

# A traffic signal optimization method for balancing the interests of cyclists and motorized traffic

Master of Science Thesis  
Department of Civil Engineering and Geosciences  
Delft University of Technology

Theofili Apostola  
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Keywords: green wave, cyclists, speed advice, traffic signal optimization.

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# Preface

*“Ithaca gave you the marvelous journey.  
Without her you would not have set out.  
She has nothing left to give you now.”  
— Constantine Cavafy*

Welcome to you, reader! In front of you lies my master thesis, with which I endeavor to become a master in the guild of engineers; for the third time. In his poem “Ithaca” Constantine Cavafy uses the familiar story of the Odyssey as a metaphor for the journey of life. In this particular time, this poem symbolizes for me the journey of my student life, which lasted 8 years, from which the last 2 are spent here in Delft. During this journey I obtained wisdom, pleasure and experience. The most important thing during this 8-year-journey is the journey itself and the experiences that I gathered along the way. Following this path I figured out that, if you go long enough you will eventually get back to where you began. As natural as this is, this starting and ending point is simply that: a starting and ending point. It is the path in between that makes the voyage worth living.

There are a number of people that have made this thesis possible. I would like to thank professor Serge Hoogendoorn for helping and guiding me from the very beginning. I am furthermore grateful to my two supervisors, Andreas Hegyi and Martijn van Noort, as without their support I would not have started let alone finished this thesis. A special gratitude goes out to Maria Salomons, since she was always there helping me with all the practical problems. I would also like to thank the two other members of my committee, Paul Wiggeraad and Lui Shuai, for their interest in my research and taking the time and effort to review it.

I am indebted to my family, Georgia, Victor and Eleni, for their understanding, patience, and continual support; without them this 8-year-journey would not be a reality. A special gratitude goes out to my best friend Elli. Last but not least, I would like to thank Ioannis for being able to put things in the right perspective and transferring his programming knowledge to me.

These are the last characters I type; from here on this thesis should speak for itself.



# Summary

This thesis proposes a traffic signal optimization method for balancing the interests of cyclists and motorized traffic. Traditionally, in bicycle traffic has not been given the same priority as motorized traffic in the signalization system planning. As a consequence, cyclists have to stop many times during their journey, which leads to a waste of energy and causes inconvenience, and at the same time experience long waiting times. In other words, stopping for a red light is a primary discouragement to cycling, since it costs a great deal of extra time and energy.

This research relies on this ascertainment and focuses on designing a system which takes into account both types of road users, cyclists and motorized vehicles. Specifically, the proposed system receives the required data from the network, speeds of motorized vehicles and position of both road users, and based on a multi-objective optimization changes the green times of the traffic lights and gives comfortable speed advice to cyclists in order to cross the intersection without having to stop.

For the aforementioned optimization the various objectives, namely delay of motorized vehicles and delay, number of stops and deviation between the desired and the advised speed of cyclists, are formulated and are combined as a weighted sum, as a function of green times and individual speed advice. The delay of both road users is formulated as the sum of the delay because of the traffic signal, the delay because of the queues formed at the intersection and the overflow delay, i.e. the additional delay caused when the arrival rate is greater than the service rate at the traffic signal. In regard to the number of stops, each cyclist receives a cost, every time that he has to stop. Last but not least, each cyclist has a desired speed and deviations of it come at a cost. This cost is higher for speeds higher than the desired speed than for speeds lower than the desired speed. The optimization is performed individually in each intersection when cyclists gets green. The time horizon length is set to 10 cycles and the first cycle of the resulting plan is implemented, before the computation is repeated. The cyclists and the motorized vehicles who arrive beyond horizon, receive a very high cost.

Different scenarios are run in order to test the proposed system. In all scenarios, the average delay and the average number of stops of cyclists decrease, while the average delay and the average number of stops of motorized vehicles increase. The first two scenarios are used for the controller's tuning and offer the first insight of the system. In the following two scenarios, the bicycle green wave is investigated. In the last two scenarios, two different components of the system, the number of stops of cyclists and the comfort of the speed advice are examined. Specifically, in the fifth scenario, the coefficient defining the relative importance of cyclist's number of stops is investigated. Regardless of the value of the

coefficient, the reduction of the average number of stops of cyclists is almost the same, with the highest value 69%. In the sixth scenario, the coefficient defining the relative importance of the deviation between the desired and the advised speed is examined. The higher the value of the coefficient, the smaller the deviation between the desired and the advised speed.

Although, traditionally not much attention is paid to cyclists in the initial adjustment of the traffic light, the proposed traffic signal optimization method takes into account both types of road users, motorized traffic and cyclists. Reduction in the average delay and the average number of stops of cyclists can be achieved, however has as a consequence the increase of the average delay and the average number of stops of motorized traffic. The same is observed about the comfort of the speed advice. In conclusion, it is possible to improve the situation for cyclists, regarding their delay, number of stops and the comfort of their advised speed, however this improvement comes at a cost for motorized traffic.

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# Chapter 1

## Introduction

*“If I had one hour to save the world I would spend fifty-five minutes defining the problem and only five minutes finding the solution.”*

— *Albert Einstein*

One of the characteristics of the Dutch society is its bicycle culture. Cycling became popular in the Netherlands a little later than it did in the United States and Britain who experienced their bike booms in the 1880s, but by the 1890s the Dutch were already building dedicated paths for cyclists (Reid, 2012). By 1911, the Dutch owned more bicycles per capita than any other country in Europe (Reid, 2012). After World War II, however, much like it had in other developed nations, the privately owned motor car became more affordable and therefore more ubiquitous and the bicycle started to be squeezed out. Even so, the number of Dutch people cycling was very high compared to other European nations (Reid, 2012).

### 1.1 Problem Statement

The efficiency of traffic flow is one of the most important considerations in transportation planning. Traditionally, bicycle traffic has not been given the same priority as motorized traffic. Most of the times, cyclists experience long waiting times because not enough attention is paid to them in the initial adjustment of the traffic lights. Whereas stopping for a red light leads to increasing delay for motorized traffic, it is also a waste of energy for cyclists. Acceleration after a stop and the effort that is made in order to regain the former speed quickly, causing inconvenience (Fajans & Curry, 2001). Furthermore, it is a struggle for some cyclists to keep their balance in the time that they are decelerating. The phenomenon becomes even worse when the cyclist carries a lot of baggage or transports a passenger. Just imagine, the difficulty faced by a mother to keep the bicycle upright and get started



Figure 1.1: Dutch mothers transporting kids on a bicycle.

again after a stop with children in front and in back. The importance of cycling in the Netherlands is undeniable, considering the bicycle policies that have been developed in order to encourage and stimulate the use of bicycle (Appendix A). However, more innovative solutions should be applied, since the problem is still relevant.

Stopping for a red light constitutes also a problem for users of E-bikes, especially for elderly. Its total extra weight has as a consequence the difficulty to getting off the E-bike at intersections. The removable battery and electric motor result in 5-10 *kg* additional weight on the E-bike. Therefore, it is 25%-50% heavier than the non-electric version. Furthermore, it should be mentioned that a significant rate of accidents associated with E-bikes are caused by starting up and slowing down before and after a stop (Lenten & Stockmann, 2010). In the acceleration phase the E-bike should change gears and this process is accompanied by little shocks (Lenten & Stockmann, 2010).

In sum, there are a number of problems that are faced by cyclists at signalized intersections, namely:

- stops at traffic lights;
- the manual registration of their appearance in the intersection by pushing a button, forces them to get off their bicycle;
- long waiting time at traffic lights;
- insufficient responsiveness in the signals, so that the cyclist stage is only available at a certain point in the signal cycle, regardless of demand.

Stopping for a red light is a primary discouragement to cycling (Rietveld & Daniel, 2004); it costs a great deal of extra time and energy (Fajans & Curry, 2001) and imposes additional stress on the body which can lead to injury (Meggs, n.d.). In addition, according to Sharples, the peak hour for cyclists is much more pronounced than for motorized traffic

(Sharples, 1997) and commuting cyclists prefer controlled environments, for instance traffic controlled intersections (Aultman-Hall, Hall, & Baetz, 1997). Based on these statements, it becomes easily understandable that intervention at signalized intersections in favor of cyclists is more than justified.

The following subsections, namely “Red Light Infringement” and “Cyclist’s Preference on Signalized Intersections” are presented below in order to strengthen the statement that a lot of problems are associated with stopping for a red light at signalized intersections. More specifically, different studies which were carried out to investigate the violation of red light from cyclists, showed that this phenomenon is not so rare (Chapter 1.1.1). In addition, other researches which were conducted to investigate the preferences and behavior of cyclists, showed that sign stops and signalized intersections reduce the utility of cyclists, since they increase their stops and delay (Chapter 1.1.2). In other words, these sections enable the reader to understand the problem and the fact that there is a need for intervention in order to find solutions.

### 1.1.1 Red Light Infringement

Red light infringement is frequently cited as the cyclist behavior that most annoys drivers and is perceived as typical cyclist behavior (Fincham, 2006; O’Brien, Tay, & Watson, 2002; Kidder, 2005). In 2007, a survey, based on questionnaires, was conducted among 11-13 year old children. 60-70 in every 100 of these children stated that they have violated the red light in their lives (Twisk, Vlakveld, & Commandeur, 2007).

In 1996 van Lieshout, evaluated the “All directions green” system at nine intersections in Deventer (2 intersections), Eindhoven (3 intersections), Enschede (3 intersections) and Zwolle (1 intersection). According to this system, cyclists get green simultaneously, regardless their direction. During observation, the red light violation was found between 3.1% - 18.8% of all cyclist’s passages (Lieshout, 1996). The smallest rate (3.1%) was observed at one of the two intersections in Deventer and the largest (18.8%) at one of the three intersections in Eindhoven.

In 2008, another research was carried out in order to examine the effects of a weather dependent traffic signal control. The study took place only at one intersection. With temperatures below 10 °C, rain or combination of these two, the cyclist traffic light had two or three realizations per cycle. On the other hand, with temperatures above 10 °C and without rain, the cyclist traffic light had only one realization. It was found that more than a quarter of cyclists violate the red light when it was raining and one tenth of them when it was cold (Harms, 2008).

Last but not least, an observation study which was conducted in Amsterdam, in 2010, showed a variation of 29% to 42% red light running depending on the different directions

of an intersection. On two intersections the red light running was measured in order to determine, by pre-post measurements, the effect of communicative measures on red light running (Rooij & Dam, 2010).

Crash data for the Netherlands over the period 1993-2009, which consists of all the registered crashes where a cyclist was involved, showed that a total of 4599 cyclists violated the red light and were registered as injured. The percentage of cyclists' crashes due to red light negation was 11.0% of all crashes. The rate of dead over the total of cyclists died in crashes was 12.1%, the rate of severely injured over the total of severely injured cyclists was 12.1% and the rate of lightly injured over the total of lightly injured cyclists was 11.4% (van der Meel, 2013).

From the above, red light infringement is one of the most obvious illegal and risky behavior of cyclists. Interference in the signalization system in favor of cyclists in order to minimize the times that they have to stop at traffic signals, could be a solution in this problem.

### **1.1.2 Cyclists' Preference on Signalized Intersections**

In 2010, in Portland, a research was carried out with a view to better understand cyclist's preferences. Bicycle-mounted GPS units were used to observe the behavior of 162 cyclists for several days each. Data that were obtained from intersections, which are relating to intersection control and traffic volumes, showed that cyclists consider stop signs and traffic signals as delay factors. However, traffic signals may be preferred from them, depending the amount of conflicting motorized traffic, at busy intersections (Broach, Dill, & Gliebe, 2012).

In general, traffic signals and stop signs, have as a consequence the decrease of the utility of a route. However, traffic signals at intersections when the conflicting traffic volumes are high, create positive effects to cyclists, which can balance the negative one. The aforementioned phenomenon is caused either because traffic signals actually reduce delay at busy intersections, or because they increase perceived safety, or a combination of the two. These results demonstrate the importance to cyclists of signalized intersections at busy street crossings (Broach et al., 2012).

Bernhoft and Carstensen (2008) studied the preferences and behavior of older pedestrians and cyclists (women and men, 70 years and above) by means of a questionnaire, and compared them with the preferences of a group of people aged 40-49. It was found that the older respondents appreciate pedestrian crossings and signalized intersections significantly more than the younger respondents do, since they feel more safe. In the younger group, though, a significantly higher proportion of women than men would choose a route with signalized crossings whereas a significantly higher proportion of men would choose the fastest

route. In general, the study showed that the younger group finds it more important to move fast and directly in traffic. On the other hand, the older respondents take it easier: they more often than the younger group argue that it is no inconvenience to wait or to stop.

From the above studies, the general conclusion is that most of the times signalized intersections act as a inhibitor factor for cyclists, especially for younger people, since they cause inconvenience and delay. So, both the stops and delay are important to them. This common observation, that delay appeared to have significant influence on commuting cyclists, has been already mentioned in different studies (Aultman-Hall et al., 1997; Howard & Burns, 2001; Stinson & Bhat, 2003). On the other hand older people prefer signalized intersections because they feel them more comfortable and safer. It is easily understandable, that the minimization of number of stops and the minimization of delay are going to create positive effects to both group of cyclists.

## 1.2 Research Objective

Cycling could be the preferred means of transport because it could be the quickest and easiest way to get around town. It is the glue that keeps people's lives together; allowing people to connect their everyday tasks in a smooth manner. However, in order to be the bicycle the quickest and easiest transport mode, the minimization of number of stops of cyclists is required. One of the things a city can do to accommodate bicycles and achieve this goal, is to create a green wave for the cyclists. Green waves can be created in the following ways:

1. by giving speed advice to cyclists based on fixed green times (Egmond, 2013);
2. with traffic signals synchronization which assuring consecutive green lights for cyclists if they travel with a constant speed;
3. by giving speed advice to cyclists and at the same time with intervention in the signalization system in favor of them (combination of the above).

**Option 1.:** By giving speed advice to cyclists, for instance with a speed advice system (Egmond, 2013), without optimizing the traffic signals in favor of them, and by taking into account only the fixed green windows, uncomfortably low or high speed advice may occur depending on the distance from the intersection. Considering that bicyclists are characterized by different desires, strength, physical fitness, age and skill, likewise differences in bicycle technology and maintenance, they are not always able to follow a certain advice, i.e. it is not always possible for them to reach the intersection while is green, and as a consequence they have to stop and wait to be served in the next cycle.

**Option 2.:** Traffic signal coordination that provides progression for cyclists, in other words creation of a bicycle green wave by following a constant speed, is definitely beneficial for them since stopping causes inconvenience. However, the impacts on motorized traffic may be adverse: increasing travel times and delays. In addition, a main disadvantage of this approach is that most of the cyclists do not have speedometers attached in their bicycles, and as a result they do not know which is the appropriate speed that they have to maintain to follow the green wave.

**Option 3.:** Taking into account the disadvantages of the first and second option, this research will focus on the last of the aforementioned solutions. In this case, speed advice will be given to cyclists which will be derived of the dynamic optimization of traffic signals, since very low or high speed advice is not desired. In order to make cycling more comfortable and to encourage cyclists to continue riding rather than shifting to vehicles, travel-time costs of both groups must be incorporated in signalization system planning. Several performance criteria can be used to evaluate a signalized intersection, such as average delay, average number of stops, average queue length and average travel time. Among these indicators, delay is perhaps the most important since it is easily understood and related to travel costs. For example, Highway Capacity Manual uses it as the only measurement to determine the level of service of signalized intersections (TRB, 1985). As a result, this indicator will be taken into account for both cyclists and vehicles. As the main objective of this research is to create a green wave for cyclists to cross the intersection without to stop, the minimization of number of stops for cyclists is another important measure of effectiveness.

*Therefore, the main objective of this research is to design a system that has a double function: optimizes the traffic lights by taking into account the number of stops, delay and desired speed of cyclists and delay of motorized traffic and gives comfortable speed advice to cyclists, which are derived from the optimization, in order to cross the intersection without to stop.*

The aforementioned problem can be divided in two sub-problems, namely traffic signal optimization and speed advice; each of them interacts with the other. The type of the traffic control and the different objectives are critical components of the first sub-problem (traffic signal optimization). For the second sub-problem, the range of comfortable speed advice should be determined.

**Traffic Signal Control:** One of the main components of the system is the traffic signal control. This component of the system controls the green phases for each signal group at the intersection. There are three different types of control, namely fixed-time control, actuated control and adaptive control. In the fixed-time control, the duration and the order of all green phases is fixed. Actuated control is more efficient than the fixed-time

control, since requires “actuation” by a vehicle, pedestrian or cyclist in order for certain phases or traffic movements to be serviced. Adaptive traffic signal control is the process by which the timing of a traffic signal is continuously adjusted based on the changing arrival patterns of vehicles at an intersection. In this research, two different types of controller were considered: VRIGen (actuated control) (Theo HJ Muller & de Leeuw, 2006) and MALATACS (multi-agent look-ahead traffic-adaptive control) (Van Katwijk, 2008).

**Objectives:** The optimization of the traffic lights will take into account multiple objectives; delay of motorized vehicles, and delay, number of stops and comfort of the advised speed of cyclists. For this multiple-objective problem, the objectives are conflicting, preventing simultaneous optimization of each objective. Due to this contradiction, a number of optimal trade-off solutions could be rise. These solutions form different trade-offs among the conflicting objectives, i.e. any objective cannot be improved without worsening the others.

**Comfortable Cyclist’s Speeds:** Different studies have been conducted in order to determine the desired speeds of cyclists. For instance, Wachtel, Forester, and Pelz (1995) for a ITE study summarized the speed of cyclists in three categories: fast, typical and school children cyclists. The observations included 26 *ft/sec* (28.5 *km/h*) for fast cyclists, 18 *ft/sec* (19.8 *km/h*) for typical cyclists and 13 *ft/sec* (14.3 *km/h*) for school children. The UC Davis’ study that was conducted by Rubins and Handy (2005) for bicycles, showed the bicycle speed 33 *ft/sec* (36.2 *km/h*) for the fastest cyclists, 13.5 *ft/sec* (14.8 *km/h*) mean speed, and 18.57 *ft/sec* (20.4 *km/h*) 85<sup>th</sup> percentile speed. Last but not least, when field observations are not available AASHTO recommends using 17.6 *ft/sec* (19.3 *km/h*) for advanced cyclists, 12 *ft/sec* (13.2 *km/h*) for basic cyclists and 9.1 *ft/sec* (10 *km/h*) for children and seniors (AASHTO, 1999). One of the things that could be done in order to improve traffic flow, is to form platoons of bicycles, which will move together, because there are empty areas between platoons with few interferences. One way to create platoons of bicycles is to divide cyclists in different categories depending their desired speed.

Considering all the above, in order to give an appropriate representation of the process playing a role in such a system, the main research objective must be supported by research questions that indicate the critical components of the system. These critical components can be found in the following points of interest:

1. selection of type of controller;
2. selection of traffic signal optimization’s objectives;
3. investigation of bicycle green wave;
4. investigation of appropriate speed advice range;

5. investigation of bicycle platoon formation;
6. investigation of optimal trade-off solutions among the contradicting objectives;

The research is mainly focused on the proposed system itself and its critical components. There are some components that inevitably come along with the system, but also some external factors that cannot be neglected. The system has two functions: optimizes the traffic lights and gives speed advice to cyclists. For the traffic signal control, the needed data (e.g. speed, position) should be collected from the network, and as a result devices that can provide this kind of information are necessary. These devices could be induction loops, detectors or cameras. Regarding the speed advice, the proposed system should also have some components for providing the related information to cyclists. In other words, a medium is needed in order to provide the speed advice to cyclists. Since the speed advice is different for each cyclist, this could be an information sender on board of the bicycle, e.g. an application on the mobile device. The components of the system are presented in Figure 1.2.

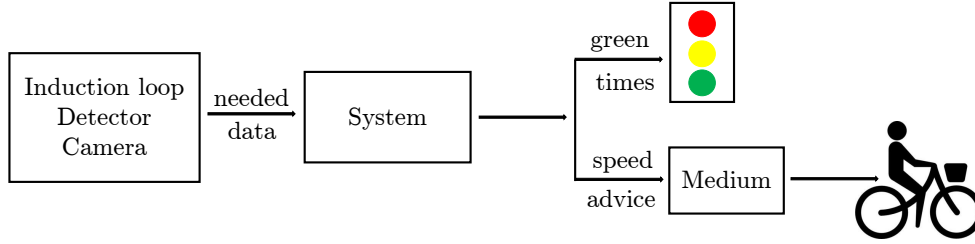


Figure 1.2: Components of the system.

### 1.3 Scientific Relevance

As it is mentioned before, some attempts have been done in order to minimize the number of stops of cyclists in signalized intersections. Egmond (2013) designed a speed advice system for cyclists in order to help them to arrive at the intersection when the traffic light is green, and as a consequence to cross it without having to stop. Although, he took into account the desired speed of cyclists, very low or very high speed advice may occur, since he did not intervene in the signalization system planning. In other words, the speed advice system communicates with the traffic lights and based on the green and red times, advises the cyclists about the speed that they have to follow in order to cross the intersection without to stop.

Traditionally, bicycle traffic has not been given the same priority as motorized traffic. The most important contribution of this research is that the proposed system not only

takes into account the cyclists in the initial adjustment of the traffic lights but also gives to them comfortable speed advice in order to cross the intersection without to stop, since the comfort of the speed advice is one of the optimization's objectives; the green times and the speed advice are the optimization variables.

Finally, it should also be mentioned the fact that, in this thesis a distinction is made between the speed advice that is higher than the desired speed and that which is lower, since for the cyclist is easier to slow down instead of speeding up.

## 1.4 Methodology

To answer the research questions posed, this thesis relies on literature, development of theoretical and mathematical model and simulations. Literature is used for investigation of the bicycle green wave alternatives and the type of controller that is used. The theoretical and mathematical model is designed by taking into account the contradicting objectives for both road users, cyclists and motorized vehicles, and is implemented in MATLAB. Last but not least, simulations are run in order to test the proposed system.

## 1.5 Outline of the Report

In Chapter 2 the literature review is presented. In Chapter 3 the conflicting objectives which are used for the traffic signal timing optimization are described and the theoretical and mathematical framework is developed. In Chapter 4 the system's implementation is analyzed, and the different software that are used and the achieved communication between them are described. Chapter 5 presents the results of the proposed model which are obtained from running simulations for different scenarios. Finally, Chapter 6 contains the conclusions of this thesis as well as recommendations for future research.

## 1.6 Conclusions

In this chapter the problems that are faced by cyclists at signalized intersections are presented. In addition, different studies which were carried out to investigate the violation of red light from cyclists, showed that this phenomenon is not so rare. In addition, other researches which were conducted in order to investigate the preferences and behavior of cyclists, showed that sign stops and signalized intersections reduce the utility of cyclists, since they increase their stops and delay. The aforementioned reasons lead to the conclusion that both, number of stops and delay, are important to cyclists, and should be taken into account in an attempt to intervene in the signalization system in favor of them. Furthermore,

the main objective of this thesis is presented, which is supported by research questions that indicate the critical components of the proposed system. Finally, its scientific relevance is indicated.

## Chapter 2

# State-of-the-art

*“Study the past if you would define the future.”*

— *Confucius*

After the formulation of the research objective, the literature survey is required to find supporting knowledge on the professional literature. The first part of the literature survey is to get acquainted with different existing options which aim to improve the traffic conditions for cyclists, since this research has the same goal. The second part presents the existing ways to create green waves for cyclists, as they have been mentioned in Chapter 1, namely speed advice to cyclists based on fixed green times (speed advice system) and traffic signals synchronization which assuring consecutive green lights for cyclists if they travel with a constant speed. In the third part, the different types of signal control are presented, because the signal control constitutes one of the main components of the proposed system, and a choice is made between the two controllers that were considered to be used in this thesis. Last but not least, one of the things that this research is focused on, is the traffic signals optimization, and as a result past research efforts which examine various signal timing optimization methods with different objectives are presented.

### 2.1 Systems That Take Cyclists Into Account

The existing literature on technologies for automatic bicycle detection is remarkably limited, perhaps because of the limited attention paid to bicycling issues in the developed countries. Since the main objective of this research is the minimization of number of stops of cyclists, it is interesting to present some examples of bicycle detection in different cities all over the world.

During the mid 1980's, in Beijing, in China, the increased traffic volumes lead the authorities to implement an urban traffic and control system in a section of the city. The

chosen system was the SCOOT traffic control system (Split Cycle Offset Optimization Technique). The system takes into account the cyclists traveling along a link, by detecting them with a loop detector, which is located a short distance from the stop line. The team established a composite measure of bicycle flow and occupancy called a Bicycle Link Profile Unit (BLPU) which was capable of aggregation with the normal SCOOT Link Profile Unit (LPU). This enabled the bicycle link to be incorporated into the standard SCOOT model in the same manner as other links. Weighting functions are then available to advantage or disadvantage the bicycle traffic stream relative to the motorized traffic stream (Wood, Bretherton, & Duan-Li-Ren, 1998).

The second example concerns the city of York in the United Kingdom. Based on the percentage of cyclists (the level of commuting by cycles is high at 19% of trips) and the level of congestion on the roads, the local authority uses different techniques, appropriate in the given circumstances. The “tail-end biasing” technique provides offsets at the ends of greens which are coordinated in favor of slower modes, like bicycles and buses. Another technique includes the detection of cyclists by using SCOOT detectors in cycle paths, and “dummy” SCOOT loops which shadow existing SCOOT links. In addition, more and more microwave detectors are used, which are able to accurately detect cyclists if they are traveling at 10 *km/h* (6.25 *mph*) or more (Clark & Page, 2002).

The third example is from the United States, where the Montana Department of Transportation has upgraded the traffic signal equipment in order to take into account the bicycles as well. Special attention was paid in the effectiveness of new loop designs in detecting bicycles. The loop design that finally introduced, is the one from the California University, in which a line and a symbol were used to mark the roadway. This path over the loop was most sensitive for bicycles (Maki & Marshall, 1997).

## 2.2 Green Wave’s Alternatives

As it has been already mentioned, one of the things that could be done in favor of cyclists, is the creation of bicycle green waves. In this section the first two aforementioned alternatives are presented. The first one is the speed advice system which is designed in order to reduce the number of stops for cyclists by giving them speed advice. Regarding the second alternative, traffic signals synchronization at cyclists speed, some of the most important green waves, which have been created for cyclists in different cities in the world, are presented.

### 2.2.1 Speed Advice System

Egmond (2013) designed a speed advice system for cyclists in order to help them to arrive at the intersection when the traffic light is green, and as a consequence to cross it without having to stop. Two speed advice systems are designed for the different types of controllers that are used at intersections.

For the fixed time controller, a speed advice is given to the cyclist once, at some distance from the intersection, in order to travel in the fastest possible way. The cyclists who is approaching the intersection with the recommended speed, is able to cross it without to stop.

For the actuated controller the cyclist should adjust his speed dependent on the state of the traffic light controller, resulting in a more flexible design of the system. The changing state of the actuated controller does not match with a speed advice that is given once at a certain distance from the intersection and should be followed until the cyclist reaches the intersection. In this case, by taking into account the state of the controller, multiple speed advice might be given to the cyclists. The flexibility of the system allows it to adjust the speed advice to the preferences of the user. In other words, the speed advice is the result of a function that describes the personal preference of the cyclist and a function that describes the utility of arriving at the intersection during the green light.

The disadvantage of this approach is that, the presence of the cyclist at the network is not taken into account by any of the controllers, and as a result uncomfortably very low or high speed advice may occur. However, the motorized traffic has not differences in the realization of green phases by the implementation of the system.

### 2.2.2 Traffic Signals Synchronization at Cyclists Speeds

The world's first green wave for cyclists was created in Odense, in Denmark. Along a bicycle route 45 low poles have been placed between two intersections, over a distance of some 350 meters, each provided with a light. The lights turn green one after the other, at an interval of some seconds. Following the timing of the lights, the cyclist has the right speed for a green wave. However, the problem is that cyclists have widely varying cruising speeds (Andersen, 2013).

In the autumn of 2006 a green wave for cyclists has been realized on Norrebrogade, in Copenhagen, by the local authorities. The green wave affects 12 traffic lights over a stretch of road of over 2 *km*. The idea is that if the bicyclist rides 20 *km/h*, he will hit green lights the whole way into the city center. The traffic lights are coordinated during the morning rush hour between 6 : 00 - 10 : 00/12 : 00 (depending on the route) and then the wave reverses so the lights are coordinated in the opposite direction between 12 : 00/15 : 00 - 18 : 00 for the trip home. Norrebrogade is a major route for both motorized and bicycle

traffic. The results for bicycles are very positive, considering the decrease of number of stops from 6 to 0 and the increase of speed from 15.1 to 20.7 *km/h*. The green wave for cyclists has also realized on three other roads (Hoegh, 2007).

In the autumn of 2007 Raadhuisstraat in Amsterdam was provided with a green wave for cyclists. At an average speed of 18 *km/h* cyclists encounter 11 green traffic lights in row over a distance of a little over 500 meters. Although most cyclists travel to the west in the afternoon peak hour, there is also a reasonable number going towards to the town center. So a green wave for both directions has clear advantages. As a consequence, the green wave for cyclists works for both directions. However, vehicle traffic becomes slower (Amsterdam, 2007).

In 2009, the Valencia Street Green Wave was started as a temporary pilot on Valencia Street, between 16<sup>th</sup> and 21<sup>st</sup> streets, in San Francisco, aimed at prioritizing bicycle traffic. After two years, the pilot program became a permanent institution and extended to 25<sup>th</sup> street. The signal optimization keeps bicycles traveling at a steady speed of 13 *mph* to encounter a green light at 10 timed traffic signals. San Francisco's green wave works in both directions simultaneously (Bialick, 2011).

In the summer of 2010, at Schieweg, in Rotterdam, lights were located in the road to indicate which speed cyclists should maintain in order to pass traffic lights without having to stop. The Rotterdam system, Evergreen, consists of LED lights, every 5 meters, starting at a distance of a few hundred meters in front of the traffic light. The LEDs display green blocks and any cyclist riding within a green block is guaranteed unhindered passage at the next traffic light. The green LED's nearest the traffic light appear more slowly than those farther away, so cyclists near the light are slowed down a little and those at the back are speeded up (Fietsberaad, 2010).

The city of Graz, in Austria, in order to reduce the number of stops for cyclists and pedestrians, has renewed its system of traffic light controlled crossings, and has created a green wave for these two types of road users. In this case, the traffic lights remain green for cyclists and pedestrians and changes in favor of cars only if they cross an inductive loop (embedded under the road surface 100 *m* before the crossing). The car driver has the chance to cross the intersection without to stop, if he approaches at a constant speed of 40 *km/h*. However, on working days, there is a fixed cycle time of 40 *sec*, due to a higher circulation of traffic, and as a result pedestrians and cyclists have to wait 28 *sec* before they are able to cross the road. This time is shorter than the previous one, and the probability that they can cross the road without having to wait at all, is 70%-86% (Magnes, 2011).

### 2.3 Traffic Signal Control

Traffic lights are used to allocate the limited resource of space within the intersection needed by conflicting traffic streams by activating the corresponding phase, i.e. switching traffic lights to green. In the following a short introduction will be provided to the possibilities how the signal control can be adapted to the actual traffic demand. Traffic controllers can be classified according to the method in which they allocate green time for each phase and can be roughly classified into three types of control: fixed-time control, actuated control and adaptive control.

#### 2.3.1 Types of Control

##### Fixed-time control

The simplest way to control an intersection is called fixed-time control. Under fixed-time control, also called pre-timed control, the duration and the order of all green phases is fixed. In this type of control, historical data is used in order to predict the traffic patterns, and as a result it can operate without traffic detectors installed at the intersection. The use of historical data instead of real-time data is the main disadvantage since it is not able to adapt itself. The lack of adaption leads to inefficient capacity usage, like giving green to traffic streams on which there are no cars at the moment. Based on the historical data, the signal cycle is divided over the various phases. Thus, the behavior of the controller is not influenced by the actual traffic situation, but it can be optimized to fit the traffic situation expected on average while the controller is active. This can be done by switching between pre-optimized parameter sets at fixed times of day, e.g. to consider different traffic patterns during the morning and evening peak periods. Because of the simplicity of the fixed-time controller, the number of parameters to be tuned is limited, namely cycle time, splits, phase sequence and offset. Cycle time is defined as the time needed until all phases have been activated. In order to split this cycle time into fractions of appropriate lengths, the sequence of all phases is considered. Finally, the offset is used in order to coordinate intersections. In this case, a global timer is used and the starting point of the cycle is shifted by a certain offset.

In other words, this type of control is well suited where the traffic pattern is predictable, but does not recognize or accommodate short-term fluctuations in traffic arrivals and long-term changes in traffic patterns.

##### Actuated control

The main difference between fixed-time and actuated signal control, is that actuated control requires “actuation” by a vehicle, pedestrian or cyclist in order for certain phases

or traffic movements to be serviced. Actuation is achieved by vehicle detection devices and pedestrian/cyclist push buttons or detectors. Two types of detectors are used: request detectors (detectors in the stop line) and loop detectors further away from the stop line. The request detectors detect the presence of traffic while red. Based on this, the traffic light controller skips the green period of the traffic direction that has no demand in a certain cycle. On the other hand, the loop detectors further away from the stop line are used to determine the duration of a green phase for a traffic direction. When the detector is not occupied during some time (defined as critical gap time), the green phase can be terminated. All signal phases have preset minimum and maximum green times and will be serviced on demand only. Actuated signal control provides greater efficiency compared to pre-timed signals. However, as the traffic demand on the network increases, the efficiency of the actuated controller decreases. This is happening because when large queues are constantly detected for all intersections, actuated controllers tend to resemble fixed-time controllers. Bretherton and Rai (1982) found that at utilization of about 80% of the maximum capacity, there is no difference in performance between the SCOOT system and a fixed-time strategy.

### **Adaptive control**

Adaptive controller is the latest solution in the field of traffic signal control. In this type of control, usually the same detection data as in the actuated control are used. Adaptive traffic signal control is the process by which the timing of a traffic signal is continuously adjusted based on the changing arrival patterns of vehicles at an intersection. During the process, a traffic signal provides green time to each intersection approach based on anticipated arrivals for adjacent intersections. As arrival patterns change from cycle to cycle, the length of green time provided to each approach also changes. Under traffic-adaptive operation the state of the entire intersection is taken into account in the decision to either continue the current green phase or to switch to a different phase, in contrast with the actuated control where the decision to switch or to extend is based purely on the presence of demand on the active green phase. Using this information the adaptive control system continuously optimizes the signal plan.

It is also important to realize that changing the traffic signal settings will cause changes in the flow and that changing the flow should cause the signal settings to be recalculated. This has given rise to a number of papers considering the two problems at the same time, also known as the Network Design Problem. Allsop and Charlesworth (1977) presents an iterative procedure which optimizes traffic signals and then solves the traffic assignment problem until mutual consistency is achieved. Chiou (1999) uses a gradient projection method for finding local optima combined with a global heuristic search. Teklu, Sumalee, and Watling (2007) tackles the problem by including a network equilibrium model as a

constraint to the traffic signal timing optimization. However, adaptive systems are less dependent on a large database of historical flow data since they use online data input from detectors. Thereby, they do not have to consider the problem of mutual equilibrium between signal settings and user equilibrium in the same degree as the offline systems.

#### 2.3.2 Design Tools

Two different types of controllers, namely VRIGen (Theo HJ Muller & de Leeuw, 2006) and Multi-Agent Look-Ahead Traffic-Adaptive Control (MALATACS) (Van Katwijk, 2008) were considered to be used in this thesis.

##### VRIGen

VRIGen (Traffic Control Generator) has been developed in Delft University of Technology to find the optimum structure, minimum total cycle time and green times for all traffic streams. All possible control structures are generated from VRIGen, by using the mutual conflicts between traffic streams and the coupling between streams on the intersection. For all those structures the cycle time is computed, which depends on the flow and the capacity of the traffic streams and the clearance times between streams. All structures that have less than the prescribed maximum cycle time, ordered by increasing cycle time and are presented from VRIGen to the user (Salomons, 2008). The structure description and tactics that are chosen from the user are saved in the control program TrafCod (Furth & T. Muller, 1999) and through a COM-interface it communicates with VISSIM.

As it is mentioned above, VRIGen uses streams and their conflicts as input to generate structures. First the conflict groups are determined and then all possible structures are generated. The structures are determined by finding all possible rankings of the full conflict groups. The other conflict groups which have fewer streams than the full conflict groups are fit in the structure. Then VRIGen tries to fill in the empty stages in the structure (Salomons, 2008).

In Figure 2.1 the flow diagram for the minimum cycle time determination as used in VRIGen is given.  $T_{Ci}$  is the cycle time of the conflict group: the difference between the offsets of the first stream of the conflict group in this and next cycle. This should be smaller or equal to the minimum cycle time. If  $T_C > T_{CMax}$  the structure is discarded, but the user is warned that the  $T_{CMax}$  must be increased to find all structures (Salomons, 2008).

VRIGen finds the path by generating the structure with the given  $T_C$ . Based on this value, the green times are calculated and the offsets of the different streams are determined. The resulting conflict group cycle time  $T_{Ci}$  should be smaller or equal to  $T_C$  (Salomons, 2008).

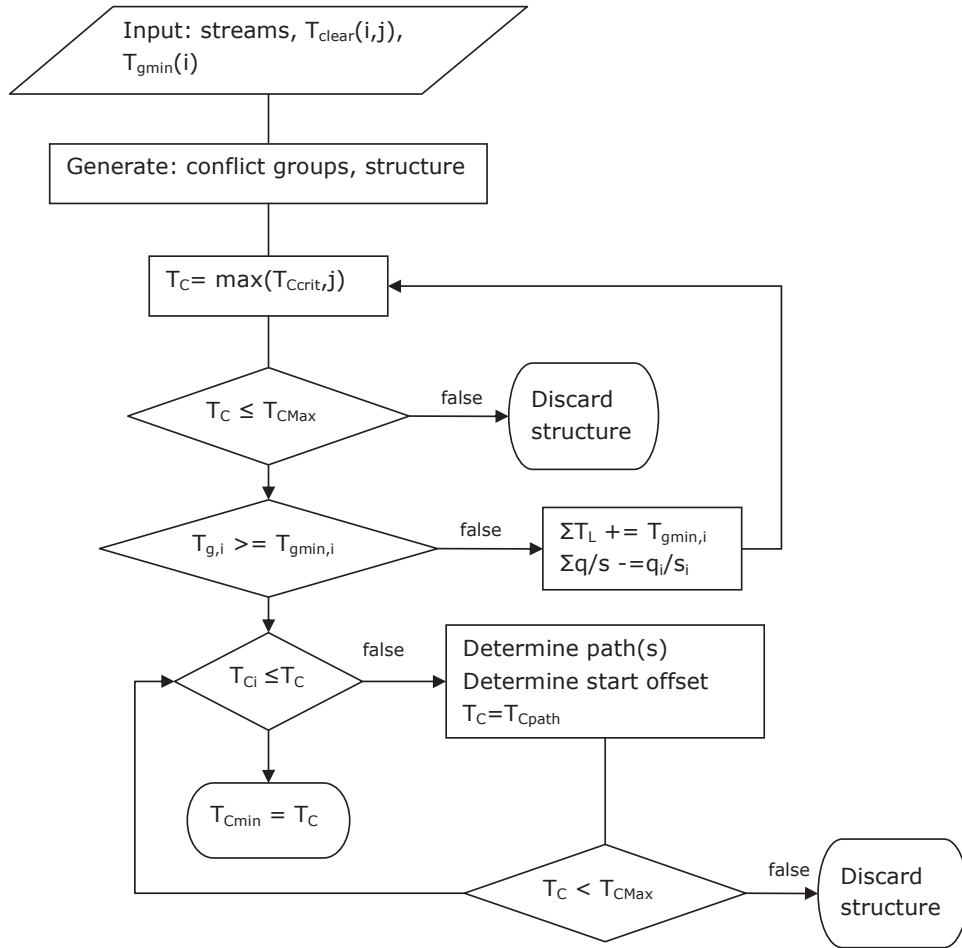


Figure 2.1: Flow diagram for determination  $T_{Cmin}$  as used by VRIGen (Salomons, 2008).

However, VRIGen cannot determine structures that have minimum delay or number of stops for given streams. This is a limitation in the context of this thesis, which requires programming effort in order to be overcome. Even though this effort is made, the values that can be changed are limited to timers values; the structure of the control cannot be changed. In other words, only green times can be extended or cut off. If it is decided that an advice speed is only possible when the control structure changes, this change cannot be realized.

### **Multi-Agent Look-Ahead Traffic-Adaptive Control System (MALATACS)**

According to Van Katwijk (2008), traffic actuated control suffers from tunnel vision as it does not consider traffic on the other approaches; decides to either extend the active green phase or to switch to the next phase based on whether vehicles are still present on the approaches of the active green phase. Traffic adaptive control differs from the actuated control, since it can evaluate a set of feasible control decisions and choose the most optimal with respect to its current objectives. A look-ahead traffic-adaptive control additionally is capable to determine the optimal control decision on the basis of a longer term analysis which often incorporates information from further upstream. Considering the disadvantages of the traffic actuated control and the advantages of the traffic adaptive and the look-ahead traffic-adaptive control, Ronald van Katwijk developed the Multi-Agent Look-Ahead Traffic-Adaptive Control System (MALATACS) at TNO and Delft University of Technology.

MALATACS gets information about the current traffic state through the loop detectors. An expected arrival pattern can be created based on this information. Based on these arrival patterns, the controller “knows” when and in which streams vehicles will arrive and when and between which streams will conflicts occur. At this point, the controller is able to create a signal plan which minimizes the delay or/and the number of stops of all users approaching the intersection (see Figure 2.2). The optimization of signal plan is done by dynamic programming in the controller. This whole process results in the decision tree in Figure 2.3 (Van Katwijk, 2008).

At every time step a decision is made by the controller that will affect the delay or/and the number of stops of the users arriving at the intersection. From every decision made the system gets into a new state and the controller has to make a new decision and as a result the decision tree grows one level every step. This process is not infinite since the time horizon limits the number of levels of the decision tree. The first decision from the path having the lowest cost is implemented at every time step (Van Katwijk, 2008).

By taking into account the advantages and disadvantages of each controller, a decision is made regarding which will be used in this research. Although, MALATACS is an

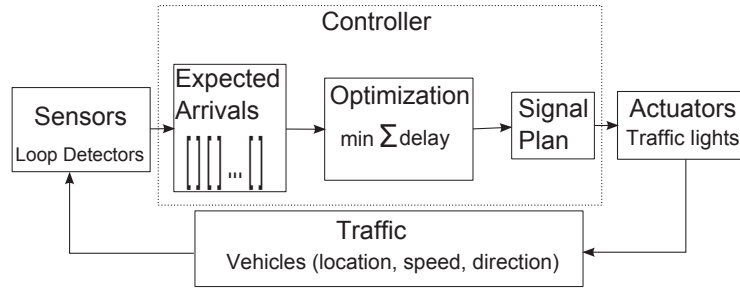


Figure 2.2: Operation of MALATACS (Van Katwijk, 2008).

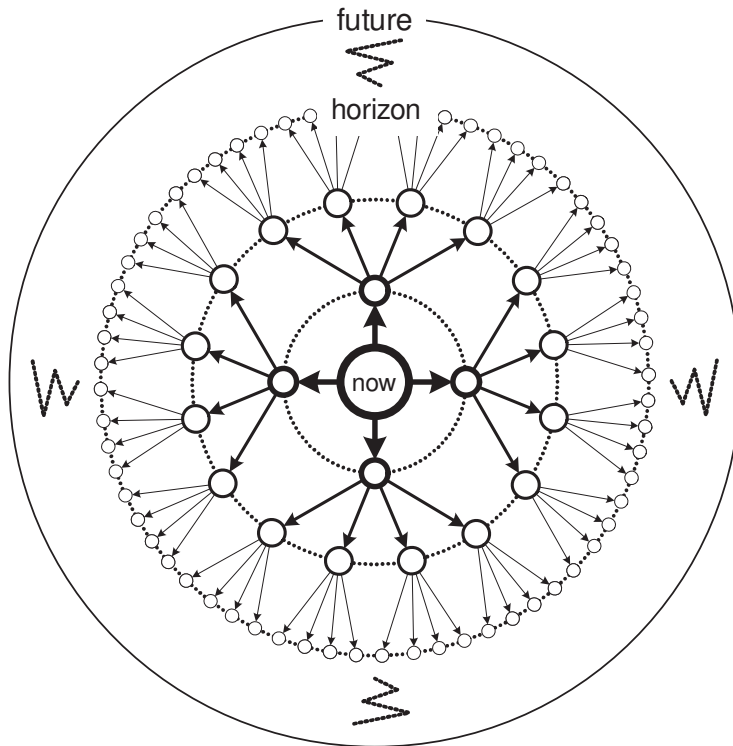


Figure 2.3: Visualization of the decision tree used in MALATACS (Van Katwijk, 2008).

adaptive controller, which continuously optimizes the signal plan, VRIGen is considered more appropriate for this thesis, due to its simplicity and the fact that it is an actuated controller, in other words widely implemented in the Netherlands in comparison with adaptive controllers.

## 2.4 Traffic Signal Optimization

Signalized intersections are a critical element of an urban transportation system. Therefore, maintaining these control systems at their optimal performance by taking into account the type of traffic which should gain benefits, has been the primary concern of the traffic engineers. Many of the past research efforts were conducted to examine various signal timing optimization methods with different objectives, and since one of the things that this research is focused on, is the traffic signals optimization, it is interesting to present these previous studies.

### Static Optimization

Foy, Benekohal, and Goldberg (1992) implemented a genetic algorithm (GA) in order to produce optimal or near-optimal intersection traffic signal timing strategies. The objective was to find a signal timing strategy that produces the smoothest traffic flow with the least automobile delay. According to them, the problem has many tentative solutions and the use of a genetic algorithm aimed to benefit the signal timing design. This gain was realized on a simulated four-intersection traffic network.

Park, Messer, and Urbanik (1999) presented a genetic algorithm-based signal optimization program that can handle over-saturated signalized intersections. The program consists of a genetic algorithm (GA) optimizer and a mesoscopic traffic simulator. The GA optimizer was designed to search for a near-optimal traffic signal timing plan on the basis of a fitness value obtained from the mesoscopic simulator. The program was tested in three different demand volume levels: low, medium and high demand.

Sun, Benekohal, and Waller (2003) investigated the application of non-dominated sorting genetic algorithm in solving the multi-objective signal timing optimization problem. In this study, three n-objective signal timing optimization problems with m-constraint, which cover both deterministic and stochastic traffic patterns, are solved. In the first problem the minimization of the average delay and the average number of stops under uniform arrival pattern, is taken into account. The second and third problem introduced some cycle length constraint, which identifies the lower bound of design cycle length calculated by Webster's minimum cycle length function. The third problem, the most complex one, copes also with a randomly distributed arrival with the Webster minimum cycle length constraint.

Hua, Yunfeng, and Xiaoguang (2010) presented a multiple-objective optimization model of fixed-time signal control of under-saturated intersections. Three objectives are taken into consideration, namely average delay, average stop frequency and average queue length of vehicular traffic at signalized isolated intersections. The used equations belong to the Webster Method. In this study a NSGA-II was used in order to optimize the functions set in an intersection at Yangpu, Shanghai.

### Dynamic Optimization

Saka, Anandalingam, and Garber (1986) investigated two innovative stochastic traffic signal optimization techniques for isolated intersections. The objective of their research was the determination of the optimum cycle and green phase lengths for signalized isolated intersections. The aforementioned determination was based on the minimization of the total average delay at the intersection for a given period of observation. Since the traffic signal timing is formulated as a stochastic inventory problem, they used a combination of simulation and dynamic programming in order to solve it. In addition, the suitability of the optimization techniques for under-saturated and over-saturated flow was discussed.

Yun and Park (2005) presented a stochastic traffic signal optimization method that consists of a heuristic simulation model and the microscopic simulation model CORSIM. For the heuristic optimization method, three heuristic methods including a genetic algorithm (GA), simulated annealing (SA) and OptQuest Engine were investigated and finally the GA was selected. The main feature of the GA-based stochastic signal control settings optimization method is the ability to optimize not only Group 1 settings (i.e., cycle length, green splits, offsets, and phase sequences) but also Group 2 (i.e., controller and detector-related settings) and Group 3 settings (i.e., volume-density control related settings) in the microscopic simulation environment represented by CORSIM.

Sánchez-Medina, Galán-Moreno, and Rubio-Royo (2010) developed a model for traffic signal optimization based on the combination of two key techniques: genetic algorithms (GAs) for the optimization task and cellular-automata-based microsimulators for evaluating every possible solution for traffic light programming times. The model was applied to a large-scale real-world test case in a congestion situation, using four different variables as fitness function of the GA.

Zhang and Wang (2011) presented a stochastic model to dynamically optimize the minimum and maximum green times for vehicle-actuated control at isolated intersections by using real-time queue lengths and traffic arrival characteristics for each phase. In their research, multiple criteria are fused and exploited as control objectives, such as avoiding cycle failures, minimizing control delays and maximizing total traffic throughput.

Costa, Almeida, and Caldeira (2011) presented a multi-objective model of traffic signal

optimization in an urban network. In this research, the model adopted the green times as the decision variables to optimize two functions, namely maximization of number of vehicles leaving the network and minimization of travel time of vehicles. The NSGA-II algorithm optimized the functions with a microscopic simulator GIS-SIM coupled to geographic information system OpenJUMP to evaluate the solutions.

Van Katwijk (2008) developed the multi-agent look-ahead adaptive controller. The controller gets information on the current traffic state through its sensors: the loop detectors. From this information it can create an expected arrival pattern. When this arrival pattern is known on all of the upstream approaches the controller knows when cars will arrive on which streams. It also knows when and between which streams will conflicts occur. Knowing these it is possible to create a signal plan that causes the least hindrance (delay and number of stops) for the all users approaching the intersection. The optimization of signal plan was done by dynamic programming in the controller.

## 2.5 Conclusions

During the literature survey the main objectives were to gain knowledge for the existing systems that take into account cyclists, the green wave alternatives for cyclists, the different types of traffic signal control and the traffic signal timing optimization.

In the first part, some examples from existing systems which take cyclists into account are presented, since this research aim to improve the traffic conditions of them. The information about the optimization process of the SCOOT system, which uses weighting functions to advantage or disadvantage the bicycle traffic relative to the motorized traffic, can give directions for the mathematical formulation of the problem.

Regarding the bicycle green wave alternatives, two approaches are presented. The first one is the speed advice system which is designed in order to reduce the number of stops for cyclists by giving speed advice. However, the presence of the cyclist in the network is not taken into account by the controller, and as a consequence very low or high speed advice may occur. For the second one, traffic signal timing synchronization at cyclists speed, examples of green waves for cyclists from different cities are presented. It is showed that sometimes these green waves, although are beneficial for cyclists, may result in increasing travel times for motorized traffic. In addition, these systems do not take into account cyclist's desired speed, and as a result a lot of cyclists they are not able or willing to deviate from it, as it is observed in Odense, in Denmark. From the above, it becomes easily understandable that both intervention in signalization system planning in favor of cyclists and comfortable speed advice for them are needed.

In the third part, the different types of signal control are presented, namely: fixed-time,

actuated and adaptive control. In this section, the two different design tools that were considered to be used in this thesis are presented, namely VRIGen and MALATACS. By taking into consideration their advantages and disadvantages, VRIGen was chosen.

Last but not least, since one of the objectives of this research is to optimize the traffic signals in favor of cyclists, different studies that have been conducted for traffic signal timing optimization with different objectives, are reviewed.

## Chapter 3

# Theoretical & Mathematical Framework

*“Start stupid, and evolve.”*

— *Kent Beck*

The goal of this research is to design a system that has a double function: optimizes the traffic lights by taking into account the number of stops, delay and desired speed of cyclists and delay of motorized traffic and gives comfortable speed advice to cyclists, which are derived from the optimization, in order the cyclists to cross the intersections without having to stop. This chapter introduces the multi-objective optimization problem and its objectives functions which are referred above.

### 3.1 Coordination of Intersections

Coordination between intersections is used in order to achieve an objective on the network level, for instance creation of green waves. Signal coordination provides a means by which the sequence (begin and end) of green lights is established along a series of traffic signals to allow for the uninterrupted flow of traffic between these traffic signals. The intent of coordinating traffic signals is to provide smooth flow of traffic along streets in order to reduce travel times, stops and delay. It would be ideal if every vehicle entering a corridor could proceed without stopping. Unfortunately, this is not possible, even in the most well designed system (FHWA, 2013).

Figure 3.1 illustrates the concept of moving vehicles through a system of traffic signals using a graphical representation known as a time-space diagram. The time-space diagram is a chart that plots ideal vehicle platoon trajectories through a series of signalized intersections. The locations of intersections are shown on the distance axis, and vehicles travel in both

directions (in a two-way street). Signal timing sequence and splits for each signalized intersection are plotted along the time axis (FHWA, 2013).

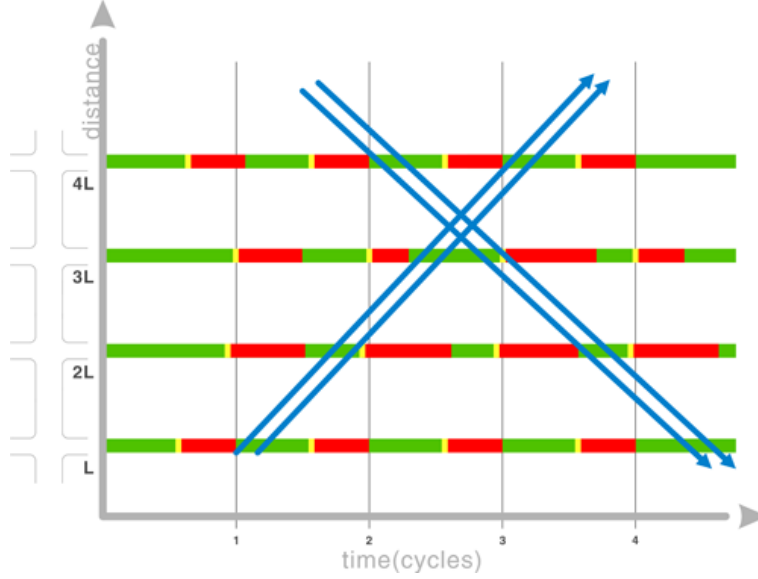


Figure 3.1: Time-space diagram of a coordinated timing plan (FHWA, 2013).

The result of signal coordination is illustrated on the time-space diagram. The start and end of green time show the potential trajectories for vehicles on the street. The trajectories are represented with straight lines, since the speed of the vehicle is assumed to be constant. It is these trajectories that determine the performance of the coordination plan. Performance measures include stops, delay, arterial travel time, etc.

Numerous factors can be used to determine whether coordination would be beneficial. Establishing coordination is easiest to justify when the intersections are in close proximity to one another and when traffic volumes between the adjacent intersections are large. If arriving traffic includes platoons that have been formed by the release of vehicles from the upstream intersection, coordination is beneficial to be implemented. If vehicle arrivals tend to be random and are unrelated to the upstream intersection operation, then coordination may provide little benefit to the system operation.

Since, the main goal of this research is not only to intervene in the signalization system planning in favor of cyclists but also to give individual speed advice to them, bicycle platoons may be created, if this option leads to an optimal solution. The main reason of the bicycle platoon dispersion, the phenomenon in which vehicles released from an upstream intersection will get segregated as they move over the distance towards the downstream intersection, is the variability of the desired speeds. However, by using speed advice, bicycle platoons will be kept together, hence the variability of the desired speeds can be reduced. Cyclists traveling in platoons can cross the intersection without having to stop, creating

gaps for the motorized traffic in order to be served.

As it has been already mentioned, green waves for cyclists may be very beneficial for them, since stopping is avoided. However, in the development of signal coordination, we have to manage the competing interests of providing continuous flow of cyclists and minimizing the delay for motorized traffic.

Figure 3.2 illustrates three cases in order to better understand in which situations the traffic signals should give priority to cyclists, by assuming that both types of road users, cyclists and motorized vehicles, have equal importance. Figure 3.2a depicts a situation where a platoon of cyclists approaches the intersection from the West and only two motorized vehicles approaching from the North. In this case the optimal solution forces the motorized vehicles to stop to allow the bicycle platoon to continue. Figure 3.2b represents a case where a platoon of motorized vehicles approaches the intersection from the North and a smaller amount of bicycles approaches from the West. In this case, the optimal solution is to allow the platoon of motorized vehicles to continue. However, the existence of the speed advice brings the possibility not to interrupt also the cyclists' movement by advising them to change their speeds in order to cross the intersection when motorized vehicles will have cleared the stop line, and if this is not possible, they will be forced to stop. In the above cases, it is obvious which is the optimal solution and therefore which type of road user gets priority in order to cross the intersection without stopping. The things are getting more complex in the situation that is depicted in Figure 3.2c. In this case, a platoon of cyclists is approaching the intersection from West and at the same time a platoon of motorized vehicles is approaching from the North. Which is the ideal solution and which platoon will get priority depends on what is considered more important in this case.

## 3.2 Optimization Problem

Most of the times, the design process of a traffic control system is complex and usually involves several assumptions and choices before a system is constructed, that solves a given traffic problem. In this process, the steps and the decisions that are taken may influence the performance or other properties of the resulting control system.

In most real-world problems, several goals must be satisfied simultaneously in order to obtain the preferred solution. A common difficulty with a multi-objective optimization problem is the appearance of an objective conflict; none of the feasible solutions allow simultaneous optimality for all objectives. This is also the case in this research, since the goal of the system is to optimize the traffic lights by taking into account the number of stops, delay and desired speed of cyclists and delay of motorized traffic.

Given the complexity of the problem, a simple network is selected in this thesis (Figure

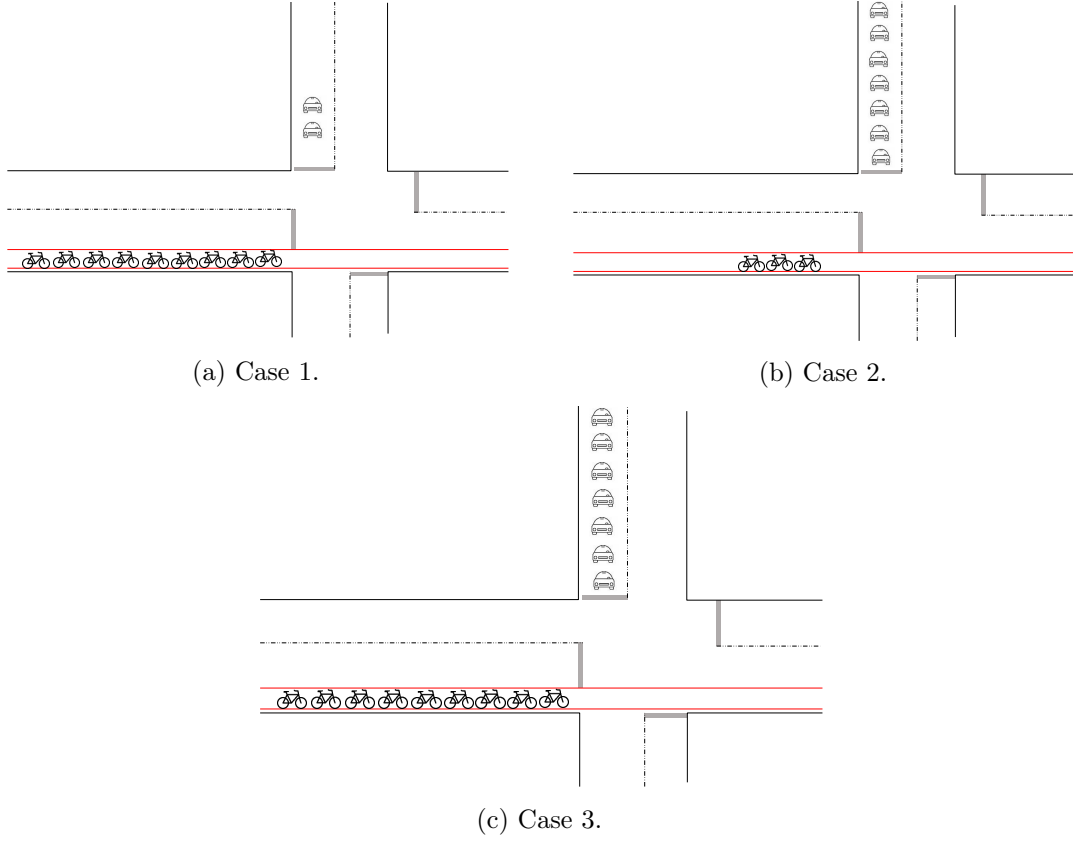


Figure 3.2: Priority to different road users.

3.3). It contains a string of three intersections, since the main objective is the minimization of number of stops of cyclists. Bicycles travel only from West to East and motorized traffic only from North to South. The distance among the intersections is approximately 500  $m$ . On the other hand the motorized vehicles have to travel about 700  $m$  in order to reach each intersection. Although, the network is simple, conclusions which concern more generic situations, e.g. cyclists in two directions, can be derived, since the optimization is performed individually in each intersection and the coordination of the intersections is implicitly achieved, without offsets.

In order to be able to solve the problem, the needed data are the speeds and the position of motorized vehicles and cyclists at each time instant, in order to calculate their arrival time at the stop line and the number of vehicles that are formed in front of them. The desired speed of each cyclist is also collected as the cyclists entering the network.

The optimization variables, i.e. the variables that can be changed in order to achieve the optimum solution, are the extension green times for both types of road users, cyclists and motorized vehicles, and the speed advice for each cyclist. At this point, it should be mentioned that the optimization is done at certain time points, when cyclists get green.

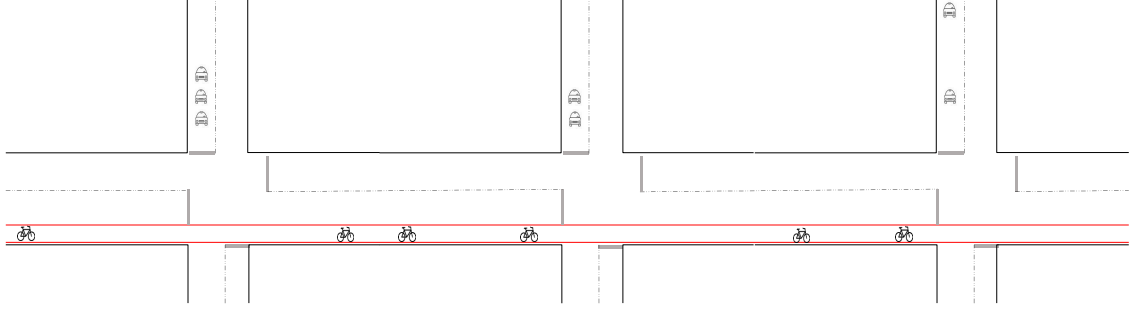


Figure 3.3: Description of the network: string of intersections with two phases.

At such a time point, both types of road users, cyclists and motorized vehicles, are taken into account, and estimates are made for their delays and for cyclist's number of stops and speed deviations from their desired speeds, given a value of the optimization variables. The above multi-objective optimization problem, which determines the control signal as a function of the measurements, can be formulated as follows.

$$\min_{g_{i,e}, u_{adv}} \quad \alpha D^{veh} + \beta D^{cyc} + S^{cyc} + \delta C^{cyc} \quad (3.1)$$

where

$$D^{veh} = \sum_{j=1}^J d_j^{veh} \quad (3.2)$$

$$D^{cyc} = \sum_{i=1}^I \sum_{k=1}^K d_{ik}^{cyc} \quad (3.3)$$

$$S^{cyc} = \sum_{i=1}^I \sum_{k=1}^K s_{ik}^{cyc} \quad (3.4)$$

$$C^{cyc} = \sum_{i=1}^I \sum_{k=1}^K c_{ik}^{cyc} \quad (3.5)$$

$D^{veh}$	total motorized vehicle delay
$D^{cyc}$	total cyclist delay
$S^{cyc}$	total cyclist number of stops
$C^{cyc}$	total cyclist deviation between the advised and desired speed
$d_j^{veh}$	delay of motorized vehicle $j$
$d_{ik}^{cyc}$	delay of cyclist $k$ at intersection $i$
$s_{ik}^{cyc}$	stop of cyclist $k$ at intersection $i$
$c_{ik}^{cyc}$	deviation between the advised and desired speed of cyclist $k$ at intersection $i$
$g_{i,e}$	extension green time in intersection $i$
$u_{adv}$	speed advice of cyclist
$I$	number of intersections
$J$	number of vehicles arriving at an intersection
$K$	number of cyclist traveling from West to East
$\alpha$	coefficient defining the relative importance of vehicle's delay
$\beta$	coefficient defining the relative importance of cyclist's delay
$\delta$	coefficient defining the relative importance of of the deviation between the desired and the advised speed of cyclist

The estimation of motorized vehicle's delay and cyclist's delay, number of stops and desired speed and the penalty function for both road users is presented in the following subsections.

### 3.3 Delay Estimation

One of the key variables that is utilized in the optimization of traffic signal timings, is delay. It is also used in computing the level of service provided to motorists at signalized intersections. The importance of vehicle delay is reflected in the use of this parameter in both design and evaluation practices. The popularity of delay as an optimization and evaluation criterion is attributed to its direct relation to what motorists experience while attempting to cross an intersection. However, the estimation of delay is difficult due to the fact that includes the delay associated with decelerating to a stop, the stopped delay and the delay associated with accelerating from a stop (Figure 3.4)(Kang, 2000). For instance, S Teply (1989) indicated that a perfect match between field-measured delay and analytical formulas could not be expected. The variety of delay models for signalized intersections that have been proposed over the years, also prove the difficulty in estimating vehicle delay.

*“Delay at signalized intersections is computed as the difference between the travel time that is actually experienced by a vehicle while going across the intersection and the travel*

### 3.3. DELAY ESTIMATION

time this vehicle would have experienced in the absence of traffic signal control” (Dion, Rakha, & Kang, 2004).

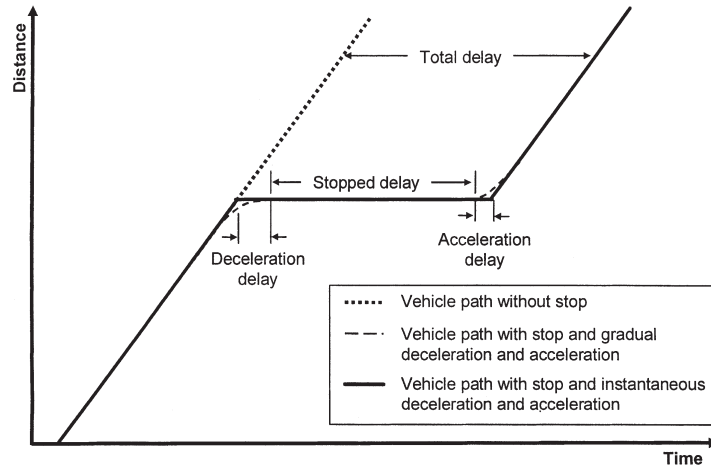


Figure 3.4: Definition of total, stopped, deceleration and acceleration delays (Dion, Rakha, & Kang, 2004).

Typically, stopped delay is defined by transportation professionals as the delay incurred when a vehicle is fully immobilized, while deceleration and acceleration delay are the delays incurred by a decelerating and accelerating vehicle respectively. However, in some cases, in stopped delay may also include the delay that is experienced by a vehicle when is moving at an extremely low speed. For instance, stopped delay is defined by the 2000 Canadian Capacity Guide for Signalized Intersections as any delay that incurred while a vehicle is stopped or moving at speeds lower than walking speed (S. Teply, Allingham, Richardson, & Stephenson, 2000).

Usually, traffic signal operation is the main reason for incurring most of the delay. However, a part of the total delay is the result of the time that is required by individual drivers to react to changes in the traffic signal display at the beginning of the green interval, to mechanical constraints, and to individual driver behavior. In ideal scenario, vehicles queued at stopping line would start moving at their desired speed immediately following the display of a green signal. Nevertheless, the first drivers usually need some seconds in order to react to the green signal and to start accelerating, and as consequence cause additional delay to all vehicles in the queue. This delay in vehicle departures is termed green start lag. In addition, the rate at which vehicles accelerate, also depends on mechanical constraints dictating the maximum feasible acceleration rate and on the rate at which individual driver chooses to accelerate (Kang, 2000).

In order to account for the additional delays due to driver reaction time and vehicle acceleration constraints, in delay estimation models, the operation of signalized intersections

is defined in terms of effective signal intervals instead of actual intervals, as presented in Figure 3.5. The effective green time ( $g_{eff}$ ) is the green time from which the green start lag is subtracted and the green end lag is added. At the end of the green phase, during a part of the yellow phase, vehicles still enter the intersection. The average time that the yellow phase is still used by vehicles entering the intersection is called the green end lag (T. H.J. Muller, Hegyi, Salomons, & van Zuylen, 2011-2012):

$$g_{eff} = g - \lambda_1 + \lambda_2 \quad (3.6)$$

where  $\lambda_1$  is the green start lag,  $\lambda_2$  is the green end lag and  $g$  is the total green time.

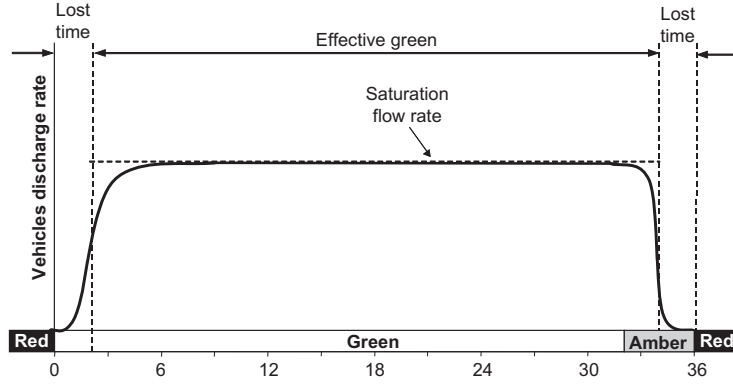


Figure 3.5: Queue modeling under deterministic queuing analysis (Dion, Rakha, & Kang, 2004).

Webster (1958) used one of the first digital computers to simulate vehicles arriving at and departing from a signalized intersection. The calculation of the delay was done from the simulations and based on it, he derived a mathematical model. This mathematical model, the well known Webster delay function, describes the simulated delays with sufficient accuracy.

In addition, the delay function was used by Webster in order to find signal settings that minimize the total delay. This has resulted in the often used Webster function for cycle time and green splits. He made a microscopic simulation program that imitated the behavior of the vehicles arriving, queuing and departing at the intersection. Subsequently, he calculated the vehicle delays by fitting a mathematical expression as good as possible to the results from the simulation. This mathematical expression consists of three terms. The first term estimates the average approach delay assuming uniform arrivals, the second term considers the additional delays attributed to the randomness of vehicle arrivals and the third term is an empirical correction factor that reduces the estimated delay by 5-15%, to be consistent with simulation results. Following Webster's work, other stochastic models

were proposed, for instance, (Miller, 1963), (Newell et al., 1960) and (Heidemann, 1994).

#### Delay Calculation

The motorized vehicle's and cyclist's delay is calculated as the sum of (Figure 3.6):

- the delay because of the traffic signal, assuming no queue;
- the delay because of the queues formed at the intersection;
- the overflow delay, i.e. the additional delay caused when the arrival rate is greater than the service rate at the traffic signal.

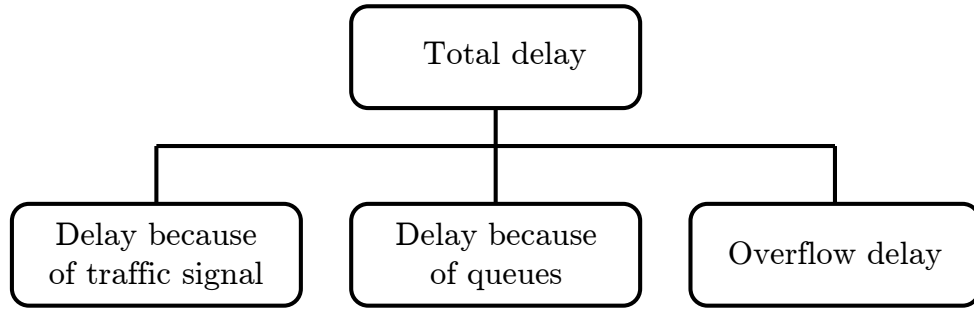


Figure 3.6: Total motorized vehicle's and cyclist's delay.

Since we have only two-phase intersections, motorized vehicle's green time will start when cyclist's green time will end and vice versa. The time point when motorized vehicle's and cyclist's green time starts at each intersection can be calculated as follows:

$$t_i^{veh} = t_i^{cyc} + g_f^{cyc} + g_{i,e}^{cyc} + t_{i,clear}^{cyc} \quad (3.7)$$

$$t_i^{cyc} = t_i^{veh} + g_f^{veh} + g_{i,e}^{veh} + t_{i,clear}^{veh} \quad (3.8)$$

where,

$t_i^{veh}$	time point when motorized vehicle's green time starts at intersection $i$
$t_i^{cyc}$	time point when cyclist's green time starts at intersection $i$
$g_f^{veh}$	motorized vehicle's fixed green time
$g_f^{cyc}$	cyclist's fixed green time
$g_{i,e}^{veh}$	motorized vehicle's extension green time at intersection $i$
$g_{i,e}^{cyc}$	cyclist's extension green time at intersection $i$
$t_{i,clear}^{veh}$	motorized vehicle's clearance time at intersection $i$ (including yellow)
$t_{i,clear}^{cyc}$	cyclist's clearance time at intersection $i$ (including yellow)

As it has been mentioned before, the data needed in order to calculate the delay are the speeds, the position of vehicles and cyclists at each time, for the calculation of their arrival time at the stop line, and the queues that are formed at the stop lines for both types of road users, cyclists and motorized vehicles (see Figure 3.7).

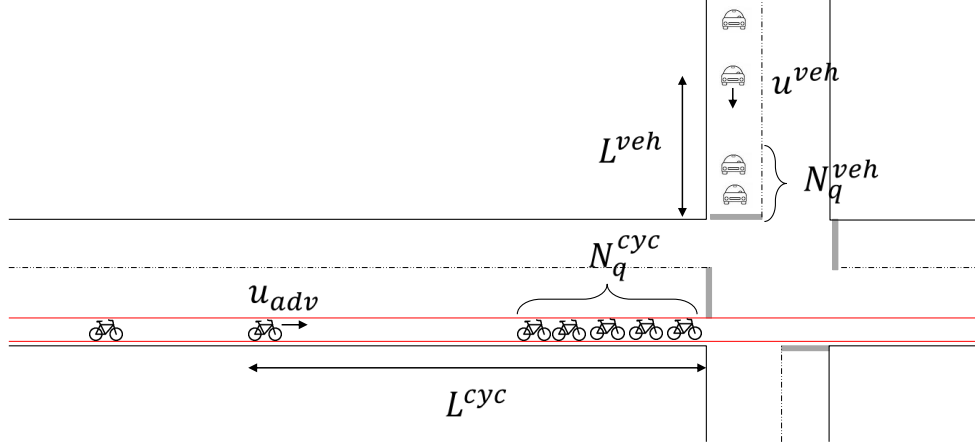


Figure 3.7: Data needed for the delay's calculation: vehicle's speed ( $u^{veh}$ ), cyclist's advised speed ( $u_{adv}$ ), vehicle's distance from the stop line ( $L^{veh}$ ), cyclist's distance from the stop line ( $L^{cyc}$ ) and vehicle's queue at the stop line ( $N_q^{veh}$ ) and cyclist's queue at the stop line ( $N_q^{cyc}$ ).

### Motorized Vehicle's Delay

Suppose that the motorized vehicle arrives during the red time, at time  $t_{i,arr}^{veh} = t_i^{opt} + \frac{L^{veh}}{u^{veh}}$ , and there is no queue at the stop line, motorized vehicle's delay is only the delay because of the traffic signal:

$$\begin{aligned}
 d_{j,t}^{veh} &= t_i^{veh} - t_{i,arr}^{veh} \implies \\
 d_{j,t}^{veh} &= t_i^{cyc} + g_f^{cyc} + g_{i,e}^{cyc} + t_{i,clear}^{cyc} - t_{i,arr}^{veh}
 \end{aligned} \tag{3.9}$$

where,

$d_{j,t}^{veh}$	delay of motorized vehicle $j$
$t_{i,arr}^{veh}$	arrival time of motorized vehicle at intersection $i$
$L^{veh}$	motorized vehicle's distance from the stop line
$u^{veh}$	motorized vehicle's speed
$t_i^{opt}$	time point when the optimization is performed at intersection $i$
$t_i^{veh}$	time point when motorized vehicle's green time starts at intersection $i$
$t_i^{cyc}$	time point when cyclist's green time starts at intersection $i$
$g_f^{cyc}$	cyclist's fixed green time
$g_{i,e}^{cyc}$	cyclist's extension green time at intersection $i$
$t_{i,clear}^{cyc}$	cyclist's clearance time at intersection $i$ (including yellow)

If the vehicle arrives during the red time, at time  $t_{i,arr}^{veh}$ , and there is queue at the stop line, the time that is needed in order the queue to be cleared, should be added to the vehicle's delay.

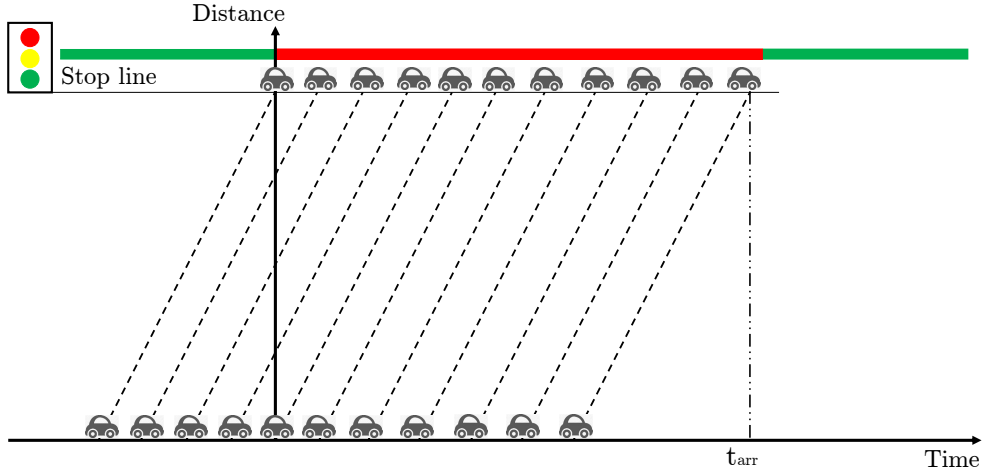


Figure 3.8: The vehicles that are arriving in the stop line during the red time have to stop. The queue in front of the last vehicle should be cleared, in order to be able to depart.

$$\begin{aligned}
 d_{j,t}^{veh} &= t_i^{veh} - t_{i,arr}^{veh} + \frac{N_q^{veh}}{s_{veh}} \implies \\
 d_{j,t}^{veh} &= t_i^{cyc} + g_f^{cyc} + g_{i,e}^{cyc} + t_{i,clear}^{cyc} - t_{i,arr}^{veh} + \frac{N_q^{veh}}{s_{veh}}
 \end{aligned} \tag{3.10}$$

where,  $N_q^{veh}$  is the number of vehicles in the queue (Figure 3.8), and  $s^{veh}$  is the road's saturation flow.

However, sometimes the arrival rate exceeds the service rate at the traffic signal and as a result the overflow delay is introduced. If the queue discharge time,  $t = \frac{N_q^{veh}}{s^{veh}}$ , is greater than the available green time,  $g^{veh}$ , the queued motorized vehicles cannot all be served in the current green phase, but some will be served in a next cycle (Figure 3.9).

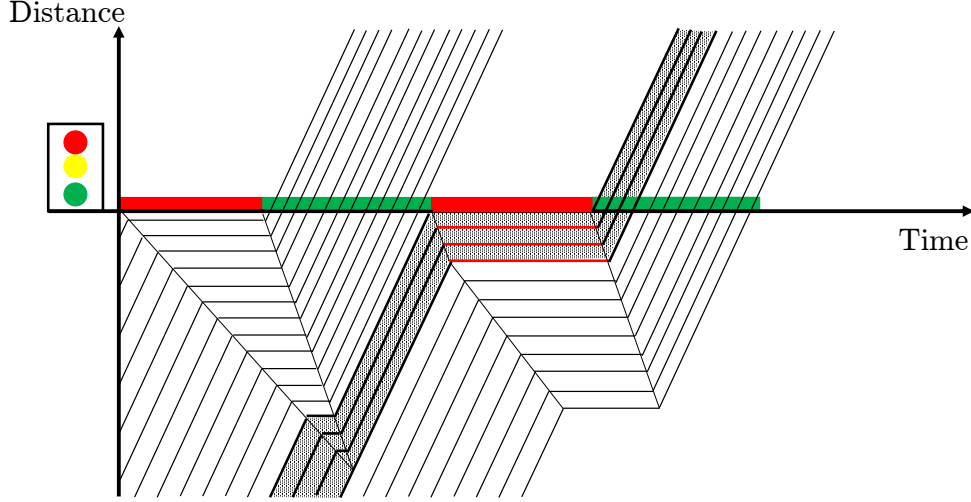


Figure 3.9: Illustration of overflow delay.

The amount of the motorized vehicles that can be served in the cycle is given by the Equation 3.11.

$$N_{served} = g^{veh} * s^{veh} \quad (3.11)$$

where  $g^{veh}$  is the green time, and  $N^{veh}$  is the maximum number of vehicles that can be served.

The delay of the motorized vehicles that are not served in the cycle in which they arrive, i.e.  $N_{not\ served}^{veh} = N^{veh} - N_{served}^{veh}$ , must be increased by the amount of the red interval,  $r^{veh}$ :

$$d_{j,t}^{veh} = t_i^{cyc} + g_f^{cyc} + g_{i,e}^{cyc} + t_{i,clear}^{cyc} - t_{i,arr}^{veh} + \frac{N_q^{veh}}{s^{veh}} + m * r^{veh} \quad (3.12)$$

where  $m$  is the number of cycles that the motorized vehicle has to wait before is able to cross the intersection.

Suppose that the green time is 20 sec, the saturation flow is 1800 veh/h and there

are 18 motorized vehicles in the queue at the stop line in the first cycle. The number of motorized vehicles that can be served in the first cycle is the following:

$$N_{served}^{veh} = 20 * \frac{1800}{3600} = 10 \quad (3.13)$$

From the 18 motorized vehicles, 10 motorized vehicles can be served in this cycle. The remaining 8 motorized vehicles have to wait to be served in the next cycle, and as a result their delay will be increased by the amount of the red interval.

As a consequence from the above, the green time for the motorized vehicles arriving in the next cycle is reduced by the time interval required to serve the residual queue from the previous cycle. Under heavy congested conditions this time interval may be larger than the green time, which means that in this cycle only motorized vehicles that arrived in the previous cycle(s) will be served, and the delay for some motorized vehicles will be larger than the red time interval.

If the vehicle arrives during the green time, at time  $t_{i,arr}^{veh}$ , and there are waiting vehicles, the delay of the vehicle equals the time needed to clear the queue in front of it:

$$d_{j,t}^{veh} = \frac{N_q^{veh}}{s^{veh}} \quad (3.14)$$

and if the arrival rate exceeds the service rate at the traffic signal, the overflow delay should be added:

$$d_{j,t}^{veh} = \frac{N_q^{veh}}{s^{veh}} + m * r^{veh} \quad (3.15)$$

On the other hand, if the vehicle arrives during the green time, at  $t_{i,arr}^{veh}$ , but no queue is waiting, the delay of the vehicle equals zero:

$$d_{j,t}^{veh} = 0 \quad (3.16)$$

The above are summarized in Table 3.1.

Table 3.1: Summary of vehicle's delay in intersection  $i$ .

	Green	Red
No queue	0	$t_i^{cyc} + g_f^{cyc} + g_{i,e}^{cyc} + t_{i,clear}^{cyc} - (t_{opt} + \frac{L^{veh}}{u^{veh}})$
Queue	$\frac{N_q^{veh}}{s^{veh}}(+m * r^{veh})$	$t_i^{cyc} + g_f^{cyc} + g_{i,e}^{cyc} + t_{i,clear}^{cyc} - (t_i^{opt} + \frac{L^{veh}}{u^{veh}}) + \frac{N_q^{veh}}{s^{veh}}(+m * r^{veh})$

### Cyclist's Delay

The same procedure is followed for the calculation of cyclist's delay. Suppose that the cyclist arrives during the red time, at time  $t_{i,arr}^{cyc} = t_i^{opt} + \frac{L^{cyc}}{u_{adv}}$ , and there is no queue at the stop line, then motorized vehicle's delay is only the delay because of the traffic signal:

$$\begin{aligned} d_{k,t}^{cyc} &= t_i^{cyc} - t_{i,arr}^{cyc} \implies \\ d_{k,t}^{cyc} &= t_i^{veh} + g_f^{veh} + g_{i,e}^{veh} + t_{i,clear}^{veh} - t_{i,arr}^{cyc} \end{aligned} \quad (3.17)$$

where,

$d_{k,t}^{cyc}$	delay of cyclist $k$
$t_{i,arr}^{cyc}$	arrival time of cyclist at intersection $i$
$L^{cyc}$	cyclist's distance from the stop line
$u_{adv}$	cyclist's advised speed
$t_i^{opt}$	time point when the optimization is performed at intersection $i$
$t_i^{cyc}$	time point when cyclist's green time starts at intersection $i$
$t_i^{veh}$	time point when motorized vehicle's green time starts at intersection $i$
$g_f^{veh}$	motorized vehicle's fixed green time
$g_{i,e}^{veh}$	motorized vehicle's extension green time at intersection $i$
$t_{i,clear}^{veh}$	motorized vehicle's clearance time at intersection $i$ (including yellow)

If the cyclist arrives during the red time, at  $t_{i,arr}^{cyc}$ , and there is queue at the stop line, the time that is needed in order the queue to be cleared, should be added to the cyclist's delay.

$$\begin{aligned} d_{k,t}^{cyc} &= t_i^{cyc} - t_{i,arr}^{cyc} + \frac{N_q^{cyc}}{s} \implies \\ d_{k,t}^{cyc} &= t_i^{veh} + g_f^{veh} + g_{i,e}^{veh} + t_{i,clear}^{veh} - t_{i,arr}^{cyc} + \frac{N_q^{cyc}}{s^{cyc}} \end{aligned} \quad (3.18)$$

where  $N_q^{cyc}$  is the number of cyclist in the queue and  $s^{cyc}$  the cyclist path's saturation flow.

As it is mentioned above, in the calculation of motorized vehicle's delay, if the arrival rate exceeds the service rate at the traffic signal, overflow delay is also caused:

$$d_{k,t}^{cyc} = t_i^{veh} + g_f^{veh} + g_{i,e}^{veh} + t_{i,clear}^{veh} - t_{i,arr}^{cyc} + \frac{N_q^{cyc}}{s^{cyc}} + m * r^{cyc} \quad (3.19)$$

If the cyclist arrives during the green time, at time  $t_{i,arr}^{cyc}$ , and there are waiting cyclists, the cyclist's delay equals the time needed to clear the queue at the stop line:

$$d_{k,t}^{cyc} = \frac{N_q^{cyc}}{s^{cyc}} \quad (3.20)$$

and if the overflow delay is appeared:

$$d_{k,t}^{cyc} = \frac{N_q^{cyc}}{s^{cyc}} + m * r^{cyc} \quad (3.21)$$

On the other hand, if the cyclist arrives during the green time, at  $t_{i,arr}^{cyc}$ , but no queue is waiting, the cyclist's delay equals zero:

$$d_{k,t}^{cyc} = 0 \quad (3.22)$$

Cyclist's delay is summarized in Table 3.2.

Table 3.2: Summary of cyclist's delay in intersection  $i$ .

	Green	Red
No queue	0	$t_i^{veh} + g_f^{veh} + g_{i,e}^{veh} + t_{i,clear}^{veh} - (t_{opt} + \frac{L^{cyc}}{u_{adv}})$
Queue	$\frac{N_q^{cyc}}{s^{cyc}} (+m * r^{cyc})$	$t_i^{veh} + g_f^{veh} + g_{i,e}^{veh} + t_{i,clear}^{veh} - (t_i^{opt} + \frac{L^{cyc}}{u_{adv}}) + \frac{N_q^{cyc}}{s^{cyc}} (+m * r^{cyc})$

### 3.4 Number of Stops, Advised & Desired Speed of Cyclists

In this section more information about the advised and the desired speed and the number of stops of cyclists is given.

### Number of Stops

In traffic signal planning the problem of choosing a measure of effectiveness depends on, among others, the type of traffic which should gain benefits. In this research, traffic signals will be optimized in favor of cyclists, in order to cross the intersection without having to stop, nevertheless without hindering too much the motorized traffic.

The problem of estimating vehicle stops at signalized intersections has been discussed by numerous researchers. As it is mentioned before, Webster (1958) made an early contribution and generated stop and delay relationships by simulating uniform traffic flows on a single-lane approach to an isolated intersection. Since their development, these relationships are fundamental to traffic signal setting procedures. Later, Akçelik (1981) estimated delay, number of stops and queue length at traffic signals for both vehicles and pedestrians. These formulas are applicable to both under-saturated (below capacity) and over-saturated (above capacity) conditions, unlike the formulas from Webster, which are only applicable to under-saturated conditions. The formulas for pedestrians have been derived from the formulas for vehicles by assuming zero flow ratios and zero overflow queues for pedestrian movements. In other words, it is assuming that no pedestrians are stopped during the green interval, i.e. pedestrian queues are discharged instantly, and that pedestrian queues are always cleared (no overflow). These assumptions could be made for cyclists as well. The number of pedestrians or cyclists stopped at traffic signals is calculated as follows:

$$h^{yc} = q^{yc} r_{eff} \quad (3.23)$$

where  $q^{yc}$  is the pedestrian/cyclist arrival rate and  $r_{eff}$  is effective red time. However, this equation is appropriate for static optimization and cannot be used in a real-time optimization process.

In this research the objective function that is used in order to estimate the number of stops for cyclists is the same as the one developed from Egmond (2013). According to Egmond (2013), multiple speed advice may be given to cyclists, depending on the different states of the actuated controller; the speed advice cannot be fixed, since the green times of the phases can be extended. In other words, based on the changing states of the controller, different speed advice should be given to cyclists in order to be able to cross the intersection without to stop (Figure 3.10). Considering the fact that cyclists are in different locations in the network when a change in the state of the controller occurs, individual advice should be given. This brings the possibility to take also into account the individual desired speed of each cyclist. Combining the above, the speed advice is split into a function that describes the personal preference of the cyclist and a function that describes the utility of arriving at

the intersection during the green light (Egmond, 2013).

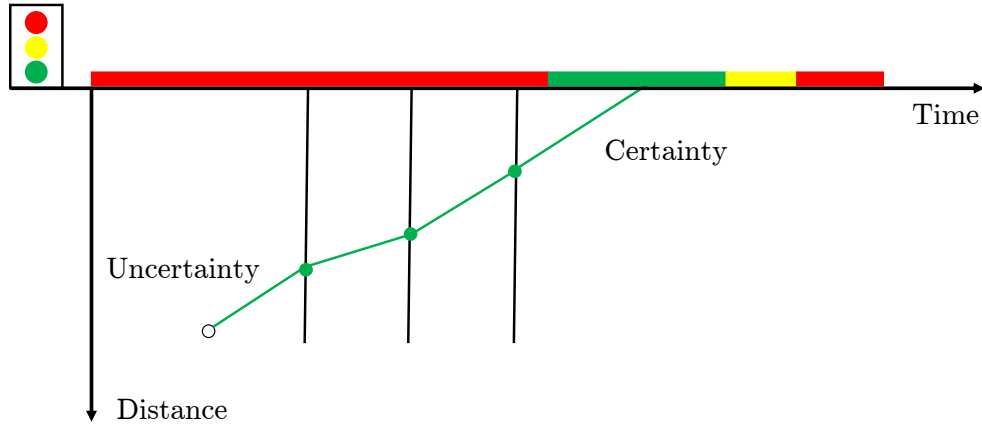


Figure 3.10: A route to the traffic light with different speed advice according to different states of the traffic controller. The black lines indicate a shift in uncertainty (Egmond, 2013).

The upcoming states of the controller should be clearly indicated in order for the speed advice to be calculated. The states are introduced as the periods that a phase is active. The state consists of the yellow time of the previous phase, the clearance time between the previous phase and the current phase and the green time of the current phase. The number of phases has a maximum dependent on the structure of the controller. The number of states has no maximum, since the green time can be extended. The number of states that have to be realized before the cyclist's traffic light is  $N$ , i.e. there are  $0, 1, 2, \dots, N$  states. State 0 is the state in which there is certainty about the duration of the green period (Egmond, 2013).



Figure 3.11: The different states of the traffic controller. The dark green bar indicates the cyclist's green time period, the light green bars are the green times for the phases that are realized before the green time of cyclist (Egmond, 2013).

### Cyclist's Personal Preference

Cyclist's desired speed is the speed at which the cyclist would travel when no interaction with other road users or speed advice system is present. Egmond (2013) used a relationship

between the advised and the cyclist's desired speed. When the cyclist rides at his desired speed, he receives the highest utility. Hence, a function that describes the value of utility for the cyclist should have a maximum at the speed associated with the desired speed; deviation from the desired speed leads to a decreased utility for the cyclist. Traveling at the desired speed has a utility equals to zero and deviating from it, leads to a negative utility; the bigger the deviation, the bigger the decline.

Taking into account the above, Egmond (2013) used the following negative parabolic function with its maximum at the desired speed, in order to describe the utility function of the personal preference of the cyclist:

$$\sigma(u_{adv}) = -|u_{adv} - u_{des}|^2 \quad (3.24)$$

The above equation takes into account the the maximum value of utility when driving with the desired speed, but also the decrease of the utility when the cyclist deviates from it.

For example, suppose a cyclist has a desired speed of 16  $km/h$ , his score function is presented in Figure 3.12.

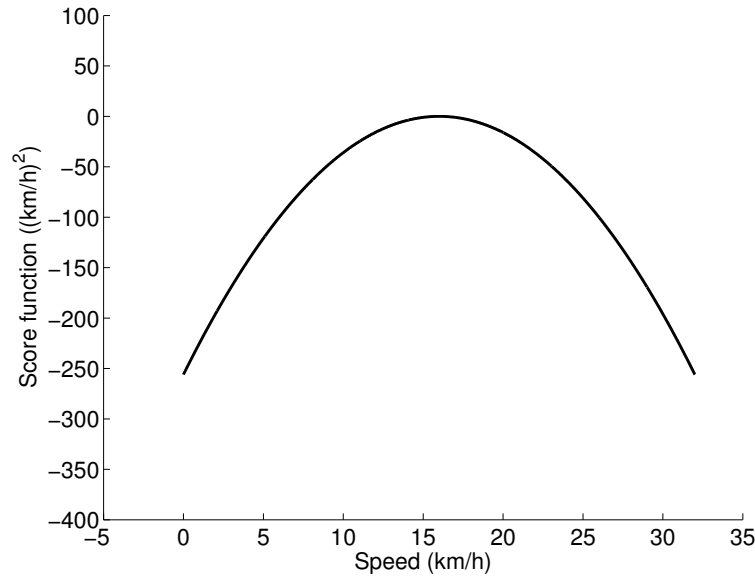


Figure 3.12: Personal preference score function for a cyclist with a desired speed of 16  $km/h$ .

Although the above parabolic function may not be the correct representation of cyclist's cost when he deviates from his desired speed, it was used because it is simple and expresses the basic behavior that is expected from the cyclist. However, for a cyclist is easier to decelerate than to accelerate and that can be proved by using the Bernoulli equation (Munson, Young, & Okiishi, 1990).

In a coordinated system fixed to the bicycle, it appears as though the air is flowing steadily toward the cyclist with speed  $u_0$ , which is the cyclist's speed (Figure 3.13). According to the principle of conservation of energy <sup>1</sup> the following equation holds (Munson et al., 1990):

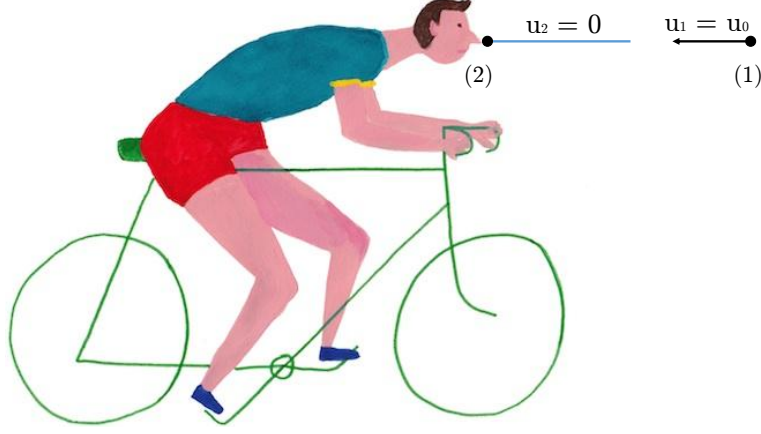


Figure 3.13: The coordinated system fixed to the cyclist. Point (1) is considered to be in the free stream so that  $u_1 = u_0$  and point (2) to be at the tip of cyclist's nose ( $u_2 = 0$ )

$$p_1 + \frac{1}{2}\rho u_1^2 + \gamma z_1 = p_2 + \frac{1}{2}\rho u_2^2 + \gamma z_2 \implies$$

$$p_2 - p_1 = \frac{1}{2}\rho u_1^2 = \frac{1}{2}\rho u_0^2 \quad (3.25)$$

where  $p_i$  is the pressure at each point,  $\rho$  is the density of air,  $\gamma$  is the air's specific weight and  $z_i$  is the elevation of each point above a reference plane.

In other words, pressure increases with the speed, actually is proportional to the square of the speed. For instance, if a cyclist wants to double his speed, he needs four times more strength. The opposite situation occurs when he wants to decrease his speed to its half.

By taking into account the above the following parabolic functions are chosen in order to describe the cost for the cyclist when deviates from his desired speed:

$$c(u_{adv}) = \begin{cases} (u_{adv} - u_{des})^2 & u_{adv} \leq u_{des} \\ 2(u_{adv} - u_{des})^2 & u_{adv} > u_{des} \end{cases} \quad (3.26)$$

In this case, the score function of a cyclist with a desired speed of 16 km/h is presented

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<sup>1</sup>The law of conservation of energy states that the total energy of an isolated system cannot change; it is said to be conserved over time. Energy can be neither created nor destroyed, but can change form.

in Figure 3.14. Since, the main objective of this research is the simultaneous minimization of different objectives, the minimum instead of the maximum value is desired.

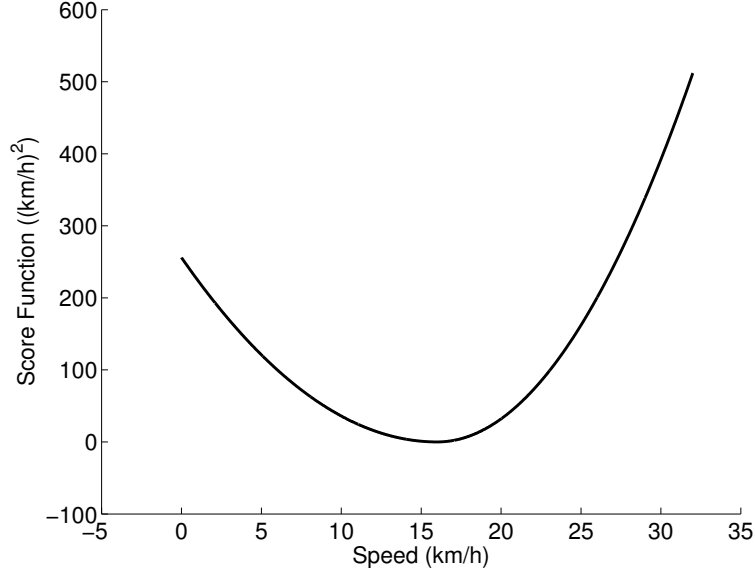


Figure 3.14: Personal preference score function for a cyclist with a desired speed of 16  $km/h$ .

### Green Light Function

As it is mentioned above, Egmond (2013) introduced the “green light function” in order to estimate whether a cyclist avoids a stop or not. The function is different for the last state of the controller, in which there is certainty about the realization of the green time and different for the other states before the last state. The function can provide a score for each distance ( $L_0^{cyc}$ ). This score has two components. The first is determined by the appearance of green for the cyclist’s traffic light and the second by the personal preference. The “green light function” which is used by Egmond (2013) for the last state is presented below:

$$F(L^{cyc}, u_{adv}) = \begin{cases} \sigma(u_{adv}) & \frac{L^{cyc}}{u_{adv}} \in [t_i^{veh}, t_{i,clear,end}^{veh}] \\ \sigma(u_{adv}) + \gamma & \frac{L^{cyc}}{u_{adv}} \in [t_i^{cyc}, t_{i,clear,end}^{cyc}] \end{cases} \quad (3.27)$$

where  $\sigma(u_{adv})$  is the function for cyclist’s personal preference and  $\gamma$  is the green bonus.

The probability of catching the green light is 0 or 1. The green light score is equal to the green bonus,  $\gamma$ , if the cyclist catches the green light and zero if the cyclist does not catch the green light. The green bonus should have a value compared to the personal preference score that represents the trade-off between the desired and the advised speed.

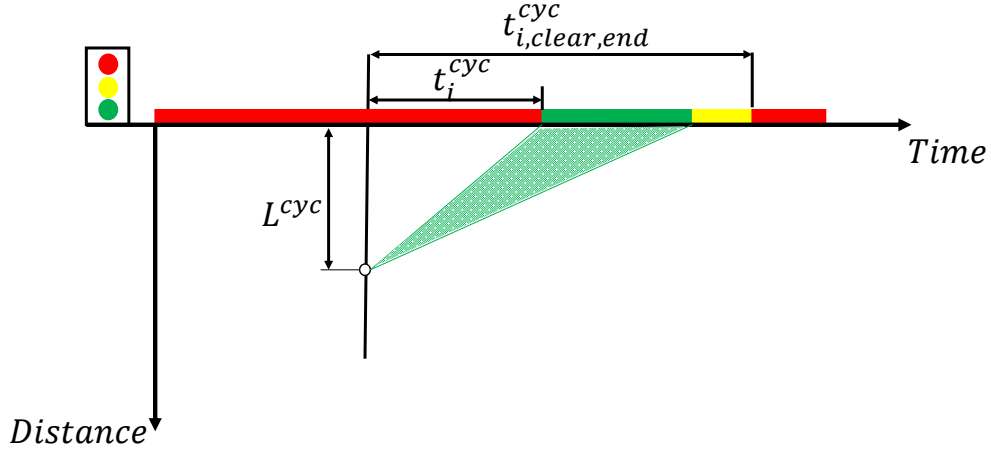


Figure 3.15: The variables of the last state that determine the green light score for the possible speeds in this state. The speeds that correspond in the green zone will provide a green light score of  $\gamma$  (Egmond, 2013).

The combination of the personal preference score and the score that is added to represent the value of avoiding a stop, creates a score for every distance with a certain speed. The speed with the maximum score for each distance  $L^{cyc}$  is selected as the advised speed.

$$F(L^{cyc}) = \max_{u_{adv}} F(L^{cyc}, u_{adv}) \quad (3.28)$$

In other words, in case of avoiding a stop, the cyclist is advised to follow a certain speed, otherwise the desired speed is suggested to be followed.

Since, the aim of this research is to minimize simultaneously the different objectives, instead of the green bonus  $\gamma$ , the red cost  $\gamma$  is used. The equation which is used for the number of stops of cyclists is the following:

$$s(L^{cyc}, u_{adv}) = \begin{cases} \gamma & \frac{L^{cyc}}{u_{adv}} \in [t_i^{veh}, t_{i,clear,end}^{veh}] \\ 0 & \frac{L^{cyc}}{u_{adv}} \in [t_i^{cyc}, t_{i,clear,end}^{cyc}] \\ \gamma & \frac{L^{cyc}}{u_{adv}} \in [t_i^{veh}, t_{i,clear,end}^{veh}] \\ 0 & \frac{L^{cyc}}{u_{adv}} \in [t_i^{cyc}, t_{i,clear,end}^{cyc}] \end{cases} \quad (3.29)$$

By taking into account Equations 3.26 and 3.29, the score function is the following:

$$F(L^{cyc}, u_{adv}) = \begin{cases} (u_{adv} - u_{des})^2 + \gamma & u_{adv} \leq u_{des}, \frac{L^{cyc}}{u_{adv}} \in [t_i^{veh}, t_{i,clear,end}^{veh}] \\ (u_{adv} - u_{des})^2 & u_{adv} \leq u_{des}, \frac{L^{cyc}}{u_{adv}} \in [t_i^{cyc}, t_{i,clear,end}^{cyc}] \\ 2(u_{adv} - u_{des})^2 + \gamma & u_{adv} > u_{des}, \frac{L^{cyc}}{u_{adv}} \in [t_i^{veh}, t_{i,clear,end}^{veh}] \\ 2(u_{adv} - u_{des})^2 & u_{adv} > u_{des}, \frac{L^{cyc}}{u_{adv}} \in [t_i^{cyc}, t_{i,clear,end}^{cyc}] \end{cases} \quad (3.30)$$

In this case, the green light score is equal to the red cost, if the cyclist reaches the intersection during motorized vehicle's green time and zero if the cyclist catches the cyclist's green light. So, instead of the maximum value, the minimum value of the score function is desired:

$$F(L^{cyc}) = \min_{u_{adv}} F(L^{cyc}, u_{adv}) \quad (3.31)$$

### 3.5 Optimization Horizon

The proposed signal and advised system provides real time signal control based on a rolling horizon process. In this system, the phase lengths and the cyclist's speed advices are considered for optimization. Cycle times are not explicitly considered and are not constant. In the beginning of every new time horizon (the beginning of cyclist's green phase), the optimization solver iteratively converge to an optimal signal timing plan and speed advice for the current time horizon. In a rolling horizon manner, only the first small fraction of the computed plan is implemented. Whenever the optimizer recalculates the signal plan and the speed advice, it takes a snapshot of the network and collects on all of its approaches. For this study the time horizon length is set to 10 cycles and the first cycle of the resulting plan is implemented, before the computation is repeated. The cyclists and the motorized vehicles who arrive beyond horizon, receive a very high cost.

### 3.6 Conclusions

In this chapter the multi-objective optimization problem is presented. The complexity of a multi-objective optimization problem resides in the fact that an objective conflict is appeared; none of the feasible solutions allow simultaneous optimality for all objectives. In addition, the different objective functions, which form the cost function that will be minimized, namely delay, number of stops and desired speed of cyclists and delay of motorized vehicles, are introduced. The motorized vehicle's and cyclist's delay is calculated as the sum of the delay because of the traffic signal, the delay because of the queues formed

at the intersection and the overflow delay, i.e. the additional delay caused when the arrival rate is greater than the service rate at the traffic signal. Regarding the cyclist's number of stops, each cyclist receives a red cost,  $\gamma$ , every time that he has to stop. Last but not least, the cost function that is used in order to estimate the desired speed of cyclists, which was developed by Egmond (2013), is presented and differentiated. Since, it is easier for a cyclist to decelerate than to accelerate, a different parabolic function is used when a cyclist has to slow down and different when he has to speed up.



## Chapter 4

# Implementation

*“Let’s make a dent in the universe.”*

— *Steve Jobs*

In this Chapter the implementation of the model is presented. As it can be seen in Figure 4.1 different software is combined, namely, VRIGen, TRAFCod, VISSIM and MATLAB, in order the model to be able to receive the needed data, optimize the traffic lights and the speed advice for cyclists and return this information for implementation. In the following subsections the aforementioned software is presented.

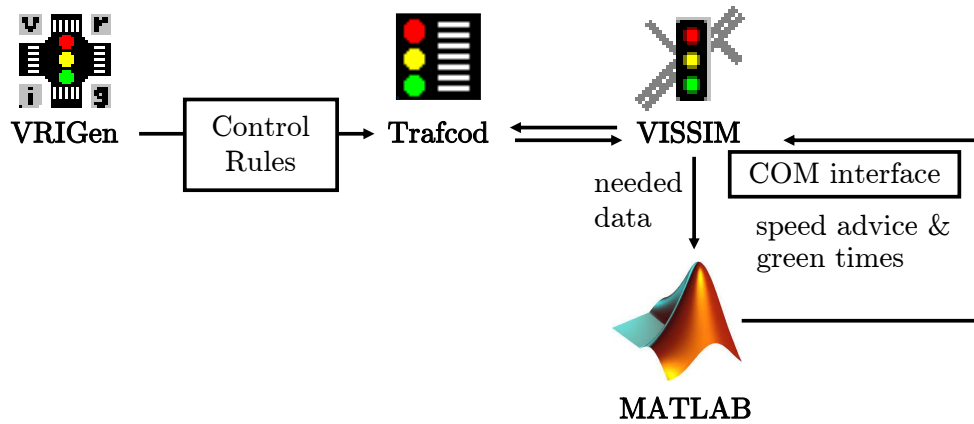


Figure 4.1: System’s implementation environment

### 4.1 Traffic Signal Control System

Two different types of controllers, namely VRIGen (Theo HJ Muller & de Leeuw, 2006) and Multi-Agent Look-Ahead Traffic-Adaptive Control (MALATACS) (Van Katwijk, 2008) were considered to be used in this thesis, as it is presented before. Given the simplicity of

VRIGen and the fact that it is an actuated controller, in other words widely implemented in the Netherlands in comparison with adaptive controllers, VRIGen is chosen for this research. All the information regarding the traffic signal control system, VRIGen, can be found in Chapter 3.

### **Controller Simulator**

The “output” of VRIGen is the “input” of TRAFCod. VRIGen generates a file with the traffic control program, based on the structure and design tactics chosen by the user. This program file can be connected with the TRAFCod controller simulator and by it with a full-scale traffic simulation program that allows for external traffic signal controllers (T. H.J. Muller et al., 2011-2012).

## **4.2 Microscopic Traffic Simulator**

In order to assist design and validation of newly developed control strategies, traffic modeling is commonly used in practice. There is a variety of road traffic simulators which are available to the user to choose among them. The majority is commercial software, however open source simulators are also available, developed by universities or research institutes. In this research, the proposed simulation environment is VISSIM (“VISSIM 5.30-05 User Manual,” 2011).

VISSIM is a microscopic simulator based on the individual behavior of the vehicles. The accurate description of the traffic dynamics is the main goal of the microscopic modeling approach. This brings the possibility to analyze the simulated traffic network in detail. The theoretical and mathematical model which is presented in Chapter 4 takes into account different objectives of individual cyclists and motorized vehicles, and this means that VISSIM fulfill the model’s requirements.

A user friendly graphical interface (GUI) is offered by VISSIM, through of which one can design the geometry of any type of road networks and set up simulations in a simple way. However, for several problems the GUI is not satisfying. This is the case, for example, when the user aims to access and manipulate VISSIM objects during the simulation dynamically. For this end, an additional interface is offered based on the COM which is a technology to enable interprocess communication between software (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011). The VISSIM COM interface defines a hierarchical model in which the functions and parameters of the simulator originally provided by the GUI can be manipulated by programming. It can be programmed in any type of language which is able to handle COM objects (e.g. C++, Visual Basic, Java, MATLAB etc.). Through VISSIM COM the user is able to manipulate the attributes of most of the internal

objects dynamically. In this research, it is programmed in MATLAB, in which the model is implemented.

As it has already been mentioned, for the development of the model, data is needed: the speeds, the position of vehicles and cyclists at each time, in order to calculate their arrival time at the stop line and the queues that are formed at the stop line for both types of road users, cyclists and motorized vehicles. This data can be taken from VISSIM via the COM interface.

The VISSIM COM object model is based on a strict object hierarchy. To access the different lower-level objects, e.g. a Vehicle object of the Net object, you have to follow this hierarchy. VISSIM is the highest object; all other objects belong to VISSIM. Figure 4.2 illustrates some of the object instantiation dependences (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011).

As it can be seen in Figure 4.2, the Net object belongs to VISSIM and gives access to the network objects like links, signal controllers and vehicles. VISSIM is a single project program, i.e. it allows to work with no more than one network at a time. Therefore, a Net instance always references the currently opened network of its VISSIM instance (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011).

The Vehicles object is a collection of Vehicle objects and belongs to the Net object. It contains all vehicles currently traveling on the network during a simulation, including the parked ones. It enables iteration through the collection or individual access to a Vehicle object (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011).

The Vehicle object represents a single vehicle and belongs to the Vehicles object. It can be accessed through the Vehicles object in two ways (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011):

- access via iteration through the collection;
- individual access via identifier number (chosen option for this research).

The Vehicle object enables access to the properties of the vehicle through the IVehicle interface.

Table 4.1 presents the attributes of the vehicle that are received via the COM interface for the model’s implementation. At this point, it should be mentioned that COM interface is used not only to obtain the needed data but also to send the outputs of the model to VISSIM. The “DESIREDSPED” attribute is used in order to send the speed advice, which are calculated from the model, to the cyclists.

The control of the traffic lights is done via the Detectors object in COM interface and by creating “cut-off detectors” in VRIGen. Stream 11 is the stream for motorized vehicles and stream 24 is the stream for cyclists. In both streams no detectors are present. However,

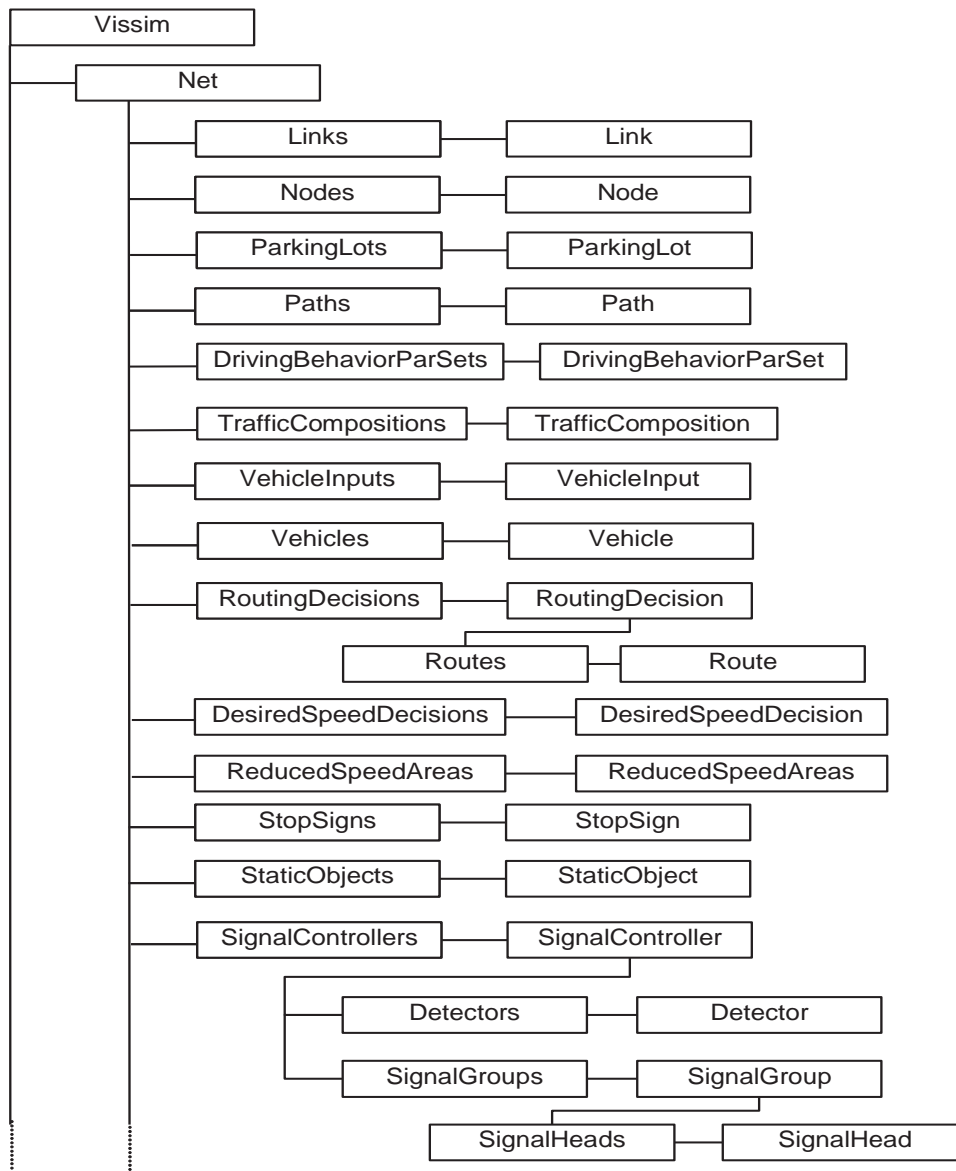


Figure 4.2: Object instantiation dependences (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011). The red circles indicate the need objects that should be accessed.

Table 4.1: Vehicle’s attributes (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011).

Attributes	Description
ID	Identifier number
DESIREDSPED	Desired speed in the units of the current options
LINK	Current link where the vehicle is positioned
LINKCOORD	Current x coordinate of the current link
QUEUECOUNTER	Number of queue encounters
SPEED	Current speed in the units of the current options

three more streams without traffic, namely streams 13, 14 and 15, are used in order to cut-off streams 11 and 24. Streams 13 and 14 are the cut-off streams and stream 15 is only used to create conflicts with 13 and 14 and is not further used at all.

The Detectors object is a collection of Detector objects, belongs to a SignalController object and contains all detectors of the referred signal controller and enables iteration through the collection or individual access to a Detector object (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011).

A Detector object belongs to a controller’s Detectors object. Through this a detector can be accessed in two ways (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011):

- access via iteration through the collection;
- individual access via identifier (chosen option in this research).

The Detector object enables access to the properties of the detector through the IDetector interface.

Table 4.2 presents the attributes of the detectors that are received via the COM interface for the model’s implementation.

Table 4.2: Detector’s attributes (“VISSIM 5.30-0.5 - COM Interface Manual.” 2011).

Attributes	Description
ID	Identifier number
CONTROLLER	Signal controller identifier number
PRESENCE	1 sets the detector to occupied at the end of the current time step 0 stops the occupancy

Whenever the green time of a stream should be terminated, with the “PRESENCE” attribute the cut-off detectors can be activated and the green phase in the stream that each detector cuts off will end. After the end of the green phase the cut-off detector has

to be deactivated. In other words, TRAFCod controls the traffic lights and TRAFCod is controlled by changing the detectors statuses in VISSIM.

### 4.3 Optimization in MATLAB

MATLAB is a multi-paradigm numerical computing environment and fourth-generation programming language which allows matrix manipulations, plotting of functions and data, optimization of functions, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran. For the aforementioned reasons, MATLAB is used for the model's implementation.

Optimization is the process of finding the point that minimizes or maximize a function (Figure 4.3). More specifically:

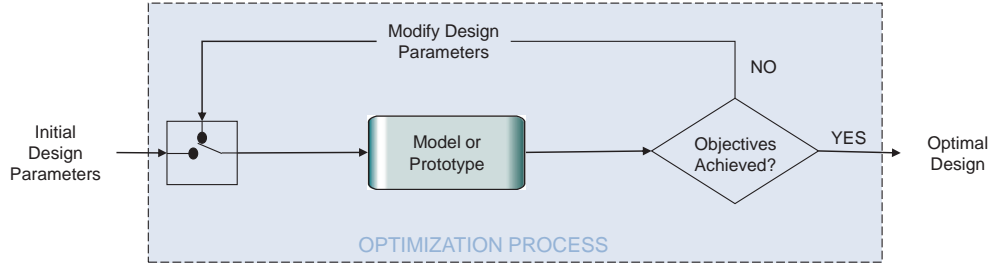


Figure 4.3: Optimization process (“Optimization Toolbox User’s Guide.” 2014).

- A local minimum of a function is a point where the function value is smaller than or equal to the value at nearby points, but possibly greater than at a distant point.
- A global minimum is a point where the function value is smaller than or equal to the value at all other feasible points (Figure 4.4).

Generally most optimization solvers in MATLAB (such as *fmincon*, *fminunc*, *fminsearch*, etc.) find a local optimum; this local optimum can be a global optimum. They find the optimum in the basin of attraction <sup>1</sup> of the starting point. In contrast, global optimization

<sup>1</sup>If an objective function  $f(x)$  is smooth, the vector  $-\nabla f(x)$  points in the direction where  $f(x)$  decreases most quickly. The equation of steepest descent, namely

$$\frac{d}{dt}x(t) = -\nabla f(x(t)) \quad (4.1)$$

yields a path  $x(t)$  that goes to a local minimum as  $t$  gets large. Generally, initial values  $x(0)$  that are close to each other give steepest descent paths that tend to the same minimum point. The basin of attraction for steepest descent is the set of initial values leading to the same local minimum (“Optimization Toolbox User’s Guide.” 2014).

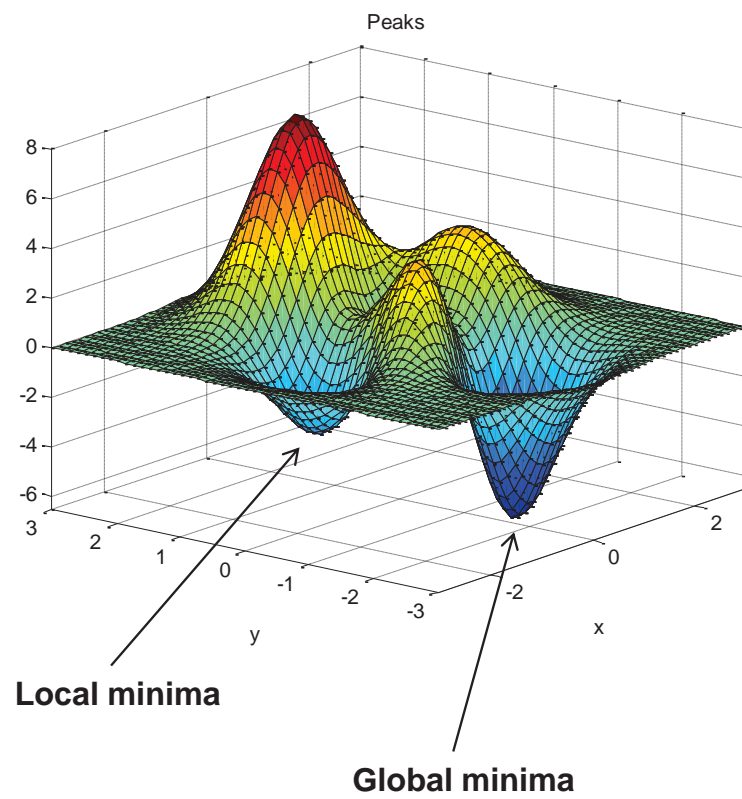


Figure 4.4: Visualization of local and global minimum (“Optimization Toolbox User’s Guide.” 2014).

solvers (such as *GlobalSearch*, *MultiStart*, *patternsearch*, *genetic algorithm*, etc.) are designed to search through more than one basin of attraction (“Optimization Toolbox User’s Guide.” 2014).

In this research, the following optimization solvers are tested, for the minimization of the different aforementioned objectives:

- *fmincon*: attempts to find a constrained local minimum, a point where the function value is smaller than at nearby points, but possibly greater than at a distant point in the search space, of a scalar function of several variables starting at an initial estimate. This is generally referred to as constrained nonlinear optimization or nonlinear programming (“Optimization Toolbox User’s Guide.” 2014).
- *fminconGlobalSearch* & *fminconMultiStart*: have similar approaches to finding global or multiple minima, a point where the function value is smaller or larger at any other point in the search space. Both algorithms start the local solver *fmincon* from multiple start points. The algorithms use multiple start points to sample multiple basins of attraction (“Optimization Toolbox User’s Guide.” 2014).

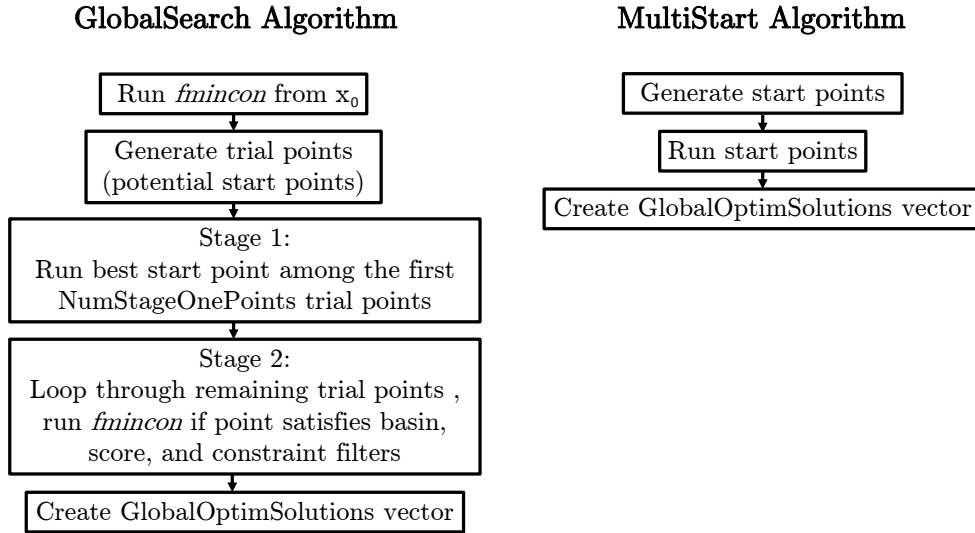
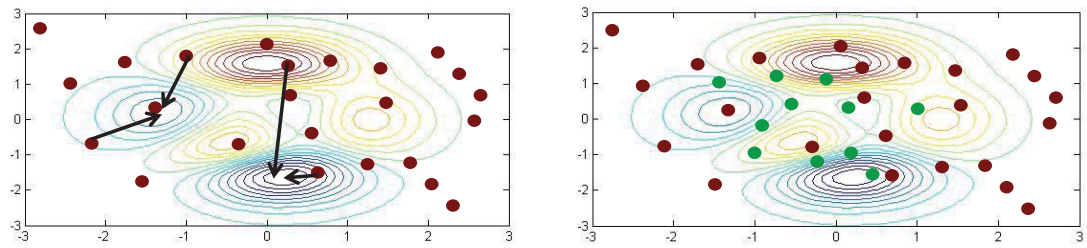


Figure 4.5: A sketch of the GlobalSearch and MultiStart algorithms (“Optimization Toolbox User’s Guide.” 2014).

One of the differences between *GlobalSearch* and *MultiSearch* is that *GlobalSearch* uses a scatter-search mechanism for generating start points, while *MultiStart* uses uniformly distributed start points within bounds, or user-supplied start points. In addition, *GlobalSearch* analyzes start points and rejects those points that are unlikely to improve the best local minimum found so far, on the other hand *MultiStart* runs all start points (or, optionally, all start points that are feasible with respect to bounds or



(a) MultiStart filters starting points based on feasibility. (b) GlobalSearch removes non-promising starting points.

Figure 4.6: MultiStart and GlobalSearch starting points (“Optimization Toolbox User’s Guide.” 2014).

inequality constraints) (Figure 4.6). The differences between these solver objects boil down to the decision on which to use. *GlobalSearch* finds a single global minimum most efficiently on a single processor, while *MultiStart* finds multiple local minima and searches thoroughly for a global minimum (“Optimization Toolbox User’s Guide.” 2014).

- *patternsearch*: finds the global minimum of a function using a pattern search by looking at a number of neighboring points before accepting one of them. If some neighboring points belong to different basins, *patternsearch* in essence looks in a number of basins at once. While more traditional optimization algorithms use exact or approximate information about the gradient or higher derivatives to search for an optimal point, this algorithm uses a pattern search method that implements a minimal and maximal positive basis pattern. The pattern search method handles optimization problems with nonlinear, linear, and bound constraints, and does not require functions to be differentiable or continuous (“Optimization Toolbox User’s Guide.” 2014).
- *Genetic algorithm (GA)*: is a method for solving both constrained and unconstrained optimization problems based on a natural selection process that mimics biological evolution. The algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm randomly selects individuals from the current population and uses them as parents to produce the children for the next generation. Over successive generations, the population “evolve” toward an optimal solution (“Optimization Toolbox User’s Guide.” 2014).

Table 4.3 summarizes the strong points of the local and the global optimization solvers.

For the aforementioned optimization solvers which are tested, the *FminconMultistart* is selected due to the fact that it gives the best results.

Table 4.3: Strong points of local and global optimization solvers(“Optimization Toolbox User’s Guide.” 2014).

	Local solvers	Global solvers
Faster/fewer function evaluations	✓	
Larger problems (higher dimensions)	✓	
Finds local minima/maxima	✓	
Finds global minima/maxima (most of the time)		✓
Better on: non-smooth, stochastic, discontinuous, undefined gradients		✓
Custom data types		✓

## 4.4 Conclusions

In this chapter the implementation of the model is presented; the four different software, namely VRIGen, TRAFCod, VISSIM and MATLAB, that combined constitute the proposed model, are described. More specifically, VRIGen is the Traffic Signal Control System which has been developed in Delft University of Technology. The “output” of VRIGen is the “input” of TRAFCod. VRIGen generates a file with the traffic control program, based on the structure and design tactics chosen by the user. This program file can be connected with the TRAFCod controller simulator and by it with a full-scale traffic simulation program that allows for external traffic signal controllers. The Microscopic Traffic Simulation Software used in this thesis is VISSIM, which is based on the individual behavior of the vehicles. Not only a user friendly graphical interface (GUI) is offered and used by VISSIM, but also the VISSIM COM interface. This COM interface defines a hierarchical model in which the functions and parameters of the simulator originally provided by the GUI can be manipulated by programming. Through VISSIM COM the user is able to manipulate the attributes of most of the internal objects dynamically. In this research, it is programmed in MATLAB, in which the model is implemented. In addition, different optimization solvers which are tested in MATLAB, for the minimization of the different aforementioned objectives, are presented. From the five tested optimization solvers, the *FminconMultistart* is selected due to the fact that it gives the best results.

## Chapter 5

# Simulation

*“Exitus acta probat (The result justifies the deed).”*

— Ovid, *Heroides*

### 5.1 Simulation Set Up

In order to test the proposed system different scenarios are run and compared with the base scenario, which is different in each case and depends on the motorized vehicle’s and cyclist’s demand. In each base scenario, the signal programs that are generated from VRIGen are used and the cyclists travel the network without speed advices. This comparison is interesting, since VRIGen and the proposed system use different optimization methods in order to determine the green times of the traffic lights. On one hand, VRIGen generates all possible control structures, which depend on the flow and the capacity of the traffic streams and the clearance time between streams. On the other hand, the proposed system optimizes the traffic lights by taking into account different objectives which are directly related with the network’s performance. In other words, it can be examined how the situation of cyclists can be improved if different objectives regarding their performance can be taken into account. There is no comparison among the different scenarios, since each scenario tries to give answers to different questions.

In total, 6 different scenarios are run in order different aspects regarding the proposed system to be examined. These points of interest which have been presented in Chapter 1.2 are the investigation of optimal trade-off solutions among the contradicting objectives, the investigation of bicycle green wave, and the investigation of appropriate speed advice range. In addition, different design choices are investigated; four different coefficients,  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$ , have been introduced, and in the following sections the effects of these choices are examined.

The first two scenarios, 1<sup>st</sup> and 2<sup>nd</sup> scenario, are used for controller’s tuning, and in

order to have a first insight of the proposed system in comparison with VRIGen. In this case, the system is tested in order to be figured out if it works as it is expected and how the user/designer will select the values of the coefficients according to policy considerations. The following two scenarios, 3<sup>rd</sup> and 4<sup>th</sup> scenario, are used for bicycle green wave investigation, which is one of the things that this thesis is focused on.

In the 5<sup>th</sup> scenario, the ability of the model to reduce the number of stops of cyclists is investigated, and as a result different cases regarding the value of coefficient  $\gamma$ , the coefficient defining the relative importance of cyclist's number of stops, are run. In the 6<sup>th</sup> scenario, the ability of the proposed system to give comfortable speed advice is examined. Three different cases, with different values of coefficient  $\delta$ , the coefficient defining the relative importance of the deviation between cyclist's desired and advised speed, are run. Table 5.1 presents the six different scenarios with their attributes. It should be mentioned that in all scenarios the investigation of optimal trade-off solutions among the contradicting objectives is investigated, since by choosing different values of the coefficients, different values of the conflicting objectives are occurred.

Table 5.1: Research questions for each scenario.

Scenario	Research Question
1 <sup>st</sup>	Does the system work as it is expected? How the values of the coefficients should be specified?
2 <sup>nd</sup>	Does the system work as it is expected, if the cyclist's demand doubled? How the values of the coefficients should be specified?
3 <sup>rd</sup>	Does the proposed system create bicycle green wave if cyclist's demand is higher than motorized vehicle's demand?
4 <sup>th</sup>	Does the proposed system create bicycle green wave if motorized vehicle's demand is higher than cyclist's demand?
5 <sup>th</sup>	Does the proposed system minimize the number of stops of cyclists?
6 <sup>th</sup>	Does the proposed system give comfortable speed advice?

In order to get a good impression of the possible stochastic spread of the results, for each scenario 10 simulation runs are performed with different random seeds <sup>1</sup>. Furthermore, it is important to ensure that the desired system state is achieved which shows the desired

<sup>1</sup>Random Seed: This parameter initializes the random number generator. Simulation runs with identical input files and random seeds generate identical results. Using a different random seed changes the profile of the traffic arriving and therefore results may also change. In this way, the stochastic variation of input flow arrival times can be simulated ("VISSIM 5.30-05 User Manual," 2011).

realistic processes. As a result the first 600 *sec* are used as warm-up period. The simulation results, after the warm-up period, are collected for analysis.

## 5.2 Performance Indicators

To validate the observed events the simulation has to record data that supports the conclusions. The performance indicators are the sections of the data that tell the most about the scenarios in relation with the questions that need to be answered in the research. Two performance indicators are used: the average delay and the average number of stops of vehicles. These performance indicators are related to the design objectives of this research.

### Delay

Based on travel time sections VISSIM can generate delay data for networks. A delay segment is based on one or more travel time sections. All vehicles that pass these travel time sections are captured by the delay segment, independently of the vehicle classes selected in these travel time sections.

According to “VISSIM 5.30-05 User Manual” (2011) the total delay time is the total delay time of all active and arrived vehicles <sup>2</sup>. The delay time of a vehicle in one time step is the part of the time step which is spent because the actual speed is lower than the desired speed. It is calculated by subtracting the quotient of the actual distance traveled in this time step and the desired speed from the length of the time step.

### Number of stops

The number of stops indicates the efficiency of the proposed system since the main objective of this research is the minimization of the number of stops of cyclists. According to “VISSIM 5.30-05 User Manual” (2011), total number of stops is the total number of stops of all active and arrived vehicles. A stop is counted if the speed of the vehicle was greater than zero at the end of the previous time step and is zero at the end of the current time step.

## 5.3 Used Road Network

As it has been mentioned above the selected network is a simple network. It consists of 3 intersections and each intersection has only two streams; stream 11 (from North to South)

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<sup>2</sup>Number of active vehicles: Total number of vehicles in the network at the end of the simulation. Does not include the already arrived vehicles or the latent demand. Number of arrived vehicles: Total number of vehicles which have already reached their destination and left the network during the simulation. Latent demand: Number of vehicles which could not enter the network.

is the motorized vehicle's stream and stream 24 (from East to West) is the cyclist's stream. The length of the bicycle's links is approximately 500 *m*, the length of the motorized vehicle's links is approximately 700 *m*, and each link has only one lane.

Figure 5.1 presents the used road network in VISSIM.

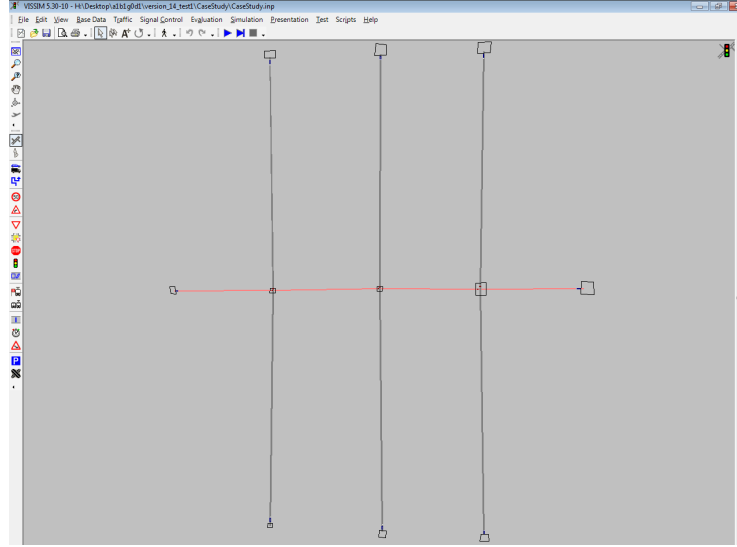


Figure 5.1: Used road network in VISSIM.

In both cases, proposed model and VRIGen, the same choices regarding the timings have been made. The values are presented in Table 5.2.

Table 5.2: Value of timers.

Timer	Value	
	motorized vehicles	cyclists
Fixed green	0.0	0.0
Minimum extension green	2.0	2.0
Maximum extension green	30.0	30.0
Yellow time	3.0	3.0
Clearance time <sup>3</sup>	0.1	0.9

<sup>3</sup>In the proposed system, the clearance times include the yellow time.

## 5.4 Scenarios

### 5.4.1 Controller's Tuning - First & Second Scenario

As it is mentioned before, the first two scenarios are used for controller's tuning, investigation of optimal trade-off solutions among the contradicting objectives (Chapter 1.2), and in order to have a first insight of the proposed system in comparison with VRIGen. The demands were chosen such to have undersaturated intersections, for the easier interpretation of the results, however in the 2<sup>nd</sup> scenario the cyclist's demand is doubled.

#### First Scenario

For the 1<sup>st</sup> scenario, the demand of motorized vehicle's and bicycle's streams is given in Table 5.3.

Table 5.3: Demand in the network for the 1<sup>st</sup> scenario.

Stream	Demand
car (1 <sup>st</sup> intersection)	500
car (2 <sup>nd</sup> intersection)	550
car (3 <sup>rd</sup> intersection)	600
bike	300

For this demand scenario, the proposed model is run with two different sets of coefficients,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ . In the first case,  $\alpha$ ,  $\beta$  and  $\delta$  are set equal to 1 and  $\gamma$  equals 20. In the second case,  $\alpha$  is doubled, while the rest remain the same (Figure 5.4). The choice of the value of  $\gamma$  coefficient is based on the fact that the TRANSYT suggests that coefficients should be set so that 1 stop  $\simeq 20$  sec delay (Robertson, 1969). The comparison of the model's results and the results by using VRIGen as the base scenario is presented below.

Table 5.4: Value of coefficients for the 1<sup>st</sup> scenario.

Coefficient	Value	
	1 <sup>st</sup> Case	2 <sup>nd</sup> Case
$\alpha$	1	2
$\beta$	1	1
$\gamma$	20	20
$\delta$	1	1

In the first case the average delay and number of stops of cyclists decreases in comparison

with VRIGen by 43% and 48% respectively, while the average delay and the average number of stops of motorized vehicles increase (Table 5.5).

Table 5.5: 1<sup>st</sup> Scenario - 1<sup>st</sup> Case: Comparison of the model's results and the results by using VRIGen as the base scenario. Set of coefficients:  $\alpha = 1$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$

Stream	Average Delay	Average Number of Stops
car (1 <sup>st</sup> intersection)	+18%	+57%
car (2 <sup>nd</sup> intersection)	+16%	+56%
car (3 <sup>rd</sup> intersection)	+14%	+51%
bike	-43%	-48%

In the second case, the coefficient  $\alpha$ , the coefficient defining the relative importance of motorized vehicle's delay, is doubled, indicating that there is a trade-off among the conflicting objectives; any objective cannot be improved without worsening the other objective. The average delay and the average number of stops of motorized vehicle's increase again, however the increase is smaller. The increase of the average delay ranges between 5% and 9% and of average number of stops between 37% and 40%. Of course, this improvement for motorized traffic deteriorates the situation for cyclists. Their average delay and average number of stops declines again, however the reduction is smaller; 38% decrease of average delay and 47% of average number of stops (Table 5.6, Figure 5.2 and Figure 5.3).

Table 5.6: 1<sup>st</sup> Scenario - 2<sup>nd</sup> Case: Comparison of the model's results and the results by using VRIGen as the base scenario. Set of coefficients:  $\alpha = 2$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$

Stream	Average Delay	Average Number of Stops
car (1 <sup>st</sup> intersection)	+5%	+37%
car (2 <sup>nd</sup> intersection)	+9%	+40%
car (3 <sup>rd</sup> intersection)	0%	+38%
bike	-38%	-47%

In this scenario, the first impression of the proposed model is given, affirming the rule that none of the feasible solutions allow simultaneous optimality for all objectives, which is the difficulty with a multi-objective optimization problem. As a results, the average delay and average number of stops are improved for cyclists by worsening the motorized traffic. However, by making different choices regarding the different values of coefficients, the one or the other road user could be benefited. Which set of coefficients is more suitable depends on what is considered more important, since the reduction especially in average number of stops of cyclists is almost the same in both cases, which is the most important for them,

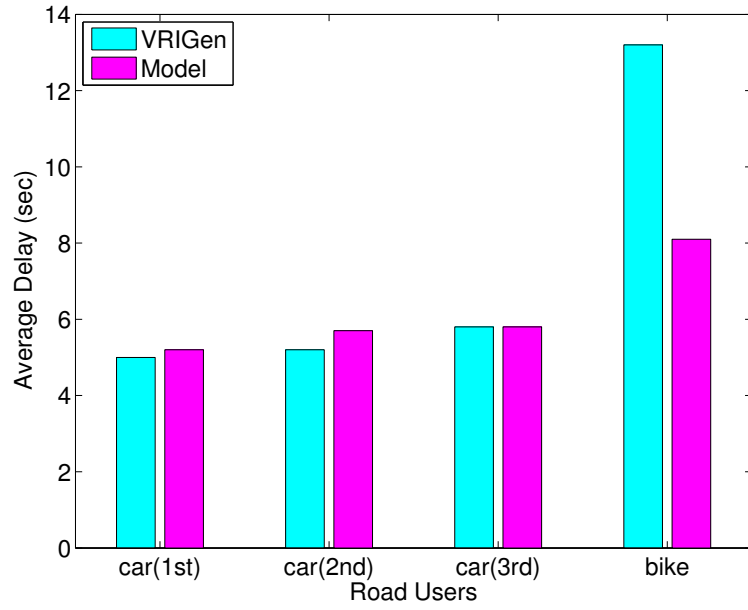


Figure 5.2: 1<sup>st</sup> Scenario - 2<sup>nd</sup> Case: Comparison of average delay. Set of coefficients:  $\alpha = 2$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$ .

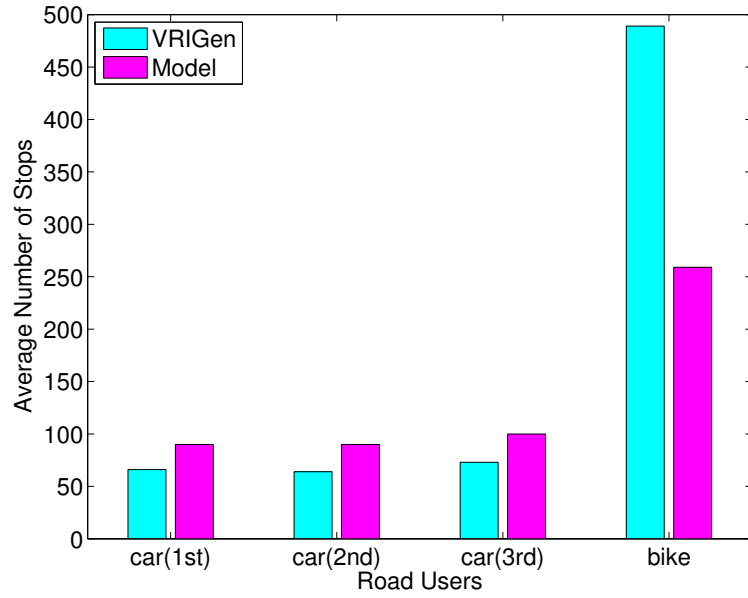


Figure 5.3: 1<sup>st</sup> Scenario - 2<sup>nd</sup> Case: Comparison of average number of stops. Set of coefficients:  $\alpha = 2$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$ .

while the increase of average delay and number of stops of motorized traffic is much higher in the first case.

### Second Scenario

For the 2<sup>nd</sup> scenario, the demand of motorized vehicle's and bicycle's streams is given in Table 5.7. In this scenario, the demand of motorized vehicles remains the same, while the demand of cyclists is doubled.

Table 5.7: Demand in the network for the 2<sup>nd</sup> scenario.

Stream	Demand
car (1 <sup>st</sup> intersection)	500
car (2 <sup>nd</sup> intersection)	550
car (3 <sup>rd</sup> intersection)	600
bike	600

For this demand scenario, the proposed model is run again with two different sets of coefficients,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ . In the first case,  $\alpha$  equals 2,  $\beta$  and  $\delta$  equal 1 and  $\gamma$  equals 20. In the second case,  $\alpha$  equals 4,  $\beta$  and  $\delta$  equal 1 and  $\gamma$  equals 20. The first case is selected based on the first scenario, since by using this set of coefficients, the average delay and number of stops of cyclists remain almost the same while the average delay and number of stops of motorized vehicles increases, however the increase is lower. The comparison of the model's results and the results by using VRIGen as the control program is presented in Tables 5.9 and 5.10.

Table 5.8: Value of coefficients for the 2<sup>nd</sup> scenario.

Coefficient	Value	
	1 <sup>st</sup> Case	2 <sup>nd</sup> Case
$\alpha$	2	4
$\beta$	1	1
$\gamma$	20	20
$\delta$	1	1

In the first case,  $\alpha = 2$ ,  $\beta = 1$ ,  $\gamma = 20$  and  $\delta = 1$ , the average delay and number of stops of motorized vehicles increases; the average delay in each intersection increases by 43%, 40% and 32% and the average number of stops by 79%, 74% and 72% respectively.

However, the average delay and number of stops of cyclists decreases by 40% and 44% (Table 5.9).

Table 5.9: 2<sup>nd</sup> Scenario - 1<sup>st</sup> Case: Comparison of the model's results and the results by using VRIGen as the control program. Set of coefficients:  $\alpha = 2$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$

Stream	Average Delay	Average Number of Stops
car (1 <sup>st</sup> intersection)	+43%	+79%
car (2 <sup>nd</sup> intersection)	+40%	+74%
car (3 <sup>rd</sup> intersection)	+32%	+72%
bike	-40%	-44%

Due to the increase of the average delay and number of stops of motorized traffic, in the second case the value of coefficient  $\alpha$ , the coefficient defining the relative importance of motorized vehicle's delay, is doubled. In this case, the average delay of motorized vehicles in each intersection increases again, however the increase is smaller than the first case. The average delay increases by 9%, 7% and 2% in each intersection respectively and the average number of stops by 34%, 32% and 30%. In addition, the average delay and the average number of stops of cyclists decreases by 28% and 34% (Table 5.10, Figures 5.4 and 5.5).

Table 5.10: 2<sup>nd</sup> Scenario - 2<sup>nd</sup> Case: Comparison of the model's results and the results by using VRIGen as the control program. Set of coefficients:  $\alpha = 4$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$

Stream	Average Delay	Average Number of Stops
car (1 <sup>st</sup> intersection)	+9%	+34%
car (2 <sup>nd</sup> intersection)	+7%	+32%
car (3 <sup>rd</sup> intersection)	+2%	+30%
bike	-28%	-34%

The results of this scenario are similar with the results of the 1<sup>st</sup> scenario. In both cases, the average delay and the average number of stops of cyclists decreases, affirming the rule that none of the feasible solutions allow simultaneous optimality for all objectives. Depending the value of the coefficient  $\alpha$ , this decline is smaller or larger and with a higher or lower cost for the motorized traffic. From the above, it becomes clear that when the cyclist's demand increases, the coefficient  $\alpha$ , the coefficient defining the relative importance of motorized vehicle's delay, should be increased in order to be achieved a smaller increase in average delay and number of stops of motorized vehicles. A conclusion that is derived from both scenarios is that, the system works as expected and enables the user/designer of the control system to choose the coefficients according to policy considerations.

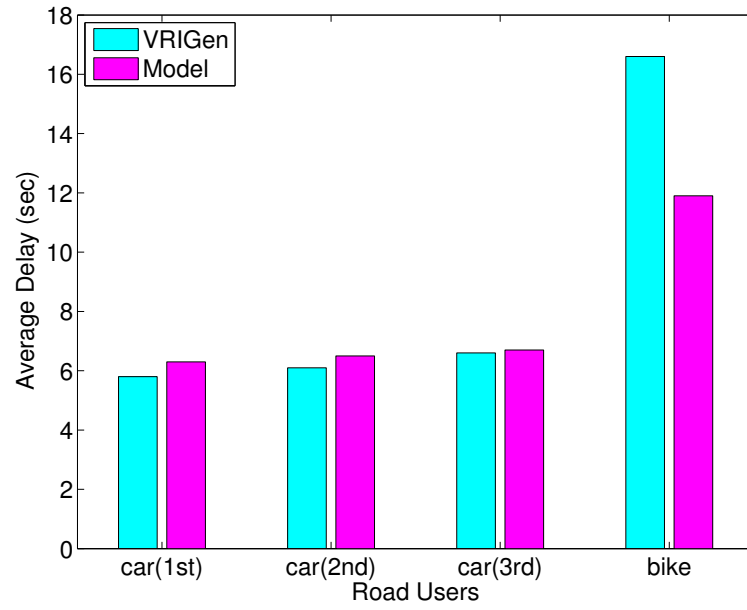


Figure 5.4: 2<sup>nd</sup> Scenario - 2<sup>nd</sup> Case: Comparison of average delay. Set of coefficients:  $\alpha = 4$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$ .

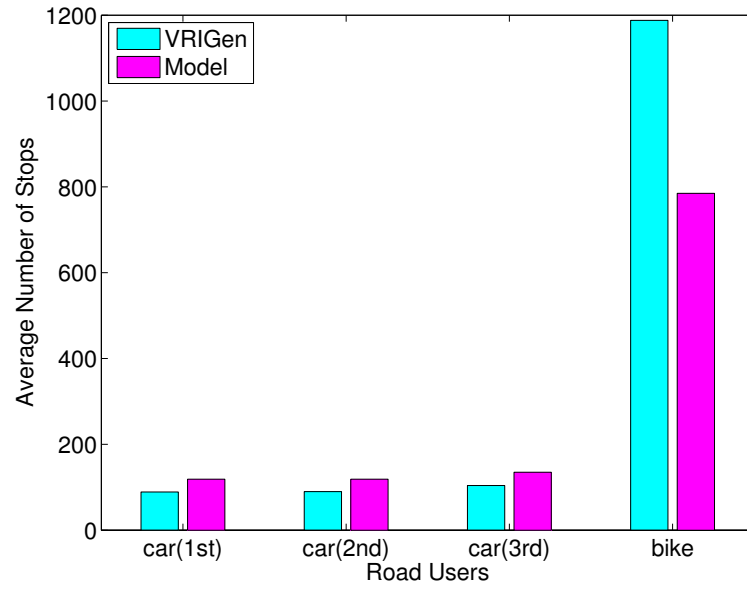


Figure 5.5: 2<sup>nd</sup> Scenario - 2<sup>nd</sup> Case: Comparison of average number of stops. Set of coefficients:  $\alpha = 4$ ,  $\beta = 1$ ,  $\gamma = 20$ ,  $\delta = 1$ .

### 5.4.2 Bicycle Green Wave - Third & Fourth Scenario

Scenarios 3<sup>rd</sup> and 4<sup>th</sup>, are used for bicycle green wave investigation, which is one of the things that this thesis is focused on (Chapter 1.2). In the 3<sup>rd</sup> scenario the cyclist's demand is high while motorized vehicle's demand is low and in the 4<sup>th</sup> scenario vice versa. These choices are made in order to be investigated if the creation of bicycle green wave is influenced of the road user's demand.

#### Third Scenario

For this scenario the demand of motorized vehicle's and cyclist's stream is given in Table 5.11; the demand of motorized traffic is low in contrast with the demand of cyclists. In this scenario, the creation of bicycle green wave is investigated.

Table 5.11: Demand in the network for the 3<sup>rd</sup> scenario.

Stream	Demand
car (1 <sup>st</sup> intersection)	300
car (2 <sup>nd</sup> intersection)	200
car (3 <sup>rd</sup> intersection)	250
bike	800

In this scenario, the following set of coefficients is used:  $\alpha = 4$ ,  $\beta = 1$ ,  $\gamma = 20$  and  $\delta = 1$  (Table 5.12). The reason of this choice is based on the fact that the reduction of the average delay and number of stops of cyclists remains almost the same while the reduction of the average delay and number of stops of motorized vehicles has a smaller increase, as it is presented in the 1<sup>st</sup> scenario. The comparison of the model's results and the results by using VRIGen as the base scenario is presented in Table 5.13.

Table 5.12: Value of coefficients for the 3<sup>rd</sup> scenario.

Coefficient	Value
$\alpha$	4
$\beta$	1
$\gamma$	20
$\delta$	1

In this scenario the average delay and number of stops of cyclists decreases, while for motorized vehicles increases. In fact, the increase of average delay of motorized vehicles ranges from 14% to 19%. In addition, the increase of average number of stops of motorized

vehicles ranges from 33% to 39%. On the other hand, the reduction of cyclist's average delay ranges between 35% and 46% and of average number of stops between 40% and 53%. At this point, it should be mentioned that bicycle green wave is created since the reduction of the average number of stops of cyclists increases from intersection to intersection. Specifically, the average number of stops decreases by 40% in the first intersection, by 46% in the second intersection and by 53% in the third intersection (Table 5.13, Figure 5.6 and Figure 5.7).

Table 5.13: 3<sup>rd</sup> Scenario: Comparison of the model's results and the results by using VRIGen as the base scenario. The bicycle green wave is investigated.

Stream	Average Delay	Average Number of Stops
car (1 <sup>st</sup> intersection)	+19%	+39%
car (2 <sup>nd</sup> intersection)	+14%	+33%
car (3 <sup>rd</sup> intersection)	+17%	+33%
bike (1 <sup>st</sup> intersection)	−35%	−40%
bike (2 <sup>nd</sup> intersection)	−43%	−46%
bike (3 <sup>rd</sup> intersection)	−46%	−53%

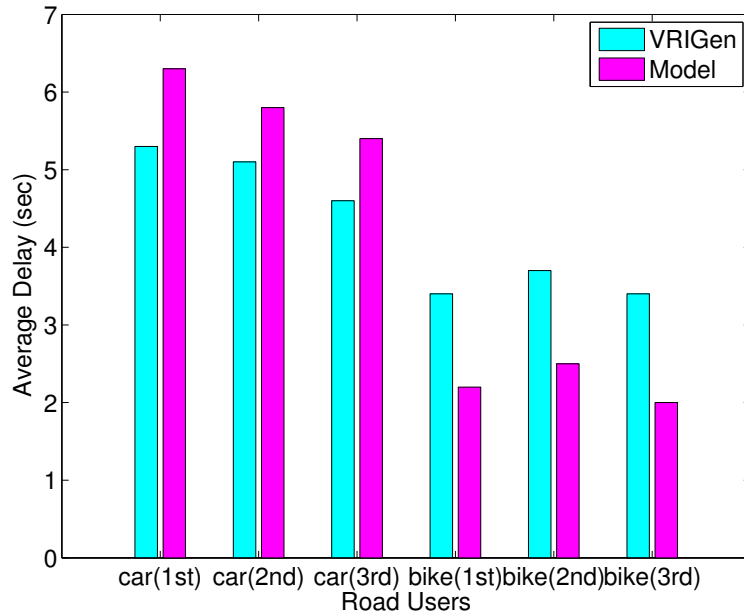
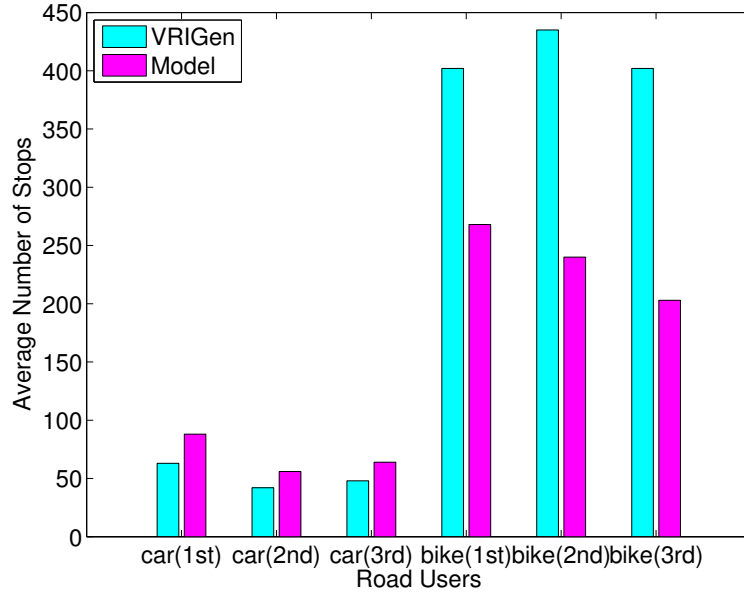


Figure 5.6: 3<sup>rd</sup> Scenario: Comparison of average delay.

Figure 5.7: 3<sup>rd</sup> Scenario: Comparison of average number of stops.

#### Fourth Scenario

For this scenario the demand of motorized vehicle's and cyclist's streams is given in Table 5.14. The demand of motorized traffic is high while the demand of cyclists is low. Also in this scenario, the creation of bicycle green wave is investigated.

Table 5.14: Demand in the network for the 4<sup>th</sup> scenario.

Stream	Demand
car (1 <sup>st</sup> intersection)	800
car (2 <sup>nd</sup> intersection)	700
car (3 <sup>rd</sup> intersection)	750
bike	300

In this scenario, the following set of coefficients is used:  $\alpha = 2$ ,  $\beta = 1$ ,  $\gamma = 20$  and  $\delta = 1$  (Table 5.15). The comparison of the model's results and the results by using VRIGen as the control program is presented in Table 5.16 and in Figures 5.8 and 5.9.

In this scenario the average delay and number of stops increase for motorized vehicles. On the other hand, the average delay and the average number of stops decrease for cyclists in all intersections. Specifically, the reduction of cyclist's average delay ranges from 27% to 33% and the reduction of cyclist's average number of stops from 36% to 42%. Bicycle green wave is not created since the reduction of the average number of stops is almost the same among the three intersections; 40% in the first intersection, 46% in the second intersection

Table 5.15: Value of coefficients for the 4<sup>th</sup> scenario.

Coefficient	Value
$\alpha$	2
$\beta$	1
$\gamma$	20
$\delta$	1

and 42% in the third intersection (Table 5.16).

Table 5.16: 4<sup>th</sup> Scenario: Comparison of the model's results and the results by using VRIGen as the control program. The bicycle green wave is investigated.

Stream	Average Delay	Average Number of Stops
car (1 <sup>st</sup> intersection)	+19%	+72%
car (2 <sup>nd</sup> intersection)	+14%	+74%
car (3 <sup>rd</sup> intersection)	+9%	+60%
bike (1 <sup>st</sup> intersection)	-33%	-40%
bike (2 <sup>nd</sup> intersection)	-27%	-46%
bike (3 <sup>rd</sup> intersection)	-30%	-42%

### 5.4.3 Investigating coefficient $\gamma$ - Fifth Scenario

The 5<sup>th</sup> scenario is used in order to test the ability of the model to reduce the number of stops of cyclists. For this reason, different cases regarding the value of coefficient  $\gamma$ , the coefficient defining the relative importance of cyclist's number of stops, are run. The demands were chosen such to have undersaturated intersections, which allows easier interpretation of the results. For the same reason, the demands of motorized vehicle's are the same in all three intersections. For the 5<sup>th</sup> scenario, the demand of motorized vehicle's and bicycle's streams is given in Table 5.17.

Table 5.17: Demand in the network for the 5<sup>th</sup> scenario.

Stream	Demand
car (1 <sup>st</sup> intersection)	300
car (2 <sup>nd</sup> intersection)	300
car (3 <sup>rd</sup> intersection)	300
bike	500

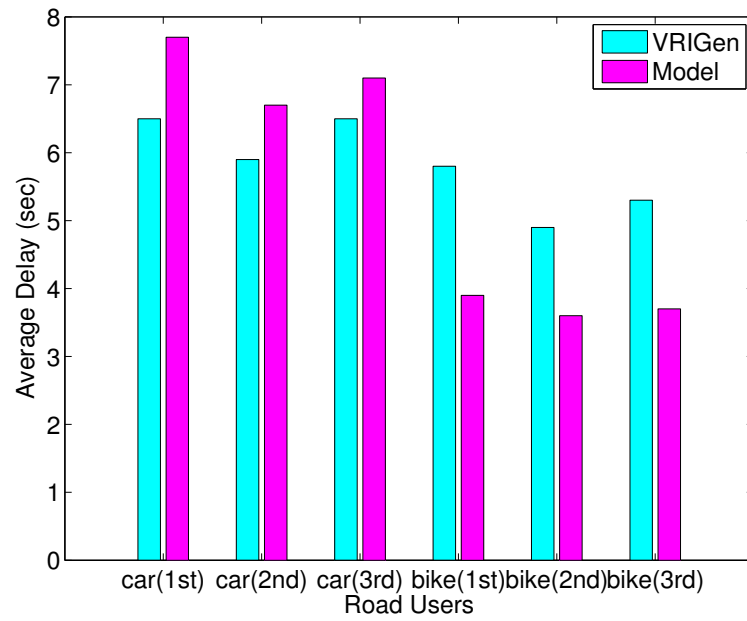


Figure 5.8: 4<sup>th</sup> Scenario: Comparison of average delay.

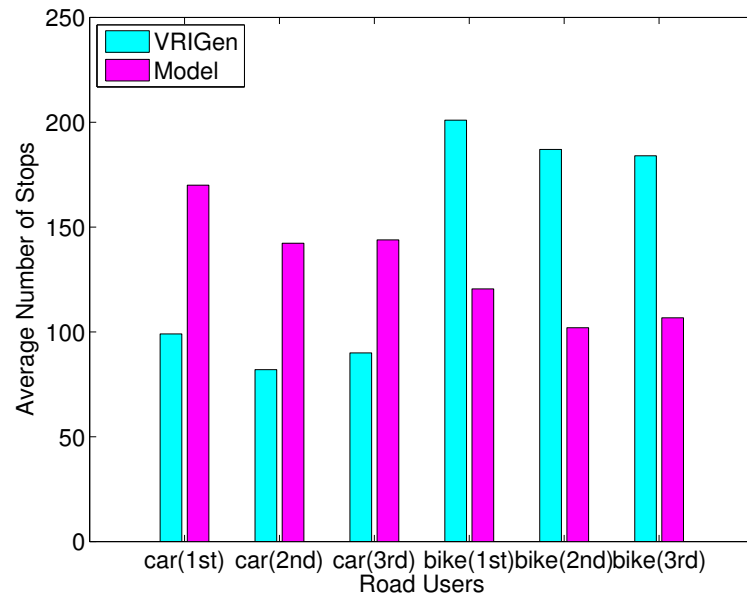


Figure 5.9: 4<sup>th</sup> Scenario: Comparison of average number of stops.

In this scenario, four different sets of coefficients are tested. In each case, coefficients  $\alpha$ ,  $\beta$  and  $\delta$  set equal to 1 and coefficient  $\gamma$ , the coefficient defining the relative importance of cyclist's number of stops, changes:  $\gamma = 100$ ,  $\gamma = 1000$ ,  $\gamma = 10000$ ,  $\gamma = 1000000$  (Table 5.18).

Table 5.18: Value of coefficients for the 5<sup>th</sup> scenario.

Coefficient	Value			
	1 <sup>st</sup> Case	2 <sup>nd</sup> Case	3 <sup>rd</sup> Case	4 <sup>th</sup> Case
$\alpha$	1	1	1	1
$\beta$	1	1	1	1
$\gamma$	100	1000	10000	1000000
$\delta$	1	1	1	1

In this extreme scenario, the average delay and the average number of stops of cyclists decreases, while the results among the different cases are almost similar. A possible explanation is that, this happens because the equation that is used for the estimation of the number of stops is a discrete function; discrete optimization deals mainly with problems where an optimal solution should be chosen from a finite or countable number of possibilities, or because the prediction fails. Specifically, the average delay and the average number of stops decrease as the value of the coefficient  $\gamma$  increases, until the value of 10000, where the reduction is the highest; the average delay decreases by 38%, 45% and 48% and the average number of stops by 58%, 61% and 69%. In the majority of the cases, bicycle green wave is created since the average number of stops reduces from intersection to intersection, having the most obvious difference when  $\gamma = 10000$ , where from the first to the third intersection the average number of stops decreases slightly more than 10% (Tables 5.19 and 5.20 and Figures 5.10 and 5.11).

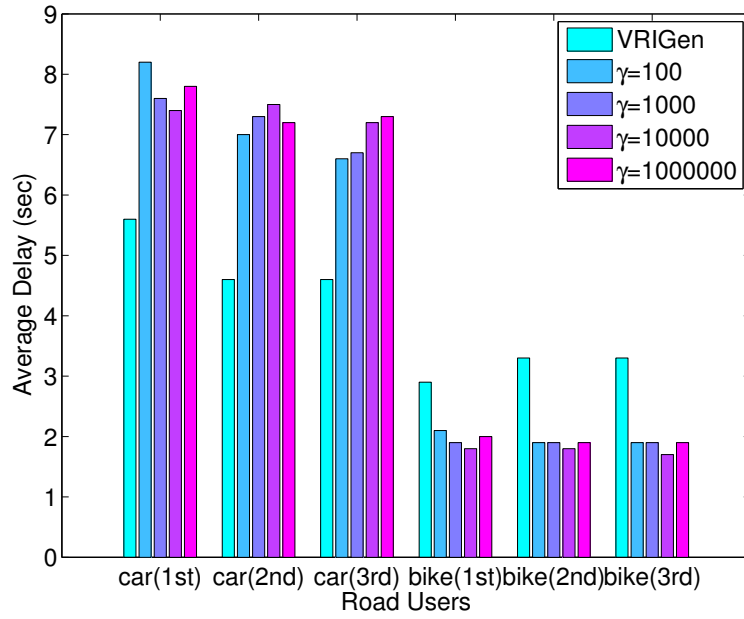
As a results of the cyclist's improvement, there is a cost for the motorized traffic, which is high, considering the extreme values that are given to the coefficient  $\gamma$ , especially regarding the average number of stops. Specifically, the increase of motorized vehicle's delay ranges between 33% and 59%, while the increase of average number of stops between 57% and 138% (Tables 5.19 and 5.20 and Figures 5.10 and 5.11).

#### 5.4.4 Speed Advice - Sixth Scenario

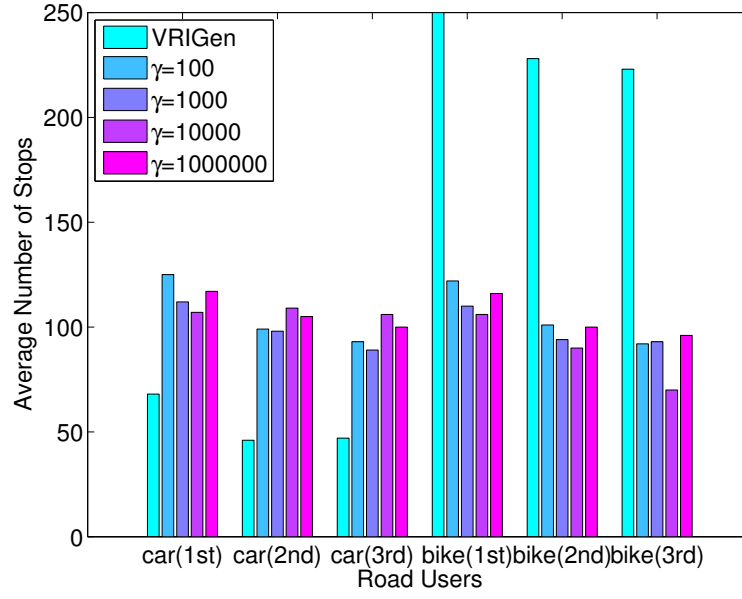
The 6<sup>th</sup> scenario is used in order to test the ability of the proposed system to give comfortable speed advice (Chapter 1.2). The demands were chosen such to have undersaturated intersections, which allows easier interpretation of the results. For the 6<sup>th</sup> scenario, the

Table 5.19: 5<sup>th</sup> Scenario: Comparison of the model's average results and the results by using VRIGen as the base scenario regarding the average delay of the different road users.

Stream	$\gamma = 100$	$\gamma = 1000$	$\gamma = 10000$	$\gamma = 1000000$
car (1 <sup>st</sup> intersection)	+48%	+36%	+33%	+40%
car (2 <sup>nd</sup> intersection)	+53%	+59%	+55%	+57%
car (3 <sup>rd</sup> intersection)	+43%	+45%	+56%	+59%
bike (1 <sup>st</sup> intersection)	-29%	-36%	-38%	-32%
bike (2 <sup>nd</sup> intersection)	-41%	-44%	-45%	-42%
bike (3 <sup>rd</sup> intersection)	-43%	-43%	-48%	-44%

Figure 5.10: 5<sup>th</sup> Scenario: Comparison of average delay.Table 5.20: 5<sup>th</sup> Scenario: Comparison of the model's average results and the results by using VRIGen as the base scenario regarding the average number of stops of the different road users.

Stream	$\gamma = 100$	$\gamma = 1000$	$\gamma = 10000$	$\gamma = 1000000$
car (1 <sup>st</sup> intersection)	+83%	+64%	+57%	+71%
car (2 <sup>nd</sup> intersection)	+115%	+113%	+138%	+130%
car (3 <sup>rd</sup> intersection)	+97%	+90%	+125%	+113%
bike (1 <sup>st</sup> intersection)	-51%	-56%	-58%	-53%
bike (2 <sup>nd</sup> intersection)	-56%	-59%	-61%	-56%
bike (3 <sup>rd</sup> intersection)	-59%	-58%	-69%	-57%

Figure 5.11: 5<sup>th</sup> Scenario: Comparison of average number of stops.

demand of motorized vehicle's and bicycle's streams is given in Table 5.21. The demand is the same with the 1<sup>st</sup> scenario.

Table 5.21: Demand in the network for the 6<sup>th</sup> scenario.

Stream	Demand
car (1 <sup>st</sup> intersection)	500
car (2 <sup>nd</sup> intersection)	550
car (3 <sup>rd</sup> intersection)	600
bike	300

For this demand scenario, the proposed model is run with three different sets of coefficients,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ . In all cases, coefficients  $\alpha$  equals 2,  $\beta$  equals 1,  $\gamma$  equals 20 and the value of coefficient  $\delta$ , the coefficient defining the relative importance of the deviation between the desired and the advised speed of cyclists, changes; in the first case  $\delta = 0.5$ , in the second case  $\delta = 1$ , which is actually the 1<sup>st</sup> scenario, and in the third case  $\delta = 10000$  (Table 5.22). In this way, it can be examined if the proposed system, acts as expected, i.e. to give speed advice that do not deviate a lot from the desired speed, and how much the average delay and the average number of stops are influenced. The aforementioned comparison is presented below.

As it is presented in Table 5.23 and Figure 5.12 the average delay of cyclists decreases in any case, however the lower the value of  $\delta$  the bigger the decrease. In the first and

Table 5.22: Value of coefficients for the 6<sup>th</sup> scenario.

Coefficient	Value		
	1 <sup>st</sup> Case	2 <sup>nd</sup> Case	3 <sup>rd</sup> Case
$\alpha$	2	2	2
$\beta$	1	1	1
$\gamma$	20	20	20
$\delta$	0.5	1	10000

second case, where the value of  $\delta$  does not differ a lot the reduction is the same, 38%. In the extreme case, where  $\delta = 10000$  the cyclist's average delay decreases by 28%, since the controller tries to give more comfortable speed advice to cyclists, i.e. speed advice with a smaller deviation of their desired speed, resulting in a higher cost for the other objectives.

Table 5.23: 6<sup>th</sup> Scenario: Comparison of the model's average results and the results by using VRIGen as the base scenario regarding the average delay of the different road users.

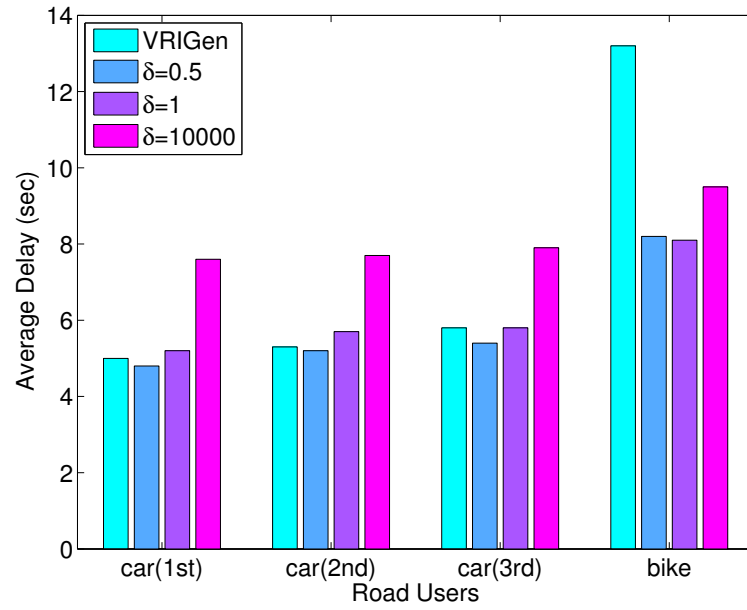
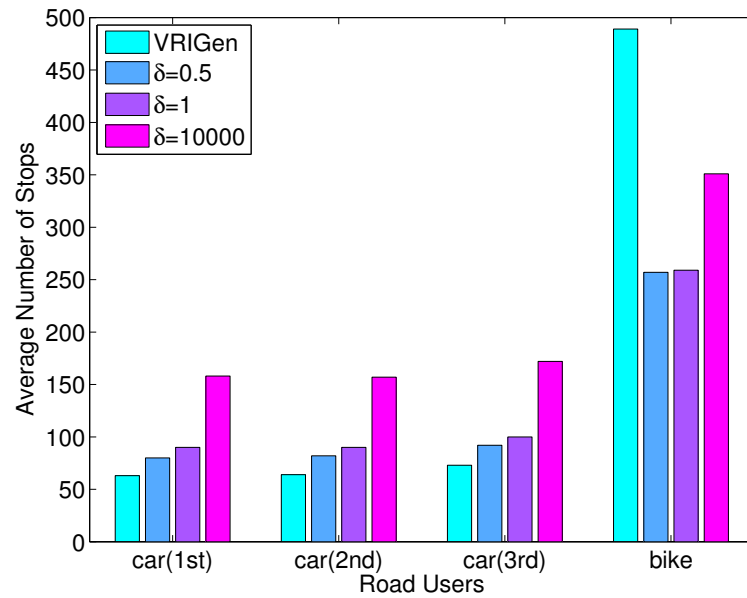
Stream	$\delta = 0.5$	$\delta = 1$	$\delta = 10000$
car (1 <sup>st</sup> intersection)	-2%	+5%	+53%
car (2 <sup>nd</sup> intersection)	-2%	+9%	+48%
car (3 <sup>rd</sup> intersection)	-7%	0%	+36%
bike	-38%	-38%	-28%

The same phenomenon is observed to motorized vehicles. In the first case, where  $\delta = 0.5$ , their average delay decreases, by 2%, 2%, 7% in each intersection respectively. As the value of  $\delta$  increases, their average delay also increases and has the highest value when  $\delta = 10000$ . In other words, the bigger the comfort of cyclists, the higher the cost that should be paid by the motorized traffic.

Table 5.24: 6<sup>th</sup> Scenario: Comparison of the model's average results and the results by using VRIGen as the base scenario regarding the average number of stops of the different road users.

Stream	$\delta = 0.5$	$\delta = 1$	$\delta = 10000$
car (1 <sup>st</sup> intersection)	+26%	+37%	+134%
car (2 <sup>nd</sup> intersection)	+28%	+40%	+145%
car (3 <sup>rd</sup> intersection)	+27%	+38%	+137%
bike	-48%	-47%	-28%

Similar results are presented in Table 5.24 and Figure 5.13 regarding the average number

Figure 5.12: 6<sup>th</sup> Scenario: Comparison of average delay.Figure 5.13: 6<sup>th</sup> Scenario: Comparison of average number of stops.

of stops. With respect to cyclists, their average number of stops decreases, however with a smaller percentage as the value of coefficient  $\delta$  increases. The same phenomenon is observed to motorized traffic as well, nevertheless with the difference that their average number of stops always increases, with the highest rise in the extreme case where  $\delta = 10000$ . In this case, motorized vehicles have to stop when it is necessary in order the cyclists to continue traveling with a speed which has a small deviation from their desired speed.

Since the coefficient  $\delta$  is the coefficient defining the relative importance of the deviation between the cyclist's advised and desired speed, it is interesting to present how the different values of this coefficient influence the deviation.

Table 5.25: 6<sup>th</sup> Scenario: Number of speed advice per interval of deviation for the three different cases.

Interval of deviation (km/h)	$\delta = 0.5$	$\delta = 1$	$\delta = 10000$
-5.9 - -5.0	8	1	0
-4.9 - -4.0	37	6	0
-3.9 - -3.0	115	37	0
-2.9 - -2.0	350	170	0
-1.9 - -1.0	535	409	0
-0.9 - 0.0	1435	1756	3169
0.0 - 0.9	895	1123	892
1.0 - 1.9	60	67	0
2.0 - 2.9	18	7	0
3.0 - 3.9	5	1	0
4.0 - 4.9	2	0	0
5.0 - 5.9	0	0	0

As it is presented in in Table 5.25 and Figure 5.14, as the value of coefficient  $\delta$  increases, the number of speed advice which belong in the intervals with bigger deviation between the desired and the advised speed decreases. These differences are not so obvious in the first and second case, since the values of  $\delta$  are really close. However, in the third case,  $\delta = 10000$ , cyclists receive speed advice which deviate at most  $\pm 0.9$  km/h.

An interesting observation is that the majority of the speed advice belong to the negative intervals and as a result the cyclists have to slow down instead of speeding up, which is more easy and convenient way to adjust their speed. In fact, all the cyclists have the ability to reduce their speed, while there are always cyclists who are not able to follow a higher speed advice. Specifically, when  $\delta = 0.5$ , 72% of the speed advice belong to the intervals where the cyclist has to reduce his speed and 28% to the intervals with the opposite effect, and

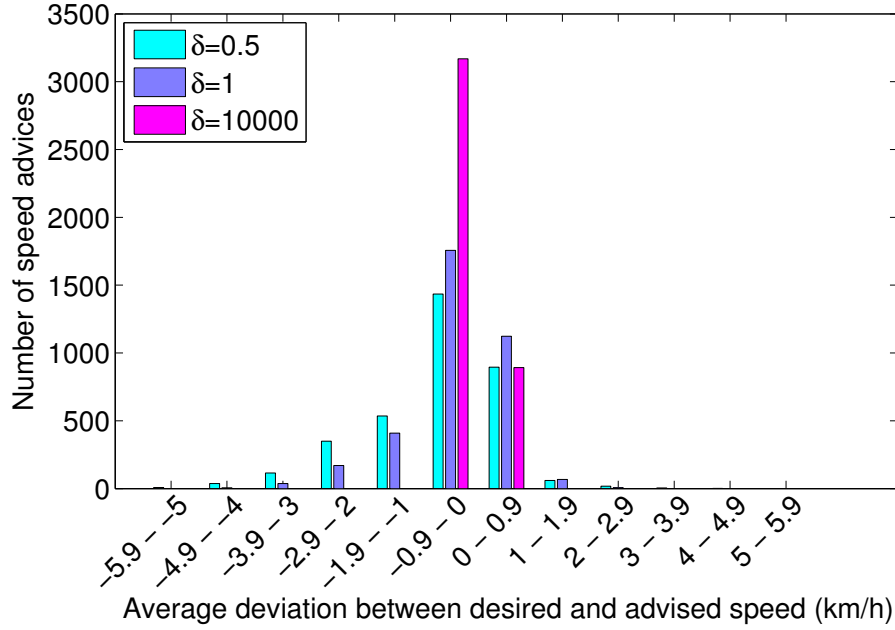


Figure 5.14: 6<sup>th</sup> Scenario: Comparison of deviation between cyclist's advised and desired speed.

actually 91% of the speed advice which demand to increase the speed, are in the 0.0 – 0.9  $km/h$  interval. When  $\delta = 1$ , 67% of the speed advice require of the cyclists to reduce their speed in contrast with 33% which demand of them the opposite; 94% of the speed advice which require increase of the speed, belong to the 0.0 – 0.9  $km/h$  interval. Finally, when  $\delta = 10000$ , 78% of the speed advice require deceleration, while 22% require to speed up not more than 0.9  $km/h$ . From the above, it is clear that the majority of the speed advice could be characterized as comfortable speed advice, because either the cyclist has to slow down or to increase his speed not more than 0.9  $km/h$ .

## 5.5 Statistical Significance

In Statistics “significant” means probably true; not due to chance. For the statistical significance of the results the Wilcoxon signed-rank test is used. The Wilcoxon signed-rank test is a non-parametric statistical hypothesis test used when comparing two related samples, matched samples, or repeated measurements on a single sample to assess whether their population mean ranks differ (i.e. it is a paired difference test). It can be used as an alternative to the paired Student's t-test, t-test for matched pairs, or the t-test for dependent samples when the population cannot be assumed to be normally distributed (Lowry, 2011).

The logic behind the Wilcoxon test is quite simple. The data are ranked to produce

two rank totals, one for each condition. If there is a systematic difference between the two conditions, then most of the high ranks will belong to one condition and most of the low ranks will belong to the other one. As a result, the rank totals will be quite different and one of the rank totals will be quite small. On the other hand, if the two conditions are similar, then high and low ranks will be distributed fairly evenly between the two conditions and the rank totals will be fairly similar and quite large. The Wilcoxon test statistic “W” is simply the smaller of the rank totals. The smaller it is (taking into account how many participants you have) then the less likely it is to have occurred by chance. A table of critical values of W shows how likely it is to obtain the particular value of W purely by chance. Note that the Wilcoxon test is unusual in this respect: normally, the bigger the test statistic, the less likely it is to have occurred by chance). The steps that should be followed are the following (Lowry, 2011):

1. Find the difference between each pair of scores.
2. Rank these differences (from the smallest difference to the highest), ignoring any “0” differences and ignoring the sign of the difference (i.e. whether it is a positive or negative difference). If two or more difference-scores are the same, this is a “tie”: tied scores get the average of the ranks that those scores would have obtained, had they been different from each other.
3. Add together the ranks belonging to scores with a positive sign.
4. Add together the ranks belonging to scores with a negative sign.
5. Whichever of these sums is the smaller, is the value of the test statistic “W”.
6. “N” is the number of differences (omitting “0” differences).
7. Define the hypotheses for the Wilcoxon signed-rank test; the hypotheses concern the population median of the difference scores. The research hypothesis can be one- or two-sided. Here a one-sided test is considered.
  - $H_0$ : The median difference is zero versus
  - $H_1$ : The median difference is positive  $\alpha = 0.05$
8. Use the table of critical Wilcoxon value. Compare your obtained value of Wilcoxon’s test statistic to the critical value in the table (taking into account “N”, the number of subjects). The obtained value is statistically significant if it is equal to or smaller than the value in the table;  $H_0$  hypothesis is rejected in favor of  $H_1$ .

Table 5.26: Statistical significance of the results - 1<sup>st</sup> & 2<sup>nd</sup> Scenario.

Scenario	Stream	Average Delay	Average Number of Stops
1 <sup>st</sup>	car (1 <sup>st</sup> )	+ <sup>4</sup>	+
	car (2 <sup>nd</sup> )	+	+
	car (3 <sup>rd</sup> )	-	+
	bike	+	+
2 <sup>nd</sup>	car (1 <sup>st</sup> )	+	+
	car (2 <sup>nd</sup> )	+	+
	car (3 <sup>rd</sup> )	+	+
	bike	+	+

Tables 5.26, 5.27 and 5.28 present the results of the Wilcoxon signed-rank test for each scenario.

## 5.6 Conclusions

In this chapter the proposed system is tested and the results for the different scenarios are presented. The first two scenarios are used for controller's tuning. In both scenarios the motorized vehicle's demand remains the same, while the cyclist's demand changes; in the 2<sup>nd</sup> scenario the demand of cyclists is double in comparison with the 1<sup>st</sup> scenario. In both cases, by using the proposed system the average delay and the average number of stops of cyclists decreases, while the the average delay and the average number of stops of motorized traffic increases, confirming the rule that none of the conflicting objectives can be improved without worsening the others. In addition, based on the 2<sup>nd</sup> scenario, it was found, that when the demand of cyclists increase, also the value of coefficient  $\alpha$  should increase.

In the 3<sup>rd</sup> and 4<sup>th</sup> scenario the bicycle green wave is investigated. In the 3<sup>rd</sup> scenario the cyclist's demand is higher than the motorized vehicle's demand and in the 4<sup>th</sup> scenario vice versa. In both scenarios the average delay and the average number of stops of cyclists decreases in comparison with VRIGen, while of motorized vehicles increases. At the same time, in the 3<sup>rd</sup> scenario, bicycle green wave is created since the reduction of cyclist's average number of stops increases from intersection to intersection.

In the 5<sup>th</sup> scenario the coefficient  $\gamma$ , the coefficient defining the relative importance of cyclist's number of stops, is investigating. In this scenario, the proposed system is run with four different sets of coefficients,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ . In all cases, the value of coefficients  $\alpha$ ,  $\beta$  and  $\delta$  remains constant, while the value of coefficient  $\gamma$  changes;  $\gamma = 100$ ,  $\gamma = 1000$ ,  $\gamma = 10000$ ,

<sup>4</sup>+: statistically significant, -: statistically not significant

Table 5.27: Statistical significance of the results - 3<sup>rd</sup>, 4<sup>th</sup> & 5<sup>th</sup> Scenario.

Scenario	Stream	Average Delay	Average Number of Stops
3 <sup>rd</sup>	car (1 <sup>st</sup> )	+	+
	car (2 <sup>nd</sup> )	+	-
	car (3 <sup>rd</sup> )	+	+
	bike (1 <sup>st</sup> )	+	+
	bike (2 <sup>nd</sup> )	+	+
	bike (3 <sup>rd</sup> )	+	+
4 <sup>th</sup>	car (1 <sup>st</sup> )	+	+
	car (2 <sup>nd</sup> )	+	+
	car (3 <sup>rd</sup> )	-	+
	bike (1 <sup>st</sup> )	+	+
	bike (2 <sup>nd</sup> )	+	+
	bike (3 <sup>rd</sup> )	+	+
5 <sup>th</sup>	car (1 <sup>st</sup> )	+	+
	car (2 <sup>nd</sup> )	+	+
	car (3 <sup>rd</sup> )	+	+
	bike (1 <sup>st</sup> )	+	+
	bike (2 <sup>nd</sup> )	+	+
	bike (3 <sup>rd</sup> )	+	+

Table 5.28: Statistical significance of the results - 6<sup>th</sup> Scenario.

Scenario	Stream	Average Delay	Average Number of Stops
6 <sup>th</sup> , $\delta = 0.5$	car (1 <sup>st</sup> )	-	+
	car (2 <sup>nd</sup> )	-	+
	car (3 <sup>rd</sup> )	+	+
	bike	+	+
6 <sup>th</sup> , $\delta = 1$	car (1 <sup>st</sup> )	+	+
	car (2 <sup>nd</sup> )	+	+
	car (3 <sup>rd</sup> )	-	+
	bike	+	+
6 <sup>th</sup> , $\delta = 10000$	car (1 <sup>st</sup> )	+	+
	car (2 <sup>nd</sup> )	+	+
	car (3 <sup>rd</sup> )	+	+
	bike	+	+

$\gamma = 1000000$ . In all cases, the average delay and the average number of stops of motorized traffic increases, while of cyclists decreases. With respect to the reduction of cyclist's average number of stops, the results are almost similar in all four case, while the biggest reduction is observed when  $\gamma = 10000$ , where it reduces almost 70%. A possible explanation is that, this happens because the equation that is used for the estimation of the number of stops is a discrete function; discrete optimization deals mainly with problems where an optimal solution should be chosen from a finite or countable number of possibilities, or because the prediction fails.

The 6<sup>th</sup> scenario presents a trade-off between the average delay and/or the average number of stops and the comfort of the advised cyclist's speed and investigates the ability of the system to give comfortable speed advice. In this scenario, the proposed system is run with three different sets of coefficients,  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ , where the value of  $\alpha$ ,  $\beta$  and  $\gamma$  remains the same and the value of  $\delta$  changes:  $\delta = 0.5$ ,  $\delta = 1$  and  $\delta = 10000$ . In all cases, the average delay and the average number of stops of cyclists declines, while of motorized vehicles rises. The higher the value of  $\delta$  the smaller the reduction for cyclists, the bigger the increase for motorized vehicles and the smaller the deviation between the desired and the advised speed.

## Chapter 6

# Conclusions & Recommendations

*“I think and think for months and years. Ninety-nine times, the conclusion is false. The hundredth time I am right.”*

— Albert Einstein

This Chapter will cover the conclusions and recommendations of this research.

### 6.1 Conclusions

It is known that very little attention is paid on cyclists in the initial traffic signalization planning. Traditionally, bicycle traffic has not been given the same priority as motorized traffic and as a result cyclists experience long waiting times and consecutive stops because not enough attention is paid to them in the initial adjustment of the traffic lights. Stopping for a red light is a primary discouragement to cycling, since it costs a great deal of extra time and energy.

#### Proposed System

A possible solution in the aforementioned problem is the bicycle green wave, which could be created either by giving speed advice to cyclists based on fixed green times, either by synchronizing the traffic lights at cyclist speeds, or by a combination of the two. This research is focused on the third solution by designing a system which is taking into account both types of road users, motorized vehicles and cyclists. More specifically, the proposed system optimizes the traffic lights by taking into account the number of stops, delay and desired speed of cyclists and delay of motorized traffic and gives comfortable speed advice to cyclists, which are derived from the optimization, in order to cross the intersection without to stop.

### Traffic Signal Control

One of the main components of the system is the traffic signal control, which controls the green phases for each signal group at the intersection. Two different types of controllers, namely VRIGen, actuated control, and Multi-Agent Look-Ahead Traffic-Adaptive Control (MALATACS) were considered to be used in this thesis. Given the simplicity of VRIGen and the fact that it is an actuated controller, in other words widely implemented in the Netherlands in comparison with adaptive controllers (MALATACS), VRIGen is chosen for this research.

### Optimization Objectives

The selection of the conflicting objectives is based on the fact that both road users, cyclists and motorized vehicles, should be taken into account in the signalization system planning. By taking into account what is considered more important for each of them, the following objectives were selected: delay of motorized vehicles and delay, number of stops and comfort of the advised speed of cyclists, since also the cyclists are advised to ride in a certain speed. The last objective is also included in the optimization, since the cyclists characterize by different desires, abilities, ages and skills and they are not always able to follow a certain speed advice.

### Simulation Results

Different scenarios are performed in order to test the system, helping to be carried out some important conclusions. First of all, the system works as expected, confirming the rule that in an multi-objective problem, the improvement of one conflicting objective leads to the worsening of the others. Thereby, the reduction of the average delay and the average number of stops of cyclists has as a consequence the increase of the average delay and the average number of stops of motorized traffic in comparison with VRIGen. By choosing different sets of coefficients which prioritize the one or the other road user, the percentages regarding the average delay and the average number of stops can fluctuate. However this finding leads to a important conclusion also for VRIGen. VRIGen generates the optimal structure and determines the timings for the traffic lights, but it is not able to differentiate it if in a certain type of road user should be given priority, e.g. different policies.

Another conclusion was verified, by doubling the demand of cyclists, while the demand of motorized vehicles remains the same. In this case, in order the motorized traffic not to be hindered too much, the coefficient which defining the relative importance of their delay,  $\alpha$ , should be increased. Although, their delay increases, the rise is smaller than in the case where  $\alpha$  does not change its value.

Another important outcome of this research is that the average number of stops of cyclists is possible to decrease from intersection to intersection, creating bicycle green waves, e.g. from 40% in the first, to 46% in the second and to 53% in the third intersection (3<sup>rd</sup> scenario). However, it is demonstrated that the highest reduction of the average number of stops is almost 70% and cannot be improved further. A possible explanation is that, this happens because the equation that is used for the estimation of the number of stops is a discrete function; discrete optimization deals mainly with problems where an optimal solution should be chosen from a finite or countable number of possibilities, or because the prediction fails. For example, the cyclist may be advised a certain speed in order to reach the intersection exactly when the traffic light turns green, however he may reach it slightly before the end of the motorized vehicle's green phase, and as a result he has to stop. A possible solution to this problem, could be to avoid the beginning of the green phases and advise the cyclists to follow certain speed which will lead them in the intersection after the start of their green phases.

Last but not least, the system is able to give comfortable speed advice to cyclists, i.e. speed advice which do not deviate a lot from their desired speed. It is understandable, that this comfort can only be achieved by worsening the other objectives and especially the motorized vehicle's delay and number of stops, which increase. In the extreme case, that the coefficient which defining the relative importance of the deviation between the desired and the advised speed of cyclists,  $\delta$ , receives a very high value the speed advice deviates of the desired speed no more than  $\pm 0.9 \text{ km/h}$ . In addition, it should be emphasized the fact that, in any case, with any value of the coefficient  $\delta$ , the majority of the speed advice can be characterized as comfortable speed advice, since either the cyclist has to slow down, which is easier than to speed up, or to increase his speed not more than  $0.9 \text{ km/h}$ . It is generally accepted that, all cyclists have the ability to reduce their speed, while there are always some cyclists who are not able to follow a higher speed advice, since there are deterrents, like the age, the skills and the bicycle technologies.

## 6.2 Recommendations

### Recommendations for Future Research

- In the proposed system the optimization is performed individually in each intersection. It would be interesting to examine the case where the optimization is performed simultaneously in all intersections. In this case, the expected downstream performance will be taken into account in the decision making process. This information is necessary in order to determine for example the delay a released vehicle will encounter as it approaches the downstream intersection.

- The literature is poor regarding the cyclists. No detailed information is available about the desired speeds of them. As a result, in this research the equation which presents the cost of cyclist when deviates from his desired speed, may not reflect the reality in the best way. More research with respect to the cyclist's behavior is proved to be very useful.
- The bicycle platoon formation could be investigated. The platoons will move together, because there are empty areas between platoons with few interferences, and the traffic flow could be improved. It is recommended to create platoons of bicycles by dividing cyclists in different categories depending their desired speed.
- In the current system, the motorized vehicle's and cyclist's delay is actually the stopped delay. It would be interesting also to include the delay due to speed advice.
- In the proposed system only the comfort of the speed advice in terms of deviation between the advised and the desired speed is taken into account. It is recommended to include also other aspects of comfort, e.g. the discomfort of changing the speed advice.
- For simplicity reasons the proposed system takes into account only two phases; motorized vehicle's phase and cyclist's phase. However, this situation is not consistent with reality in the majority of signalized intersections. For example, if there are more than two phases, there is the advantage of flexibility in terms that a certain green phase can have earlier or extra and not only longer realizations, as it is happened in the proposed system, when other conflicting green phases have no demand. In other words, there is the possibility to intervene in the signalization system by changing the control structure and not only the green times. In addition, bicycle streams could belong in different phases, and as a result their objectives, i.e. delay and number of stops, will be contradicting. It is recommended to investigate more complicated intersections with more phases.

### Practical Recommendations

- In the current situation, the optimization horizon is set to 10 cycles and the first cycle of the resulting plan is implemented. Waiting the end of the first cycle in order the optimization to be done again, can have a significant impact on delay. Consider, for example, the case where a queue dissipates earlier than predicted. For example, with a 1-second decision resolution, controllers can more quickly terminate phases as queues clear out, reallocating this time to phases that do have traffic to serve. As a

result, it is recommended to implement only the first seconds of the first cycle instead of the whole cycle.

- In the proposed system in order to run a simulation with duration 4200 *sec*, i.e a little bit more than 1 *h*, 3 – 5 *h* are needed. This is the result of the choice regarding the number of optimization's starting points, which is selected to be 20. This means that each time the optimization is started in one intersection, it is repeated 20 times. Each time a local minimum is found and from the 20 local minimums the global minimum is selected. Given the number of the intersections and the number of the optimizations that is performed, the simulation duration increases. It is recommended to find ways to improve the efficiency of the code in order to speed up the process.



## Appendix A

# Policies to Stimulate Cycling

The importance of cycling in the Netherlands is undeniable, considering the bicycle policies that have been developed in order to encourage and stimulate the use of bicycle.

- Amsterdam: According to municipality of Amsterdam, traffic lights are a crucial factor for cyclists and as a result focuses on Dynamic Traffic Management for bicycle. This program includes: regular detection at bigger distance to give green at the right moment, radio frequency identification (rfid) to detect cyclists with the same purpose, route information for cyclists, green wave, waiting time predictors that indicate how long it takes before a light turns green and the construction of a second “Core Bicycle Network”, that will provide fast routes for medium-distance journeys (minimum of seven kilometers) on which the cyclist has priority at traffic lights (Hilhorst, 2010).
- Rotterdam: The municipality of Rotterdam endeavors to have maximum cycle times of 90 seconds for the signalized intersections. When this is not the case, the municipality tries to give green light to cyclists twice in the cycle. In addition, in primary cycle routes, detection of cyclists on a larger distance before the stop line is desirable (dS+V, 2007).
- The Hague: The municipality of The Hague found that traffic lights and air quality are deterrent factors for cyclists in roads of a higher level in the network, and as a result they choose smaller roads with less traffic lights. The extension of the city borders of The Hague asks for a quick non-stop cycling routes. The policy states that cyclists get priority in the city center ring. Furthermore, the municipality wants to decrease waiting times at intersections to 20 seconds on primary routes and 40 seconds on secondary routes (Ontwikkeling, 2011).
- Utrecht: One of the objectives of Utrecht bicycle policy is to retain the high bicycle share in the modal split. This goal has been achieved by reducing the distance



(a) Hovenring.



(b) OFOS.

Figure A.1: Stimulation of bicycle use.

needed to detour around obstacles and by increasing the average journey speed (particularly by reducing the waiting time at traffic control measures) (Ditewig, n.d.). In addition, some policy is made on specific cases when cyclists have to cross signalized intersections; actually it is mainly focused on left-turning cyclists. OFOS (Opgeblazen FietsOpstelStrook) is a setup surface for cyclists, which is positioned before the stop line of the cars. In this way, cyclists no longer have to wait until all the cars are driven away, in order to turn left.

- Zwolle: Zwolle is one of the five nominees to become best Cycling City of the Netherlands in 2014. The main goal regarding bicycles is “Cycling without barrier”. Its cycle network includes among others: direct routes for cycling without detours, many bicycle tunnels and bicycle bridges in order to reduce the waiting times and to increase cycling speed, nine bicycle streets on routes with little motor traffic, an innovative bicycle roundabout (no default priority for motor traffic, but a fast flow for cycling) and priority for cycling at traffic lights (Wagenbuur, 2014b).
- Eindhoven: Eindhoven is also one of the five nominees to become best Cycling City of the Netherlands in 2014. The attention which is paid on cyclists, is reflected on the “Hovenring”, the first suspended bicycle roundabout in the world. Furthermore, the municipality of Eindhoven wants to decrease the waiting times of cyclists at traffic lights and to change the policy in that way so cycling is taken into account from the start of plans and not as an afterthought (Wagenbuur, 2014a).

From the above, it is obvious that much attention is paid on cycling in The Netherlands. The municipalities in different cities have already understood the main problems of cyclists and try to find solutions, in order to stimulate cycling.

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