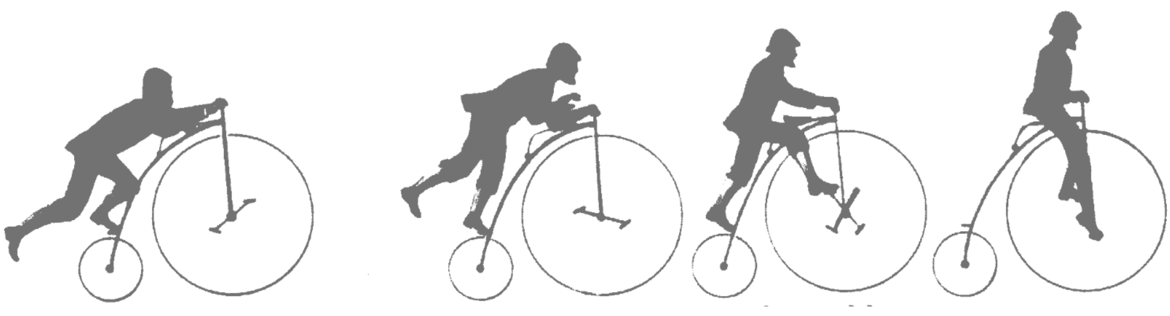
THE START-UP LOSS TIME OF CYCLIST AT A SIGNALIZED INTERSECTION



ROBIN DISSEL
BACHELOR THESIS

THE START-UP LOSS TIME OF CYCLIST AT A SIGNALIZED INTERSECTION

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ABSTRACT

The number of bicycle kilometers in the Netherlands increases every year. This can result in traffic jams at signalized intersections. One of the characteristics that has influence on traffic jams is start-up lost time. This is the time loss due to cyclists need to react to green light and to accelerate at an intersection. To keep up with the increase, the capacity must be improved. The bicycle traffic capacity of a signalized intersection can also be defined as the discharge flow. Discharge flow is a bicycle traffic characteristic which indicates the number of cyclists who crosses the stop line during one discharge period with cyclists per seconds as unit. In order to gain information about the influence of start-up loss time on the traffic bicycle flow, the relationship between start-up loss time and discharge flow is meaningful. Previous research (Goñi-Ros et al, 2018) showed that the discharge flow is strongly related to another characteristic shockwave speed. So, the main purpose of this report is to analyze the impact of start-up loss time on the characteristics discharge flow and shockwave speed. It is expected that the relationship between start-up loss time and discharge flow and start-up loss time and shockwave speed will be negatively correlated.

In order to analyze the impact of the start-up loss time, the start-up lost time has to be calculated first. The start-up lost time is the time interval between certain begin time and end time. The start time is calculated by the sub-lane method, which is a better method to determine the predecessor of the cyclists. To determine the end time, the time at which the cyclist has reached the average speed of 14 km/h (Es, 2019) is considered. Using the Pearson correlation coefficient, linear regression analysis and Lowell method, the impact of the start-up loss time on the two other characteristics was determined.

The results of the start-up loss time calculations showed that the mean start-up loss time decreases as the sub-lane width increases. In terms of impact, the three analyzes showed that the mean start-up loss time only had a positively correlated relationship with the discharge flow that was significant enough with an R value of 0.3. This

The conclusion is therefore that with the calculated start-up loss time, the impact of this time interval has a positively correlated effect on the discharge flow. This means that the discharge flow increases with an increase in start-up lost time. This does not match my hypothesis. The reason why the results deviate from the hypothesis could be the incorrect assumptions made in the definition of the start-up loss time. So, the results could also be seen as incorrect. The recommendations are therefore to analyze the impact of the start-up loss time with a different definition for the start-up loss time. Here it can be checked whether a different result comes out.

Cover illustration: Hoge bi – miniatuurfietsen

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LIST OF PARAMETERS

Parameter	Unit	Description
$T_{SL,i}$	s	Start-up loss time, time cyclist i needs to go from standstill to the average cycle speed.
$T_{RT,i}$	s	Reaction time of cyclist i.
$T_{AL,i}$	s	Acceleration loss time of cyclist i.
v_m	km/h	Average speed
v_i	m/s	
n	-	Indication of the time index
$y_{i,n}$	m	The n th y coordinate of cyclist i
$y_{i,n-1}$	m	The n-1 th y coordinate of cyclist i
$t_{i,n}$	s	The n th time of cyclist i
$t_{i,n-1}$	s	The n-1 th time of cyclist i
a_i	m/s^2	The acceleration of cyclist i
$v_{i,end}$	m/s	Last known speed of the data of cyclist i
$v_{i,end-1}$	m/s	Second to last known speed of the data of cyclist i
$t_{i,end}$	s	The last known time of the data of cyclist i
$t_{i,end-1}$	s	Second to last known time of the data of cyclist i
ω	m/s	Shockwave speed
q_d	Cyc/s	Discharge flow
Δx	m	Distance between stop line and the added line
χ_i	m	The distance cyclist i travels through the area
Δt	s	The time needed to pass all cyclist through the area
W	m	Width of the bicycle path
t_{GL}	s	Time stamp of green light phase
$t_{AS,i}$	s	Time stamp of reaching average speed of cyclist i
$t_{SA,pred,i}$	s	Time stamp of start acceleration phase of predecessor of cyclist i
w	m	Width of the sub-lane
v_i	km/h	Speed of the cyclist i

1. INTRODUCTION

Over the last years, the use of bicycles has increased. The Netherlands is at the top of the list of countries with the highest share of bicycle use as a percentage of the total number of trips, with a percentage of more than 25 (Harms & Kansen, 2018). This amount of bicycle use, causes a higher bicycle transport flow in especially cities. In the cities of the Netherlands, traffic is mostly regulated by traffic signals. These signals cause delay in traffic flow, because traffic has to stop at a red light and have to start again at a green light. More insight into bicycle flow will be useful in achieving the goal that the Dutch government has in mind. This organisation has set up a program “Tour the Force” to make The Netherlands more bicycle-friendly, with the aim of achieving 20% more bicycle kilometres by 2027 compared to 2017 (Ministerie van Algemene Zaken, 2020). The outcome of this program will be an increase of bicycle traffic. Because signalized intersections can be seen as bottlenecks of bicycle flow, the increase of bicycle kilometers can create more traffic jams at the bicycle lanes. One of the characteristics that has influence on those traffic jams is the time loss due to cyclists need to react to green light and to accelerate at an intersection. This time is called start-up loss time. The start-up loss time belongs to the microscopic characteristics, meaning that this characteristic relates to the parameters of an individual cyclist.

To get more knowledge about the flow of traffic at these signalized intersections, research is needed to define the characteristics of traffic flow. Liu et al. (2012) shows that by using signal countdown timers, the start-up loss time reduces by 0.6 seconds per cycle for left-turn movements and 2.25 seconds per cycle for through movements. Sharme et al. (2009) also showed that there is a clear difference in start-up loss time, depending on using a signal countdown timer or not. These papers were focused on car traffic flow on signalized intersection. A clear difference between the two papers is that Sharme et al. (2009) studied the car traffic flow in India with heterogenous traffic conditions. Although the flow characteristics for cars differs from cyclists (Raksuntorn and Khan, 2003), you can expect a similar result with bicycle flow due to the heterogenous conditions of bicycle traffic flow. The relationship between signal countdown timers and start-up loss time is not part of this research, it solely proves that gaining information about start-up loss time is important. This could help improving geometry of the intersections and bicycle lanes. Moreover, more knowledge may help optimize the traffic control scheme, with the aim of improving the capacity of the intersections and bicycle lanes.

This bicycle traffic capacity of a signalized intersection can also be defined as the discharge flow. The discharge flow of a signalized intersection is a macroscopic characteristic of bicycle flow which indicates the number of cyclists who crosses the stop line during one discharge period with cyclists per seconds as unit. As already stated, discharge flow is a macroscopic characteristic, this means that the characteristics relate to a group of cyclists.

In order to gain information about the influence of start-up loss time on the traffic bicycle flow, the relationship between start-up loss time and discharge flow is meaningful.

The hypothesis is when the start-up loss time is reduced, the discharge flow increases (negative correlated). Previous research (Goñi-Ros et al, 2018) showed that the discharge flow is strongly related to two other macroscopic characteristics: the shockwave speed and jam density. The shockwave speed is the velocity of the wave which occurs by the start of the greenlight phase. The wave starts at the front of the queue where the first cyclist makes a transition from waiting phase to acceleration phase. This transition moves through the cyclist queue with a certain shockwave speed. The jam density is the density in which the cyclists are queueing. The hypothesis is with a decreasing start-up loss time the shockwave speed increases. It is also expected that the start-up loss time will not affect the way people queue. Therefore, the jam density will not be included in the analysis. The relationship between start-up loss time and shockwave speed will be included in this research.

The start-up loss time will be determined using actual data of a signalized intersection. The Dutch government, municipalities and other organizations that are involved in the safety and safety of bicycle traffic in the Netherlands will benefit from this report. This could help understand the role of start-up loss time in improving bicycle flow at intersection, for example by adding signal countdown timers for bicycles. In addition to the aforementioned organizations, road users will also benefit by understanding the bicycle flow at a signalized intersection. Because this knowledge could help improve the flow at a bicycle path, and therefore also keep the travel pleasure for cyclists high and safe.

The purpose of this report is to look into existing bicycle trajectory datasets and determine and analyze the start-up loss time of cyclists at a signalized intersection. And to find out what relation this time has on the macroscopic characteristics' shockwave speed and discharge flow.

To complete the main goal of this report, the following research question has been formulated.

What is the impact of the start-up loss time on the shockwave speed and the discharge flow of a bicycle lane?

In order to achieve a solid answer on this question, the following questions should be answered:

- What definition should be used to quantify the start-up loss time?
- By what methods should the predecessor be determined?
- How should the discharge flow and shockwave speed be determined?
- By using regression methods, what will be the relationship between the start-up loss time and the two macroscopic characteristics shockwave speed and discharge flow?

This introduction is followed by chapter 2 which describes the dataset and the methodology that will be used to make the research possible. The results obtained by the methodology are shown in chapter 3. Subsequently, chapter 4 presents the discussion and at last, chapter 5 summarizes the conclusions.

2. METHODOLOGY

In this chapter the theory on which the research is based is discussed. This chapter is divided in four sections. The first section illustrates the content of the dataset. After this section the definition of the start-up loss time will be illustrated. The third section describes how the macroscope characteristics are calculated. And in the last section it is described how the relationship between start-up loss time and macroscope characteristics are defined.

2.1 DATASET INTRODUCTION

The data was obtained from a 2-meter-wide cycle path at a signalized intersection in Amsterdam. At this intersection, video material was shot at a height of 10 meters with the help of two cameras. By means of these video recordings, the positions of the heads of each passing cyclist are defined in function of time. The positions of the heads are transformed to x- and y-coordinates projected at the ground surface. This gives a clear overview of the position of the cyclists in function of time.

Figure 1: Sample video recording (Goñi-Ros et al, 2018)

The data contains 59 different files, each of which contains the data from one discharge period. One discharge period is denominated as a discharge cycle of cyclists who crosses the stop line after the green light turns on. The dataset of a single discharge period consists of multiple subfiles. The two sub files 'initial position' and 'trajectory' will be used in this research. The initial position file gives the x and y coordinate of each cyclist of that particular discharge flow. The trajectory file contains all the measured x and y coordinated in function of time for each cyclist.

2.2 START-UP LOSS TIME

The start-up loss time is the time cyclist i needs to go from standstill to the average cycle speed which is obtained from literature (v_m). The start-up loss time can be defined as the summation of the reaction time and the acceleration loss time.

$$T_{SL,i} = T_{RT,i} + T_{AL,i} \quad (1)$$

Where $T_{SL,i}$ is the start-up loss time of cyclist i, $T_{RT,i}$ is the reaction time of cyclist i and $T_{AL,i}$ the acceleration loss time of cyclist i.

In this report, the start-up loss time will not be calculated separately like formula 2.1. But will be defined as a time interval explained in section 2.2.2.

2.2.1 PREDECESSORS

There are no clear queues in a row of cyclists waiting for a traffic light. This makes it difficult to determine who is the predecessor of a cyclist i in line. In this report, the predecessor will be determined by using the original lane method and the sub-lane method.

2.2.1.1 ORIGINAL LANE METHOD

The original lane method only looks at the y-coordinate of the cyclists. To determine the predecessor of cyclist I, if looking at figure 2, cyclist j is closest to cyclist i in terms of y coordinates, even if cyclist k would rather be chosen as a predecessor of cyclist i. In the basic method cyclist j is seen as the predecessor of cyclist i.

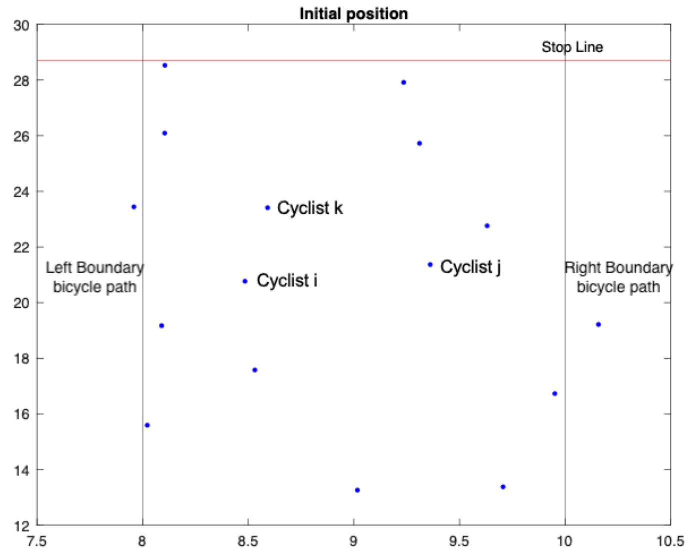

Figure 2: Original lane method

2.2.1.2 SUB-LANE METHOD

In contrast to the original lane method, the sub-lane method does not look at the entire width of the cycle path. Virtual sub-lanes with width 'w' are created within 2 meters of the cycle path and only cyclist within this sub-lane can be defined as predecessor. In figure 3 it can be sees that for a width of 0.5m cyclist k is defined as predecessor of cyclist i. When the width of the sub-lane is doubled, it becomes clear that cyclist j now also falls within the sub-lane and is thus defined as the predecessor of cyclist i. The difficulty of using the sub-lane method is the determination of the width.

In literature a lot of different widths are been suggested: 0,78 meters in the Netherlands by Botma and Papendrecht (1991) and 1,60 meters in Norway by Allen et al. (1998). Yuan et al. (2019) considered the range between 1,00 and 1,40 meters reasonable. Based on above literature, the range of 'w' in this research is set from 0.8 to 1.60 meters, with steps of 0,2 meters.

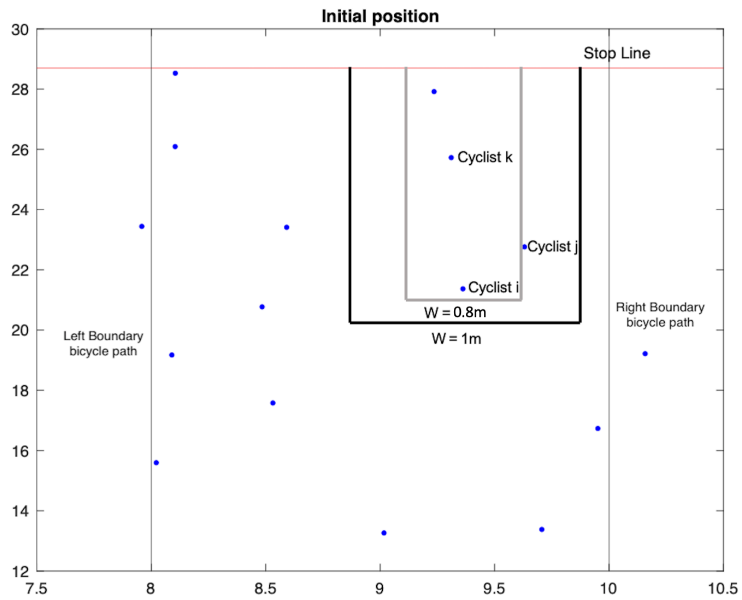

Figure 3: Sub-lane method example

2.2.2 INDIVIDUAL START-UP LOSS TIME

The determination of the start-up loss time depends on whether there is a predecessor or not. If there is no predecessor, the start-up loss time is the time interval between the time that the light turns green (t_{GL}) and the time that the cyclist has reached the determined average speed ($t_{AS,i}$). The average speed (v_m) in Amsterdam is 14.4 km / h (Es, 2019). If the cyclist does have a predecessor, the start-up loss time will be calculated using formula 3, where $t_{SA,pred}$ is the time at which the predecessor starts to accelerate.

$$T_{SL,i} = t_{AS,i} - t_{GL} \qquad no\ predecessor \quad (2)$$

$$T_{SL,i} = t_{AS,i} - t_{SA,pred,i} \qquad has\ a\ predecessor \quad (3)$$

Determining the end time at which the cyclist has reached the determined average speed ($t_{AS,i}$) will be done by calculating the tangent of two consecutive y coordinates of a cyclist:

$$v_i = \frac{y_{i,n} - y_{i,n-1}}{t_{i,n} - t_{i,n-1}} \qquad (4)$$

If a specific cyclist does not reach the average speed within his existing trajectory, the following assumption applies: The end time of the start-up loss time is calculated by means of the acceleration of that specific cyclist (a_i).

This acceleration will be calculated by dividing the difference between the two last known speeds of the cyclist by the time:

$$a_i = \frac{v_{i,end} - v_{i,end-1}}{t_{i,end} - t_{i,end-1}} \quad (5)$$

In this case we will assume that the acceleration of the cyclist will be constant. This assumption makes it possible to calculate the remaining time it takes the cyclist to reach the average speed (v_m). This assumption will cause some drawback, because in practice the acceleration of a cyclist could not be exactly constant.

2.3 MACROSCOPIC CHARACTERISTICS

To compare the start-up loss time with the macroscope characteristics, these characteristics must first be defined. Based on the hypothesis made in the introduction, this report only looks at the characteristics of discharge flow and shockwave speed. The calculation of the discharge flow and shockwave speed has already been done in previous research by Goñi-Ros et al (2018), which will be used in this report. These characteristics are briefly explained below.

2.3.1 DISCHARGE FLOW

The discharge flow (q_d) is defined as an average flow through an area. This area is created by adding a second line (black dotted line: line a) downstream of the stop line (see figure 4).

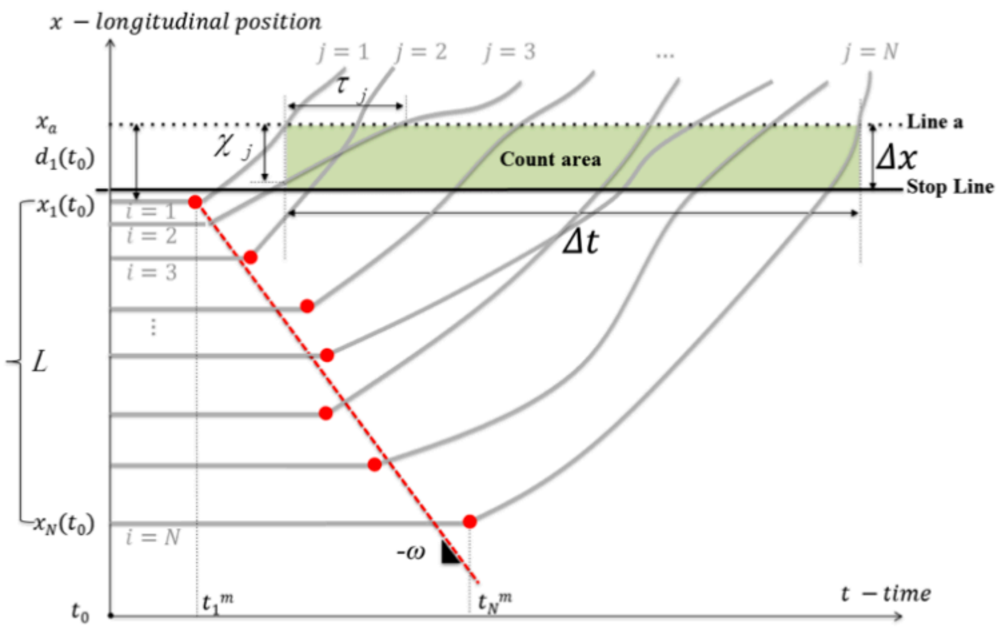

Figure 4: Real bicycle trajectories (Goñi-Ros et al, 2018)

By using this area, the discharge flow can be calculated with the following equation (Goñi-Ros et al, 2018):

$$q_d = \frac{\sum_{i=2}^{N} \chi_i}{\Delta x * \Delta t * W} \qquad (6)$$

Where Δx is distance between stop line and the added line, Δt is the time needed to pass all cyclist through the area, W is the width of the bicycle path and χ_j is the distance cyclist j travels through the area.

2.3.2 SHOCKWAVE SPEED

The shockwave occurs when a group of cyclists are standing still, waiting at the intersection and the traffic light turns green. When the light turns green, the cyclists want to accelerate and start moving. The wave that arises due to the successive cyclists who want to start moving is the shock wave. The speed at which this wave propagates is the shockwave speed (ω). This shockwave speed is determined by a given code provided by Goñi-Ros et al. (2018), that takes the time stamps of the cyclists at the moment they start moving (see red dots in figure 4). This creates points upon which a linear regression will be performed to create a linear line through these points (red dashed line figure 4). The slope of this linear line is the shockwave speed of that specific discharge period.

2.4 RELATIONSHIP

The start-up loss time is mainly calculated in proportion to time per cyclist, and the discharge flow and shock wave speed both have only one value per discharge period. To be able to compare these three variables with each other, a mean reaction time for every single discharge period will be defined.

First, the Pearson correlation coefficients R and p-value will be calculated. These values give us an initial overview in the relations between start-up loss time and the two macroscopic characteristics. Because the two macroscopic characteristics are given per discharge period, the individual start-up loss time will also have to show a single value per period. This is done by taking the mean and median of all start-up loss times within a period. The coefficient R is the value representing the magnitude of the correlation between two variables. This value can vary between -1 and 1. If R has a value of -1 then the two variables have a perfect negative linear relationship and with a value of 1 the two variables have a perfect positive relationship. When the coefficient R gives a value of 0, the two variables have no correlation. The significance of the coefficient R is determined by the p-value. When the p-value has a value below the established value 0.05, the coefficient R may be considered significant.

Subsequently, a linear regression will be performed to show the scatterplot of mean start-up loss time and discharge flow, and mean start-up loss time and shock wave speed. Linear regression will be performed to determine the relationship between the characteristics as well as the relationship between the different sub-lane widths. By looking at which regression lines corresponds, the mean start-up loss time will be plotted against the x-axis vs the discharge flow and shockwave speed against the y-axis. This because the aim of this report is to define the impact of start-up loss time on for example the discharge flow and shockwave speed.

When the graphs show that there is no linear relationship between the mean start-up loss time and the two macroscopic characteristics, other possible relationships will be examined using 3D plots.

3. RESULTS

In order to answer the questions formulated in the introduction, this chapter presents the results. This is done in several steps. First, the determination of the predecessors by means of the original lane method and sub-lane method. Subsequently, the start and end times of the start-up loss time are determined. The start-up loss time will be displayed per discharge period. Before a relation between the start-up loss time and the macroscopic characteristics will be made, the calculations of the discharge flow and shockwave speed will be shown. Finally, the start-up loss time is plotted against the macroscopic characteristics, to be able to analyze the relationship between these parameters

For this research, 55 of the 59 files were used to perform the calculations. The four files are excluded due to unrealistic outcomes. Out of the 55 files came an average queue size of 12.38 cyclist per period. 83.6% of the periods contains a queue that consist of 10 or more cyclists. Further into this chapter the distribution of start-up loss time, discharge flow and shockwave speed will be illustrated.

3.1 START-UP LOSS TIME

The calculation of the start-up loss time of each discharge period is divided into four sub-sections: predecessors, start time, end time and start-up loss time distribution. These separate sections will help to understand which steps are made for calculating the start-up loss time.

3.1.1 PREDECESSORS

To determine the start time of the start-up lost time interval for a cyclist, it is checked whether this cyclist has a predecessor or not. This is done through the original lane method and sub-lane method discussed earlier. For illustration, the predecessors of the cyclists in discharge period 1 are shown in Table 1. In the first column the indexes of all cyclists are shown. All cyclists in the queue have been given an index number. This index number refers to the y coordinate of the relevant cyclist. For example, number 1 is the leader of the queue and number 2 is the cyclist who, looking at the y coordinate, is behind this cyclist.

For instance, looking at cyclist number 10 in table 1, you will see that the cyclist in the sub-lanes with the widths 0.8 meter and 1.0 meter has no predecessor (0) and will therefore react to the green traffic light. But in the sub-lanes with the widths of 1.2 meter and 1.4 meter, cyclist number 10 will react on the movement of cyclist number 9. This shows that the width of the sub-lane will affect the magnitude of the start-up loss time.

Table 1: Predecessors for each cyclist in period 1

No. Cyclist	Original lane	sub-lane: 0.8m	sub-lane: 1.0m	sub-lane: 1.2m	sub-lane: 1.4m	sub-lane: 1.6m
	Discharge period: Traj_2016-06-02_12-45-16_1					
1	0	0	0	0	0	0
2	1	0	0	0	0	0
3	2	1	1	1	1	1
4	3	2	2	2	2	2
5	4	3	3	3	3	3
6	5	0	3	3	5	5
7	6	4	4	4	4	4
8	7	7	7	7	7	7
9	8	6	6	6	6	6
10	9	0	0	7	7	8
11	10	9	9	9	9	9
12	11	9	11	11	11	11
13	12	10	10	10	10	10
14	13	11	11	12	12	12
15	14	13	13	13	13	13
16	15	8	12	12	15	15

3.1.2 START TIME

With the information obtained about the predecessor, the start time of the time interval start-up loss time can be determined. This is the time when the predecessor starts to accelerate ($t_{SA,pred,i}$). Table 2 shows an example of the different start times with regard to the different sub-lanes.

Table 2: Start time in seconds for each cyclist in period 1

No. Cyclist	Original lane	sub-lane: 0.8m	sub-lane: 1.0m	sub-lane: 1.2m	sub-lane: 1.4m	sub-lane: 1.6m
	Discharge period: Traj_2016-06-02_12-45-16_1					
1	885,0200	885,0200	885,0200	885,0200	885,0200	885,0200
2	885,7190	885,0200	885,0200	885,0200	885,0200	885,0200
3	887,1310	885,7190	885,7190	885,7190	885,7190	885,7190
4	886,0980	887,1310	887,1310	887,1310	887,1310	887,1310
5	886,5630	886,0980	886,0980	886,0980	886,0980	886,0980
6	887,3560	885,0200	886,0980	886,0980	887,3560	887,3560
7	886,2470	886,5630	886,5630	886,5630	886,5630	886,5630
8	886,5630	886,5630	886,5630	886,5630	886,5630	886,5630
9	886,3880	886,2470	886,2470	886,2470	886,2470	886,2470
10	886,5490	885,0200	885,0200	886,5630	886,5630	886,3880
11	887,0870	886,5490	886,5490	886,5490	886,5490	886,5490
12	887,8880	886,5490	887,8880	887,8880	887,8880	887,8880
13	888,0760	887,0870	887,0870	887,0870	887,0870	887,0870
14	887,6670	887,8880	887,8880	888,0760	888,0760	888,0760
15	889,0790	887,6670	887,6670	887,6670	887,6670	887,6670
16	888,8850	886,3880	888,0760	888,0760	888,8850	888,8850

Combining table 2 with table 1, it is visible that the start time with no predecessor is the green light time (in discharge period 1: 885.02 seconds). These green light times are given in the data.

3.1.3 END TIME

Unlike the start time, the end time ($t_{AS,i}$) does not differ across the different sub-lane widths This has to do with the fact that the end time is calculated by means of the trajectory of the cyclist himself and therefore has nothing to do with the cyclist's predecessor. Table 2 shows an example of the end times of cyclists in discharge period 1.

Table 3: End time in seconds for each cyclist in period 1

Discharge period: Traj_2016-06-02_12-45-16_1						
No. Cyclist	Original lane	sub-lane: 0.8m	sub-lane: 1.0m	sub-lane: 1.2m	sub-lane: 1.4m	sub-lane: 1.6m
1	889,8817	889,8817	889,8817	889,8817	889,8817	889,8817
2	893,2373	893,2373	893,2373	893,2373	893,2373	893,2373
3	887,1357	887,1357	887,1357	887,1357	887,1357	887,1357
4	889,9446	889,9446	889,9446	889,9446	889,9446	889,9446
5	890,0070	890,0070	890,0070	890,0070	890,0070	890,0070
6	890,9198	890,9198	890,9198	890,9198	890,9198	890,9198
7	891,0379	891,0379	891,0379	891,0379	891,0379	891,0379
8	892,0266	892,0266	892,0266	892,0266	892,0266	892,0266
9	894,0172	894,0172	894,0172	894,0172	894,0172	894,0172
10	892,8390	892,8390	892,8390	892,8390	892,8390	892,8390
11	893,1685	893,1685	893,1685	893,1685	893,1685	893,1685
12	891,0100	891,0100	891,0100	891,0100	891,0100	891,0100
13	895,3792	895,3792	895,3792	895,3792	895,3792	895,3792
14	894,1500	894,1500	894,1500	894,1500	894,1500	894,1500
15	895,0890	895,0890	895,0890	895,0890	895,0890	895,0890
16	895,0890	895,0890	895,0890	895,0890	895,0890	895,0890

In section 2.2.2. is described how the end time is calculated, and what assumption is made during the calculations. The assumption of a constant acceleration has a big influence on the variable 'end time' and so a verification is needed to know whether this assumption is true or not. This big influence is proved in table 4, where the constant acceleration calculation was needed by 11 of the 16 cyclists. This means that 68,8% of the end time data of period 1 is based on the assumption.

Table 4: Acceleration distribution of the actual trajectory data of period 1

	number of cyclists	assumption used	min	max	mean	stdev	p25	p50	p75
Acceleration	16	11	-19,461	33,501	0,490	4,660	-1,448	0,658	2,721

Besides the major influence of the assumption, the table also shows that the acceleration is not constant in reality. In Appendix A the actual accelerations of any cyclist are plotted as a function of time. Just like the table, these graphs show that the actual acceleration of a cyclist is not constant.

3.1.4 START-UP LOSS TIME DISTRIBUTION

By subtracting the start time from the end time, the time interval of the start-up loss time can be calculated. These calculations have been made per width of the sub-lanes to show the difference in distribution per width.

Table 5: Comparison of statistical properties per method

		Mean SLT [s]	Stdev SLT [s]	negative SLT [%]	Quantiles		
					0.25	***0.5***	***0.75***
Original lane method		4,352	2,4054	2,1097	2,975	4,374	5,660
Sub-lane method	w = 0.8m	4,845	2,4006	1,9691	3,504	4,771	6,181
	w = 1.0m	4,739	2,3615	1,9691	3,422	4,724	6,061
	w = 1.2m	4,667	2,3436	2,1097	3,396	4,667	5,984
	w = 1.4m	4,619	2,3400	2,1097	3,354	4,624	5,898
	w = 1.6m	4,586	2,3297	2,1097	3,354	4,464	5,786

These properties are shown per lane method in table 5 and are the average start-up loss time, the standard deviation, the percentage of negative outcomes and various quantiles. In addition, Appendix B shows the various graphs of the distribution of start-up loss time. The results show that the average start-up loss time differs across the different widths. Table 5 shows that the highest mean is at the sub-lane width of 0.8 meters, and when the sub-lane width is increased, there is a decrease in the mean start-up loss time. When looking at the percentage of negative outcomes, no clear decision can be made as to which width is best. Since the percentage differences are between 0% - 0.1406%, it can be seen as constant.

3.2 MACROSCOPIC CHARACTERISTICS

The main reason for defining and calculating the start-up loss time is to find out whether this characteristic is related to the bicycle traffic flow characteristics discharge flow and shockwave speed. The calculation of these two characteristics is shown in section 2.3 and are used for the same 55 period files as for the calculation of the start-up loss time. The parameters derived from the calculations are shown in table 6.

Table 6: Descriptive statistics from 55 data periods

	Min	Max	Mean	Stdev	p25	p50	p75
Discharge flow	0,341	0,786	0,595	0,098	0,522	0,598	0,672
Shockwave speed	1,857	7,675	3,943	1,262	2,988	3,756	4,697

To determine whether there is an influence or relationship of the start-up loss time on the macroscopic characteristics, the first insight of the relationships will be given by the Pearson correlation coefficients. After that, the relationships will be discussed further by means of linear regression analysis. At last, several 3D plots will give an extra overview of relations between start-up loss time, shockwave speed and discharge flow together.

3.2.1 PEARSON CORRELATION COEFFICIENT

The Pearson correlation coefficients are calculated separately for each sub-lane width, as well as for the original lane method for comparison. These results are shown in table 7 for the correlation between start-up loss time and shockwave speed, and in table 8 for the correlation between start-up loss time and discharge flow.

Table 7: Pearson coefficients start-up loss time vs. shockwave speed

			Mean SLT			Median SLT	
			R	*p-value*		*R*	*p-value*
Original lane method			0,1268	0,3562		0,0493	0,7205
Sub-lane method	*w = 0.8m*		0,0548	0,6912		-0,0981	0,4761
	w = 1.0m		0,0784	0,5694		-0,0764	0,5791
	w = 1.2m		0,0678	0,6227		-0,0795	0,5639
	w = 1.4m		0,0716	0,6033		-0,0840	0,5419
	w = 1.6m		0,0809	0,5572		-0,0817	0,5530

Table 8: Pearson coefficients start-up loss time vs. discharge flow

			Mean SLT			Median SLT	
			R	*p-value*		*R*	*p-value*
Original lane method			0,2246	0,0993		0,1482	0,2801
Sub-lane method	*w = 0.8m*		0,3561	0,0076		0,3010	0,0256
	w = 1.0m		0,3152	0,0191		0,2061	0,1311
	w = 1.2m		0,3152	0,0191		0,2208	0,1052
	w = 1.4m		0,2724	0,0443		0,1809	0,1862
	w = 1.6m		0,2620	0,0533		0,1885	0,1681

Table 7 shows that both the p-value calculated by means of the mean and the p-value calculated by means of the median are in a range of between 0.476 and 0.691 when w = 0.8 meters. This is both well above the significant level of 0.05, which means that for the start-up lost time results calculated in this report, there is no one-to-one linear relationship. This is further substantiated by the fact that the R coefficient is close to zero for all sub-lane widths.

In table 8 it is noticeable that the difference in p-value between the mean method and the median method. Based on these p-value results, the mean start-up loss time and discharge flow should have a significant positive linear relationship except for sub-lane width 1.6 meters. And the median start-up loss time vs. discharge flow should not have a significant one-to-one linear relationship, except for the sub-lane width 0.8 meters.

3.2.2 LINEAR REGRESSION ANALYSIS

Subsequently, the linear regression method will be used to discuss several graphs. The x-axis of both graphs shows the start-up loss time, and the y-axis shows one of the two macroscopic characteristics. For each macroscopic characteristic, the data is plotted in different colors for each sub-lane width. This provides a good overview to analyze whether there is a linear relationship between the start-up loss time and one of the two macroscopic characteristics. To continue on the results of tables 7 and 8, the relationship between the mean start-up loss time vs. discharge flow and median start-up loss time vs. discharge flow are been plotted. This could help to understand the cause of the differences from table 8.

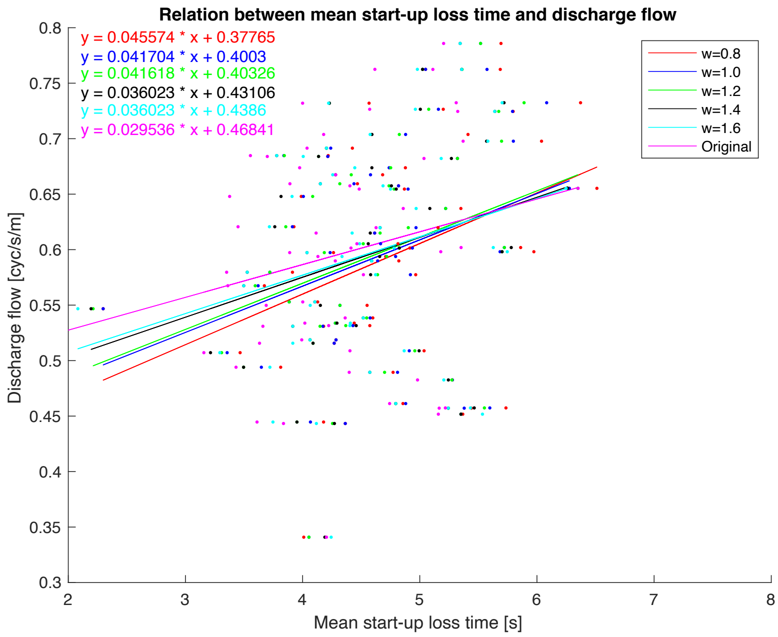

Figure 5: Linear regression mean start-up loss time vs. discharge flow

Figure 5 shows the linear regression of mean start-up loss time vs. discharge. The data points have a slightly linear course, but the distribution of the data points is still present. But compared to the scatter plot of the data points of the median start-up loss time vs. discharge flow in figure 6, the difference in spread is clearly visible and this may also be the cause of the difference in p-value in table 8. The reasonable spread and the slightly linear course of the data points in figure 5 corresponds to the coefficient R of about 3 across the different sub-lane widths. What also can be gleaned from the graph is the fact that all the regression lines show a positive relationship. For example, it can be seen that with a 1 second increase in the mean start-up loss time, the discharge flow will experience an increase in a range of 0.0295 and 0.0456 cyclist per second per meter.

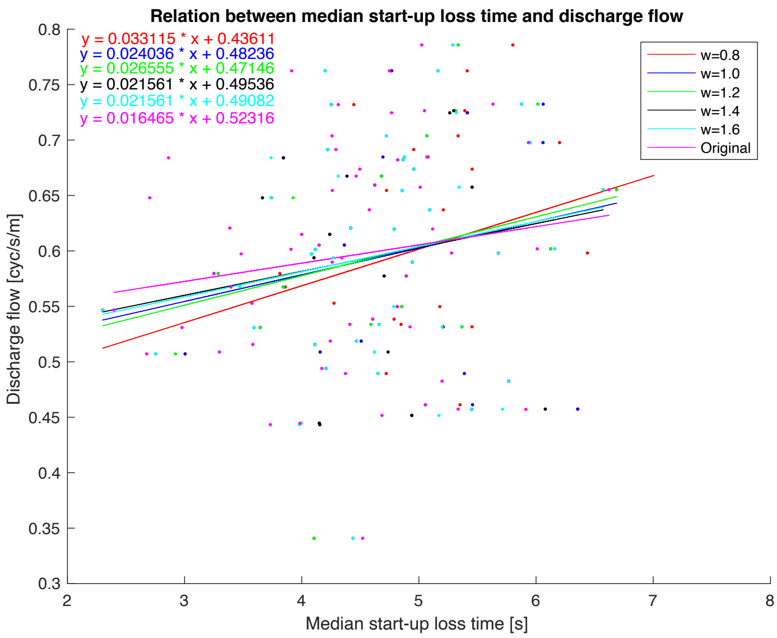

Figure 6: Linear regression median start-up loss time vs. discharge flow

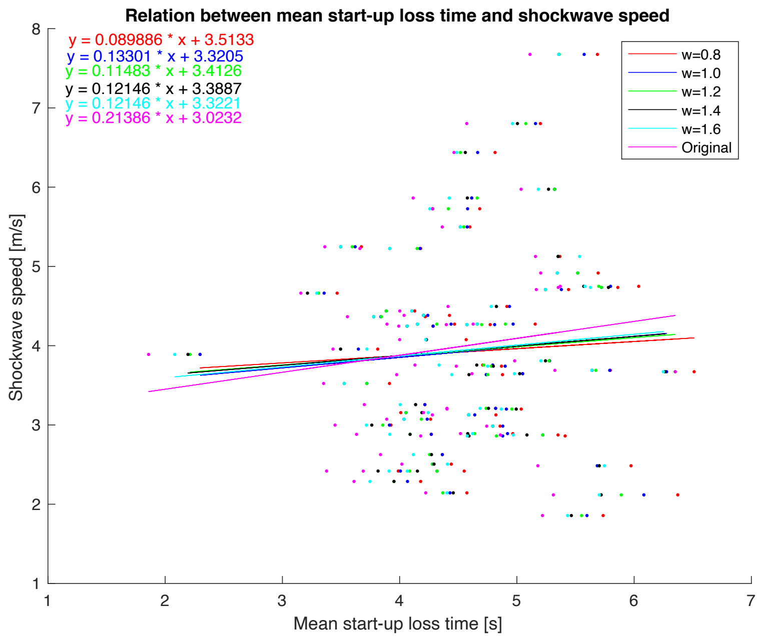

Figure 7: Linear regression start-up loss time vs. shockwave speed

Table 7 shows that both mean and median start-up loss time have not any significant linear relation with the shockwave speed. As in Figures 6, the scatter plot of Figure 7 shows a wide scatter of data points. This large spread does not indicate a clear linear relationship between the mean start-up loss time and shockwave speed. This corresponds with the results from table 7. Using 3D plots, other possible relationships between shockwave speed, discharge flow and mean start-up lost time will be examined.

3.2.3 3D PLOTS

The Pearson correlation coefficients and the linear regression analysis identify the relationship between mean start-up loss time and discharge flow as only one of the 4 one-to-one relationships (table 7 and 8) significantly. To gain a different insight into relationships between multiple variables, there are several 3D graphs. The scatter plots of the mean start-up loss time, discharge flow and shockwave speed are plotted in these graphs. The combination of these scatter plots and the Lowess method forms planes that show the possible relationships between variables. The lowess method creates a smooth plane by using local linear regression. Figure 8 shows the 3D plot of the mean start-up loss time and shockwave speed vs. discharge flow. The mean start-up loss time is calculated with a sub-lane width of 1.2 meter. The other 3D plots with the mean start-up loss time of the sub-lane widths: 0.8m, 1.0m, 1.4m, 1.6m and the original lane are shown in Appendix C.

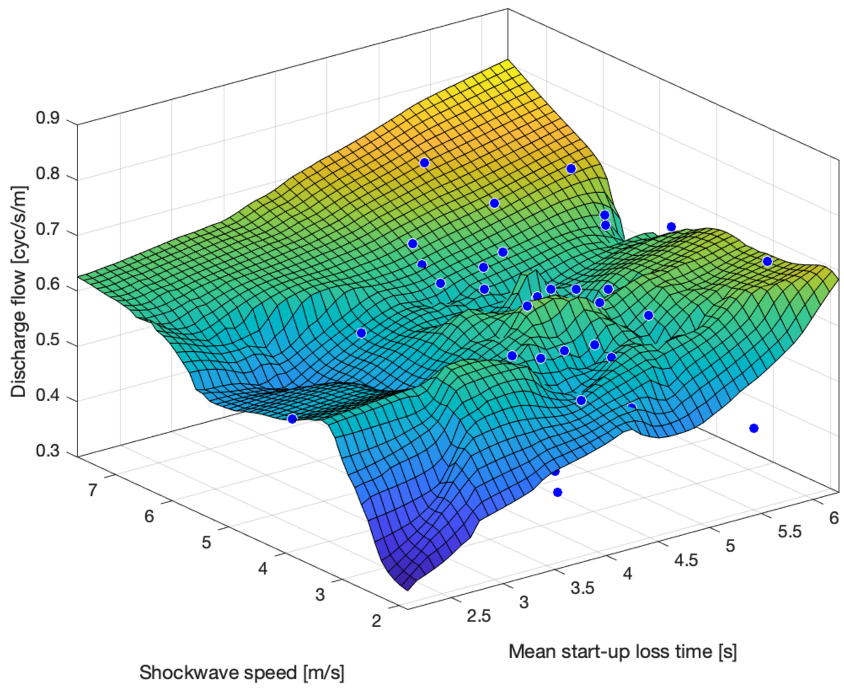

Figure 8: 3D plot mean start-up loss time (w = 1.4 m) and shockwave speed vs. discharge flow

Figure 8 shows that a combination of an increase in mean start-up loss time and an increase in shock wave speed results in an increasing discharge flow. Comparing the 3D plots of different sub-lane widths gives the result that the relationship applies to each sub-lane width. The sub-lane widths 1.2, 1.4 and 1.6 meters form a group with well-matched results.

4. DISCUSSION

This research on the determination of cyclists' the start-up loss time and the impact of this characteristic has yielded several interesting results. These results are explained in this chapter by means of the assumptions and definitions made in this report.

First, the definition of the start-up loss time. This definition is split into the start time and end time. The definition of the start time is based on the determination of the predecessors. These predecessors were determined using the virtual sub-lane method. The selection for widths of the sub-lanes are based on literature (section 2.2.1.2) and form a solid range. There are therefore no extraordinary outcomes in the begin time results.

Various assumptions have been made in the definition for determining the end time. Establishing the target speed of 14 km/h (Es, 2019) and assuming that the acceleration of a cyclist would be constant after the existing trajectory data. The results of section 3.1.3 and Appendix A showed that the constant acceleration assumption had a major influence on the end time results and was also found to be incorrect. This would cause inaccurate and incorrect end time results. The assumption of defining a cyclist's acceleration as an average of all recorded accelerations would already been a better assumption for future research.

Although the end time results are probably incorrect due to the assumptions taken. Can useful conclusions be drawn from the distribution of the start-up loss time? The fact that the assumptions taken have been used constantly over the calculations of each sub-lane width, makes it possible to compare the results of these different sub-lanes. With the aim of providing a reasonable range of widths as recommendations for future research.

The computed distribution in table 5 shows that the start-up loss time decreases as the sub-lane width increases. This can be explained by the fact that a smaller sub-lane width increases the chance that the start time will be based on the green light instead of a predecessor. This can result in a slower response and therefore a higher start-up loss time. To determine if the change in mean over different sub-lane width is significant enough, a T-test can be done. This test will not be included into this thesis, but can be done in future researches.

The presence of these negative values in table 5 will be due to the reaction time portion of the start-up loss time (equation1). This can occur because in practice cyclists, for example, start driving before it is green or that cyclists nevertheless react to the green light instead of the predetermined predecessor.

Finally, the results of the linear regression. The results of the Pearson correlation coefficients, linear regression analysis and 3D local linear regression plots show that with the obtained results of the start-up loss time there is no linear relationship with the traffic flow characteristic shockwave speed.

The relationship between the mean start-up loss time and discharge flow is the only one that appears to have a linear relationship with a value R of 0.3. This outcome is not in accordance with my hypothesis where a negatively correlated relationship was predicted and expected.

It is remarkable that, in contrast to the mean start-up loss time, there is no linear relationship between the median start-up loss time and discharge flow. The difference between the results of the mean and median can be caused by the aforementioned assumptions when determining the end time.

The 3D plots of mean start-up loss time and shockwave speed vs. discharge flow confirm the outcome of the linear regression. The plot shows that a combination of an increase in mean start-up loss time and an increase in shock wave speed results in an increasing discharge flow. The result is that with a discharge period high mean start-up loss time and a high shockwave speed, a high discharge of cyclists takes place in a queue. Meaning that the capacity will increase when the cyclist starts off faster in succession but has to take longer to reach the average speed.

The fact that no correlation between shockwave speed and start-up loss time has been established with Pearson correlation method, Linear regression method and Lowell method, may be the result of two possibilities. First of all, that the incorrect assumption of the acceleration results in such incorrect results that the results of the relations are not representative of reality. The other scenario is that there is actually no linear relationship between the bicycle traffic flow characteristic shockwave speed and start-up loss time. To check if the second scenario is true, further investigation of the relationship by multiple regression method will be recommended.

5. CONCLUSION AND RECOMMENDATION

The main goal of this report is to investigate the impact of the start-up loss time of cyclists on shockwave speed and discharge flow. This main purpose consisted of two parts. First, define the start-up loss time characteristic and determine which variables are needed to make the calculations possible. And the second part is to map the impact of start-up loss time on the bicycle traffic flow characteristics of shockwave speed and discharge flow. Discharge flow is the most important of the two because this characteristic is the link to the capacity of a signalized intersection.

The definition of start-up loss time adopted in this report is the time interval between the start time and the end time (section 2.2.2). The sub-lane methods were used to define the start time. The sub-lanes width varied in a range of 0.8 meters - 1.6 meters with steps of 0.2 meters and are based on literature. From the results of the Pearson correlation coefficient it can be concluded that in the relationship between start-up lost time and discharge flow the widths 1.0 meter to 1.4 meter have the best results. It can also be seen in the linear regression that these sub-lane widths have comparable regression lines. The end time in this report is incorrectly defined. This was caused by an assumption of constant acceleration of a cyclist in the methodology that turned out to be incorrect afterwards. This incorrect calculation will therefore also have consequences for the determination of the impact of the start-up loss time.

The impact of the start-up lost time on the shockwave speed and discharge flow was investigated by means of Pearson correlation coefficients, Linear regression analysis and Lowell method. The data of the macroscopic characteristics shockwave speed and discharge flow used for these methods has been calculated as described in section 2.3 and has a distribution shown in table 6.

In general, it can be concluded that with the definition of the start-up loss time drawn up in this report, the impact of this characteristic has the following outcomes. The relationship between the mean start-up lost time and discharge flow was found to be the only significant linear relationship with an R value of 0.3 and a p-value below 0.05. No significant linear connections have been found between start-up loss time and shockwave speed. These conclusions are based on the results of the Pearson correlation coefficients (section 3.2.1). Where the p-value must be below 0.05 for the linear relationship between the two characteristics to be significant.

To gain more insight into the impact of start-up loss time, the recommendation for future research would be to design a better method for defining the start-up loss time. For example, a correct assumption for the cyclist's acceleration could already give a better result. Or adjusting the sub-lane method so that the negative values of the start-up loss time could be minimized. In addition to improving the definition of start-up loss time, the recommendation would also be to go further in the research of the different relationships between characteristics by using for instance multiple regression method.

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APPENDICES

APPENDIX A: ACCELERATION ASSUMPTION

A major assumption has been made in this report with the aim of making it possible to calculate the end time by means of a target speed of the cyclist (14.4 km / h). The assumption implies that a cyclist's acceleration is constant over both his recorded and future trajectory. In order to check afterwards whether this assumption is correct or not, the accelerations of random cyclists of random periods have been calculated in this appendix. These accelerations are plotted to show how they change over time.

Figure 9 shows 8 of these graphs. These graphs show very clearly that the cyclists' acceleration is not constant and therefore the assumption is wrong. However, it can be seen that the accelerations fluctuate around a certain average.

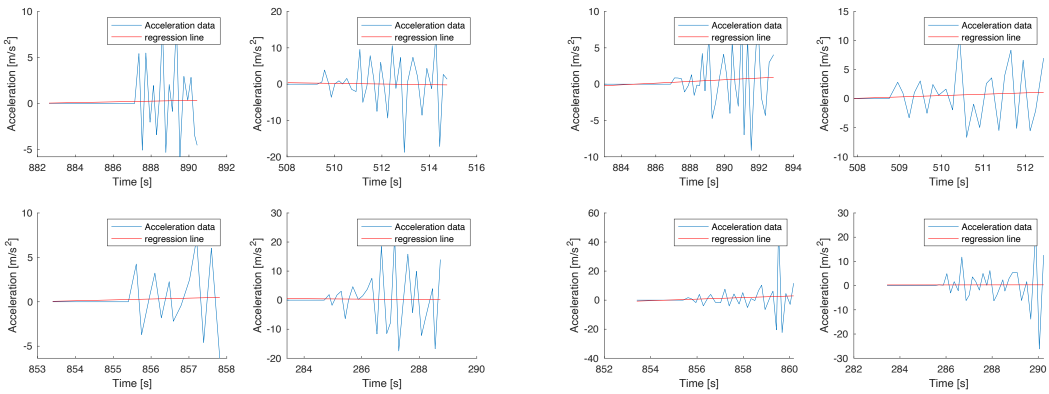

Figure 9: The acceleration of different cyclist throughout there existing trajectory

APPENDIX B: START-UP LOSS TIME DISTRIBUTION

To give a better visualization of the distribution of the start-up loss time, several histograms are shown with normal distribution.

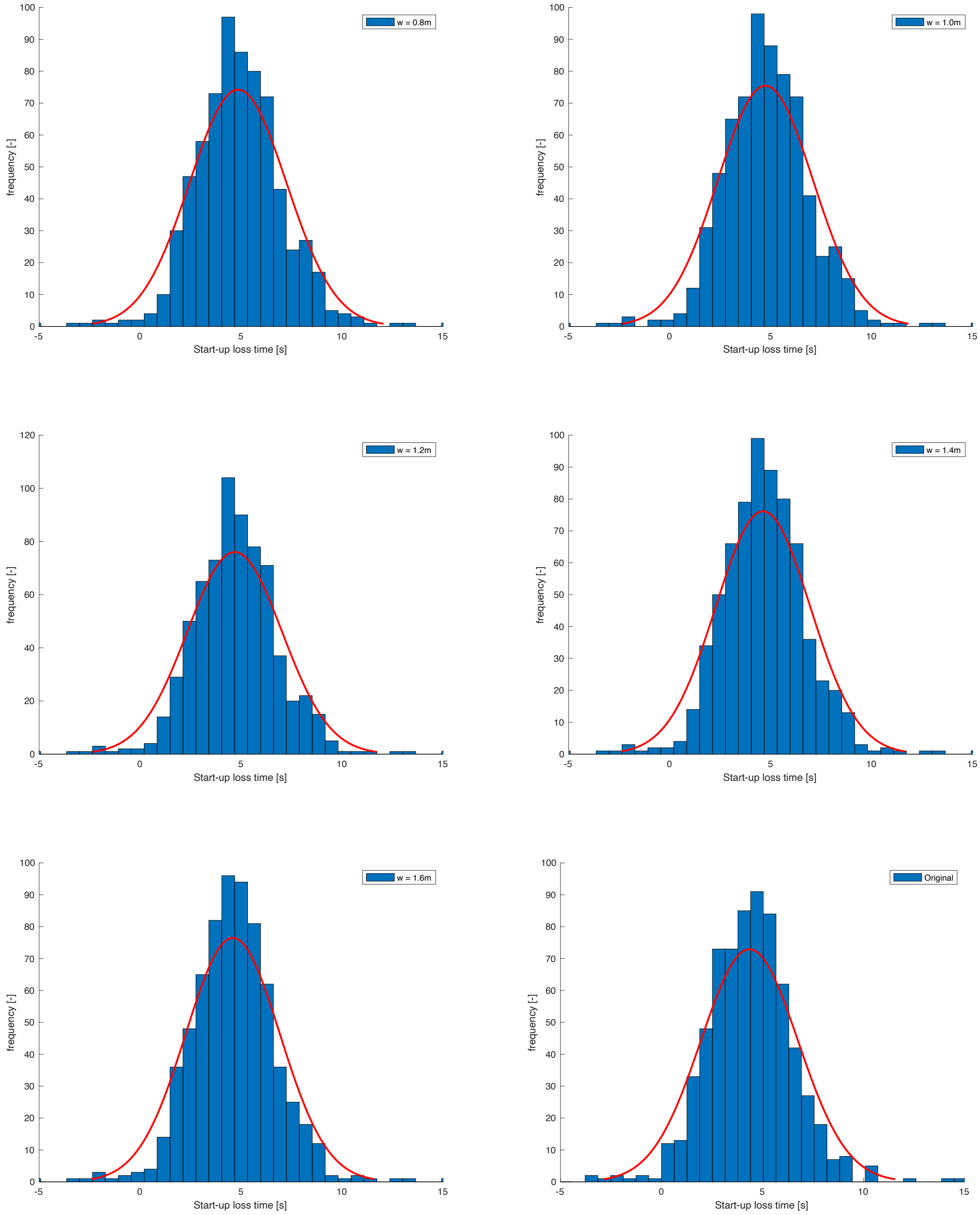

Figure 10: Normal distributions of start-up loss time for different widths

APPENDIX C: 3D PLOTS

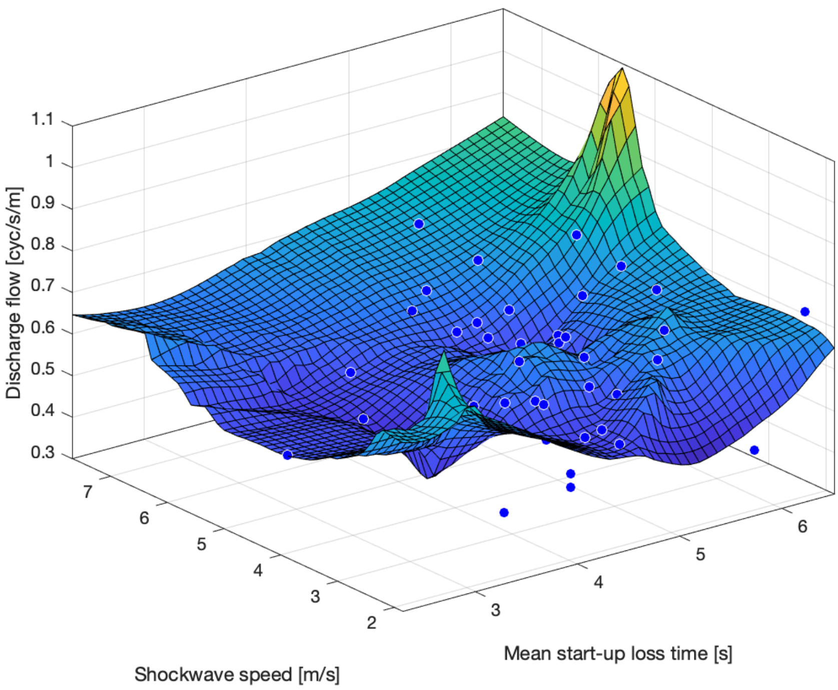

Figure 11: 3D plot mean start-up loss time (w = 0.8 m) and shockwave speed vs. discharge flow

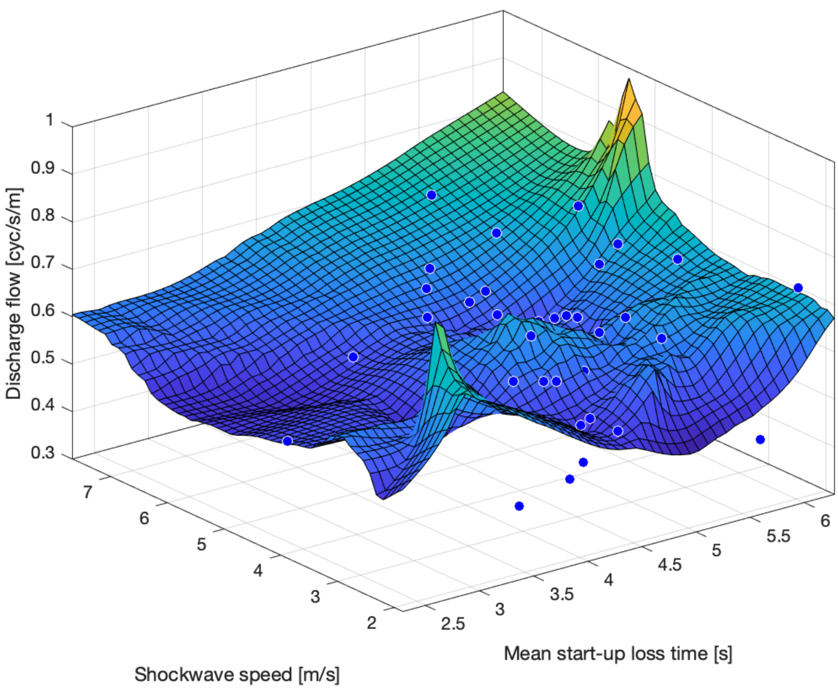

Figure 12: 3D plot mean start-up loss time (w = 1.0 m) and shockwave speed vs. discharge flow

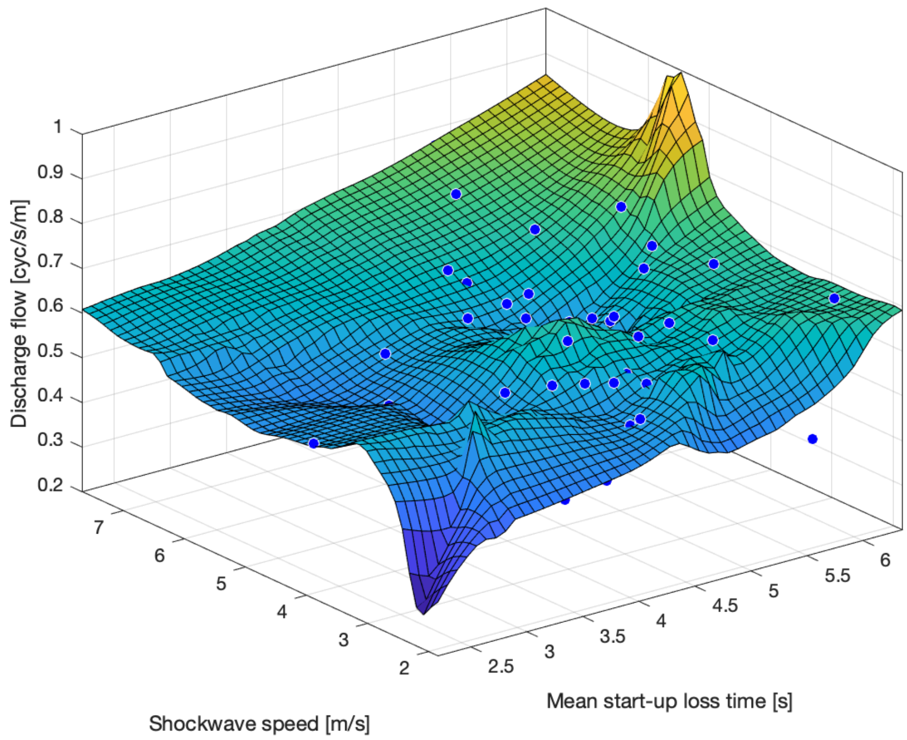

Figure 13: 3D plot mean start-up loss time (w = 1.2 m) and shockwave speed vs. discharge flow

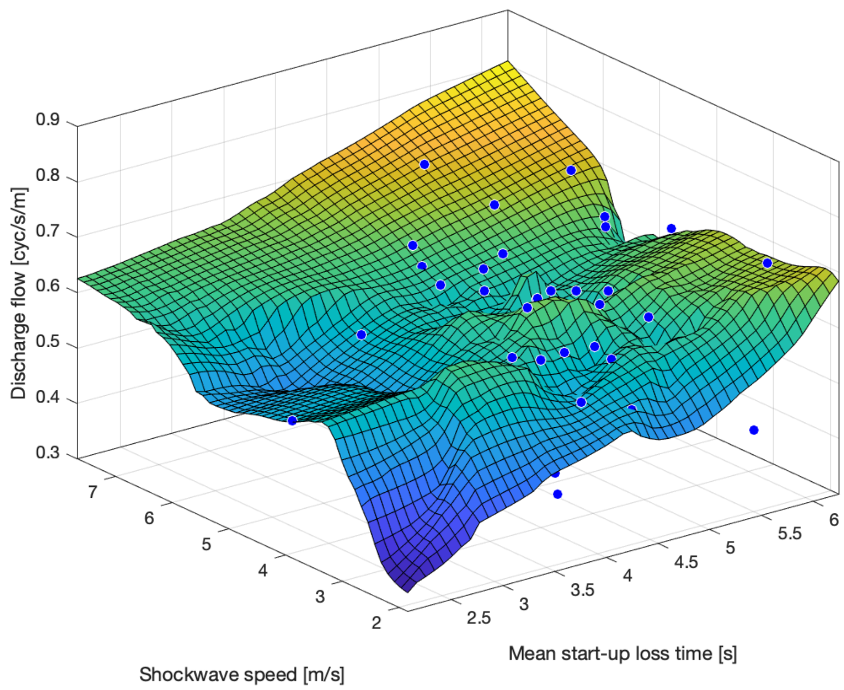

Figure 14: 3D plot mean start-up loss time (w = 1.6 m) and shockwave speed vs. discharge flow

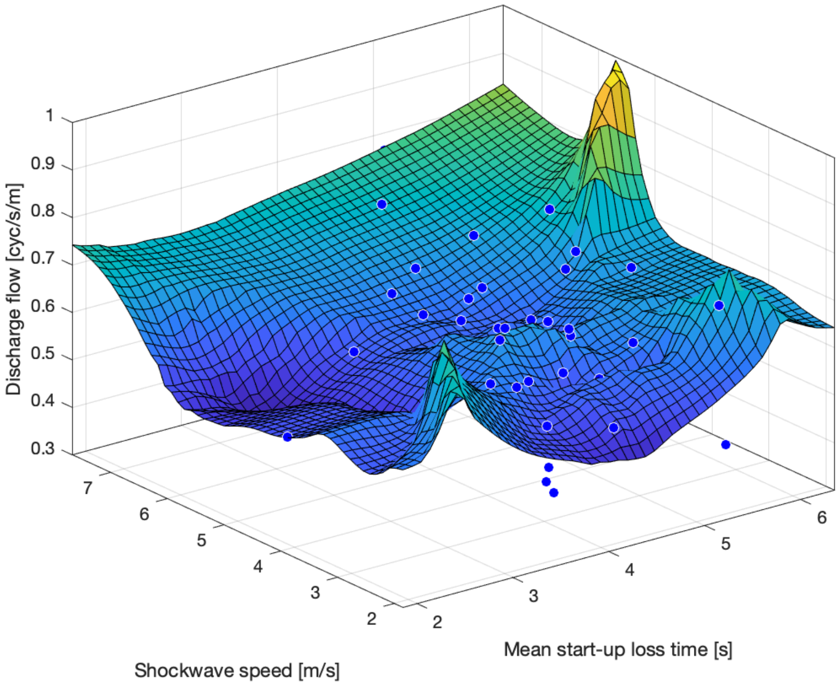

Figure 15: 3D plot mean start-up loss time (original lane) and shockwave speed vs. discharge flow