Speed advice for cyclists

Design task to reduce the stops at traffic lights

Joeri van Egmond

Thesis committee:

Prof. Dr. Ir. S. Hoogendoorn
Dr. Ir. Andreas Hegyi
Dr. Martijn van Noort
Ir. Paul Wiggenraad
Shuai Liu MSc

Preface

The report that lies in front of you is the written consequence of my master thesis at the department of Civil Engineering. It belongs to the educational track “Transport & Planning” at the TU Delft. The subject of the thesis is inspired on an exercise in the course of “Intelligent Vehicles” during the master. For this course we had to come up with an ITS-system for the cyclist, that is used on board of the bicycle. Together with Evelien van der Meel, I came up with a system that would direct cyclists to a green phase of the traffic light it was heading to. In the framework of the “Intelligent Vehicles”-course the system was described and viewed from different perspectives. The interesting aspects of such a system encouraged me to do something with the work done in this course and that les to this master thesis on the subject.

Although not always convinced on an ITS-system for cyclists Martijn van Noort and Andreas Hegyi were always there during my thesis period to present my progress. They gave me comments and advices that triggered me to think about the subject in a more structured way. I want to thank them for that and want to thank TNO for giving me the chance to do this research and use their resources.

I would also like to thank the other members of my graduation committee (Serge Hoogendoorn, Paul Wiggenraad & Shuai Liu) for reviewing the work in different stages of the research. Further my gratitude goes to Maria Salomons of the TU Delft, who answered all my questions on the functioning of traffic controllers.

At last I would like to thank friends and family for the mental support they gave me during this project.

Abstract

Stops en route are a main concern for cyclists as they want to travel in the most comfortable fashion possible. The braking and acceleration at traffic lights cause losses of kinetic energy and make the trips of cyclists more strenuous than they would have been without stops. By reducing the number of stops for cyclists, the attraction of the bicycle as transport mode could be increased.

This research will focus on the reduction of stops by implementing a speed advice for cyclists that will help the cyclist to arrive at intersections when the traffic light is green. The design of a system that can reduce the number of stops is presented for the situation with a fixed time controller and an vehicle actuated controller.

The design for the fixed time controller consists of a speed advice that is given once to the cyclist approaching the traffic light. The cyclist can approach the traffic light with this speed to arrive at the intersection with a green light. The advice is given by a road side sign that can be read by the cyclist. Reductions in the fraction of stopped cyclists are in the order of 10-20%.

The actuated controller asks for a more flexible structure of the speed advice in which the cyclist should adjust its speed dependent on the state of the traffic light controller. The speed advice system must be implemented in a way that the consequence of the state of the controller for the advice of the cyclist can be distributed to the cyclist at the moment this change of state occurs. The flexible appearance of the system allows it to adjust its speed advice to the preferences of the user. This is done by a score function that takes into account the probability to catch the green light and the sacrifice the cyclist has to make in his desired speed to end up at the green traffic light. The reductions in fraction of stopped cyclists are largely dependent on the chosen values for the attributes in the speed advice system. The tested scenarios indicate a maximum reduction of stopped cyclists of 45%.

Content

1 Introduction

One of the characteristics of the Dutch society is its bicycle culture. The origin of the bicycle begins with the invention of the wheel in earlier societies. In the 1860's the bicycle came into fashion by a bigger audience. The bicycle was lighter than its predecessors and consisted of a big wheel at the front side and a smaller wheel on the back. The driving force was delivered by direct pedals on the front wheel. The bigger the front wheel, the bigger the realized speeds became. The high saddle and the instability of the bicycle caused a lot of accidents with fatalities. Every bump in the road could lead to falling off the bike from a considerable height. The rubber tyres and lower saddles ultimately made the bike more useful as means of transport and suitable for a bigger share of the population (Lesisz, 2004).

1.1 Problem definition

As car traffic started to augment tremendously, intersections became a problem point in the throughput and safety of the mixed traffic. That was the point traffic lights were introduced to guide traffic on intersections. The existence of big bicycle traffic flows in the Netherlands made it necessary to provide dedicated infrastructure and traffic lights specifically for cyclists, but in designing the traffic controller the slower traffic often has a low priority for the designer (Binnenlands Bestuur, 2012).

According to the Dutch Cyclers Association (Glas, 2012) the traffic lights are a main concern for the bicyclist in a Dutch city nowadays. The braking and acceleration at traffic lights causes losses of kinetic energy, which make journeys more strenuous (Fajans & Curry, 2001). Cyclists also find it unfair that they are confronted with large waiting times. "Waiting times caused by the slow acceleration of car traffic. In the controller program most of the time is reserved for car traffic. Every car needs 2 seconds to pass the stopping line, meanwhile in two seconds six bicycles can pass the stopping line." Consequence of this ratio of starting times is that the chance of stopping at an intersection for bicycles is bigger than for car traffic because the time reserved for car traffic to cross the intersection is bigger than that for cyclists (Glas, 2012).

The policies from the bigger cities in Holland show that the municipalities have interest in the stimulation of bicycle traffic but do not really know how they should improve the circumstances for cyclists. The presence of red light negation under cyclists, show that stops are a problem in the mind of the cyclist. Stops at intersections with traffic lights are illustrated from 'annoying' due to the energy losses until 'dangerous' because of the possible accidents when stepping off or on the bike (van Boggelen, van Oijen, & Lankhuijzen, 2013).

Stops at intersections en route are a problem for cyclists.

To solve these comfort and safety problems caused by stopping at traffic lights, one should look at manners to reduce the number of stopping cyclists at intersections. Stops can be reduced in different ways. Here, three directions of solutions are presented, which will be discussed more comprehensive in Chapter 2:

1. Removing conflicts by introducing tunnels/bridges for cyclists
2. Replacing traffic light guided intersections by uncontrolled intersections or roundabouts
3. Reducing stops at intersections with traffic lights

This research will focus on the last of aforementioned solution directions. This direction doesn't confront the road authorities with high investment costs, but does give possibilities to reduce the number of stops a cyclist has to make.

1.2 Research objective

In this research the question is whether a system with speed advice to reduce stops at traffic light guided intersections could be implemented for bicycle traffic. The main objective of this research is therefore to:

Design a system that can reduce the number of stops for cyclists at traffic lights by giving speed advices, without hindering the other traffic in an unacceptable manner and without decreasing the mobility of the cyclist himself.

To give an appropriate representation of the processes playing a role in such a system, this 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:

A. Ability of cyclist to travel with the advised speed;
B. Willingness of cyclist to travel with the speed advice;
C. Uncertainty of an actuated controller and the consequence for the speed advice;

The research is mainly focussed on the speed advice system itself and the critical components in calculating a suitable and useful speed advice for the cyclist. There are some components that inevitably come along with a speed advice system, but also some external factors that cannot be neglected. These components are identified. A speed advice system already must have some components that make sure the cyclist can receive the information it needs. In some way this information has to be send to the cyclist. This will happen via the medium for the cyclist. This could be an information sender on board of the bicycle (app on mobile device) or on the road side (signs next to the bicycle path or LED-lights along the path that flicker through with the advised speed). The information is coming from the traffic controller that also sends signals to the traffic lights to switch to the light which corresponds with the state of the controller. The state of the controller gives indications on which speed is appropriate to ride for the cyclist. The system thus consists of at least the components in Figure 1-1.

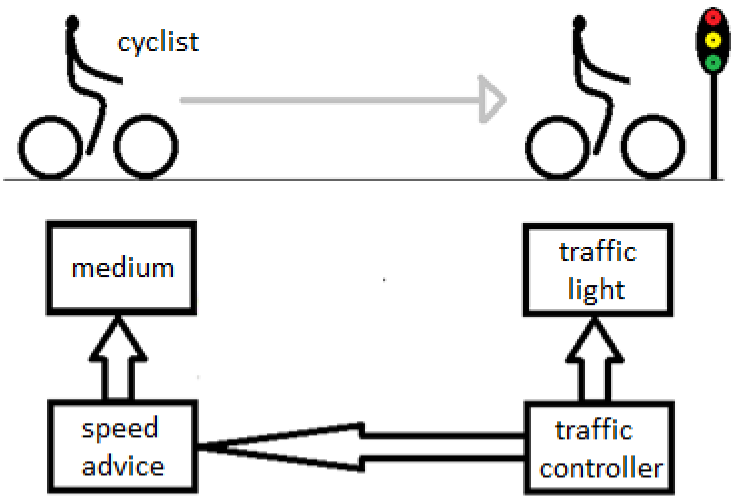

Figure 1-1: Components of the speed advice system

Human behaviour

Question is what the bike rider or car driver does with the given speed advice. Does the driver/rider understand the message, and if so is he willing to travel with the advised speed. The users are more willing to stick to the advice when the driver/rider experiences an advantage when he/she sticks to the given advice and when the advice is close to the initial desired speed at which the rider of the bike can pedal comfortably.

Signalized intersection

The control program is one of the main components of the system. This component of the system controls the green phases for each signal group at the intersection. There are different ways to control the intersection, with a fixed time controller, actuated controller and an adaptive controller. The type of controller determines the extent to which green phases can be predicted. In a fixed time controller the start and end of a green phase are 100% predictable. The controller goes through a cycle in which the start and end of all green phases are determined. When the cycle is done, the controller will start again with a new cycle with the same sequence of green phases. In an actuated controller the exact start and end of a green phase is not known in advance, but the place of the green phase in the structure of the controller makes prediction of the green time possible. Adaptive controllers give green phases based on the available requests for the different directions, it has no structure and cannot easily be predicted because every signal group can realize a green phase on any moment in time. The next traffic light that switches to green is not on forehand determined.

An optimal sequence of the traffic light installation of an intersection is the starting point for a system that could further reduce the comfort of the cyclist at an intersection. When the traffic light installation does not meet the traffic demands, an investment in a system that increases comfort is probably not the best way to honour wishes of users. Instead of implementing this system, an optimization of the current infrastructure and control sequence can reduce travel times and stops without an expansion of infrastructure. When this is simple improvement is done, the system improving comfort for cyclists could be a way to make cycling more attractive on certain routes.

1.3 Outline of the Report

In the next chapter the types of study used in this research are discussed together with the methodology to design the system. Chapter 3 outlines the societal background of the problem already sketched in section 1.1 and discuss it more elaborated. The chapter also gives information on existing systems with similar objectives. Chapter 4 introduces the theoretical and mathematical design of the system and the main components. Chapter 5 will give insight in the implementation of the system in the simulation program. Chapter 6 will discuss the results from simulation and Chapter 7 contains the conclusions and recommendations of this research.

2 Literature study

This chapter introduces the reader with some background on the societal perspective of a speed advice for cyclists. Firstly the current state of the bicycle policies related to cyclists at traffic light guided intersection is discussed. From there on the problems that exist at these intersections are further elaborated which leads to the definition of the problem. At last the current state of art of similar systems is presented. Most of these systems are focussed on car traffic, but have a similar purpose as the system that is designed in this research.

2.1 Bicycle policies

Although bicycle traffic is the most important means of transport in the biggest city centres in Holland, policies do not pay much attention to bicycle traffic. Car traffic and public transport are the subjects that get most attention of policy makers (Binnenlands Bestuur, 2012). In traffic and transport policies of the big municipalities in the Netherlands, bicyclists and bicycle traffic get attention in a separated chapter. This illustrates the good intentions of policy makers, but often bicycle traffic is mentioned as a measure to reduce the number of car trips. Certainly in trips on small distances bicycle traffic could be a competitive means of transport. However policy documents are also loaded with car traffic policies. These two means of transport are often conflicting on urban intersections. Therefore municipalities have to prioritize in cases where car traffic and bicycle traffic meet. In these cases car traffic often gets priority for this means of transport has a big influence on the emissions in the city. Although the bicycle is often mentioned as alternative for car traffic in policy documents, the prioritization over car traffic is not a common phenomenon. Municipalities are searching for ways to improve the flow of bicyclist, but on the other side don't want to hinder the flow of car traffic in such a way that emissions and delays become a problem. A policy to promote the bicycle is an important measure for the acquisition and preservation of an optimal accessibility is necessary (Gemeente Utrecht, 2002).

In Appendix A the bicycle policies of the four biggest cities in the Netherlands are reviewed on topics that combine cyclists and traffic lights. In most of the policy documents safety is concerned as a bigger problem when it comes to cyclists at traffic light guided intersection than throughput. However to promote the use of the bicycle the documents show that there is a will to improve the time losses at traffic light guided intersections. The municipalities of Rotterdam and Utrecht do this by limiting the total cycle time of traffic controllers. For Rotterdam holds that at traffic controlled intersections with a cycle time that exceeds 90 seconds, the municipality will review the possibilities of giving cyclists an additional phase in the controller (dS+V, 2007). The municipality of Utrecht wants to limit waiting times for cyclists at these intersections to a maximum of 60 seconds. Only the municipality of Amsterdam focusses on Dynamic Traffic Management for the bicycle by green light realization dependent on the detection of cyclists, the implementation of green waves for cyclists and waiting time indicators (Hilhorst, 2007). Overall the tendency of the reviewed municipalities is to increase the comfort of the cyclist at traffic lights by reducing waiting times and the probability of stops, but a speed advice for the cyclist is not a measure in the existing policies.

2.2 Red Light negation of cyclists

Red light negation is one of the causes of traffic accidents in city centres (see Figure 2-1). Running the red light can be intentional or unintentional. The unintended red light negation is often found in the dilemma zone, when the light switches to yellow. Intentional behaviour occurs mostly when the drivers feels that the utility/risk of running the red light is bigger than to apply to the traffic rules. Research in Amsterdam indicates that traffic accidents for cyclists in which the victim is also the cause of the accident exists 13% of cyclists running the red light. This a much higher degree than for other modes (Dienst Infrastructuur, Verkeer en Vervoer, 2012).

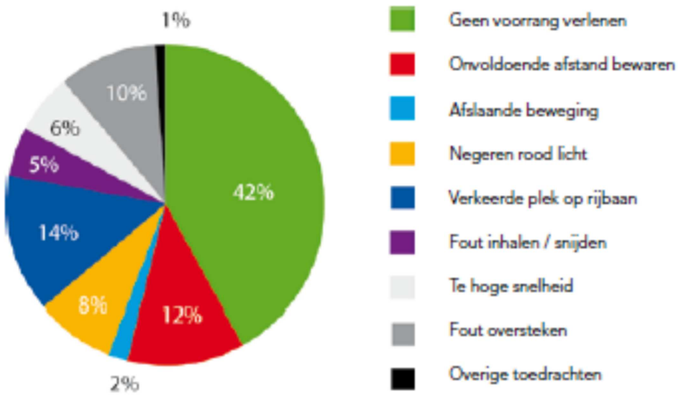

Figure 2-1: Accident causes in Amsterdam, 2009

When the origin of an accident is clearly caused by the victim, he/she still plays the role of victim by saying that he ‘couldn’t help it for he was tired, distracted or in a hurry’. People tend to explain clearly why it’s acceptable to run the red light, some even indicate “running the red light is safer than running the green light. In the first case you are aware of the other traffic, in the last case you trust the traffic light, which may not be just.” Running the red light seems to be a descriptive norm. Although the behaviour is not desirable from a societal point of view, people are willing to run red lights because other people do it as well. In this way it looks like it is accepted by society to run the red light. Especially the younger groups of cyclists do not comply to the rules with respect to traffic lights. They read the traffic light as a warning for other traffic (Berveling & Derriks, 2012). A system that avoids that the cyclist has to stop at a traffic light could decrease the intentional red running of cyclists and reduce the accidents caused by this offense.

2.3 E-bikes

The introduction of the e-bike increases some of the problems experienced by making a stop. For example elderly have difficulties getting off and on their e-bike at intersections, because the E-bike is heavier than a normal bike and the balance while getting off is difficult for elderly (Kapaan, 2012). This problem for elderly also occurs when riding a normal bicycle, but because of smaller weight of the normal bike, the magnitude of the problem is smaller. Also a big part of the accidents are caused by the starting up and slowing down before and after stopping. In the acceleration phase the e-bike needs to change gears. A change of gear is accompanied by (sometimes unexpected) little shocks (Lenten & Stockmann, 2010).

The commuters are a target user of the e-bike. Commuters find it important to get to work as easy and fast as possible. To get them from the car to e-bike (or bicycle) this means of transport needs to have advantages. A non-stop path from residence to the place of work is one of the things that could help to enlarge the modal split for commuters towards cycling (Hendriksen, Engbers, Schrijver, Gijlswijk, Weltevreden, & Wilting, 2008). The non-stop route will also increase the action radius of e-bikes, which makes the e-bike more competitive in trips of longer distances.

2.4 Problem definition

According to the Dutch Cyclers Association (Glas, 2012) the traffic lights are a main concern for the bicyclist in a Dutch city nowadays. The braking and acceleration at traffic lights causes losses of kinetic energy, which make journeys more strenuous (Fajans & Curry, 2001). This strenuous character of a journey reduces the comfort of the traveling bicyclist. Comfort is one of the factors that plays a role in the mode choice. It can be defined by

Cyclists also find it unfair that they are confronted with large waiting times. "Waiting times caused by the slow acceleration of car traffic. In the controller program most of the time is reserved for car traffic. Every car needs 2 seconds to pass the stopping line, meanwhile in two seconds six bicycles can pass the stopping line." Consequence of this ratio of starting times is that the chance of stopping at an intersection for bicycles is bigger than for car traffic because the time reserved for car traffic to cross the intersection is bigger than that for cyclists (Glas, 2012).

The policies from the bigger cities in Holland show that the municipalities have interest in the stimulation of bicycle traffic but do not really know how they should improve the circumstances for cyclists. The following sections on red light negation, show that stops are a problem in the mind of the cyclist. Stops at intersections with traffic lights are illustrated from 'annoying' due to the energy losses until 'dangerous' because of the possible accidents when stepping off or on the bike.

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2.5 Solution directions

The policies from the bigger cities in Holland show that the municipalities have interest in the stimulation of bicycle traffic but do not really know how they should improve the circumstances for cyclists. The following sections on red light negation, show that stops are a problem in the mind of the cyclist. Stops at intersections with traffic lights are illustrated from 'annoying' due to the energy losses until 'dangerous' because of the possible accidents when stepping off or on the bike. To solve these comfort and safety problems one should look at manners to reduce the number of stops at intersections. "Comfort" is a state of physical ease and freedom from pain or constraint (example: there is room for four people to travel in comfort). The stop and go action of a cyclist reduces the physical ease of a cyclist to travel. The reduction or avoidance of stops at an intersection can be seen as a comfort for the cyclist as comforts are "things that contribute to the physical well-being" (Oxford Dictionaries, 2013).

Preventing stops for cyclists at intersections can happen in many ways. The possibilities for cyclist to avoid stops are here mentioned in three different levels. The highest level is the level in which the origin of the installation of traffic lights is removed, the second level is removing the traffic lights for alternative crossings of traffic streams. The third level is keeping the traffic light in place but preventing the stops from happening.

2.5.1 Preventing crossings

To prevent the crossing of cyclists streams and car traffic streams, one can choose to bring the streams on different levels. In this way the traffic light only applies for car traffic and the bicycle traffic can pass the intersection via a tunnel or bridge. Although this is an appropriate solution for the problem, investments costs are high, 2-3 million Euro dependent on the chosen slope for a tunnel (CROW, Solve Maatregelenmix, 2011). Certainly when this measure has to be applied for different intersections along a road stretch. In crossings with roads of a high network level realization of a tunnel or bridge can be feasible, for smaller roads not. Furthermore space is needed to provide the slope to the bridge or tunnel. This space is hard to find in urban settings.

2.5.2 Replace/Avoid traffic lights

The second level is removing traffic lights. In an infrastructural perspective, this leads to alternative options for conflicts on intersections without traffic lights. If we assume that cyclists are willing to change their routes in order to avoid traffic lights, this is for cyclists a way to get rid of traffic light guided conflicts and their stops.

Uncontrolled intersection

Capacity of an uncontrolled intersection is determined by the extent to which the traffic streams make use of the same conflict areas. Capacity is reached, when one of the conflicting streams does not have enough time on the conflict area to facilitate its traffic. The flow of traffic on the different directions determine the extent of conflicting traffic and therefore the capacity of the intersection.

Priority rules and priority signs have a big influence on the performance of an intersection. When there is a main stream on the intersection. This stream is in many cases prioritized above the side streams. Traffic that has to cross the prioritized stream has to wait for gaps large enough for crossing the stream in a safe manner. The composition of traffic flows will influence the performance of the intersection. The bigger the side streams will be, the smaller the streams on the main flow direction can be to allow for sufficient gaps for traffic on the side stream (Muller, Hegyi, Salomons, & van Zuylen, 2011-2012).

Capacity is then determined by:

- Geometry of the intersection
- Priority rules and priority signs
- Traffic flows on each direction
- Composition of modes in traffic flow

Roundabout

The roundabout is a special configuration of an uncontrolled intersection. By separating conflict areas the performance of a roundabout is higher than the performance of most regular uncontrolled priority intersections. Roundabouts also seem to have a positive impact at traffic safety. Severe accidents are less frequent at roundabouts than on regular uncontrolled intersections. Performance of car traffic on roundabouts is derived from the main conflict between the circulating traffic and entering traffic and the conflict with slow traffic at the entries and exits of the roundabout. For slow traffic no big delays will occur in urban environments, because following the CROW recommendations (CROW, Fietsoversteken op Rotondes, 2002) cyclists should have priority on urban roundabouts. The roundabout will therefore always increase the comfort of the cyclist in stopping maneuvers, but the implementation will not always be feasible as the roundabouts capacity should be sufficient for the given flows. Differences in flows of the traffic streams are limiting the capacity and roundabouts require more space than regular intersections (SWOV, 2012).

Another route

Bicyclists searching for a route without traffic lights is a form of preventing traffic lights for a bicyclist himself. Probably the bicyclist still has to cross the road that could be crossed at the traffic lights. It will however search for another crossing. This will be an intersection in which the cyclist can cross on a different level than car traffic or will be an uncontrolled intersection or roundabout. Concerns of these types of intersections are mentioned above.

In this case the cyclist then has to adjust his route. As he still has to cross the road, he will search for non-guided crossings. Flows on the road that has to be crossed, should not be very large, while the cyclist has to find a gap for crossing the road. Question is whether this non-guided crossing is safer than a guided crossing. Given the accident numbers in Amsterdam, a lot of accidents happen by not giving right of way (Dienst Infrastructuur, Verkeer en Vervoer, 2012).

2.5.3 Preventing stops at the traffic light

As the infrastructural adjustments of the intersection are not always possible, due to space limitations, capacity limitations and budget. The possibility of changing properties of the traffic controller or adding systems that reduce stops for cyclists doesn’t require these big infrastructural adjustments, but can help facilitate the bicyclist. Increasing the green time of bicycle streams at traffic lights will certainly improve the bicycle flows in the network, but has disadvantages for the other traffic. Road authorities have to weigh the benefits for the cyclist against the disadvantages for other traffic. A system that prevents stops for bicyclists and E-bike riders at the traffic light can cope with the above mentioned problems and doesn’t hinder other traffic. In the following section existing systems for avoiding stops at traffic lights are discussed. Green waves for cyclists are good measures for the problems. These green waves are already implemented in the cities of Amsterdam and Copenhagen on a number of consecutive traffic light guided intersections. Disadvantage of these green waves is that to catch the green wave, one has to move with a set speed. In the case of Copenhagen 20 km/h, in Amsterdam 18 km/h is chosen as green wave speed. Cyclists that do not move with this speed will not experience positive effects of the implementation of these green waves. Therefore a more comprehensive system that takes the speed of the biker into account, can provide a green wave for more cyclists.

Already a lot of research exists with regard to preventing stops for motor vehicles with individual speed advices. Sometimes with the objective to reduce emissions in car traffic (EcoMove), sometimes to improve/smoothen the traffic flow (ODYSA). In most of the cases an improvement in the objective of traffic flow also decreases the emissions and vice versa, compared to the operations without speed advice.

eCoMove is an European project with the purpose to reduce emissions in traffic, by tackling inefficiencies in car traffic. One of those inefficiencies is the stop-start behaviour at traffic light guided (and other) intersections. Giving speed advice at these intersections can reduce emissions and fuel use. The sketched problem in the eCoMove project has common ground with the inefficiency cyclists experience at traffic lights. The objective of emissions is less relevant for bicycle traffic, but comfort can be improved by preventing bicyclists to stop. For E-bikes, the prevention of stops can improve the efficiency of the bike. This will reduce the amount of power needed for charging the bike (riding the same distance) and will enlarge the radius of action for the bike (van Katwijk & Vreeswijk, 2010).

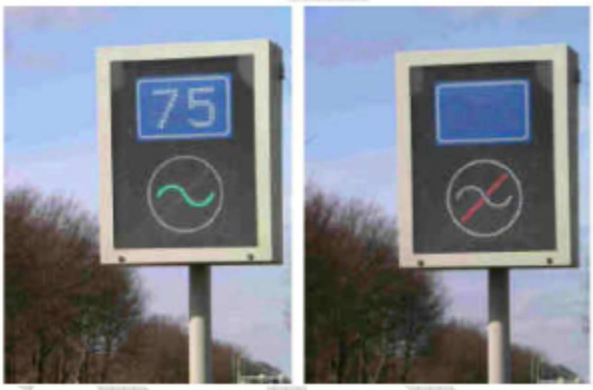


Figure 2-2: Speed advice in ODYSA-system (left: green wave advice, right: no green wave)

ODYSA is a system to prevent stops at traffic guided intersections. It supports the existing green wave and gives speed advice to the cars on the green wave route so that the cars will drive in platoons through the green windows at the intersections. This system is realised for the N329 near the municipality of Oss. The speed advice varies between speeds of 50 and 80 km/h dependent on the state of the traffic light at the downstream intersections (see Figure 2-2). It also indicates when no speed advice between 50 and 80 km/h is possible (van Noort & Hogema, 2012). The GLOSA-system is a system similar to the eCoMove and ODYSA-systems, but is initiated from a car users' perspective. It gives an advice based on information given by the traffic light controller that provides a speed advice for the driver. The advised speed is determined within the car.

"Tovergroen" is an existing measure for the prevention of stops for trucks and lorries at intersections. The detection of trucks and lorries will extend the green window of the direction, at which the truck or lorry is detected. Difference in bicycle traffic is that green lights for bicycles could be realized with parallel car traffic streams in the same direction. The "Tovergroen" is implemented as measure to improve the flow of car traffic by preventing trucks and lorries to stop. These car traffic types have lower acceleration rates than other car traffic. Preventing stops from these types of traffic will therefore improve the performance of the intersection. Freilot handles truck traffic with a similar method, but then within a set of measures to reduce the fuel consumption of trucks.

For the cyclist then, already some systems exist for preventing stops, but these systems do not consist dynamic components that take into account the presence of cyclists. In Copenhagen and Amsterdam green waves exist that gives green lights on a number of intersections on the same road stretch when the cyclists ride at a certain speed. For Copenhagen this speed is 20 km/h, for Amsterdam 18 km/h. Disadvantage of the system is that the cyclist doesn't know whether he/she makes the green wave, when he/she does not have a speedometer attached to his bike. The Evergreen system does give feedback to the cyclist on which speed is needed to cruise through the intersection in green. The system does so using led-lights to indicate the area of the green wave. These lights move forward to the intersection with typical bicycle speeds.

Furthermore here are mentioned two other systems that do not have the goal of preventing stops, but consist of components that could be used for a system that is preventing stops. The first of them is the DSI. This system informs the driver on his/her current speed to make him aware of his speed in comparison to the maximum speed. A speed advice system with an individualized component could make use of road side techniques used in the DSI. The second system gives speed advice with the goal to prevent traffic jams that do not have a certain cause. By giving the drivers speed advice, the system tries to prevent those traffic jams.

The different systems that are in use or in progress are listed in Table 2-1. This table also gives insight in the goal of the system, the mode for which it is meant and the measure components of the system. As one can see from the different reference systems that are used in traffic control and management nowadays, the bike systems that are in use are not the most complicated systems. In car traffic more complicated systems are already implemented. Therefore some travel time gain could be realized by making smarter systems for cyclists. The Danish systems mentioned are giving direction for a more bicycle based system with applications for cyclists. Speed advices are only implemented for cyclists in the Evergreen system used in Odense for a fixed time traffic controller.

Table 2-1: Reference systems

	goal		mode			measure		
	fuel savings	traffic performance	bike	car	truck	detection	speed advice	affecting controller
eCoMove	x			x		x	x	
ODYSA		x		x		x	x	
GLOSA		x		x		x	x	
Tovergroen		x			x	x		x
Freilot	x				x	x		x
Green Wave, Copenhagen		x	x					
Evergreen, Odense		x	x				x	
DSI		x		x		x		
CONTRAST	x	x		x		x	x	

3 Theoretical and mathematical framework

This chapter will introduce the theory that is behind the advice system. The chapter will introduce the traffic processes that play a part in the implementation of the system and will give ways to handle with unwanted side-effects of an implemented system. This chapter includes three components of the system: the traffic light, the actors and the speed advice system. These components will be discussed in different sections. Part of the theory consists of formulas, especially in the speed advice section. The equations used in this chapter are time dependent as the status of the network and controllers change over time. This is not always made explicit in the equations.

At the end of this chapter a speed advice system including equations to implement the system in a simulation environment is set up. The combination of equations used in this chapter is the framework that needs to be found. Relation between controller advice and behaviour should be clear and the advice should be implementable for a simulation environment at the end of this chapter.

3.1 Traffic light controller

In this section the working of the controllers is explained to give insight in the functioning of the controllers. This is important when a speed advice is given. The state of the traffic controller determines to a large extent the character of the speed advice. When no knowledge about the nature of the controller is present, it is hard to understand the connection between controller state and speed advice. Therefore this section explains the types of controllers used in this research. The explanation of the controllers is briefly and only highlights the most important parts of the controller for the speed advice system.

An optimal sequence of the traffic light installation of an intersection (without speed advices) is the starting point for a system that could further reduce the comfort of the cyclist at an intersection. When the traffic light installation does not meet the traffic demands, an investment in a system that increases comfort is probably not the best way to honour wishes of users. Instead of implementing this system, an optimization of the current infrastructure and control sequence can reduce travel times and stops without an expansion of infrastructure. When this relatively simple improvement is done, the system improving comfort for cyclists could be a way to make cycling more attractive on certain routes with traffic lights that are preferred by policy makers.

Conflicts on the intersection are the base input for identifying the possible structures of a traffic controller. Conflicts are present when vehicles travelling on different routes use the same space within the intersection. This space is called the conflict zone (see Figure 3-1) (Muller, Hegyi, Salomons, & van Zuylen, 2011-2012). Without traffic lights, negotiation or priority rules would prevent the vehicles from bursting into each other. With traffic lights, the settings of the controller don't allow the two different streams to drive into this conflict zone at the same time.

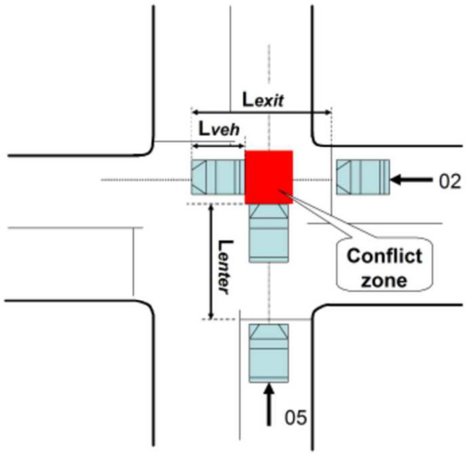


Figure 3-1: Example of a conflict zone, between the flows of signal group 02 and 08.

Conflicts are found by drawing the paths of the different traffic streams on an intersection. In this way one can see the different properties of every conflict. Relevant for composing a controller scheme are the times needed to enter the conflict zone and times needed to clear the conflict zone per conflicting pair of traffic streams. As traffic lights are introduced to accommodate these conflicts the last vehicle coming from the traffic light turning red has to exit the conflict zone before the first vehicle starting from the traffic light turning green is entering this zone. The difference between these two times determines the time needed in the controller scheme between the two signal groups of these traffic streams. This time is called the clearance time. This procedure has to be followed for all conflicting streams at the intersection. The table representing all identified conflicts on a certain intersection this will is called the conflict matrix. The matrix has filled boxes when traffic streams are conflicting and empty boxes when there's no conflict between the two streams (see Figure 3-2).

from signal group ... \ to signal group ...	01	02	03	04	05	06	07	08	09	10	11	12	22	24	26	28
01					0.0				0.0				0.0			1.1
02					0.0	0.0			0.0	0.0	2.0	1.8	0.0		3.3	
03					0.0	0.4	4.0	3.8			1.8	0.0	0.0	5.1		
04								0.0				0.0	1.1	0.0		
05	2.2	2.0	1.8					0.0	0.0			0.0		0.0		3.3
06		1.8	0.0					0.0	0.4	0.0	3.8			0.0	5.1	
07			0.0								0.0			1.1	0.0	
08			0.0	2.2	2.0	1.8					0.0	0.0	3.3		0.0	
09	4.0	3.8			1.8	0.0					0.0	0.4			0.0	5.1
10		0.0				0.0									1.1	0.0
11		0.0	0.0			0.0	2.2	2.0	1.8					3.3		0.0
12		0.0	0.4	4.0	3.8			1.8	0.0				5.1			0.0
22	2.1	2.0	1.9	0.0				0.0				0.0				
24			0.0	2.1	2.0	1.9	0.0				0.0					
26		0.0				0.0	2.1	2.0	1.9	0.0						
28	0.0				0.0				0.0	2.1	2.0	1.9				

Figure 3-2: Conflict matrix, in green the conflict that do not require time to protect the conflict, in white the conflicts that do ask for a reservation of time in the controller to protect the conflict.

As the time needed between the signal groups can be derived from the conflict matrix, the only variable needed to calculate the cycle time of a certain structure, is the green time needed per traffic stream. This is a function of the flow of the stream and the capacity of the lanes at the intersection. The capacity of a lane is the maximum number of vehicles that can pass the stop line within a certain time frame. The flow of the stream is the demand for a certain traffic stream (number of vehicles in a certain time frame). The green time has to be large enough to accommodate the traffic arriving at the intersection within the time of a cycle.

An iterative process can now be started to find the best structure possible. In this process minimizing the cycle time is the objective. A minimization of the cycle time leads to smaller red times, which reduces the number of vehicles waiting in queue for the next green light. The calculated clearance times are important, because the time required for these conflicts could be minimized by implementing a sequence with small clearance times between two signal groups.

The VRIGen software program from the TU Delft is a tool to find the structure with the smallest cycle time. VRIGen examines different structures with the input (conflict matrix, geometry and flows) corresponding to the chosen intersection. Through iteration, it will end up with a list of structures sorted from small cycle time to large cycle time. The programme is used in the determination of the sequence for the traffic controller applied in this research.

3.1.1 Fixed time controller

The Fixed time controller basically will distribute green lights following the implemented structure. The individual lights will turn green, followed by yellow and red. The appearance of the color of the lights are fixed for every cycle and occur as in Figure 3-3. In every cycle these appearances happen at the same time within the cycle and when a cycle ends a new cycle will begin. For the speed advice the fixed structure allows for a speed advice that can be given at a time, long before the traffic light actually turns green.

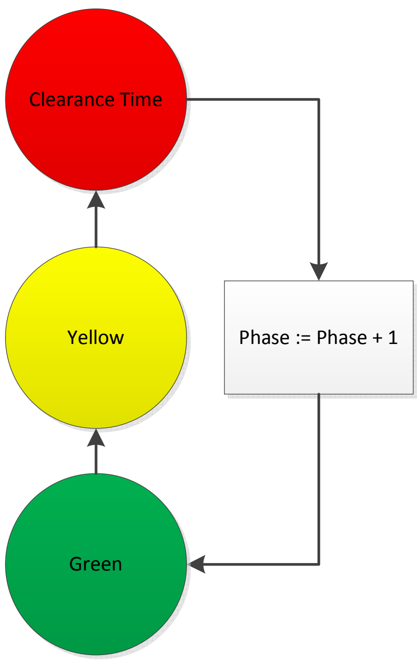


Figure 3-3: The colour of the traffic light given by the controller. After the clearance time of a combination of traffic lights has passed, the next traffic light (phase + 1) can turn green.

3.1.2 Actuated controller

When an actuated controller is implemented on the intersection, the green phase for cyclists is not known in advance. The actuated controller controls the phases of the different traffic streams based on the demand at the intersection at the time. The controller therefore controls the intersection more effectively than the fixed time controller. The fixed time controller has fixed green phases for traffic streams. It can provide a traffic flow in its demand (of traffic) by giving it a green traffic light, but also provides this green light when no demand is present. Green times can last too long compared to the present demand or last too short compared to the demand. At times that a traffic light is green but there is no demand for this flow, the light still turns green and the conflicts that are raised by the flows are still guaranteed. In the same time other traffic could have used this critical space on the intersection to accommodate their demand. This space is not used and traffic is waiting on traffic that is not there.

The actuated controller is introduced to get rid of this occupation of conflict areas when there is no demand from the traffic. It introduces detectors on the roadway in advance of the traffic light, where the traffic waits to get a green light. The occupation of these request detectors (right after the stopping line) must detect whether demand is present or not. The traffic light controller skips the green period of the traffic direction that has no demand in a certain cycle. This is not the only way in which the actuated controller increases the efficiency of the intersection. It also has long loop detectors further away from the stopping light to detect traffic. These detectors are used to determine the duration of a green phase for a traffic direction. A timer that is connected to this detector, times how long this detector is not occupied during the green time of the traffic light it belongs to. When the timer exceeds a specified value, the controller assumes no more traffic at this direction. The traffic light can now turn yellow in order to give space to the other traffic at the intersection provided that also the minimum green time has passed. The minimum green time allows the traffic that is waiting at the stopping line to cross the stopping line before the traffic light turns yellow again.

In this research the actuated controller is simplified to a controller that can vary its green time on the occupation of the long detectors further away from the stopping line. The controller however does not skip certain directions when no traffic is present. This simplification allows to develop the theory for the actuated controller with a minimum number of variables. The second simplification is the inclusion of the signal groups per traffic stream into a phase, that can vary in duration.

The used variables in an actuated controller for this theoretical framework are shown below. Their order of realization is graphically shown in Figure 3-4.

- **Fixed green time:**
  The fixed green time is the green time that occurs no matter how busy or empty the intersection is. If a traffic light realizes green, the traffic light will stay green for at least the number of seconds defined by the fixed green time.
- **Maximum extension green:**
  The maximum green extension is the maximum time that a green phase can last, added to the fixed time green. The extension green is the extension of green time after the fixed green time because of detected traffic on the extension loop (long loop further away from stopping line).

- **Yellow time:**
  The yellow time is the duration of the yellow phase, this phase is implemented after the green phase. It is used as a caution to stop, but you can continue your crossing when you're unable to stop safely.
- **Clearance time:**
  The clearance time is the time from the moment the first traffic light turns red until the next traffic light in the sequence turns green. In this time none of the conflicting traffic lights has a green light. This is implemented to make sure the conflict area is clear. The last vehicle of the first direction has to clear the conflict area before the first vehicle of the next direction arrives at the conflict area.

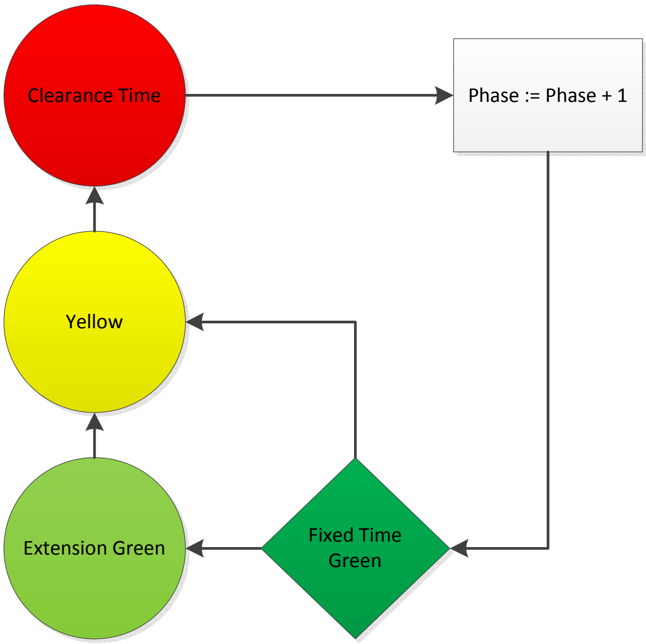


Figure 3-4: The sequence of traffic light states for the simplified actuated controller. After the clearance time of the phase of signal groups has passed, the next phase can turn green.

The consequences of the simplifications are numerous, the most important are covered here:

- The combination of different signal groups per traffic light into four different phases of signal groups with equal green times and position within the structure reduces the ability of the traffic controller to separately control the different signal groups
- The biggest difference between the "real" actuated controller and the actuated controller used for this research is the absence of the possibility to skip a signal group within the controller structure. In this research every signal group will realize a green period in every cycle of the controller program. The skipping of a phase could be interpreted as a phase with a fixed green time of zero and only an extension green which determines the green time for this phase.

In the simplified version of the actuated controller these four variables are necessary to determine the success of a speed advice system for this type of controller. With these variables one can indicate at what time the signal group for cyclists has its green time. This should be the time the cyclist has to arrive at the intersection. The start of the green phase depends on the extension of the green phase or green phases that realize before the green phase for bicycle traffic. When there's a lot of traffic on this conflicting traffic stream, the green phase of this conflicting stream can reach the maximum extension time. This has big consequences for the prediction of the time of realization for the different traffic streams. As the controller used in this research will realize every signal group in every cycle. The speed adviser "knows" that every phase will be present and that every phase will at least realize with the fixed green time. The only uncertainty the speed advisor has to deal with is the extension of the signal groups that have a green phase before the traffic light -in which direction the cyclist is driving- turns green.

If we look at the case that only one signal group in advance is decisive for the fluctuation in estimated time to green. The possibilities can be sketched as in Figure 3-5. In case of no extension on the decisive conflicting stream, the conflicting stream will have a green time equal to its fixed green time. After the end of this fixed green time, the yellow time and clearance time must pass before the bicycle stream gets a green light.

Figure 3-5: Consequence of extension or no extension of conflicting streams for green times of cyclists

When we look at the case in which the demand on the decisive conflicting stream is still present when the fixed green time is expired, the green phase of this conflicting stream will be extended in order to accommodate this traffic. The extension of this conflicting green will result in a later moment of green light for the cyclist flow.

Levels of certainty

The speed advice must take into account the possibility that a signal group earlier in the sequence extends its green time to accommodate the traffic at this direction. However the traffic controller does not know in advance whether a signal group will be extended or not. This makes the prediction of the moment in time a next green phase occurs uncertain. This uncertainty about the occurrence of a green phase could be indicated in three different levels of uncertainty (see Figure 3-6) including a maximum time and minimum time until the realization of the cyclist's green light:

1. ***Uncertainty***
   Uncertainty is the case, when the previous conflicting green phase has not yet begun or when this green phase is still in its fixed time green. The conflicting green could still have no extension or maximum extension on its green phase or anything between these two values.

Therefore the speed advisor must preferably advise a speed that makes the cyclist "catch the green light" in both of these cases, but also when the conflicting green phase has an extension between zero and the maximum extension.

2. ***Decreasing uncertainty***
   At the moment the fixed green time of the conflicting signal group has occurred, the certainty increases. If there is no extension after the fixed time green, no uncertainty is present as the only time between realization of the cyclist's light is the yellow time of the conflicting signal group and the clearance time needed between the two signal groups. When extension occurs, there is always the possibility that the extension can stop, but also that it will last until the maximum extension is reached. Therefore the speed advice should strive to give the cyclist a green light advice in both of the cases.
3. ***Certainty***
   After the end of the conflicting green phase certainty exists about the moment of green for the cyclist's traffic light. The only time between realization of the cyclist's light is the yellow time of the conflicting signal group and the clearance time needed between the two signal groups.

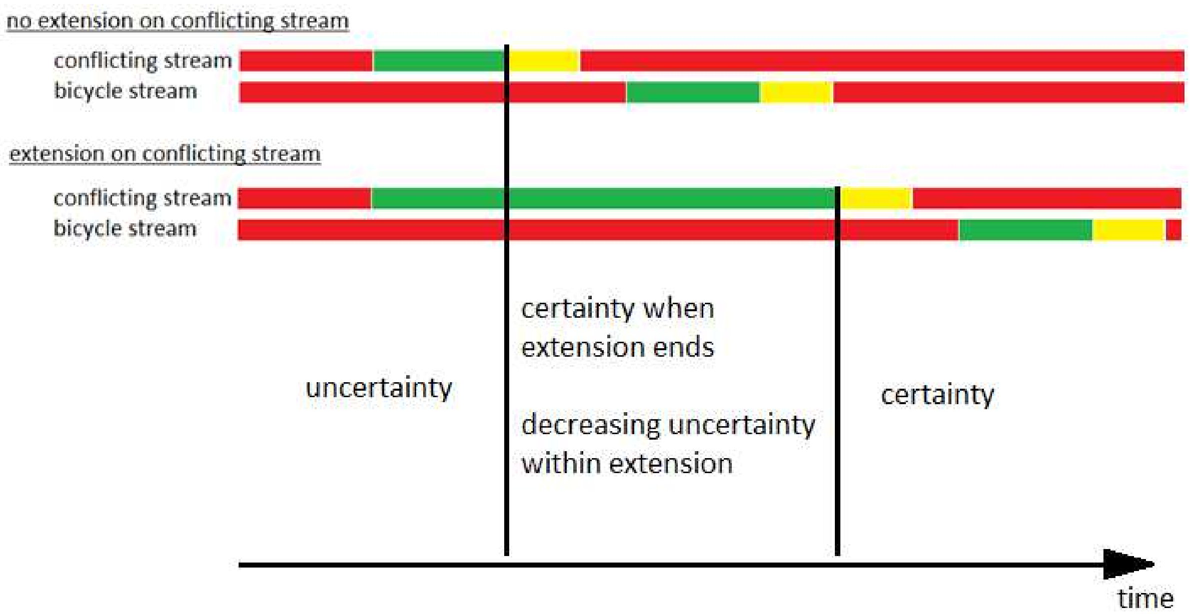


Figure 3-6: The uncertainty levels compared to the state of the lights of the conflicting and bicycle stream

The level of uncertainty has consequences for the strategy that is useful for the calculation of a speed advice. Every level of uncertainty has a different estimated time of green and consequently a different desired arrival at the intersection as result of the speed advice. The following three cases show compositions of green that have different results for the speed advice and trajectories of approaching cyclists assuming a maximum and minimum speed of a cyclist.

3.1.3 Left turning cyclists

Left turning cyclist have a very high probability of having to stop at least once. It is higher than the cyclists going straight ahead, because the cyclist has to clear two traffic lights at the intersection. These two traffic lights both have to be green at the arrival time of the cyclist. The probability of a stop for left turning cyclists can be reduced by influencing the sequence of the controller programme in a way that the second light that has to be cleared when turning left is positioned after the first light in time.

For an intersection which only allows cyclists to cross the roadway in one direction, this could be realized by a specific coupling of the four bicycle streams. With standard numbering of the bicycle streams it would mean that the structure should have couplings between streams 22 and 28, 24 and 22, 26 and 24, 28 and 26 (see Figure 3-7-left).

A perfect sequence for left turning cyclists should therefore have a sequence as in Figure 3-7-right accommodating all couplings necessary to have smooth left turns. However the coupling of all bicyclist streams has disadvantages for the total performance of the traffic controller, as the number of constraints for the sequence structure increases. When implementing a structure the extent to which the left turning bicycles are accommodated has to be determined.

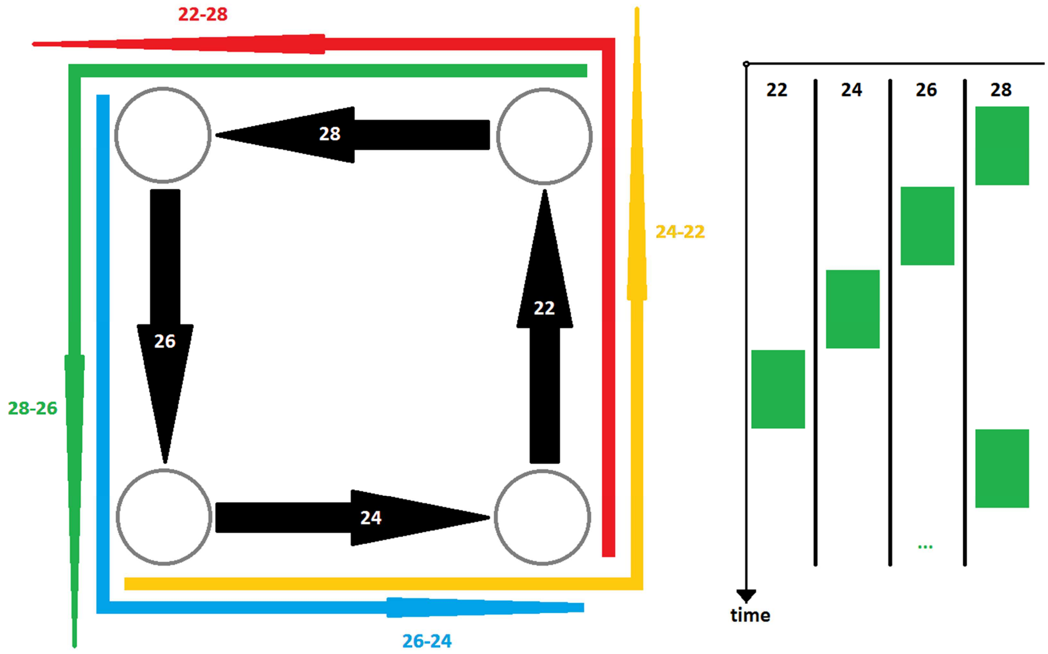


Figure 3-7: On the left: the left turning movements on the intersection. On the right: the desirable phase scheme for left turning bicyclists.

Another way to tackle the problem of left turning bicycles – without forcing the structure of the traffic controller – is to give green on the same moment to all bicycle streams on the intersection. The bicycles are then allowed to cross the intersection via the shortest route possible when turning left (across the intersection). In this case the conflicts between bicyclists on the intersection are not secured by the traffic lights. Bicyclists should negotiate mutually when confronted with a conflict. This is one of the disadvantages of the implementation of this kind of traffic controller in traffic safety perspective. In the traffic controller perspective the disadvantage of 'green for all cyclists' is the addition of one critical signal group (the bicyclist's green cannot realize together with any other signal group, when conflicts are protected). The addition of this critical signal group will result in a traffic controller with five instead of four phases. This will increase waiting times and green times, which might negatively influence the travel time and chance of arriving at the intersection with a green traffic light. In this research the left turning bicyclists will not be accommodated by the all bicycle structure.

3.2 Actors

The behaviour of the actors is an important component for the functioning of the implemented ITS-systems. As the system heavily relies on the influence of the measure(s) on the behaviour of the involved actors. In this chapter the behaviour of the actors is described. Firstly the behaviour of cyclists, the main target group of the ITS system will be reviewed. Afterwards the behaviour of the other modes (mostly cars) will be described.

3.2.1 Cyclists

As from information from a Goudappel Coffeng study (Blankers, 2012) can be retrieved the median speed of the cyclist is 18 km/h. However the speeds on the high side of this median has a much wider spread than the speeds on the lower side of this median. Speeds lower than 12 km/h are not common for cyclists, because it is difficult to ride the bike stable with these low speeds. Other assumptions on the speed profile are that a light peak should be around 25 km/h, as this is the maximum speed for e-bikes to give pedal support (van Boggelen, van Oijen, & Lankhuijzen, 2013).

In practice the speed advice should be within a speed range which the cyclist is able to cycle. Data on the extent of deviation from the original speed possible for a speed advice are not known. Therefore this research will try to use parameters to find out, what compliance with the advice is needed to have a satisfying results for the performance of the system.

Two different possibilities of compliance of the speed advice are discussed for this report:

1. Speed advice is taken over by all bicyclists no matter what their desired speed is. Although this is not the best representation of reality, the simple implementation of the system doesn't allow cyclists to deviate from the given advice.
2. Speed advice is only taken over by the cyclist, when the advice deviates not more than μ % from the initial speed of the cyclist. The variable μ should be determined throughout the research. By varying the variable, one can also see what happens when cyclists are less or more willing to stick to their own desired speed.
3. Speed advice takes into account the desired speed of the individual cyclist and will adjust its advice to minimize the deviation from the desired speed. In this way the probability of compliance to the speed advice is more likely.

The first of these three options is rather simple and will give total control to the speed advice system which makes the potential of the system clear, when human behaviour and abilities do not have any influence on the system. The second option is more equal to the cyclist in reality, it will give the speed advice a smaller impact as only a certain share of the cyclist population will be able to follow a speed advice. In the speed advice system for the fixed time controller the speed advice will be taken over by the cyclist according to the first option of compliance. In the speed advice system for the actuated controller the speed advice will be adjusted to the individual cyclist and does the speed advisor decide on whether a speed advice is possible.

3.2.2 Car drivers

For the other modes holds that processes taking place in the traffic environment are not changed. Car traffic is mostly represented in this research to investigate whether the implementation of systems have influence on the other modes. It is a way to weigh the interests of cyclists against the interests of car drivers. This research does not incorporate changes in the traffic situation for the car traffic. The behaviour of the car traffic is therefore no focal point in this report.

3.3 Speed advice

In this section a theoretical approach for the speed advice is sketched for a simple fixed time controller and an actuated controller. The section discusses what happens if a speed advice is implemented and what theories are used to give a speed advice. The speed advice system for the fixed time controller and actuated controller are elaborated with a different approach. The two controllers have such different properties that they ask for a speed advice that is focused on the specific controller. Firstly the relative simple structure doesn't ask for a flexible structure for the speed advice. The design of the speed advice is not more difficult than strictly necessary. On the other hand requires the actuated controller a more flexible structure that reacts to a change in expected state of the controller. The advice system has an aberrant set-up compared to the advice system of the fixed time controller. The two advice systems are discussed in this section and will ultimately result in a speed advice system for both controllers.

The two different controllers have different properties and also the speed advices have different properties. To understand the approach for the controllers the differences in approach are summed up here:

- **Location of advice:**
  The location of advice differs for the two different controllers. The situation with a fixed time controller will give a speed advice at some distance to the intersection the cyclist is advised to ride to travel the intersection in the fastest way without having to stop. The situation with an actuated controller has a speed advisor on board of the cyclist that takes account of the individual distance to the traffic light for every cyclist.
- **Calculation method of advice:**
  The calculation method also differs for the two types of controllers. The fixed time controller is on the roadside and therefore gives only one advice to all the cyclists. This advice is calculated by an objective function with a number of constraints. The on board speed advice generated for the actuated controller results in a score function that generates a score for every possible speed between the 0 and 30 km/h. The speed with the highest score is the advised speed.

Table 3-1 shows the differences of the approaches for the two types of controllers. The two set ups of are discussed separately: In section 3.3.1 you will find the framework for the advice of the fixed time controller and in section 3.3.2 for the actuated controller.

Table 3-1: Differences in approach for the fixed time controller and actuated controller

Fixed time controller	Actuated controller
roadside advice	on board advice
objective function	score function

3.3.1 Speed advice for fixed time controller

With a speed advice the chance of a stop can be reduced. Through speed advice the distribution of cyclists can be regulated to some extent. In this way we can change the arrival pattern at the traffic light from evenly distributed to peaks at certain times. To minimize the number of stops these peaks in demand have to be at the green times of the bicycle traffic light. Objective of the system is therefore to have peaks in demand at the green times of the bicycle traffic light and have low (or no) demand at the non-green times of the bicycle traffic light, where green time is defined as the duration of the green light (t_{g}). In the same way red time (t_{r}) is the duration of red light, yellow time (t_{y}) is the duration of yellow time. Cycle time (t_c) is defined as the total of red, yellow and green times of the different traffic streams that return in time. If the green time is the part of the cycle we want to have high demand, the time the traffic light is not green (t_{ng}) is part of the cycle time we want to avoid demand:

$$t_{\mathrm{ng}} = t_{\mathrm{r}} + t_{\mathrm{y}} = t_{\mathrm{c}} - t_{\mathrm{g}} \qquad (3.1)$$

The first steps in indicating the theoretical approach are based on the fixed time traffic controller. It takes the green time for cyclists and the cycle time as starting point for the implementation of a speed advice. With a uniform arrival pattern of cyclists at the intersection, the expectation to the probability of a stop would be a function of the green time divided by the cycle time.

$$\mathrm{p}^{stop}(t_{\mathrm{g}}, t_{\mathrm{c}}) = 1 - t_{\mathrm{g}}/t_{\mathrm{c}} \qquad (3.2)$$

Furthermore assumptions have to be made on which speeds are possible to ride. Vehicles can always catch a green light when every speed is possible ranging from 0 to infinity, but in practice the vehicle and the driver/rider of the vehicle (the combination is called actor) cannot travel at every speed. Therefore in advance a range of speeds has to be determined in which the actor is able to travel. This range is given by the maximum speed and minimum speed suitable for a speed advice. This speed advice can differ in different situations dependent on the target user. In an individualized system even the minimum and maximum speed can differ per user. For the simple version of the system which is used to explore possibilities, the maximum (v_{max}) and minimum (v_{min}) speed that the algorithm will advise to a cyclist is fixed for all cyclists.

With these maximum and minimum speed the green times at the traffic light can be extended towards the road section of the bicycle path upstream of the traffic light (see Figure 3-8). This allows us to see at what combination of moment in time and distance to traffic light a speed advice is possible. The black area (0) shows the combination of time and distance in which no speed advice within the speed advice interval (between v_{min} and v_{max}) is possible. The yellow area (1) in the figure shows the combination of time and distance in which the speed advice can lead the cyclist to the green time in one cycle. When two yellow areas in the figure overlap it is possible for a speed advice system to direct a cyclist to green phases of two different cycles. The light green area (2) in Figure 3-8 indicates the matching combinations of time and distance for direction to two different green phases. At last the dark green area (3) consists the combination of time and distance at which even three green phases are available for speed advice within the speed advice interval.

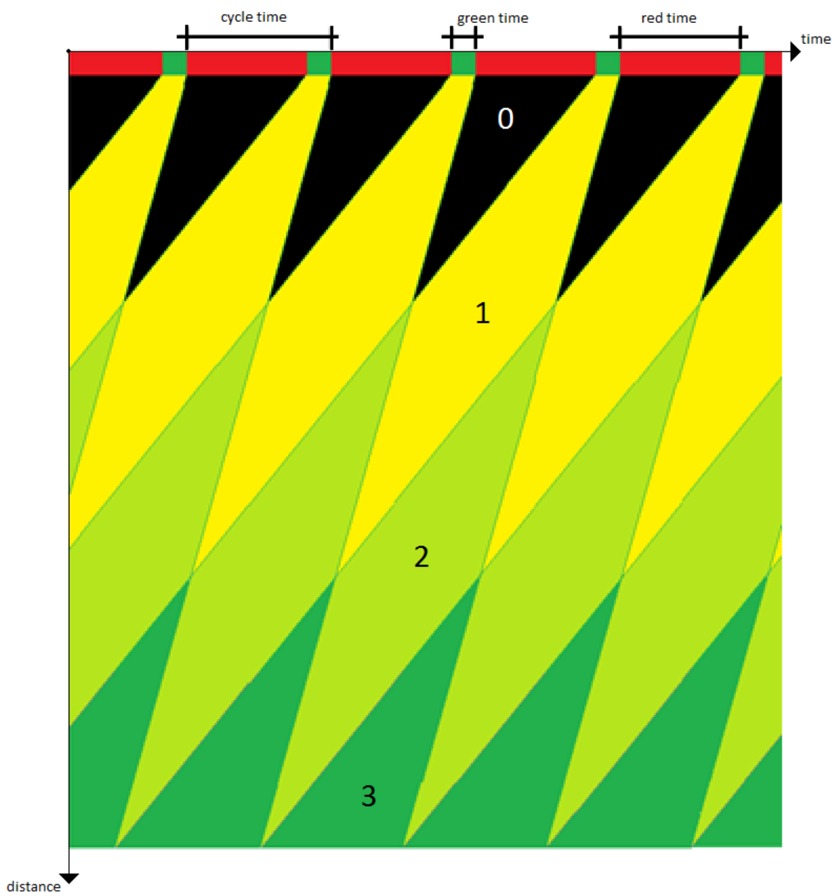


Figure 3-8: Green phases and intervals suitable for speed advice.

The distance of the speed advice from the traffic light and the green time for the cyclist stream and the total cycle time are the quantities which determine the number of speed advices possible. Further on, the possibilities in giving different speed advices can be used for giving speed advice fitted to the individual needs and desires of cyclists. For the simple system of the first PDCA-cycle of this research the position of the speed advice is chosen on the point that only one speed advice is possible for every moment in time.

When the cyclist keeps traveling to the traffic light by the given speed of the speed advice controller, the cyclist arrives at the intersection when the traffic light is green. The disadvantage of the configuration with a speed advice on one location en route to the intersection is the absence of any feedback to the cyclist on the deviation from the advice.

3.3.1.1.1 Variables

To come to an advisable speed for the fixed time controller, the first steps follow an approach which can be derived from Chapter 3. However the variables functioning as input for the system are somewhat different from the terms used in the framework, because here the time is taken as a variable that starts at the beginning of a cycle. In this way the formulas can easily be rewritten for simulation purposes.

The first variable that is not a fixed variable, is the time. Time is zero at the moment the controller program is turned on and the first cycle starts. The input times needed to come to an advice are presented in Figure 3-9. As every green phase of the different signal groups starts at a different point in time, we cannot simply use red times and green times to determine the time it takes before a traffic light turns green. In addition we have to know the time it takes before the first green phase starts in the simulation. This is the 'about green time'. The 'end green time' determines the time at which the green phase ends. Additional to these times, a distance to the traffic light is needed to calculate the possible speeds.

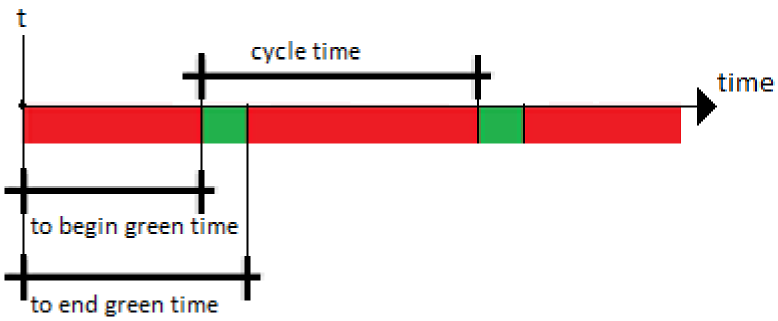


Figure 3-9: Begin green time and end green time for a signal group.

Finally this gives us the following variables:

Table 3-2: Variables for speed advice fixed time controller

t_{tbg}	begin green time (s)
t_{teg}	end green time (s)
t_{c}	cycle time (s)
d	distance to traffic light from the location of speed advice
t	time (s)

3.3.1.1.2 Speed advice calculation

The speed needed to reach the green phase is calculated by dividing the distance to the traffic light by the time it takes before the green phase starts or ends is. In this way two speeds are calculated for a green phase. Not only the first green phase should be taken into account, but also green phases of next cycles are important for the system. Therefore a variable for taking into account these next cycles is necessary. This variable n can reach integer numbers starting with 0 (next green phase). The speeds to catch the beginning or ending of a green phase are now:

$$v_{\mathrm{tbg}}^{n} = \frac{d}{t_{\mathrm{tbg}} + n * t_{\mathrm{c}}} \tag{3.3}$$

$$v_{\mathrm{teg}}^{n} = \frac{d}{t_{\mathrm{teg}} + n * t_{\mathrm{c}}} \tag{3.4}$$

for n = 0, 1, 2, 3, 4, …

3.3.1.1.3 Choosing a speed advice

The previous two steps to come to the possible speeds are very straightforward and don't include any decision making, they only describe what speed ranges are possible to catch a green light. After completion of these steps we end up with a number of speed advices per instant of time, that indicate the possible speed advices.

Table 3-3: possible speed advices after calculations from Equations 4.1 to 4.4.

	Green phase 0 (n=0)	Green phase 1 (n=1)	Green phase 2 (n=2)	Green phase 3 (n=3)	…
For beginning green phase:	v_{tbg}^{0}	v_{tbg}^{1}	v_{tbg}^{2}	v_{tbg}^{3}	v_{tbg}^{n}
For end of green phase:	v_{teg}^{0}	v_{teg}^{1}	v_{teg}^{2}	v_{teg}^{3}	v_{teg}^{n}

Obvious the speed to catch the first green is the highest and all other speeds will reduce, when n grows. The generated speeds should be tested to generate a speed advice that is suitable for the cyclist. By making it suitable for the cyclist, it has a higher chance of compliance.

In our first version of the advice, there exists an upper and lower limit for the speed advice. Every given advice should be between these numbers. So after the determination of the different speeds possible to catch a green light, these speeds should be checked on whether they fall between the upper and lower limit. And if so, the speed advice is used. This means introducing

Then still, different possibilities exist to come to a speed advice. Dependent on your objective it is possible to choose a selection method from the different speed advices possible. Observations (from simulation or real-life) can make it necessary to fine-tune the way of selecting a speed advice.

Option 1:

> <u>Maximization of speed</u>
>
> It is the objective to direct all cyclists to only the beginning of the green phase (if possible). Only one speed is then available for every control cycle. When it is not possible to direct a cyclist to the beginning of a green phase, the system should choose for a speed with which the cyclist can still catch another part of the green phase with v_{max}.

Option 2:

> <u>Increase of reliability I</u>
>
> It is the objective to direct all cyclists to the middle of the green phase if possible, so the cyclist has a bigger chance of reaching the green phase when processes en route to the traffic light make the cyclist deviate from the speed advice.

Option 3:

Increase of reliability II

Another way to force the cyclist to catch the middle part of the green phase is to reduce the size of the green phase on both sides with μ seconds, with μ is a positive integer. This will reduce the risk of arriving too early or late at the intersection due to speed deviations on the route to the traffic light, e.g. due to other traffic or the time needed for acceleration to the correct speed at the place of the speed advice. The introduction of this option also can lead the way for the system to be implemented on more car dependent traffic controllers. As in these controller situations the certainty of a green period is restricted because only a small period of time gives certainty on catching the green light. This option is a variant on Option 1. It maximizes the speed but not for the whole green period but for a smaller part of the green period.

In all options the reduction of stops is the main aim of the system. When the options score the same on this criterion other factors of the options become more important. From a cyclist's perspective therefore travel time is the most important measure to make his trip shorter. The other two options assume that the cyclist is not always able to stick to the given speed advice and therefore are options that look at the important factors from a system's perspective. Ultimately the Maximization of speed (Option 1) is the chosen option to find out what the first implications of the speed advice system for cyclists are.

The distance of the speed advice from the traffic light and the green time for the cyclist stream and the total cycle time are the quantities which determine the number of speed advices possible. Further on, the possibilities in giving different speed advices can be used for giving speed advice fitted to the individual needs and desires of cyclists. For the simple system of the first PDCA-cycle of this research the position of the speed advice is chosen on the point that only one speed advice is possible for every moment in time.

When the cyclist keeps traveling to the traffic light by the given speed of the speed advice controller, the cyclist arrives at the intersection when the traffic light is green. The disadvantage of the configuration with a speed advice on one location en route to the intersection is the absence of any feedback to the cyclist on the deviation from the advice.

The preference is to guide the cyclist to a green phase with a $v_{\text{tbg}}^{n}(t)$ and $v_{\text{teg}}^{n}(t)$ within the max/min-speed boundaries. Of course this is not always possible, so the system then has to look for a value between $v_{\text{tbg}}^{n}(t)$ and $v_{\text{teg}}^{n}(t)$.

The objective is to maximize the speed advice. In that way the cyclist can reduce his travel time the most. Disadvantage of this way of giving a speed advice is that the cyclists with lower speeds have to make bigger adjustments in speed to catch a green wave, because the speed advice will be at the higher side of the spectrum of speeds between $v_{\max}$ and $v_{\min}$.

If the speed for catching the beginning of the green window is bigger than $v_{\max}$ and the speed for catching the end of the green window is smaller than $v_{\max}$, $v_{\max}$ should be the speed advice. If the speed for catching the beginning of the green window is smaller than $v_{\max}$ and bigger than $v_{\min}$, the speed advice should be $v_{\text{tbg}}^{n}(t)$. This is illustrated by the decision tree in Figure 3-10.

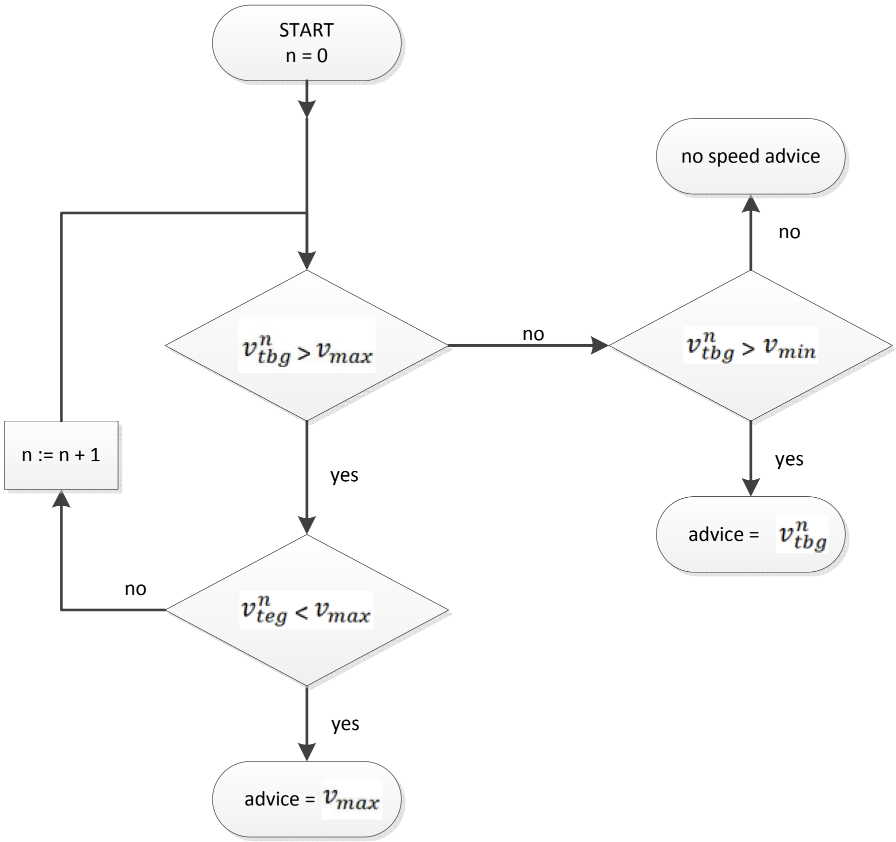


Figure 3-10: Decision tree for choosing a speed advice.

Following examples are made to show what the decision tree produces as speed advice in different situations. This gives insight in the processes that play a part in giving advice and makes the reader familiar with the flow diagram presented in Figure 3-10.

Scenario A

Following the decision tree beginning with the speeds for catching the first green phase (n=0), the $v_{\text{tbg}}^{0}(t)$ is bigger than the maximum advice speed ($v_{\max}$). $v_{\text{teg}}^{0}(t)$ is not smaller than the maximum advice speed, so following the decision tree leads to the next green phase with n=1. Hence, here speed to catch the beginning of the green phase ($v_{\text{tbg}}^{1}(t)$) is bigger than the maximum advice speed. This leads us to the check whether the speed to catch the end of the green phase ($v_{\text{teg}}^{1}(t)$) is smaller than the maximum advice speed. This is the case, so the speed advice should be equal to the maximum advice speed ($v_{\max}$).

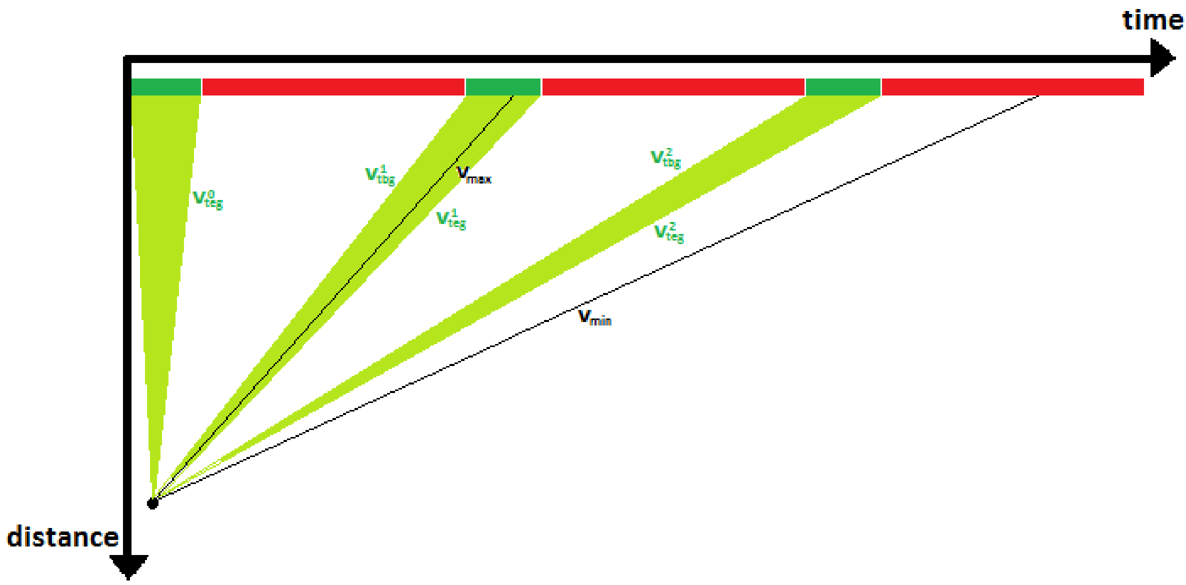


Figure 3-11: Speed diagram for Scenario A.

Scenario B

Following the decision tree beginning with the speeds for catching the first green phase (n=0), the $v^0_{\text{tbg}}(t)$ is bigger than the maximum advice speed (v_{max}). $v^0_{\text{teg}}(t)$ is not smaller than the maximum advice speed, so following the decision tree leads to the next green phase with n=1. The speed to catch the beginning of this green ($v^1_{\text{tbg}}(t)$) is not bigger than the maximum advice speed. Following the decision tree, we have to check whether this speed is bigger than the minimum advice speed (v_{min}). As this is the case the adviced speed is equal to $v^1_{\text{tbg}}(t)$.

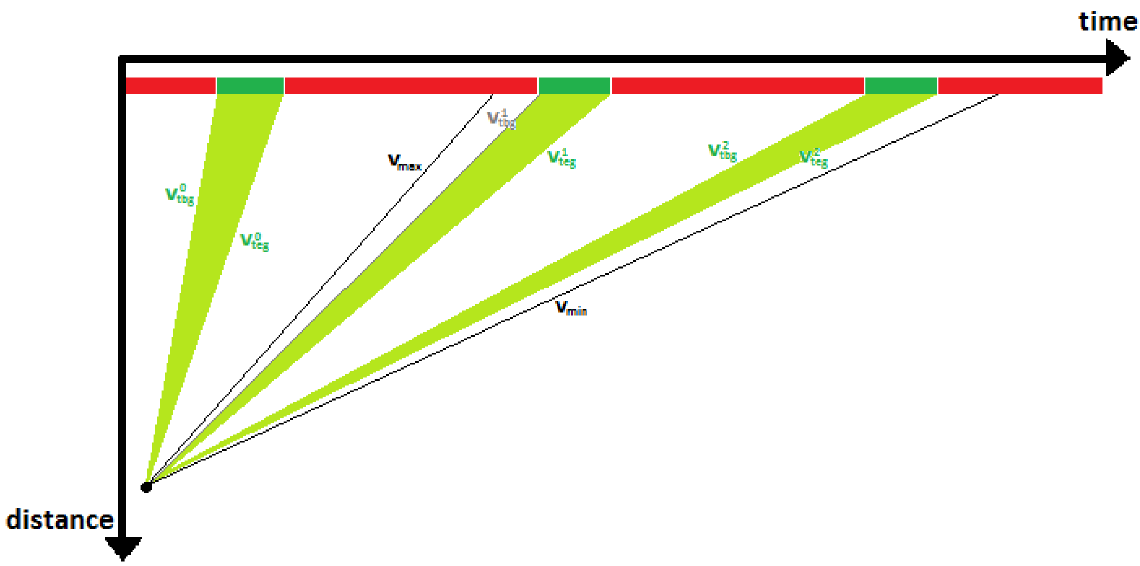


Figure 3-12: Speed diagram for Scenario B.

Scenario C

Following the decision tree beginning with the speeds for catching the first green phase (n=0), the $v^0_{\text{tbg}}(t)$ is bigger than the maximum advice speed (v_{max}). $v^0_{\text{teg}}(t)$ is not smaller than the maximum advice speed, so following the decision tree leads to the next green phase with n=1. The speed to catch the beginning of this green ($v^1_{\text{tbg}}(t)$) is not bigger than the maximum advice speed. Following the decision tree, we have to check whether this speed is bigger than the minimum advice speed (v_{min}). As this is not the case this leads to speed advice at all.

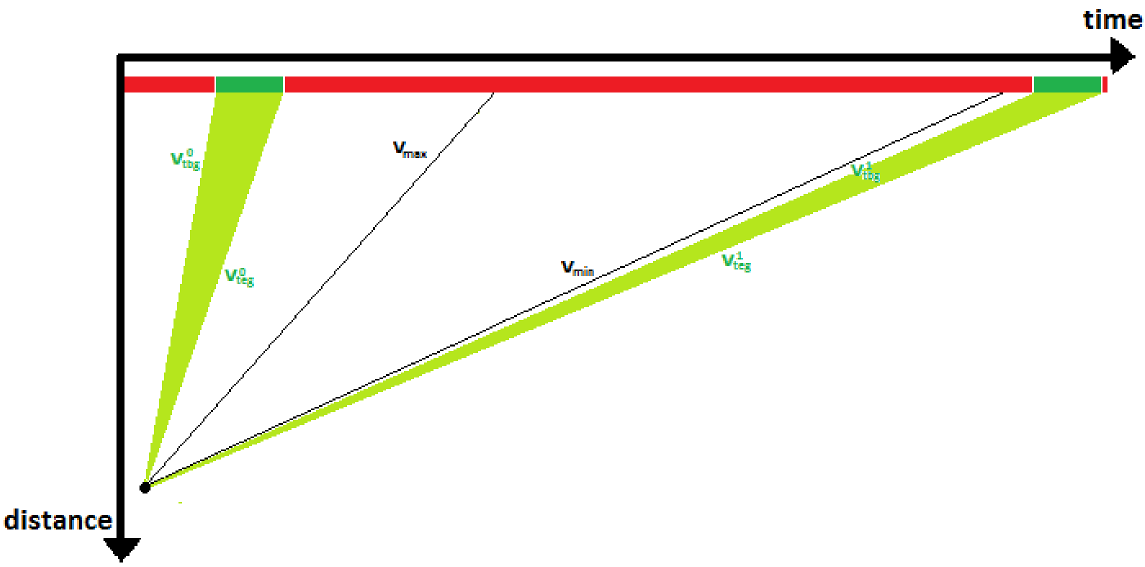


Figure 3-13: Speed diagram for Scenario C.

3.3.2 Speed advice for actuated controller

The speed advice system as used for the fixed time controller is not suitable for the configuration with an actuated controller. The changing state of the actuated controller doesn't match a speed advice that is given at one point in time and location and must be followed until the cyclist reaches the intersection. Instead of the system that gives only one speed advice, the speed advisor in a context with an actuated controller, should preferably adjust its speed to the state of the controller. En route to the intersection the cyclist thus has to get a different speed advice when this speed advice is more appropriate then the speed advice given earlier, so the advice has to adjust over time. As every cyclist is on a different place in the network at the moment a change in state occurs a local advisor doesn't satisfy the nature of the controller anymore. The cyclist should have an adjusted advice on any place in the network before he passes the traffic lights. Therefore the introduction of a system that can give this advice on any place in the network is chosen in the form of a advisor that is on board of the bicycle.

The implementation of the advice on board brings the possibility to also apply a speed advice that is in line with the individual desires of the cyclist riding on a bike. The speed advice could strive to bring the speed advice as close as possible to the desired speed of the cyclist himself. To attain to this personal advise, the speed advice has to change drastically. Therefore 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 at a green light. After the description of these two functions in the next section the two functions are combined to come to a total speed advice that should on every moment give an optimal speed advice, by a summation of both functions. The last part of section 3.3.2 will introduce the speed advice system that takes into account both the personal preference and the green light arrival, but also takes into account what consequences a speed advice at the moment of advice will have for speed advices in the near future and the probability of catching the green light.

If we sketch this approach to come to the optimal speed in a time distance-diagram the cyclist will have certain points in the diagram that give it the best approach to the traffic light (Figure 3-14). The speed advisor is made in a way that the cyclist is directed towards these different points. It so to speak connects the different dots in the diagram, but these dots are dependent on the state of the traffic light and the position of the cyclist.

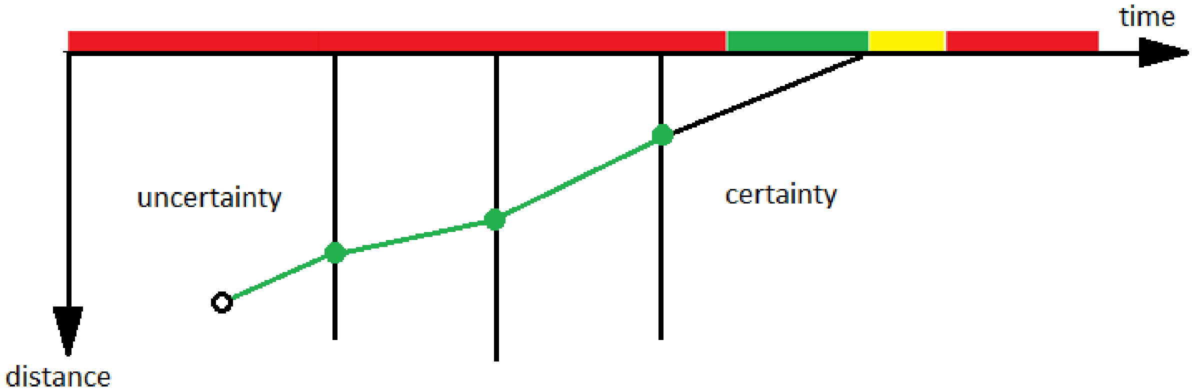


Figure 3-14: A route to the traffic light with speed advices that deviate within the route for the changes of the state of the traffic controller. The black lines indicate a shift in uncertainty.

For the framework of advising a speed based on the upcoming states of the traffic controller these states must be clearly indicated to calculate the best advice. 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 phase and the green time of the phase. Within the state uncertainty about the time of realization is equal. The number of phases has a maximum dependent on the structure of the controller. The number of states has no maximum, because of the fact that a cyclist can be directed towards a state a certain number of cycles ahead. Figure 3-15 shows the different states of the traffic light that are distinguished. The relation with the speed advice is made in the following sections. The number of states that have to realize before the light for cyclists is N, we can now distinguish the states 0,1,2,…N. State 0 is the state in which certainty exists about the time of the green period.

Figure 3-15: The different states of the traffic controller and thus speed advice system. The dark green bar indicates the green time period for the cyclists, the light green bars are the green times for the phases that realize before the cyclist's light turns green. In this example there are three states to come before the cyclist's light will turn green.

3.3.2.1 Personal preference

The personal preference of the cyclist is closely related to his desired speed. This is the speed at which the bicyclist would pedal when no interaction with other actors or speed advice mechanisms is present. The highest utility for the user based on personal preferences will be present when the cyclist can ride at his own desired speed. Therefore 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 will mean that the utility of the cyclist declines. In this research riding at the desired speed has a utility of zero and deviating from this speed will cause a negative utility (costs). The bigger the deviation, the bigger the decline. As it is harder to deviate with the same value of speed when you're already driving at a speed far away from the desired speed. Therefore the derivative of the utility function should be higher when the speed is further deviated from the desired speed and lower when the speed is closer to the desired speed.

As an example a negative parabolic function with its maximum at the desired speed has a fitting structure for describing the utility function of the personal preference of the cyclist. It takes into account the maximum value of utility when driving with the desired speed, but also the utility drop when a cyclist has to deviate from the desired speed. Although this parabolic function may not be the correct representation of the costs when deviating from the desired speed, it represents the basic behaviour that is expected from a cyclist. That is why the parabolic function is chosen as the mathematical base for the personal preference score. The score function for the personal preference is therefore written as:

$$\sigma(v) = -|v - v_{\mathrm{des}}|^2 \qquad (3.5)$$

Example

Suppose a cyclist with a preferred speed of 16 km/h has no chance of catching a green wave. The score function now will result in a score function solely based on the personal preference. Therefore the scores are as shown in Table 3-4 and Figure 3-16. The maximum of this scores is achieved when riding at 16 km/h, the speed advisor thus advices the cyclist to cruise at his desired speed.

Table 3-4: Personal preference score function for a cyclist with a desired speed of 16 km/h.

Speed (km/h)	12	13	14	15	16	17	18	19	20
S_{pp}	-16	-9	-4	-1	0	-1	-4	-9	-16

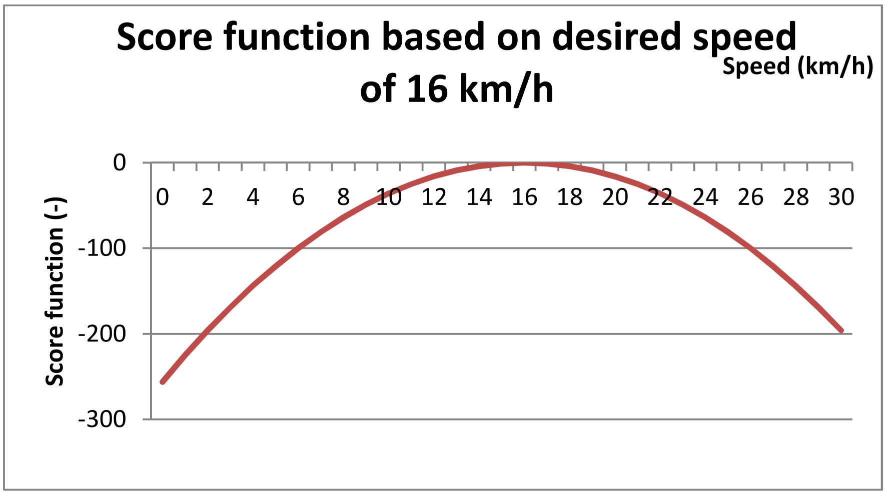


Figure 3-16: Personal preference score function for a cyclist with a desired speed of 16 km/h.

3.3.2.2 Green light function

The green light function can only be determined for the last state before the traffic light the cyclist is heading to turns green. Certainty about the realization of green is needed when applying the score function for catching the green light. Otherwise the function would be based on speculation of the time the green window would appear.

The score function is as simple as possible and will give the cyclist a score equal to zero when the advised speed is not allowing the cyclist to catch the green wave and gives a score equal to the green bonus, when the advised speed will direct the cyclist towards a green light. The green bonus (γ) should have a value compared to the personal preference score that represents the trade-off between the utility of the cyclist to catch a green wave and deviate from his speed. No literature on the trade-off between these two values is found. Therefore the value for the green bonus is a variable that is changed in this research. The sensibility of this parameter can be found by using different values for this parameter.

The calculation of the green light function is now as follows:

$$S_g\ (g) = g * \gamma$$

$$\begin{aligned} &\text{with } g = 1, \text{when catching green light} \\ &\text{and } g = 0, \text{when catching no green light} \end{aligned} \qquad (3.6)$$

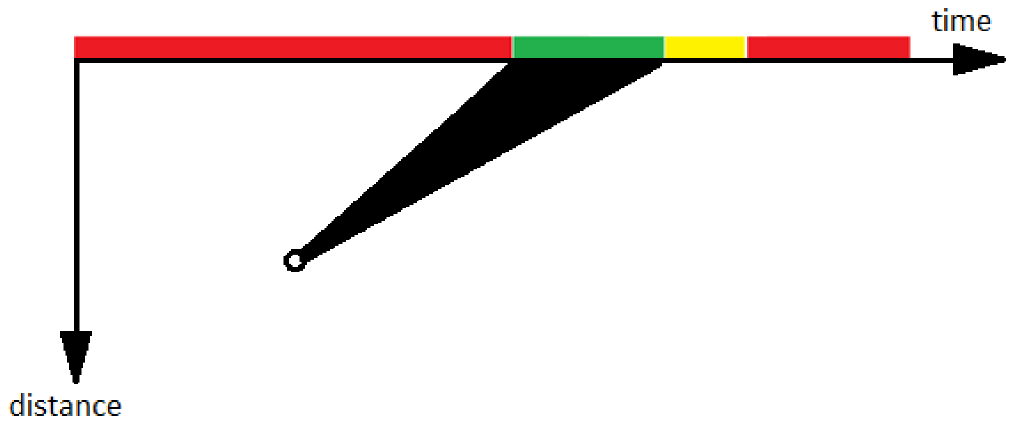


Figure 3-17: Speeds that score a green bonus.

3.3.2.3 Speed advice including future states

The speed advice with the highest value based on the combined score determined by the deviation of the desired speed and the chance of catching the green light gives the speed advice. However it is not simply a matter of addition of two variables, because the speed advisor has to take into account all possible states of the traffic light in the near future (until the traffic light turns green). The future changes in state of the controller will have consequences for the advised speed. The speed advice should give the cyclist an advice that within a period of equal uncertainty on the estimated time to green (a state) the cyclist should not change as there is no change in the probability of future events in the controller.

If the speed advice combines a value of desired speed and a value of catching the green light, the green bonus causes the cyclist to cycle at a different speed than his desired speed. Sometimes this happens even when this deviation of the desired speed only gives a small chance of catching the green light. A shift of the expected green time due to the decreasing uncertainty of what the controller will do can cause a shift in the speed scores so that the cyclist can no longer catch a green wave within the score framework. The initial deviation from the desired speed of the cyclist then did not cause a reduction of stops, but did advice the cyclist to deviate from his desired speed. The speed advisor does so because it only optimizes the speed of the cyclist for the level of uncertainty that exists when the speed advice is given. Afterwards it could be concluded that the speed advice did not give the optimal speed advice, because it was better to ride at the desired speed from the beginning. However this was not known when the advice was given.

The speed advice in a certain state will direct the cyclist to a starting point for the next state. The chosen speed by the system will be the speed with the highest score on the combination of the score for the speed and the distance at which the cyclist starts in the new state. The highest score for the start of the next state is realized when the cyclist can travel with his desired speed and the cyclist has the biggest chance of catching a green light. The speed advice is thus not directly directing the cyclist to the estimated arrival of a green phase, but looks for the best position to start the estimated arrival of a green phase next state taking into account the costs that it will encounter to end up at this position.

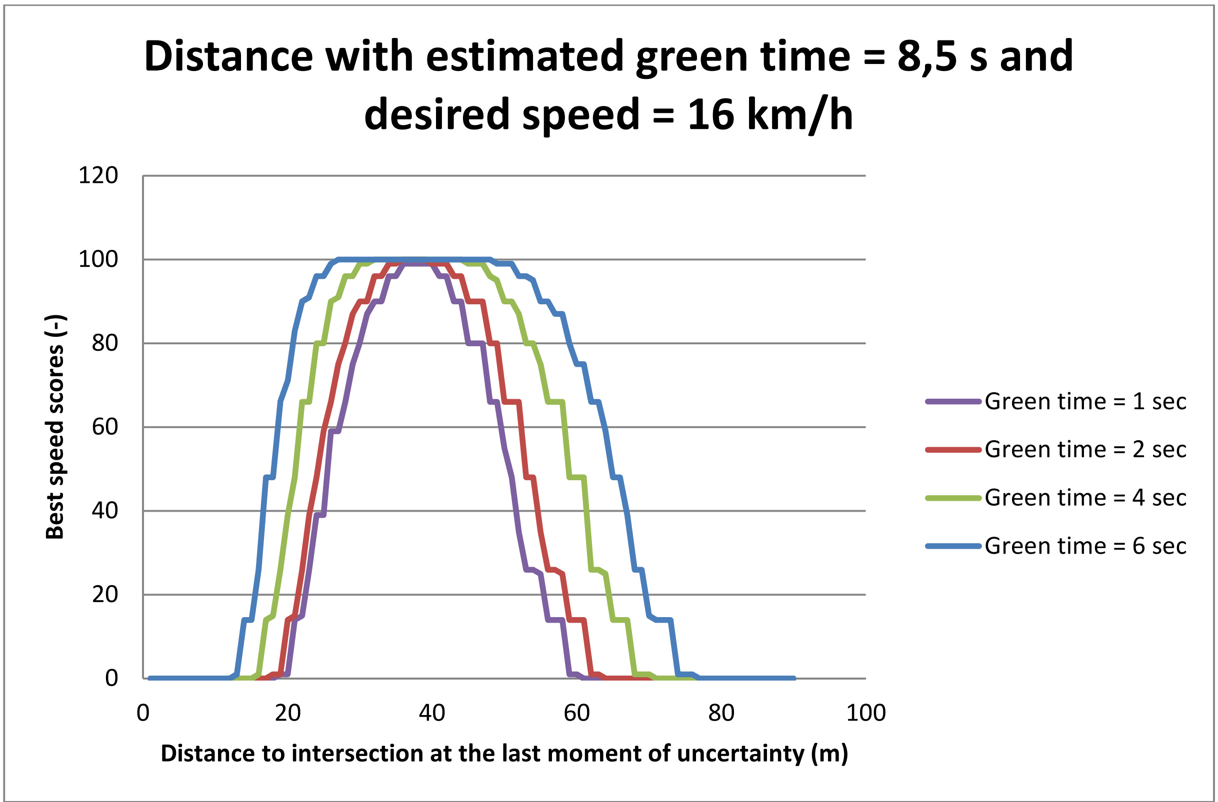


Figure 3-18: Example of a score function over the distance to the intersection, with various green times and a fixed estimated time to green. Maximum score will occur for a distance at which the cyclist can catch the green by riding its desired speed.

An example of a score function for a single phase is given in Figure 3-18. The score function shows the score of the starting points for the last phase before the traffic light turns green for various durations of the cyclist's green. Because the cyclists can arrive at the intersection during a certain period of time the highest score belongs to several distances that allow the cyclist to catch the green and travel at his desired speed. All distances with a score that is between the maximum and minimum score of zero, provide a speed advice that deviates from the desired speed of the cyclist but enables the cyclist to cath the green light. The minimum score of zero is encountered when the cyclist can travel at its desires speed, but will not catch a green light.

The total speed advice will take into account the score for the distances of every next state. As the score of the last state is incorporated in the score calculation of the phase that is before this state and so on. An example of a total speed advice taking into account the next phases is graphically presented in Figure 3-19. The calculation of the separate score will be determined on the next pages.

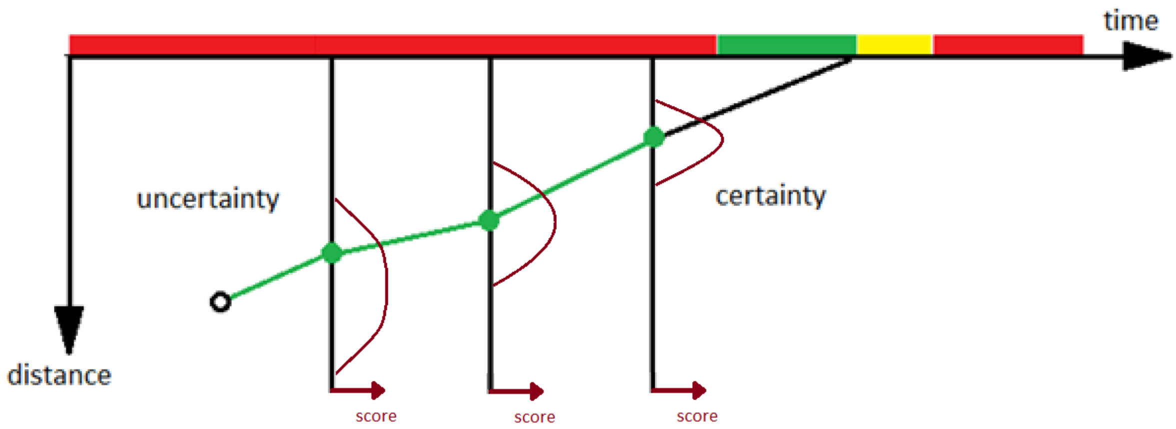


Figure 3-19: Example of a score distribution for the distances in all next states when there are three states to come

Last state (= state 0)

The last phase of the speed advice is the phase in which the uncertainty of the realization of green is certain. The duration of this phase is the time between the end of green for the signal groups of the phase that realizes before the targeted bike green and the end of green of the targeted bike green. With the knowledge of the duration of the phase and the times the green light appears, the system could provide a score for every distance d_0 the bicycle could have at the time the change to certainty appears. This score has two components. The first is determined by the appearance of green for the bicyclist traffic light and the second by the personal preference.

A green function will generate a value for the score that consists of a probability of avoiding a stop multiplied by the relative value of avoiding a stop. This probability is dependent on the time the bicycle arrives at the intersection, which is the distance of the bicycle to the intersection divided by the chosen speed in the last phase. The formula doesn't account for the possible extension of the green phase for bicyclists as the uncertainty of this extension and the small distance to the intersection on the moment of extension, reduce the performance of this measure. The probability of catching green is therefore 0 or 1. The green light score is equal to the green bonus when the cyclist catches the green light and zero when the cyclist does not catch the green light. The personal preference score is equal to the formula of Equation 4.5.

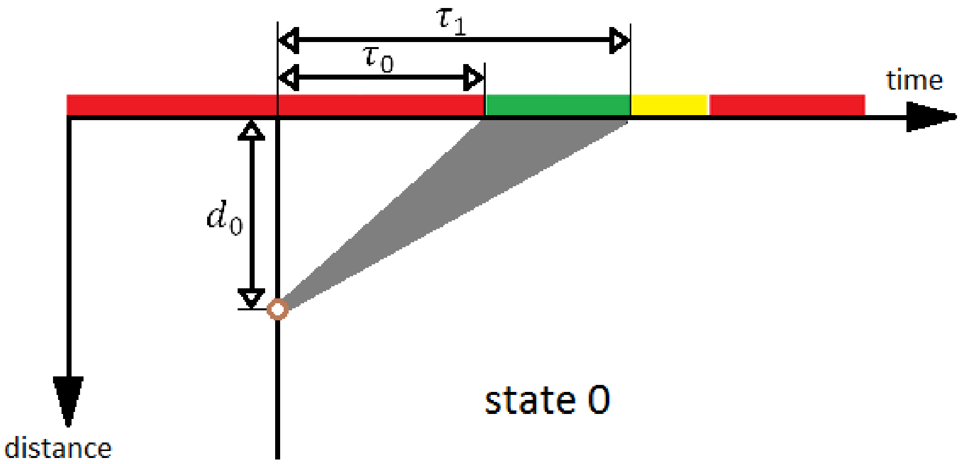


Figure 3-20: The variables of the last state that determine the green light score for the possible speeds in this state. The speeds that correspond with the grey zone in the figure will provide a green light score of γ.

$$S_0\ (d_0, v) = \begin{cases} \sigma(v) & \text{if } \frac{d_0}{v} \notin [\tau_0, \tau_1] \\ \sigma(v) + \gamma & \text{if } \frac{d_0}{v} \in [\tau_0, \tau_1] \end{cases} \tag{3.7}$$

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 d_0 then determines the value of the score for every distance to the traffic light when the last phase starts.

$$S_0\ (d_0) = \max_v S_0\ (d_0, v) \tag{3.8}$$

Now there exists a score for every distance at which the last phase for the cyclists could be approached. From these scores the speed advisor can discourse back to the current phase of the controller. Every phase in front of the last phase has a variable duration that is not known until the phase ends.

State before last state (= state 1)

For the phase before the last phase, the decision on the distance at the start of this phase has no direct influence on the green score for the phase, because of the fact that at the end of this phase another phase exists that has certainty on the realization of green. The distance at which the cyclist is at the end of the state 1, is the same distance it starts the last state (state 0). Therefore the total score belonging to this distance for the Last Phase together with the chosen speed should account for the total score of the Phase before the Last Phase (see also Figure 3-21).

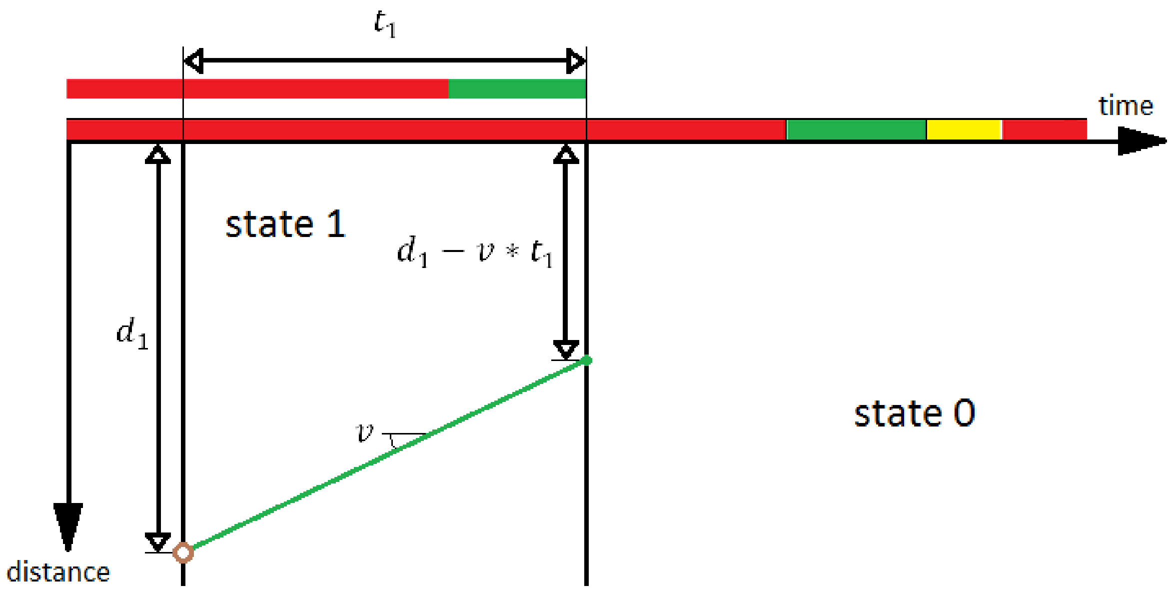


Figure 3-21: Fixed green

The duration of state 1 is however not known on forehand. It is known that the state at least lasts for the period of yellow, the clearance time and the fixed green time. These times together are the fixed duration of state 1 (t_1). However the duration of extension is not known in advance. Therefore the speed advice should also consider a possible extension of the state. The weight of the scenarios considered should be equal to the probability of the considered extensions ($p_{n,m}$). This extension has a minimum dependent on the decision frequency of the controller. A controller can decide to end the extension any time when no vehicles are detected for a period of time. However the controller has a certain update frequency with which the controller can react to the detectors. This minimum time between the decisions is Δt. The number of decisions that count to the maximum extension is *M* and *m* is the evaluated number of decisions with values 0,1,2,…,M. Like the score function of state 0, the score of a certain distance at the start of state 1 is defined by the maximum of the scores over the different speeds.

$$S_1\ (d_1, v, m) = \sigma(v) + S_0\ (d_1 - v * (t_1 + m * \Delta t_1)) \qquad \mathbf{(3.9)}$$

$$S_1\ (d_1, v) = \sum_{m=0}^{M} S_1\ (d_1, v, m) * p_{n,m} \qquad \mathbf{(3.10)}$$

$$S_1\ (d_1) = \max_{v} S_1\ (d_1, v) \qquad \mathbf{(3.11)}$$

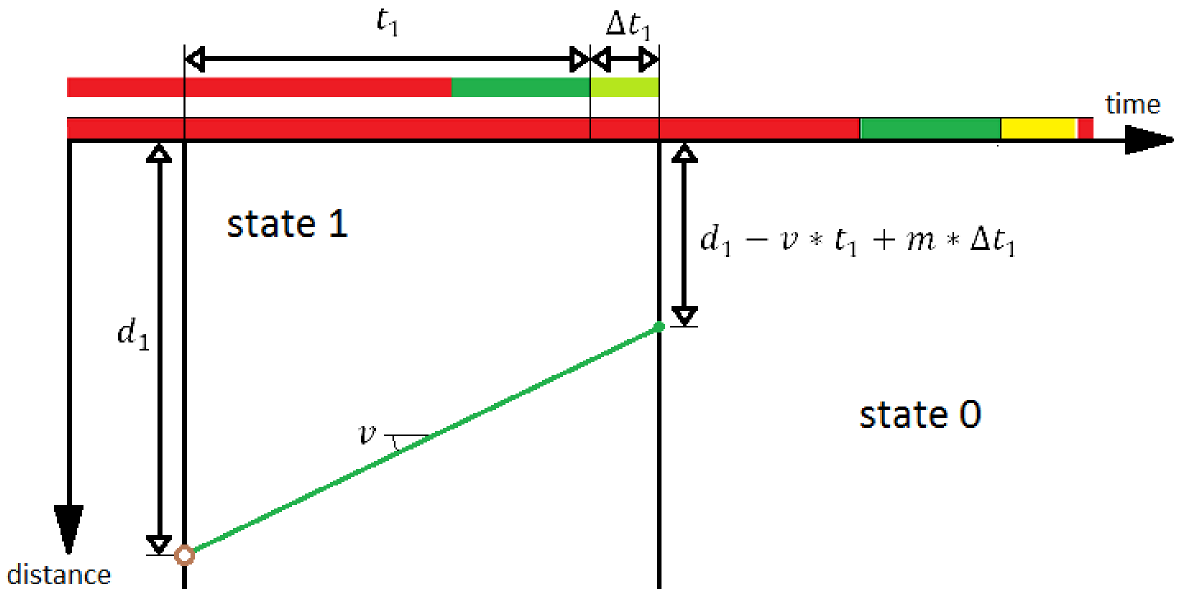


Figure 3-22: Extension green

Other states before last state

The calculation of the score of every phase before the last phase and after the current phase is similar to the calculation of the Phase before the last phase. For all these phases the score for the start time of this phase can be calculated by maximizing the scores of the different possible speeds. The score of the possible speeds consists of the score for this speed according to the personal preference score calculation in Equation … and the score that belongs to the next phase for the distance at which the bicycle begins the next phase when riding with that certain speed.

$$S_n\ (d, v, m) = \sigma(v) + S_{n-1}(d_n - v * (t_n + m * \Delta t_n)) \qquad (3.12)$$

$$S_n\ (d, v) = \sum_{m=0}^{M} S_n\ (d_n, v, m) * p_{n,m} \qquad (3.13)$$

$$S_n\ (d_n) = \max_{v}\ S_n\ (d_n, v) \qquad (3.14)$$

Note: the minimum score is reached when the bicycle is riding at his desired speed but does not have a probability of catching the green light. The maximum score is that of a cyclist riding at his desired speed with a 100% probability of catching the green light.

Current state

For the current phase the distance within the face cannot be changed as the vehicle is already at some location present in the network. In this phase the speed advisor can advise a speed with which the bicycle can have a better starting point for the next phase by maximizing the score for the speed of the current and all phases that still have to come before the traffic light turns green. This is done by combination of the score for the speed advice and the distance-score of the next phase when riding with this speed until the end of the current phase.

$$S_N\ (d_N, v, m) = \sigma(v) + S_{N-1}(d_N - v * t_N + m * \Delta t_N) \qquad \textbf{(3.15)}$$

$$S_N\ (d_N, v) = \sum_{m=0}^{M} S_N\ (d_N, v, m) * p_{N,m} \qquad \textbf{(3.16)}$$

$$v_N\ (d_N) = \arg\max_{v}\ S_N\ (d_N, v) \qquad \textbf{(3.17)}$$

The speed advice given is the speed with the highest score according to Equation 4.13. A more graphic representation of the processing of the speed advice is given in Figure 3-23. In this decision tree the steps of calculation are shown for every moment in time a speed advice is given to the cyclist. The N represents the number of states before the traffic light turns green. When N = 0 the calculation differs from the calculation of the other situations, because there are no states after this state is finished. The calculation of the speed value for N=0 should immediately include the green bonus function, while in speed calculations with higher N's the green bonus is incorporated in the used distance calculations of later states.

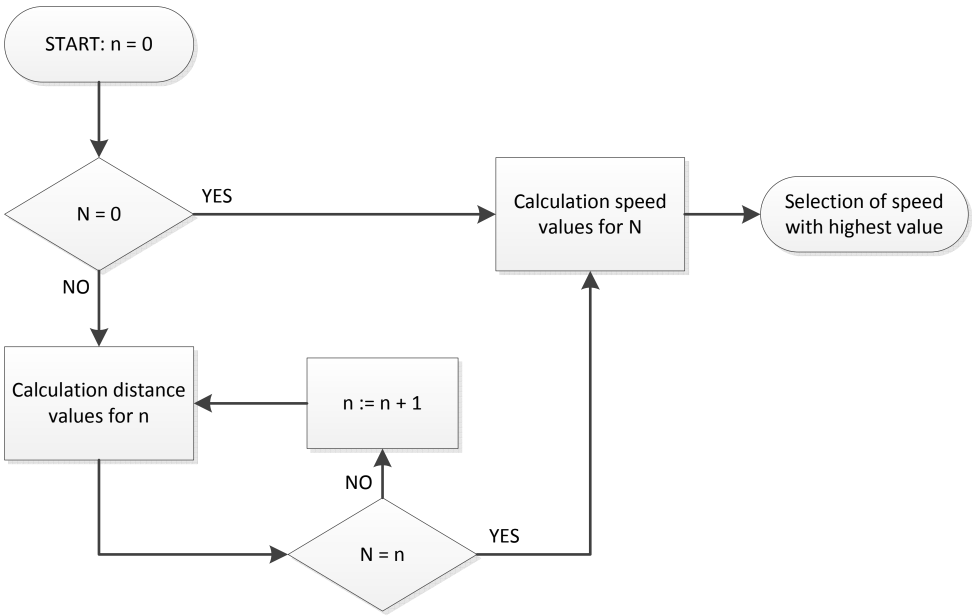


Figure 3-23: Decision tree for the speed advisor that takes into account future states of the traffic controller.

3.4 Conclusion

We now have two theoretical frameworks to come to a speed advice for the cyclist:

- One for a configuration with a fixed time controller. This speed advice can be given at a time long before the traffic light actually turns green, because the appearance of green is known in advance.
- One for the configuration with an actuated controller. This speed advice takes into account the future states of the traffic controller and its consequences for the future speed advice.

The found speed advice have to be implemented in a system that allows the cyclist to react to the calculated speed advice. For the research this implementation will be applied in simulation. For the implementation the equations and decision trees showed in this section have to be adjusted to the network configuration, this process is described in the next chapter.

4 Implementation

This chapter will explain the components of the simulation program that together form the total simulation. Part of the components was not yet available in the simulation software and had to be programmed in order to make the simulation program capable of dealing with a speed advice system for cyclists. Building blocks for the implementation of the simulation consist of a controller, a combination of actor models dependent on the scenario and some additional components. This chapter describes the building blocks of the simulation. The choice of building blocks in simulation is largely dependent on the chosen scenario and the purpose of the simulation in the research. The chapter has a similar format as the previous chapter and so it firstly discusses the controllers used in this research.

The traffic controller is not an infrastructure measure that is already incorporated in the ITS Modeller. Only a controller that can give green and red times according to a specified number of seconds is part of the simulation program. Therefore the Controller-section will firstly discuss the controller sequence generated by VRIGen for the specific network used in simulation. Afterwards it generates the assumptions and properties of the fixed time controller and actuated controller as implemented in the simulation.

For the actors holds that different models that represent a specific behaviour of the actor can be assigned to them. These models together will determine how the actors reacts to its environment. Because no cyclist models are available in the ITS Modeller, some models are made to more realistically describe the cycling behaviour. Also additional models have to be made to describe the reaction of a cyclist to a given speed advice. Different model compositions for the cyclist have to be assigned to the cyclist to deal with the different scenarios in this research. Section 4.2 will explain the different models separately and will give an overview of the model compositions used in simulation.

Additional to the controllers and actor models is the dynamic speed limit controller. This is a roadside infrastructure component that can bring a speed advice to the actor. Originally this piece of infrastructure is meant to inform the actor about the speed limit, but in this research it is thus used in another way. Description of the use of the dynamic speed limit controller can be found in section 4.3.

4.1 Controllers

Before explaining the functioning of the fixed time controller and actuated controller. The optimal sequence for the given network is calculated. It is necessary to have a sequence of the signal groups turning green in order to program the specific controllers. The found sequence with some adjustments is then used for both the fixed time and actuated controller.

4.1.1 Controller sequence

In VRIGen the optimal control program for the given network is calculated. VRIGen returns different programs with a cycle time of 58 seconds (rather short). This structure is determined by the flows present on the streams of the intersection and the clearing times of the intersection. The VRIGen returns the calculated structures sorted by ascending cycle time and descending flexibility. The structure with the smallest cycle time and highest flexibility is chosen to use in the implementation of a controller. The chosen structure's sequence is given in Figure 4-1.

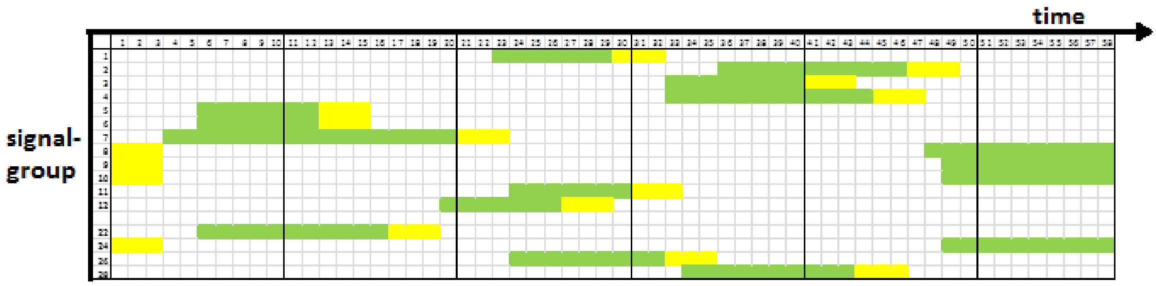


Figure 4-1: Green phases per signal group of the chosen controller structure

As mentioned in chapter 3 left turning cyclists have a bigger chance of making a stop, because they have to cross two roadways that are controlled by traffic lights. To see which structures cope best with these left turning bicyclist, they are examined. For the structures VRIGen calculates Table 4-1 shows how much and what left turning movements are supported by having the required signal groups in the right sequence (see Figure 3-7). As can be deduced from the table no generated structure can take advantage of all desired sequences of bicycle streams, the maximum number of left turning movements that can be accommodated is two.

Table 4-1: Left turning movements in sequence structures generated by VRIGen

Structure	Tcmin	Flexibility	TCw	# coupl.	28-26	22-28	24-22	26-24
1	57.9	18	103.8	1			X	
2	57.9	16	103.8	2		X		X
3	57.9	16	103.8	0				
4	57.9	16	103.8	2	X	X		
5	57.9	16	103.8	2			X	X
6	58.0	17	103.8	1		X		
7	58.8	17	103.8	1	X			
8	59.7	18	103.8	1	X			
9	59.9	16	103.8	0				
10	61.8	16	103.8	2	X			X
11	64.6	17	103.8	1	X			
12	70.8	16	103.8	2		X	X	

4.1.2 Fixed time controller

The fixed time controller's sequence can be directly deducted from the sequence of Figure 4-1. Every traffic light has its own traffic light controller in simulation. These traffic light controllers will turn green based on the specified value determined in the controller. The controller will switch its colour related to the simulation time. In ITS Modeller there already exists a unit that controls traffic lights called the "Static Traffic Light Controller". This controller is however not able to cope with all possible fixed time controllers. Therefore the controller is changed in order to make the implementation of a broader range of fixed time controllers possible. Here, firstly the existing controller is discussed and later on the changes in this controller are explained.

Static Traffic Light Controller

In the existing Static Traffic Light Controller, the phases of a signal group are determined by the specified green time, red time, yellow time and about green time. One can choose in what phase the signal group begins in simulation and afterwards the signal group will go through the different phases in the sequence:

about green time → green time → yellow time → red time → about green time → … etc.

In this way the phase scheme can be implemented per signal group as resulted from the VRIGen calculations. However the way of implementing the phase scheme has big disadvantages, as one can only implement phases that are at the start of the green, yellow or red period when the simulation starts. For the signal groups that start in red, the about green can help to synchronize the phases. The about green time can be specified with the time between the start of the cycle and the start of green time. If the traffic light is then started in its about green time, it will run through the sequence as intended. About green time is however not meant to function with the aim of having the different phases on the right time. It is originally implemented to relate turning yellow of conflicting traffic streams to the traffic light. Still it is not possible to cope with signal groups that are green at the start of the simulation, but are not at the start of their green time.

To implement a static controller scheme, one has to search for a period in the cycle with only red phases or starting points of yellow and green phases. In some sequences these time instances are available in some not. Therefore the code of the Static Traffic Light Controller is adjusted in a way that it is possible to implement every static traffic controller, no matter what the sequence structure looks like.

Cyclic Traffic Light Controller

The first thing that is adjusted is the replacement of red time for cycle time. The red time can be calculated by the program by the formula by distracting the green and yellow time from the cycle time. As cycle time is often more visible in software to compose traffic light structures than red time, in this way this number can simply be taken over from the composing software.

Furthermore the about green time is replaced by begin green time. This parameter is only used for determining the time between the start of the cycle and the first green time, afterwards the begin green time is not used anymore. The green time and yellow time of the traffic light controller will remain in the new version. Now every traffic light starts in red and will remain red after the begin green time has passed. From here on it will have the same sequence as the existing traffic light controller. So the new sequence of phases is:

begin green time → green time → yellow time → red time → green time → …

The only thing that is not fixed yet by defining the structure in this way is implementing signal groups that realize green phases more than once a cycle. The new programming structure only allows for one realization within the cycle. This copes with the given structure from Figure 4-1, so it will not give problems for the simulation.

4.1.3 Actuated controller

To transform the fixed time controller with speed advices into an actuated controller with speed advices, the first thing that needs to be changed is the controller program that controls the different traffic lights at the intersection. This controller has to adjust its program in a way that it is equal to the simplified actuated controller described in section Actuated controller3.1.2. The controller is not only the driving force for the control of the traffic lights, but also has to send information about its state to the actors. The sent information related to the state of the traffic light is discussed at the end of this section.

In practice an actuated controller will respond to the observed traffic at the intersection. The loop detectors in the road give indications on present traffic at the different signal groups. This leads to the distribution of green times for the traffic lights of these signal groups. However the loop detector is a non-existent element in the simulation program that is used in this research. The detectors available in ITS Modeller can give information on for example speed and acceleration of vehicles that run into a loop, but do not detect whether the loop is occupied or not. The loops only detect the vehicle at the moment it first hits the loop. Every time instance after this event, the loop does only take into account new vehicles that hit the loop.

The composition of a controller that detects vehicle asks for a new loop detector that can detect occupation of the detector by a vehicle. The fact that the detector responds to the presence of actual traffic is however not the most important attribute for the functioning of the speed advice for cyclists. A simpler controller that doesn’t need the occupation detectors, but does extend green times gives a clear indication of how a speed advice system would work in combination with an actuated controller program.

The implemented actuated controller is simplified from the actuated controller in real life by giving the signal group a specified number of seconds green time for every cycle. Additional to this green time that is always distributed to the signal group the controller could extend the green period for the signal group by distributing a period of extension green. The maximum extension is defined to limit this additional green extension to a certain level. Figure 4-2 shows an example of the phase for an actuated controller. In the simulation programme the phase exists of 1 second of red time for the traffic light, a fixed green time, the extension green and the yellow time. When the phase is over, the traffic lights belonging to the phase turn red and the next phase will become active.

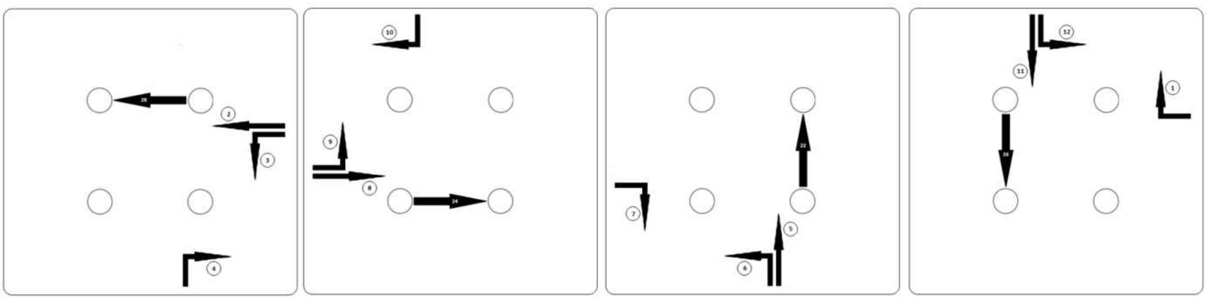
		cycle time (s)		
		min	mean	max
PHASE		1	1	1
	FIXED GREEN	2	2	2
		3	3	3
		4	4	4
		5	5	5
		6	6	6
		7	7	7
	EXTENSION GREEN		8	8
			9	9
			10	10
			11	11
			12	12
				13
				14
				15
				16
				17
		8	13	18
		9	14	19
		10	15	20

Figure 4-2: Example of the composition of a phase for the actuated controller. The example has a fixed time green of 6 seconds and a maximum extension of 10 seconds

The controller only differentiates four different phases in the cycle with four signal groups in it. The structure of the subsequent signal groups is similar to the controller program deducted from VRIGen (used when the fixed time controller was made). Every phase consists of a fixed green phase of 6 seconds and a possible extension of green with a maximum of 10 seconds. The controller divides the different signal groups in different phases, but the signal groups have all equal green and yellow times within the phase it represents. So no differentiation between the different signal groups within a phase is implemented.

Table 4-2: The composition of phase by signal groups

PHASE 1	PHASE 2	PHASE 3	PHASE 4
signal group 2	signal group 8	signal group 5	signal group 1
signal group 3	signal group 9	signal group 6	signal group 11
signal group 4	signal group 10	signal group 7	signal group 12
signal group 28	signal group 24	signal group 22	signal group 26



Future speed advice

The speed advice system based on the future speeds of the cyclist asks for information from the controller. This information should be sent to the system that calculates the advice. Most important is that the variables needed in the Equations on pages 35 to 37 are retrieved from the information that is given from the controller. This means that the controller has to send updates on its state and the number of states to come for the different phase groups in the controller. The sent information can be summarized by:

1. The number of states still to come for the different signal groups. As the controller consists of four signal groups the controller has to send information about the N (states to come) for the controller. This number N is not directly related to the phase in which the controller operates. As the states for the speed advice end when the green times of the phases end. In the controller the phase will change after the yellow light has turned into red. So the information on number N is dependent on the phase of the traffic controller, but also on the time instance within this phase.
2. Duration of the current state is also important for the speed advisor. As the state for the speed advisor deviates from the phase used in the traffic controller in the same way as the N is not directly related to the phase. The duration of the current state is not equal to the total time of a phase minus the time that has already passed in the phase. The end of the green does determine the duration of the current state. The duration of the current phase can therefore be determined by two different equations within one phase. The first will last until the end of green, the other will be active when the traffic light is yellow.
3. Deviation of the current state duration is also important. When the fixed green time has passed the controller can extend the green time. In the period of extension the deviation of the duration of the current state becomes smaller. When the green is extended the possibility that there is no extension is gone and so the number of possible extensions becomes smaller as time passes within the extension green.
4. Duration of the current phase for 0 states to come differs from the duration of the current state. State 0 has a smaller duration then the duration of the phase for higher N's. The state actually has to direct the cyclist towards the green window within the state. This green window appears earlier than the end of the green window. Also should the speed advisor not direct the cyclist to extension green, as it is not certain whether this will appear.

As an example the traffic controller is taken with a fixed green time of 6 seconds and a maximum extension of two seconds. Possibilities for extension of a phase of the traffic controller are possible of 0 or 2 seconds. So the minimum for the duration of a phase is 10 seconds and the maximum 12 seconds. These are also the durations of the states for the speed advice as they are of the same length as the phases in the traffic controller, but shifted within the phases. The duration information of the current phase that is sent to the speed advisor consists of the minimum duration before the next end of a green period is reached. Together with the deviation of this duration the speed advisor can calculate all possible durations simply by adding the deviation of the duration to the minimum duration. As the minimum duration of the state is 10 seconds

		duration		current state				sent information: states to come			
		min	max	N=0	dur.	dev.		PHASE 1	PHASE 2	PHASE 3	PHASE 4
PHASE 1		1	1	1	7	2		0	1	2	3
	FIXED GREEN	2	2	1	6	2		0	1	2	3
		3	3	1	5	2		0	1	2	3
		4	4	1	4	2		0	1	2	3
		5	5	1	3	2		0	1	2	3
		6	6	1	2	2		0	1	2	3
		7	7	1	1	2		0	1	2	3
	EXTENSION GREEN		8	-	0	1		4	1	2	3
			9	-	0	0		4	1	2	3
	YELLOW	8	10	4	10	2		3	0	1	2
		9	11	3	9	2		3	0	1	2
		10	12	2	8	2		3	0	1	2

Figure 4-3: Information sent from controller to speed advice system.

4.2 Actors in ITS Modeller

The interaction of bicycles with the traffic infrastructure and the other road users is captured by the models that describe behaviour. These behavioural models applied in simulation are described in this section. Emphasises is on the bicycle traffic, because this is the mode of transport that is considered in this research and because no models for this specific mode are available in the current simulation model. Bicycle traffic is simulated based on existing car traffic models and models composed for this research.

4.2.1 Combination of models

For the bicycle traffic two different behavioural combinations of models for cyclists are applied. Bike framework 1 with interaction between the cyclists and framework 2 without interaction between the cyclists. Table 4-3 shows the applied models for the different modes in the ITS Modeller. Trucks use the same models as car traffic, but have different parameters. The cycle traffic also has different parameters compared to car traffic (certainly with regard to spacing). The different models are explained in section 4.2.2 and the combination of models and their consequences is discussed in this section.

Table 4-3: Models included in ITS Modeller for accelerations and speeds. The "#" indicates that the different scenarios use different kinds of models for this type. The # refers to the number the specific model has.

	car	bike 1	bike 2	
controller:	all	fixed time		actuated
Free Driving Model	x	x	x	x
Car Following Model	x	x		
Adjacent Lane Speed Model	x			
End of Lane Model	x	x	x	x
Anticipatory Behaviour Model	x	x		
Gap Searching Model	x			
Speed Limit Model	x			
Bike Speed Model		x	x	
Bike Speed Advice Model				x
Traffic Light Brake Model	x	x		
Traffic Light Brake Model for Speed Advice				x
Speed Limit Advice Model		x	x	

Bike framework 1

The models of framework 1 consider the processes in bicycle traffic similar to those of car traffic. In the simulator the Bike Speed Limit Model replaces the Speed Limit Model (for cars). Also the Adjacent Lane Speed Model and Gap Searching Model are abandoned compared to the models used in car traffic.

Observation:

The mutually interactive behaviour makes the cyclists stop behind each other at the traffic light. Queues are moving downstream which causes blockages for the cyclists wanting to turn right. They have to join the queue for the traffic light, meanwhile they don't have to cross the intersection by traffic light. The dedicated bicycle path allows the cyclist to turn right without controlled conflicts (only conflicts with cycle streams appear).

Bike framework 2

The framework without the car following model, doesn't make cyclists wait in line at the stopping line of a traffic light. Without this model cyclists are able to ride through each other. They will stop at the same location at the traffic light and will differentiate their position by their difference in desired speed after the light has turned yellow.

Observation:

Although the representation of cyclists riding through each other is not what happens in reality, abandoning the car following model takes into account that cyclists are not neatly standing in line for a traffic light as cars do. Actually they are finding a place to stand still according to the available space on the road surface, letting cyclists pass that turn right and therefore don't have to stop at the intersection. This can be seen as a mix of the two mentioned frameworks of models for cyclists.

4.2.2 Models

The models that are represented in the frameworks for behaviour are separately discussed in this section. The models that are not changed for this research are briefly discussed and the models that are set up specifically for this research are discussed more comprehensive.

- *Free Driving Model*

This is the model that controls the speed of the actor, when no actors are in front. It will accelerate the driver to the highest speed possible. The highest speed possible is in most cases limited by the speed limit of the road section. The Free Driving Model makes sure the actor accelerates towards this speed limit.

- *Car Following Model*

This model guarantees that the actor travels with a desired distance to the actor in front. The model takes into account the current distance to this vehicle and the speed compared to his predecessor. When needed the actor will accelerate to abide to the desired distance.

- *Adjacent Lane Speed Model*

This model determines the acceleration of an actor needed to keep an accepted speed difference with respect to the speed on the lane left of the actor. This model makes sure the actors are not overtaking each other on the right hand side.

- *End of Lane Model*

This model controls the braking behaviour of an actor when the actor approaches the end of a lane. In the network of a single intersection no end of roads exist. The model is defined for on-ramps or a drop of a lane. This is not the case for the used network.

- *Anticipatory Behaviour Model*

The anticipatory behaviour model controls the distance gap and speed difference with the respect to the expected lane change of actors in front.

- *Gap Searching Model*

This model searches for an available gap and then adjusts the speed of the car, so the car can smoothly manoeuvre in the gap of his preference.

- *Speed Limit Model*

The speed limit model will take the minimum of the speed limit of the road and the maximum actor speed to find the desired speed. However implementation of a Dynamic Speed Limit cannot be implemented in a nice way. Therefore some additional code for cyclists is written to the Speed Limit Model, resulting in the Bike Speed Model.

- *Bike Speed Model*

A maximum actor speed for the cyclist is added to the model. For every class of cyclists this maximum actor speed can be differentiated, but within the class the maximum actor speed is random generated according to a uniform distribution. The minimum and maximum speed of this distribution can be chosen by the user of the model. The random generator of the ITS Modeller returns a random number between zero and one. To generate a desired speed for every cyclist the desired speed determined by a function of the random generator and the specified minimum and maximum speed:

$$v_{\mathrm{des}} = v_{\mathrm{min}} + \mathrm{rand}(0,1) * (v_{\mathrm{max}} - v_{\mathrm{min}}) \qquad \textbf{(4.1)}$$

The existing speed limit model will ensure that the actor is influenced by the speed limit. As for car traffic the speed limit is the base of the desired speed of the actor. The deviation from the speed limit by the actor is taken into account, when a new speed limit is given by a Dynamic Speed Limit Sign. This is done by the deviation factor, that is the speed of an actor divided by the prevailing speed limit of the road section:

$$d = \frac{v}{v_{\mathrm{lim;r}}} \qquad \textbf{(4.2)}$$

This factor accounts for the individual behaviour of actors. When a dynamic speed limit sign is ahead, cars will accelerate or decelerate to a new desired speed, determined by:

$$v_{\mathrm{des}} = d * v_{\mathrm{lim;d}} \qquad \textbf{(4.3)}$$

For cyclists the deviation factor is very low, because of the implemented speed limit on the bicycle paths of 50 km/h. Some of the cyclists travel with a speed of 10 km/h and therefore will have:

$$d = \frac{10\ km/h}{50\ km/h} = {}^{1}/_{5} \tag{4.4}$$

Meaning the cyclist will choose to ride with a speed that is only 20% of the given dynamic speed advice. To use the dynamic speed advice signs for a speed advice, the Bike Speed Limit Model has to be adjusted to cope with this event. This is solved by getting rid of the deviation factor and simply use the dynamic speed advice as a measure for the desired speed.

The bicyclist has to adjust to the advice speed no matter what his desired speed initially is. No minimization between the dynamic speed advice and the maximum actor speed is present in the new Bike Speed Model.

- *Bike Speed Advice Model for Actuated Controller*

The implementation of the advice system that takes into account the future states of the controller and the corresponding speed advices, has to make different calculations than the methods used for the speed advice that is used in the actor models above. The Bike Speed Limit Model 3 only works when it is implemented together with the Traffic Light Braking Model 2, as this model writes the remaining distance to the traffic light in the code so other models can use the information.

To implement a speed advice that is different from the random distributed desired speed, the actor must have a remaining distance from Traffic Light Braking Model 2. When it does not have a remaining distance written from this model, the vehicle doesn't have a traffic light on his route to the destination. It is therefore useless to give a speed advice that reduces the probability of having to stop at a traffic light.

Also when the actor has already passed a traffic light, no speed advice is given. Actors that have to pass several traffic lights in the network are cyclists that turn left on the intersection. These cyclists have a small distance from the first traffic light to the second traffic light. There is no point in adjusting the speed of the cyclist for a traffic light on such a short distance from the traffic light. The cases in which the Bike Speed Limit Model will not give a speed advice, the cyclist cruises with his own preferred speed, which is the randomly distributed cycle speed as introduced in the "Bike Speed Limit Model".

The criteria for giving a speed advice makes sure that cyclist that do not benefit from a speed advice will not get a speed advice. The "*Speedadvice*"-parameter is introduced to exclude cyclists that already passed a traffic light from the group of actors that is given a speed advice. Furthermore the availability of a "*distanceLight"* parameter retrieved from the Traffic Light Braking Model 2 is necessary to give a speed advice. Cyclists that do not have such a distance in their context are either not en route to a traffic light (bicyclists that turn right) or do not have the traffic light within the view distance that is defined in the Traffic Light Braking Model. The view distance in this model is set at 1000 meter. So the whole roadway ahead of the traffic light in the used network is taken into account for the speed advice. Success of giving a speed advice at big distances is however dependent on the number of cycles that are evaluated in the speed advice. When the bicycle is within five meters of the traffic light, no speed advice is given as the traffic light braking model will overrule the desired speed generated by the Bike Speed Limit Model 3.

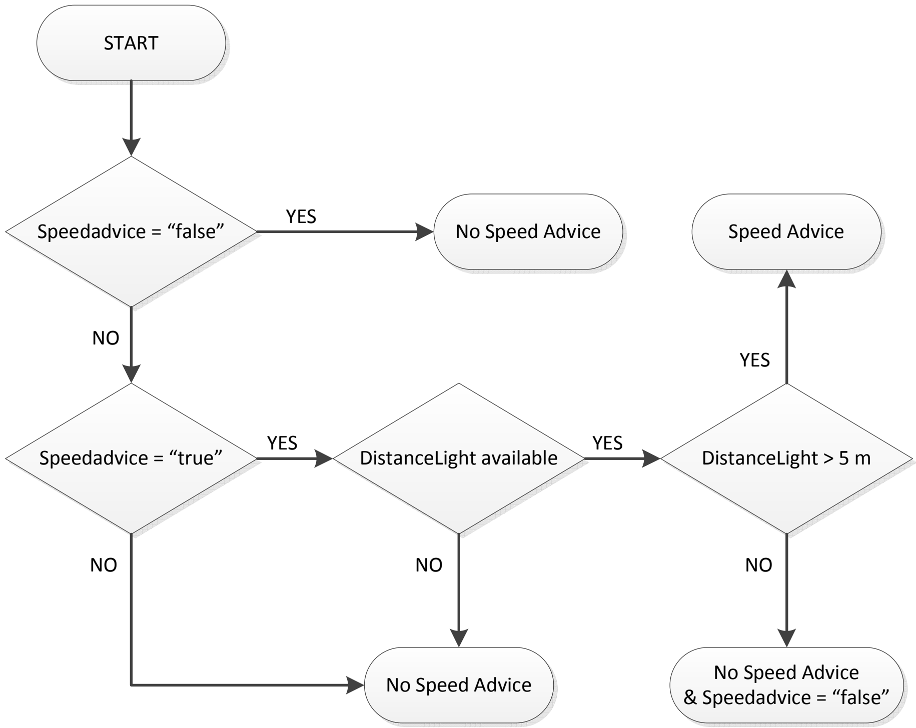


Figure 4-4: Decision tree including conditions for the calculation of a speed advice. Speedadvice is a parameter that indicates whether a speed advice could be given. The Speed Advice is the existence of a speed advice. In the figure this is indicated with "Speed Advice" or "No Speed Advice". The Distance to Light parameter indicates the distance from the actor to the next traffic light.

When all conditions to give a speed advice are met, the Bike Speed Limit Model will run through a number of calculation steps dependent on the state of the traffic light in combination with the phase in which the traffic light the cyclist is heading to turns green. This information will be delivered by the traffic controller. It consists of the number of states that are to come before the traffic light turns green and the duration of the current phase and. Other parameters as the duration of fixed time green and the duration and possible deviation of the different states of the traffic light are defined in the Bike Speed Limit Model itself as these parameters do not change over time.

Calculations of the speed advice are equal to the equations in section 3.3.2 and the decision tree of Figure 3-23. However the number of calculations is limited to keep the simulation times within bounds. The speed advice is only changed every second the cyclist is in the network and not with the simulation step frequency of 0,1 seconds. Furthermore the scores belonging to the distances of the separate states are calculated once and written in the context of the individual cyclist. These scores differ dependent on the desired speed of every cyclist, but do not differ over time. Only the score belonging to the current speed advice has to be calculated every time step an advice is given.

- *Traffic Light Braking Model*

The Traffic Light Braking Model makes sure the actors brake when they are approaching a red traffic light. The model consists of variables that determine the distance they keep from the traffic light and the distance at which they start to brake for the traffic light. The car traffic will stop at a greater distance from the traffic light than the bicycle traffic.

- *Traffic Light Braking Model for Speed Advice*

Traffic Light Braking Model 2 is an extension of the Traffic Light Braking Model, which not only takes care of the braking for traffic lights on the route of an actor, but also returns the remaining distance to the context of the cyclist. This remaining distance to the traffic light could be used when applying an in-vehicle speed advisor. For this advisor the remaining distance must be received per actor as no fixed distance to the traffic light is applicable.

- *Speed Limit Advice Model*

This model simply provides the advice from a Dynamic Speed Limit Sign to the actor. When this model is not turned on the Bike Speed Limit Model will not take into account the Dynamic Speed Limit, which is used to give a speed advice as shown in the next section. Parameters that can be influenced are the view distance, the update interval and the delay time.

4.3 Dynamic speed limit controller

The dynamic speed limit controller is a type of roadside equipment that normally gives information about the prevailing speed limit on a road stretch via a sign. The actor has to adjust its speed to the speed that is given by this sign. In this research the speed limit controller is used to give a speed advice. The cyclist is not given a speed limit, but an advice speed by the roadside sign. For this research this type of speed advice is used in combination with a fixed time controller.

No information from the controller has to be sent to make the equipment operational, as the green light realization of the fixed time controller is directly related to the simulation time. The calculations for the roadside equipment can be related to the simulation time too in order to avoid a data structure that allows the data transfer from controller to speed limit controller. In this section the additional formulas to relate the variables in simulation to the variables in the mathematical framework from Chapter 3 are discussed.

Initial variables in simulation for speed advice:

- $t_{\mathrm{bg}} = \text{begin green time (s)}$
- $t_{\mathrm{eg}} = \text{end green time (s)}$
- $t = \text{time (s)}$

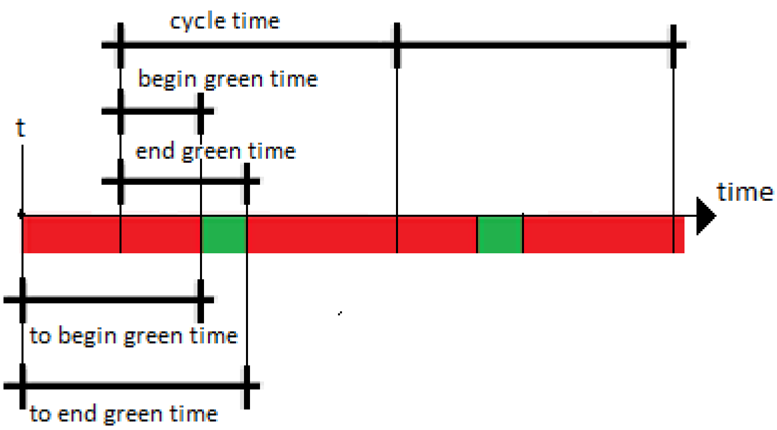


Figure 4-5: Graphical representation of variables

First of all the current simulation time is operated in a way that we know at which moment we are in the cycle. When dividing the current time by the cycle time we know in which cycle we are, but we still don't know in what part of the cycle we are. The remainder of this division determines at which phase of the cycle we are, which leads to the position in the controller program. The time within the cycle is calculated by:

$$t = n * t_{\mathrm{c}} + t_{\mathrm{wc}} \tag{4.5}$$

$$t_{\mathrm{wc}}(t) = t - n * t_{\mathrm{c}} \tag{4.6}$$

Equations 4.5 and 4.6, have value n that is the maximum integer number with which $t_{\mathrm{wc}}(t)$ is positive. In programming this easily done by introducing the modulo (%). With this operation .2 can be written as:

$$t_{\mathrm{wc}}(t) = t \,\%\, t_{\mathrm{c}} \tag{4.7}$$

The speed advice should direct cyclist to the green phase, but still then a spread of advices for one green phase is possible. Cyclists could be directed to the beginning of the green phase, the end of the green phase or any other moment of the green phase. However minimum and maximum speeds to reach a green phase are most important for the operating system. These minimum and maximum speeds are reached when directing cyclist towards the end and beginning of the green phase. Remaining time until the beginning of the green phase (t_{tbg}) and the end of the green phase (t_{teg}) are:

$$t_{\mathrm{tbg}}(t) = t_{\mathrm{bg}} - t_{\mathrm{wc}}(t) \tag{4.8}$$

$$t_{\mathrm{teg}}(t) = t_{\mathrm{eg}} - t_{\mathrm{wc}}(t) \tag{4.9}$$

Now the equations (3.3 and 3.4) described in the Mathematical Framework can be used to come to the speeds possible to arrive at the intersection with a green phase. These formulas can be rewritten with only initial variables of this chapter to:

$$v_{\mathrm{tbg}}^{n}(t) = \frac{d}{t_{\mathrm{bg}} - t_{\mathrm{wc}}(t) + n * t_{\mathrm{c}}} = \frac{d}{t_{\mathrm{bg}} - {}_{t_{\mathrm{c}}}remainder(t) + n * t_{\mathrm{c}}} \tag{4.10}$$

$$v_{\mathrm{teg}}^{n}(t) = \frac{d}{t_{\mathrm{eg}} - t_{\mathrm{wc}} + n * t_{\mathrm{c}}} = \frac{d}{t_{\mathrm{eg}} - {}_{t_{\mathrm{c}}}remainder(t) + n * t_{\mathrm{c}}} \tag{4.11}$$

Speed advisor in one location

In the first PDCA-cycle of this research only a simplified version of the bicycle behaviour is represented in simulation. Therefore the cyclist always adjusts his speed to the advised speed, when it passes a zone in which speed advice is given.

The speed advice is given to the cyclist via a Dynamic Speed Limit Sign. This sign gives the speed limit for a certain road stretch, based on whatever parameter you want it to cope with. In the case of our speed advice, we use the formulas from the previous chapters to implement the correct speed advice, see Equations (4.7) and (4.8).

Now we have to speeds for every green phase from the current cycle until n^{th} cycle in the future. The Dynamic Speed Limit Sign has to check whether these green wave speeds are within the boundaries and are useful for the cyclist, so one speed can be used and will appear on the speed limit sign. This procedure happens as described in Figure 3-10 and doesn't contain any differences in calculation in this decision tree.

5 Simulation set up

In this chapter the properties of the simulations are shown. After this the network composition is presented and the chapter ends with a description of the performance indicators of the simulation, to give the reader some understanding of the way the speed advice systems are tested.

5.1 Network composition

The network consists of an intersection regulated with traffic lights, but also has the roadways and bicycle paths that lead to the intersection within its boundaries. This roadway sections are the approach of the traffic light for the cyclist and the place where the advice should be given. The bicycle paths are all one way roads, even on the intersection itself. This means that bicycles on the intersection that have to make a left turn can only do this by traveling on the right hand side of the intersection.

For the network a full standard intersection is chosen with signal groups from 1 to 12 for car traffic and dedicated one way bicycle paths along the roadways (see Figure 5-1) with flows as given in Table 5-1 . With the given flows a roundabout's capacity is not big enough to cope with the demand of traffic. This is tested in order to exclude the solution of this other intersection form (see Appendix B). Also turbo-roundabouts are tested in the Meerstrooksrotondeverkenner (Provincie Zuid-Holland, 2008).

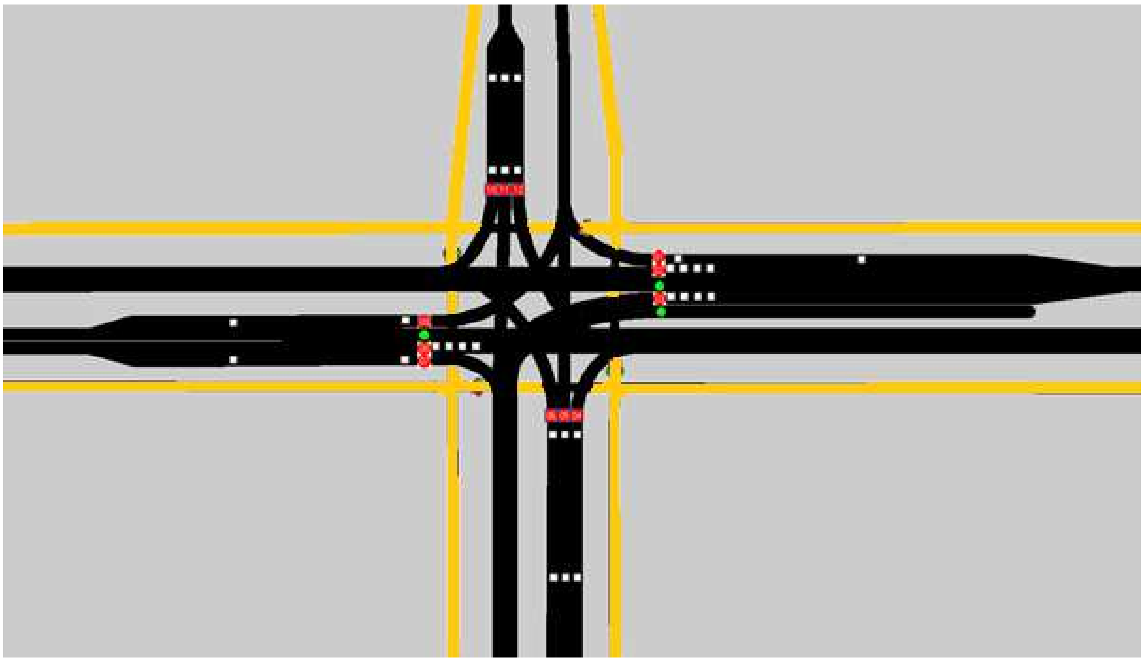


Figure 5-1: Intersection with bicycle paths in orange

Table 5-1: Flows per signal group

Signal group	Flow (veh/h)	Signal group	Flow (veh/h)	Signal group	Flow (veh/h)
1	220	**7**	440	**22**	600
2	660	**8**	660	**24**	600
3	440	**9**	220	**26**	600
4	220	**10**	200	**28**	600
5	220	**11**	200		
6	220	**12**	200		

The simulation duration is set at an hour. In this hour the vehicles belonging to the OD-pairs are put into simulation. In order to make sure the vehicles have left the simulation before it ends, the simulation will run an additional ten minutes before the simulation is stopped. In this way the data doesn't contain vehicles that started their trip but never reached their destination in the network. On the other hand the data does contain vehicles that started their trip when the network was not yet fully loaded. However when the cyclists do not have a car following behaviour in their models, there will be hardly differences in the observed data for a fully loaded network and an empty network.

To reduce a big effect of randomness on the simulation results, the simulation scenarios are performed in 10 runs with different random seeds. Both the controller randomness that determines the extension of the green phases for the actuated controller as the distribution of vehicles in the network are dependent on the chosen random seed.

5.2 Performance indicators

Looking at the simulation and ascertain what happens by observation is not a very quantitative measure of reassuring that there are differences between simulated scenarios. 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 tells the most about the scenarios in relation with the questions that needs to be solved in the research. This section of the Simulation Chapter will give insight in the used performance indicators. There are three performance indicators tested: the fraction of stopped vehicles, the average speed and the travel time of the actors. The first of these performance indicator is related to the design objective of this research and will therefore have the highest weight in the results of the simulation. The other two indicate whether the speed advice system also will cause reductions in travel time and are somewhat related to each other. This three performance indicators mentioned in this section are calculated for the separate OD-pairs for cyclists that are present at the intersection. The simulation results will therefore consist of twelve times three indicators per simulation scenario.

Fraction of stopped vehicles

The number of stops indicates the efficiency of the speed advisor. As the intention of implementing the speed advisor is supposed to reduce the number of stops for the cyclist, the performance of the system is highly determined by the reduction in number of stops. It is the main indicator for the performance of the speed advice system.

For every vehicle from the simulation the lowest recorded speed is determined. If this speed is lower than 1 m/s the vehicle is classified as a vehicle that had to make a stop during the simulation. As the network doesn't consist of any other infrastructural irregularities than the intersection. A stop is most likely made because the cyclist was confronted with a red light on his trip. For every OD-pair the fraction of stopped vehicles is divided by the total number of vehicles. This percentage is used as indicator for the fraction of stopped vehicles.

This indicator does indicate the fraction of stopped vehicles, but does not give information on the number of stops made by these vehicles. In this research the fraction of stopped vehicles is an adequate indicator for the number of stops as the traffic at maximum passes one intersection with traffic lights. Cyclists moving straight forward are confronted with one traffic light and left turning cyclists with two traffic lights. The only thing that is not adequately incorporated in the indicator is the reduced number of stops by left turning traffic. Reduction of stops at the first traffic light could be reached by implementing the speed advisor, but reduction of stops for the second light are dependent on the sequence structure of the controller program. The controller has to accommodate the left turns in order to see result of the speed advice in the chosen indicator for stops.

Average speed

The average speed of an OD-pair gives an indication on the gain or loss in speed due to a speed advisor. The speed advice is a direct interfering or influencing factor for the speed of the cyclist. A change in the speed of actors that deal with the speed advice is therefore expected .The average speed is taken by averaging the speed of each actor that has been put into the model. The average speed for the OD-pair is determined by the summation of the average speeds per bicycle divided by the number of vehicles that appeared within this set of vehicles.

$$\bar{v} = \frac{\sum \frac{\sum v}{n_{\mathrm{t}}}}{n_{\mathrm{v}}} \tag{19.0}$$

with $v = \text{speed}$
$n_{\mathrm{t}} = \text{number of timesteps}$
$n_{\mathrm{v}} = \text{number of vehicles}$
$\bar{v} = \text{average speed}$

Travel time

The travel time indicates the time vehicles have spent in the network. When travelling, people tend to like a fast route from their origin to their destination. The time lost in traffic could have been used for activities that have more value for a person. The travel time is determined by the difference between the time the actor enters the simulation and the moment it leaves the network. For every OD-pair the travel time is averaged over the actors. The travel time is for every cyclist is dependent on the attributed desired speed of the cyclist and the speed advice he receives.

6 Simulation results

Then for each scenarios the properties of the performed simulation are discussed first, after which the results are show in a table. This results will be accompanied by some interpretation of the results and highlights the most striking outcomes. All traffic streams are labelled according to the traffic streams with the same origin and destination for car traffic at an intersection.

6.1 Results of fixed time controller

The results in the fixed time controller simulations have been an indication to optimize the simulation network and the properties for the bicycle behaviour, but also . There have been two types of simulations for this type of controller. In the first the simulations were run with car following behaviour for cyclists, later on the results of the simulation without car following behaviour is shown.

Fixed time controller with car following

The first results from simulation show that the fraction of stopped cyclists is reduced by the speed advice. This indicates the potential of a speed advice for cyclists, with the circumstances of the given intersection and preconditions for the speed advice system. The speed advice is presented to the cyclists at the location that at least always will confront them with a speed advice and the behaviour of cyclists will make them adjust their speed to the advised speed.

Table 6-1: Simulation properties for fixed time controller

Property	
Traffic controller	Fixed time traffic controller
Bike framework	Bike with car following
Speed advice	“Maximize speed” for signal groups 1-9

Reductions of 10-20% in the fraction of stopped cyclists are detected for traffic that does not change directions at the intersection. For the right turning traffic that doesn’t have to cross any lanes at the intersection, the travel times will slightly worsen. This is caused by the bicycles riding towards the traffic light with a speed advice. They are forming platoons, which hinder the bike riders that want to cruise through the network with their own preferred speed higher than the speed of the platoon. Overtaking manoeuvres to keep riding with the preferred speed are difficult to make, if even possible within the platoons. The percentage of stops is not zero for right turning traffic although these cyclists do not have to wait for traffic lights. The existence of stops for these cyclists is a consequence of the queues that form at the traffic lights when it is in a red phase. The queuing spills back to the section of the bicycle path where cyclists must ride whether they turn left, right or go straight ahead. This results in queuing for right turning cyclists that don’t have to wait for the traffic light. Left turners have a smaller reduction in the fraction of stopped vehicle, because they are restricted by the sequence structure of the traffic controller. The reduction of stops at the first traffic light by the speed advice will be wiped out by the stop the left turner has to make at the second traffic light. The results in fraction of stopped vehicles are therefore worse than that for cyclists going straight ahead and shows reductions from 0-10%.

Table 6-2: Results simulation for fixed time traffic controller with and without speed advice system (car following)

	without speed advice			with speed advice			difference		
	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)	speed (%)	% stop	travel time (s)
stream 1	5,41	3,17%	259,5	5,19	6,50%	265,8	-4,03%	3,33%	6,3
stream 2	**4,93**	**85,20%**	**325,7**	**4,99**	**63,04%**	**320,4**	**1,35%**	**-22,16%**	**-5,3**
stream 3	4,27	99,85%	275,3	4,4	97,88%	266,1	3,10%	-1,97%	-9,3
stream 4	5,53	6,81%	258,8	5,32	8,85%	260,2	-3,94%	2,04%	1,5
stream 5	**4,95**	**82,10%**	**229,8**	**5,04**	**72,68%**	**224,7**	**1,72%**	**-9,42%**	**-5,1**
stream 6	4,64	99,49%	246,7	4,79	99,39%	245,7	3,07%	-0,10%	-1
stream 7	5,48	3,25%	284,9	5,22	4,13%	289,8	-4,65%	0,88%	4,9
stream 8	**5,01**	**84,91%**	**328,7**	**5,06**	**63,77%**	**320,1**	**1,09%**	**-21,14%**	**-8,6**
stream 9	4,75	90,96%	278,9	4,88	81,60%	267,9	2,77%	-9,37%	-10,9
stream 10	5,42	3,53%	280,5	5,39	4,62%	280,6	-0,54%	1,08%	0,1
stream 11	**4,76**	**87,18%**	**231,2**	**4,77**	**86,95%**	**231,7**	**0,20%**	**-0,24%**	**0,5**
stream 12	4,42	99,44%	229,4	4,42	99,85%	235,0	-0,02%	0,41%	5,6

The indicators show a positive trend in the performance indicators for the cyclist that are influenced by the speed advice. However the reduction of stopped cyclists is not as big as expected. When a cyclist is able to take over every speed advice given by a speed advice system, one expects that all cyclists should catch a green light. However the results show something else. Processes of traffic interacting with each other may reduce the effect of the speed advice. Whether these processes are a big influence is tested by a simulation that does not take into account car following processes. The low reduction of stopped cyclists could also be attributed to the acceleration phase of a cyclist. The speed advice is given assuming the cyclist will ride at this speed from the location this advice is given. Cyclists that arrive at this location however have a speed that differs from the speed advice. The acceleration period of the cyclist makes him deviate from the speed advice for a short period of time. This could have led to a different speed advice for the rest of the route to the traffic light.

Fixed time controller without car following

The second configuration for the fixed time controller is implemented to see what consequences the car following model has for the functioning of the speed advice system as described for the fixed time controller. Therefore the bike framework is changed in this simulation.

Table 6-3: Simulation properties for comparison of fixed time controller

Comparison	without speed advice	with speed advice
Traffic controller	Fixed time traffic controller	
Bike framework	Bike without car following	
Speed advice	Option 1 for signal groups 1-9	

Table 6-4: Results simulation for fixed time traffic controller with and without speed advice system (no car following)

	without speed advice			with speed advice			difference		
	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)
stream 1	5,72	0,00%	249,3	5,56	0,00%	249,1	-2,75%	0,00%	-0,2
stream 2	**5,34**	**81,52%**	**342,8**	**5,46**	**53,74%**	**328,2**	**2,27%**	**-27,78%**	**-14,5**
stream 3	4,59	100,00%	334,0	4,64	99,72%	322,7	1,08%	-0,28%	-11,3
stream 4	6,11	0,00%	240,7	5,67	0,00%	247,9	-7,22%	0,00%	7,2
stream 5	**5,39**	**78,51%**	**234,6**	**5,46**	**68,96%**	**225,7**	**1,28%**	**-9,55%**	**-8,9**
stream 6	5,06	100,00%	328,9	5,11	99,57%	316,0	0,98%	-0,43%	-12,8
stream 7	5,71	0,00%	275,2	5,54	0,00%	276,3	-2,96%	0,00%	1,1
stream 8	**5,30**	**80,28%**	**344,1**	**5,42**	**57,32%**	**328,8**	**2,24%**	**-22,96%**	**-15,3**
stream 9	5,17	94,21%	314,8	5,28	96,13%	300,4	2,04%	1,91%	-14,4
stream 10	5,77	0,00%	270,4	5,76	0,00%	268,5	-0,26%	0,00%	-1,9
stream 11	**5,20**	**83,79%**	**241,7**	**5,23**	**83,46%**	**240,6**	**0,58%**	**-0,34%**	**-1,1**
stream 12	4,86	100,00%	305,5	4,83	99,37%	308,6	-0,61%	-0,63%	3,1

Reductions in fraction of stopped cyclists of 20-30% are realized compared to the situation without a speed advice for cyclists going straight ahead. This number is comparable with the outcomes of the simulation with car following. For the right turning traffic the number of stops is reduced to zero. This is a more logical number as we expect cyclists that aren't confronted with a traffic light not to make stops at the intersection.

The only direction that should profit from the speed advice but has a bigger number of stops compared to the situation with a car following model is stream 9. It is possible for these cyclists to ride the intersection without a stop, because the sequence of the traffic controller has the second traffic light that the cyclist has to pass right after the first traffic light to be passed. The absence of car following probably causes a faster approach of the second traffic light which forces the cyclists on stream 9 to stop at the second traffic light before regaining their speed.

6.2 Results of actuated controller

Before the results of the simulation for the actuated controller are presented a short recap of the simulation properties is discussed here. The implementation of the future state speed advice system concentrates the cyclists at the beginning and ending of the green times of the traffic lights. The used actuated controller consists of a controller that has a fixed time green of six seconds, an maximum extension of one second at most and a yellow time of three seconds. The speed advice system in the simulation scenarios is on board of the bicycle and will decide on the advice speed based on the score function. It takes into account the next two cycles of the controller program. So the cyclist will ride at his desired speed as long as he does not have a distance to the traffic light that produces a speed between 1-30 km/h with which a green light is caught. The actor following models are no longer used based on the findings of the simulation with the fixed time controller. All bicycle streams in the network will be influenced by the speed advice. Table 6-5 shows the properties of the simulation with the actuated controller and the designed speed advice system for the actuated controller.

Table 6-5: Simulation properties for comparisond of actuated controller

Comparison	
Traffic controller	Actuated traffic controller (green 6-1)
Bike framework	Bike without car following
Speed advice	Score function

Green bonus of 10

The green bonus in the speed advice system for the actuated controller can be chosen according to the trade-off that exists between the deviation of the desired speed of the cyclist and the value of catching the green light. For the simulation different green bonuses are chosen to investigate the effect of the green bonus for the results of the system. The results for the simulation with a green bonus of γ=10 are given in Table 6-6.

Table 6-6: Results simulation for actuated traffic controller with and without speed advice system with green bonus = 10

	without speed advice			**with speed advice**			**difference**		
	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)
stream 1	5,76	0,00%	249,3	5,77	0,00%	249,3	0,07%	0,00%	0,0
stream 2	**5,40**	**80,24%**	**341,3**	**5,42**	**76,35%**	**339,7**	**0,38%**	**-3,90%**	**-1,6**
stream 3	4,86	100,00%	314,7	4,89	100,00%	314,6	0,37%	0,00%	-0,1
stream 4	5,95	0,00%	245,1	6,25	0,00%	233,6	5,07%	0,00%	-11,5
stream 5	**5,42**	**82,65%**	**233,4**	**5,70**	**76,79%**	**222,0**	**5,07%**	**-5,86%**	**-11,4**
stream 6	5,21	100,00%	316,8	5,37	99,86%	307,5	3,01%	-0,14%	-9,3
stream 7	5,76	0,00%	275,2	5,77	0,00%	275,2	0,08%	0,00%	0,0
stream 8	**5,42**	**80,17%**	**340,3**	**5,45**	**76,64%**	**339,0**	**0,48%**	**-3,52%**	**-1,3**
stream 9	5,36	87,33%	306,4	5,37	84,54%	305,6	0,21%	-2,79%	-0,7
stream 10	5,68	0,00%	269,8	5,68	0,00%	269,8	0,07%	0,00%	0,0
stream 11	**5,26**	**80,31%**	**237,5**	**5,30**	**77,53%**	**236,5**	**0,70%**	**-2,78%**	**-1,1**
stream 12	5,02	100,00%	298,9	5,02	100,00%	298,8	0,09%	0,00%	-0,1

For this relatively small value of the green bonus already gains in the fraction of stopped cyclists are present. The number of stops for the streams going straight ahead at the intersection the fraction of stopped cyclist is reduced by 2,78% to 5,86%. The gains in travel time and speed are present, but are very small. Remarkable is that the speeds of the streams 4 to 6 are all have a much bigger increase in speed than the other streams. This cannot be explained as the speed advice should have the same consequence for all streams.

Figure 6-1 again shows the reduction in the fraction of stopped cyclists graphically per traffic stream in the network. The only traffic streams affected by the speed advice system are again the cyclists going straight ahead and the left turners on stream 9. This is in accordance with the results of the fixed time controller.

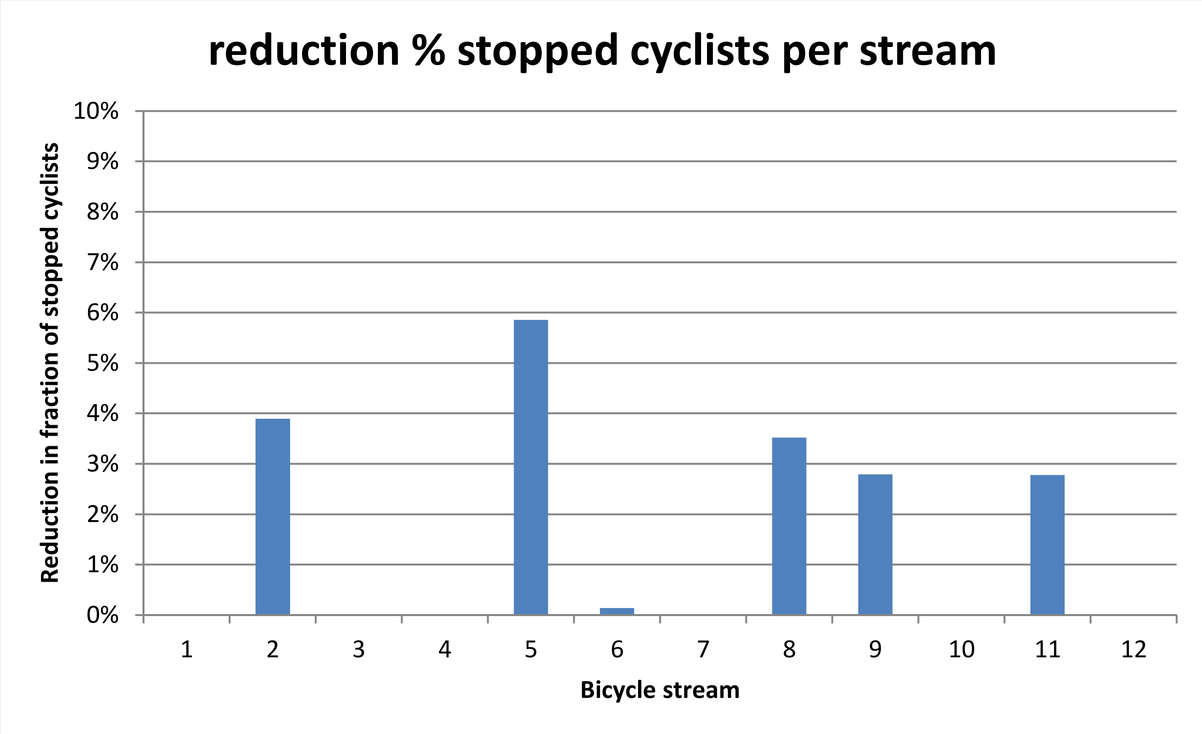


Figure 6-1: Reduction in fraction of stopped cyclists for actuated controller with speed advice (green bonus = 10)

Green bonus = 100

To see what the effect of a higher green bonus means, the next simulation has an increment of the green bonus to 100. Catching the green light has a bigger positive effect than the situation with a green bonus of 10. Consequently the cyclists should be directed more towards the green period of the traffic light. So Expected is that the number of stops for the cyclists that have to pass a traffic light will decline in comparison with the speed advisor that has a green bonus of 10. The results of the simulation with a green bonus of 100 are shown in Table 6-7.

Table 6-7: Results simulation for actuated traffic controller with and without speed advice system with green bonus = 100

	without speed advice			with speed advice			difference		
	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)	speed (m/s)	% stop	travel time (s)
stream 1	5,76	0,00%	249,3	5,77	0,00%	249,3	0,07%	0,00%	0,0
stream 2	**5,40**	**80,24%**	**341,3**	**5,50**	**58,22%**	**334,4**	**1,83%**	**-22,02%**	**-6,9**
stream 3	4,86	100,00%	314,7	4,95	100,00%	310,0	1,81%	0,00%	-4,7
stream 4	5,95	0,00%	245,1	6,25	0,00%	233,6	5,07%	0,00%	-11,5
stream 5	**5,42**	**82,65%**	**233,4**	**5,78**	**60,61%**	**218,8**	**6,56%**	**-22,04%**	**-14,7**
stream 6	5,21	100,00%	316,8	5,41	99,86%	304,8	3,78%	-0,14%	-12,1
stream 7	5,76	0,00%	275,2	5,77	0,00%	275,2	0,08%	0,00%	0,0
stream 8	**5,42**	**80,17%**	**340,3**	**5,54**	**56,28%**	**333,3**	**2,13%**	**-23,89%**	**-7,0**
stream 9	5,36	87,33%	306,4	5,45	74,31%	301,4	1,77%	-13,02%	-5,0
stream 10	5,68	0,00%	269,8	5,68	0,00%	269,7	0,07%	0,00%	0,0
stream 11	**5,26**	**80,31%**	**237,5**	**5,40**	**60,83%**	**232,0**	**2,51%**	**-19,48%**	**-5,5**
stream 12	5,02	100,00%	298,9	5,09	99,86%	294,7	1,46%	-0,14%	-4,2

The results show that the fraction of stopped cyclists going straight ahead is again reduced, but now by around 20% compared to the 5% reduction in the situation with a green bonus of 10. Also speeds have become higher and travel times smaller. Still for the travel times of the streams 4 to 6 holds that the speed advice has a bigger positive impact on the speed and travel time than for the other bicycle streams on the intersection. The reduction in fraction of stopped cyclists are shown in Figure 6-2. Only the traffic streams going straight ahead and the coupled left-turning stream 9 face reductions in the fraction of stopped cyclists, which is in line with the previous simulation results.

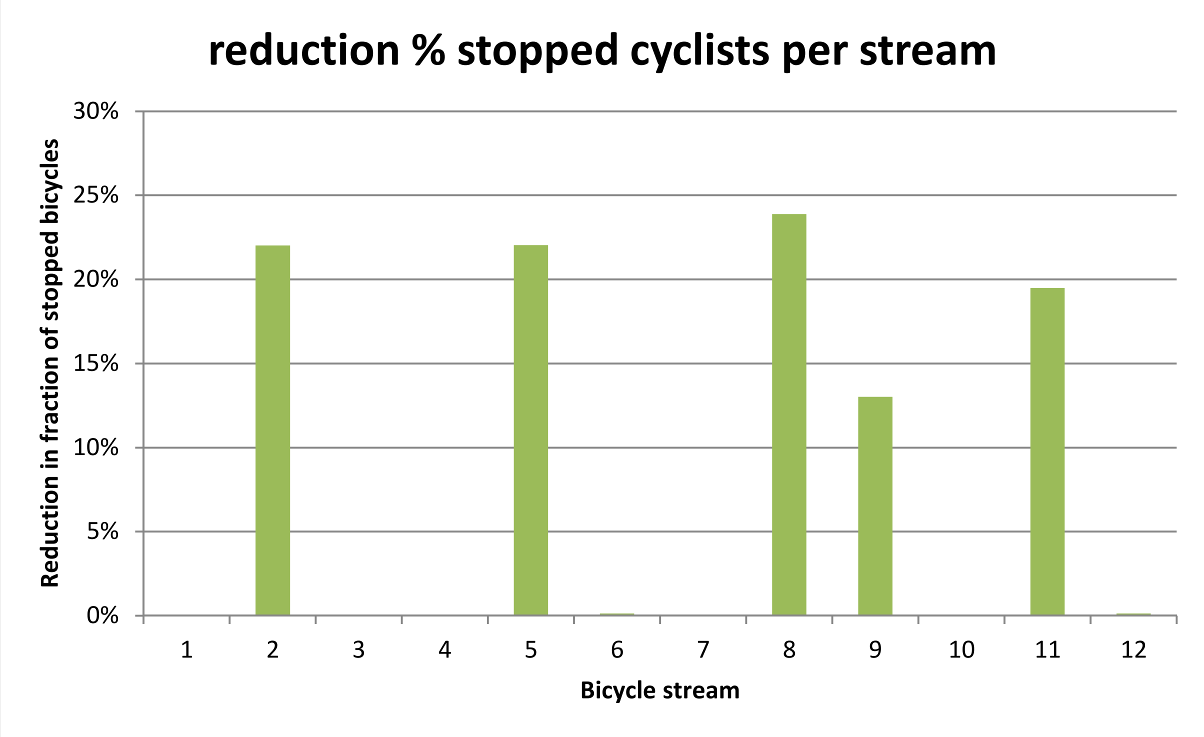


Figure 6-2: Reduction in fraction of stopped cyclists for actuated controller with speed advice (green bonus = 100)

Sensitivity of green bonus

From the results gathered by the simulation of the scenarios with a green bonus 0f 10 and 100, a positive trend in the performance of the system concerning the fraction of stopped cyclists is noted. The green bonus is thus an important parameter in the determination of success for the speed advice system. A closer look at simulations with a wider range of green bonuses will give more information on how performances will improve with an increasing value for the green bonus. Although there are no clear indications what the value of the green bonus should be, results of these different green bonuses could indicate the expected gains at the moment a realistic green bonus is known. Results in terms of number of stops for the streams 2, 5, 8 and 11 can be found in Figure 6-3. The full tables with result of the separate streams per simulation can be found in Appendix C.

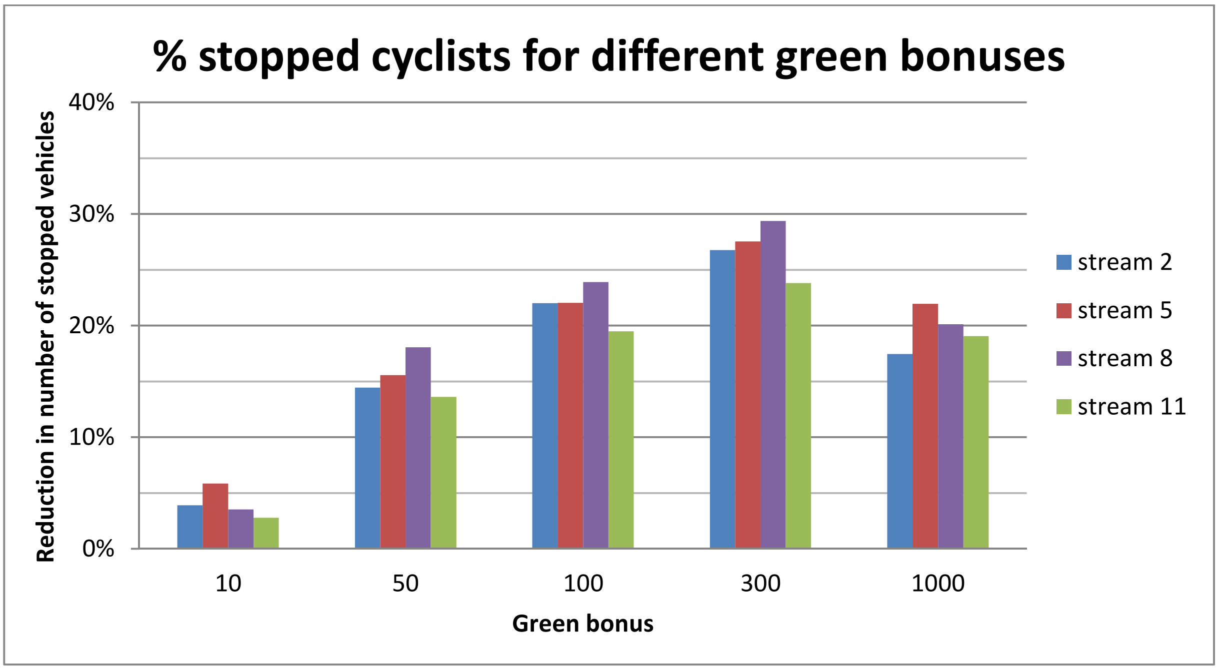


Figure 6-3: Reduction in fraction of stopped cyclists for the streams 2, 5, 8 and 11 with different green bonuses in the speed advice.

From the results of the simulations the expected trend of an increasing reduction of stopped cyclists when the green bonus grows is confirmed by the data until the green bonus of 300. The simulation with a green bonus of 1000 however breaks with this trend. The reduction of stopped cyclists is smaller than that of the speed advice with a green bonus of 300 and even slightly smaller than for the simulation with a green bonus that is ten times smaller.

This decline in performance was not expected for the speed advice system with a higher green bonuses, a level-off of the realized reduction was anticipated. There probably would be a limit to the reduction of stopped cyclists, because the maximum number of stops is restricted to the number of cyclists that previously (without speed advice) did not stop for the traffic light. For the scenario tested this limit is at 80,8%. One would expect that if the green bonus is the only component of the scoring function, then all cyclists would make green. However the tested green bonuses don't cause a speed advice system that solely consists of a green bonus or the maximum acceleration of the bicycle models don't allow the cyclist to always catch green.

Sensitivity stop criterion

The influence of the chosen stop criterion is not out of discussion. However some value had to be attributed to indicate whether a vehicle has made a stop. The value of 1 m/s may be relative high, but the cyclists in simulation have a desired speed between 12 and 30 km/h. The drop of his speed to a value lower than 3,6 km/h is therefore not expected. However it is a value higher than the speed advice system is able to give to the cyclist. Therefore this section will discuss and investigate the sensitivity of the criterion by means of a test on the simulated scenarios. Three different values are tested, starting with the used criterion used in the previous sections (1,0), but also two lower values (0,5 and 0,1). The test is applied to the simulations of the different green bonuses used for to investigate the influence of the green bonus. The results of the test are shown in Figure 6-4. Full results can be found in Appendix D.

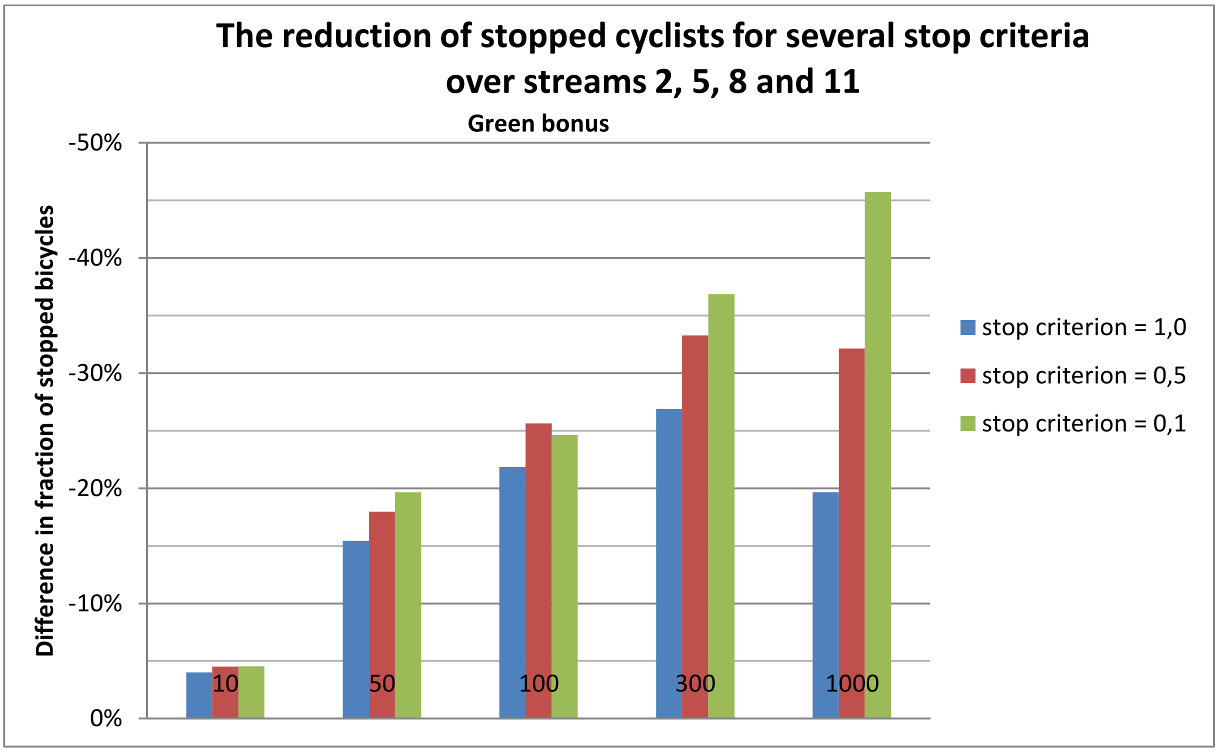


Figure 6-4: Mean reduced number of cyclists going straight ahead for different stop criteria

The results of the stop criterion test show that results of the simulations in the previous experiments are influenced by the chosen stop criterion. As we can see from Figure 6-4, the increase in stopped cyclist reduction by a higher green bonus is not found for all simulations with the stop criterion of 1 m/s. However the experiments with a lower stop criterion show this trend definitely. Remarkable is the increase of reduction for the speed advice system with a green bonus of 1000 for lower criteria. Probably the height of the green bonus causes the cyclist to travel with a very low speed to still catch the green light.

Conclusions

From the simulation results we can conclude that the speed advice system does reduce the number of stops. This was the main purpose of designing the system and therefore it satisfies the assignment. However the chosen parameters have made the probability of success for the simulation scenarios higher than expected in reality. First of all no traffic controllers exist that only have a deviation of green times of one second. Furthermore the assumptions on the extent to which cyclists stick to the advice are chosen in a way that all cyclists will follow the advice. More variations in these parameters should be tested to resemble reality and test the designed speed advice system.

7 Conclusions and recommendations

This research is meant as a first step to explore the possibilities of a speed advice for cyclist that reduces the probability of stops at a traffic light guided intersection. In this light the design objective was to enlarge the probability of catching a green light, but also to come with a system that satisfies the cyclist's desires. As result of this design challenge the first research towards a speed advice system cannot cover all elements that come along with such a system. In this chapter the findings of the research are presented and also the elements that haven't got the attention they deserved are outlined to show the uncovered areas of the system. Directions of future research should lead to the coverage of these areas.

7.1 Conclusions

Two different speed advice systems are designed for the different types of controllers that are used on intersections. These two controllers bring different challenges with them and therefore should have a speed advice system that is designed for the specific controller. None of the controllers is influenced by the presence of cyclists at the network, so the other traffic on the intersection will not have a differences in the realization of green phases by implementing the speed advice.

Influence controller

With a fixed time controller it is possible to give a speed advice to the cyclist that holds for the rest of the route to the traffic light. The time-dependent circumstances in which the controller operates do not change the controller program in anyway, so the next green times are known in advance. One single speed advice which the cyclist can ride for the remaining distance to the traffic light should be sufficient to eliminate stops.

The actuated controller asks for a more flexible structure of the speed advice in which the cyclist should adjust his speed dependent on the state of the traffic light controller. The state of the controller is defined as a period in time with equal uncertainty about the occurrence of the cyclist's green. The speed advice system must be implemented in a way that the consequence of the state of the controller for the advice of the cyclist can be distributed to the cyclist at the moment this change of state occurs.

Ability of cyclists

The cyclist is able to travel with the desired speed as long as the advice speed fits within the range of speeds close to the speed he would drive when no speed advice was present. In the design of the speed advice for the actuated controller this is done by scoring the speeds according to their deviation from the desired speed of the individual cyclist. The individual preference of the cyclist is taken into account in order to enlarge the acceptance of the given speed advice. Assumptions have been made about the extent to which a deviation in speed influences the associated score. It would be interesting to see whether this score does really fit the function of the design in this research. In the design of the speed advice for the fixed time controller no measures are taken to make the advice more suitable for the cyclist, but the personal score framework used in the actuated controller could also work in a speed advice system for the fixed time controller. In this way there is also a trade-off between deviation from desired speed and catching green for the cyclists that approach the fixed time controller.

Results simulation

The speed advice system for the actuated controller gives a positive effect on the fraction of stopped cyclists at the intersection. A maximum reduction of 45 % in stopped cyclists for the total amount of cyclists going straight ahead is reached for the speed advice system (green bonus of 1000 and a stop criterion of 0,1 m/s). Speed advice systems with other values for the green bonus and the stop criterion also reduce the fraction of stopped cyclists. A remark has to be made about this result: it is largely dependent on the assumptions made in the design of the speed advice system and reached with a simplified version of an actuated controller that only varies the green times of the signal groups. Most of the parameters are specified based on assumptions and may not match reality. Validity of the used parameters in the designed system on a more global level is therefore not guaranteed. The system should be tested more thoroughly to prove that it is capable of reducing the stops of cyclists with the parameter values that are tested in reality.

7.2 Recommendations

The speed advice systems of this research are tested on some performance indicators and on several parameters of the design. However in this research no time was available to test the systems on a wider variety of parameters. Therefore this section sums up recommendations for extended research on the speed advice system for cyclists.

Traffic controller

- ❖ It could be profitable for the number of stops to look for sequence structures that allow more left turning cyclists to arrive at the second traffic light when it is green. To realize this the traffic controller should have couplings between the bicycle streams within the intersection. These bicycle streams then determine for a large share the sequence structure of the controller.
- ❖ Another way to reduce the number of stops for left turning cyclists drastically is to implement a phase that allows left turners to ride diagonally across the intersection. The implementation of such a green phase for all cyclists on the intersection results in a controller that has an additional phase. This increases the total cycle time of the controller and will cause more delay for the other actors on the intersection.
- ❖ In the framework of the speed advisor the actuated controller is simplified by reducing the number of flexibilities and uncertainties for the signal groups. All signal groups will at least realize a fixed green period and the simulated controller's extension green is limited. To find out whether the speed advice system also works for an actuated controller with more flexibility, it should be applied and tested with a more flexible actuated controller.
- ❖ The adaptive controller that has no fixed structure in the sequence of the signal groups is not covered in this research. However this type of controller provides opportunities for adapting the controller based on the number of cyclists and their estimated arrival at the traffic light. Together with a speed advice to let the cyclist arrive in platoons, this could lead to huge reductions of stopped cyclists at the intersection.

Cyclist behaviour

- ❖ Assumptions on the free flow speed of cyclists have been made on estimations from experts to determine their desired speed, but no detailed information from studies was available on the speeds of cyclists. Although the numbers will differ because of the circumstances (wind/slope), field tests could be done to give a more accurate distribution of the desired speeds of cyclists.

- As can be seen from the simulation, the green bonus determines to a large extent whether a speed advice system is useful. The green bonus that corresponds with the value a cyclist experiences when it doesn't have to stop at a traffic light is not known. Further research on the value of this event for cyclist could indicate what the green bonus should be and consequently indicate whether the implementation of the speed advice system could be successful.
- The success of the system not only depends on the green bonus, but more or less depends on the trade-off between the green bonus and the function that describes the costs for deviating from the desired speed. The used formula is based on common sense and suits the existing ideas about the sacrifice that the cyclist has to make when deviating from its speed. The form of the function is assumed parabolic, but may have a different form and may even have a steeper slope when the cyclist deviates at a higher speed compared to deviating at a lower speed. There should be more research on this function that describes the costs of deviating from the desired speed.
- The cyclists are not influenced by the cycle traffic that is on the same road stretch as the cyclist moves, due to unrealistic processes close to the stopping line of the traffic light. However this absence of interaction between cyclists does not match with reality as cyclists will be hindered to ride at the desired or advised speed by the traffic that surrounds him. To catch this event in simulation a model should be implemented that takes into account the interaction between cyclists, without giving unrealistic implications close to the traffic light.
- In the simulations all cyclists are influenced by the given speed advice both for the on-board unit as the road side communicator. The advice is thus taken over by all cyclists. In reality only a share of the cyclist population would have the on-board speed advice or understands and interprets the road side signs. Therefore a penetration rate could be introduced to account for the population that is not influenced by the speed advice. The penetration will probably only have an influence on the advised speed when the cyclist reacts to the other cycle traffic. This is not the case in the simulations performed in this research.

Speed advice

- In the performed simulations the speed advice did only consider the first two green phases per traffic light. The advice could be elaborated in a way that it takes into account more green phases of the traffic light. This means the cyclist is directed to a green phase earlier in time. The cyclist thus gets a speed advice that deviates from its desired speed when it is at a bigger distance from the traffic light and would probably get a better position for arriving at a green light.
- The speed advice system is set up in a way that it takes into account the desired speed of the individual cyclist. It would be interesting to see how much the cyclist that uses the speed advice deviates from his desired speed. This not measured by the used performance indicators and could be an additional performance indicator. Also the realized scores by the speed advice system would be a performance indicator that could be added to the realized simulations.

Circumstances network

- ❖ The speed advice system is tested on an intersection with a relative high number of arms and high demand. This results in a relative high cycle time for the controllers applied in the network. Testing the speed advice system on a range of intersection with fluctuating demands and differences in geometry could show the situations in which a speed advice for cyclists has the biggest value for the cyclist.
- ❖ The addition of pedestrians has a big influence on the traffic controller and its cycle time. When applying the pedestrians, we can observe how big this influence is. Probably controller cycle times will increase due to the big green times for pedestrians to make them able to cross the roadway with their low speeds. This will negatively influence the time reserved in the controller for the cyclists.
- ❖ The current simulation only consists of one single intersection. It would be interesting to see whether a the speed advice system could create a dynamic green wave on a string of intersections. Scaling up one step to a city or regional network will give more insight on the implications of the system on a higher scale.

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Appendix

Appendix A

Amsterdam

The municipality of Amsterdam acknowledges that traffic lights are a crucial factor for cyclists and focusses on Dynamic Traffic Management for the bicycle (Hilhorst, 2007). Measures in this program are:

- 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 bicyclists;
- Green waves for cyclists;
- Waiting time predictors that indicate how long it takes before a light turns green.

Rotterdam

The municipality of Rotterdam strives to have maximum cycle times of 90 seconds for their traffic light guided intersections. When cycle times exceed 90 seconds, the municipality is willing to review the possibilities of giving cyclists two green phases in the cycle. In primary cycle routes detection of bicyclists on a larger distance of the stopping line is desirable (dS+V, 2007).

The Hague

The municipality of The Hague states that cyclists are avoiding crossings with roads of a higher level in the network, because of the traffic lights and the air quality, instead the cyclists choose for smaller roads with less traffic lights. The extension of the city borders of The Hague asks for quick non-stop cycling routes. As waiting times at traffic light guided intersections are important for cyclists, it's desirable to avoid stops at primary cycle routes. The policy states that the cyclist gets priority within the city centre ring. The municipality has the intention to decrease waiting times at intersections to 20 seconds on primary routes for bicycle traffic and 40 seconds on secondary routes (Dienst Stedelijke Ontwikkeling, 2011).

Utrecht

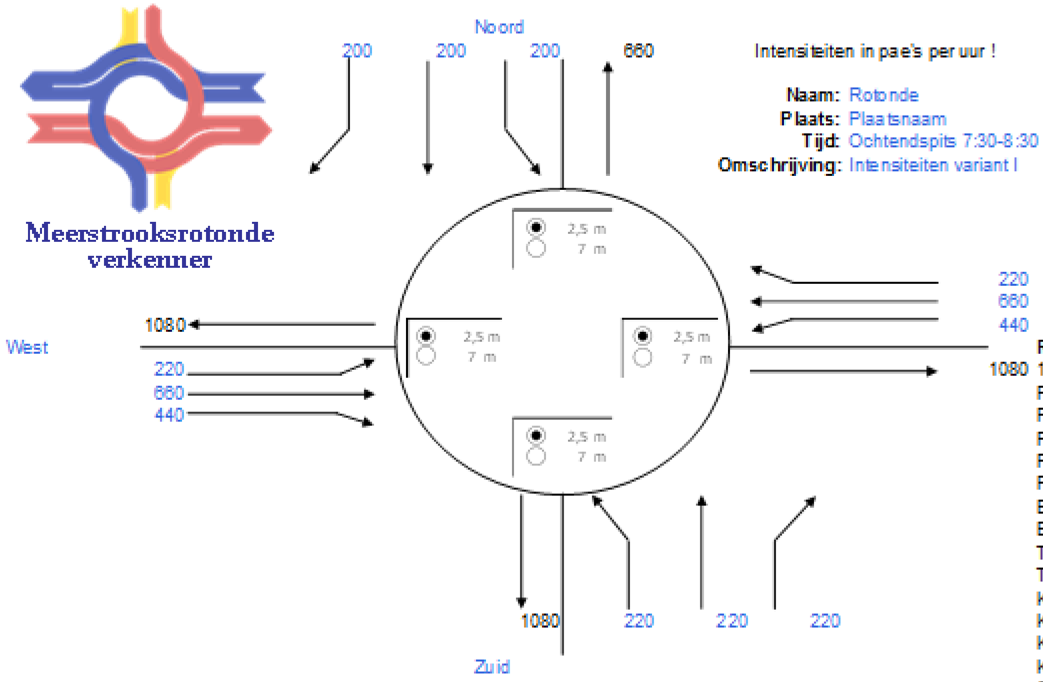
In Utrecht some policy is made on specific cases where bicycle traffic has to pass traffic light guided intersections. They are specifically concerned on left-turning bicyclists. On straightforward intersections it is eligible to position waiting bicycles in front of the waiting car traffic by applying an OFOS (opgeblazen fietsersopstelstrook - *Dutch*). Two way bicycle paths cannot realize together

Figure 0-1 Example of an 'opgeblazen fietsersopstelstrook' (OFOS)

with turning movements of cars. Therefore these types of conflicts need to be guaranteed by adding a lane and signal group for left- and right-turning cars crossing this path (Gemeente Utrecht, 2002). With regard to flow the municipality of Utrecht realizes that traffic lights are playing an important role in the comfort and attractiveness of the bicycle network. If waiting times at traffic lights increase, this is a demotivating factor in using the bike and stimulating factor for red light negation. Red light negation leads to unsafe situations for cyclists. This is why the municipality of Utrecht aims a maximum waiting time for cyclists of 60 seconds (Kramer & Koolhaas, 2002).

Appendix B

Invoer



Intensiteiten in pae's per uur !

Naam: Rotonde
Plaats: Plaatsnaam
Tijd: Ochtendspits 7:30-8:30
Omschrijving: Intensiteiten variant I

Resultaten		VG	ri.	Tgem	ri.
1str. rotonde		2,21	W	999999,9	N
Passeerb. rotonde		1,38	O	999999,9	N
Partiële eirotonde |		2,13	W	999999,9	W
Partiële eirotonde --		1,72	N	999999,9	N
Partiële turborotonde |		1,43	OL	999999,9	WL
Partiële turborotonde --		1,28	WR	999999,9	NL
Eirotonde |		2,09	W	999999,9	W
Eirotonde —		1,59	N	999999,9	N
Turborotonde |		1,41	OL	999999,9	WL
Turborotonde —		1,06	NL	999999,9	NL
Knierotonde └		1,22	OL	999999,9	OL
Knierotonde ┌		1,42	WL	999999,9	WL
Knierotonde ┐		1,11	WL	999999,9	NL
Knierotonde ┘		1,49	WR	999999,9	WR
Spiraalrotonde |		0,94	WM	82,4	WM
Spiraalrotonde—	OK	0,76	WL	20,6	NL
Rotorrotonde	OK	0,57	OL	11,9	NM
Specifieke 3-taks rotondes:					
Gestr. knie -'- └		nvt	nvt	nvt	nvt
Gestr. knie I- ┌		nvt	nvt	nvt	nvt
Gestr. knie -,- ┐		nvt	nvt	nvt	nvt
Gestr. knie -I ┘		nvt	nvt	nvt	nvt
Sterrotonde -'- |		nvt	nvt	nvt	nvt
Sterrotonde I- —		nvt	nvt	nvt	nvt
Sterrotonde -,-		nvt	nvt	nvt	nvt
Sterrotonde -I		nvt	nvt	nvt	nvt
				in s/pae	

Spiraalrotonde --

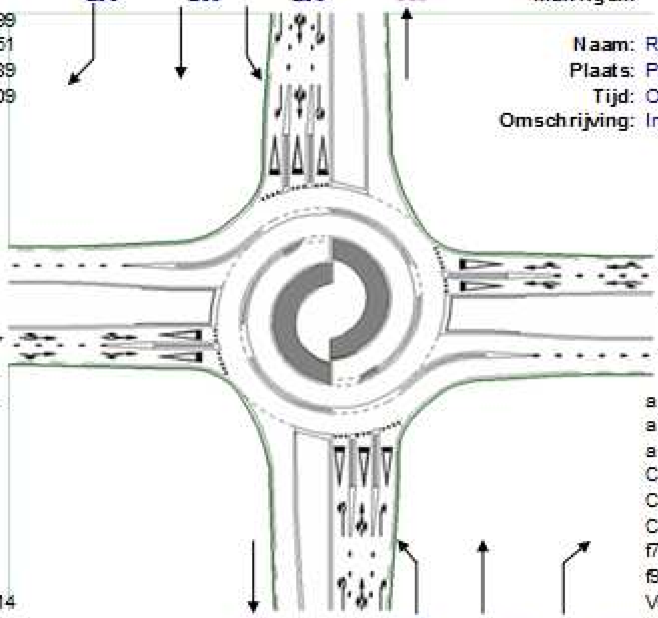
a nr	0,06	a nm	0,13	a nl	0,21

Cnr	1073	pae/h	
Cnm	414	pae/h	
Cnl	362	pae/h	
f1	1	1,74099	
f3	0,931951	0,931951	
VGnr	0,19	1,740989	
VGnm	0,52	1,442809	
VGnl	0,52		
Tgem nr	4,1	s/pae	
Tgem nm	17,9	s/pae	
Tgem nl	20,6	s/pae	
Ngem nr	1,2	vtg	
Ngem nm	2,1	vtg	
Ngem nl	2,1	vtg	

Max VG	0,76		ri. WR
Max Tgem	20,6	s/pae	ri. NL
Max Ngem	4,2	vtg	ri. WL

Naam: Rotonde
Plaats: Plaatsnaam
Tijd: Ochtendspits 7:30-8:30
Omschrijving: Intensiteiten variant I

a oru	0		
a ori	0,14		
a olu	0		
a oli	0,21		
Cor	1096	pae/h	
Col	875	pae/h	
f5	0,778411	0,778411	
VGor	0,67		
VGol	0,67		
Tgem or	9,9	s/pae	
Tgem ol	12,4	s/pae	
Ngem or	3,0	vtg	
Ngem ol	3,0	vtg	



a wru	0		
a wri	0,14		
a wlu	0		
a wli	0,21		
Cwr	966	pae/h	
Cwl	771	pae/h	
f11	0,445314	0,445314	
VGwr	0,76		
VGwl	0,76		
Tgem wr	15,5	s/pae	
Tgem wl	19,5	s/pae	
Ngem wr	4,2	vtg	
Ngem wl	4,2	vtg	

a zr	0,06					
a zm	0,13					
a zl	0,21					
Czr	1233	pae/h				
Czm	525	pae/h				
Czl	438	pae/h		1,684329		
f7	1	1,684329		1,40292		
f9	0,910295	0,910295				
VGzr	0,18					
VGzm	0,46					
VGzl	0,46					
Tgem zr	3,6	s/pae				
Tgem zm	12,6	s/pae				
Tgem zl	15,1	s/pae				
Ngem zr	1,2	vtg				
Ngem zm	1,8	vtg				
Ngem zl	1,8	vtg				

VG	0,76	WR	0,67	OR
Tgem	20,55	NL	15,12	ZL
Ngem	4,17	WR	3,03	OR

Meerstrooksrotonde verkenner

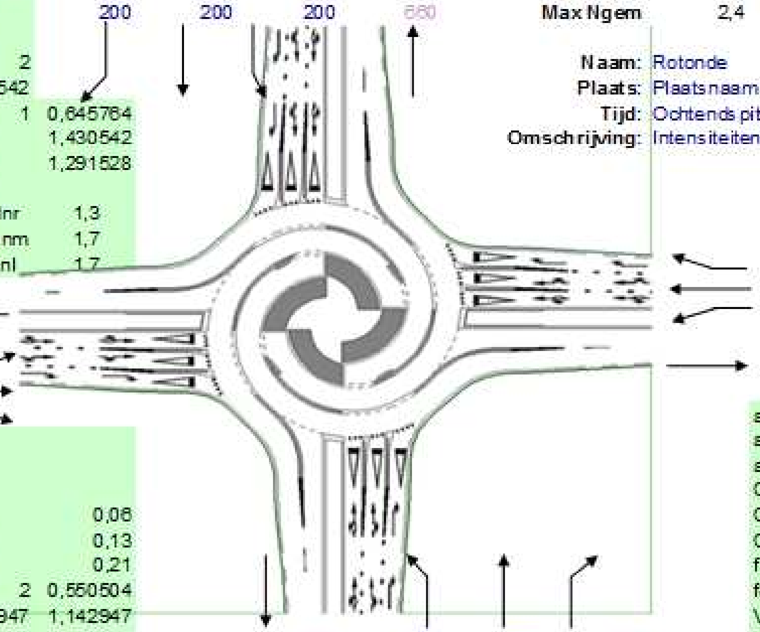
Rotorrotonde

a nru	0	a nri		0,06	
a nmu	0	a nmi		0,13	
a nlu	0	a nli	0,21		
Cnr	914	pae/h			
Cnm	502	pae/h			
Cnl	502	pae/h	2		
f1	1	1,430542			
f2	1		1	0,645764	
VGnr	0,22			1,430542	
VGnm	0,40			1,291528	
VGnl	0,40				
Tgem nr	5,0		Nnr	1,3	
Tgem nm	11,9		Nnm	1,7	
Tgem nl	11,9		Nnl	1,7	Noord

Max VG	0,57		ri. OM
Max Tgem	11,9	s/pae	ri. NM
Max Ngem	2,4	vtg	ri. OL

Naam: Rotonde
Plaats: Plaatsnaam
Tijd: Ochtendspits 7:30-8:30
Omschrijving: Intensiteiten variant I

a oru	0	a ori		0,06	
a omu	0	a omi		0,13	
a olu	0	a oli		0,21	
Cor	1176	pae/h			
Com	966	pae/h			
Col	948	pae/h	2	0,549127	
f4	1	2,283687		2,283687	
f5	0,840919	0,840919		2,196509	
VGor	0,19				
VGom	0,57				
VGol	0,57				
Tgem or	3,8	s/pae			
Tgem om	8,8	s/pae			
Tgem ol	8,9	s/pae			
Ngem or	1,2	vtg			
Ngem om	2,4	vtg			
Ngem ol	2,4	vtg			Oost



a wru	0				
a wmu	0				
a wlu	0				
Cwr	1019	a wri		0,06	
Cwm	832	a wmi		0,13	
Cwl	824	a wli		0,21	
f10	1		2	0,550504	
f11	0,670049	1,142947		1,142947	
VGwr	0,43	0,670049		1,376259	
VGwm	0,53				
VGwl	0,53				
Tgem wr	6,2	s/pae			
Tgem wm	9,2	s/pae			
Tgem wl	9,3	s/pae			
Ngem wr	1,8	vtg			
Ngem wm	2,1	vtg			
Ngem wl	2,1	vtg			West

VG	0,53	WL	0,57	OM
Tgem	11,9	NM	8,9	OL
Ngem	2,1	WM	2,4	OM

a zru	0	a zri		0,06	
a zmu	0	a zmi		0,13	
a zlu	0	a zli		0,21	
Czr	1023	pae/h			
Czm	682	pae/h			
Czl	682	pae/h	2	0,600048	
f7	1	1,285861		1,285861	
f8	1		1	1,200096	
VGzr	0,21				
VGzm	0,32				
VGzl	0,32				
Tgem zr	4,5	s/pae			
Tgem zm	7,8	s/pae			
Tgem zl	7,8	s/pae			
Ngem zr	1,3	vtg			
Ngem zm	1,5	vtg			
Ngem zl	1,5	vtg			Zuid

Meerstrookrotonde verkenner

Appendix C

Appendix C - Table 1: Results simulation for actuated controller with and without speed advice with green bonus = 10

	zonder speed advice			met speed advice			verschil		
	speed (m/s)	% stop	reistijd (s)	speed (m/s)	% stop	reistijd (s)	speed (%)	% stop	reistijd (s)
richting 1	5,7624394	0,00%	249,29918	5,7664444	0,00%	249,3	0,07%	0,00%	0,0
richting 2	**5,400034**	**80,24%**	**341,3486**	**5,420354**	**76,35%**	**339,7**	**0,38%**	**-3,90%**	**-1,6**
richting 3	4,8644959	100,00%	314,70588	4,8826836	100,00%	314,6	0,37%	0,00%	-0,1
richting 4	5,9464382	0,00%	245,10741	6,2481165	0,00%	233,6	5,07%	0,00%	-11,5
richting 5	**5,421042**	**82,65%**	**233,4154**	**5,695926**	**76,79%**	**222,0**	**5,07%**	**-5,86%**	**-11,4**
richting 6	5,2126748	100,00%	316,84196	5,3693203	99,86%	307,5	3,01%	-0,14%	-9,3
richting 7	5,7608073	0,00%	275,16857	5,7651714	0,00%	275,2	0,08%	0,00%	0,0
richting 8	**5,420357**	**80,17%**	**340,2706**	**5,446585**	**76,64%**	**339,0**	**0,48%**	**-3,52%**	**-1,3**
richting 9	5,3551435	87,33%	306,36373	5,3662631	84,54%	305,6	0,21%	-2,79%	-0,7
richting 10	5,6754962	0,00%	269,77682	5,6796498	0,00%	269,8	0,07%	0,00%	0,0
richting 11	**5,263832**	**80,31%**	**237,5415**	**5,300423**	**77,53%**	**236,5**	**0,70%**	**-2,78%**	**-1,1**
richting 12	5,0184292	100,00%	298,93173	5,0228269	100,00%	298,8	0,09%	0,00%	-0,1

Appendix C - Table 2: Results simulation for actuated controller with and without speed advice with green bonus = 50

	zonder speed advice			met speed advice			verschil		
	speed (m/s)	% stop	reistijd (s)	speed (m/s)	% stop	reistijd (s)	speed (%)	% stop	reistijd (s)
richting 1	5,7624394	0,00%	249,29918	5,7668571	0,00%	249,2	0,08%	0,00%	-0,1
richting 2	**5,400034**	**80,24%**	**341,3486**	**5,445769**	**65,78%**	**337,7**	**0,85%**	**-14,46%**	**-3,6**
richting 3	4,8644959	100,00%	314,70588	4,937778	100,00%	310,8	1,51%	0,00%	-3,9
richting 4	5,9464382	0,00%	245,10741	6,2481165	0,00%	233,6	5,07%	0,00%	-11,5
richting 5	**5,421042**	**82,65%**	**233,4154**	**5,701904**	**67,10%**	**221,6**	**5,18%**	**-15,55%**	**-11,8**
richting 6	5,2126748	100,00%	316,84196	5,3946562	99,86%	305,3	3,49%	-0,14%	-11,6
richting 7	5,7608073	0,00%	275,16857	5,7651924	0,00%	275,2	0,08%	0,00%	0,0
richting 8	**5,420357**	**80,17%**	**340,2706**	**5,457662**	**62,12%**	**337,5**	**0,69%**	**-18,05%**	**-2,8**
richting 9	5,3551435	87,33%	306,36373	5,4188271	79,21%	302,4	1,19%	-8,12%	-4,0
richting 10	5,6754962	0,00%	269,77682	5,6828536	0,00%	269,6	0,13%	0,00%	-0,2
richting 11	**5,263832**	**80,31%**	**237,5415**	**5,331486**	**66,69%**	**234,8**	**1,29%**	**-13,63%**	**-2,8**
richting 12	5,0184292	100,00%	298,93173	5,0755101	99,87%	295,4	1,14%	-0,13%	-3,5

Appendix C - Table 3: Results simulation for actuated controller with and without speed advice with green bonus = 100

	zonder speed advice			met speed advice			verschil		
	speed (m/s)	% stop	reistijd (s)	speed (m/s)	% stop	reistijd (s)	speed (%)	% stop	reistijd (s)
richting 1	5,7624394	0,00%	249,29918	5,7665254	0,00%	249,3	0,07%	0,00%	0,0
richting 2	**5,400034**	**80,24%**	**341,3486**	**5,498688**	**58,22%**	**334,4**	**1,83%**	**-22,02%**	**-6,9**
richting 3	4,8644959	100,00%	314,70588	4,9525156	100,00%	310,0	1,81%	0,00%	-4,7
richting 4	5,9464382	0,00%	245,10741	6,2481165	0,00%	233,6	5,07%	0,00%	-11,5
richting 5	**5,421042**	**82,65%**	**233,4154**	**5,776586**	**60,61%**	**218,8**	**6,56%**	**-22,04%**	**-14,7**
richting 6	5,2126748	100,00%	316,84196	5,4096488	99,86%	304,8	3,78%	-0,14%	-12,1
richting 7	5,7608073	0,00%	275,16857	5,7651733	0,00%	275,2	0,08%	0,00%	0,0
richting 8	**5,420357**	**80,17%**	**340,2706**	**5,535997**	**56,28%**	**333,3**	**2,13%**	**-23,89%**	**-7,0**
richting 9	5,3551435	87,33%	306,36373	5,4499589	74,31%	301,4	1,77%	-13,02%	-5,0
richting 10	5,6754962	0,00%	269,77682	5,6793846	0,00%	269,7	0,07%	0,00%	0,0
richting 11	**5,263832**	**80,31%**	**237,5415**	**5,396149**	**60,83%**	**232,0**	**2,51%**	**-19,48%**	**-5,5**
richting 12	5,0184292	100,00%	298,93173	5,0918818	99,86%	294,7	1,46%	-0,14%	-4,2

Appendix C - Table 4: Results simulation for actuated controller with and without speed advice with green bonus = 300

	zonder speed advice			met speed advice			verschil		
	speed (m/s)	% stop					speed (%)	% stop	reistijd (s)
richting 1	5,7624394	0,00%	249,29918	5,766518	0,00%	249,3	0,07%	0,00%	0,0
richting 2	**5,400034**	**80,24%**	**341,3486**	**5,426913**	**53,47%**	**334,2**	**0,50%**	**-26,77%**	**-7,2**
richting 3	4,8644959	100,00%	314,70588	5,1302102	100,00%	299,2	5,46%	0,00%	-15,5
richting 4	5,9464382	0,00%	245,10741	6,1574653	0,00%	245,1	3,55%	0,00%	0,0
richting 5	**5,421042**	**82,65%**	**233,4154**	**5,770283**	**55,10%**	**219,1**	**6,44%**	**-27,55%**	**-14,4**
richting 6	5,2126748	100,00%	316,84196	5,4157199	100,00%	304,3	3,90%	0,00%	-12,6
richting 7	5,7608073	0,00%	275,16857	5,7651431	0,00%	275,2	0,08%	0,00%	0,0
richting 8	**5,420357**	**80,17%**	**340,2706**	**5,524338**	**50,80%**	**334,4**	**1,92%**	**-29,37%**	**-5,9**
richting 9	5,3551435	87,33%	306,36373	5,4531415	73,80%	301,5	1,83%	-13,53%	-4,9
richting 10	5,6754962	0,00%	269,77682	5,682703	0,00%	269,6	0,13%	0,00%	-0,2
richting 11	**5,263832**	**80,31%**	**237,5415**	**5,389975**	**56,50%**	**232,5**	**2,40%**	**-23,81%**	**-5,1**
richting 12	5,0184292	100,00%	298,93173	5,1109774	99,73%	294,1	1,84%	-0,27%	-4,8

Appendix C - Table 5: Results simulation for actuated controller with and without speed advice with green bonus = 1000

	zonder speed advice			met speed advice			verschil		
	speed (m/s)	% stop	reistijd (s)	speed (m/s)	% stop	reistijd (s)	speed (%)	% stop	reistijd (s)
richting 1	5,7624394	0,00%	249,29918	5,7676784	0,00%	249,2	0,09%	0,00%	-0,1
richting 2	**5,400034**	**80,24%**	**341,3486**	**5,376056**	**62,79%**	**347,1**	**-0,44%**	**-17,45%**	**5,8**
richting 3	4,8644959	100,00%	314,70588	4,9792842	100,00%	306,8	2,36%	0,00%	-7,9
richting 4	5,9464382	0,00%	245,10741	6,2481165	0,00%	233,6	5,07%	0,00%	-11,5
richting 5	**5,421042**	**82,65%**	**233,4154**	**5,61162**	**60,69%**	**229,0**	**3,52%**	**-21,96%**	**-4,4**
richting 6	5,2126748	100,00%	316,84196	5,4230966	99,85%	303,7	4,04%	-0,15%	-13,2
richting 7	5,7608073	0,00%	275,16857	5,7655677	0,00%	275,2	0,08%	0,00%	0,0
richting 8	**5,420357**	**80,17%**	**340,2706**	**5,39399**	**60,04%**	**344,7**	**-0,49%**	**-20,13%**	**4,4**
richting 9	5,3551435	87,33%	306,36373	5,4432251	81,14%	301,5	1,64%	-6,19%	-4,9
richting 10	5,6754962	0,00%	269,77682	5,6951346	0,00%	268,9	0,35%	0,00%	-0,8
richting 11	**5,263832**	**80,31%**	**237,5415**	**5,273656**	**61,26%**	**238,8**	**0,19%**	**-19,05%**	**1,2**
richting 12	5,0184292	100,00%	298,93173	5,1219883	99,47%	292,5	2,06%	-0,53%	-6,4

Appendix D

Appendix D - Table 1: Stopped cyclists with and without speed advice with green bonus = 10 and stop criterion = 0,5 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**78,28%**	**74,20%**	**-4,07%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**80,96%**	**72,86%**	**-8,10%**
richting 6	99,74%	99,86%	0,12%
richting 7	0,00%	0,00%	0,00%
richting 8	**76,46%**	**73,07%**	**-3,39%**
richting 9	81,30%	77,90%	-3,40%
richting 10	0,00%	0,00%	0,00%
richting 11	**77,93%**	**75,50%**	**-2,43%**
richting 12	99,34%	100,00%	0,66%

Appendix D - Table 2: Stopped cyclists with and without speed advice with green bonus = 10 and stop criterion = 0,1 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**70,70%**	**66,71%**	**-3,99%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**75,44%**	**68,55%**	**-6,89%**
richting 6	98,54%	98,78%	0,24%
richting 7	0,00%	0,00%	0,00%
richting 8	**70,67%**	**66,54%**	**-4,12%**
richting 9	72,02%	67,84%	-4,18%
richting 10	0,00%	0,00%	0,00%
richting 11	**72,01%**	**68,86%**	**-3,16%**
richting 12	97,66%	98,54%	0,88%

Appendix D - Table 3: Stopped cyclists with and without speed advice with green bonus = 50 and stop criterion = 0,5 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**78,28%**	**60,96%**	**-17,32%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**80,96%**	**61,39%**	**-19,57%**
richting 6	99,74%	99,58%	-0,17%
richting 7	0,00%	0,00%	0,00%
richting 8	**76,46%**	**58,28%**	**-18,19%**
richting 9	81,30%	69,57%	-11,73%
richting 10	0,00%	0,00%	0,00%
richting 11	**77,93%**	**61,13%**	**-16,80%**
richting 12	99,34%	99,36%	0,02%

Appendix D - Table 4: Stopped cyclists with and without speed advice with green bonus = 50 and stop criterion = 0,1 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**70,70%**	**51,30%**	**-19,39%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**75,44%**	**54,95%**	**-20,50%**
richting 6	98,54%	97,08%	-1,46%
richting 7	0,00%	0,00%	0,00%
richting 8	**70,67%**	**49,65%**	**-21,02%**
richting 9	72,02%	57,46%	-14,56%
richting 10	0,00%	0,00%	0,00%
richting 11	**72,01%**	**54,32%**	**-17,69%**
richting 12	97,66%	96,98%	-0,68%

Appendix D - Table 5: Stopped cyclists with and without speed advice with green bonus = 100 and stop criterion = 0,5 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**78,28%**	**52,27%**	**-26,01%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**80,96%**	**55,12%**	**-25,85%**
richting 6	99,74%	99,86%	0,12%
richting 7	0,00%	0,00%	0,00%
richting 8	**76,46%**	**49,95%**	**-26,52%**
richting 9	81,30%	63,20%	-18,10%
richting 10	0,00%	0,00%	0,00%
richting 11	**77,93%**	**53,81%**	**-24,12%**
richting 12	99,34%	99,86%	0,53%

Appendix D - Table 6: Stopped cyclists with and without speed advice with green bonus = 100 and stop criterion = 0,1 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**70,70%**	**46,12%**	**-24,57%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**75,44%**	**50,58%**	**-24,87%**
richting 6	98,54%	97,53%	-1,01%
richting 7	0,00%	0,00%	0,00%
richting 8	**70,67%**	**44,81%**	**-25,86%**
richting 9	72,02%	48,46%	-23,56%
richting 10	0,00%	0,00%	0,00%
richting 11	**72,01%**	**48,77%**	**-23,25%**
richting 12	97,66%	97,46%	-0,20%

Appendix D - Table 7: Stopped cyclists with and without speed advice with green bonus = 300 and stop criterion = 0,5 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**78,28%**	**45,36%**	**-32,92%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**80,96%**	**45,57%**	**-35,40%**
richting 6	99,74%	99,73%	-0,02%
richting 7	0,00%	0,00%	0,00%
richting 8	**76,46%**	**41,90%**	**-34,56%**
richting 9	81,30%	59,54%	-21,77%
richting 10	0,00%	0,00%	0,00%
richting 11	**77,93%**	**47,75%**	**-30,18%**
richting 12	99,34%	99,60%	0,26%

Appendix D - Table 8: Stopped cyclists with and without speed advice with green bonus = 300 and stop criterion = 0,1 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**70,70%**	**34,65%**	**-36,05%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**75,44%**	**35,80%**	**-39,64%**
richting 6	98,54%	96,84%	-1,70%
richting 7	0,00%	0,00%	0,00%
richting 8	**70,67%**	**33,47%**	**-37,20%**
richting 9	72,02%	39,48%	-32,53%
richting 10	0,00%	0,00%	0,00%
richting 11	**72,01%**	**37,51%**	**-34,50%**
richting 12	97,66%	96,01%	-1,65%

Appendix D - Table 9: Stopped cyclists with and without speed advice with green bonus = 1000 and stop criterion = 0,5 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**78,28%**	**48,43%**	**-29,85%**
richting 3	100,00%	100,00%	0,00%
richting 4	0,00%	0,00%	0,00%
richting 5	**80,96%**	**46,52%**	**-34,44%**
richting 6	99,74%	98,38%	-1,36%
richting 7	0,00%	0,00%	0,00%
richting 8	**76,46%**	**43,58%**	**-32,88%**
richting 9	81,30%	64,94%	-16,36%
richting 10	0,00%	0,00%	0,00%
richting 11	**77,93%**	**46,55%**	**-31,38%**
richting 12	99,34%	98,03%	-1,31%

Appendix D - Table 10: Stopped cyclists with and without speed advice with green bonus = 1000 and stop criterion = 0,1 m/s

	zonder	met	verschil
	% stop	% stop	% stop
richting 1	0,00%	0,00%	0,00%
richting 2	**70,70%**	**27,26%**	**-43,43%**
richting 3	100,00%	99,88%	-0,12%
richting 4	0,00%	0,00%	0,00%
richting 5	**75,44%**	**27,29%**	**-48,15%**
richting 6	98,54%	93,66%	-4,88%
richting 7	0,00%	0,00%	0,00%
richting 8	**70,67%**	**24,97%**	**-45,69%**
richting 9	72,02%	33,93%	-38,09%
richting 10	0,00%	0,00%	0,00%
richting 11	**72,01%**	**26,46%**	**-45,56%**
richting 12	97,66%	93,28%	-4,39%