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Calculating cycling delay at signalized intersections using smartphone data

Tim Velthuijsen
Bachelor Thesis
S1003690

Supervisors
Prof. Dr Ing. K.T. Geurs
Dr. T. Fioreze
Dr. J. Koolwaaij

Faculty of Engineering & Technology
University of Twente

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Preface

You now have my bachelor thesis in front of you. Writing and research on this thesis took place in 2019 and 2020. And this report is the conclusion to my Civil Engineering bachelor at the University of Twente. This thesis was done internally at the University of Twente in cooperation with the company Mobidot, which was invaluable to the research by providing the cycling data required for the analyses.

During this project, the greatest lesson I have learned is to focus on the important factors of a project. Having clear boundaries and a vision of the scope of the research were problems I had early on in my research and only by resolving these was I able to complete this thesis project.

At the conclusion of this project, there are many people whom I would like to thank. But primarily thanks go to all three of my supervisors. This project started under the supervision of Tiago Fioreze. Who would was always ready to provide me with advice and insight into the requirements of the research. At the later stages of my research, Karst Geurs took over as my primary supervisor. And while it was not always easy I could not have gotten where I am now without his feedback and his focus on finishing this research. My final supervisor was Johan Koolwaaij during my research he was my contact at Mobidot. The company who helped my research by providing me with the required cycling data, apart from the data Johan also gave me invaluable feedback which helped me with better presenting the data and results of my research in this report.

Additional thanks go to Caroline de Koning and Annet de Kiewit and the different members of the graduation support group with whom I had weekly meetings to talk about our progress. Thanks also go to my roommate Florian who was always open for conversations about SPSS and statistics in general. And lastly, thanks go for the support of my girlfriend and family who were there for me during all the hard parts.

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Summary

Cycling has many advantages, people who are cycling are generally more physically active. And more people on bicycles instead of in cars can lead to less congested cities. Due to these factors research in different aspects of cycling have become more prominent. Local Dutch governments and companies have started working together in the Talking Traffic partnership to get more insight into the utilization and optimization of data usage in traffic. As a part of this process, they are also looking for ways to stimulate people to cycle and better understand what is deterring people from cycling. Delays are one such deterring factor and a better understanding of cycling delays can lead to more optimized policies, and hopefully more overall cyclists on the road.

The focus of this thesis is on the implementation of smartphone GPS data to calculate cycling delay at signalized intersections on the Singel in Enschede. One of the members of the Talking Traffic partnership the company Mobidot was able to provide a database consists of cycling data in Enschede gathered between the first of January and the first of July 2019. The overall dataset consisted of 2999 individual users who registered 740.973 intersection crossings in this period. First. the research area was narrowed down to 9 specific intersections on the Singel of Enschede. These were chosen due to their similarities both in features and the traffic that passes them as well as their relative proximity to the city center and then filtering the data 60.347 intersection crossings by still 2463 individual users were left over for further analysis.

For this thesis research, two questions were asked. The first question asked how different variables could be implemented in the research and how these could influence the calculation of the cycling delay. For this question four variables were selected, these variables would be implemented in the research and analyzed. The following four variables are included in this research:

- Trip purpose,
- Whether or not it is Raining,
- The level of separation of traffic
- And the implementation of all cyclists simultaneous green

The second question that was asked for this research concerned the use of different reference scenarios could to calculate the cycling delay and how these different scenarios could influence the cycling delay. Three reference speed scenarios were used in this research. The primary scenario was very similar to the way that Mobidot currently uses the data. Another scenario was set up as an experiment on this method and the third to take into account conditions found near the intersections. The first scenario used the aggregated speed per cyclist, the second scenario used the aggregated speed per cyclists at specific time intervals and the third scenario used the speed of the cyclists as they approach the intersection. These scenarios were used to compare data at the intersection level but also in the different intersection crossing directions. This gives the following three reference speed scenarios:

I. Reference speed scenario 1: Average Cycling speed
II. Reference speed scenario 2: Time of Day speed.
III. Reference speed scenario 3: Entry speed.

When comparing the three different reference scenario’s no clear difference was found between scenario 1 which used the overall average cycling speed and scenario 2 which used the average cycling speed at specific time intervals. For this reason, the final analyses were only done using the calculations of reference scenarios 1 and 3.

Analyzing the chosen variables differences were found for three of the four variables. Trips with the office as their *trip destination* showed lower delays compared to trips that had the home as their trip destination. Intersection crossing part of trips going to the office had a mean delay of 15,8 seconds for scenario 1 and 11,8 seconds for scenario 3. Whereas intersection crossings going back home had a mean delay of 19,6 seconds for scenario 1 and 15,5 seconds for scenario 3.

The different *separations* of traffic also showed different delays per category with generally the lowest delay at intersections with moderate amounts of separation, with a mean of 16,7 seconds for scenario 1 and 12,4 seconds for scenario 3. The intersection crossings with the highest amount of separation also showed the longest delay times, with a mean of 19,4 seconds for scenario 1 and 16,7 seconds for scenario 3.

On the intersection level the *all cyclists simultaneous green* measure showed only a small difference in cycling delay. At 18,2 seconds for intersection crossings with the measure and 18,5 seconds without the measure for scenario 1. And 13,5 seconds with the measure and 14,5 seconds without the measure in scenario 3. However, when comparing the delay by the different directions that cyclists can cross an intersection the differences became more pronounced. The cyclists following along the Singel or crossing to the left had the most benefit when the all cyclists simultaneous green measure was present, and the cyclists crossing the intersection perpendicular to the Singel benefitted the most when this measure was not present. For scenario 1 the mean difference ranged between 2,2 and 4,3 seconds. And for scenario 3 the difference ranged between 1,6 and 5,4 seconds.

The different *separations of traffic* also showed different delays per category with generally the lowest delay at intersections with moderate amounts of separation, with a mean of 16,7 seconds for scenario 1 and 12,4 seconds for scenario 3. The intersection crossings with the highest amount of separation also showed the longest delay times, with a mean delay of 19,4 seconds for scenario 1 and 16,7 seconds for scenario 3.

The variable of *rain* did not show any significant differences, the biggest difference at specific intersections ranging around 1 second. Additionally, 3 of the 9 selected intersections have integrated rain sensors which are capable of detecting rain and then potentially giving a preferential green light to cyclists. These were also tested but based on this dataset no real significant differences were found.

When comparing the three different reference scenario's no clear difference was found between the overall average cycling speed and the average cycling speed at specific time intervals most intersections and even the different crossing directions on the intersections only showed minute differences in the reference speed and the delay. The third scenario which uses the speed of the cyclist right before the intersection crossing did show different results when calculating both the cycling speed and the delay at the signalized intersections. Overall the entry speed scenarios showed lower cycling speeds and lower delays. The distribution of speeds was larger with standard deviations that could be up to twice as large compared to the first two scenarios. Future research should be done to confirm the suspicions that combining the speed of the cyclists with boundaries set by their average cycling speed could result in more accurate results. As this would have the advantage of both the localized data from the entry speed and the aggregation of the average cycling speed of the cyclists.

1. Introduction

This bachelor thesis presents research on how GPS smartphone data can be used to calculate cycling delay at signalized intersections. Firstly the importance of cycling delay is examined to provide context to this research. The chapter concludes with the objective and the research questions of this thesis.

1.1. Problem context

Many municipalities in and outside of the Netherlands have realized the importance and benefits that cycling gives to both the city and the people living in it. In the Mobility Vision of 2019, the municipality of Enschede has set out accessibility ranges of 7,5 km for general cyclists and up to 15 km for cyclists on e-bikes. With the goal to allow for situations where cyclists can better utilize these ranges as they strive for their goal of reducing intracity car traffic by 10% by 2030 (Smulling, 2019). With this goal in mind, the municipality has set out to improve the attractiveness of cycling in the city.

Distance, time, safety and comfort are driving factors when people choose their mode of transport. In this regard, it is not just the actual but more often the perceives value that is important to cyclists. The duration and perceived duration of a cycling trip can vary greatly. Just the act of stopping at a signalized intersection was perceived to be equal to one-minute of cycling, and in addition to this, the actual wait time was perceived to be twice as long as the same time spend cycling (Börjesson, 2012). What this means is that a 1-minute wait at an intersection can add up to 3 minutes of perceived time to a cycling trip. This effect was also found in a recent study in Enschede where cyclists tended to overestimate their waiting time by a factor of 5 (Fioreze, 2019). When cycling trips generally include multiple intersection crossings this is an important factor to include when evaluating cycling routes. And it should underscore how important the delay of cyclists becomes for the wider cycling policy of a municipality.

1.2. Problem description

With cars, there are automated systems that can identify a car at different places and times using cameras that detect a license plate or by detecting an inductive vehicle signature using loops or sensors (Ki, 2005). Traffic loops can still be used to count cyclists but it is harder to identify and track specific cyclists. One alternative is to use in situ measurements. Either by analyzing the signalized intersections using cameras or by having people actively monitoring the intersection on location. Both of these methods are labor-intensive and for this reason not practical when evaluating multiple signalized intersections over longer periods of time.

Tracking cycling trips with GPS has become a popular way to analyze the movements of cyclists. One way of gathering GPS-data is by getting a group of volunteers to with special GPS systems connected to their bicycles. This has the advantage that people are more likely to share personal data like gender and age, but it does have a bias in the fact that people know they are being monitored. A good alternative to this comes is the tracking and storing of smartphone GPS-data. With the GPS integration of smartphones, it is possible to know where and how people are moving. And this data can be anonymously gathered, stored and accessed according to European privacy legislation. And with this data businesses and governments are able to learn more about peoples movements and habits.

Talking Traffic is a partnership between businesses and local governments that are looking to utilize the data and knowledge that is being gathered from smartphones, and to combine these with intelligent traffic control systems. The Talking Traffic partnership is aimed at using real-time data for different use cases. These use cases are focused on either providing information to people in traffic via navigation or other applications, or they are aimed at integrating real-time data gathered from smartphones with intelligent traffic control systems to optimize traffic flow and safety (Velde, 2019).

This thesis research is done in collaboration with the company Mobidot. Who joined the Talking Traffic partnership in 2018. The company which was established in 2013 describes themselves as an innovative ICT service provider. They provide support for governments, transport companies, service providers and a variety of employers. They have many projects but in Enschede, they are probably best known for the SMART mobility application. This application was commissioned by the municipality of Enschede to provide users with more insight into their trips and to stimulate users to take alternatives to the car. The application was launched on the 9th of November 2013 and rebranded to Enschede Fietst in September of 2020. Build on the Move Smarter platform Mobidot can anonymously collect and store data from users of the SMART application (Thomas, 2018).

This thesis will be using data from users of the SMART application to research the delay cyclists incur while crossing signalized intersections in Enschede. The database uses trips taken in the period between the first of January 2019 and the first of July 2019. In total 2999 unique users were registered in this period.

1.3. Research aim

This objective of this thesis is to research how GPS smartphone data can be used to calculate the delay of cyclists at signalized intersections. The choice to focus only on signalized intersections was done because this delay is more pronounced and cyclists have less direct control over their delay at these crossings compared to non-signalized intersections. But at the same time, policymakers at the municipality do have some measure of influence on this delay. They can for example set longer or shorter green lights or implementing multiple green lights per signal cycle, which will influence the delay that cyclists experience. Furthermore, this research will research how smartphone GPS-data can be used to analyze what other factors can influence the cycling delay calculation. This thesis will also research how choosing different ways of calculating the reference speed of the cycling delay calculation can influence the results.

1.4. Research question

To reach the stated objectives a main research question has been defined for this thesis. The main question aims to provide a better understanding of how GPS data can be used to calculate the cycling delay at signalized intersections. With sub-questions geared towards finding out what the effects for different choices in this calculation are.

Main question: *"How can smartphone GPS data be used to calculate cycling delay at signalized intersections?"*

Sub-questions:

1) What variables and factors can influence the cycling delay at signalized intersections, and which can be incorporated in this research using smartphone GPS-data?
2) Which reference scenarios can be used to calculate cycling delay at signalized intersections, and what is the effect of these different scenarios?

Combining the answers to these sub-questions will give a better understanding of how smartphone GPS-data can be better implemented into the calculation of cycling delay at signalized intersections. Which in turn will help with the evaluation of traffic control systems and give a better understanding of the overall attractiveness of different route choices in a city. Which should help policymakers when they are deciding on future improvements of cycling routes in their city.

2. Literature review

The literature review is a meaningful part of the research because it establishes the place of this research into the already existing research. Trough the literature review understanding of the things that have been done before is gained, and potential gaps in the available knowledge are highlighted. The first part of the literature review is focused on the calculation of delay. To calculate delay the speed at an intersection needs to be compared to a reference cycling speed. Over the years different types of researches into cycling behavior have been performed, this part of the literature review is focused on these studies. The rest of the literature review is focused on factors and variables that can potentially influence the calculation of cycling delay. For this thesis, these factors are divided into 4 different categories: infrastructural factors, environmental factors, individual factors, and policy factors.

2.1. Calculating delay

Traditionally delay at a signalized intersection is defined by the combination of how often and for how long cyclists stop at an intersection. How long cyclists stop at an intersection can be defined as the red time portion of the total intersection signal cycle time. One traditional formula for this is:

$$\textit{Average cycle delay at a signalized intersection} = \frac{\text{Red time}^2}{2 * \text{Signal Cycle time}}$$

This is a very static formula that assumes that the arrival of cyclists at an intersection is random and evenly distributed, but in reality, cyclists tend to group into small platoons (Wang, 2011). This formula also ignores the delay caused by deceleration and acceleration and other externalities like the increasing integration of intelligent traffic control systems.

Looking at existing research will give a better understanding of what has been done more recently regarding the calculation of delay. One recent example of research into the delay of cyclists at intersections is research done in 2017 in Montreal (Strauss, 2017). In this research, they used GPS smartphone data of 1000 cyclists for a period of 137 days to calculate the speeds the cyclist were travelling at for different road segments. They then also measured the cycling speeds at intersections. By comparing these two speeds they calculated the cycling delay. This then gave them a database of the average delay at different intersections. In this research, only cyclists crossing intersections straight ahead were considered.

There have been researches that use similar data as this research will use. One example of this is the research based on data from STRAVA to examine cycling patterns in Johannesburg (Musakwa, 2016) and a year later in Glasgow (Sun, 2017). There are other alternative applications similar to the SMART app in the Netherlands. Two examples of these are the Crosscycle application developed by Dynniq (Dynniq, 2018) for use in the city of Tilburg. And the Schwung application used in Den Bosch and developed by Vialis (Vialis, 2017).

To calculate the delay information relevant to the research area is good to have. A previous Bachelor thesis was done in 2019 researched the effects of traffic measurements on waiting times and the safety of cyclists in Enschede (Hemme, 2019). This research used data gathered by Vialis from detection loops at different intersections. The average intensity of cyclists per hour between 07.00 and 18.00 was determined as part of his research. The lowest intensity was on the Auke Vleerstraat in the West of the city at around 20 cyclists per hour. And the highest intensities were found near the city center and on the crossing of the Hengelosestraat with the Goolkatenweg, and the Roessinghsbleekweg. At 160 cyclists per hour. With many of the other intersections around 40 and 80 cyclists per hour. There is also data specific to the rush hours, where the intensity at some intersections increases to over 200 cyclists per hour.

2.2. Infrastructural factors

Different infrastructural factors can influence cycling behavior. A study performed in 2015 in Italy compared different cycle infrastructure and found that in mixed traffic situations pedestrians were moderate speed reductions and motorized disturbances had the strongest impact on lowering cyclists' travel speeds (Bernardi, 2015). Implying that the separation of different modes of transport can influence cycling speeds. The width of cycling paths also influences cycling speeds. As the width of a cyclists path increases, in general, the distance between cyclists also increases for a higher cycle path width (Buch, 2015). And the higher width can lead directly to a slightly higher capacity on the cycling paths. They also found that the distribution of speeds was reduced at higher cycling volumes.

The way cyclists use the space in front of an intersection can vary. In a study where 691 cyclists approaching a signalized intersection in Amsterdam they found an increase in the start-up lost time of cyclists at signalized intersections with different virtual sub lanes width between 0.7 and 1.1, where a width between 1.1 and 2.0 showed a decrease in the start-up loss time. The differences in this research however were small, ranging between 3 and 4 seconds (Yuan, 2019). Another approach to headway research in Poland (Kucharski, 2019) found similar results. One of their observations showed 5 people standing within 2.5 meters from the intersection when they used a 3-channel set up. Where a different setup showed 3 single-channel cyclists in a row of 6 meters. A multichannel queue can have a lower discharge time than a higher single-channel queue. A multichannel queue of seven cyclists had a 13 second discharge time where a single-channel queue of 5 cyclists had a 16 second discharge time.

The length of the intersection crossing is also relevant. A study done near the University of California at Davis examined ten signalized intersections with a similar method over 11 hours and concluded that the crossing times vary widely for different crossing distances (Rubins, 2005). And not all infrastructural factors can be influenced. The slope of a cycle path and intersection is an example of this. A study in 2013 where the crossings of cyclists over two signalized intersections in Portland were tracked using camera images (Figliozzi, 2013) concluded that the distribution of crossing times for the intersection at an incline is smaller than when the intersection is situated on a decline and the acceleration in the summer was found to be higher than in winter.

2.3. Environmental factors

Weather is something that can also influence the choice of a mode of transport and the behavior of people when they chose to cycle. The temperature, duration of sunshine on a day, duration of precipitation, and the average wind velocity were all found to be important to the demand for cycling (Thomas T. &., 2013). One of the conclusions of the Montreal study was that the cycling speed is the highest between 10 and 20 degrees Celsius (Strauss, 2017). The presence of rain was found to have a small yet significant influence on cycling speed, where the speed in bad weather was around 0,5 km/h faster than in clear weather (Keypoint, 2017). Furthermore, there are also some traffic signals in Enschede which are fitted with rain sensors, to give a faster green signal to cyclists when bad weather is detected. When a cyclist gets a green light they will spend some time on accelerating but also the congestion caused by other cyclists in their proximity might prevent them from hitting their free flow cycling speed for a distance after the intersection, especially at higher intensity crossings (Tang, 2018).

2.4. Individual factors

Cycling behavior is also a very individual thing. Where different people can show very different cycling behavior. Age and gender play big roles in this. Especially with the rise of the e-bike more old people have continued to keep on riding their bikes for longer distances. But the type of bike also increases the baseline speed for younger people. The trip purpose can be determined by analyzing the origin and destination of a trip. A study found that the changes in travel behavior in response to weather conditions are highly dependent on trip purpose (Wets, 2010) In this research, they looked at different weather conditions and how they influence travel behavior. Concluding the research they found that trip purpose has a big effect on the mode of transport changes, postponement, and cancellation. A study using data from the countryside near Gouda and Ede confirms this effect (Thomas, 2013). This research found that the influence of weather on the demand of cycling was very different, where commuters were less sensitive to negative effects of weather and recreational was much more sensitive. They did conclude however that they experienced the weather in more or less the same way.

Another difficult to predict behavior trait that directly influences cycling speeds on intersections are red-light runners. These are cases where cyclists do not wait for a green light but prematurely cycle through a red light. This lowers the mean of the delay but it is also a distortion of the actual traffic control system. Research from 2013 where camera images of traffic intersections in Den Haag were examined concluded that different sorts of intersections are susceptible to different numbers of red-light runners (Meel, 2013). Due to the nature by which the data is gathered, there is nothing to prevent people from running red lights. And this could distort the results of the research. Intersections with lower intensity and more male cyclists showed a higher number of red-light runners. Many of these conclusions were collaborated on in more recent research done in Nanjing. They furthermore found that cyclists on electric bicycles were also more likely to run a red light (Bai, 2020)

2.5. Traffic control factors

There are also factors that policy makers can directly influence. Like the amount of green time that can be given in a signal cycle green time. Or the number of times that Times green per cycle, When setting up the traffic control system at an intersection different signal cycle lengths can be used. CROW has determined that these are generally either 90 or 120 seconds (Hoen, 2014). Longer signal cycle times are used to better optimize the efficiency of car traffic. And a lower signal time cycle generally results in lower delay for cyclists. Another policy choice that has a large effect on cyclists is whether they get one or twee green signals allotted per total cycle. Something that is still very regional is the implementation of All cyclists simultaneous green intersections. On these intersections, cyclists get a green time at the same time without having to cross the intersection at the same time as cars. The first of these was implemented in Enschede in 1989, where 11 are now present. And it is especially popular in Groningen where 28 of the intersections now give simultaneous green.

Traffic control is not just about what is done on the background it is starting to become more outwardly visible as well. Visualizing how long you have to wait for a green light using wait time predictors is a system that has been widely implemented in the Netherlands. And over the past years, this has been taking new forms. For example in Utrecht on the intersection between the Marnixlaan and the Amsterdamsestraatweg they have implemented Intelligent poles that measure the cyclists' speed and then advise if a speed change is necessary to make the next green light (Wilgenburg, 2017). A thumbs-up means they are on course to make it, where either the hare or the tortoise means that changing their speed should help them. And the cow means that no matter what they will have to wait. The smartphone application ring-ring is doing something similar. This application gathers real-time GPS-data and communicates with intelligent traffic control systems. When it detects an upcoming signalized intersection it will give a ring. And when it detects that the intersection will turn green it will give a second ring. This does require that the traffic control system can communicate with the smartphone.

2.6. Conceptual model delay factors

In this literature, the factors that can influence cycling speed have been divided into four different categories, some of these factors will influence the general or normal cycling speed and some will influence the cycling speed specifically near intersections or even both of these. Figure 1 shows these four categories and the discussed factors that are part of these categories. It also shows how these categories relate to either the normal cycling speed or the cycling speed at intersections. Due to the scope of this research not all 20 of these factors will be analyzed. Instead per category, one factor will be selected. These four factors will then be tested on the bases of the different speed reference scenarios.

The choice is made to test the following four factors:

- Separation of traffic.
- The presence of rain.
- Trip purpose.
- All cyclists simultaneous green.

This set of factors will provide a varied set of variables that can be tested. By analyzing the road conditions of the approach and crossing sections of a trip the separation of traffic is a factor that can be categorized for all the different intersections. Data about the presence of rain during a trip can be gathered from the local meteorological KNMI-station Twenthe. If a user of the SMART application makes multiple trips Mobidot is able to speculate what different locations mean to a user and assign associated trip purposes, this data can be combined with the specific intersection crossings. And finally the group of intersections with an all cyclists simultaneous green measure in Enschede is known so this comparison can also be incorporated in the data.

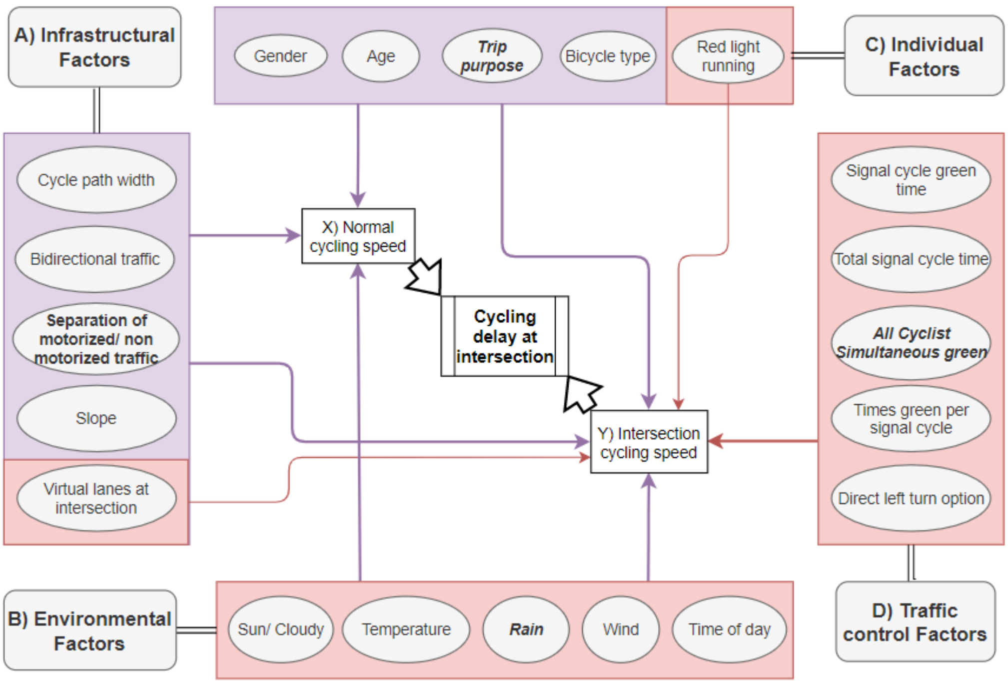


Figure 1: Conceptual model cycling delay at intersections

3. Research method

This thesis is focused on analyzing numerical data provided by Mobidot in the form of the smartphone GPS-data. The big advantage of having an existing database is that the collection process of the research could be mostly be skipped. For this research, steps were taken to select parts of the raw data to be used for calculating the cycling delay at different signalized intersections. And finally, this data was used for research into potential correlations between different variables and the delay of cyclists at signalized intersections. The different choices in the calculation set up are also reviewed to get a better understanding of how these choices can affect the results. The data Mobidot provided was used in accordance with the European AVG. Mobidot anonymously stores GPS-trip data from users of the SMART application. Part of this data is extracted and used for this thesis research.

3.1. Research framework

The research framework is shown in the flowchart in figure 2. The flowchart starts at the overall smartphone GPS data set. And then shows the different steps to calculate the intersection delays. These different steps are discussed in more detail in this chapter. Chapter 4 focusses on examining the data. Followed by the results in chapter 5. The conclusion of this thesis is presented in Chapter 6 followed by a small discussion in Chapter 7.

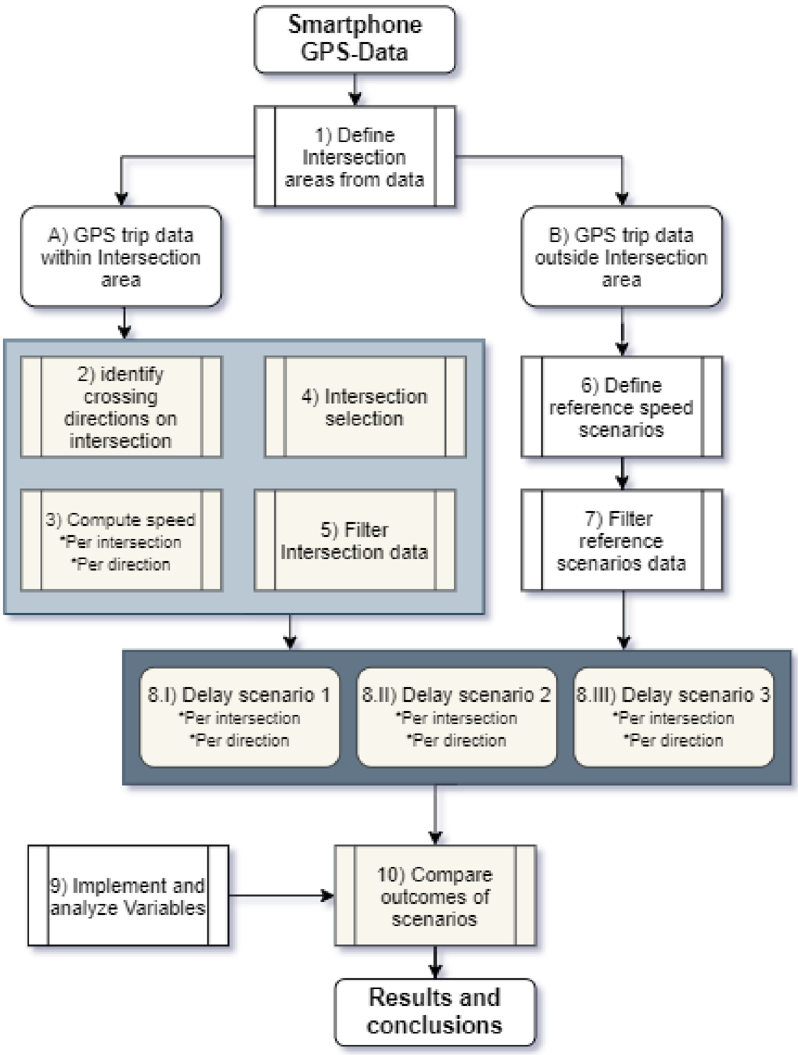


Figure 2: Research framework

3.2. Intersection areas

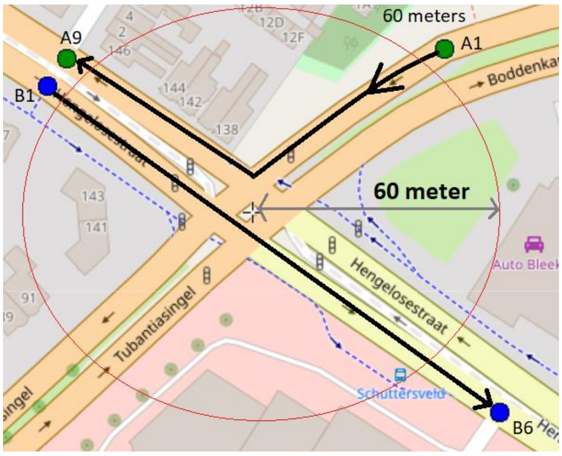


Figure 3: Identifying the intersection radius

To calculate delay at the signalized intersections a comparison between two situations needs to be made. The first situation, with no influence of the traffic lights and intersection crossing. In this situation, the distance that the cyclists travel would be calculated using a certain free flow-speed. And the second situation, where the cyclists are in fact affected by the traffic light and intersection crossing. To get data from these two situations boundaries on what constitutes an intersection are set. The choice is made to define everything within 60-meters of the intersection midpoint as being within the intersection sphere of influence. And everything outside of this 60 meter radius to be outside of it. This separation is incorporated into the GPS data from Mobidot. Due to the accuracy of smartphone GPS-data some concessions were made here, the choice was made to include one GPS point before and one directly after the influence sphere in the intersection crossing. For this research, these choices are shown in figure 3. Using this concept the duration and distance of different intersection crossings were determined. In total 740.973 signalized intersections crossings were found in the dataset from the first of January till the first of July 2019. Due to privacy concerns the direct access to the Move Smarter platform was not available, instead, Mobidot was able to provide an anonymized dataset focused on just the 740.973 intersection crossings.

3.3. Crossing directions

The cyclists crossings an intersection either to the left, right or straight will have very different waiting times and cycling patterns to each other. In total there are 12 ways of crossing a four-way intersection. Figure 4 gives an overview of these 12 directions. The data set uses a node system where the entry and exit points are given values based on their relative position to the center of the intersection. These grid points are defined in 25-meter intervals in both the longitude and latitude directions. Then based on these points the GPS data points are assigned to the closest nodes. Using the data from these nodes gives a quick overview of the overall travel patterns at different intersections, more detail about this process in given is Appendix A: Data transformation.

Based on the orientation of the intersection the nodes can be assigned to specific travel directions per figure 4 and table 1. Using the node system the entry and exit points of intersection crossings were categorized into the 12 different directions. And 4 categories, with a separation between cyclists cycling with the main road and those crossing the main road perpendicularly.

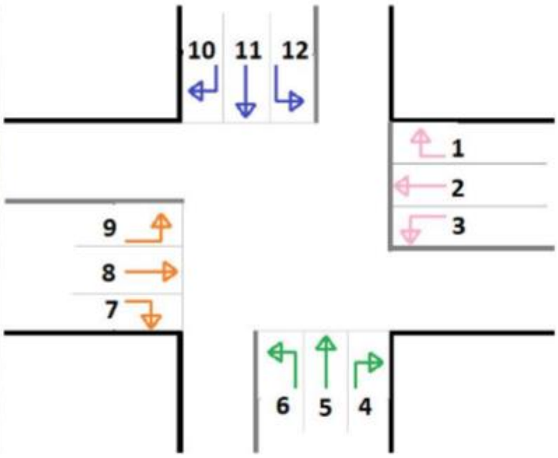


Figure 4: Division cycling directions

Table 1: Division cycling directions in categories

No	Direction	Stream
1	E-N	4. right turn
2	E-W	1. Straight ahead
3	E-S	3. left turn
4	S-O	4. right turn
5	S-N	2. Straight perpendicular
6	S-W	3. left turn

7	W-S	4. right turn
8	W-E	1. Straight ahead
9	W-N	3. left turn
10	N-W	4. right turn
11	N-S	2. Straight perpendicular
12	N-E	3. left turn

3.4. Compute speed

By determining the distance and the duration of each intersection crossing the crossing speed per intersection crossings could now be calculated. For the distance, the registered GPS-distance was used. For the duration, the difference between the timestamps of the entry and exit point as discussed in paragraph 3.2 were used. With this process, the crossing speed for all intersection crossings could now be calculated. For this research however, not all intersection crossings will be used. Paragraph 3.5 will elaborate on the reasons to chose only a selection of intersections for this research. And paragraph 3.6 will show why even on this subset of intersection not all registered crossings were used.

3.5. Intersection selection

In the database, Mobidot has defined 62 different signalized intersections. Of these 62 there are 55 with enough cycling registrations in the period from the 1st of January till the first of July 2019 to be relevant for this research. Of these intersections, 24 have between 1.000 and 10.000 registered intersection crossings. 27 have between 10.000 and 20.000 intersection crossings. And there are 7 intersections with more than 20.000 registered crossings. For this research, comparisons will be made for cyclists at different times and different weather conditions. With the selection of intersections, they must be comparable to each other to a certain degree. The choice at this stage was made to focus on 9 intersections on the Singel of Enschede. These 9 intersections have similar traffic compositions and are all located at similar distances to the city center. For these 9 signalized intersections 141.152 intersections crossings were registered.

The position of the 9 intersections is shown in figure 5. For this report, the choice is made to start numbering the intersections counterclockwise starting from the bottom left intersection.

Figure 5: Location of the 9 intersections on the Singel of Enschede

3.6. Intersection data filters

Not all registered intersection crossings were valid or suitable for this research. In reality some intersection crossings might have been cars or even pedestrians that are miscategorized as cyclists. Furthermore, traffic at 2 am will be much lower than at 8 am. This means that before the data could be used for analysis different filters had to be implemented. In total six filters are implemented in this research These are distance, duration, direction, time of day, day of the week and finally registered versus calculated distance.

Distance: Starting with the distance of registered intersection crossings specific boundaries were set. In the set up for the intersection crossings a minimum radius of at least 60 meters is used. Depending on how a cyclist crosses the intersection a minimum distance around 120 meters could be expected from this. After examining the data it was found that the distance of the registered intersection crossings was fairly larger than this. The mean distance of the intersection crossings at the nine intersections was 204 meters, with a standard deviation of 70 meters. Both intersection crossings that have very small and very large distances are most likely outliers or GPS registration errors, so the choice was made to implement both an upper and a lower boundary to the distance. Setting the boundaries for distance at twice the standard deviation gave a lower bound of 64 meters and an upper bound of 344 meters. 4,7% of the intersection crossings are found outside these boundaries.

Duration: For duration, the boundaries were chosen on an empirical basis. With the assumption that intersection crossings that were too fast or slow would not represent realistic cycling situations. The lower bound was set 10 seconds and the upper bound was set at 180 seconds. The upper boundary was set using the knowledge that most intersection control units have total signal cycle times of 90 or 120 seconds, and adding enough time for cyclists to clear the intersection. 2,8% of the intersection crossings are found outside of these boundaries.

Direction: Paragraph 3.3 discussed the different intersection crossing directions that are possible. Based on these directions the choice was made to only use the intersection crossings of cyclists going either straight through an intersection or that are crossing it to the left. In general, in the Netherlands cyclists that cross an intersection to the right do not have to wait for an intersection signal, but can cross to the right straight away. And as a direct consequence of this, these cyclists are less influenced by crossing a signalized intersection. 16,8% of the intersection crossings are right-turning cyclists.

Time of day: The next choice was to only use intersection crossings between 07.00 and 19.00. This choice was made because most traffic happens between these hours, and intersection crossings between these times best represent the situation for which the traffic control units are set up for. A bar chart with the amount of the registered intersection crossings per hour at the 9 intersections is given in figure 6. This bar chart confirms that most intersection crossings in the database also happen between 07.00 and 19.00. 22,4 % of the intersection crossings are found before 07.00 or after 19.00.

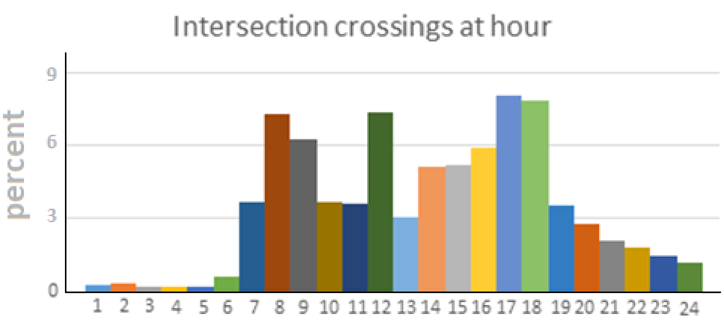


Figure 6: Bar chart of intersection crossings per hour

Day of the week: The traffic composition and general situation on the road at 8 am on a Monday morning is very different to the same time on a Sunday morning. For this reason, the choice was made to only use data from weekdays, Monday till Friday. Figure 7 shows a bar chart with the distribution of intersection crossings based on the day of the week. 16,9% of the registered intersection crossings took place on either a Saturday or Sunday.

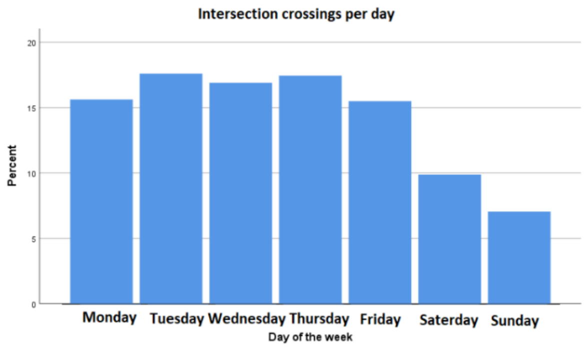


Figure 7: Bar chart of intersection crossings per day

Registered versus calculated distance: Finally, a decision needed to be made concerning the GPS-registered distance of an intersection crossing. When comparing these to the distance between the entry and exit points of the intersection crossing there tended to be a big discrepancy. The GPS registered intersection crossing distances as registered in the Mobidot database has a mean value of 210 meters with a standard deviation of 64 meters. Whereas calculating the distance between the entry and exit points gave a mean distance of 168 meter with a standard deviation of 52. This shows there are intersection crossings that can have big discrepancies between the GPS registered distance and the straight line distance. The consideration of left-turning cyclists was incorporated here by including the midpoint of the intersection when calculating their distance. As shown in figure 8 where an example is given of 2 intersection crossings, both starting on the East-side, one going straight to the West and the other crossing to the South and left.

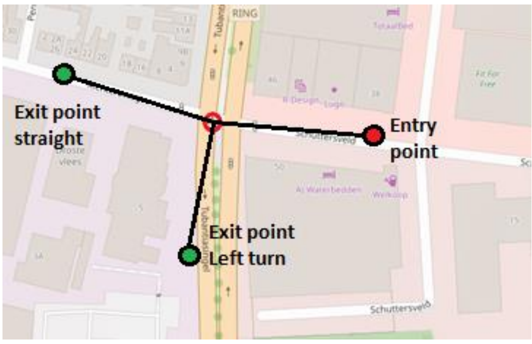


Figure 8: Calculating crossing distance

The discrepancy between the measured and calculated distance can be explained in part due to the oversimplification of the calculated distance. But another part most likely comes from inaccuracies in the GPS registration of the crossings. The choice was made to filter out intersection crossings with a registered distance that was more than 1,5 times the calculated distance. These intersection crossings are likely to represent some form of GPS inaccuracy. 24% of the intersection crossings were found to be above this set value. Table 2 gives a summary of the choices that were made concerning the filtering of the data.

Table 2: Boundaries to intersection data

Category	Lower bound	Upper bound
Distance	64 m	344 m
Duration	10 s	180 s
Direction	Left and straight only	
Time of day	7 am	7 pm
Day of the week	Weekdays only	

Registered vs Calculated distance	none	1,5 x

Before filtering there were 141.152 registered intersection crossings over the 9 intersections. After filtering 60.347 valid intersection crossings are left over. This equals about 43% of the total intersection crossings.

Figure 9 shows the pre and post filter count of registered intersection crossings per intersection.

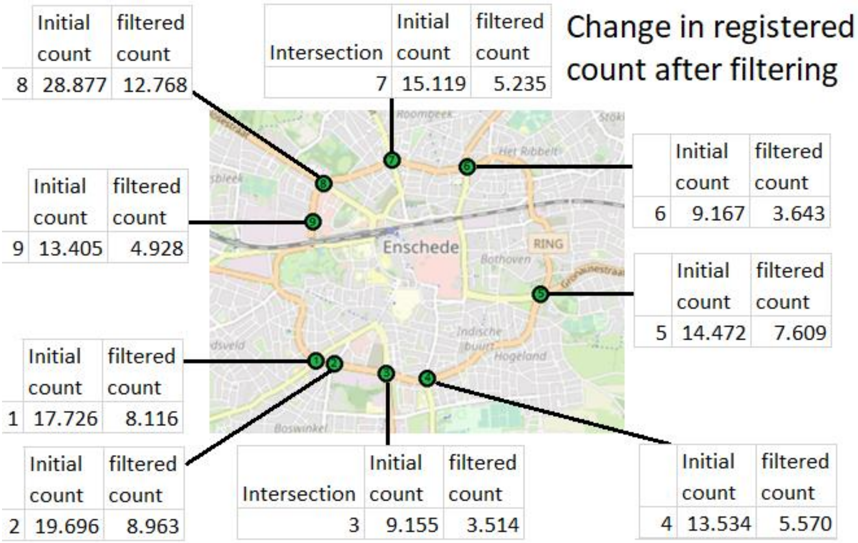


Figure 9: Change in registered intersection crossings after filtering

3.7. Reference speed scenarios

The way that most resembles how Mobidot uses the data themselves is by aggregating the cycling speed per cyclists on cycling paths. This method allows for variety in individual cycling speeds, where some cyclists have higher overall cycling speeds than other cyclists. Good examples of these are cyclists on electrical bicycles compared to cyclists on normal bicycles but also younger cyclists compared to older cyclists. By only using cycling data on cycling paths any GPS registration errors at the start and end of trips are also avoided. Part of this research is about finding different ways of calculating the cycling delay at intersections and for this reason two more reference scenarios to calculate the cycling speed are devised.

One alternative scenario will incorporate the time of day in the aggregation of the cycling speeds. And the other alternative scenario will use the cycling speed of cyclists on the cycling paths right before the intersection crossing.

The following 3 reference speed scenarios will be used in this thesis:

I. Reference speed scenario 1: Average Cycling speed
II. Reference speed scenario 2: Time of Day speed.
III. Reference speed scenario 3: Entry speed.

Where scenario 1 uses the data from all registered cyclists from the period of the 1st of January 2019 till the 1st of July 2019. Using this data the average cycling speed per individual cyclists is then calculated. Scenario 2 combines the cycling speed of the cyclists with the time of the day. With this, the average cycling speed of a cyclist at the time interval of their intersection crossing is calculated. Scenario 3 uses the cycle path segment previous to the intersection crossing to calculate the cycling speed. The location of this segment is dependent on the choices made for the intersection area as described in paragraph 3.2.

With these 3 different ways of calculating the cycling speed of the different cyclists, there will also be 3 different delay calculation scenarios. The differences between the speed and delay for these different scenarios will be compared in this research, and the results of this comparison will be discussed at the conclusion of this thesis.

3.8. Filter cycling data and reference scenarios

The data outside of the intersections which was used to calculate the reference speed scenarios also needed to be filtered. Due to errors in the GPS registration sometimes car or bus trips are registered as cycling trips, or on the lower end, some pedestrians could be included. For this reason, all trips with cycling speeds above 45 km/h are filtered at this stage. Furthermore, cycling data with speeds below 4 km/h second are also filtered as these are most likely pedestrians.

The different reference speeds are computed using the GPS trip data outside of the intersection areas. Due to European privacy laws, this data was not generally accessible but was instead handled on location by Mobidot. Due to the nature of the application GPS-data at the start and end of trips is less accurate as it can take some time for the application to register the start and end of a trip, for this reason only data on cycle paths was incorporated in calculating the different speeds.

Not all computed data will be used for the different analyses, boundaries are implemented to get the data that best represents the scenarios that are useful for the different analyses. Due to the aggregation of data in the Cycle and Time of Day scenarios their distribution is more condensed than that of the Entry speed scenario. As a result, the choice for the boundaries was set at two times the standard deviation for the Cyclist and Time of day speed scenarios and only one times the standard deviation for the Entry speed scenario. Table 3 shows the boundaries that will be implemented to the different speed reference scenarios.

Table 3: Speed reference mean

	Cyclist speed	time of day speed	Entry speed
Count of crossings	132959	132588	132960
Mean	20, 5 km/h	20,5 km/h	18 km/h
Standard deviation	2,9 km/h	3,2 km/h	8,6 km/h
Boundaries	14,8 <--> 26,3	14,4 <--> 27	9,4 <--> 26,6

With these barriers established figure 10 shows an overview of the distribution of the 3 different reference speed scenarios. This figure again shows that the registered speeds for the Entry speed scenario (green) show a wider distribution. The overlap between the Cycle speed (red) and Time of day speed (blue) scenarios is also clearly visible.

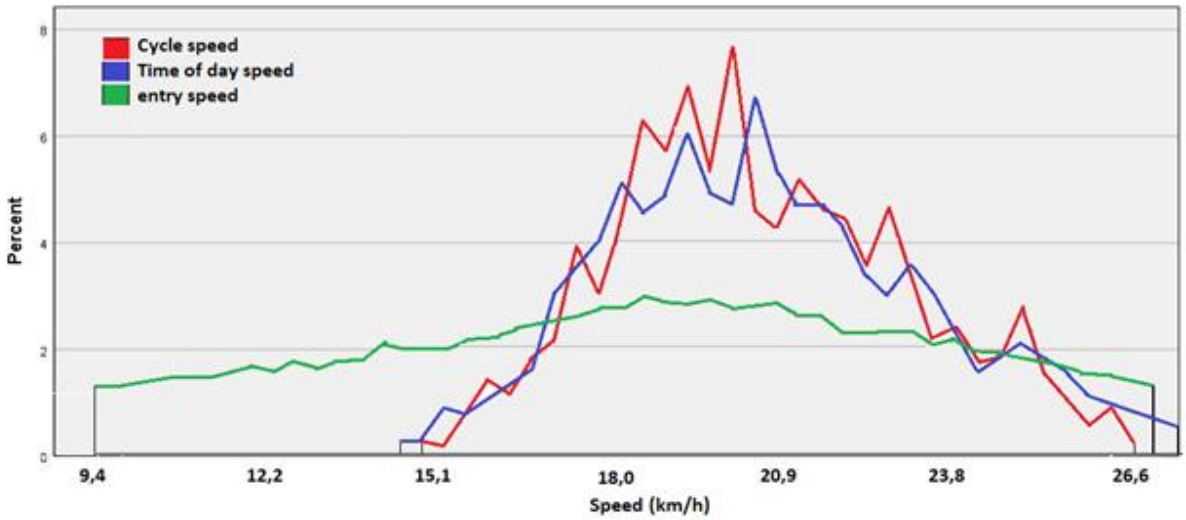


Figure 10: Distribution of reference speed based on the 3 scenarios

There are 95 intersection crossings where the Cyclists speed is below 14,8 km/h and there are 2.742 crossings where the Cyclists speed is above 26,3 km/h. This leaves 57.510 registered intersection crossings with the Cyclists speed withing the set thresholds.

There are 761 intersection crossings where the Time of Day speed is below 14,4 km/h and there are 2.357 crossings where the Time of Day speed is above 27 km/h. This leaves 57.131 registered intersection crossings with the Time of Day speed withing the set thresholds

There are 11.662 intersection crossings where the Entry speed is below 9,4 km/h and there are 8.165 crossings where the Entry speed is above 26,6 km/h. This leaves 40.520 registered intersection crossings with the Entry speed withing the set thresholds.

3.9. Calculate the delay and implement variables

By comparing the filtered data from the intersections and the different bounded reference speed scenarios the reference speed and delay for all 3 scenarios was calculated. An overview of the data of the three reference scenario calculations is presented in Chapter 4 paragraph 2. And an overview of the data for the four variables as chosen at the end of the literature review is presented in Chapter 4 paragraph 3.

4. Data Examination and Comparison

This chapter is all about the examination of the data and preliminary results. In the first paragraph, initial results are presented concerning duration and distance of crossings along the 9 intersections. The second paragraph will present results specific to the delay calculations using the 3 reference scenarios as well as the speed and delay in the different directions on the intersections. The third paragraph then shows the first results of implementing the variables in the delay calculations. Based on the examination in this chapter different analysis are implemented the results of which are presented in Chapter 5.

4.1. Descriptive results 9 intersections

First a comparison between the data that is used for this research and the Vialis data that Hemme used for this research into the effects of municipal measures on cycling delay is done. This comparison can give some insight into how well the data represents the real world intensities on the different intersections. Table 4 shows the initially registered intersection crossings, as well as the filtered count and the cyclists per hour between 07.00 and 19.00 from the Vialis data.

The biggest deviation is found at intersections 8. This intersection shows significantly more registered crossings in the Mobidot database compared to the data from Vialis. This intersection is one of two intersections integrated with the SMART application, and the SMART application is advertised at this intersections with stickers which might explain why this intersection is over-represented in the database, it might also be true that due to platooning of cyclists approaching this intersection the induction loops used for the Vialis dataset do not distinguish between different cyclists enough and might be an underrepresentation. Another big deviation between the two datasets is found on the sixth intersection on the Laaressingel & Lasondersingel, which seems to be underrepresented in the Mobidot database. The other 7 intersections do not show significant differentiation to take into account.

Table 4: Selected intersections and registered crossings per intersection

No.	Intersection streets	Registered Crossings	Filtered Crossings	Cyclists per hour (*Vialis data*)
1.	Haaksbergerstraat & Getfertsingel	17.726	8.116	120
2.	Burgemeester M van Veenlaan & Getfertsingel	19.696	8.963	120
3.	Zuiderval & Varviksingel	9.155	3.514	80
4.	Kuipersdijk & Varviksingel	13.534	5.570	80
5.	Boulevard 1945 & Gronausestraat	14.472	7.609	80
6.	Laaressingel & Lasondersingel	9.167	3.643	120
7.	Deurningerstraat & Boddenkampsingel	15.119	5.235	120
8.	Hengelosestraat & Boddenkampsingel	28.877	12.768	120
9.	Richtersweg & Schuttersveld	13.405	4.928	80

Using the now filtered data set the durations and distances off the valid intersection crossings was calculated. Figure 11 shows the mean of the distance and duration of the different intersection crossings per intersection. Looking at this data intersection 2 seems to be an outlier when it comes to the mean distance which at 289 meters is significantly higher than the mean of the other 8 intersections. This intersection also has a significantly higher duration per intersection crossings. This combination should mean that the delays at this intersection will be comparable to the other intersections.

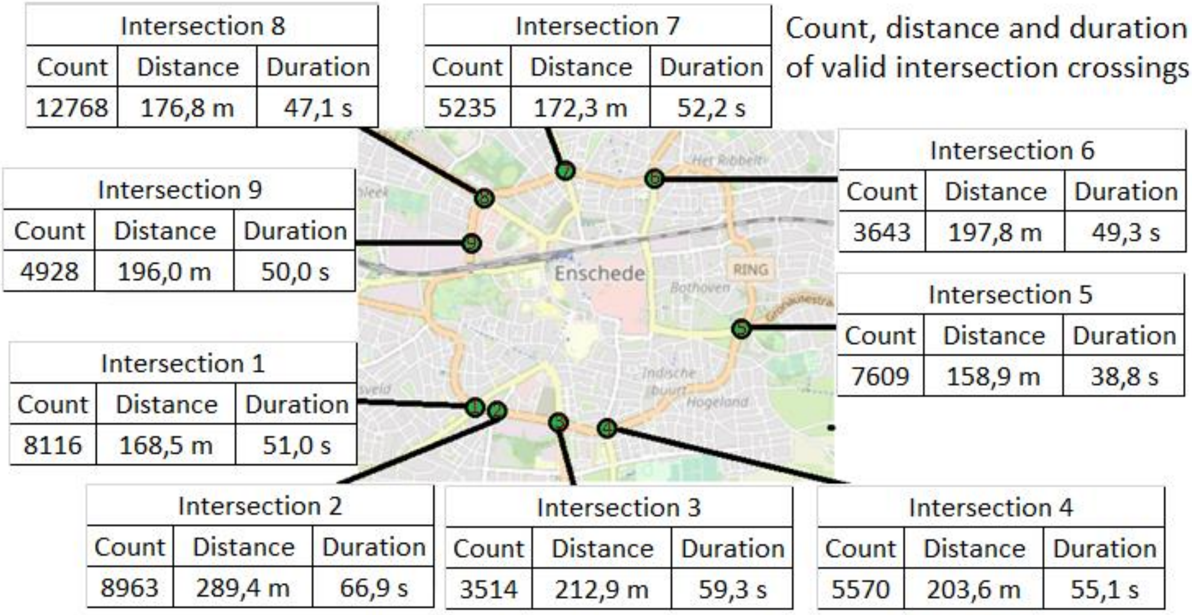


Figure 11: Overview of count and mean distance and duration at different intersections

4.2. Speed and delay calculation reference scenarios

Figure 12 shows the count of valid intersection crossings, as well as the mean and the standard deviation of the speed and delay for all 3 reference scenarios at each of the 9 intersections. After this figure 13-54 show the same results per scenario but then further specified in the straight trough, perpendicular and left-turning intersection crossings. Where the straight trough direction follows the Singel and the perpendicular direction crosses the Singel.

When comparing the delay at the different intersections the mean delay at different intersections ranges from as low as 11,1 seconds to as high as 24,1 seconds. Figure 12 shows that the aggregated speed of the Entry scenario is generally lower than the other two scenarios. This can be explained from the fact that this scenario uses data near the intersection to calculate the cycling speed, a location which tends to be more congested compared to the overall cycling trip that is used in calculating the reference speed of the other two scenarios. Another interesting detail is that as discussed in paragraph 3.8 the standard deviation for the Entry speed scenario is significantly higher than the other 2 scenarios, but when looking at the calculated delay this difference not nearly as pronounced. Meaning that the distribution is more similar to the other 2 scenarios.

Overall intersection reference speed and delay

Cyclist delay
Time of day delay
Entry delay

Intersection 8

Count	Speed	Std Dev	Delay	Std Dev
12427	20,3 km/h	2,2	17,2 s	20,4
12385	20,5 km/h	2,4	17,4 s	20,4
8532	18,5 km/h	4,6	13,0 s	18,4

Intersection 7

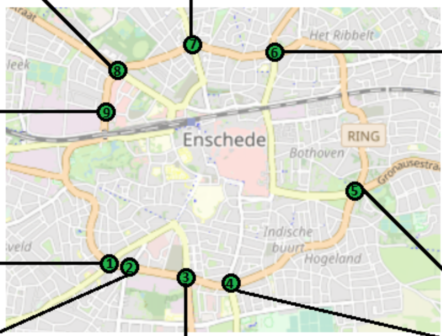
Count	Speed	Std Dev	Delay	Std Dev
5004	20,3 km/h	2,5	22,3 s	23,3
4920	20,5 km/h	2,7	22,3 s	23,2
3369	18,5 km/h	4,5	15,5 s	21,2

Intersection 9

Count	Speed	Std Dev	Delay	Std Dev
4664	20,4 km/h	2,3	17,0 s	20,1
4689	20,4 km/h	2,5	16,9 s	20,1
3083	18,1 km/h	4,5	11,2 s	16,6

Intersection 6

Count	Speed	Std Dev	Delay	Std Dev
3350	20,0 km/h	2,6	16,5 s	20,1
3295	20,0 km/h	2,9	16,2 s	20,1
2555	17,2 km/h	4,5	12,7 s	17,7



Intersection 1

Count	Speed	Std Dev	Delay	Std Dev
7792	20,3 km/h	2,4	21,9 s	23,9
7645	20,4 km/h	2,7	22,1 s	24,0
5675	18,1 km/h	4,5	17,1 s	22,8

Intersection 5

Count	Speed	Std Dev	Delay	Std Dev
7087	20,7 km/h	2,4	13,3 s	19,7
7058	20,7 km/h	2,7	13,2 s	19,6
4745	19,4 km/h	4,7	11,1 s	18,2

Intersection 2

Count	Speed	Std Dev	Delay	Std Dev
8685	20,1 km/h	2,2	17,2 s	20,2
8599	20,1 km/h	2,4	17,1 s	20,2
6474	18,1 km/h	4,3	12,9 s	18,3

Intersection 3

Count	Speed	Std Dev	Delay	Std Dev
3174	20,5 km/h	2,6	24,0 s	26,6
3304	20,9 km/h	3	23,8 s	26,0
2263	18,6 km/h	4,4	20,8 s	25,7

Intersection 4

Count	Speed	Std Dev	Delay	Std Dev
5327	20,1 km/h	2,4	19,7 s	22,0
5235	20,2 km/h	2,5	19,9 s	22,1
3823	18,1 km/h	4,6	15,1 s	20,3

Figure 12: reference speed and delay for all 3 scenarios.

The data in figure 13, 14 and 15 always shows the direction 1: following the Singel first, followed by direction 2: perpendicular to the Singel and direction 3: left turning. Due to the orientation of intersection 5, 8 and 9 relatively to the single the symbols are turned around. But the data follows the same pattern as the other intersections.

Scenario 1: Reference Speed and Intersection Delay

Intersection 8

Dir	Count	Speed	Delay
↕	2836	20,3 km/h	17,7 s
↔	8021	20,3 km/h	15,7 s
↱	1570	20,1 km/h	24,3 s

Intersection 7

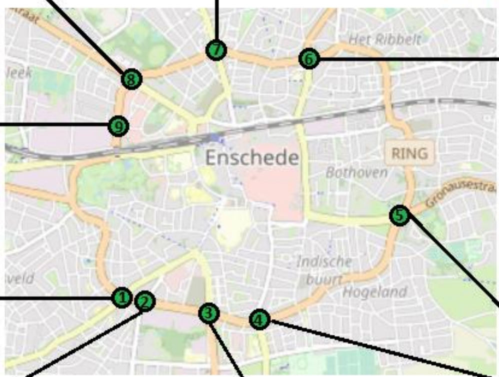
Dir	Count	Speed	Delay
↔	1875	20,1 km/h	18,0 s
↕	2378	19,7 km/h	23,9 s
↱	751	20,0 km/h	27,7 s

Intersection 9

Dir	Count	Speed	Delay
↕	3175	20,4 km/h	13,8 s
↔	333	20,4 km/h	25,0 s
↱	1156	20,2 km/h	23,4 s

Intersection 6

Dir	Count	Speed	Delay
↔	885	19,9 km/h	13,1 s
↕	2130	20,4 km/h	17,8 s
↱	335	19,1 km/h	16,8 s



Intersection 1

Dir	Count	Speed	Delay
↔	1810	20,1 km/h	19,2 s
↕	5181	20,3 km/h	22,6 s
↱	801	20,5 km/h	24,0 s

Intersection 5

Dir	Count	Speed	Delay
↕	1618	20,2 km/h	19,7 s
↔	4816	20,8 km/h	9,2 s
↱	653	20,6 km/h	28,0 s

Intersection 2

Dir	Count	Speed	Delay
↔	677	20,3 km/h	15,5 s
↕	7220	20,0 km/h	16,8 s
↱	788	20,3 km/h	22,7 s

Intersection 3

Dir	Count	Speed	Delay
↔	1815	20,4 km/h	23,9 s
↕	651	21,0 km/h	22,0 s
↱	708	20,2 km/h	26,3 s

Intersection 4

Dir	Count	Speed	Delay
↔	1515	20,3 km/h	17,2 s
↕	3237	19,9 km/h	20,9 s
↱	575	20,2 km/h	19,8 s

Figure 13: Mean Speed and Delay in different directions for scenario 1 Cyclist speed

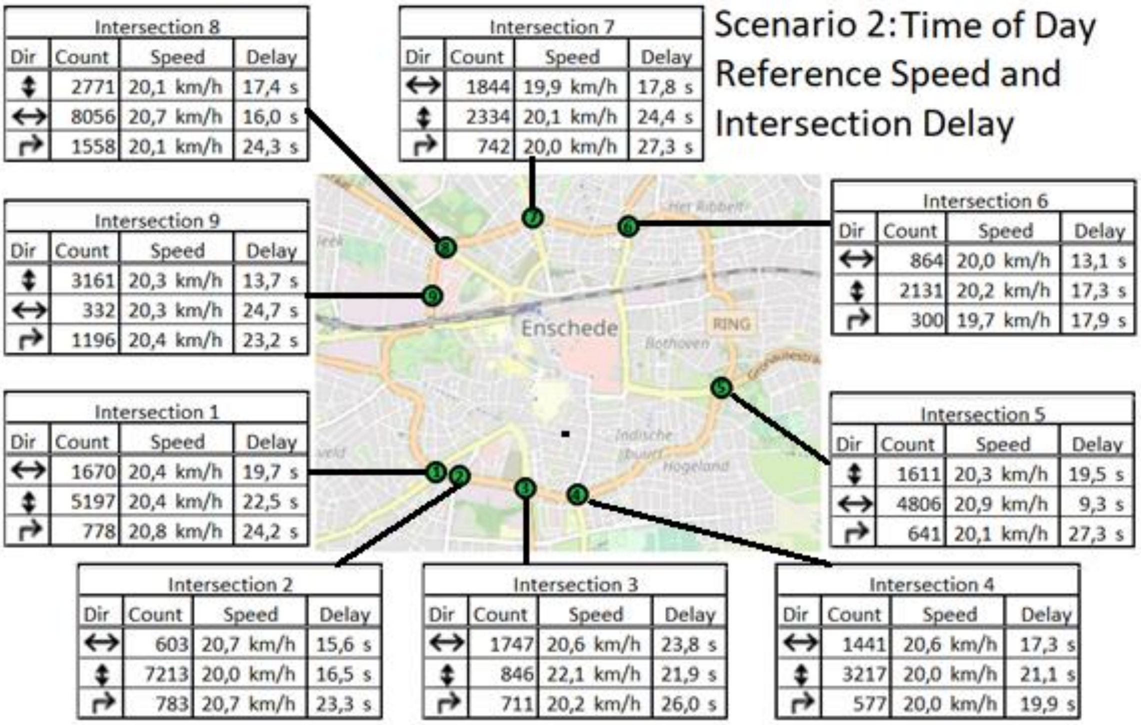


Figure 14: Mean Speed and Delay in different directions for scenario 2 Time of Day speed

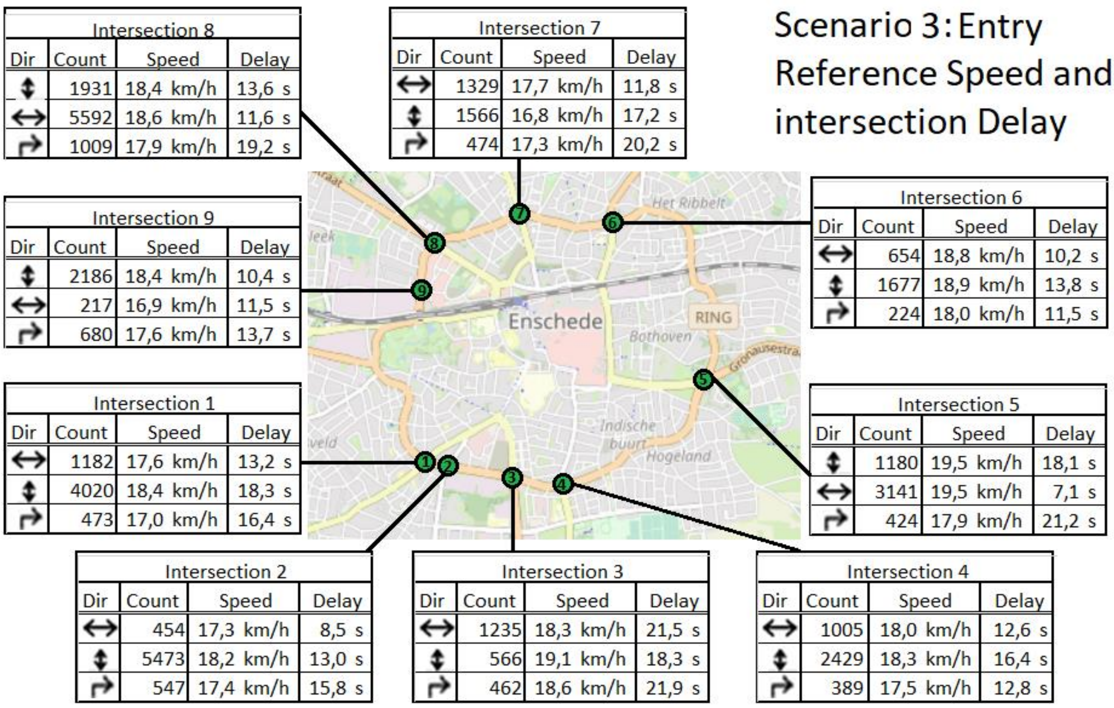


Figure 15: Mean Speed and Delay in different directions for scenario 3 Entry speed

4.3. Overview of the 4 hypotheses

At the end of the literature review, four different hypotheses were selected for further analysis. These were the *Trip purpose, rain with the implementation of rain sensors, separation of traffic and all cyclists simultaneous green.* This part of the chapter will give an overview of the data for these four different hypotheses. More detailed tables with information per factor are presented in Appendix C.

Trip purpose

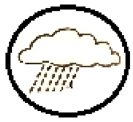
For trip purpose over 40 different destination types are used in the Mobidot database. Of the 60.346 intersection crossings there 20.016 intersection crossings that are identified as being part of trips going back home. And 13.440 intersection crossings are part of trips going to the office. Table 5 shows an overview of the delay for the three different reference scenarios for both the Home and Office bound trips.

Table 5: Count and mean delay trip destination

Reference speed	Count of home trips	Home Mean (Std dev)	Count of Office trip	Office Mean (Std dev)
Cyclist delay	20016	19,6 s (22,7)	13440	15,8 s (19,8)
ToD delay	19783	19,5 s (22,6)	13356	15,9 s (19,9)
Entry delay	14464	15,5 s (20,9)	9382	11,8 s (18,1)

Looking at the data in table 5 the entry delay shows consistently lower delay times. But it is also clear that all 3 scenarios show similar differences between the home and office trips. The mean is about 3,6 seconds lower for office trip and the deviation is also around 3 seconds lower.

Rain



First, an overview of the data, when it is and is not raining, is given. Looking at the data of the 4 intersections. Around 7,5% of the intersection crossings are registered when it is raining. Which is similar to the average amount of trips when raining in the Netherlands which in 2019 was around 8,8% (Poels, 2020) Meaning that this subset of data is a good representation of the real-world situation. Table 6 shows the mean delay and standard deviation for trips registered when it is and is not raining.

Table 6: Count and mean delay difference when Raining

Refence speed	Count when raining	Raining Mean (Std dev)	Count when not raining	Not Raining Mean (Std dev)
Cyclist delay	3992	18,4 (22,0)	52761	18,3 s (21,7)
ToD delay	3976	18,4 (22,0)	52416	18,3 s (21,7)
Entry delay	2796	13,7 (20,0)	37203	14,0 s (19,9)

As shown in table 6 the overall difference between when it is and is not raining appears to be negligible. 3 of the 9 intersections are outfitted with rain sensors that can provide faster green lights for cyclists when it is raining these are located at:

Intersection 6: Oldenzaalsestraat – Singel; 7: Deurningerstraat -Singel; 8: Hengelosestraat – Singel

For the final analysis, the delay at these intersections will be compared to the intersections without the integrated rain sensors.

Separation of traffic

For the separation of traffic 4 different classifications will be used to classify how the approach crossing and exit of the different intersections compare to each other based on the separation between cycling and car traffic. The first classification is when there is no real separation between cyclists and cars at either the intersection crossing or cycle path before and after the crossing. The second classification only has some a small amount of separation between cars and cyclists at the intersection. The third classification shows intersections with a moderate amount of separation at either the entry, crossing or exit of the intersection. And the fourth classification shows very distinct separations of traffic at all 3 parts of the intersection. Figure 16 shows an example of high separation at the approach (left), the crossing (middle) and the exit of the intersection 9 (right), this particular example is the Northern approach of intersection 5: Boulevard 1945 - Singel. Figure 17 and Table 7 show how the different approaches of the intersections are classified for this research. And table 8 shows an overview of the delay for the different scenarios and separations

Figure 16: Example of an intersection with high separation

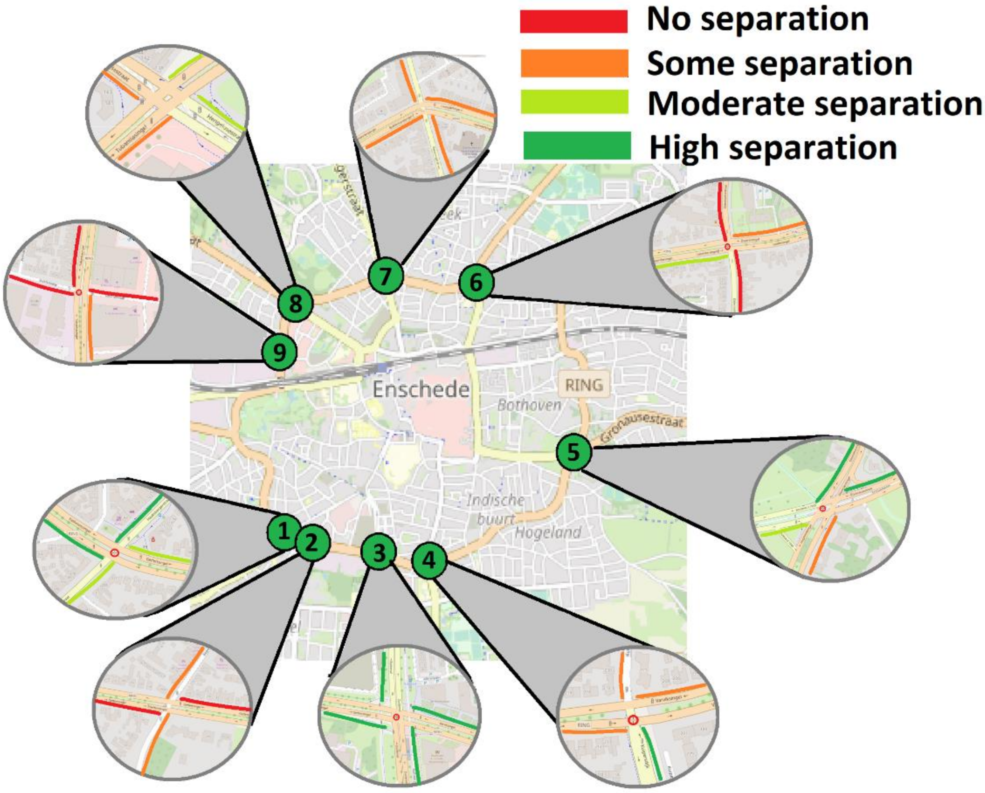


Figure 17: Separation of traffic at all intersections

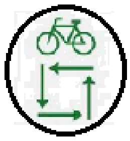
Table 7: Division of separation form at intersections

Intersection	East	South	West	North
1. Haaksbergerstraat & Getfertsingel	Moderate	Moderate	High	High
2. Burgemeester M van Veenlaan & Getfertsingel	No	Some	No	Some
3. Zuiderval & Varviksingel	High	High	High	High
4. Kuipersdijk & Varviksingel	Some	High	Some	Some
5. Boulevard 1945 & Gronausestraat	High	Some	Moderate	High
6. Laaressingel & Lasondersingel	Some	No	Moderate	No
7. Deurningerstraat & Boddenkampsingel	Some	Some	Some	Some
8. Hengelosestraat & Boddenkampsingel	Moderate	Some	Some	Moderate
9. Richtersweg & Schuttersveld	No	Some	No	No

Table 8: Mean and standard deviation of delay based on separation of traffic

Reference speed	No separation Mean (Std dev)	some separation Mean (Std dev)	moderate separation Mean (Std dev)	High separation Mean (Std dev)
Cyclist delay	18,2 s (21,1)	18,8 s (21,2)	16,7 s (20,9)	19,4 s (23,7)
ToD delay	18,1 s (21,3)	18,7 s (21,2)	16,9 s (21,0)	19,5 s (23,6)
Entry delay	11,6 s (17,2)	14,0 s (19,3)	12,4 s (18,8)	16,7 s (22,8)

All cyclists simultaneous green



The all cyclists simultaneous green is a distinct set up of the traffic control system at an intersection. This means that different intersections will need to be compared with each other. One set of intersections with the all cyclists simultaneous green set-up and one set without this set up.

Intersection 2, 4, 6, 7 and 9 all have the All Cyclists simultaneous green measure. Intersections 1, 3, 5 and 8 do not have the All Cyclists simultaneous green measure. Table 14 presents the preliminary delay results. In this table there are no real pronounced differences in the overall delay at intersections with or without the ACSG measure. Further analysis is done based on the different directions that cyclists can cross the intersection in, this is discussed in the next chapter.

Table 9: Count and mean delay All Cyclists Simultaneous Green

Refence speed	Count ACSG	ACSG Mean (Std dev)	Count no ACSG	No ACSG Mean (Std dev)
Cyclist delay	27.030	18,2 s (22,1)	30.480	18,5 s (21,2)
ToD delay	26.738	18,3 s (22,2)	30.392	18,5 s (21,3)
Entry delay	19.304	13,5 s (19,0)	21.215	14,5 s (20,7)

4.4. Similarity cyclist speed and time of day speed

Based on these preliminary results, it is concluded that the Time of day delay and the Cyclists delay do not differentiate enough to continue the analyses with both scenarios. Looking at the overall speed and delay calculation the mean was extremely similar and even though the standard deviation showed some difference it was still very close. Furthermore, the only real measurable difference is between left-turning cyclists on the first intersection (Getfertsingel & Haaksbergerstraat & Pathmossingel) with a mean difference of 1,6 seconds. Most other differences range between 0,1 or 0,2 seconds. Furthermore the distribution of reference speeds found in paragraph 3.8 as shown in figure 10 corroborate this decision. For this reason, the choice is made to only use scenario 1: cyclist speed and scenario 3: entry speed for the final analyses. The data from scenario 2: time of day speed are still shown in the tables of Appendix C.

5. Analyses and Results

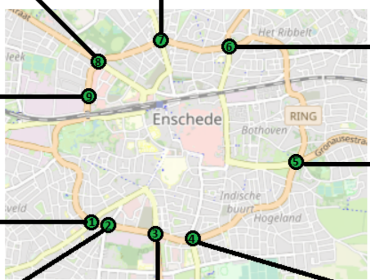
This chapter will present the results of the different analyses. As discussed at the end of Chapter 4, due to the similarity in the results of scenario 1 and 2, only scenario 1: cyclist delay and scenario 3: entry speed will be used in this chapter. This means that four different hypotheses are tested with two different reference scenarios for a total of eight analyses. This chapter will present a summary of the results of the SPSS analyses for the different hypotheses, all eight analyses are presented in more detail in Appendix D.

5.1. Trip purpose analyses

The final overview of the valid intersection crossings either Home or the Office as their trip purpose is shown in figure 18, this figure also shows the mean and standard deviation of the reference speed and calculated delay. From this figure, it can be surmised that there is quite some fluctuation between the number of trips going to home and the office. Intersection 8 and 6 are the only intersections where the amount of cyclists with both trip purposes is very similar. Intersection 3 (44%) and 9 (43%) have the lowest number of cyclists going to the office compared to those going home. Interestingly intersection 3 is the only intersection that shows a lower delay for cyclists with the home as their destination (1,3 seconds) and intersection 9 shows the highest advantage for cyclists on their way to the office (7,5 seconds). The speed with which cyclist approached the intersections when they have different trip purposes does not change a lot. For scenario 1 this was 20,3 km/h for trips going home compared to 20,5 km/h for trips going to the office. And looking at scenario 3 the speeds were respectively 18,4 km/h and 18,7 km/h.

The Mann-Whitney test found statistically significant differences between intersections crossings part of trips going home compared to trips going to the office for both scenarios. With trips going to the office showing less delay than trips going to home.

Trip Purpose:
Mean Speed and Delay
Home and office per
intersection



Intersection 8					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	3513	20,3 km/h	2,2	15,9 s	19,2
Home	3351	20,6 km/h	2,3	17,0 s	20,3
Office	2446	18,8 km/h	4,5	12,1 s	17,7
Home	2233	18,4 km/h	4,5	12,7 s	18,3

Intersection 7					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	1019	20,3 km/h	2,8	20,5 s	21,3
Home	1551	19,7 km/h	2,6	22,4 s	23,9
Office	654	17,3 km/h	4,7	12,8 s	18,1
Home	1057	17,2 km/h	4,5	15,9 s	22,0

Intersection 6					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	821	19,9 km/h	2,8	13,7 s	19,2
Home	901	20,3 km/h	2,6	18,3 s	20,6
Office	683	19,1 km/h	4,6	10,6 s	16,8
Home	690	18,8 km/h	4,4	14,4 s	17,9

Intersection 9					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	870	20,7 km/h	2,3	11,4 s	15,8
Home	2022	20,2 km/h	2,3	18,9 s	20,9
Office	589	18,8 km/h	4,6	8,0 s	13,6
Home	1325	18,1 km/h	4,5	13,0 s	17,9

Intersection 1					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	1832	20,6 km/h	2,5	19,2 s	21,1
Home	3216	20,3 km/h	2,3	24,0 s	25,5
Office	1328	17,9 km/h	4,5	14,1 s	20,2
Home	2397	18,4 km/h	4,5	19,7 s	24,4

Intersection 5					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	1936	21,3 km/h	2,3	10,6 s	16,9
Home	2473	20,6 km/h	2,6	14,4 s	21,0
Office	1178	20,6 km/h	4,7	10,0 s	17,0
Home	1779	18,8 km/h	4,6	11,4 s	18,7

Intersection 2					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	1816	20,2 km/h	1,9	14,3 s	17,6
Home	3265	20,0 km/h	2,3	19,0 s	21,2
Office	1346	17,3 km/h	4,1	8,1 s	13,9
Home	2547	18,8 km/h	4,2	16,0 s	19,9

Intersection 3					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	549	21,1 km/h	2,8	24,9 s	28,0
Home	1241	20,4 km/h	2,6	23,6 s	26,5
Office	394	18,4 km/h	4,5	20,8 s	26,6
Home	931	18,7 km/h	4,3	20,8 s	25,2

Intersection 4					
Trip Purpose	Count	Mean speed	Std Dev	Mean Delay	Std Dev
Office	1084	20,3 km/h	2,3	17,7 s	20,6
Home	1996	19,9 km/h	2,5	20,9 s	23,0
Office	764	18,9 km/h	4,6	14,6 s	19,7
Home	1505	17,8 km/h	4,6	16,0 s	21,1

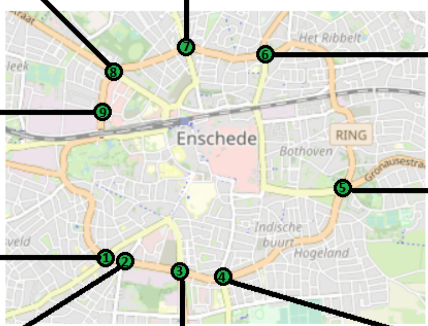
Figure 18: Trip Purpose; Mean speed and delay. For Home and Office per intersection

5.2. Rain analyses

The final overview of the valid intersection crossings when it is either raining or dry is shown in figure 19, this figure also shows the mean and standard deviation of the reference speed and calculated delay. Overall it was found that around 8% of the valid intersection crossings were done when it was raining. From the data, it can be surmised that the differences in reference speed and calculated delay when it is either raining or not are fairly low. Both for the aggregated delay as well as the individual delays per intersection. For scenario 1 the mean speed was 20,3 km/h when dry and 20,1 km/h when raining. And the delay when dry was 18,3 seconds compared to 18,4 seconds when it was raining. And for scenario 3 the mean approaching speed was 18,3 km/h when dry and 18,1 km/h when raining. With a delay of 14 seconds when it was dry and 13,7 seconds when it was raining.

Intersections 6, 7 and 8 are outfitted with integrated rain sensors. For this analysis, only these 3 intersections were selected. One of the underlying requirements for these sensors is a measure of flexibility in the overall green time cycle. For this reason, the choice was made to analyze the difference in delay when it is raining and not raining at different hours. For scenario 1 there was a significant difference found between the hours: 07.00-08.00 & 09.00-10.00 & 15.00 & 16.00. for scenario 3 the only significant difference was found between 15.00 and 16.00. These are indeed some of the least busy times on the road. But overall the research of this thesis does not provide conclusive results about the effectiveness of the rain sensors. And the conclusions based on this research are that there is no significant difference found in the delay when it is either raining or dry.

Raining:
Mean Speed and Delay
Raining and not Raining
per Intersection



Intersection 8

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	11418	20,3 km/h	2,2	17,2 s	20,3
True	861	20,2 km/h	2,1	17,0 s	20,2
False	7835	18,5 km/h	4,6	13,0 s	18,5
True	598	18,2 km/h	4,6	11,8 s	17,9

Intersection 7

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	4611	19,9 km/h	2,5	22,3 s	23,3
True	335	19,9 km/h	2,4	21,6 s	23,1
False	3102	17,2 km/h	4,5	15,5 s	21,3
True	224	17,4 km/h	4,5	15,9 s	20,7

Intersection 6

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	3094	20,2 km/h	2,6	16,4 s	20,1
True	213	19,6 km/h	2,4	16,8 s	20,9
False	2372	18,8 km/h	4,5	12,7 s	17,8
True	158	18,2 km/h	4,2	12,6 s	17,0

Intersection 9

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	4270	20,4 km/h	2,3	17,0 s	15,8
True	329	20,2 km/h	2,3	15,9 s	19,0
False	2815	18,1 km/h	4,6	11,2 s	13,6
True	229	18,1 km/h	4,8	11,3 s	17,3

Intersection 1

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	7093	20,3 km/h	2,4	21,9 s	23,8
True	601	20,2 km/h	2,4	22,2 s	24,3
False	5165	18,1 km/h	4,5	17,0 s	22,7
True	435	18,0 km/h	4,6	17,3 s	22,6

Intersection 5

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	6524	20,6 km/h	2,4	13,3 s	19,6
True	470	20,6 km/h	2,5	13,9 s	20,3
False	4366	19,4 km/h	4,7	11,0 s	18,0
True	319	19,0 km/h	4,9	12,2 s	19,8

Intersection 2

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	7936	20,0 km/h	2,2	17,3 s	20,2
True	607	19,9 km/h	2,2	16,3 s	19,7
False	5928	18,1 km/h	4,3	13,0 s	18,3
True	442	17,8 km/h	4,4	11,7 s	17,5

Intersection 3

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	2910	20,4 km/h	2,6	24,0 s	26,6
True	227	20,6 km/h	2,7	25,9 s	27,5
False	2095	18,6 km/h	4,4	20,8 s	25,5
True	144	18,7 km/h	4,5	22,6 s	28,3

Intersection 4

Raining	Count	Mean speed	Std Dev	Mean Delay	Std Dev
False	4905	20,1 km/h	2,4	19,7 s	21,9
True	349	19,9 km/h	2,4	20,5 s	23,1
False	3525	18,2 km/h	4,6	15,2 s	20,3
True	247	17,7 km/h	4,7	13,2 s	20,1

Figure 19: Rain; Mean speed and delay. When raining or not per intersection

5.3. Separation of traffic analyses

The final overview of the valid intersection crossings per category of traffic separation is shown in table 10. This table also shows the mean and standard deviation of the reference speed and calculated delay for reference scenario 1 and 3. When inspecting the intersections there seems to be a correlation between the amount of traffic at an intersection and the amount of separation between traffic flows that was present. This might explain why the intersection crossings with the highest amount of separation also have the longest delay times as these tend to be located at the busiest intersection directions.

Because there are four different categories of separation first the Kruskal Wallis test was used. This test found significant differences. Which means all the groups had to be evaluated using the Mann-Whitney U test. From the follow-up Mann-Whitney U tests significant differences were found for: Cyclist delay: between group 1 and 3; group 2 and 3; group 2 and 4, and group 3 and 4.

Entry delay: between group 1 and 2; group 1 and 4; group 2 and 3; group 2 and 4, and group 3 and 4.

No significant difference was found for the Cyclist delay between group 1 and 2, and 1 and 4. Also no significant difference was found for the Entry delay between group 1 and 3.

Looking at the data the intersection approaches with the lowest measurements of traffic separation where found following the Singel, this fact is reflected in the final results by the relatively low number of registered intersection crossings for separation category.

Table 10: Count and delay per scenario for different classifications of separation

Refence speed	No separation		Some separation		Moderate separation		High separation	
	Count	Mean delay (SD)	Count	Mean delay (SD)	Count	Mean delay (SD)	Count	Mean delay (SD)
Cyclist delay	4.846	18,2 s (21,1)	26.391	18,8 s (21,2)	13.702	16,7 s (20,9)	12.571	19,4 s (23,7)
Entry delay	3.303	11,6 s (17,2)	18.642	14,0 s (19,3)	9.752	12,4 s (18,8)	8.822	16,7 s (22,8)

5.4. All cyclists simultaneous green analyses

Table 11 shows the reference speed and calculated delay per intersection crossing direction for both scenarios. What stands out from this table is that there does not seem to be a difference between the straight intersection crossings and the perpendicular intersection crossings. Both scenarios do show the difference with left-turning cyclists.

Table 11: Overview of reference speed and delay in different directions

Scenario 1: Cyclist	Count	Mean Speed	SD	Mean Delay	SD
Straight with Singel	16.206	20,2 km/h	2,4	17,6 s	20,9
Straight Perpendicular	33.967	20,2 km/h	2,3	17,5 s	21,1
Left turning	7.337	20,2 km/h	2,4	24,1 s	25,4
Scenario 3: Entry	Count	Mean Speed	SD	Mean Delay	SD
Straight with Singel	11.156	18,3 km/h	4,5	13,6 s	19,3
Straight Perpendicular	24.681	18,5 km/h	4,5	13,6 s	19,4
Left turning	4.682	17,7 km/h	4,6	17,4 s	23,1

However when the intersections are split up according to the all cyclists simultaneous green measure there is a clear difference between the straight and perpendicular intersection crossings. Table 12 shows an overview of this comparison for scenario 1 and table 13 shows this overview for scenario 3. These tables show the mean and standard deviation of the reference speed and calculated delay for reference scenario 1 and 3, comparing the four intersections without ACSG to the five intersections with the ACSG.

Table 12: Results scenarios 1 all cyclists simultaneous green

ACSG = False	Count	Mean Speed	SD	Mean Delay	SD
Straight with Singel	8.079	20,2 km/h	2,4	19,8 s	22,3
Straight Perpendicular	18.669	20,5 km/h	2,3	16,1 s	20,7
Left turning	3.732	20,3 km/h	2,4	25,2 s	26,6
ACSG = True	Count	Mean Speed	SD	Mean Delay	SD
Straight with Singel	8.127	20,2 km/h	2,3	15,5 s	19,1
Straight Perpendicular	15.298	20,0 km/h	2,3	19,1 s	21,4
Left turning	3.605	20,1 km/h	2,5	23,0 s	24,0

Table 13: Results scenarios 1 all cyclists simultaneous green

ACSG = False	Count	Mean Speed	SD	Mean Delay	SD
Straight with Singel	5.528	18,4 km/h	4,5	16,3 s	21,1
Straight Perpendicular	13.319	18,8 km/h	4,6	12,8 s	19,4
Left turning	2.368	17,9 km/h	4,7	19,6 s	25,2
ACSG = True	Count	Mean Speed	SD	Mean Delay	SD
Straight with Singel	5.628	18,1 km/h	4,5	10,9 s	17,0
Straight Perpendicular	11.362	18,1 km/h	4,4	14,4 s	19,4
Left turning	2.314	17,5 km/h	4,5	15,2 s	20,4

Looking at the data in these tables there is a clear separation between the 3 selected intersection crossing directions. These results are also shown in figure 20 with clustered boxplots of the delay in the different directions for scenario 1 and 3.

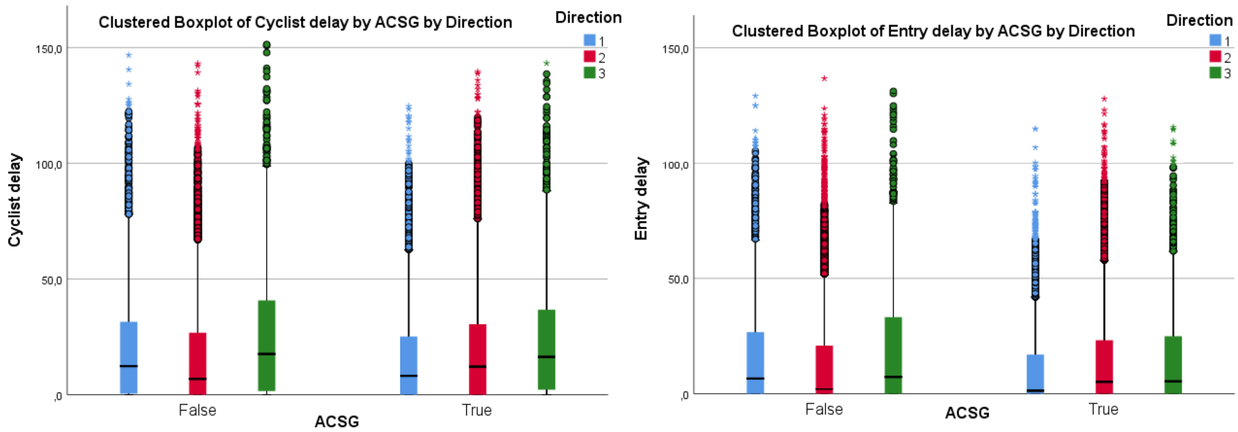


Figure 20: Clustered boxplot delay ACSG split in direction

Looking at the data it appears that the presence of all cyclists simultaneous green did not change the overall average delay. But it does change the amount of delay the different directions experience. And at the intersections with the, all cyclists simultaneous green measure, the maximum waiting times were decreased.

Furthermore, the Mann Whitney U tests showed significant differences for both scenarios when comparing the intersections with and without all cyclists simultaneous green in the different intersection crossing directions. Cyclists crossing intersections following the Singel and crossing to the left had smaller delays at intersections with the ACSG measure. Whereas cyclists crossing perpendicular to the Singel had lower delays at intersections without the ACSG measure.

This result can be explained by the higher number of cyclists that cross perpendicular to the Singel. The number of cyclists in the database that perpendicularly cross intersections is over twice the size of the cyclists following the Singel. When an intersection has the flexibility to finetune how much green time every direction is given the most dominant stream of cyclists is more likely to benefit from this. Another factor to take into account is the selection process by which the intersections with all simultaneous green are selected. As these tend to be selected on less busy intersections. Looking at the locations of the different intersections it does appear that the roads crossing the Singel at intersections with the all cyclists simultaneous green measure are smaller than those crossing intersections without all cyclists simultaneous green.

5.5. Reference scenarios

Looking at the results of the different scenarios the preliminary conclusion is made that due to the nature of aggregation no significant difference was found between the cyclist and time of day scenarios. These scenarios however did show significant difference with the third scenario entry speed. In all situations the entry speed scenario showed lower reference speeds which resulted in lower delay times. This difference is most likely due to fact that the reference speed in the first two scenarios is calculated using data from more ideal cycling conditions, including data from long stretches of cycling paths. Whereas the entry scenario only uses data close to signalized intersections where cycle paths are more likely to be congested, which tends to lower the overall cycling speed that is registered. Both options when selecting the reference speed have their own advantages. Scenario 1 and 2 will more accurately calculate the delay as if there were no intersections at all on the chosen route. Whereas scenario 3: Entry speed, better represent the conditions around the signalized intersection. However, as other studies have determined that cyclists tend to overestimate the time they are delayed by intersections the results of the first 2 scenarios might more accurately reflect reality according to the cyclists.

6. Conclusions

Using data of 2999 unique cyclists in Enschede 740.973 intersection crossings were registered. This data was then specified to only crossings at 9 intersections on the Singel of Enschede. At this point, the database consisted of 141.151 intersection crossings. Which was further reduced by selecting only intersection crossings that were between 64 and 344 meters, between 10 and 180 seconds, that took place on weekdays between 7 am and 7 pm and those that cross intersections either straight ahead or to the turning to the left. One final filtering was done by comparing the registered GPS distance and a calculation of the distance between the intersection entry and exit. This still left 60.347 valid intersection crossings which were then analyzed.

With these 60.347 signalized intersection crossings this research would focus on two questions. Firstly, how different variables could potentially influence the calculation of cycling delay and secondly how different reference scenarios could be used and what effect these would have on the calculation of cycling delay.

For this purpose, four factors were incorporated in this research these four being: trip purpose, rain, the separation of traffic and implementation of all cyclists simultaneous green. And to find out how different scenarios can be used to calculate the cycling delay and what the effect of these different scenarios was three different reference scenarios were made to calculate the delay. The first scenario used the average cycling speed per cyclist, the second used the average cycling speed per cyclist at a specific time-period of the day and the third scenario used the speed at the last segment before entering the intersection

The next step was to calculate the reference speeds and delays at the 9 intersections. The distribution of reference speeds for the first two scenarios showed a great amount of overlap, which was also reflected in the calculated delays for both scenarios, for this reason, scenario 2 time of day would not be used for the analyses of chapter 5. The third scenario did show a different distribution of reference speeds, and also different levels of calculated delays. Overall the calculated delay showed a difference of approximately 4 seconds in favor of the third scenario.

After this, the variables were tested. When comparing the delay at intersections that are part of trips going to the office compared to trips going home the office trips showed significantly lower delay times. The second was the comparison between when it was raining or dry, this comparison showed no significant difference favoring one group over the other. The third comparison was between four categories of separation between cars and cyclists during intersection crossings. And here multiple groups showed different results. The entry scenario showed the highest measure of variability. And both scenarios showed the highest calculated delay at the intersection crossings with the highest amount of separation, probably due to the fact that these intersection crossings represent very car-oriented intersection crossings. The final comparison between intersections with all cyclists simultaneous green showed advantages for both groups. With the intersections without all cyclists simultaneous green being favored for cyclists crossing perpendicular to the Singel. And cyclists crossing with the Singel or to the left being favored on intersections with the all cyclists simultaneous green measure.

7. Discussion and recommendations

This research set out with the objective to research how GPS-smartphone data can be used to calculate the delay of cyclists at signalized intersections. A large part of the thesis was spent getting a better understanding of the available data and how this could be used. When the data was processed the next step was to interpret the data with the different variables. And how to compare the different subsets of data in the form of different reference scenarios.

During this process, I found out that the way that you look at data becomes increasingly important. Just the fact that one group of cyclists has a bigger population than another can mean something, and thus can influence how I should test them. At the start of this research, I made the choice to focus only on the intersections of the Singel of Enschede as I presumed these intersections would have similar features to each other. From my general studies, I knew that most cycling trips are aimed at population centers and specific destinations, and this was reinforced in my research when I started to look at the directions cyclists are crossing the different intersections. The number of cyclists following the Singel was relatively low compared to the cyclist going to or from the city center. And by looking at this data and the delays in the different directions I was able to find interpretations of the data that I otherwise would not have been able to find. This was especially pronounced for the all cyclists simultaneous green measure.

There were quite a few results that showed statistical significance for the Mann-Whitney U tests however when looking at the effect size of the different analyses the largest was found to only be 0,019 which was the test between cyclists crossing intersections with and without the all cyclists simultaneous green measure following the Singel of Enschede in the entry delay scenario. Most of the other tests were slightly below 0,01 or even closer to 0. What this means is that the total variance that can be accounted for by the different group memberships is generally small. This is corroborated by the fact that the difference between most groups is only a few seconds with relatively high group populations.

Follow up possibilities

There is a lot of potential for follow up research. One example is to take another look at the reference scenarios. The way the data is currently registered means that the calculations are vulnerable to GPS errors which then need to be filtered out. One option would be to smooth these filters out by combining using a value that combines multiple GPS registrations and only using a running median value. Furthermore, this research has focused only on intersections on the Singel of Enschede, implicit to this selection was a subset of smaller and bigger intersections. Follow up research could be done which makes this separation more explicit to research if different factors are more present and or have greater influence on smaller or larger intersections.

Looking at the data the discrepancy between the GPS measured distance and the distance calculated using the entry and exit point was larger than expected. This most likely has to do with larger inaccuracies at lower cycling speeds and the application being used in the background. Follow up research can be done in this phenomenon to find a way to register a more accurate crossing distance. Furthermore this research ended up focused mostly on the difference between the reference scenarios. Where the conclusion is that the entry speed scenario is significantly slower compared to the other two scenarios. During this research one of the points of interest was thinking about an alternative way of calculating the cycling delay. A combination of the average cycling speed and the entry speed over a longer distance might prove useful for this. Follow up research into this subject would be useful. Where the average speed of a cyclists is used as boundaries for the entry speed. And what the advantages and disadvantages to this could be.

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Appendix A Data transformation example

To clarify some steps of setting up the data for the research this appendix will show how the GPS data is transformed to directional data. For this example intersection 4 is used:

Kuipersdijk & Varviksingel*; located at 52.209432, 6.894812*

On this intersection there are a total of 13.534 registered intersection crossings. Of these, there are 124 that are dismissed due to incomplete or faulty registrations. For the examination of the other 13.410 intersection crossings, the GPS data points needed to be summarized into a more manageable system. For this purpose the points were matched to a node system. Figure 21 shows an example of the GPS positions of the entry and exit point of one intersection crossing. These positions were then matched both on the x and y-axis to the closest node point. Consequently this was done for all the data on all intersections. And with the resulting collection of node points could be compared to each other in a way that was more manageable then if the collection of GPS points was used for this purpose. Figure 22 shows some more node points on this intersection.

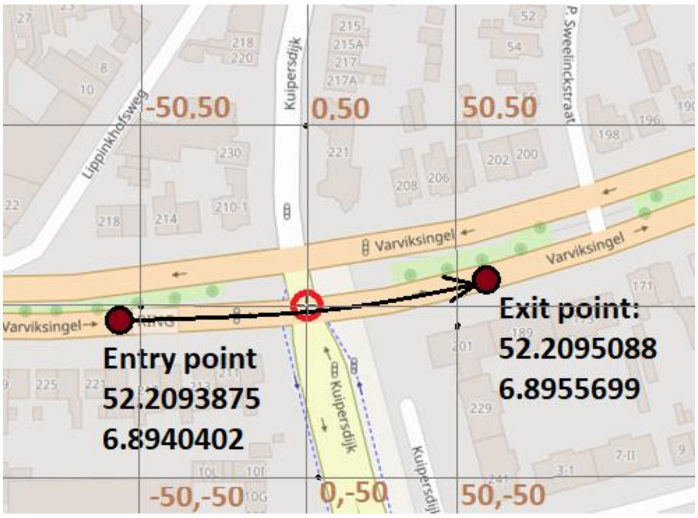

Figure 21: Example entry and exit points

For this intersection table 14 shows the pivot table of the resulting entry and exit nodes. For the entry there are 4 nodes with significant registrations. These are 0,100; 100,25; 25,-75; and -75,0. For the exit there are also 4 nodes with significant registrations. These are 0,100; 75,0; 0,-75 and -100,0. Figure 22 shows the relative position of the different nodes on the intersection. The entry and exit nodes share the same node in the North at 0,100. The other 3 directions they differ.

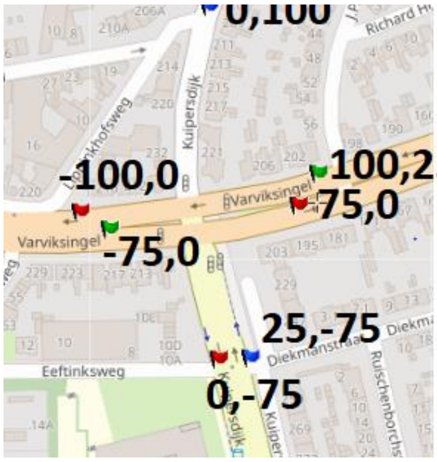

Figure 22: Example of the node system

Table 14: Pivot table all nodes intersection Kuipersdijk and Singel

	0 , 100	0 , 75	0 , -75	-100 , 0	100 , 25	25 , 100	25 , -75	75 , 0	-75 , 0	Total
0 , 100	2		3873	246	1		73	175	1	4371
0 , 25								1		1
0 , -75	9			1				3		13
-100 , 0	1			1	3		1			6
100 , 25	234		362	1401			4	1		2002
-175 , 75								1		1
25 , -75	3760		8	560	1	1		438		4768
250 , -300	1									1
75 , 0	2		1	2			1	1	1	8
-75 , 0	182	1	504	5	4		14	1529		2239
Grand Total	**4191**	**1**	**4748**	**2216**	**9**	**1**	**93**	**2149**	**2**	**13.410**

Limiting this overview to only the node points with counts over 20 and then assigning them the corresponding directions gives the results shown in table 15. The intersection crossings which have the same entry as exit direction are considered anomalies and not representing normal cycling behavior. For this reason they were not included for further analyses.

Table 15: Directional crossings filtered on nodes

	N	O	W	Z	Grand Total
N	2	175	246	3873	4296
O	234	1	1401	362	1998
W	182	1529	5	504	2220
Z	3760	438	560	8	4766
Grand Total	**4178**	**2143**	**2212**	**4747**	**13280**

This process was done for the other 8 intersections on the Singel as well.

Appendix B Intersections in detail

This appendix will discuss the 9 intersections on the Singel of Enschede in more detail. The position of the 9 intersections is again shown in figure 23 and table 16 shows both the pre and post-filter count of the registered intersection crossings in the database. Finally, the mean speed on the different intersections is calculated from the data of the different intersection crossings. The standard deviation of the mean speed is given in parentheses. The rest of this appendix discusses all 9 intersections in more detail. Showing delay data for the specific intersections as well as the delay when it is raining or dry and the different delays for trips with either the home or office as their destination.

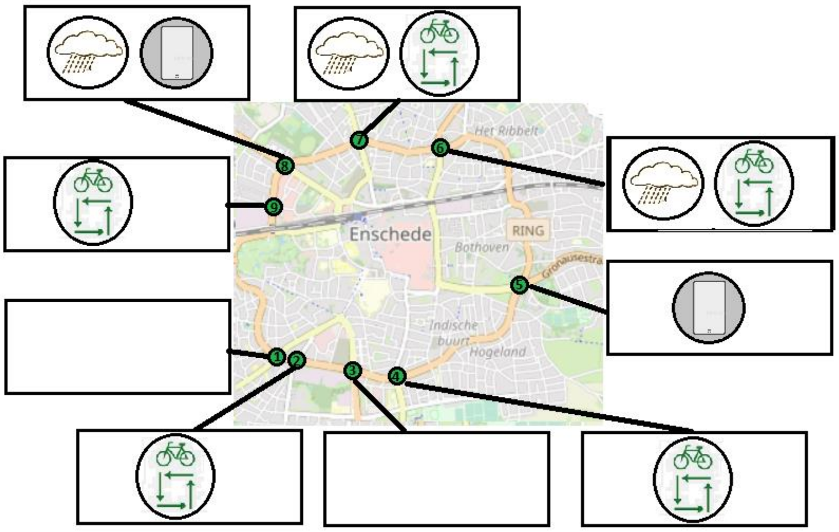

Figure 23: Location of intersections on the singel

Table 16: Intersections on the Singel of Enschede

	Intersection streets	Of interest	Pre filter count	Post filter count	Mean speed (std dev)
1.	Getfertsingel & Haaksbergerstraat		17.726	8.116	14,8 km/h (7,2)
2.	Broekheurnerweg & Burgemeester M van Veenlaan	All Cyclists Simultaneous Green	19.696	8.963	17,3 km/h (6,5)
3.	Getfertsingel & Varviksingel		9.155	3.514	16,2 km/h (8,3)
4.	Kuipersdijk & Varviksingel	All Cyclists Simultaneous Green	13.534	5.570	15,8 km/h (7,2)
5.	Boulevard 1945 & Gronausestraat	SMART integration	14.472	7.609	18,7 km/h (8,3)
6.	Laaressingel & Lasondersingel	Rain sensor All Cyclists Simultaneous Green	9.167	3.643	17,6 km/h (7,6)
7.	Boddenkampsingel & Deurningerstraat	Rain sensor All Cyclists Simultaneous Green	15.119	5.235	14,8 km/h (7,6)
8.	Boddenkampsingel & Hengelosestraat	Rain sensor SMART integration	28.877	12.768	16,6 km/h (7,6)
9.	Richtersweg & Schuttersveld	All Cyclists Simultaneous Green	13.405	4.928	16,9 km/h (7,2)

1. ***Getfertsingel & Haaksbergerstraat & Pathmossingel;*** *52.211192, 6.879437*

In total 17.726 intersection crossings are registered for this intersection. After filtering 8.116 valid intersection crossings are left which will be used for the different analysis. Filters out 54% of the intersection crossings. Furthermore, scenario 1 is left with 44% valid intersection crossings, scenario 2 with 43%, and scenario 3 with 32% of all intersection crossings for the final analysis. At a mean intersection speed of 14,8 km/h this intersection has a relatively low crossing speed for the cyclists.

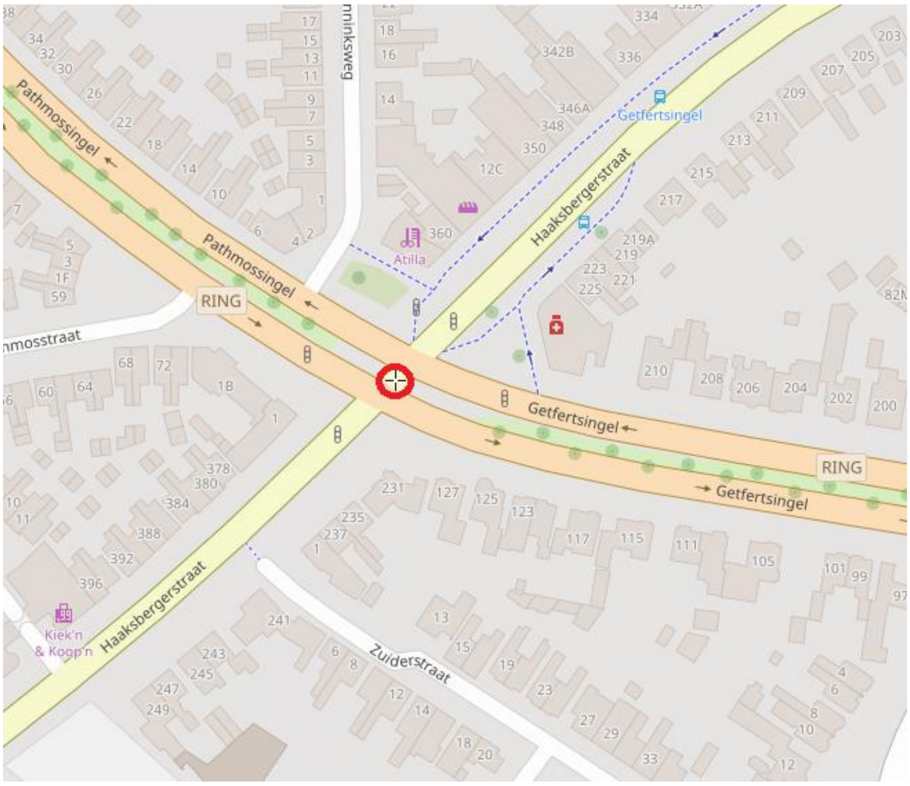

Figure 24: Intersection 1 Haaksbergerstraat with Singel

For directions the Haaksbergerstraat will be considered the North to South connection, and the Pathmossingel will be considered the West with the Getfertsingel on the East. This intersection does not posses any special features for this research. The North and West side have a high separation between traffic, and the East and South side have a moderate amount of separation between traffic.

Table 17 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 17: Speed and delay at intersection 1 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	1810	20,1 km/h	19,2 s
	5181	20,3 km/h	22,6 s
	801	20,5 km/h	24,0 s
2: Time of Day speed and delay	1670	20,4 km/h	19,7 s
	5197	20,4 km/h	22,5 s
	778	20,8 km/h	24,2 s
3: Entry speed and delay	1182	17,6 km/h	13,6 s
	4020	18,4 km/h	18,3 s
	473	17,0 km/h	16,4 s

*2. **Broekheurnerweg & Burgemeester M van Veenlaan & Getfertsingel;** 52.210858, 6.881835*

In total 19.696 intersection crossings are registered for this intersection. After filtering 8.963 valid intersection crossings are left over. This equals a decrease of 54%. With a mean intersection speed of 17,3 km/h this intersection is on the higher end.

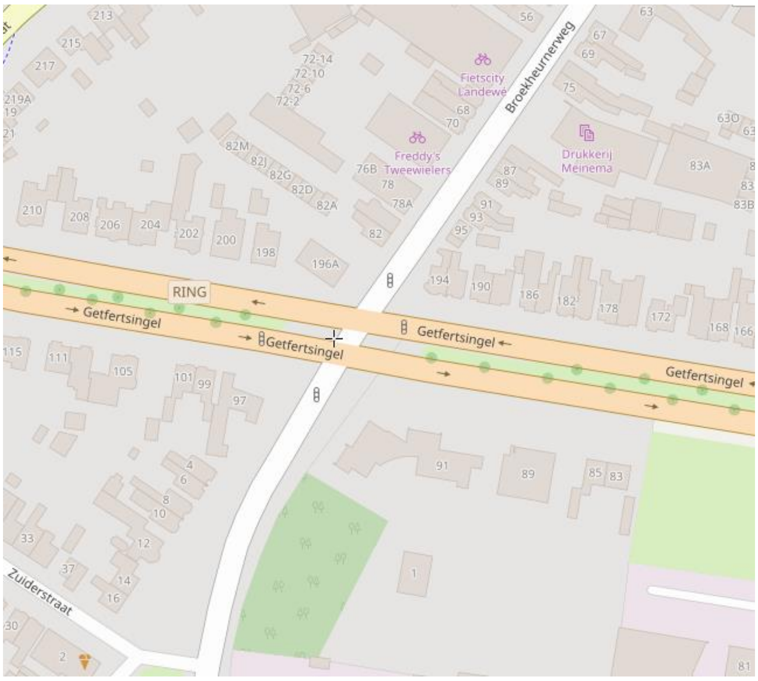

Figure 25: Intersection 2. Broekheurnerweg & Burgemeester M van Veenlaan

For directions the Broekheurnerweg will be considered the North to South connection, and the Getfertsingel will be considered for the West to East connection. This intersection does have the All Cyclists Simultaneous Green measure, but no other special features. The North and South approaches have some separation between traffic, and the West and East have no real separation of traffic.

Table 18 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 18: Speed and delay at intersection 2 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	677	20,3 km/h	15,5 s
	7220	20,0 km/h	16,8 s
	788	20,3 km/h	22,7 s
2: Time of Day speed and delay	603	20,7 km/h	15,6 s
	7213	20,0 km/h	16,5 s
	783	20,7 km/h	23,3 s
3: Entry speed and delay	454	17,3 km/h	8,5 s
	5473	18,2 km/h	13,0 s
	547	17,4 km/h	15,8 s

*3. **Getfertsingel & Varviksingel & Zuiderval;** 52.210093, 6.889243*

In total 9.155 intersection crossings are registered for this intersection. After filtering 3.514 valid intersection crossings are left over. This means a reduction of 62%. With a mean intersection speed of 16,2 km/h this intersection is somewhere in the middle.

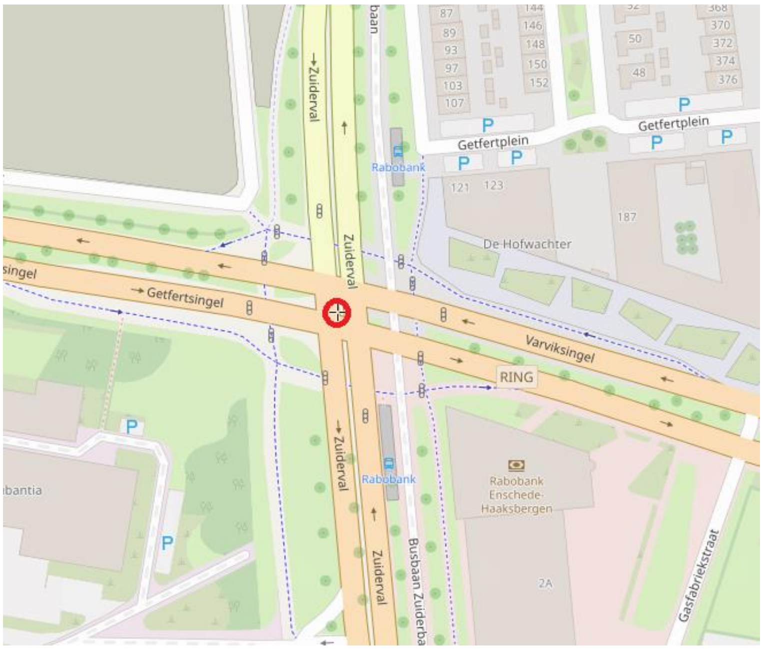

Figure 26: Intersection 3. Getfertsingel & Varviksingel

For directions the Zuiderval will be considered the North to South connection, the Getfertsingel will be considered the West and the Varviksingel will be considered to be on the East. This intersection does not have any particular features of interest to this research. All 4 approaches to the intersection show high amounts of separation between traffic.

Table 19 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 19: Speed and delay at intersection 3 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	1815	20,4 km/h	23,9 s
	651	21,0 km/h	22,0 s
	708	20,2 km/h	26,3 s
2: Time of Day speed and delay	1747	20,6 km/h	23,8 s
	846	22,1 km/h	21,9 s
	711	20,2 km/h	26,0 s
3: Entry speed and delay	1235	18,3 km/h	21,5 s
	566	19,1 km/h	18,3 s
	462	18,6 km/h	21,9 s

*4. **Kuipersdijk & Varviksingel;** 52.209432, 6.894812*

In total 13.534 intersection crossings are registered for this intersection. After filtering 5.570 valid intersection crossings are left over. This means a reduction of 59%. With a mean intersection speed of 15,9 km/h this intersection is in the middle group.

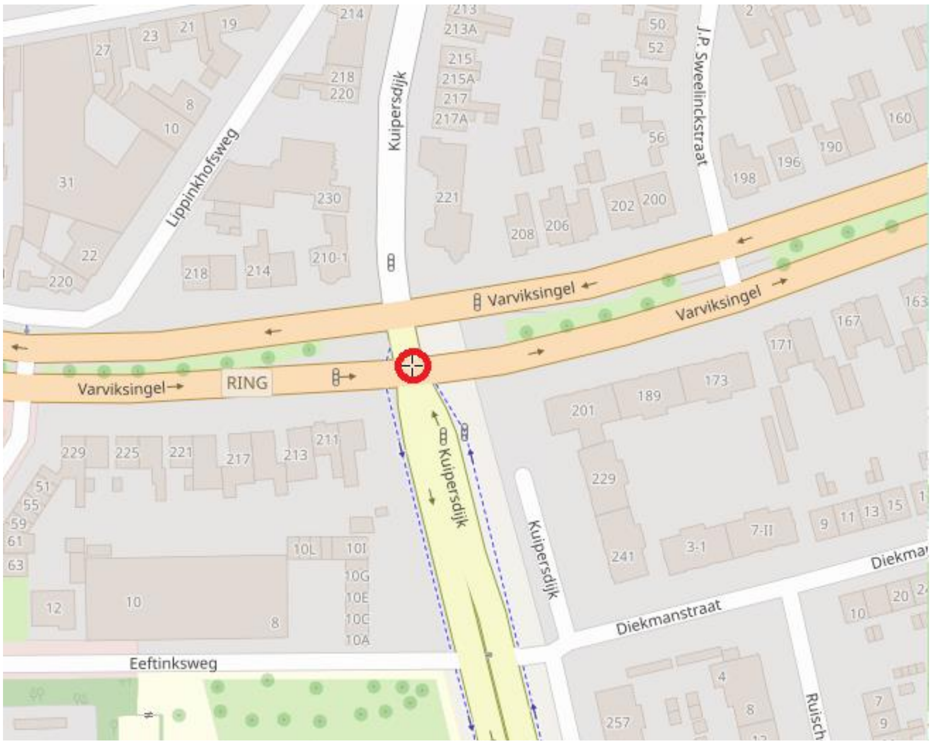

Figure 27: Intersection 4. Kuipersdijk & Varviksingel

For directions the Kuipersdijk will be considered the North to South connection, the Varviksingel will be considered the West and the East. This intersection has the All Cyclists simultaneous green measure, but no other special feature. The East, West and North side have moderate separations between traffic. And the South and has a high separation of traffic.

Table 20 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 20: Speed and delay at intersection 4 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	1515	20,3 km/h	17,2 s
	3237	19,9 km/h	20,9 s
	575	20,2 km/h	19,8 s
2: Time of Day speed and delay	1441	20,6 km/h	17,3 s
	3217	20,0 km/h	21,1 s
	577	20,0 km/h	19,9 s
3: Entry speed and delay	1005	18,0 km/h	12,6 s
	2429	18,3 km/h	16,4 s
	389	17,5 km/h	12,8 s

5. Boulevard 1945 & Gronausestraat & Hogelandsingel & Oliemolensingel; 52.216837, 6.910879

In total 14.472 intersection crossings are registered for this intersection. After filtering 7.609 valid intersection crossings are left over. This equals a change of 47%. With a mean intersection speed of 18,7 km/h this intersection is on the higher end.

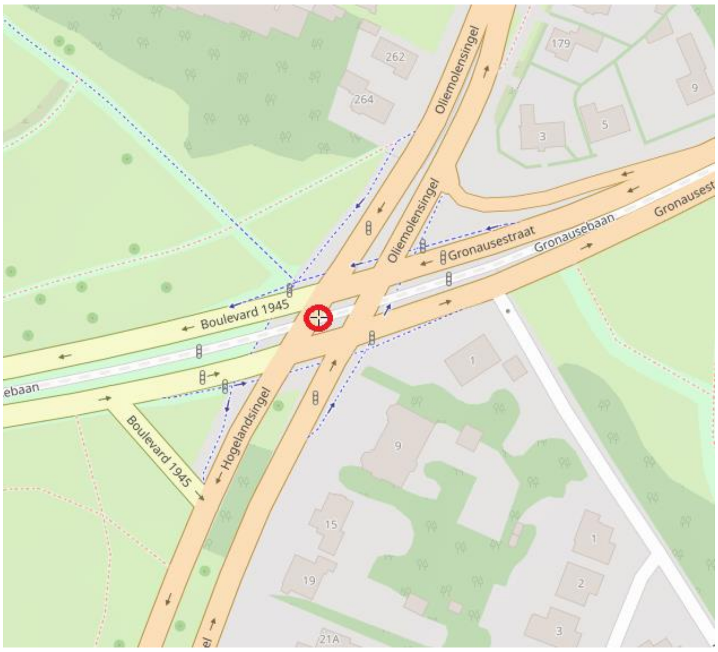

Figure 28: Intersection 5. Boulevard 1945 & Gronausestraat

For directions the Oliemolensingel will be considered the North side, Hogelandsingel will be South, the Boulevard 1945 will be considered on the West and the gronausestraat will be considered to be on the East. This intersection does is integrated with the SMART application. The North and East approach have haigh separations of traffic, the West has a moderate separation and the South has some separation of traffic.

Table 21 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 21: Speed and delay at intersection 5 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	1618	20,2 km/h	19,7 s
	4816	20,8 km/h	9,2 s
	653	20,6 km/h	28,0 s
2: Time of Day speed and delay	1611	20,3 km/h	19,5 s
	4806	20,9 km/h	9,3 s
	641	20,1 km/h	27,3 s
3: Entry speed and delay	1180	19,5 km/h	18,1 s
	3141	19,5 km/h	7,1 s
	424	17,9 km/h	21,2 s

6. ***Laaressingel & Lasondersingel & Oldenzaalsestraat;*** *52.227756, 6.900373*
All cyclists simultaneous green

In total 9.167 intersection crossings are registered for this intersection. After filtering 3.643 valid intersection crossings are left over. This equals a reduction of 60. With a mean intersection speed of 17,6 km/h this intersection is on the higher end.

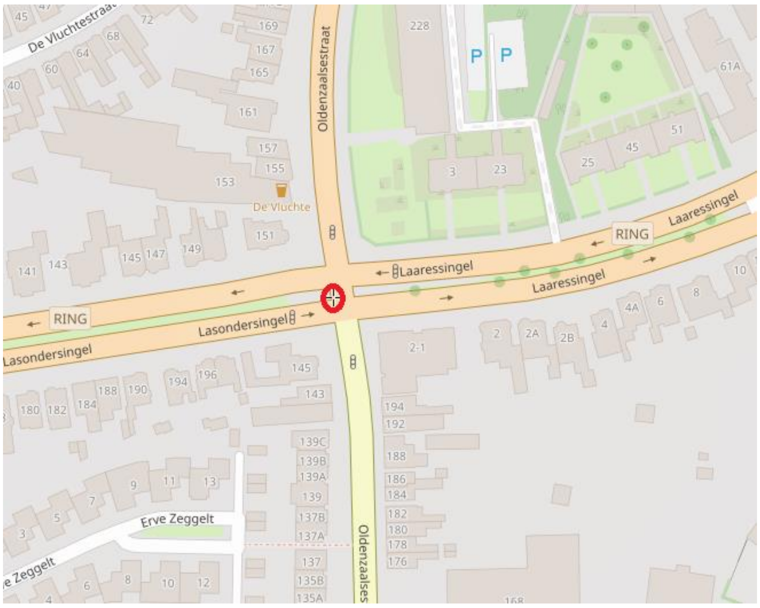

Figure 29: Intersection 6. Laaressingel & Lasondersingel

For directions the Oldenzaalsestraat will be considered the North to South connection, the Lasondersingel will be considered the on West and the Laaressingel will be considered to be on the East. This intersection has the All Cyclists simultaneous green measure and integrated rain sensors. The West side of the intersection has a moderate separation of traffic, the East side has some separation, and the North and South side have no real separation of traffic.

Table 22 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 22: Speed and delay at intersection 6 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	885	19,9 km/h	13,1 s
	2130	20,4 km/h	17,8 s
	335	19,1 km/h	16,8 s
2: Time of Day speed and delay	864	20,0 km/h	13,1 s
	2131	20,2 km/h	17,3 s
	300	19,7 km/h	17,9 s
3: Entry speed and delay	654	18,8 km/h	10,2 s
	1677	18,9 km/h	13,8 s
	224	18,0 km/h	11,5 s

*7. **Boddenkampsingel & Deurningerstraat & Lasondersingel;** 52.228442, 6.889961*

In total 15.119 intersection crossings are registered for this intersection. After filtering 5.235 valid intersection crossings are left over. This equals a reduction of 65% . With a mean intersection speed of 16,6 km/h this intersection is in the middle group.

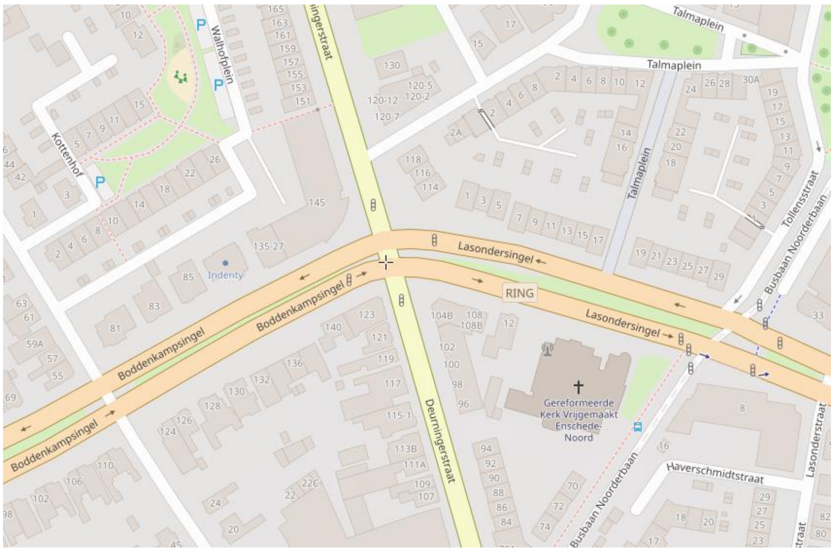

Figure 30: Intersection 7. Boddenkampsingel & Deurningerstraat

For directions the Deurningerstraat will be considered the North to South connection, the Boddenkampsingel will be considered the West and the Lassondersingel will be considered to be on the East. This intersection has the All Cyclists simultaneous green measure as well as integrated rain sensors. All approaches to the intersection have some separations between traffic.

Table 23 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario’s.

Table 23: Speed and delay at intersection 7 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	1875	20,1 km/h	18,0 s
	2378	19,7 km/h	23,9 s
	751	20,0 km/h	27,7 s
2: Time of Day speed and delay	1844	19,9 km/h	17,8 s
	2334	20,1 km/h	24,4 s
	742	20,0 km/h	27,3 s
3: Entry speed and delay	1329	17,7 km/h	11,8 s
	1566	16,8 km/h	17,2 s
	474	17,3 km/h	20,2 s

8. Boddenkampsingel & Hengelosestraat & Tubantiasingel;
52.226293, 6.880557

In total 28.877 intersection crossings are registered for this intersection. After filtering 12.768 valid intersection crossings are left for further analyses. This is a reduction of 56%. At a mean intersection speed of 16,6 km/h this intersection is in the middle group.

Figure 31: Intersection 8. Boddenkampsingel & Hengelosestraat

For directions the Boddenkampsingel will be considered the North, the Tubantiasingel will be the South connection, and the Hengelosestraat will be considered the West to East connection. This intersection does not have the All Cyclists simultaneous green measure, but it does have both integrated rain sensors as well as integration to the SMART application. The North and East approach to this intersection have moderate separations of traffic, and the West and South side have some separation of traffic.

Table 23 shows the overall delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 24: Speed and delay at intersection 8 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	2836	20,3 km/h	17,7 s
	8021	20,3 km/h	15,6 s
	1570	20,1 km/h	24,3 s
2: Time of Day speed and delay	2771	20,1 km/h	17,4 s
	8056	20,7 km/h	16,0 s
	1558	20,1 km/h	24,3 s
3: Entry speed and delay	1931	18,4 km/h	13,6 s
	5592	18,6 km/h	11,6 s
	1009	17,9 km/h	19,2 s

9. *Richtersweg & Schuttersveld & Tubantiasingel;*

52.223104, 6.878632

In total 13.405 intersection crossings are registered for this intersection. After filtering 4.928 valid intersection crossings are left over for analysis. This equals a reduction of 54%. At a mean intersection speed of 16,9 km/h this intersection is on part of the middle group.

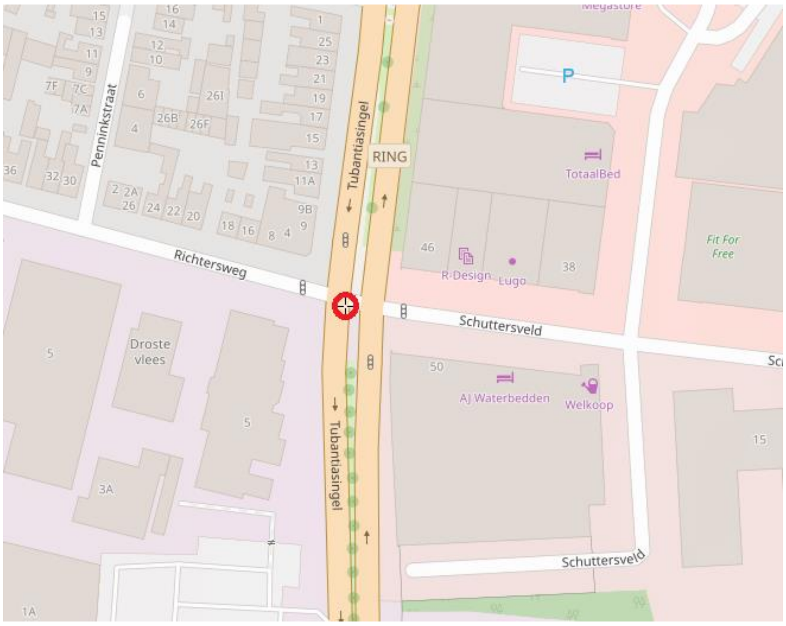

Figure 32: Intersection 9. Richtersweg & Schuttersveld

For directions the Tubantiasingel will be considered the North to South connection, the Richtersweg will be considered the West and the Schuttersveld will be considered to be on the East. This intersection does have the All Cyclists simultaneous green measure but no other features of interest for this research. The North, West and East side do not have any real separation between traffic. And the South approach has some separation of traffic.

Table 25 shows the overall reference speed and delay at this signalized intersection in the 3 different categories that cyclists can cross it. The delay is shown for all 3 reference scenario's.

Table 25: Speed and delay at intersection 9 in different directions

Scenario	Count	speed	Delay
1: Cyclist speed and delay	3175	20,4 km/h	13,8 s
	333	20,4 km/h	25,0 s
	1156	20,2 km/h	23,4 s
2: Time of Day speed and delay	3161	20,3 km/h	13,7 s
	332	20,3 km/h	24,7 s
	1196	20,4 km/h	23,2 s
3: Entry speed and delay	2186	18,4 km/h	10,4 s
	217	16,9 km/h	11,5 s
	680	17,6 km/h	13,7 s

Appendix C Overview of the four variables

In this appendix an overview of the calculated delay for the 3 different reference scenarios is presented. The count, mean and standard deviation on all 9 intersections are calculated and tabulated. Overviews based on the four chosen variables are shown in this chapter. Even though the final analysis does not use data from the second scenario: Time of Day the results of the different delay calculations will be presented in this chapter. Data from the tables of this appendix is used in Chapter 4.

Trip purpose.

Table 26: Scenario 1 Cyclist delay; Trip purpose

Scenario 1: Cyclist delay			
Intersection		Home	Office
1	Count	3216	1832
	Mean (SD)	24 s (25,5)	19,2 s (21,1)
2	Count	3265	1816
	Mean (SD)	19 s (21,2)	14,3 s (17,6)
3	Count	1241	549
	Mean (SD)	23,6 s (26,5)	24,9 s (28)
4	Count	1996	1084
	Mean (SD)	20,9 s (23)	17,7 s (20,6)
5	Count	2473	1936
	Mean (SD)	14,4 s (21)	10,6 s (16,9)
6	Count	901	821
	Mean (SD)	18,3 s (20,6)	13,7 s (19,2)
7	Count	1551	1019
	Mean (SD)	22,4 s (23,9)	20,5 s (21,3)
8	Count	3351	3513
	Mean (SD)	17 s (20,3)	15,9 s (19,2)
9	Count	2022	870
	Mean (SD)	18,9 s (20,9)	11,4 s (15,8)

Table 27: Scenario 2 Time of Day delay; Trip purpose

Scenario 2: Time of Day delay			
Intersection		Home	Office
1	Count	3135	1775
	Mean (SD)	24,3 s (25,6)	19 s (21,2)
2	Count	3164	1846
	Mean (SD)	19 s (21,2)	13,8 s (17,6)
3	Count	1265	652
	Mean (SD)	22,8 s (25,7)	24,8 s (26,9)
4	Count	1917	1071

	Mean (SD)	21,2 s (23,2)	18 s (20,7)
5	Count	2479	1922
	Mean (SD)	14,2 s (20,8)	10,8 s (16,9)
6	Count	899	792
	Mean (SD)	17,8 s (20,4)	13,5 s (19,3)
7	Count	1537	974
	Mean (SD)	22,3 s (23,7)	21 s (21,3)
8	Count	3334	3479
	Mean (SD)	16,9 s (20,4)	16,3 s (19,3)
9	Count	2053	845
	Mean (SD)	18,8 s (21)	11 s (15,5)

Table 28: Scenario 3 Entry delay; Trip purpose

Scenario 3: Entry delay			
Intersection		Home	Office
1	Count	2397	1328
	Mean (SD)	19,7 s (24,4)	14,1 s (20,2)
2	Count	2547	1346
	Mean (SD)	16 s (19,9)	8,1 s (13,9)
3	Count	931	394
	Mean (SD)	20,8 s (25,2)	20,8 s (26,6)
4	Count	1505	764
	Mean (SD)	16 s (21,1)	14,6 s (19,7)
5	Count	1779	1178
	Mean (SD)	11,4 s (18,7)	10 s (17)
6	Count	690	683
	Mean (SD)	14,4 s (17,9)	10,6 s (16,8)
7	Count	1057	654
	Mean (SD)	15,9 s (22)	12,8 s (18,1)
8	Count	2233	2446
	Mean (SD)	12,7 s (18,3)	12,1 s (17,7)
9	Count	1325	589
	Mean (SD)	13 s (17,9)	8 s (13,6)

Rain

Table 29: Scenario1 Cyclist delay; Raining/ not raining

Scenario 1: Cyclist delay			
Intersection		raining	not raining
1	Count	7093	601
	Mean (SD)	21,9 s (23,8)	22,2 s (24,3)
2	Count	7936	607
	Mean (SD)	17,3 s (20,2)	16,3 s (19,7)
3	Count	2910	227
	Mean (SD)	24 s (26,6)	25,9 s (27,5)
4	Count	4905	349
	Mean (SD)	19,7 s (21,9)	20,5 s (23,1)
5	Count	6524	470
	Mean (SD)	13,3 s (19,6)	13,9 s (20,3)
6	Count	3094	213
	Mean (SD)	16,4 s (20,1)	16,8 s (20,9)
7	Count	4611	335
	Mean (SD)	22,3 s (23,3)	21,6 s (23,1)
8	Count	11418	861
	Mean (SD)	17,2 s (20,3)	17 s (20,2)
9	Count	4270	329
	Mean (SD)	17 s (20,1)	15,9 s (19)

Table 30: Scenario 2 Time of Day delay; Raining/ not raining

Scenario 2: Time of Day delay			
Intersection		raining	not raining
1	Count	6962	587
	Mean (SD)	22 s (23,9)	22,6 s (24,6)
2	Count	7856	603
	Mean (SD)	17,1 s (20,2)	16,3 s (19,8)
3	Count	3033	233
	Mean (SD)	23,8 s (26)	24,1 s (25,9)
4	Count	4825	340
	Mean (SD)	19,8 s (22,0)	20,9 s (23,6)
5	Count	6497	474
	Mean (SD)	13,2 s (19,5)	14,2 s (21)
6	Count	3039	214
	Mean (SD)	16,1 s (19,9)	16,9 s (21,8)

7	Count	4534	330
	Mean (SD)	22,4 s (23,2)	21,3 s (22,4)
8	Count	11370	868
	Mean (SD)	17,4 s (20,4)	17,1 s (20,2)
9	Count	4300	327
	Mean (SD)	16,9 s (20,2)	15,6 s (19)

Table 31: Scenario3 Entry delay; Raining/ not raining

Scenario 3: Entry delay			
Intersection		raining	not raining
1	Count	5165	435
	Mean (SD)	17 s (22,7)	17,3 s (22,6)
2	Count	5928	442
	Mean (SD)	13 s (18,3)	11,7 s (17,5)
3	Count	2095	144
	Mean (SD)	20,8 s (25,5)	22,6 s (28,3)
4	Count	3525	247
	Mean (SD)	15,2 s (20,3)	13,2 s (20,1)
5	Count	4366	319
	Mean (SD)	11 s (18)	12,2 s (19,8)
6	Count	2372	158
	Mean (SD)	12,7 s (17,8)	12,6 s (17)
7	Count	3102	224
	Mean (SD)	15,5 s (21,3)	15,9 s (20,7)
8	Count	7835	598
	Mean (SD)	13 s (18,5)	11,8 s (17,9)
9	Count	2815	229
	Mean (SD)	11,2 s (16,4)	11,3 s (17,3)

Separation of traffic.

Table 32: Count and delay for no separation

Refence speed	Count no separation	No separation Mean (SD)
Cyclist delay	4846	18,2 s (21,1)
ToD delay	4792	18,1 s (21,3)
Entry delay	3303	11,6 s (17,2)

Table 33: Count and delay for some separation

Refence speed	Count some separation	some separation Mean (SD)
Cyclist delay	26391	18,8 s (21,2)
ToD delay	26078	18,7 s (21,2)
Entry delay	18642	14,0 s (19,3)

Table 34: Count and delay for moderate separation

Refence speed	Count moderate separation	moderate separation Mean (SD)
Cyclist delay	13702	16,7 s (20,9)
ToD delay	13750	16,9 s (21,0)
Entry delay	9752	12,4 s (18,8)

Table 35: Count and delay for high separation

Refence speed	Count High separation	High separation Mean (SD)
Cyclist delay	12571	19,4 s (23,7)
ToD delay	12510	19,5 s (23,6)
Entry delay	8822	16,7 s (22,8)

It is not really feasible to look at the delay for different separations at different intersections. For this reason the choice is made to look at the different intersection directions instead.

Table 36: Scenario 1 Cyclist delay; Separation of traffic

Scenario 1: Cyclist delay					
Direction		No	Some	Moderate	High
Straight	Count	2324	7992	2205	3685
	Mean (SD)	14,9 s (18,3)	17,1 s (20)	18,4 s (21,3)	20,2 s (23,5)
Perpendicular	Count	1402	15424	9841	7300
	Mean (SD)	19 s (22,1)	18,8 s (21,1)	14,9 s (19,3)	17,7 s (22,8)
Left turning	Count	1120	2975	1656	1586
	Mean (SD)	23,8 s (23,8)	23,1 s (24,2)	24,9 s (26,9)	25,5 s (26,9)

Table 37: Scenario 2 Time of Day delay; Separation of traffic

	Scenario 2: Time of Day delay				
Direction		No	Some	Moderate	High
Straight	Count	2228	7815	2165	3504
	Mean (SD)	14,7 s (18,2)	16,9 s (20)	18,3 s (21,3)	20,2 s (23,5)
Perpendicular	Count	1407,00	15348	9945	7432
	Mean (SD)	18,7 s (22,2)	18,7 s (21,1)	15,2 s (19,4)	18 s (22,8)
Left turning	Count	1157	2915	1640	1574
	Mean (SD)	23,8 s (24,1)	23,3 s (24,1)	25 s (27,1)	25 s (26,5)

Table 38: Scenario 3 Entry delay; Separation of traffic

	Scenario 3: Entry delay				
Direction		No	Some	Moderate	High
Straight	Count	1623	5508	1461	2564
	Mean (SD)	10,3 s (15,8)	12,7 s (18,4)	13,9 s (19,1)	17,3 s (22,7)
Perpendicular	Count	1023	11222	7213	5223
	Mean (SD)	12,7 s (17,5)	14,2 s (19,3)	11,2 s (17,5)	15,8 s (22,1)
Left turning	Count	657	1912	1078	1035
	Mean (SD)	13,4 s (19,7)	16,6 s (21,2)	18,5 s (24,7)	20,1 s (25,8)

All cyclists simultaneous green

Table 39: Count and mean delay All Cyclists Simultaneous Green

Refence speed	Count ACSG	ACSG Mean (Std dev)	Count no ACSG	No ACSG Mean (Std dev)
Cyclist delay	27.030	18,2 s (22,1)	30.480	18,5 s (21,2)
ToD delay	26.738	18,3 s (22,2)	30.392	18,5 s (21,3)
Entry delay	19.304	13,5 s (19,0)	21.215	14,5 s (20,7)

Appendix D SPSS results and tables

To not clutter the main reporting with every table from SPSS this appendix is used to show all of them. The results of these analyses are discussed in Chapter 5.

Trip purpose

The *first* hypothesis tests if the delay for trips with either the office or home as their destination have different delays. In this analysis the dependent variable is continuous (Delay), and the independent variable has 2 categories (Destination; office/home). For these reasons the Mann Whitney U test was used. For this analysis all intersections are used, but only intersection crossings that are part of trips with either the Home or Office as their trip purpose are selected.

Trip purpose; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections with the *Office* as their destination in the Cyclists Speed scenario (Mdn = 7,7) had a shorter delay than cyclists crossing intersections with their *Home* as their destination (Mdn = 11,7) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{Office} = 13440; N_{Home}= 20016) = 121358591,5; z = -15,3; p < ,001

Effect size: $\eta^2 = \frac{Z^2}{N-1} = 0{,}007$

Trip purpose; Entry Delay: Mann-Whitney:

Cyclists crossing intersections with the *Office* as their destination in the Entry Speed scenario (Mdn = 1,8) had a shorter delay than cyclists crossing intersections with their *Home* as their destination (Mdn = 5,3) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{Office} = 9382; N_{Home}= 14464) = 60809806,5; z = -13,9; p < .001

Effect size: $\eta^2 = \frac{Z^2}{N-1} = 0{,}008$

Rain

The *second* hypothesis tests if there is a difference in delay at 3 specific intersections with integrated rain sensors when it is either raining or dry. In this analysis the dependent variable is continuous (delay) and the independent variable has two categories (raining/ not raining). For these reasons the Mann Whitney U test was used. The test was done for both reference scenarios at every hour between 07.00 and 19.00. For scenario 1 3 intervals were found with statistical differences. These were between 07.00-08.00 & 09.00-10.00 & 15.00 & 16.00. And for scenario 3 the only significant difference was found between 15.00 and 16.00.

Raining; between 07.00 and 08.00; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections with rain sensors between 07.00 and 08.00 when it was raining in the Cyclists Speed scenario (Mdn = 9,6) had a shorter delay than cyclists crossing intersections with rain sensors when it was dry (Mdn = 16,6) A Mann-Whitney test indicated that this difference was statistically significant, U($N_{Raining}$ = 166; N_{Dry}=2194) = 157423; z = -2,946; p = ,003

Effect size: $\eta^2 = \frac{Z^2}{N-1} = 0{,}004$

Raining; between 09.00 and 10.00; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections with rain sensors between 09.00 and 10.00 when it was raining in the Cyclists Speed scenario (Mdn = 4,9) had a shorter delay than cyclists crossing intersections with rain sensors when it was dry (Mdn = 10,1) A Mann-Whitney test indicated that this difference was statistically significant, U($N_{Raining}$ =121; N_{Dry}=1494) = 79194,5; z = -2,300; p = ,021

Effect size: $\eta^2 = \frac{Z^2}{N-1} = 0,003$

Raining; between 15.00 and 16.00; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections with rain sensors between 15.00 and 16.00 when it was raining in the Cyclists Speed scenario (Mdn = 5,1) had a shorter delay than cyclists crossing intersections with rain sensors when it was dry (Mdn =11,1) A Mann-Whitney test indicated that this difference was statistically significant, U($N_{Raining}$ = 80; N_{Dry}=1333) = 44468,0; z =-2,527; p = ,012

Effect size: $\eta^2 = \frac{Z^2}{N-1} = 0,005$

Raining; between 15.00 and 16.00; Entry delay: Mann-Whitney:

Cyclists crossing intersections with rain sensors between 15.00 and 16.00 when it was raining in the Entry Speed scenario (Mdn = 0,1) had a shorter delay than cyclists crossing intersections with rain sensors when it was dry (Mdn =2,6) A Mann-Whitney test indicated that this difference was statistically significant, U($N_{Raining}$ = 54; N_{Dry}=890) =20186,0; z =-2,044; p = ,041

Effect size: $\eta^2 = \frac{Z^2}{N-1} = 0,004$

Separation of traffic

For the third hypothesis is about the influence of separation between cyclists and cars is tested. In this analysis the dependent variable is continuous (Delay), and the independent variable has 4 categories (No separation, some separation, moderate separation and high separation). For these reasons the Kruskal Wallis test was used for these analysis. The results of the Kruskal Wallis test showed significant differences between the groups for both the Cyclist delay (H(3) = 154,12 p < ,001) and the Entry Delay (H(3) = 230,01, p < ,001)

From the follow up Mann-Whitney U tests significant differences were found between

- Cyclist delay:
  group 1 and 3; group 2 and 3; group 2 and 4, and group 3 and 4.
- Entry delay:
  group 1 and 2; group 1 and 4; group 2 and 3; group 2 and 4, and group 3 and 4.

Cyclist delay separation of traffic

No significant difference between group 1: No separation and group 2: some separation was found:
Mann-Whitney U : (U= 62850164,0, z = -1,92 p = ,055)

Significant difference between group 1: No separation and group 3: Moderate separation was found:
Mann-Whitney U : (U= 31261816,0, z = -6,13 p < ,001)

No significant difference between group 1: No separation and group 4: High separation was found: Mann-Whitney U : (U= 30403529,5, z = -,18 p = ,849)

Significant difference between group 2: some separation and group 3: Moderate separation was found: Mann-Whitney U : (U= 167319905,5, z = -12,40 p < ,001)

Significant difference between group 2: some separation and group 4: High separation was found: Mann-Whitney U : (U= 162877446,0, z = -2,92 p = ,003)

Significant difference between group 3: Moderate separation and group 4: High separation was found: Mann-Whitney U : (U=81452200,5, z = -7,71 p < ,001)

Entry delay separation of traffic

Significant difference between group 1: No separation and group 2: some separation was found: Mann-Whitney U : (U= 28754418,5, z = -6,24 p < ,001)

No significant difference between group 1: No separation and group 3: Moderate separation was found: Mann-Whitney U : (U= 15975946,5, z = -,72 p= ,473)

Significant difference between group 1: No separation and group 4: High separation was found: Mann-Whitney U : (U= 12787149, z = -10,63 p < ,001)

Significant difference between group 2: some separation and group 3: Moderate separation was found: Mann-Whitney U : (U= 85695017,0, z = -8,18 p < ,001)

Significant difference between group 2: some separation and group 4: High separation was found: Mann Whitney U : (U=77571978,5, z = -7,78 p < ,001)

Significant difference between group 3: Moderate separation and group 4: High separation was found: Mann-Whitney U : (U=38134839,5, z = -13,74 p < ,001)

All cyclists simultaneous green

The fourth hypothesis is about testing data from a traffic light with and without the All Cyclists Simultaneous Green measure (ACSG). The data is non-parametric, the dependent variable (Delay) is continuous and the independent variable (ACSG) has 2 categories. For these reasons the Mann-Whitney U test is used. Intersections 1, 3, 5 and 8 are grouped as not having ACSG and intersections 2, 4, 6, 7 and 9 are grouped as having ACSG.

ACSG; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections *with ACGS* in the Cyclists Speed scenario (Mdn = 11,4) had a longer delay than cyclists crossing intersections *without the ACGS* measure (Mdn =9,5) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 27030; $N_{Non\text{-}ACGS}$= 30480) = 40029817,0, z = -5,923; p < ,001

Effect size: $\boldsymbol{\eta^2} = \frac{Z^2}{N-1}$ = 0,001

ACSG; Entry Delay: Mann-Whitney:

Cyclists crossing intersections *with ACGS* in the Entry Speed scenario (Mdn = 3,6) had a longer delay than cyclists crossing intersections *without the ACGS* measure (Mdn =3,3) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 19304; $N_{Non\text{-}ACGS}$= 21215) = 201280527,0, z = -3,049; p = ,002

Effect size: $\boldsymbol{\eta^2} = \frac{Z^2}{N-1}$ = 0,000

Furthermore these tests are also done per directional group. Starting with group 1: Straight ahead.

ACSG, straight ahead; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections straight ahead *with ACGS* in the Cyclists Speed scenario (Mdn = 8,1) had a shorter delay than cyclists crossing intersections straight ahead *without the ACGS* measure (Mdn = 12,3) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 8127; $N_{Non\text{-}ACGS}$= 8079) = 28998272,0, z = -12,997; p < ,001

Effect size: $\eta^2 = \frac{Z^2}{N-1}$ = 0,010

ACSG, *straight ahead*; Entry Delay: Mann-Whitney:

Cyclists crossing intersections straight ahead *with ACGS* in the Entry Speed scenario (Mdn = 1,2) had a shorter delay than cyclists crossing intersections straight ahead *without the ACGS* measure (Mdn = 6,7) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 5628; $N_{Non\text{-}ACGS}$= 5528) = 13128383,5, z = -14,675; p < ,001

Effect size: $\eta^2 = \frac{Z^2}{N-1}$ = 0,019

ACSG, *perpendicular*; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections in a perpendicular fashion *with ACGS* in the Cyclists Speed scenario (Mdn = 12,1) had a longer delay than cyclists crossing intersections in a perpendicular fashion *without the ACGS* measure (Mdn = 6,8) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 15298; $N_{Non\text{-}ACGS}$= 18669) = 127891569,0, z = -16,798; p < ,001

Effect size: $\eta^2 = \frac{Z^2}{N-1}$ = 0,008

ACSG, *perpendicular*; Entry Delay: Mann-Whitney:

Cyclists crossing intersections in a perpendicular fashion *with ACGS* in the Entry Speed scenario (Mdn = 5,0) had a longer delay than cyclists crossing intersections in a perpendicular fashion *without the ACGS* measure (Mdn = 2,0) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 11362; $N_{Non\text{-}ACGS}$= 13319) = 71469883,5, z = -7,743; p < ,001

Effect size: $\eta^2 = \frac{Z^2}{N-1}$ = 0,002

ACSG, *left turning*; Cyclist delay: Mann-Whitney:

Cyclists crossing intersections to the left *with ACGS* in the Cyclists Speed scenario (Mdn = 16,3) had a shorter delay than cyclists crossing intersections to the left *without the ACGS* measure (Mdn = 17,6) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 3605; $N_{Non\text{-}ACGS}$= 3732) = 6544948,5, z = -2,016; p = ,044

Effect size: $\eta^2 = \frac{Z^2}{N-1}$ = 0,001

ACSG, *left turning*; Entry Delay: Mann-Whitney:

Cyclists crossing intersections to the left *with ACGS* in the Entry Speed scenario (Mdn = 5,2) had a shorter delay than cyclists crossing intersections to the left *without the ACGS* measure (Mdn = 7,3) A Mann-Whitney test indicated that this difference was statistically significant, U(N_{ACGS} = 2314; $N_{Non\text{-}ACGS}$= 2368) = 2529829,5, z = -4,641; p < ,001

Effect size: $\eta^2 = \frac{Z^2}{N-1}$ = 0,005