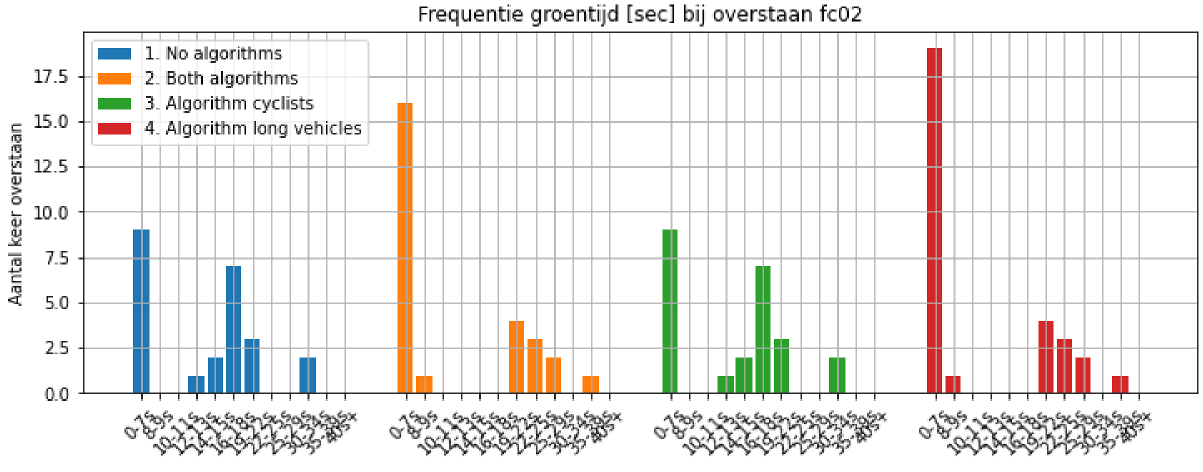

Figure 28: The number of stops for different green times for signal group 02

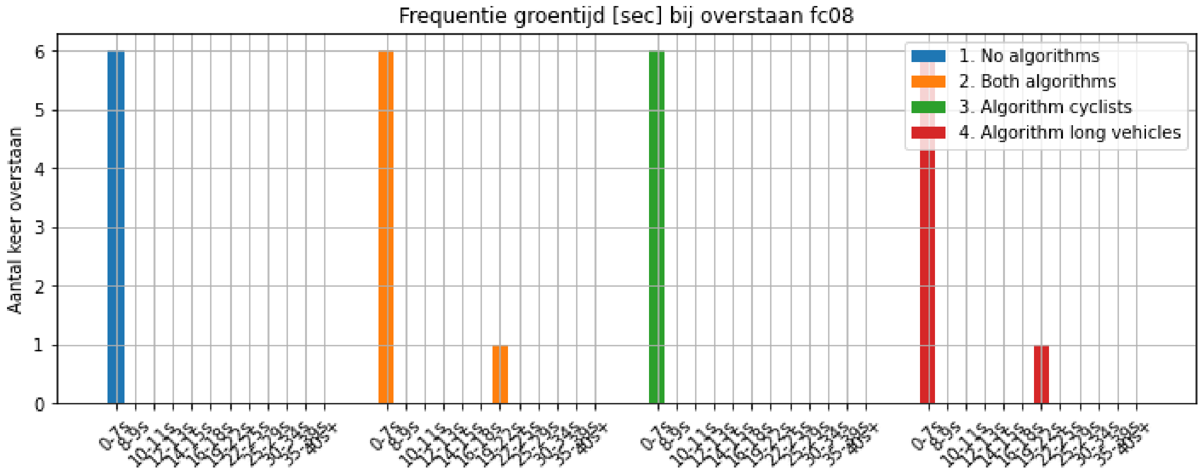

Figure 29: The number of stops for different green times for signal group 08

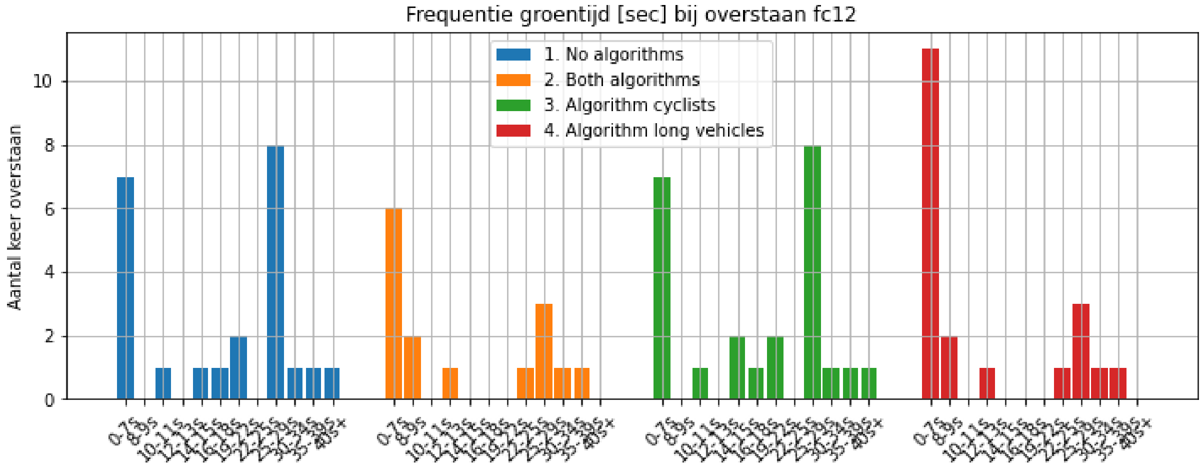

Figure 30: The number of stops for different green times for signal group 12