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Intersection control for cyclists with iSignum

TU Delft

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At the signalized intersection Julianalaan-Nassaulaan in Delft

By

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Preface

Since the beginning, I already knew that I wanted to pursue the track of Transport & Planning within the faculty of Civil Engineering and Geosciences, which ended up in a cyclist related topic for my Bachelor thesis. Thus my motivation and goal at the start of this research were to successfully take on the task I was facing and to conclude that cyclists have benefits from this research in the end. What motivated me more was that I had the feeling that I somehow could relate to the topic, when using the bicycle I find it unfair to constantly wait and stop to get a green light even when many people are waiting with you as well on a bike. In my opinion, in a country where many people transport themselves with this particular mode, it is necessary and achievable to better the comfort and experience towards these road users particularly at locations where bottlenecks are visible and prone to develop.

Therefore, I'm presenting this report of my final Bachelor Thesis with results and further elaboration of my research towards intersection control for cyclists at signalized intersections using the iSignum sensor at the particular location of Julianalaan-Nassaulaan.

Additionally, I want to my thank my supervisors from the TU Delft, the municipality of Delft and the company of CycleData, namely Dr. ir. A.M. Salomons, Dr. ir. W.J. Schakel, Peter Broekhuijsen and Deodaat Boer. Lastly, I also want to thank my peers from group 1 during the Bachelor End Project in 2021-2022 Q1 at the department of Transport & Planning, by giving feedback on all handed in documents.

Madeline Lai
Delft, October 2021

Abstract

The Netherlands is like no other country enthusiastic about cycling and is the home of 37.000 kilometers of bicycle paths. These bicycle paths need to cross other modalities and therefore intersections are needed. At signalized intersections, the control is mostly regulated using sensors such as push buttons and one or multiple inductive loops. Sensors for cyclists are running slightly behind in comparison with those from cars and the company of CycleData anticipated on this fact by developing a new sensor, the iSignum, that works on radar and laser service and is capable to determine speed. The iSignum is capable of communicating with the iVRI (intelligent traffic light control) where it is installed and notify that a cyclist is coming. The sensor is placed further away from the stop line meaning there is time to communicate with the iVRI that a cyclist was detected and for example with what speed. This can benefit the comfort and traffic flow of cyclists when a notification leads to green light such that cyclists simply do not have to stop unnecessarily before the intersection.

Part of this research was a literature study towards stakeholders and existing bicycle sensors. The latter was needed to be able to make a comparison of what makes the iSignum stand out from the rest or if it is just another bicycle sensor. A literature study has indicated that inductive loop sensors in combination with push buttons are used the most. Additionally, there are other cyclists sensors on the market nowadays. These sensors include infrared sensors, smart cameras and mobile phones and WiFi/Bluetooth applications. These are however not used on a big scale yet.

In this report, research was done towards the newly developed sensor that is installed at an intersection in Delft, the Julianalaan-Nassaulaan intersection. Several matters were looked into, such as the accuracy of the iSignum in comparison to the reality at this location and what potential situations can result in disturbances in detecting cyclists. Furthermore, preventions are explored to an extent of what could be possible at this specific location.

To test the exactness of the iSignum, manual bike counting is done over the course of three days. This data was then compared to the data that the sensor of iSignum logs. Conclusions that have been made after the comparison is that the newly developed sensor is not as accurate as the company CycleData claims it to be, the promised 95% is not reached. During the measurements, the sensor did not manage to pass the 78.2% accuracy. However, disturbances that happened, such as the presence of a delivery van or garbage truck or cars that drive over the bicycle path, while counting cyclists are included. Making the preciseness less in particular cases, with the worst case being 75.3%. V-log data, which logs traffic status and information such as detection and signal groups from an iVRI, is additionally used to check whether those disturbances can be covered by the existing control of the intersection. The outcome states that the existing intersection control of a loop sensor and push-button manage to still detect cyclists during the time of disturbances.

Next to this, prevention methods for the disturbances are researched such that relying on the existing intersection control may not be needed in the future and the full potential of the iSignum can be reached after more precision from the sensor itself is achieved. A prevention method that could help all the occurred disturbances is to move the sensor more downstream from the bicycle path where the disturbances do not influence the sensor anymore. This is therefore also the recommendation for this particular intersection such that unnecessarily errors are filtered out of the data. Additionally, further research is needed after the relocation of the sensor and towards the enhancement of the accuracy because other errors are present that are not accountable to a disturbance. It is valuable to do more extensive research on this topic to determine if these errors can be erased from the system to reach the full potential of the iSignum such that the objective of shorter waiting times and more comfort for cyclists can be reached at signalized intersections.

Contents

1 Introduction

The Netherlands is like no other country enthusiastic about cycling. From a relaxed trip through nature, a simple trip to get to work or to pick up children from kindergarten. The Dutch have a real bike mentality, which is not remarkable when looking at the numbers. 28% of all travels are done by bike and is the most used transportation mode next to the car. During the whole year of 2019, on average a person biked almost 1100 kilometers (Centraal Bureau voor de Statistiek, 2021). The Netherlands is also the home of 37.000 kilometers of bicycle paths. Since these paths have to eventually cross other types of transportation modes such as automobile vehicles or pedestrians, intersections are needed within the transport network to make travelling from point A to point B go smoothly and could be more if cyclists would be prioritised more.

Intersections in The Netherlands can be roughly categorized into two categories, unsignalized and signalized intersections. Signalization is used at places where traffic flows cross one another that may experience difficulties regarding congestion or safety (CROW, 2014). According to literature and experience, it turns out that the use of traffic light systems in The Netherlands is more complicated than that of most other countries due to the different modalities using the same roads in this country (CROW, 2014). These signalized intersections are mostly vehicle-actuated controlled, meaning that the green time depends on the number of vehicles that can be detected which is often done by inductive detector loops distributed over several places in the ground. The characteristic of these vehicle-actuated controlled intersections is that the green time depends on the measured amount of vehicles on each lane and a certain gap-out time. The alleged gap-out time is a time reference for the system that during a certain amount of time no vehicle passes the detector, the green time stops. Nonetheless, when the maximum green time for a direction has reached, the light turns red to avoid too long waiting times for conflicting directories.

1.1 Problem Statement

For modalities that are to cross a signalized intersection like described above, cars and cyclists, there is however a significant difference regarding the comfort and green time. This is mostly in favour of cars, where multiple detectors are used more upstream to detect where the vehicles are until they reach the stop line and additionally have a detector loop in front of the stop line. Furthermore, these detector loops are also capable to indicate roughly how many cars are waiting in front of the stop line to anticipate how long the green time should be.

On the contrary to cars, cyclists have to stick with one sensor close by the stop line and a push button. This concept for cyclists has most of the time two results. The first one is that the light will turn green at the moment cyclists slowed down or completely standstill at the stop line or either have to wait. Next to the waiting time, comfort plays also a role with this particular type of modality. Stopping at a traffic light and getting away takes more effort for cyclists than for a car user ((Fietsersbond, 2017), (Börjesson & Eliasson, 2012)). With all of this in mind and knowing that The Dutch cycle considerably many kilometers with an estimate of 1100 kilometers a year per person in 2019 (Centraal Bureau voor de Statistiek, 2021), there is still plenty of room left to improve the waiting time at intersections for cyclists. Therefore, a new sensor is looked into that works differently than the common push buttons and inductive detector loops. This sensor, namely the iSignum has the potential to count every separate cyclist that pass by and communicate that cyclists are approaching to cross the intersection in advance which can be valuable in the end so that not all cyclists have to stop unnecessarily.

1.2 Research and goals

1.2.1 Research

This research focuses on a new instrument which is installed at the intersection Julianalaan-Nassaulaan in Delft called the iSignum. During eight weeks, the aim of the research was to check the accuracy of this particular new instrument thoroughly during a zero measurement and to determine if there is a particular error present. In case a constant error can be witnessed in the instrument, the significance needs to be determined. Furthermore, special reasons these errors occur are looked into to conclude the best way to implement such a sensor like the iSignum in general and at the mentioned location in a more sufficient approach in the future.

1.2.2 iSignum

The new instrument developed by the company CycleData is a new cyclists sensor named the iSignum which is installed at the intersection of Julianalaan-Nassaulaan. This sensor works on radar-service and projects a cloud of points onto the bike lane. In case a cyclist passes by, the radar-service determines that an object went through the cloud of points and a laser is used to determine the number of cyclists, the speed and direction. Besides cyclists, the iSignum is also capable to detect other vehicles than just cyclists e.g. scooters and mopeds that make use of the bicycle path. In brief, the sensor manages to count vehicles that are located on the bicycle path. The iSignum is able to collect all information, such as the number of cyclists and speed, and communicate this to the signalization system. To communicate the detected information, the data is converted to CAM-data, which stands for Cooperative Awareness Messages. This particular type of data is used to interact with the data platform from iVRI's (intelligent traffic light control system) since it contains information such as the location and speed. CAM-data essentially notifies the system that a cyclist or even multiple cyclists are approaching and making their way to cross the intersection (Talking Traffic, 2019). With this notification the system can request a green light for cyclists, depending on the amount of other traffic the request could be rewarded with approval. This happens most often when large pelotons of cyclists are nearing the intersection or either when the traffic flow is low enough that priority can be given to cyclists. In such a situation, the time in between a cyclist got detected and is at the intersection can be estimated by the sensor with the observed speed. Therefore, the light turns green on time and ensures that cyclists do not have to stand still or slow down near the stop line when this is not needed. This effect causes cyclists to use less energy and experience more comfort with the sensor.

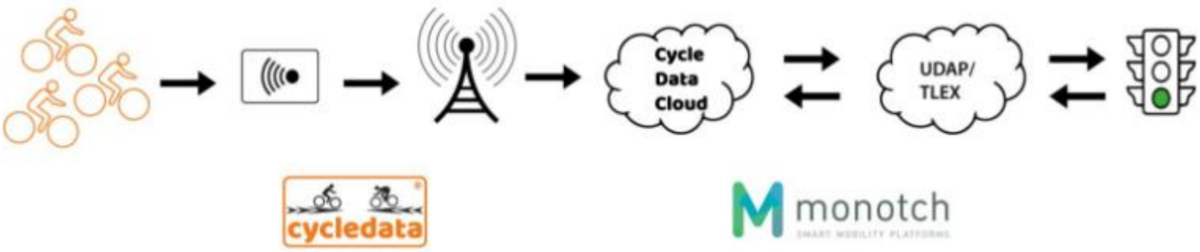

Figure 1: Schematic view of the use of the iSignum (CycleData, 2021)

1.2.3 Goals

The goal of this research is to determine what the best way is to install the iSignum at the intersection Julianalaan-Nassaulaan.

For this reason, the research question is, 'What are the main difficulties the iSignum can experience during commissioning at the current spot and can it be prevented at the Julianalaan-Nassaulaan?'. This goal is going to be achieved with a couple of sub-goals that provides the following sub-questions:

1. How accurate is the iSignum in detecting cyclists at this particular location?
2. What kind of situations results in a disturbance of the measurements?
3. How can these disturbances be prevented and implemented?

2 Literature Research

Before taking on the research question, time was spent on literature research. This includes taking a closer look into what kind of stakeholders there are and where their interests lie in and the types of sensors that are already on the market. These sensors have a relation with cyclists since this research is aimed at the iSignum. Information about these sensors is helpful to compare sensors that are already on the market with the iSignum to conclude what makes this specific sensor different from the others.

2.1 Stakeholders

It is crucial to know who has interests and of what kind in this research. Therefore, a stakeholder analysis has been done in order to get a better insight on what every party has their eye on and what they ultimately want out of the use from the iSignum at signalized intersections.

2.1.1 CycleData

This company anticipates on the desire that the world urges to become greener and more sustainable. Ultimately, they believe that cyclists contribute towards this goal by being more environmentally friendly and having healthy living habits (Cycle Data B.V., 2021a). CycleData is the company that developed the iSignum and has extensive interest in the sensor to work excellently. This is in order to stimulate more bicycle use in cities in The Netherlands and perhaps even outside the country. To achieve this, it is beneficial for CycleData that the sensor working on radar-service performs well in order to sell and install more iSignums at multiple locations.

2.1.2 Municipality of Delft

The municipality of Delft has an iSignum sensor installed in the city at the intersection Julianalaan-Nassaulaan. This particular stakeholder is interested in the advantages for cyclists by using the iSignum. Furthermore, the municipality of Delft has a new mobility program due in 2040 in mind. A certain goal that is included in the program states that the city of Delft aspires to be a better and more cyclable city. Achieving this the municipality wants the traffic flow of bicycles to be smoother and given more priority (Gemeente Delft, 2021). By taking on the research initially at the location Julianalaan-Nassaulaan, further insights can be given to the municipality of Delft if and where they want more intersection control for cyclists by using the iSignum and most certainly how the instalment should be approached. This all with the prospect of fulfilling the mobility program Delft 2040.

2.1.3 Government and other municipalities

Not only the municipality of Delft but also the government and other municipalities are intrigued by the research towards the iSignum. The government, the Ministry of Infrastructure and Water Management in particular has set up the plan of ‘Tour de Force’(Ministerie van Infrastructuur en Waterstaat, 2021). In short, this plan includes expanding the main network and to stimulate the usage of bicycles for several main reasons such as an environmentally friendly aspect, better health and liveability for citizens in bigger cities. Additionally, local municipalities can have their own policy besides the one from the government. These policies are mostly in a similar order as the plans from the municipality of Delft. Knowing this, both the government and other municipalities can commit to investing in a sensor like the iSignum to realize the policies and goals they have set towards cyclists mobility and comfort.

2.1.4 Traffic Engineers
The people designing signalized intersections also have an interest with regards to the development of the new sensor of iSignum. If the sensor is used more and more nationwide over time then traffic engineers have to, at some point, design a control that involves the possibilities of what this sensor can do and achieve. Therefore, these engineers are interested in what the outcome of the research is and what this means in the future for them, workwise.

2.1.5 Cyclists
Cyclists, the stakeholder who directly experience the benefits that the iSignum has intended. With an operational unit of the iSignum and the iVRI, the cyclists should experience shorter average waiting times and better comfort. This is more convenient for cyclists and this allows cycle trips to cost less energy by constantly stopping since this has been witnessed by the research of Börjesson & Eliasson (2012). Experiencing more comfort and shorter waiting times could be ultimately the deciding factor for car-users to make more use of a bicycle instead of a car. Therefore, this effect has relation towards the stakeholders of the government and the municipalities in The Netherlands.

2.1.6 Cars and other road users
Most intersections have to deal with multiple road users besides the cyclist. These stakeholders have relatively low to zero influence when it comes down to the instalment of an iSignum sensor. However, these types of road users would not appreciate large consequences e.g. a considerable increase in waiting time, due to the shorter waiting times for cyclists.

2.1.7 TU Delft
Delft University of Technology, a suitable higher education institute that can be used for further research regarding the topic and this new sensor. With a department within the faculty of Civil Engineering and Geosciences of Transport and Planning, this could be a valuable location to take on further and more extensive research when commissioning the sensor on larger scales over the country or even worldwide.

2.2 Existing bicycle sensors
As mentioned in the introduction, cyclists mostly have to stick with the two most common types of sensors. A detector loop or a push button, and commonly both of these sensors are available at a signalized intersection. Along with these sensors, there are also other less common sensors or appliances on the market.

2.2.1 Push buttons and induction loop sensors
Shortly mentioned in the introduction, push buttons and inductive loop sensors are commonly used as cyclists detectors. These loop sensors work with an electromagnetic field, when a cyclist stops on a loop sensor or passes by, the magnetic field is disturbed and a cyclist is detected. However, the loop sensor does not always detect cyclists correctly. Especially when a bicycle made out of very little metal is used (Sterk, 2020). Therefore, the combination with push buttons is more sufficient in case such a situation occurs. However, during the time of research, a global pandemic COVID-19 is happening. With the consequence that people need to maintain distance or advised to keep distance from each other which may result in lower traffic volumes and fewer spikes in normal situations. As a result, the induction loop sensor can be treated as broken and is switched off (Salomons, 2020). Consequently, this particular combination of sensors then only relies on a push-button at that point which is only located at the stop line.

Figure 2: A inductive push button (CROW, 2014)

Figure 3: A loop sensor (Dirk de Baan, n.d.)

2.2.2 Infrared sensor

Infrared sensors work on the technique of electromagnetic waves either from the radiation of people due to warmth or by the sensors own radiation. Distinguishing these two principles into respectively passive and active sensors. Passive sensors identify a person by their warmth and therefore needs to be directed towards a bicycle path to detect a cyclist otherwise a pedestrian can be mistaken for a cyclist (Sterk, 2020). On the other hand, active sensors are an additional option. These sensors work on a similar principle as the iSigum and emit their own radiation towards the bicycle path and are reflected back. When a cyclist go through the radiation the return time is more rapid than before and consequently, a detection has taken place. Just as the iSignum, the active infrared sensors are capable of determining speed, the traffic flow, and waiting time on a bicycle path due to the difference in the amount of radiation that is constantly detected when the sensor is directed towards the stop line. These sensors do however come with the downside of being inconsistent during bad weather (Sterk, 2020).

2.2.3 Smart cameras

Smart cameras work with the techniques of artificial intelligence and are capable to use intelligent processing software and pattern recognition. These techniques are applied to the shots the camera is witnessing. Accordingly, smart cameras are capable of detecting similar cyclists information as the infrared sensor does. Additionally to this information, the cameras can determine queues and personal information regarding a person's gender or age (Sterk, 2020). However, data about someone's gender and age is sensitive information towards their privacy and is not preferable but there are cameras available that can directly anonymize the data. The only issue would be if this particular function fails and the data is not anonymized anymore.

2.2.4 Mobile phone and WiFi/Bluethooth applications

Nowadays, several mobile applications exist that can track cyclists, e.g. green wave apps such as Schwung or Trafficpilot/GreenCatch. The first app has possibilities to influence the traffic signal and the latter two gives advice on the optimal approach speed. The green wave apps work in the background and detect when an intersection is neared that is connected with the app itself. Therefore, a request for a green light can be made when a cyclist is close by the intersection and the principal of the green wave is active (Verbeeke, 2020). Next to that, applications that give the optimal speed have the same purpose and collect information from traffic control systems about the current and upcoming green times (Verbeeke, 2020). This is valuable information, such that a calculation can be made for certain cyclists what the best approach speed is to arrive near the intersection when the lights are green. Close at hand to the mobile applications, WiFi and Bluetooth applications are developed as well. The main difference is that most devices are already equipped with these functions, meanwhile, apps need to be downloaded by the person itself. However, the discovery mode has to be activated in order to collect data from the trip and to track the cyclists. Eventually, this data such as waiting time, speed, flow, routes and travel time can be used to estimate queues (Sterk, 2020).

3 Methodology

The methodology that is used to take on this research project consisted of different stages due to the different sub-goals that have been achieved along the line.

The different phases were:

1. Perform fieldwork and collect data in Delft
2. Collect registered data from the iSignum in Delft and process it according to the same timeslots of fieldwork.
3. Comparing method with V-log Data
4. Concluding on basis of outcomes

3.1 Perform fieldwork and collect data in Delft

During the first step, real data was collected in the field. The plan was to choose 1 week beforehand to perform real-life counting of cyclists that pass by through the iSignum sensor at the intersection Julianalaan-Nassaulaan within a specific hour. This occurred between the dates of 15th and 17th September.
Due to the lack of research time and also differences in traffic volumes regarding what time it is of the day, the times for measurement are chosen to be specifically. Three measurements were be done in total with two during rush hours and one during off-peak hours. The schedule was as followed:

Date	Time	Rush hour
Wednesday 15/09	11:00 – 12:00	No
Thursday 16/09	08:15 – 09:15	Yes
Friday 17/09	08:00 – 09:00	Yes

Table 1: Schedule for counting cyclists at the intersection Julianalaan-Nassaulaan in Delft

Rush hour time slots were determined by looking at the largest volumes that the iSignum is already witnessing. This was done through the platform where CycleData stores their data from the iSignum. These rush hours tend to happen daily between the hours of 8 and 9. To give an idea about the registered numbers during these rush hours, the amount of cyclists between 8:00 and 9:00 is roughly three times as high as for example between 14:00 and 15:00.
The counting was done using the app 'Teller' (Teller, 2021), this app is also capable to put a timestamp on the observation and could export the measurements to a CSV/Excel-file, which made processing it more effortless.

3.2 Collect registered data iSignum Delft and compare with fieldwork

The part of collecting the registered data from the iSignum was partly done directly after a measurement has taken place to have a quick glimpse if either the counting compares to the registered data. This data can be retrieved in a CSV-file which then can be processed with for example Excel or Python. A couple of adjustments were needed to process the data since timestamps of the two different files, manual measurements and iSignum data were not in the same order. To validate the correctness of the iSignum the previously mentioned data is compared to the observed measurements and a minimum exactness of 95% is compared to. This is similar to the claims the company of CycleData made regarding the precision of their instrument, even during rush hours (CycleData, 2021). The accuracy of the sensor is determined with an error of 5 seconds between the two different types of data set. Due to the fact that there could be an internal clock difference regarding the sensor and the app, meaning that the time is not in sync and the sensor is falsely accused of showing an error. While in fact, the timestamps differ a few seconds and due to manually counting, there could also be possibilities of falsely pointing out errors while in reality there is none. At the end of this stage, the first sub-question of 'How correct is the iSignum in detecting cyclists' can be answered at this specific location in Delft.

3.3 Comparing method with V-log Data

Subsequently, V-log data is used to see if certain errors that are made by the iSignum can be recognized by the already existing section control system at the location. V-log data is used to log traffic status and information such as detection and signal groups from an intelligent traffic control intersection (iVRI)(CROW, 2016). This was done by using the measurements from the manual observations and matching up the cyclists that passed by with a certain cycle of the traffic lights.
Next to that, during large errors with disturbances close to the iSignum more detailed attention is paid if either the current intersection control with loop sensors is capable of functioning and detecting cyclists in the 'old fashioned' way when the iSignum is experiencing troubles. Resulting in the intersection flow to continue.

3.4 Concluding on basis of outcomes

Since the location of Julianalaan-Nassaulaan in Delft has certain properties, it is essential to look at what the main difficulties can be and what could cause trouble for the sensor at the location. Based on the outcome conclusions are made and what eventually is the best way to prevent the most common irregularities and if these are also applicable from a more general point of view.

4 Results from fieldwork in Delft

In this chapter, the fieldwork to verify the sensor iSignum is described in more detail. The verification step of the radar-service sensor is done by simply counting cyclists during a set amount of times during the dates between the 15th September 2021 and the 17th September 2021 in Delft at the intersection of Julianalaan-Nassaulaan equipped with the iSignum (Table 1).

4.1 Measuring method

Manually measuring how many cyclists pass by at both intersections is done with a clicker app called 'Teller' (Teller, 2021). This app collects the timestamp every time a cyclist is counted. Various timeslots are chosen to get a general traffic flow overview by choosing between rush hours and less busy hours.

4.2 Results Delft: Julianalaan-Nassaulaan

The data is processed in the programming language Python (Appendix A) using the data stored in Excel-files. In Appendix A, the code that is used for Wednesday 15/09 is essentially the base code and was used to compute Thursday 16/09 and Friday 17/09 along with it. Dates and timestamps from the collected data from the sensor and the clicker app are alternated which needed modification beforehand in the code. An example of how the data looks like is to be found in Appendix B, this is nonetheless not the real data but completely made up due to confidential purposes and the two sets of data is therefore not matching up in any way. However, when using the real data within the Python code some graphs are the result. The few graphs show the time and the number of cyclists and are displayed in Figures 4-6 and shown larger in Appendix D. Due to fewer cyclists on Wednesday, Figure 4 includes markers for each count/detection to illustrate the separate measurements better. This cannot be done for Figures 5 and 6 due to the large number of cyclists which results in an unclear graph.
As witnessed, the two graphs in all figures are not exactly on top of one another, meaning that the data does not match completely. To highlight the individual points, markers are used in all graphs except for Figures 5 & 6 due to the many markers the graph will become unclear and these graphs are elaborated on in the next section in more detail. Furthermore, it can be observed that the divergence is not constant over the course of the measurement from the sensor in comparison with the manual counting and therefore it is valuable to take a closer look at only the differences between the two. These are on display in Figures 7-9.

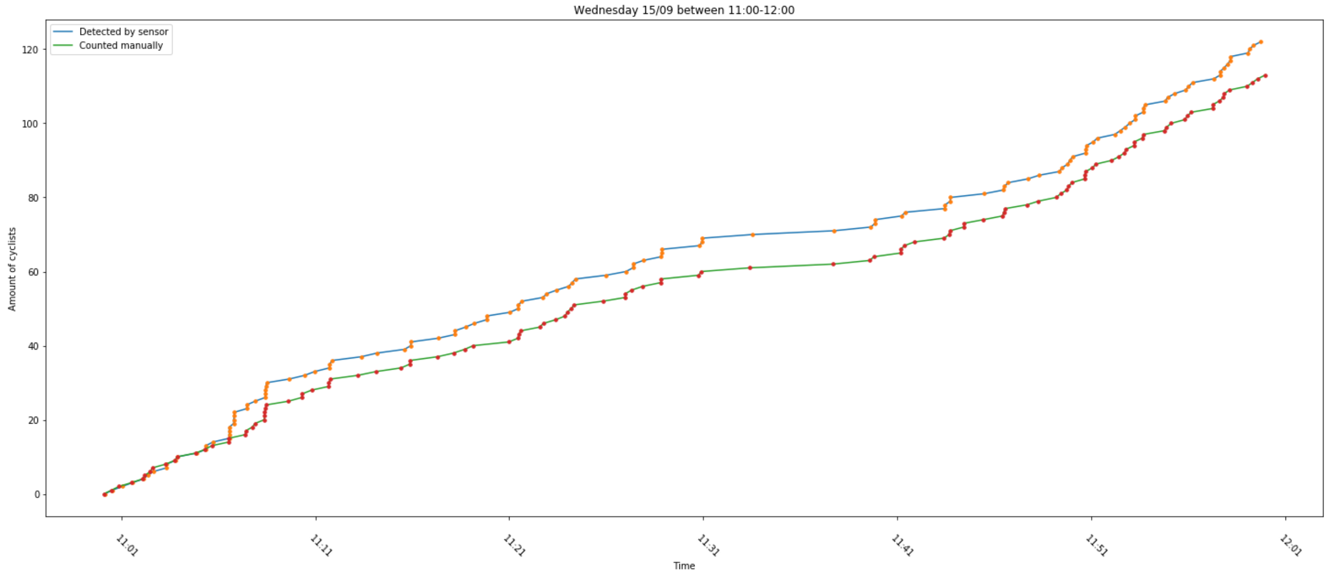

Figure 4: Comparison between manually counting and sensor detecting on 15/09 11:00-12:00.

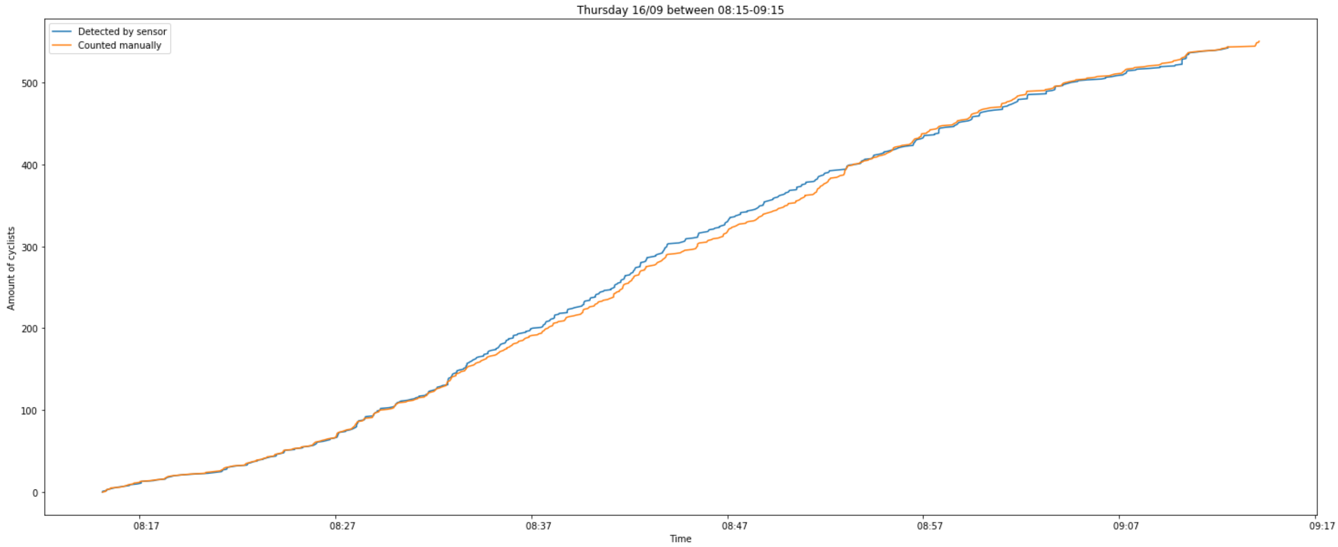

Figure 5: Comparison between manually counting and sensor detecting on 16/09 8:15-9:15.

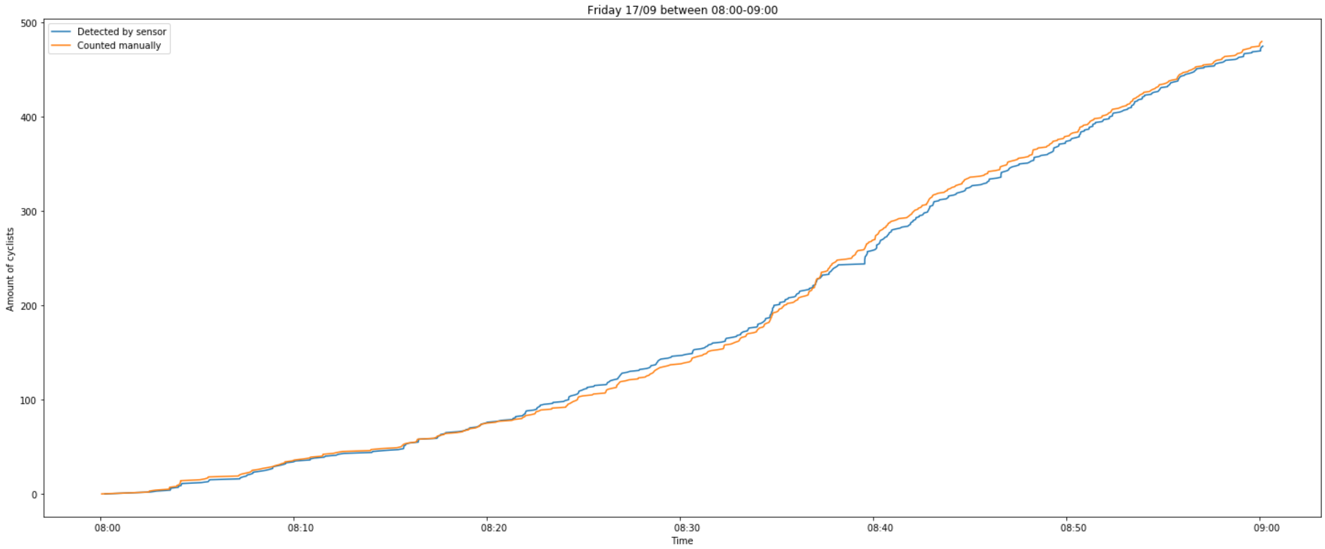

Figure 6: Comparison between manually counting and sensor detecting on 17/09 8:00-9:00.

Elaborating on this, the data from the two sets of lists got matched with one another. This was done using the manual measurements as a reference point and a time window of 5 seconds due to the possibilities of internal clock errors and real measurement errors. If a match is present the corresponding data is stored in a new data list and the timestamp in the existing list is changed to another time that is not near the time of measurement such that the difference is always larger than 5 seconds. This is in order to prevent that two timestamps from the iSignum data match up with the manual data. Meaning that the first encountered match within 5 seconds is matched with each other. The newly made list is comparable with the original data list of the manual detected cyclists such that the preciseness over the measurement can be calculated. However, the length is not the same since only the matches ended up in this list. This lead to an overall matching rate of 75.4%, 75.3% and 78.2% for Wednesday, Thursday and Friday. Furthermore, this newly created list contains timestamps that are used to compare the amount of sensor and manual detections at those times and thus what the differences are.
The amount of sensor detections is subtracted from the amount of manually counted cyclists. This can be found back in the code in Appendix A. Subtracting in this means that a positive slope in the graph is an error of the sensor more cyclists are passing by than that there are detected. The other way around, a negative slope is interpreted as the sensor counting falsely while no cyclists are passing by. The differences are all cumulative from the start time which means that a constant difference means that no error has taken place during that specific time window. In a general view, all graphs show fluctuations and some spikes which will be elaborated on in Sections 4.3 and 4.4.

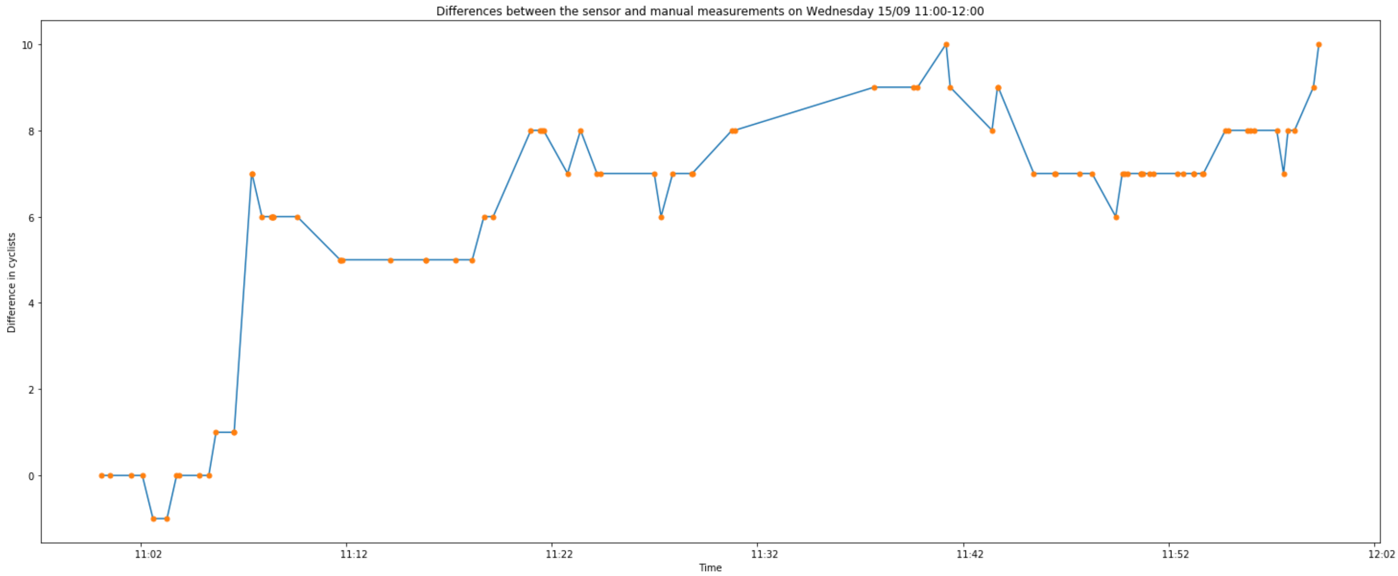

Figure 7: The difference between manually counting and the sensor on Wednesday 16/09 11:00-12:00

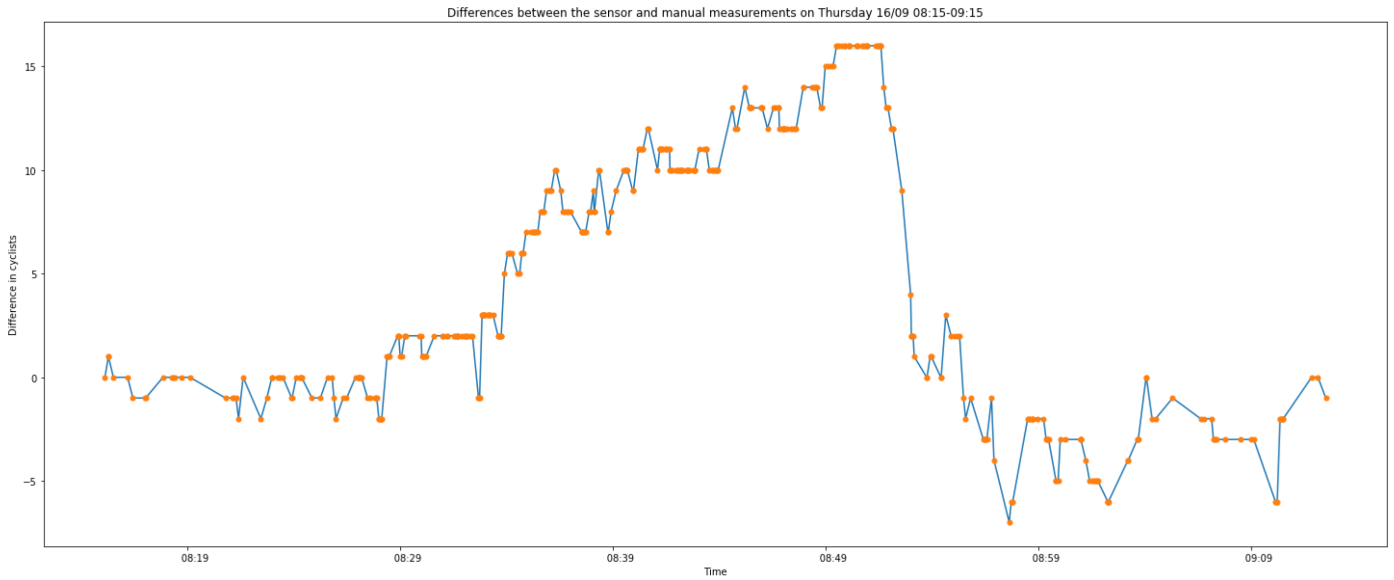

Figure 8: The difference between manually counting and the sensor on Thursday 17/09 08:15-09:15

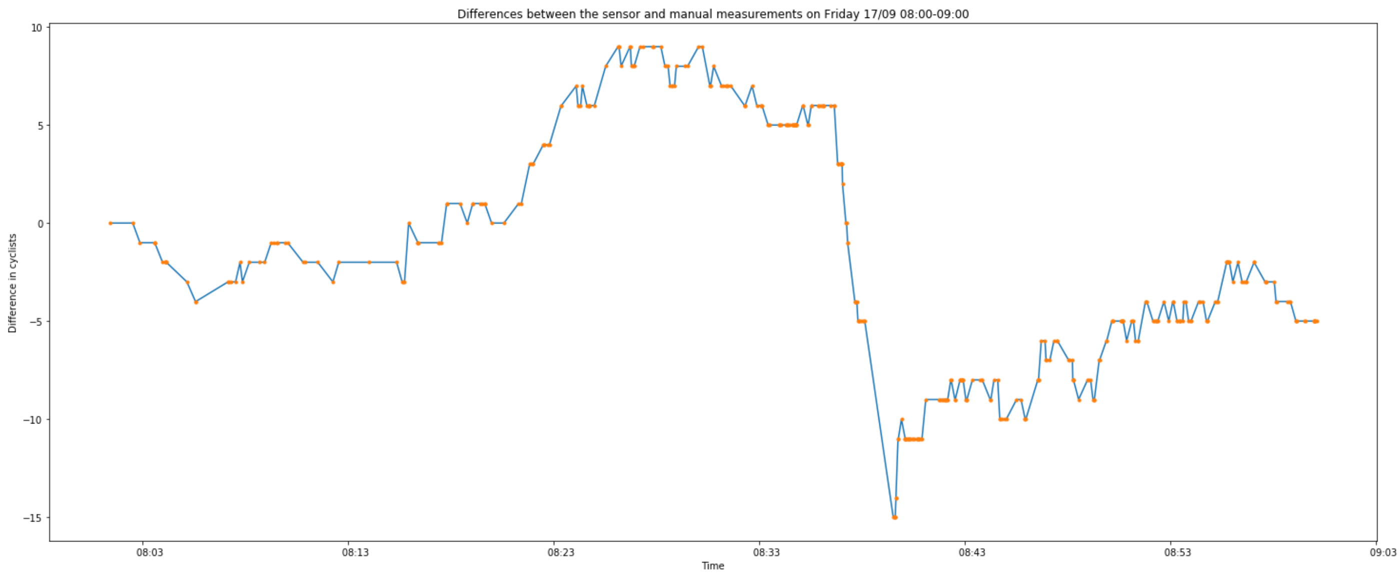

Figure 9: The difference between manually counting and the sensor on Friday 19/09 08:00-09:00

4.3 Observed hinderances in Delft

In Figures 4-6, it is witnessed that the graphs of manually and sensor measurements are not always exactly on top of each other. Additionally, Figures 7-9 that show the difference between the measurements are not constant at all. During real-time measurements, many factors contribute to the observed data. This also includes disturbances that oppose the objective of the iSignum and the company CycleData had intended for the sensor.

4.3.1 Wednesday 15/09 11:00-12:00

During the time of measurement no rush hour was happening at the moment and it was respectively not that busy on the bicycle path, with a total of 114 cyclists observed within the hour. However, this did give cars the opportunity to drive on the bicycle path when intended to take a right turn and the road is blocked off by cars waiting to go straight on the Julianalaan-Nassaulaan intersection. An intersection overview is displayed in Figure 10. These cars driving on the part where the sensor of iSignum is trying to detect cyclists, caused the sensor to count a car on the bicycle path as a cyclist, resulting in nine more measurements from the sensor than manually counted over the course of the entire observation. Most witnessed situations like described above happened at once at 11:06 due to drivers copying the behaviour from drivers in front of them. Taking a closer look at the graph in Figures 4 and 7, a large difference is recognized between the manually counted and detected by the sensor graph. This is especially visible in Figure 7 with a spike in the graph around 11:06.

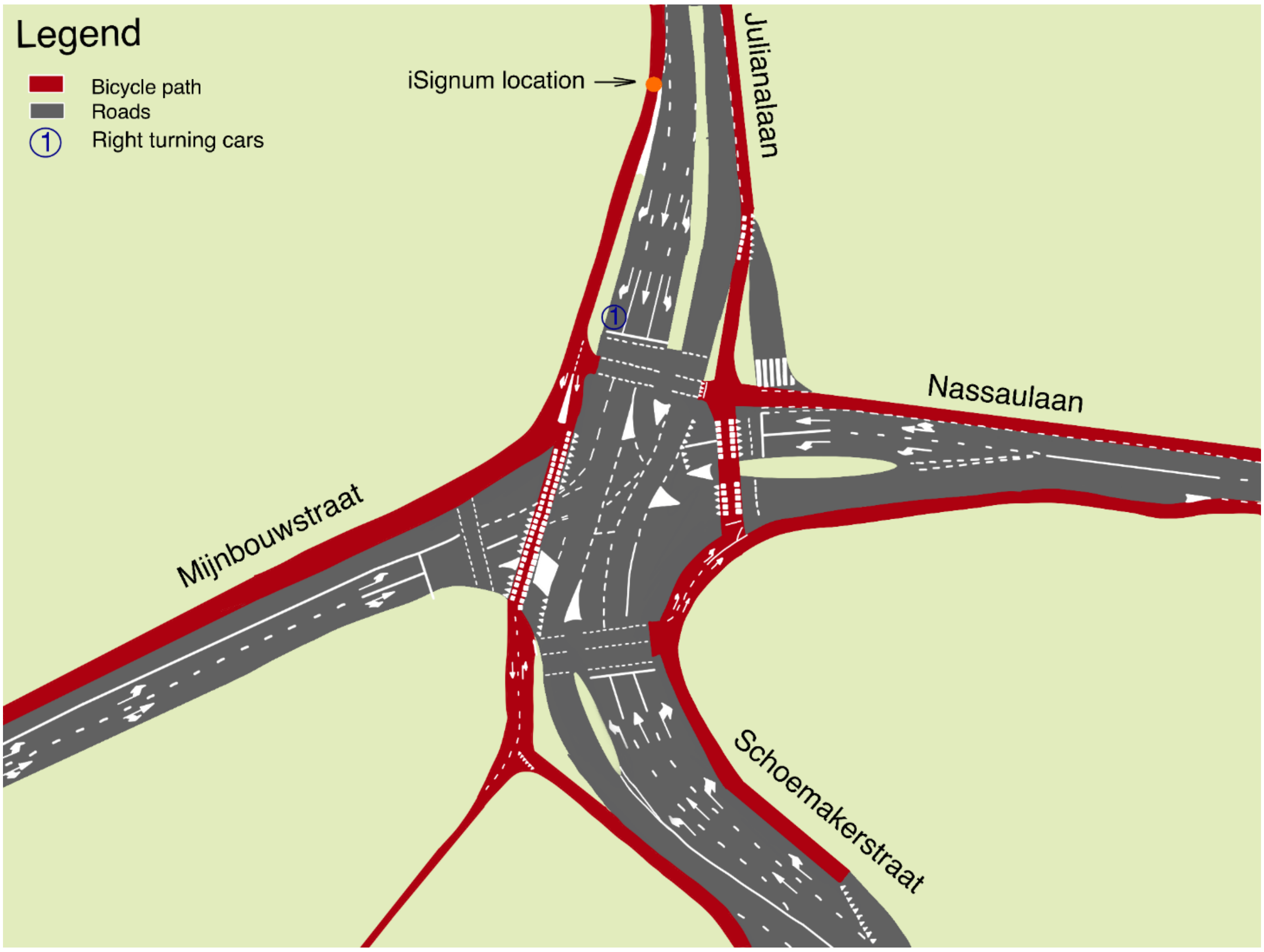

Figure 10: Intersection map of Julianalaan-Nassaulaan

Therefore, two new graphs are plotted in Figures 11 and 12 to illustrate the detection of cyclists from 11:07 onwards. The previously counted cyclists and falsely detected cars from that event are removed from the data list to show a better representative image over the course of the remaining time of measurement. In the graphs, it is noticeable that after the occurrence of a few cars driving over the bicycle path the sensor is not showing big errors in means of numbers of cyclists as before. The constant difference that was present in Figure 4 has disappeared mostly and was accountable towards one event of cars driving on the bicycle path and getting detected as a cyclist by the iSignum. However, there are still fluctuations visible when it comes down to the comparison of measurement methods in Figure 12. These fluctuations are not all from the same kind of error type. Due to the graph going up and down multiple times, it can be seen that errors occur frequently but at the end balance each other out which is not particular what the goal is of the sensor. Computing the number of correct detected cyclists into a percentage expressed in the total scrutinized number of cyclists gives in this case for the shortened measurement, around 74.5% which is even lower than the overall percentage.

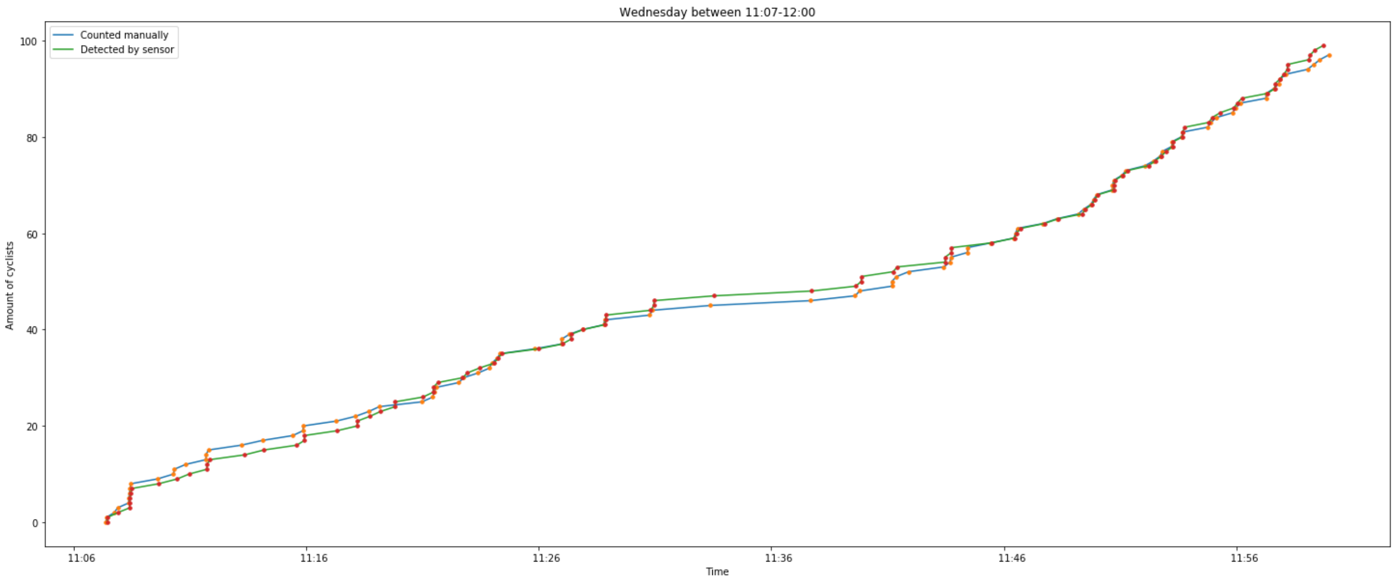

Figure 11: Comparison between manually counting and sensor detecting on 15/09 11:07-12:00.

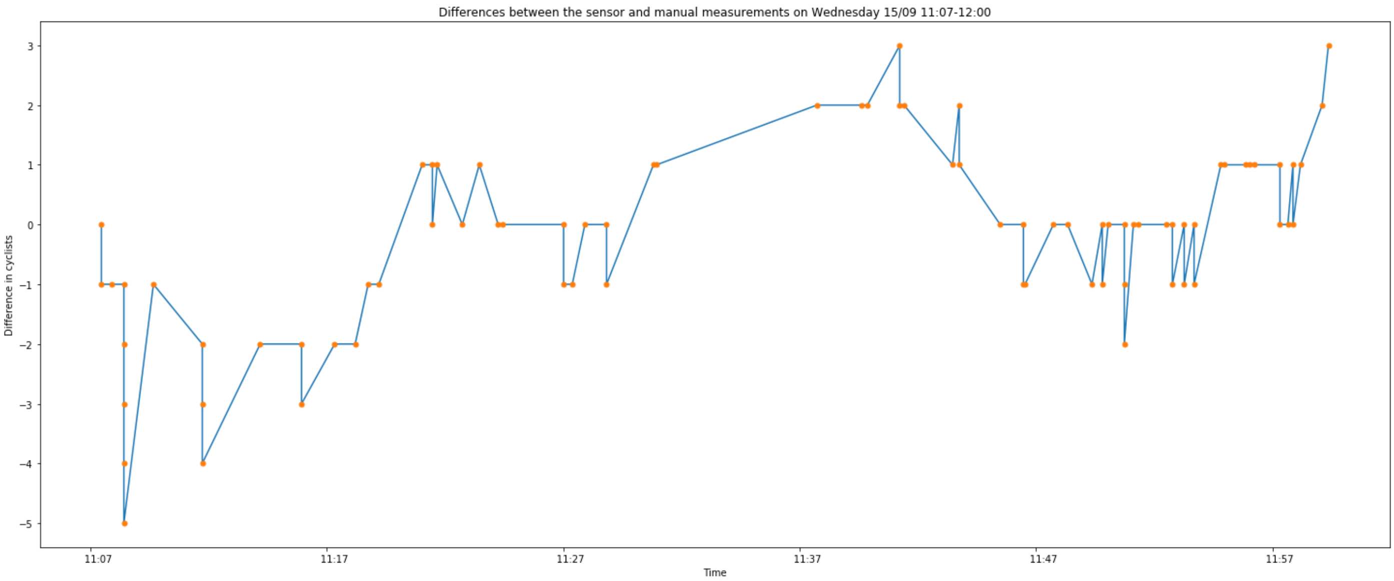

Figure 12: The difference between manually counting and the sensor on Wednesday 16/09 11:07-12:00

4.3.2 Thursday 16/09 8:15-9:15

Over the course of the measurement on Thursday 16/09 between the hours 8:15 and 9:15, the greatest part is within the rush hour limits. This was also remarkable in the difference in the number of cyclists with the previous measurement on Wednesday 15/09. During this analysis a problem as described on Wednesday 15/09 with cars driving on bicycle lanes is not present. Due to rush hours, many more cyclists were present and cars did not get the opportunity to make a manoeuvre to divert onto the bicycle lane without physically hitting a cyclist. However, during the time of observation two disturbances were present (Figures 13 & 14). At 8:52-8:54, a delivery van was partly blocking the bicycle lane causing the sensor to have trouble counting all the cyclists. Several cyclists that went around the van were not detected by the sensor since practically they were cycling on top of the car lane. During the time span, a total of 34 cyclists approached the

Figure 13: A delivery van partly blocking the bicycle path from 8:52-8:54 on 16/09.

Figure 14: A garbage truck blocking the whole bicycle path from 9:12-9:15 on 16/09.

Figure 15: A delivery van partly blocking the bicycle path from 8:35-8:37 on 17/09.

intersection and 25 were detected. However only 17 were detected correctly, only 50% was within the five seconds margin using the method in the code in Appendix A were only correct detections are included and not the false extra logged cyclists. The graphs from this event are illustrated in Figures 16 & 17. In these graphs, it is observed that the difference becomes larger overtime when the delivery van is present and the sensor misses cyclists. In short, the delivery van managed to cause the iSignum to have difficulties. Furthermore, a garbage truck was present at the end of the analysis from 9:12-9:15. In comparison with the delivery van, the entire bicycle lane was hindered by the garbage truck. This caused the sensor to miss all cyclists that neared the crossing which is likewise visible in the graph of Figure 5 and a more detailed graph of only the last five minutes of the measurement in Figure 16. The graph of the sensor detecting cyclists immediately stopped around 9:12:35 until the end time of the measurement which is withal the time that the garbage truck left the position. Another concern is the spike at the beginning around the minute of 9:10, multiple cyclists were detected while not that many were present. Arousing more doubts towards the accuracy of the sensor.

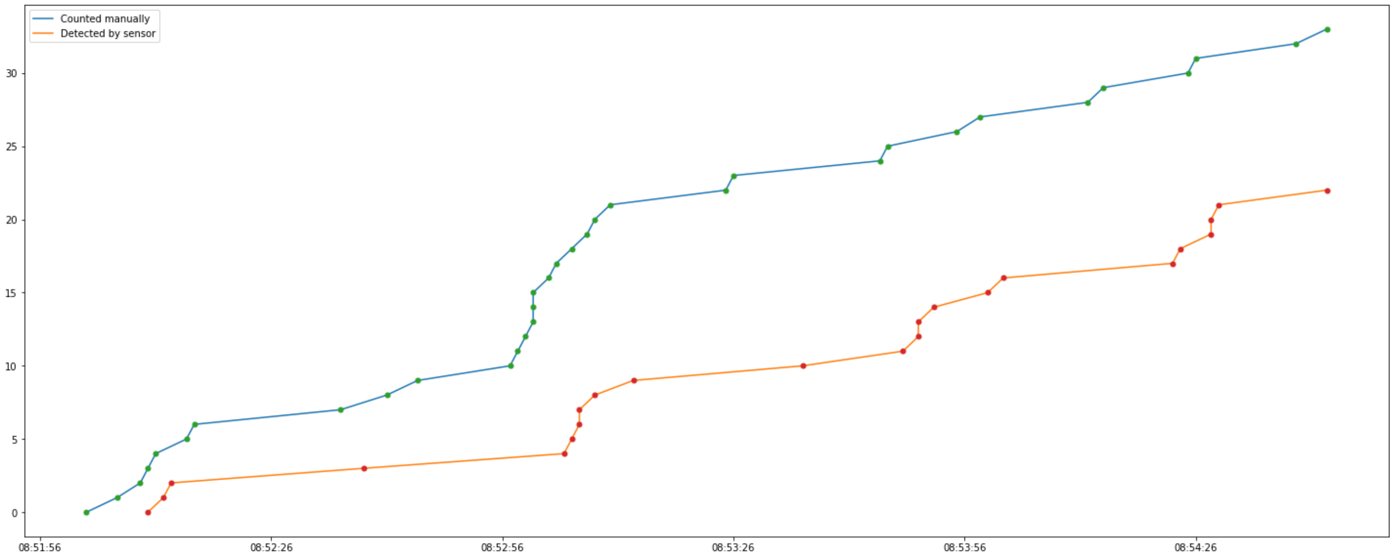

Figure 16: Comparison between manually counting and sensor detecting on Thursday 16/09 08:52-08:54.

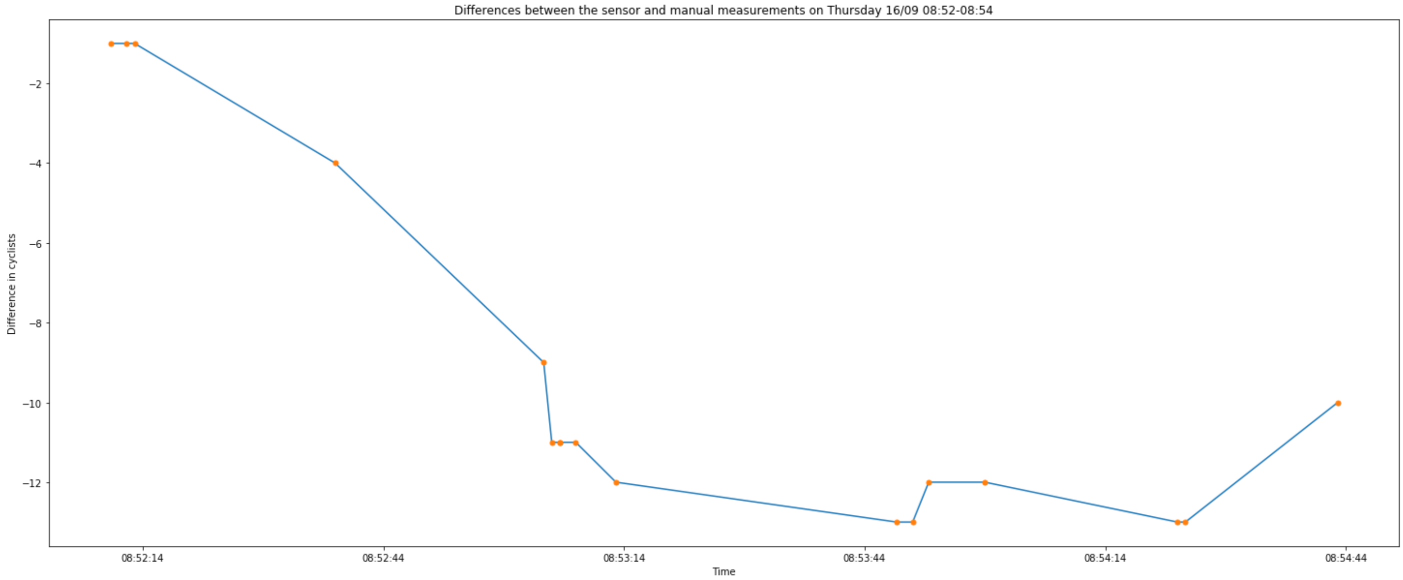

Figure 17: The difference between manually counting and the sensor on Thursday 16/09 08:52-08:54.

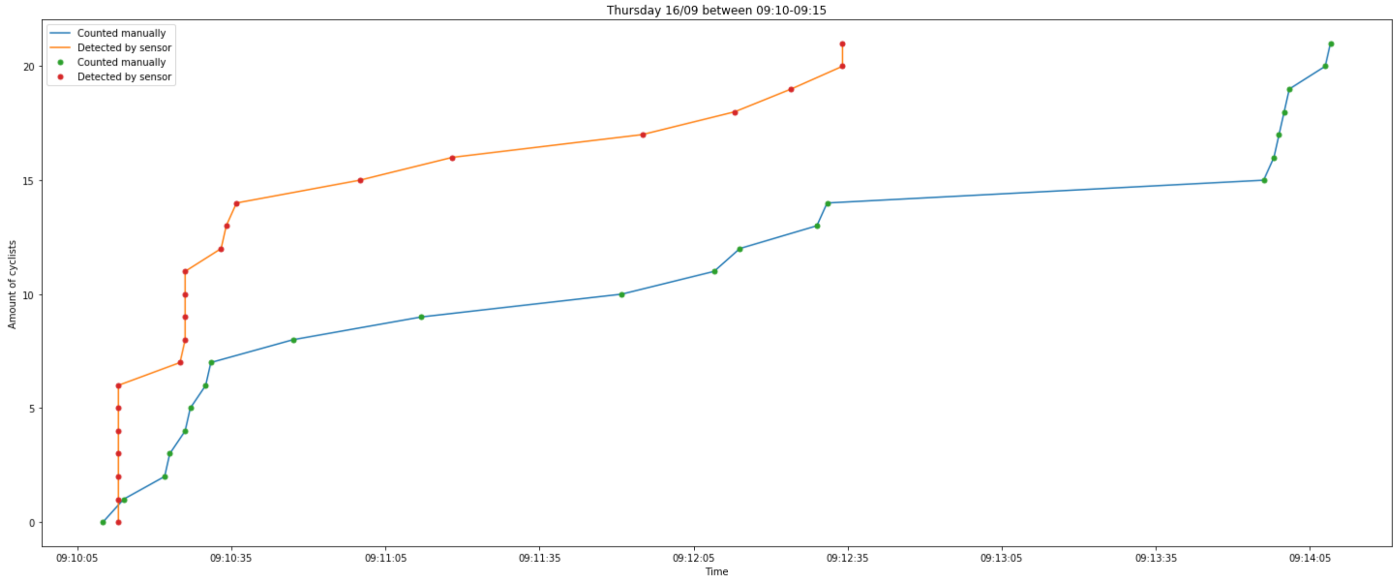

Figure 18: Comparison between manually counting and sensor detecting on 16/09 09:10-09:15.

4.3.3 Friday 17/09 8:00-9:00

During the rush hour of Friday the 17th of September 2021, one disruption appeared (Figure 15). A similar disturbance as the day before with a delivery van occurred. On this day, the van was parked on the bicycle path from 8:35-8:37. The event caused a comparable error in the number of cyclists. A total of 53 cyclists passed by the sensor and 39 according to the sensor, with 35 being valid using a time error of 5 seconds. Meaning that the sensor missed roughly 33% of the total cyclist during the event that the delivery van was present on top of the bicycle path. In Figure 19, the representation of the difference during the timespan is given. It can be seen that for a minute the sensor still detects without any flaws but around 8:36:40 more cyclists approached the intersection and the sensor experienced troubles in detecting all of the cyclists due to the delivery van blocking the bicycle path.

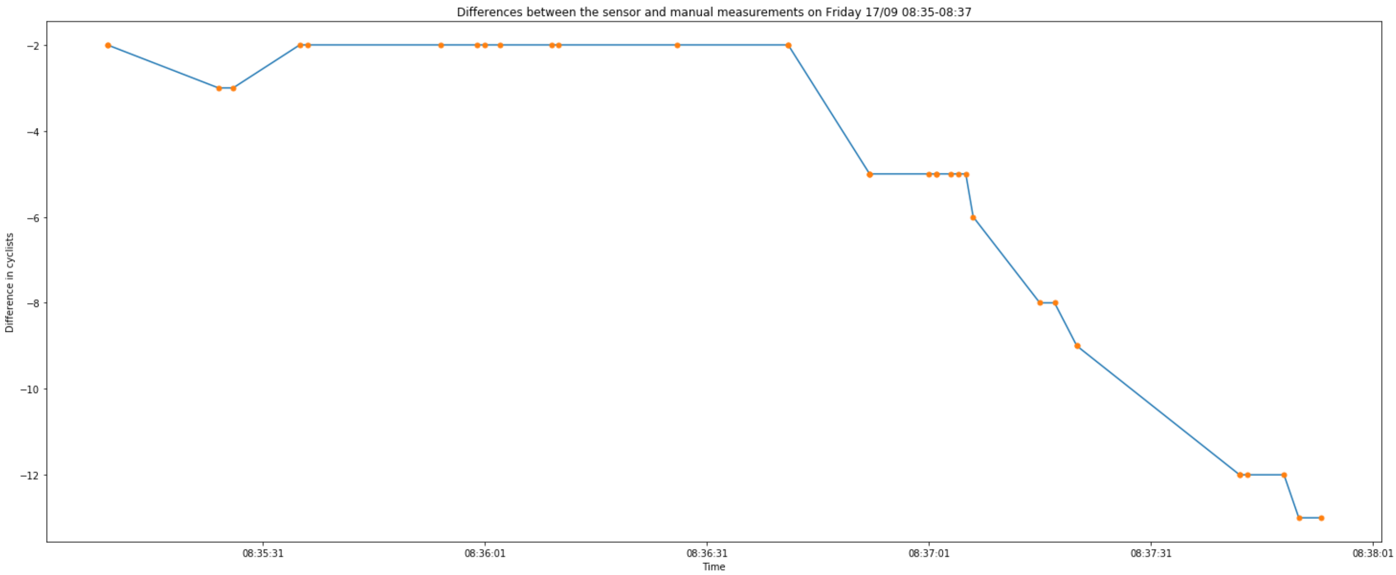

Figure 19: The difference between manually counting and the sensor on Friday 17/09 08:35-08:37

4.4 Conclusions based on results

Based on the observations and data processing, several conclusions can be made already. When roughly comparing the end amount of cyclists of the sensor and the manual counting, it seems like no big or multiple errors are present. However, after taking a closer look at the graphs in Figures 7-9, multiple errors are witnessed. With the graphs experiencing fluctuations, meaning that occasionally an extra cyclist is counted that was not there or either a cyclist was missed. Knowing these errors, it can be said that the end total of cyclists does not raise doubts of the correctness due to a balance of the different kind of errors cancelling each other out. In spite of this, the errors exist and do not give a clear overview of all the cyclists passing by. Even though various disturbances were present which caused the sensor to be less exact than normal, the overall precision was not near the 95% that the company of the iSignum claims it to be.

A final conclusion that can be made at this stage is that these errors in combination with an iVRI will arise problems when the sensor is in commissioning. Falsely detected cyclists by the sensor that are not present are going to request a green light while fewer or no cyclists are in fact there. While missing a cyclist that is actually present causes the sensor not to communicate with the iVRI that a cyclist is approaching which normally the sensor should do.

5 Comparing VLOG data

The iSignum does not reach the promised 95% accuracy but also does not score dramatically low while data from the disturbances are included. Therefore, it is valuable to have a closer look if either the errors that are accountable towards hinderances can be compensated with V-log data. This can be beneficial in the end so that not the whole traffic flow for cyclists becomes disarranged. However, using V-log data is not the same as using own measurements. This is partly due to the fact that cyclists also have the opportunity to take a right turn at the intersection without passing the loop sensor. Next to that, additional cyclists from example the Nassaulaan who take a left turn are not counted by the iSignum sensor that is located more upstream from the intersection but is detected by the inductive loop sensor at the crossing. Additionally, the loop sensor can only detect when it is occupied and not the number of cyclists. Therefore the total amount of detections stored in the V-log data is perhaps lower or not quite the same as what is counted near the iSignum sensor. Nonetheless, it is probably still possible to see if the loop sensor can pick up the undetected cyclists in case a delivery van or a garbage truck blocks off the bicycle path.

5.1 Comparing method

The V-log data that is used to compare the data set of the manual measurements are confidential, therefore no real representation can be given. However, in Figure 20 an example is displayed on how V-log data is shown in a VLOG Viewer application called YAVV. On the left side, the traffic light and sensors can be filtered such that only the relevant items regarding cyclists at the intersection are visible. Next to that, an item including public transport was kept to indicate if that has large influences on cyclists flow at the intersection. The blue colours represent the specific sensor to be occupied while the colours red, green, white and yellow represent the status of the traffic lights. During the comparison, the cyclists that are counted in

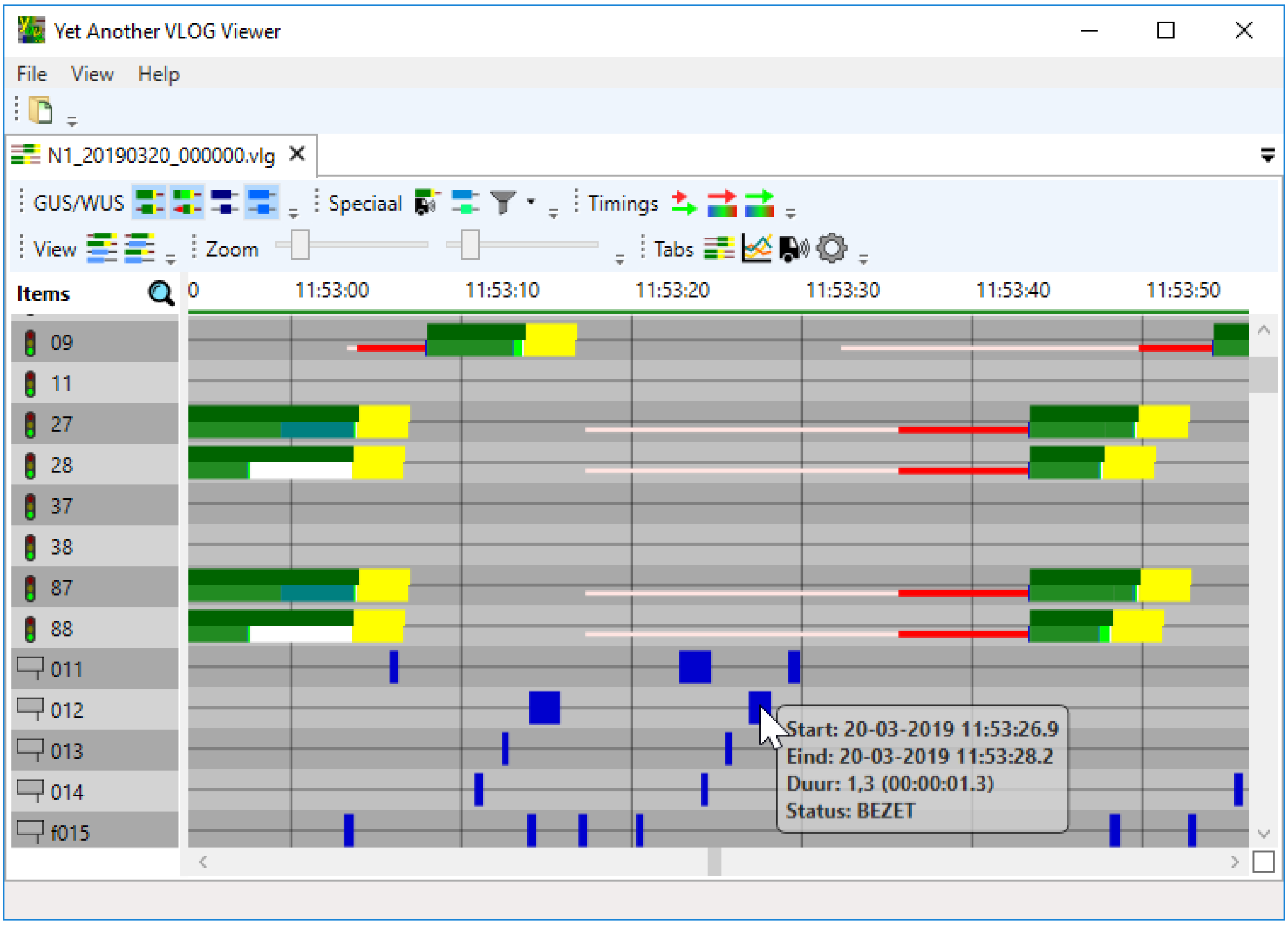

Figure 20: Example of V-log data in YAVV (CodingConnected e.U, 2019)

the manual measurements are paired with a cycle of the traffic light. Manual measurements were done with the same principles as the iSignum at this location, detecting cyclists without knowing whether the cyclists made a right turn or not. To have a clear overview of the data, the data set is modified when comparing with the V-log data and the modification can be seen in Appendix C. However, this is not the real data with the actual timestamps and are all made up but with a sense of plausibility. In the appendix, it can be observed that remarks about a specific cycle are made on the right side.
One cycle is defined as the first cyclist who occupies the sensor, either the loop sensor or the push button, until the last cyclist can cross the intersection until the traffic light turns red. In that way, a couple of right-turning cyclists stay undetected, however right-turning cyclists that fall outside these cycles can be classified as right-turning cyclists which is more valuable information since in the future the iSignum is going to be in commissioning resulting in communication with the iVRI that a cyclist wants to cross the intersection while in fact, the cyclist turns right. Next to that, during the times that disturbances occurred more attention is paid towards the data from the push button and loop sensor and if the existing intersection control is functioning proper enough to cover the errors from the iSignum.

5.2 General observations

While comparing the V-log data from the intersection Julianalaan-Nassaulaan with the data set of manual measurements it is observed that most commonly the time difference from observing a cyclists near the sensor and reaching the inductive sensor loop near the stop line is around 10 to 12 seconds. The distance is roughly 50 meters between the two objects meaning that the average speed from most cyclists has to be around 15-18 km/h. Furthermore, it was noticed that in certain cycles public transport busses were present, resulting in longer waiting times.

5.3 Wednesday 15/09 11:00-12:00

Inspecting the V-log data from the time of measurements, not all observed cyclists were detected by the loop sensor that is located in front of the stop line, this is in line with the expectations. Using the method of assigning cyclists to a particular phase and filtering out right-turning cyclists, resulted in four cyclists that turned right that would have triggered the iSignum sensor falsely to request a green light. On the other hand, three times the loop sensor was occupied without a manual measurement which is probably due to the occurrence of left-turning traffic from the Nassaulaan. For these particular cyclists, no request will be made when the iSignum is in commissioning since they are not detected by the sensor. Next to these events, it happened three times that the traffic light turned immediately green when a cyclist was detected and probable already had to stop. Additionally, at one point the light turned green and red again three times while no cyclists were detected by either manual measurement and the loop sensor. At this point, no cyclists were present for a period of 4.5 minutes. This is a great measure to have in case either the loop sensor or the iSignum is out of order to keep potential cyclists to be able to cross the intersection. Lastly, on a few occasions, the loop sensor had difficulties to detect cyclists and the push buttons were used and extensively in some moments. Whereas, the loop sensor got activated in one case after roughly half a minute the push button was already used.
During the disturbance of cars driving over the bicycle path, the iSignum was not in commissioning yet, which means that the cars did not trigger the sensor to communicate with the iVRI to request a green light. However, at that exact time the right-turning cars had a green traffic light and all the cars that drive over the bicycle path to get to the intersection to catch the green light caused the green light to last longer. And therefore, resulting in longer waiting times for cyclists in the end.

	Right-turning cyclists who falsely trigger the iSignum	Cycles with no cyclists	Immediately green cycles	Cycles that started without a detection at the iSignum location	Average number of cyclists in one cycle
Wednesday	4	3	3	3	2
Thursday	0	0	1	1	10-15
Friday	0	0	1	0	8-13

Table 2: Summarized data of all measurements

5.4 Thursday 16/09 08:15-09:15

At the time of measurement, a rush hour was present which was already seen in the number of cyclists that passed by the sensor in comparison with Wednesday. Additionally, more cyclists go through one phase of the traffic lights to give a better view, this is about 10-15 cyclists. With some outliers that are less than 10 or more than 15, however, it is mostly between 10-15 cyclists in one phase. It is observed that no extreme long waiting times that exceed the maximum waiting time are present. The first cyclists that arrived at the intersection when the traffic lights are red have to wait around 1-1,5 minutes. There was one extreme case, which included four public transport busses to pass by in one cycle with the consequence that conflicting directories have to wait longer including the cyclists. The impatience can be concluded due to the many detections from the push button within one phase. Since it was a rush hour it is harder to be able to get an immediate green light when occupying the sensor. Nonetheless, it took place once at the end of the rush hour. This case could have been picked up by the iSignum if the communication with the iVRI was in use. Throughout the disturbances, not all cyclists were detected. During the delivery van and garbage truck, 60% and 83% of all cyclists that were present near the iSignum were detected by the loop sensor. The first percentage is already higher than the results from the iSignum and additionally, the loop sensor did manage to detect cyclists when the garbage truck was there at the time. Bearing in mind that right-turning cyclists are not detected and that multiple cyclists occupying the sensor count as one cyclist.

5.5 Friday 17/09 08:00-09:00

On Friday, another rush hour was happening. The first 20 to 30 minutes of the measurement less cyclists were present than the rest of the measurement. The number of cyclists after that time is similar to what was described in Section 5.4 for Thursday.

In line with the previous measurement during rush hour, it was still possible to have once an immediate green light after a cyclist was detected. What is remarkable in comparison to other measurements and also seen during the real-life measurement is that it occurred once that not all cyclists that were present could go through one green light at once. In other words, there was an extreme flow of cyclists approaching the intersection at the time and not all were able to cross the intersection due to the maximum green was reached before all cyclists could cross the intersection. Furthermore, similar patterns as in Section 5.4 are seen when it comes down to the number of cycles and what the time is in between the first cyclists that occupy the sensor and the moment the lights turn green.

Analysing the V-log data in more detail at the time when the delivery van was present, the V-log data only logged only half the number of cyclists as detections. At the time many cyclists were waiting for a green light and therefore two cyclists next to each other on the sensor is counted as one. Concluding that the loop sensor detected fewer cyclists than the iSignum did but still managed to fulfil its function as intersection control system.

5.6 Conclusions on V-log data

On basis of observing the V-log data and comparing it with the manual counting data, it can be concluded that the loop sensor most of the time during commissioning does accurately detect a cyclist when the sensor is occupied. In a few cases, the loop sensor had troubles, however, the push button makes up for it. During the events of the delivery van and garbage truck, the loop sensor managed to still detect cyclists. In the case of the delivery van on Friday the loop sensor did more poorly than the iSignum in purely counting the number of cyclists which is however not the function of the loop sensor. Nonetheless, the loop sensor kept functioning on Thursday when the iSignum was not able to detect cyclists when the garbage truck was blocking the bicycle path. The main point is that the current intersection control is able to cover and in the worst case to cover partly the iSignum in case a disturbance arises.

Lastly, the immediate green light that frequently happens during off-peak hours can work in advantage for the commissioning of the iSignum. It is noticeable in the V-log data and this also supports the objective of the new bicycle sensor. To reach this objective without the use of V-log data and the existing intersection control, the next chapter is dedicated towards prevention methods such that the chances are lower for disturbances to influence the iSignum negatively.

6 Prevention

In the previous chapter, a comparison with V-log data was done to determine if the existing traffic control could compensate and function while disturbances are present near the iSignum sensor. In spite of that, having a prevention method for the iSignum at the current location is more valuable than that the existing intersection control is taking it over from the iSignum during such an event. Therefore, attention is dedicated to looking at what could be possible as a prevention method.

6.1 Placement upstream

Upstream placement of the iSignum is one option that could serve as a prevention solution. Placing the sensor more upstream means that the location of the iSignum falls out of the image in Figure 10 and is located above the current placement. Therefore the upstream location can be witnessed in Figure 21 as a pink circle. The distance towards the intersection is larger and likewise between the sensor and the lane to take a right turn (Figure 10, encircled number one). The latter is convenient since it is illogical for cars to drive on top of the bicycle path when further away from the intersection. Next to that, when placing the iSignum more upstream the delivery van and garbage truck are not capable of disturbing the sensor. These two events are related to the building of a company called Trident that is based next to the iSignum sensor location. Therefore the chances of a delivery van or a garbage truck being present more upstream from the current location are quite low. However, multiple parking spots and a bus station are located upstream of the Julianalaan.

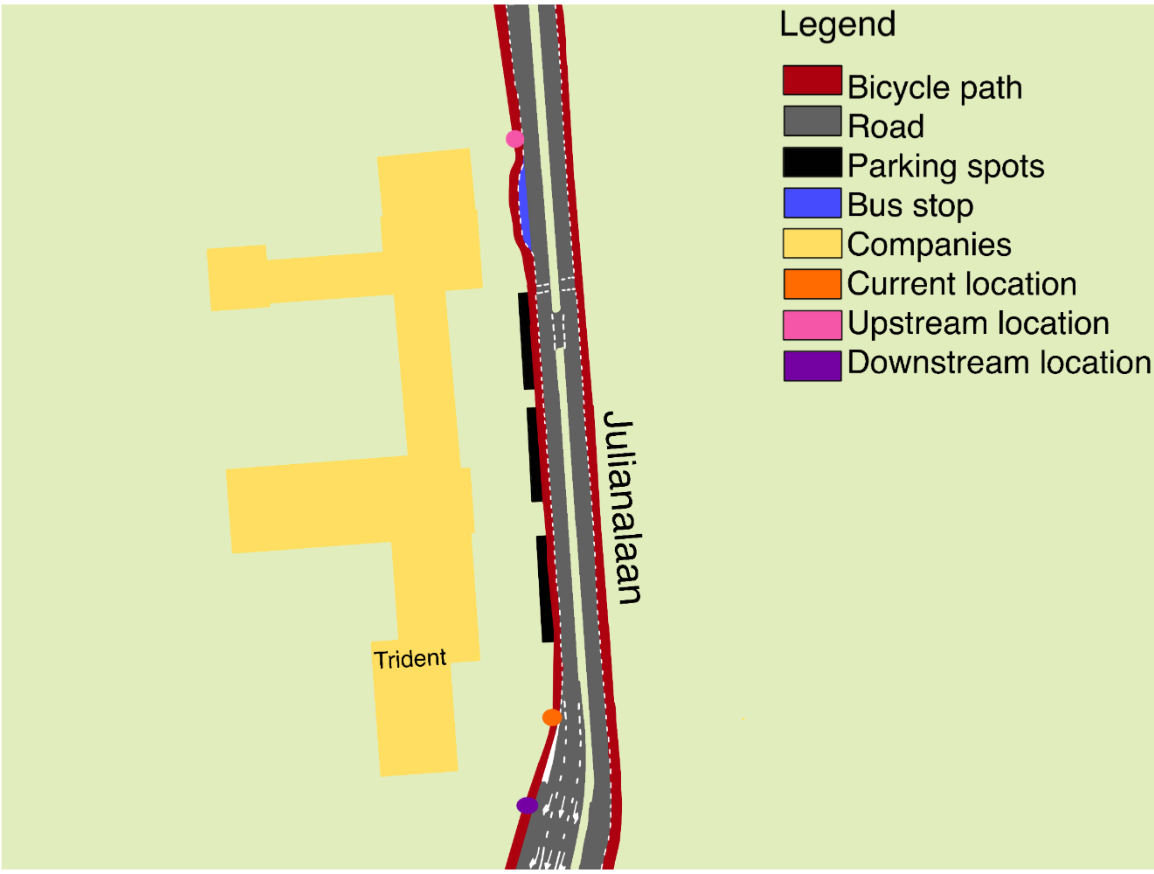

Figure 21: Zoomed in map of the Julianalaan street

This may be sensitive to other disturbances towards the iSignum when for example it is installed near the parking spots. A driver who is attempting to park the car blocks the bicycle path and therefore cyclists have to manoeuvre on the car lane again which is not the best solution. Next to that, during a manoeuvre of the car or leaving the parking spot, the car can set off the iSignum to count the vehicle as a cyclist idem ditto with the bus stop along the Julianalaan where people cross the bicycle path to get to the bus and may cause a disturbance or an extra detection. To still relocate the iSignum upstream from the current location means that the sensor would fit best when further away from the crossing than the parking spots and the bus stop. However, this distance from the current and new location would be at least 110 meters while the current distance between the iSignum and the intersection is roughly 50 meters. This does give the iSignum more time to communicate the information of passing cyclists but also has opportunities for the information to be less reliable when considering speed. The speed of cyclists is more prone to changing when a long distance is still needed to cycle up until the intersection. Additionally, cyclists that are intending to visit the building from Trident are now contributing to a false request for a green light when in reality they are not planning to cross the intersection which is also not solving the problem. Therefore, placing the sensor upstream creates new factors that can contribute towards a negative influence for the sensor than only the existing right-turning cyclists.

6.2 Placement downstream

Placing the iSignum more downstream is the other option to relocate the sensor along the bicycle path on the Julianalaan. In contrast with the previous solution in Section 6.1, the distance between the iSignum and the intersection itself becomes shorter and therefore the time for the iSignum to communicate and the iVRI to anticipate becomes shorter. Moving the sensor closer to the intersection solves the occurring disruptions during the measurements. No vehicle that needs to be present near the company of Trident such as a delivery van or garbage truck are able to force the iSignum directly to make an error. Additionally, placing the iSignum more downstream in a strategic way along the bicycle path should prevent cars that drive on the bicycle path to disturb the sensor by counting extra cyclists that are not present. With this in mind, the new location that satisfies this and is the furthest away from the intersection to give the sensor decent time to communicate information with the iVRI, is marked with a purple dot in Figure 21. The distance to the stop line goes from roughly 50 meters to 37.5 meters meaning that the average time between detection and arriving at the intersection becomes 7.5-9 seconds. Next to this, the sensor should count the same number of cyclists that are really present as the old location. At the new location, no diverging cyclists to for example the company of Trident are present, only the right turning cyclists are still included. Therefore the difference is with the upstream location that the detection of cyclists is not sensitive to other factors than there already was. The benefit lies in preventing the disturbances that occurred during the measurements and not filtering out the right turning cyclists. This would be too difficult, in order to do so, the iSignum has to be even closer to the intersection, leaving around 10 meters of distance left between the sensor and the stop line which is definitely too short of a notice for the system to make full use out of the advantages the iSignum can bring with communicating with the iVRI.

6.3 Barriers

Another option besides repositioning the sensor could be placing barriers near the iSignum location to block the bicycle path in such a way no disturbances can be present. Making it impossible for a vehicle to stop in front of the iSignum and forcing delivery vans and garbage trucks to stop at another location than in front of the sensor. This prevents cyclists to make a detour on the regular car lanes at precisely the height of where the sensor is aimed. Thus, in the end, cyclists that are actually present will not stay undetected by events as these anymore. With barriers, one can think of concrete blocks that are displayed in Figure 22 or 23 which are the Haisafe barrier and the Jumbo block. The first type of barrier is commonly used when construction is taking place and temporary barriers are needed and the latter functions as collision protection. Both of these barriers are able to function as barriers in this particular situation and location where the iSignum is installed

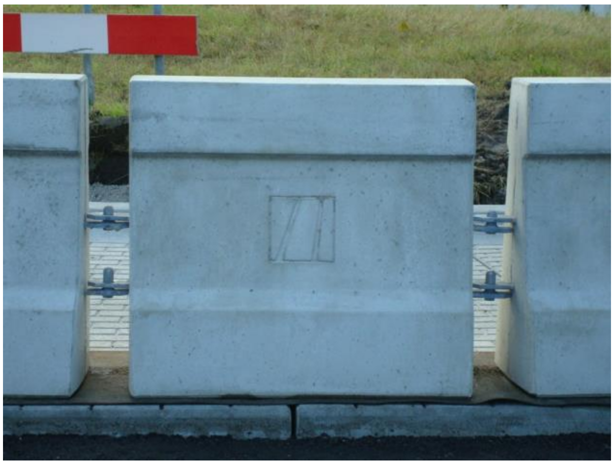

Figure 22: A Haisafe barrier (Traffic Service Nederland, 2020) *Figure 23: A Jumbo block (Betondingen, n.d.)*

at the moment. Additionally, vehicles are not able to go through one of these and are forced to follow the prescribed lines on the ground and right-turning cars have to wait patiently until cars that are in front of them crossed the intersection before reaching the lane for right-turning cars without driving on top of the bicycle lane. With this prevention, one should keep in mind that barrier blocks make the lanes for cyclists and cars smaller than the current situation or the other prevention methods and can seem blunt when used for one spot in particular and not along the whole street of the Julianalaan. However, the municipality has stated not to actively prevent offences such as wrongly parked vehicles with concrete barriers near the iSignum location. Consequently, this prevention method is an option on paper but is not going to be realized by the municipality.

6.4 Conclusion

After considering three prevention methods, there is one prevention that could work out in the end. Placing the sensor upstream from the current location is prone to arising new factors that could affect the sensor negatively such as parking cars and pedestrians crossing the bicycle path near the bus station. Plus the method of barriers that blocks off vehicles to stop near the iSignum and also force cars to follow the prescribed lanes on the ground is not going to be executed by the municipality. Therefore, the one prevention that fits best and is plausible is to relocate the iSignum more downstream in comparison with the current location. Doing so solves the disturbances that were witnessed during the three measurements between the dates of 15/09/2021 and 17/09/2021 and therefore the accuracy of the sensor should be higher in the end when this measure is taken.

7 Conclusions

The first part of the research was to determine the accuracy of the iSignum. After the experiments were done and data was used from both the manual measurements and the iSignum to check the accuracy using the programming language Python, it can be concluded that the promised 95% accuracy is not met at the location of the intersection of Julianalaan-Naussaulaan where the iSignum is installed in Delft. The percentages of accuracy came back around 75-78% and were not near the 95% the company of CycleData has promised. Looking at just the end total of the number of cyclists, nothing seems off but when processing the data through matching the two data sets it was seen that the sensor show errors. Errors including counting extra cyclists that are not physically present or not counting cyclists that are actually present at the intersection. In the first case, the error would cause extra requests for a green light while no or fewer cyclists are in fact present which worsens the traffic flow overall by disturbing the other directories to cross the intersection. On the other hand, missing a cyclist would mean that the sensor does not communicate with the iVRI that a cyclist is approaching, taking away the objective of the sensor to stimulate a better traffic flow and comfort for cyclists.
Next to this, it was also observed that disturbances are present that negatively influence the outcome of the sensor data which the sensor cannot do anything about such as the presence of a delivery van or a garbage truck or even vehicles driving on top of the bicycle path and getting detected as a cyclist. Knowing this, V-log data that represents the occupation of the sensors near the stop line and the traffic light is used next to the manual measurements data to check whether the existing intersection control could handle the disturbances instead of the iSignum in such an event. The outcome of this was that the existing intersection control of the loop sensor is definitely able to do so and does it properly. Additionally, more insight was given after analysing the V-log data about the potential use of the iSignum. During off-peak hours, it was noticeable that a cyclist is more likely to get rewarded with an immediate green light when activating the loop sensor. Therefore, it can be concluded that during off-peak hours there is potential for the iSignum to successfully request a green light for a cyclist when in commissioning. In rush hours, this is almost not possible to achieve due to the large flows of all transport modes to directly get a green light for the first detected cyclists in a new phase of the traffic control system. In the end, it can be seen that the use of the newly developed sensor iSignum is only beneficial during off-peak hours to enhance the cyclists' traffic flow and the comfort for these particular cyclists. To still try to prevent errors during the measurements, solutions are thought of. Several methods are not plausible or could even cause new errors such as parking cars and pedestrians crossing a bicycle path near the bus station which is not preferred. Consequently, the prevention method that should work is to relocate the iSignum downstream to the current location where disturbances do not have the chance to force the iSignum to make errors in its data.
Recommendations that can be done is to move the iSignum to the downstream location which is 37.5 meters away from the intersection stop line to at least eliminate the disturbances that now force the iSignum to make unnecessary errors. Additionally, further research towards the iSignum sensor at this particular location is recommended before the sensor is in full commissioning and not to let the iSignum communicate with the iVRI before the 95% accuracy is met since dishonest information would lead to unfair green times and a disordered intersection control. With the prospect of achieving 95% accuracy, thereafter the comparison with the current alternative bicycle sensors can be made clearer. If it is the case that the iSignum never reaches 95% accuracy, the comparison can still be done but with a different prospect for the sensor. At this point, a comparison has no additional value and is prone to differ when changes are to be made to the location and further research has to start. A more detailed description of what further research entails is discussed in the next chapter.
In a more general view, it can be concluded that the specific location of the iSignum sensor has to be thought out in detail before installing it at a certain spot at any location. It is best to take out experiments in real life and detect just as the iSignum does beforehand to see if irregularities arise and search for the best location with almost none or even with no disturbances influencing the iSignum.

8 Further research

Several specific topics are up for further research regarding the installed iSignum sensor at the intersection of Julianalaan-Nassaulaan. In this chapter, the topics are discussed that are appealing for further research after the results and conclusions from this current research.

8.1 Placing the iSignum downstream

In Chapter 6, the outcome stated that the best prevention method for the disturbances that are currently present is to move the iSignum more downstream towards the stop line. Events of a delivery van or cars driving on top of the bicycle path are not able to cause errors in the iSignum data anymore and no new factors could influence the sensor negatively and therefore the data would only consist of observations from the sensor itself. Further research can be done towards the sensor after relocating the sensor more downstream to the new location. This research should include similar measurements as the ones during this research to make a solid comparison between the old and the new location. What is the exact improvement in the accuracy when the sensor is moved to this specific location and is it able to meet the 95% accuracy the company of CycleData promised, should be discussed and determined if it is indeed a better location than before and if either the remaining errors are still present that are not due to the disturbances.

8.2 Sensor accuracy

At this moment of time, the sensor only reaches an accuracy of 75-78% including the data during disturbances. However, there are still several errors that are not accountable due to these disturbances and more research is needed on how and why these errors occur and if these errors could be solved. By doing more research on this topic a solution may be founded for this problem such that the sensor is not experiencing errors such as extra cyclists or missing detections in the future and the full potential of the sensor can be reached during commissioning.

8.3 Pattern detection

Another option is to keep the iSignum at the current location and more extensive research is needed with manual measurements to keep track if a pattern is clearly visible and noticeable in the data during disturbances which then can be researched if this can be programmed into the sensor to immediately detect such an event in the future. If this is not possible other options as moving the iSignum or enhancing the accuracy outside those events should be reconsidered.

8.4 Sensor commissioning

Sensor commissioning is one of the last topics where further research is needed for this particular location where the iSignum is installed. However, this is best to be done after the sensor is performing acceptable enough to reach 95% accuracy. Otherwise, there is still room left for other topics to research on while the iSignum is not functioning in the best way. When this stage is reached, multiple research directions can go through. One example can be to determine the extent of progress regarding waiting time for cyclists before and after the commissioning of the iSignum with the iVRI. This is most valuable to determine for the cyclists that arrive first at the intersection during a new cycle in the past and during the commissioning of the iSignum.

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Appendix A: Python script

In [1]:

```
import numpy as np
import math
%matplotlib inline
import matplotlib.pyplot as plt
from pandas import read_csv
import pandas as pd
from datetime import datetime
```

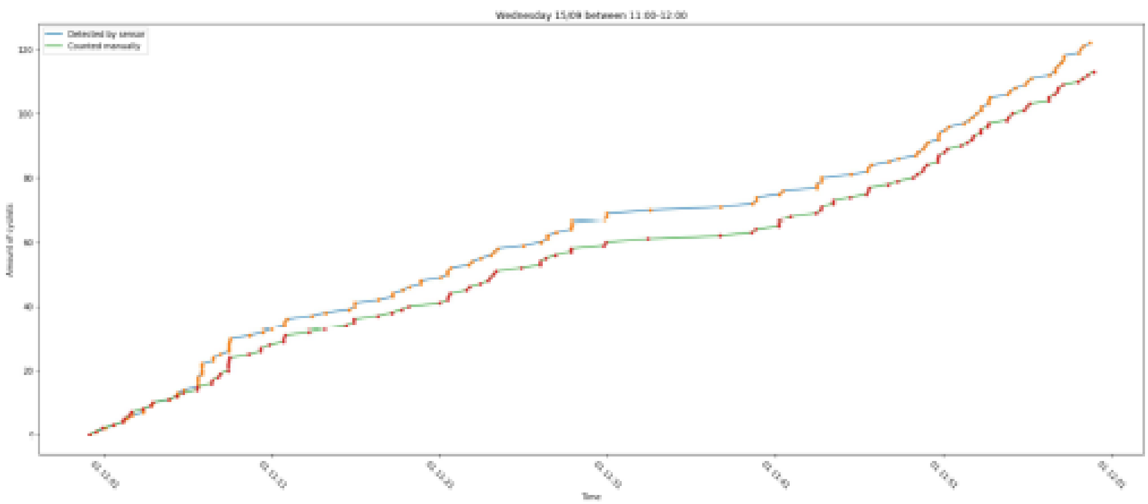
In [2]:

```
sensordata = pd.read_csv('Sensordatametsec.csv',skipinitialspace=False,  delimiter = ';' )
gemeten = pd.read_csv('Gemetenwoensdag2.csv',skipinitialspace=False, delimiter = ',' )
tijdsensor = sensordata.DatumTijd
tijdgemeten = gemeten.Tijd
g = []
s = []
s2 = []
s3 = []
for i in range(len(tijdgemeten)):
    tg = datetime.strptime(tijdgemeten[i], '%H:%M:%S ')
    g.append(tg)

for i in range(len(tijdsensor)):
    ts = datetime.strptime(tijdsensor[i], '%H:%M:%S')
    s.append(ts)
    s2.append(ts)
    s3.append(ts)

count = 0
newlist = []
numberss = []
numbersg = []


for i in range(len(tijdgemeten)):
    start = g[i]
    for j in range(len(tijdsensor)):
        end = s2[j]
        diff = end - start
        diffsec = abs(diff.total_seconds())
        if diffsec < 5:
            count+= 1
            newlist.append(start)
            numberss.append(j)
            numbersg.append(i)
            s2[j]= datetime(1900,1,1,8,0,0)
            break
```

In [3]:

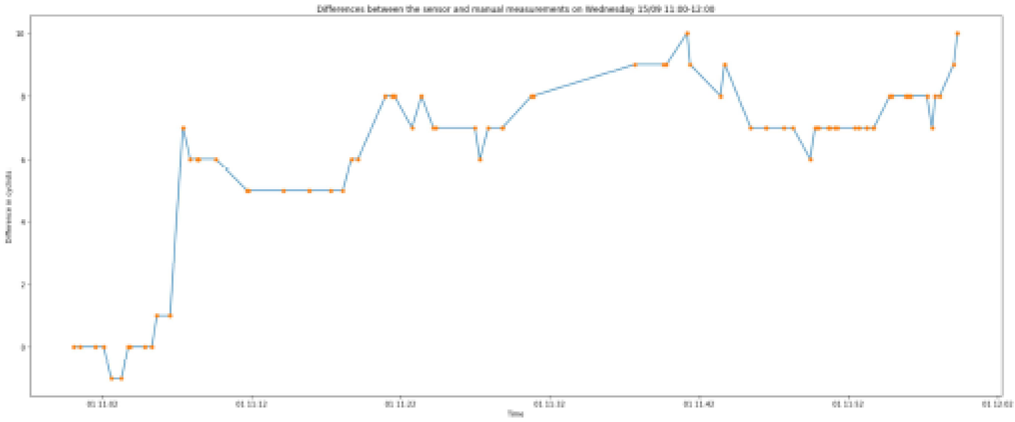
```
a = np.zeros(len(numberss))
b = np.zeros(len(numbersg))

for i in range(len(numberss)):
    a[i]= numberss[i]
    b[i]= numbersg[i]

diff = a - b
print(len(newlist))

percentage = len(newlist)/ len(tijdgemeten) * 100
print(percentage,'%')
plt.figure(figsize=(25,10))
plt.plot(s,np.arange(0, len(sensordata)),label = 'Detected by sensor')
plt.plot(s,np.arange(0, len(sensordata)),'.', markersize = 7)

plt.plot(g,np.arange(0, len(gemeten)), label = 'Counted manually')
plt.plot(g,np.arange(0, len(gemeten)), '.', markersize = 7)

plt.title('Wednesday 15/09 between 11:00-12:00')
plt.xlabel('Time')
plt.ylabel('Amount of cyclists')
plt.legend()
plt.xticks(rotation=- 45);
```

```
86
75.43859649122807 %
```



In [4]:

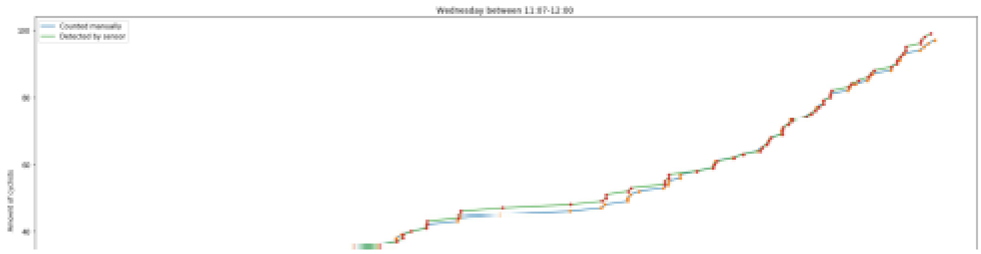
```
plt.figure(figsize=(25,10))
plt.plot(newlist,diff)
plt.plot(newlist,diff, '.', markersize = 10)

plt.ylabel('Difference in cyclists')
plt.xlabel('Time')
plt.title('Differences between the sensor and manual measurements on Wednesday 15/09 11:00-
```



In [5]:

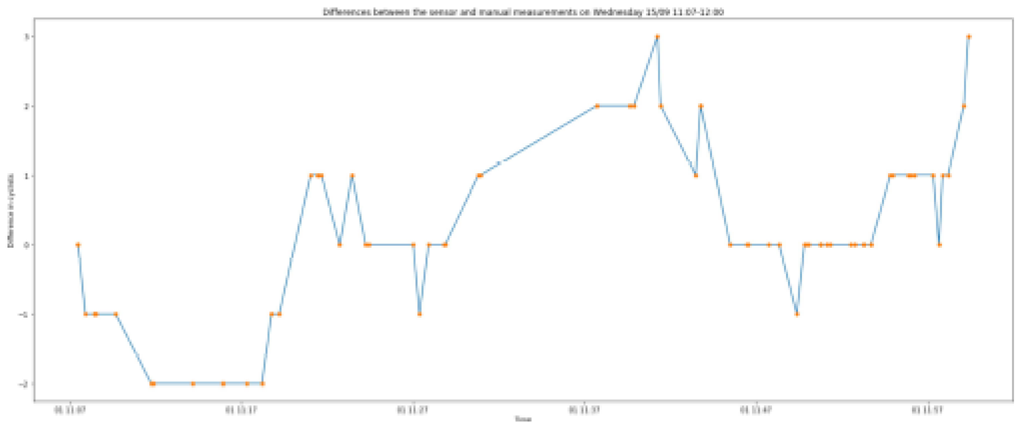
```python
#After 11:06, from 11:07 on

plt.figure(figsize=(25,10))
plt.plot(g[16:], np.arange(0, (len(g)-16)),label = 'Counted manually')
plt.plot(g[16:], np.arange(0, (len(g)-16)), '.', markersize = 7)

plt.plot(s[23:], np.arange(0, (len(s)-23)),label = 'Detected by sensor')
plt.plot(s[23:], np.arange(0, (len(s)-23)), '.', markersize = 7)

plt.legend()
plt.title('Wednesday between 11:07-12:00')
plt.xlabel('Time')
plt.ylabel('Amount of cyclists')

count = 0
newlist = []
numberss = []
numbersg = []


for i in range(len(tijdgemeten)-16):
    start = g[i + 16]
    for j in range(len(tijdsensor)-23):
        end = s3[j + 23]
        diff = end - start
        diffsec = abs(diff.total_seconds())
        if diffsec < 5:
            count+= 1
            newlist.append(end)
            numberss.append(j)
            numbersg.append(i)
            s3[j+23]= datetime(1900,1,1,4,0,0)
            break

a = np.zeros(len(numberss))
b = np.zeros(len(numbersg))

for i in range(len(numberss)):
    a[i]= numberss[i]
    b[i]= numbersg[i]

diff = a - b
percentage = len(newlist)/ (len(tijdgemeten)- 16) * 100
print(percentage,'%')
print(len(newlist))
```

```
74.48979591836735 %
73
```



In [6]:

```
plt.figure(figsize=(25,10))
plt.plot(newlist,diff)
plt.plot(newlist,diff, '.', markersize = 10)

plt.ylabel('Difference in cyclists')
plt.xlabel('Time')
plt.title('Differences between the sensor and manual measurements on Wednesday 15/09 11:07-
```



Appendix B: Data format

Fake data using clicker app

Timestamp, Date, Time, Counter value, increase
2021-09-15 11:00:15.6396 AM, 2021-09-15, 11:00:15 AM, 1, 1
2021-09-15 11:00:45.8366 AM, 2021-09-15, 11:00:45 AM, 1, 1
2021-09-15 11:02:16.9375 AM, 2021-09-15, 11:02:16 AM, 1, 1
2021-09-15 11:02:17.2639 AM, 2021-09-15, 11:02:17 AM, 1, 1
2021-09-15 11:04:03.5936 AM, 2021-09-15, 11:04:03 AM, 1, 1
2021-09-15 11:04:43.8453 AM, 2021-09-15, 11:04:43 AM, 1, 1
2021-09-15 11:05:32.0356 AM, 2021-09-15, 11:05:32 AM, 1, 1

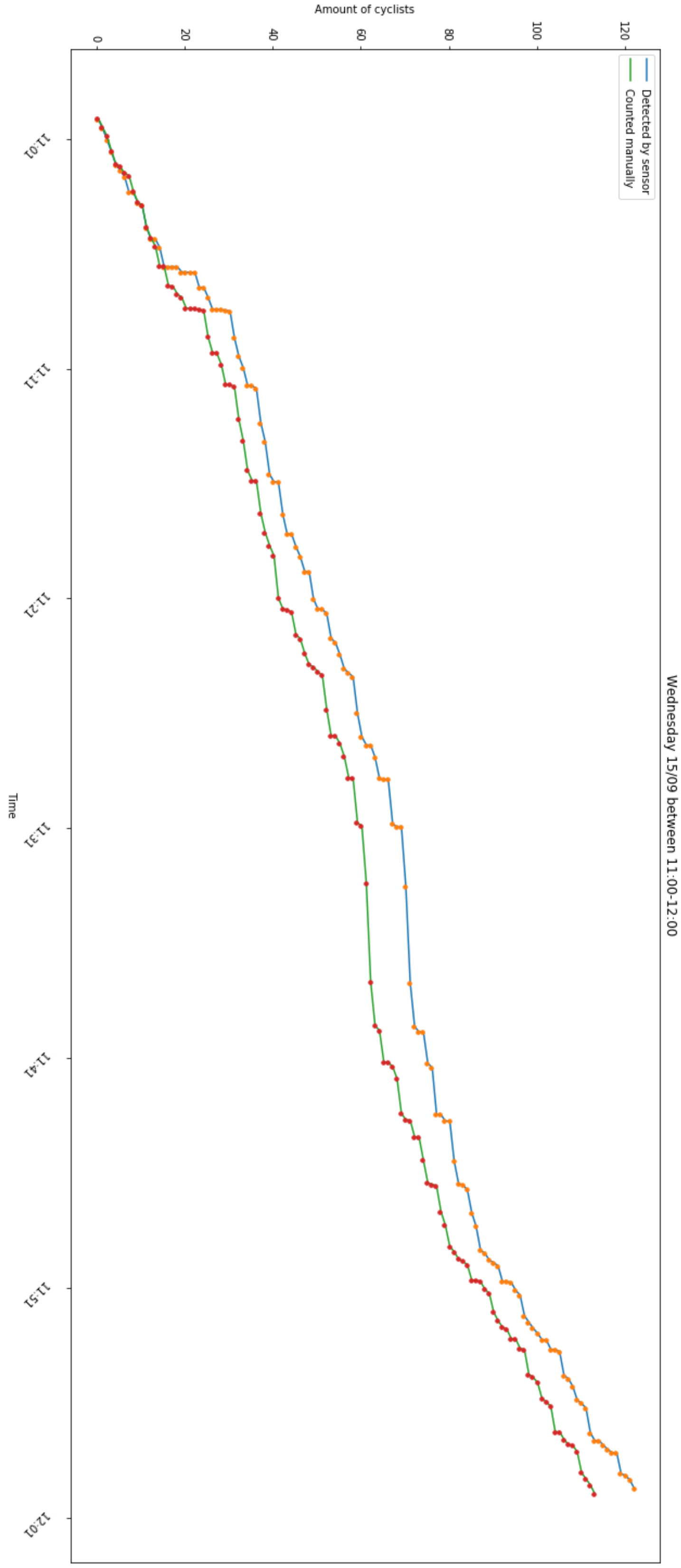
Fake data sensor

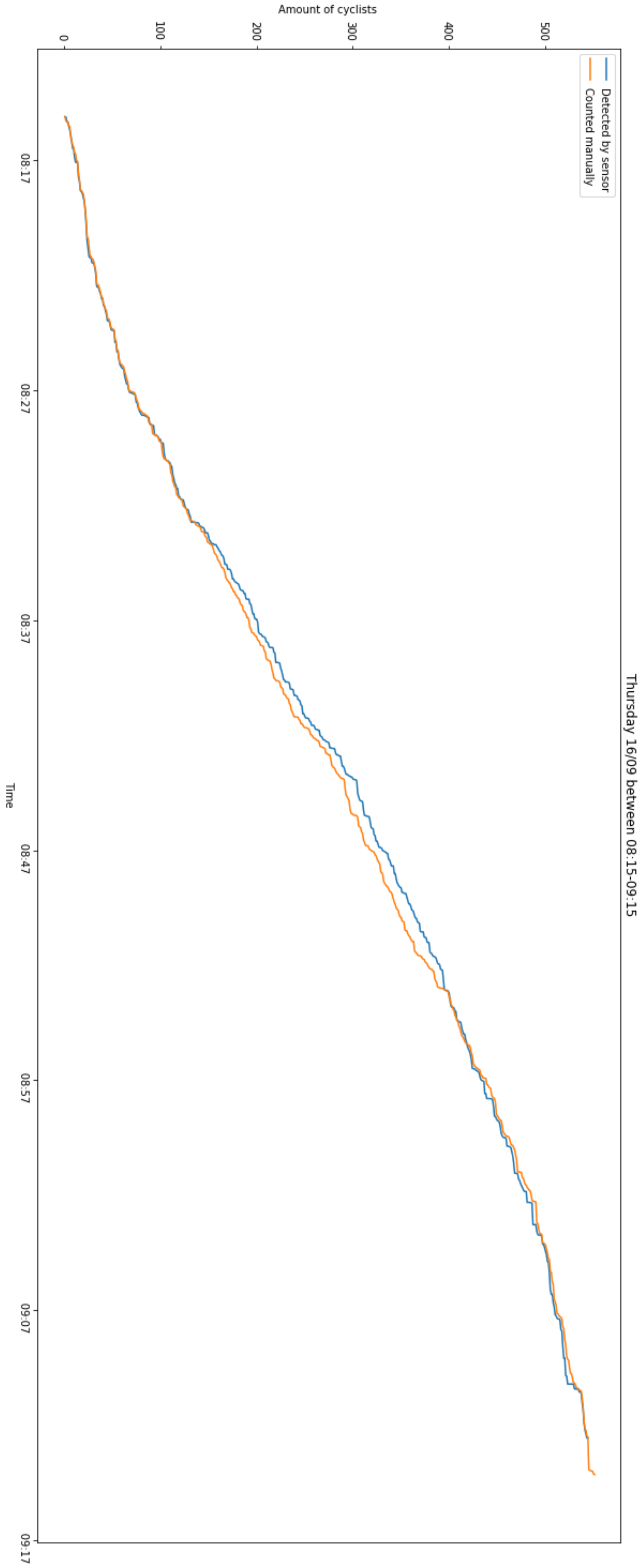
DateTime	Location n:	Latitude	Longitude	Rain	Temperature	Speed	DatumTijd2
15-9-2021, 11:00:54	Julianalaar	4,371595	52,00787	0,3	17,5	14	Sep 15 2021 11:00:54.752 AM
15-9-2021, 11:01:15	Julianalaar	4,371595	52,00787	0,3	17,5	11	Sep 15 2021 11:01:15.286 AM
15-9-2021, 11:01:17	Julianalaar	4,371595	52,00787	0,3	17,5	20	Sep 15 2021 11:01:17.022 AM
15-9-2021, 11:01:56	Julianalaar	4,371595	52,00787	0,3	17,5	9	Sep 15 2021 11:01:56.684 AM
15-9-2021, 11:03:01	Julianalaar	4,371595	52,00787	0,3	17,5	12	Sep 15 2021 11:03:01.938 AM
15-9-2021, 11:03:45	Julianalaar	4,371595	52,00787	0,3	17,5	13	Sep 15 2021 11:03:45.185 AM
15-9-2021, 11:03:58	Julianalaar	4,371595	52,00787	0,3	17,5	17	Sep 15 2021 11:03:58.743 AM
15-9-2021, 11:04:36	Julianalaar	4,371595	52,00787	0,3	17,5	14	Sep 15 2021 11:04:36.349 AM

Appendix C: Comparison with V-log

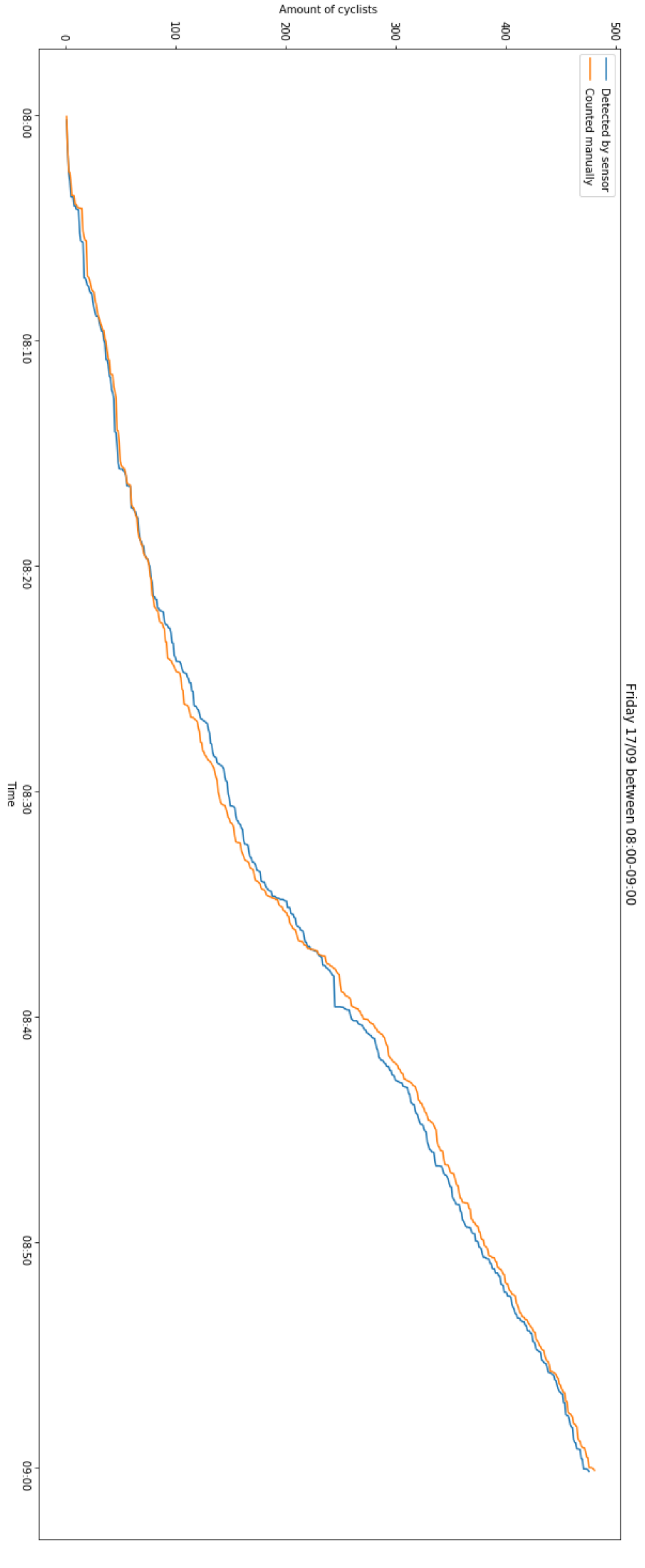
Timestamp			
15-9-2021	07:00:15	Start	
15-9-2021	07:00:20	End	
15-9-2021	07:00:50	Right turn	
15-9-2021	07:03:20	Right turn	
15-9-2021	07:03:50	Start	First push button and then sensor
15-9-2021	07:03:55	End	
15-9-2021	07:04:55	Start	3x bus
15-9-2021	07:05:25	End	
15-9-2021	07:05:45	Start	
15-9-2021	07:06:35	Start	
15-9-2021	07:06:35	End	Impatience by pressing push button many times
15-9-2021	07:07:30	Start	
15-9-2021	07:07:35		
15-9-2021	07:07:50		
15-9-2021	07:07:55	End	
15-9-2021	07:08:25	Start	
15-9-2021	07:08:30		
15-9-2021	07:08:35		
15-9-2021	07:08:40		
15-9-2021	07:08:45	End	
15-9-2021	07:09:45	Start	Immediately green light
15-9-2021	07:10:20		
15-9-2021	07:10:25	End	

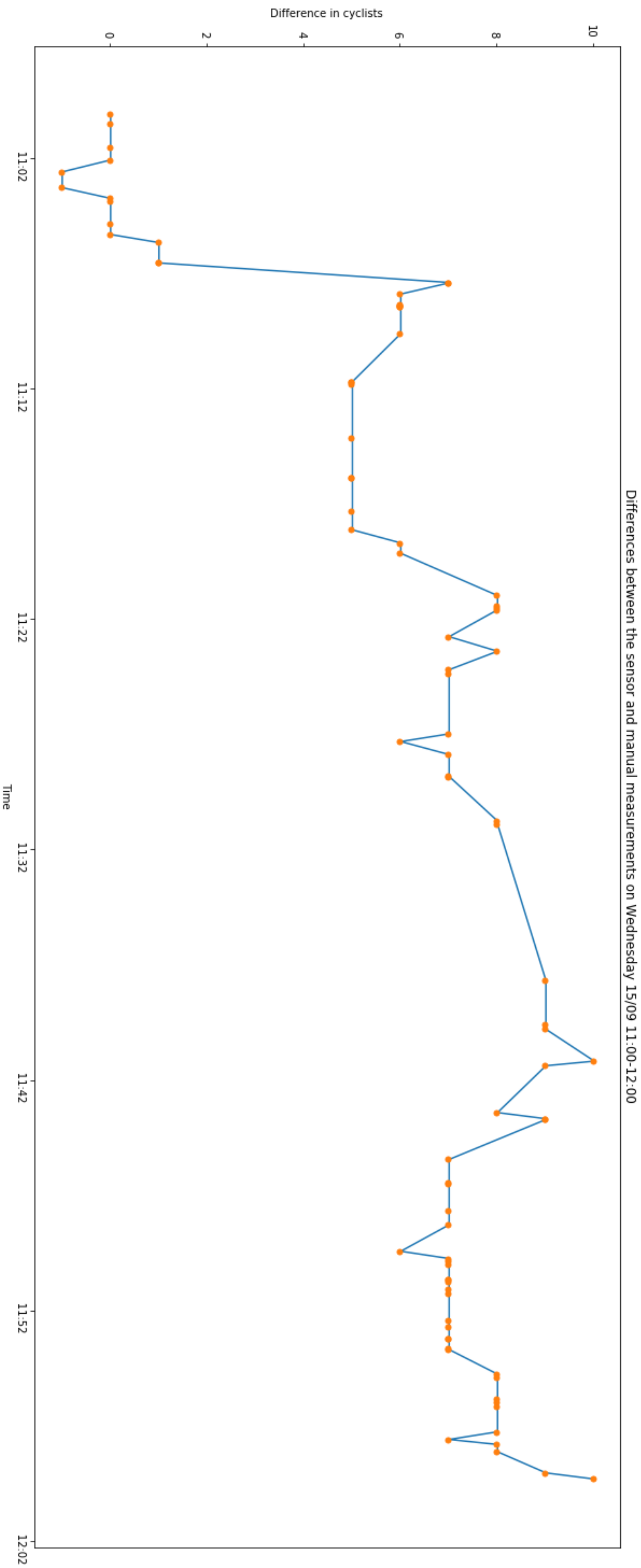
Appendix D: Python graphs

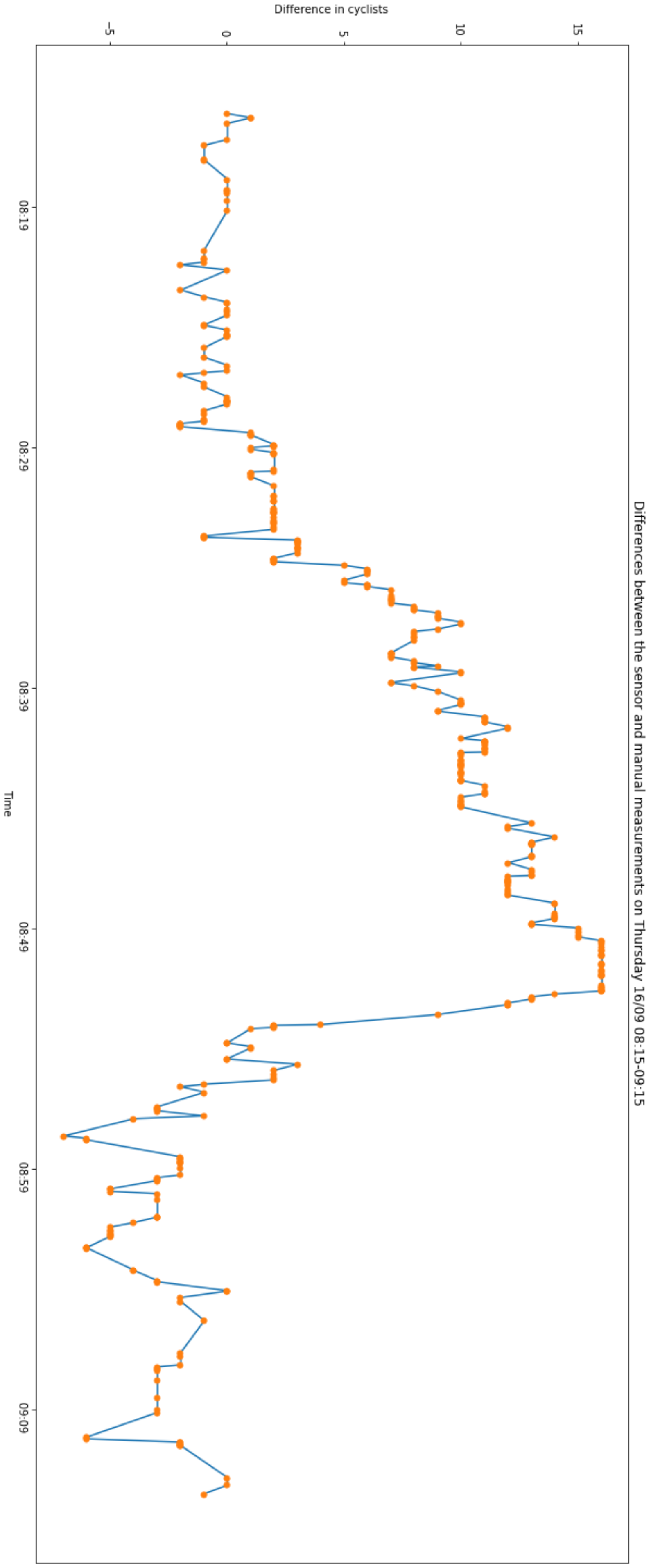


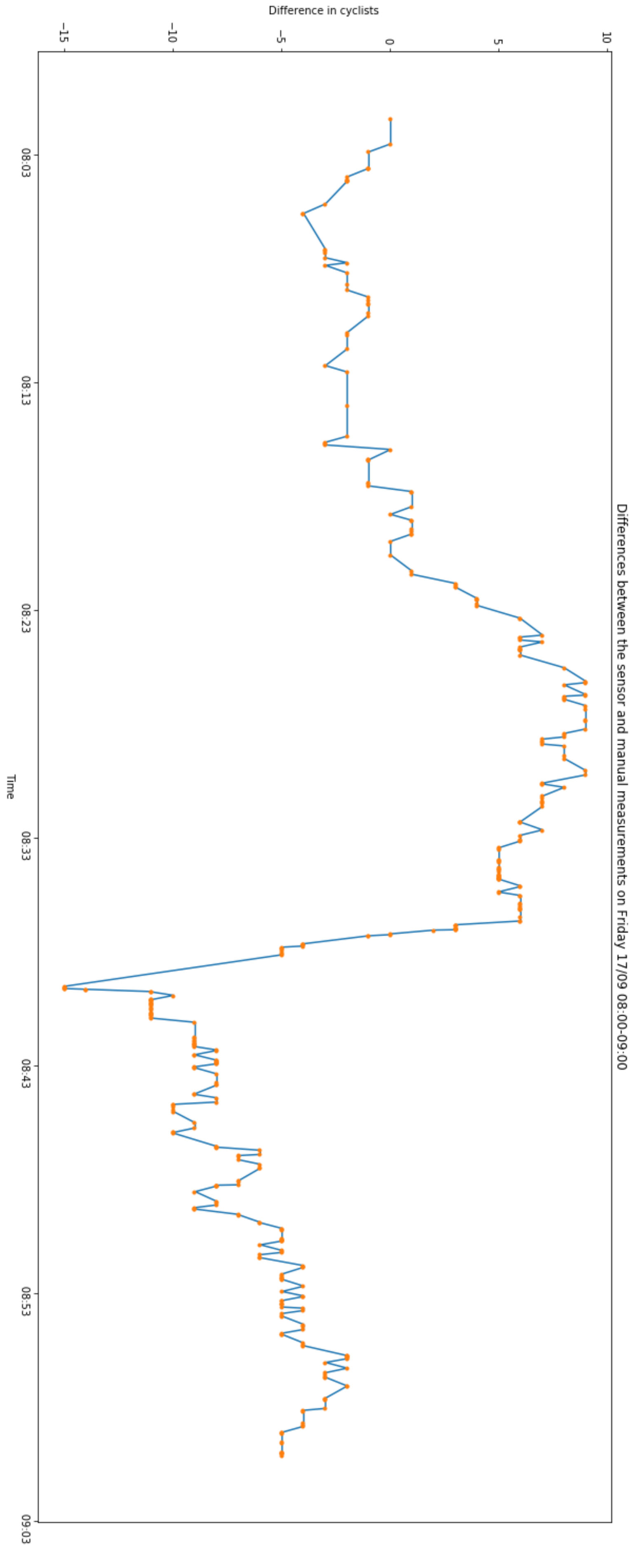


Thursday 16/09 between 08:15-09:15
Detected by sensor
Counted manually
Amount of cyclists
0
100
200
300
400
500
Time
08:17
08:27
08:37
08:47
08:57
09:07
09:17

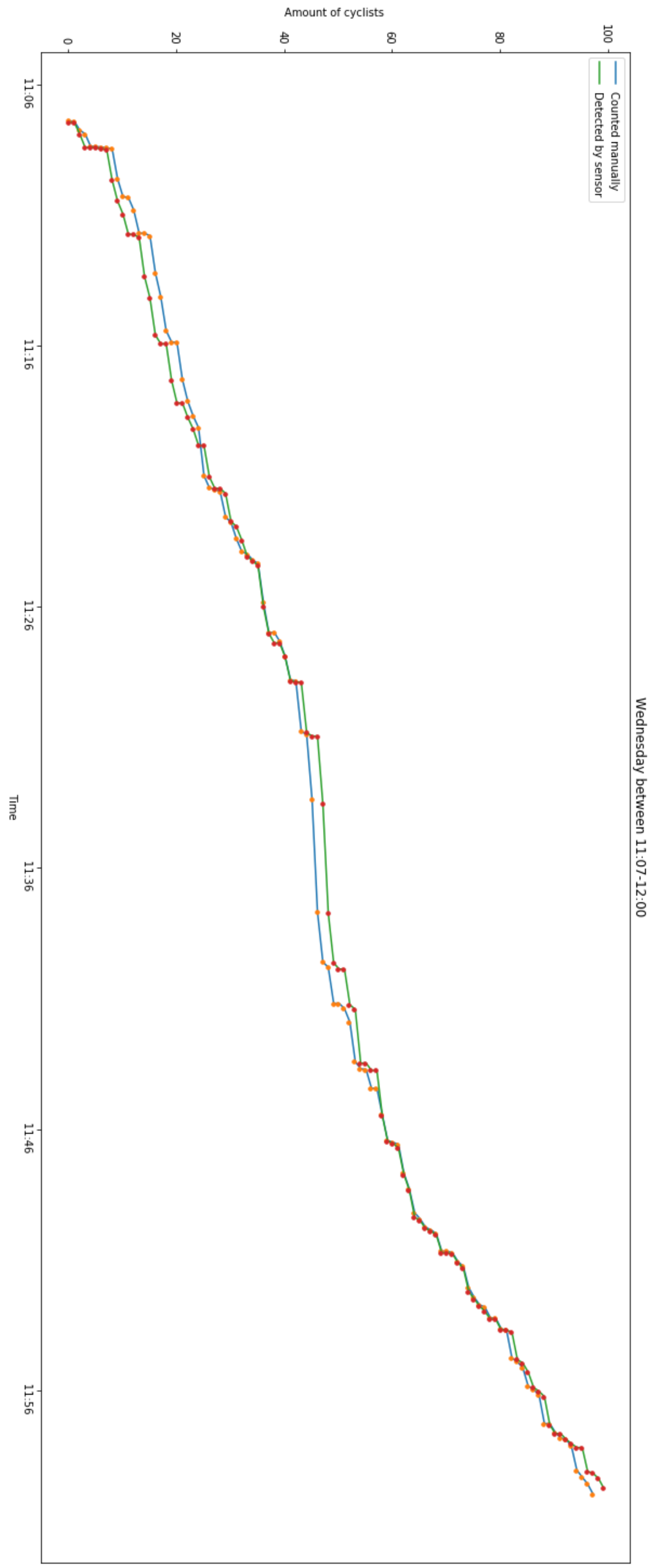

Friday 17/09 between 08:00-09:00
Amount of cyclists
0
100
200
300
400
500
Time
08:00
08:10
08:20
08:30
08:40
08:50
09:00
Detected by sensor
Counted manually


Differences between the sensor and manual measurements on Wednesday 15/09 11:00-12:00
Difference in cyclists
Time
0
2
4
6
8
10
11:02
11:12
11:22
11:32
11:42
11:52
12:02

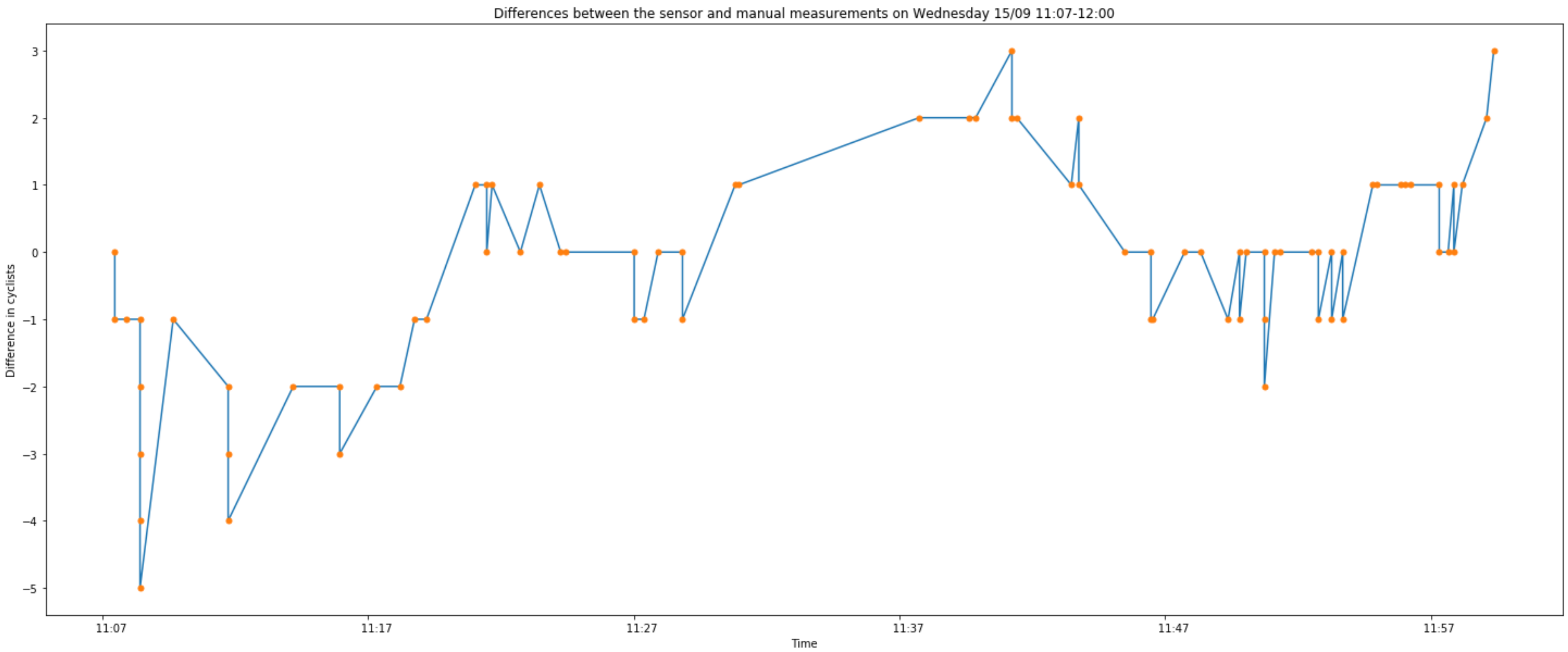

Differences between the sensor and manual measurements on Thursday 16/09 08:15-09:15
Difference in cyclists
−5
0
5
10
15
Time
08:19
08:29
08:39
08:49
08:59
09:09

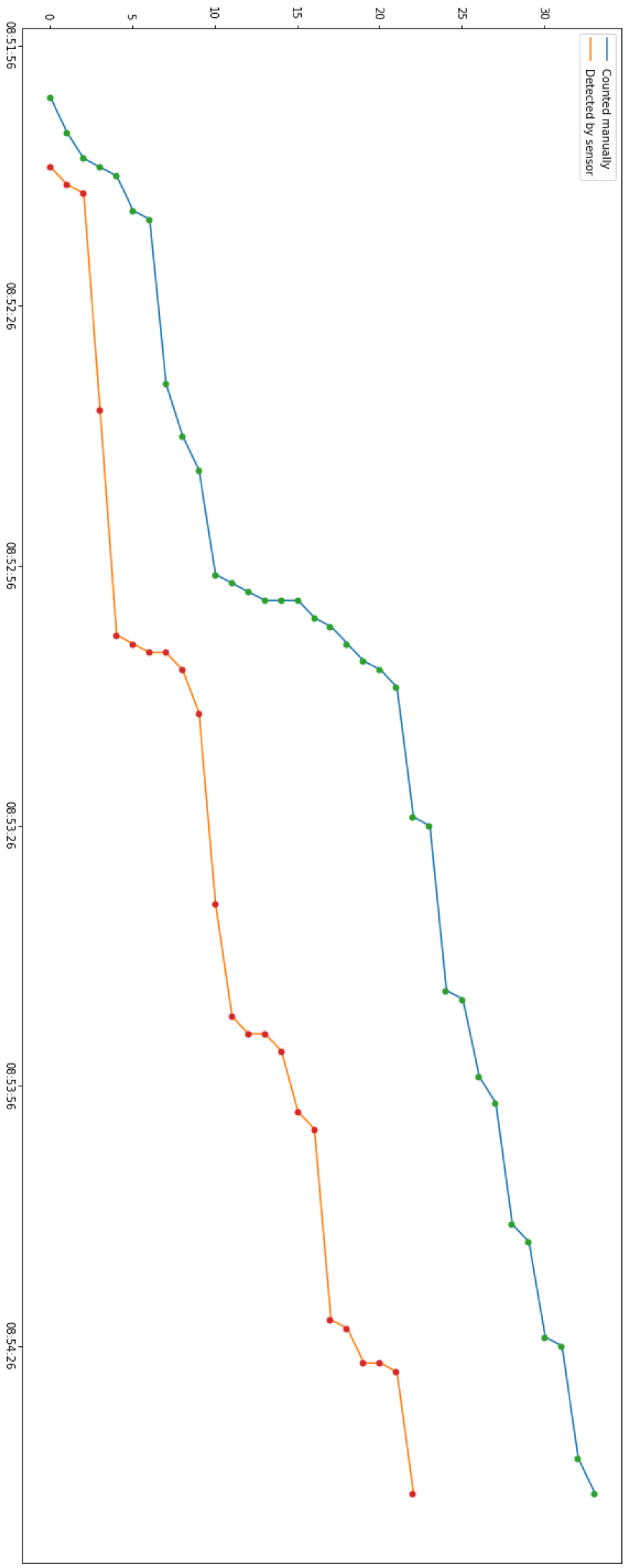


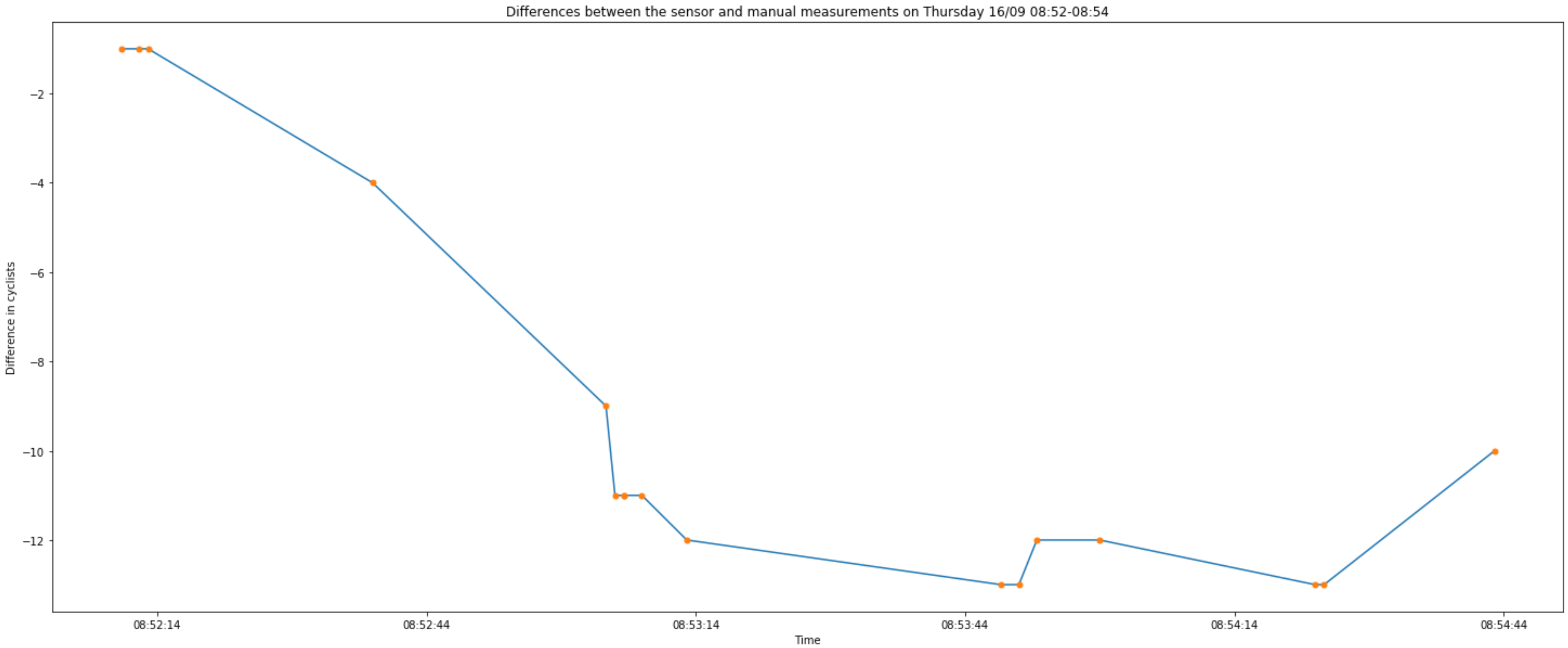
Differences between the sensor and manual measurements on Friday 17/09 08:00-09:00
Difference in cyclists
−15
−10
−5
0
5
10
Time
08:03
08:13
08:23
08:33
08:43
08:53
09:03



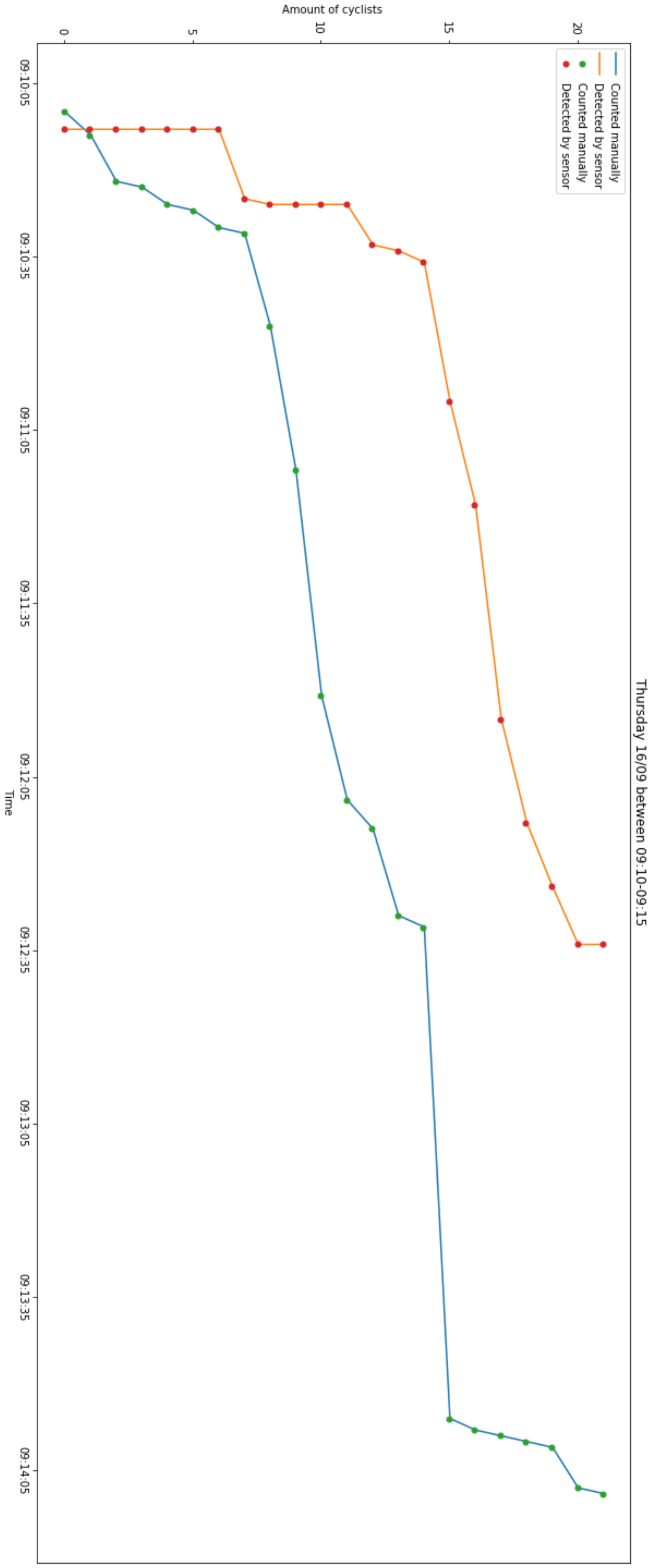
Wednesday between 11:07-12:00
Amount of cyclists
Time
Counted manually
Detected by sensor
0
20
40
60
80
100
11:06
11:16
11:26
11:36
11:46
11:56


Differences between the sensor and manual measurements on Wednesday 15/09 11:07-12:00
Difference in cyclists
3
2
1
0
−1
−2
−3
−4
−5
11:07
11:17
11:27
11:37
11:47
11:57
Time

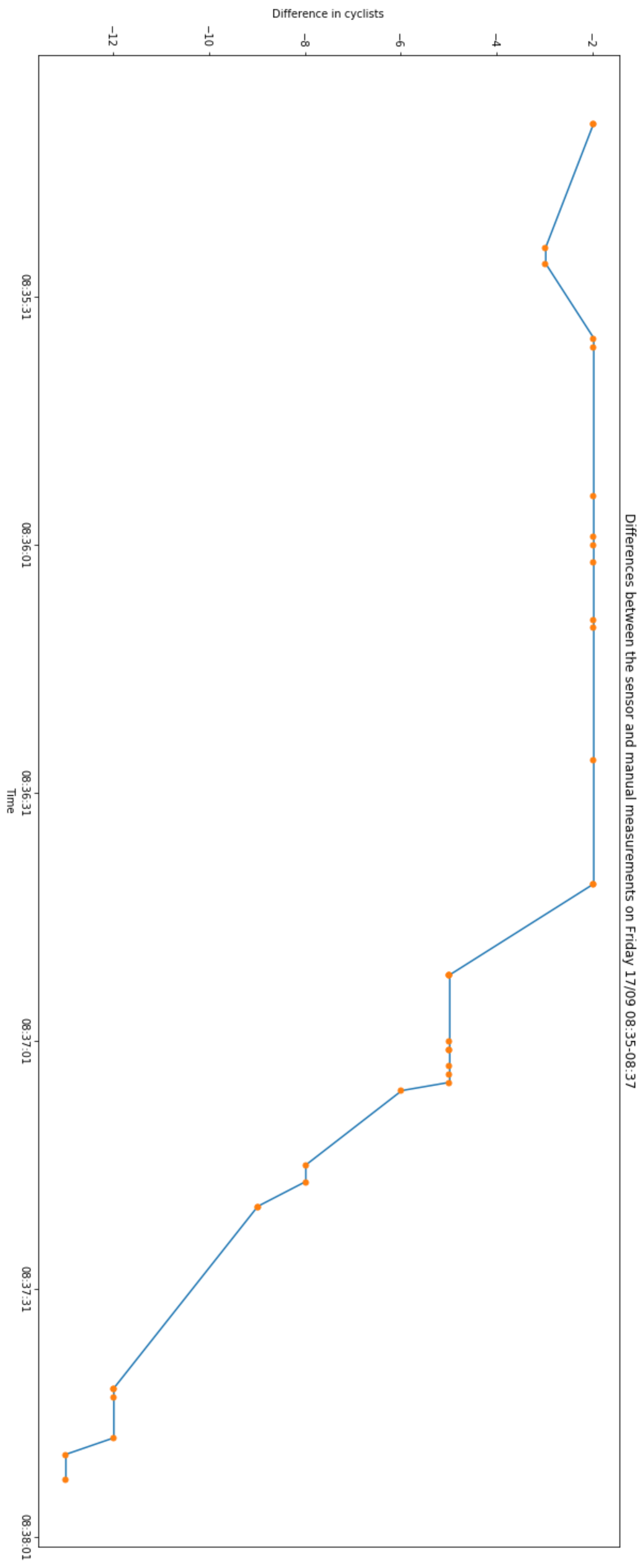

Counted manually
Detected by sensor
0
5
10
15
20
25
30
08:51:56
08:52:26
08:52:56
08:53:26
08:53:56
08:54:26



Differences between the sensor and manual measurements on Thursday 16/09 08:52-08:54
Difference in cyclists
−2
−4
−6
−8
−10
−12
08:52:14
08:52:44
08:53:14
08:53:44
08:54:14
08:54:44
Time



Thursday 16/09 between 09:10-09:15
Amount of cyclists
0
5
10
15
20
Counted manually
Detected by sensor
Counted manually
Detected by sensor
09:10:05
09:10:35
09:11:05
09:11:35
09:12:05
09:12:35
09:13:05
09:13:35
09:14:05
Time


Differences between the sensor and manual measurements on Friday 17/09 08:35-08:37
Difference in cyclists
−12
−10
−8
−6
−4
−2
08:35:31
08:36:01
08:36:31
08:37:01
08:37:31
08:38:01
Time