Delft University of Technology
Masterthesis

Equity in traffic light control

Identifying- and measuring equity in traffic light control. A case study to improve equity at the intersection A050 in Deventer for intelligent Traffic Light Controller: Flowtack

Royal
HaskoningDHV
Enhancing Society Together

TUDelft

Author:
Onno Hendriks

Equity in traffic light control

Identifying- and measuring equity in traffic light control. A case study to improve equity at the intersection A050 in Deventer for intelligent Traffic Light Controller: Flowtack

by

Onno Hendriks

Student:	O. Hendriks	Delft University of Technology
Supervisors:	Prof.Dr.Ir. J. W. C. van Lint,	Delft University of Technology
	Dr. ir. A. Hegyi,	Delft University of Technology
	Dr. ir. J. A. Annema,	Delft University of Technology
	ir. M. C. Verkaik-Poelman,	Delft University of Technology
	Ing. G. Hut,	Royal HaskoningDHV
	Ir. M. S. Jesus,	Royal HaskoningDHV
Project duration:	September, 2021 – June, 2021	

TU Delft

Abstract

A new generation of intelligent Traffic Light Controllers uses Model Predictive Control to minimise delay at signalised intersections. The conventional cycle of set sequences of green phases is dropped for optimisation purposes. This research uses the ethical theories utilitarianism, egalitarianism, sufficientarianism & deontology to define equity. An explicit connection of these ethical theories and technical principles of conventional traffic light controller CCOL & new generation traffic light controller Flowtack, has been provided to identify the change in ethical landscape, from predominantly egalitarian towards relatively utilitarian. Performance indicators for equity in traffic control are defined based on earlier research. Multiple setting changes in Flowtack are proposed and tested in simulation experiments with Aimsun. These experiments show that adjusting Flowtack's objective function can improve the equity scores according to egalitarianism & sufficientarianism, at the cost of the equity score of utilitarianism. The best results are validated using various flow compositions on an alternative intersection. As a result, the gain in equity by the proposed settings becomes greater, as the flow composition becomes more uneven.

Preface

This master thesis is written in partial fulfillment of the master of science in Transport, Infrastructure & Logistics (TIL) at Delft University of Technology. This thesis is a joint project between the faculties of Civil Engineering & Geosciences (CEG) and Technology, Policy and Management (TPM). The multidisciplinary element of the TIL program is emphasized by the collaboration between the faculties, challenging the student (me) to merge the prior experiences at various faculties into this one final project.

Even though the unusual circumstances caused by COVID-19, I have happily dedicated the past 9 months of my life to this thesis.

I would like to thank my daily supervisors, Muriel Verkaik-Poelman & Gert Hut, who have always been available for guidance, feedback, brainstorming and friendly conversations. I hope you guys enjoyed the Tuesday meetings as I did! I have learned a lot from you guys in the past months.

Next, many thanks to all of the other supervisors: Marson Jesus, Jan Anne Annema, Andreas Hegyi and Hans van Lint (the chair of the committee). All of you have given me great guidance to write this thesis. Andreas and Marson were the first ones I contacted for a thesis related to traffic control, we have had calls to discuss the topics of interest whether I was in the mountains (Andreas) or cycling in the rain (Marson). These are the memories I will never forget. By the time I started preparing a proposal in September, I knew I wanted to do something with optimisation and traffic control. During one of the first meetings, I mentioned something about fairness, Jan Anne immediately knew it: *this should be your research question!* Thanks for this great hunch Jan Anne, and thanks everyone for the flexibility of moving along with this new topic. Hans, thanks for being the super enthusiastic chair to the committee, your enthusiasm has definitely ignited mine.

I would also like to thank Kelvin Könst, of the Flowtack team for helping me getting started with the simulation environment of Aimsun and Flowtack settings. And thanks to Henk-Jan Lebbink & Hans Wolfrat, the daily office crew. Your regular presence at the office in Uithoorn has made this period still feel something like an internship while the office in Amersfoort was limited or closed due to COVID-19.

A special thanks to my parents, Hans & Jenny, who have provided me with an ergonomic office desk and sufficient nutrition & caffeine. You guys were always supportive, understanding and open to discuss daily proceedings with me.

I hope you enjoy discovering this thesis' content, or parts of it, as much as I enjoyed it!

Onno Hendriks
Delft, June 2021

Contents

Executive summary

A new generation of Traffic Light Controllers

Nowadays, about 5500 signalised intersections are up and running in the Netherlands (Talking Traffic, 2019). These signalised intersection are implemented to both *safely* and *efficiently* manage the flow of traffic. Most of the signalised intersections are equipped with an intelligent Traffic Light Controller (iTLC) that runs with set sequences, or cycles. Some of those iTLCs use a fixed time control, but more commonly these iTLCs use the more sophisticated (fully) actuated control.

A new generation of intelligent Traffic Light Controllers (iTLCs) that can anticipate incoming traffic flow is now being developed and tested. This new generation iTLCs do not necessarily follow a cycle pattern or particular sequences, instead, it controls in a structure-free order of directions, and optimises the sequence and time of the control plan for green phases. This allows the new generation of iTLCs to respond more freely on the measured and anticipated traffic, which creates opportunities for even more efficient intersection control.

Losing the structure of cycles in intersection control also rises questions. When efficiency is one of the leading purposes for the new development, will the new generation of iTLCs be fair? Cycles ensure a frequency of turns, which could be perceived as fair, where free structures do not ensure this. An example of this problem is given by a side road with a single road user on it, who has to wait for a busy main road during peak hour. Using a cycle-based iTLC guarantees this road user to have their turn within one cycle under unsaturated conditions. However, without cycles it is probably optimal to let this road user wait until peak hour is over. This however, is an unacceptable long waiting time. On the other hand, prioritising this single road user would not be fair to the substantial group of road users that then would have to stop. The solution lays somewhere in between these 2 scenarios. The relevant question to ask with the present development and opportunities is: ”What is acceptable - or what is *fair*?”

Multiple principles are added into the iTLC, in order to influence the behavior of the iTLC in such a way that it will be accepted. One of the reasons why these principles were added is to reduce the maximum waiting time. This thesis aims to make the *explicit connection* between these principles and the ethics that were implicitly considered when implementing such principles.

Research question 1:

”How are ethics implicitly implemented in the current (i)TLCs?”

Next, experiments with an iTLC in practise are performed with the objective of *improving* equity. In order to know whether there is an improvement, *a measure* for equity will be established.

Research question 2:

”How to improve equity in an iTLC, according to various ethical theories?”

Equity definition & measure

Four ethical theories are elaborated, each providing a definition of equity. Three of the considered ethical theories are teleological: with the focus on the consequences of the action rather than the intention of the action. The teleological ethical theories are utilitarianism, egalitarianism and sufficientarianism.

Utilitarianism is an ethical theory most are acquainted with, because of the broad use of utilitarian approaches. Namely, utilitarianism concerns the maximisation of utility, which can be translated to maximisation of profit or social value. A utilitarian approach that is often applied is the cost-benefit analysis, considering the total utility (benefits) opposed to the total costs. Equity is then defined as the maximisation of the sum of utility for all of the population, that produces the greatest possible utility, in other words, the greatest good for the greatest group.

On a signalised intersection, road users want to minimise their delay. The greatest good for the greatest group means in this case, that the sum of the total delay should be minimised, which correlates with minimisation of average delay. In this thesis, average delay is the indicator that will be used to measure equity, from utilitarian perspective.

Egalitarianism defines equity on a more social level. Egalitarianism strives towards equality of goods and capabilities, based on an individual's needs. An egalitarian argues that an unborn individual, without any knowledge of their future social status, would want to be born with equal capabilities, regardless of which environment they are born in. In order to reach such a society, goods should be distributed in such a way they are of the greatest benefit to the least-advantaged individuals in society (Rawls, 2009), also known as the Maximin principle.
A distribution of goods can be measured by the Gini coefficient, which is a dimensionless number from 0 to 1 that indicates perfect equality if the value is 0, and perfect inequality if the value is 1. The distributed 'good' is the delay of the road users at the intersection. This implicates that all road users experience the exact same delay if the Gini coefficient would be 0, or one group of road users experienced all the delay (never got to cross), whilst another group of road users didn't have any delay at all if the Gini coefficient would be 1.

Sufficientarianism sets a minimum boundary for the amount of goods each individual should have. The main idea behind this is that everyone has the right for basic needs. Once every individual has reached this minimum value, no other constrictions to the distribution of goods are desired by the sufficientarian philosophy.
Sufficientarianism can be measured with a boundary of sufficiency. At the intersection however, delay is a good that is not desired, therefore the boundary should be a maximum boundary. This thesis does not aim to define such a boundary. Thus, the maximum *measured* delay is used instead, which indicates to what extend the system complies to a variable boundary.

Deontology is about the intention of an action rather than the consequence. This ethical theory uses moral rules, which should be universal, apply to everyone. The individual is key and is to be respected as a person. Deontology and religion are closely connected.
Deontology is not measured in this thesis. As deontology considers the intention rather than the consequence, whilst consequences are usually what is measured.

From egalitarian control, towards utilitarian control

Where conventional iTLCs are controlled via a "feedback control" method, nowadays the "Model predictive control" (MPC) method is implemented in modern iTLCs. The difference between those control strategies is that, where feedback control reacts to the present traffic based on rules, the MPC optimises by actively predicting the impact of (variable) possible control plans. Additionally, example MPC iTLC Flowtack, does not use predefined sequences, or cycles. Due to this extra degree of freedom, which is referred to as being structure-free, the solutions Flowtack can come up with are even more efficient.

The development of using cycles in feedback control towards structure-free MPC causes differences in the principles that are applied in these controllers. For example, for the feedback controller, a maximum green time is applied to ensure progress of the cycle, whilst there is no limitation on the amount of green time in the structure-free MPC. The MPC controller switches its green phase based on other principles.

Altogether, both iTLCs are represented with principles regarding to all of the before mentioned ethical theories. Due to the leading cycles and optimisation principles, feedback control iTLC (CCOL as example) is identified rather egalitarian relative to structure-free MPC Flowtack, whilst Flowtack is identified rather utilitarian compared to CCOL.

Ethics-based TLC by alternative Flowtack settings

Next, a simulation experiment is performed with Flowtack at an isolated intersection, A050, in Deventer. Because Flowtack was identified as predominantly utilitarian, the goal of this experiment is to improve Flowtack's equity performance by the egalitarian and sufficientarian definitions, in other words: reduction of the maximum delay and reduction of the Gini coefficient for a more equal distribution.

Flowtack has multiple settings that can be adjusted to reach such a goal:

- The weight function, the relative importance of time, defines how much 'weight' a road user gains over time. Every second that a road user is delayed is multiplied by the corresponding weight at this time. This function can have different shapes, leading to different control behavior of Flowtack.
- Road user type specific multiplication factors, these factors define a relative weight between different road user types. The entire weight function is multiplied by this factor.
- Direction specific multiplication factors, these factors work the same as those above, but instead they can be tuned per direction on the intersection.

Four experiments were performed, individually adjusting the above mentioned settings for the first 3 experiments, and combining the best results for a fourth experiment. A linearly increasing weight function turned out to be the best weight function based on all 3 equity indicators from experiment 1. Experiment 2 did not show significant impact on the equity measures from the road user type specific multiplication factors, and are left out of consideration for experiment 4 due to external factors that play a role for implementation of the initial factors. Experiment 3 showed great improvement on the Gini coefficient and maximum delay, by implementation of settings directional multiplication factors based on the amount of conflicting and non-conflicting road-users per direction. A weight is determined for each direction, based on this amount, since non-conflicting road-users help a direction to achieve green light, whilst conflicting road-users oppose this direction to achieve green light.

Experiment 4, therefore combined the best settings of experiments 1 and 3, to see whether the positive effects on the equity indicators accumulate. This hypothesis was correct, the results are shown in Figure 1. To cancel out variation in results due to latency issues in the simulation environment, every experiment is performed a number of times (5-6) with the same settings. Referential settings are created, close to the settings that are currently used in practise. The only difference is that directional multiplication factors are set to 1, reducing the impact of local policy on the reference for this experiment. Figure 1 shows that the experiment 4, which is the combination of experiment 1 & 3, accumulates the effects as expected. Therefore, this combination of settings generated the greatest equity improvement of the tested settings, in terms of Gini coefficient for egalitarianism and maximum delay for sufficientarianism.

This thesis proposes to use this combination of settings for a more egalitarian & sufficientarian iTLC, the ethics-based eTLC.

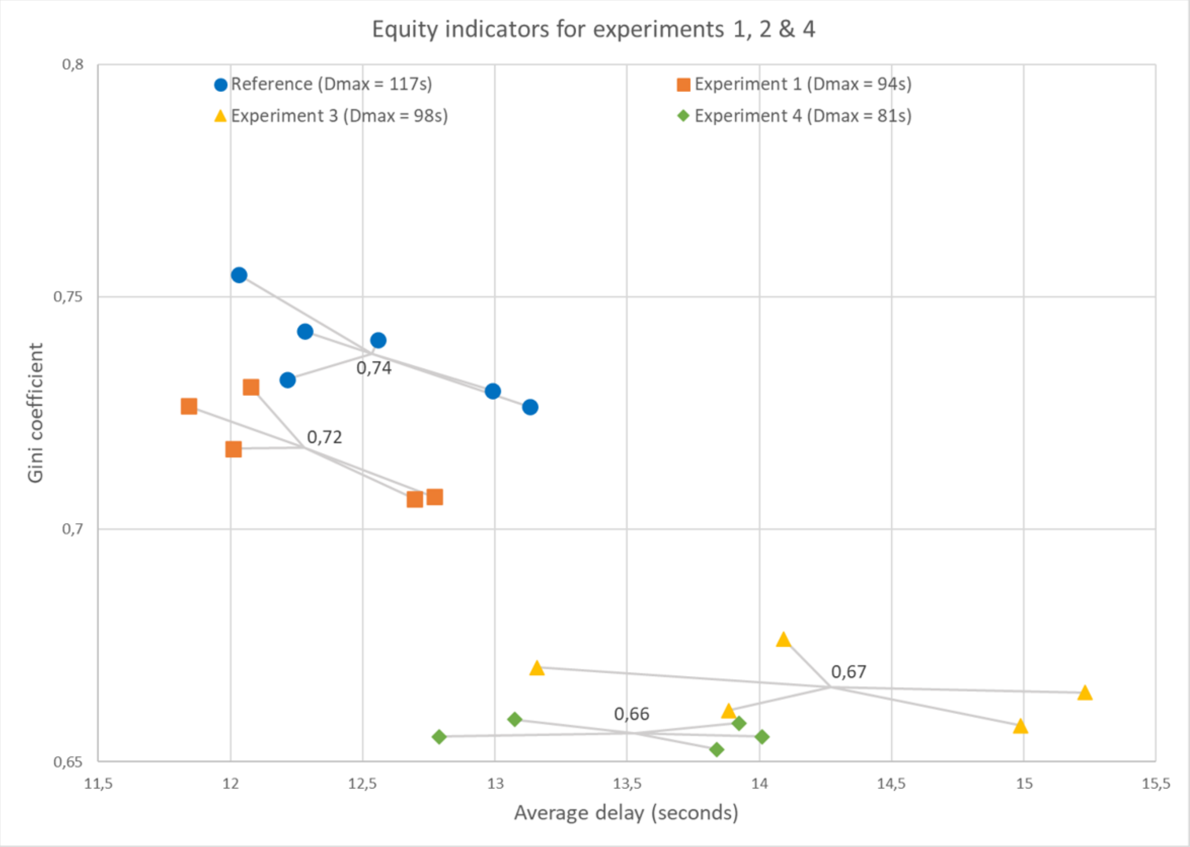


Figure 1: Equity scores of Referential settings, best settings of experiment 1, 3 and the results of experiment 4: the combination of the presented results from experiments 1 & 3.

Potential impact of eTLC depends on the inequality of flow

Next, the proposed settings for an eTLC are validated by varying the OD matrices, on an intersection with a different layout. The goal of this validation experiment is to validate whether the proposed method for creating the eTLC settings for Flowtack, still improve the egalitarian and sufficientarian equity on the intersection, for a different intersection and variable compositions of flow, by determining different OD matrices.

This validation concluded that the improvement of egalitarian and sufficientarian equity is still achieved when applying the eTLC method there. However, the amount of improvement that is achieved when applying the eTLC, is dependent on the flow distribution. When the flow on all directions is about equal, there is little to gain by the eTLC settings. The egalitarian / sufficientarian solution for an equally distributed flow on all directions lays very close to the utilitarian solution (greatest good for the greatest group, but the groups of road users on each direction are of the same size). Thus, when increasing the differences in flow on the directions, the amount of gain from the eTLC method increases too.

The perception of delay

Whether the eTLC will be accepted in practise, depends on perception of delay and Gini coefficient to the road users and policy makers. Road users perceive their delay different from the actually measured delay. This perceived delay generally increases over time. Looking back at the results of the proposed settings, this means that an average delay of 1 second higher might not even be noticed, whilst the reduction of maximum delay by more than half a minute could be perceived rather positive.

Identified, measured and improved - equity

This thesis combined the complex fields of control theory & ethics to explicitly identify Flowtack as relatively utilitarian & CCOL as relatively egalitarian. Furthermore, performance indicators to measure equity according to utilitarianism, egalitarianism & sufficientarianism are defined. These performance indicators allowed an improvement in egalitarian and sufficientarian equity to be measured, by successfully adjusting Flowtack's settings in simulation experiments. These settings showed not only to improve egalitarian and sufficientarian equity on the A050 intersection during evening-peak hour in Deventer, but also proved themselves valid for more general use on another intersection for various flow compositions.

This thesis concludes that it is technically feasible to improve equity in an egalitarian & sufficientarian way. It is up to the traffic engineers and policy makers to choose between egalitarianism, sufficientarianism and utilitarianism. Their choices can now be explicitly substantiated by a combination of ethical theories, control theory and principles in iTLCs.

1

Introduction

Every time we move outside to do groceries, commute or even for leisure purposes, we encounter intersections on our way. Whether we travel by public transport, bicycle or car, each of these travel modes intersect with others at some point in their journey. Some of these intersection are just based on give-way rules, some are dimensioned as roundabouts and others are signalised. Give-way intersections are generally implemented on quiet roads, and roundabouts and signals on busier roads. Roundabouts are generally chosen over signals mainly for safety reasons whilst a signalised intersection is mainly chosen for its higher capacity (Farah, 2018).

How did we get to this point of traffic control via signalised intersections? Over 200 years ago, the first traffic lights were implemented at ports for naval traffic. However, practise showed that normal lights were not visible enough through the fog, therefore studies from 1831 concluded that red and green light would be visible and distinguishable best. This idea was adopted for railway signals and later, for intersection signals as we know it. The first intersection signals were implemented in the mid 19th century in London, in order for the Parliamentarians to cross over busy streets in this rapidly growing city. This traffic signal was operated manually by a police officer (Stone, 2016).

No major traffic light developments were made until the early 19th century, when the amount of motorised traffic started to increase rapidly. This is when yellow lights were added for traffic control in the USA, whilst at that time, the first autonomous traffic light controller was installed in England. The first experiments for actuated TLCs were done a few years later, where a vehicle would be detected by a microphone when honking - which was a very unpopular solution for the local population. In the 1970's, a solution was found in the form of loop detectors in the roads, creating the opportunities for vehicle actuated control (Stone, 2016).

Nowadays, about 5500 signalised intersections are up and running in the Netherlands (Talking Traffic, 2019). These signalised intersection are implemented to *safely* manage the flow of traffic, in an efficient way. Most of the signalised intersections are equipped with a Traffic Light Controller (TLC) that runs with set sequences, or cycles. Some of those intersection are equipped with a fixed time control if there is no detection and commonly equipped with the more sophisticated (fully) actuated control.

In addition to detection via loop detectors and push buttons for pedestrians and cyclists, the increased use of connected devices (like mobile phones) are new sources of data that lead to new opportunities. Where actuated control reacts on detected vehicles, a new generation of intelligent Traffic Light Controllers (iTLCs) anticipate incoming traffic flow before they have arrived. This new generation iTLCs do not necessarily follow a cycle pattern or particular sequences, instead they are structure free in order to respond more freely on the measured and anticipated traffic. This creates opportunities for more efficient intersection control.

Losing the structure of cycles within intersection control also rises questions. When efficiency is one of the leading purposes for the new development, will the new generation of iTLCs be fair? Cycles ensure a frequency of turns, which could be perceived as fair, where free structures do not ensure anything.

An example of this problem is given by a side road with a single road user on it, who has to wait for a busy main road during peak hour. Using a cycle-based iTLC guarantees this road user to have its turn within one cycle under unsaturated conditions. However, without cycles it is probably optimal to let this road user wait until peak hour is over. This however, is unacceptable. The relevant question to ask with the present development and opportunities is as mentioned before: ”What is acceptable - or what is *fair*?”

1.1. Research gap & objectives

Philosophers in the field of ethics have discussed about the definitions of *fairness* or *equity* for plenty of years, and there is no unambiguous answer to this question. There are plenty of ethical theories, with each an own definition of equity.

This research will elaborate on some of those definitions of equity in order to find out *how* equity is currently implemented in the world of traffic light controllers. However research in the field of transport policies and traffic management is already acquainted with ethics for evaluation and design (for example (Van Wee & Roeser, 2013), (Mladenovic & McPherson, 2016)), explicitly connecting the *state of the art* iTLCs with their ethical background has not been done before. This research aims to make the *explicit connection* between the principles that drive an iTLC and the ethics that were implicitly considered to implement those principles.

Furthermore, this research intends to perform experiments on an iTLC in practise with the objective of *improving* the equity. In order to know whether there is an improvement, a measure for equity needs to be established first. Equity has been measured before by other studies ((Yarger, 1993), (Kesten, Ergün, & Yai, 2013), (Lucas, Van Wee, & Maat, 2016) (Wu, Ghosal, Zhang, & Chuah, 2017), (Liang, Guler, & Gayah, 2020)). Other than the previous studies, this research will select its measures specific for traffic light control with a foundation of multiple ethical theories.

Two research objectives are stated as follows:

1. To explicitly state what principles are currently implicitly implemented for equity on an intersection, regarding to various definitions of equity by ethical theories.
2. To measure and improve equity of a present iTLC, based on the insight of various definitions of equity by ethical theories.

The ambition of this research is to create more awareness of ethics in the world of traffic light control. Such awareness could lead to a movement of ethics-based TLCs (eTLCs) in the near future, where the addition or fine tuning of principles in an eTLC answer to dilemmas - such as priority, efficiency, equity and sustainability - explicitly supported by ethics. Research objective 2 could kick-start this movement by defining the performance indicators and a demonstration the eTLC.

1.2. Research Questions

The research questions follow from the research objectives and are stated in such a way that answering the research questions will achieve the research objective. Since there are two research objectives stated, two main research questions are stated below:

Research question 1:

”How are ethics implicitly implemented in the current (i)TLCs?”

Research question 2:

”How to improve equity in an iTLC, according to various ethical theories?”

1.3. Scope

Research question 1 shows the need for ethics and present (i)TLCs. However, ethics is a very broad topic, therefore it is not possible to take all theories into account for this research. The amount of ethical theories will be narrowed down to the outlines of a selection of four relevant theories. The selection of ethical theories will be elaborated in Chapter 3.

The present (i)TLCs that these ethics are linked to will be narrowed down to 2 types: one cycle-based and one event-based (i)TLC, each of which is represented by 1 (i)TLC that is currently active in the Netherlands.

For research question 2, an experiment with measures of equity is performed. This experiment will be performed in a simulation environment rather than the real world and focuses solely on the management of a signalised intersection, including cycling paths and pedestrian sidewalks. Road users are the population of interest, thus human related factors stays on the intersection itself, excluding, for instance, effects on local inhabitants and politics. The measures of equity are only connected to this single intersection, not involving any effects on network level. This experiment will be performed with realistic flow amounts of road users during peak hour.

1.4. Thesis outline

The following chapters of this thesis are depicted in Figure **??**. The information that is found in the following chapters will be shortly introduced in this section. Chapters 2 and 3 are used to answer research question 1, and is used as a foundation for the second part (chapters 4, 5 and 6) of this thesis, answering research question 2.

- *Chapter 2* provides the methodology of this thesis.
- *Chapter 3* provides a literature review of ethical theories that set the definitions of equity.
- *Chapter 4* explains iTLCs based on control theory and makes an explicit connection between ethics and example iTLCs CCOL & Flowtack. Answers research question 1.
- *Chapter 5* selects a measurement method for equity that will be used to judge whether equity is improved or not by the following simulation experiment.
- *Chapter 6* contains the experiment setup and hypotheses.
- *Chapter 7* presents the results of the simulation experiment and provides an analysis of these results.
- *Chapter 8* contains the discussion and conclusion of this thesis.
- *Chapter 9* provides recommendations for further research and recommendations for implementation.

2

Methodology

This thesis is split in 2 main bodies with 2 main differences in methodology. The first part uses mainly literature to find an answer to research question 1, whilst the second part uses a combination of literature and simulation experiments in order to find an answer to research question 2. The first main body of this thesis consists of:

- Definition of equity
- Control theory
- Traffic light controllers & equity

And the second main body of this thesis consists of:

- Selection of a equity measurement method
- Simulation experiments
- Validation experiment

The 2 main bodies of this thesis are indicated by the dashed lines, and the different parts are depicted as blocks in Figure 2.1.

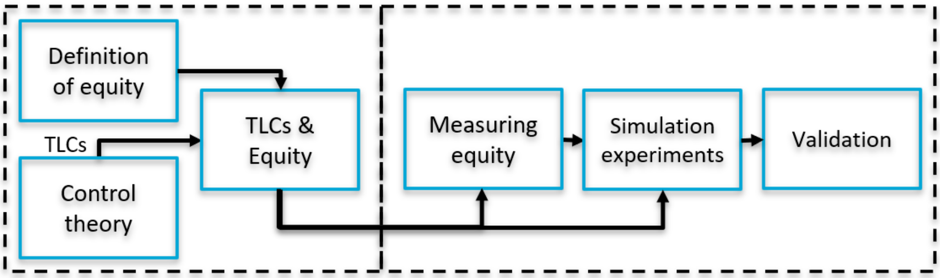


Figure 2.1: Flowchart of this thesis

During this thesis, one main method is to *connect* multiple fields of research. Existing literature is interpreted in such a way that a connection between the research fields can be explained. Generalisation of ethical theories and argued consequences and intentions. This method can be found in the following parts of Figure 2.1:

- **TLCs & Equity**, linking control theory & equity to traffic light controllers
- **Measuring equity**, linking equity to mathematical/pragmatic measures in traffic management
- **Simulation experiments**, linking previously obtained knowledge of equity, control theory and measures together to perform simulation experiments with the goal of improving of equity

The other main methods consist of literature review and a simulation experiment. The following paragraphs elaborate the methods that were used per subject in this thesis.

Definition of equity

Ethics is a broad and comprehensive subject, that originates from the early cultures about 2500 years ago (Yu, 2005). Ever since, the topics of ethics is debated and new ideas of ethical theories arise. Ethics describes what is *morally* right or wrong, including definitions of equity. These definitions of equity are used as foundation for this thesis. Because of the accumulated amount of available ethical theories over a long period of time, a selection of ethical theories is made, based on ethical theories that have been selected for previous literature in the field of traffic management. This selection includes utilitarianism, egalitarianism and sufficientarianism as a broad spectrum of teleological theories, which judges based on the consequences of an action. Consequences of technical implementations can be measured, and are therefore useful for this thesis. Deontology on the other hand, judges based on the intention of the action and also finds its place in traffic control.

The main body of the ethical theories is described with the use of philosophical journals and books written by major philosophers, rather than transport / traffic related literature. This split is made because the definition(s) of equity should not be correlated with the topic of research. This literature review aims to *find the main definitions (axioms) of equity for the considered ethical theories*, which is the input for the follow up parts of this thesis.

Control theory, traffic light controllers & equity

Next, general control theory is used to shed light on the different ways that controllers interact with their processes in general. Such control theory is applicable for signalised intersection control, and helps to clarify the similarities and differences between different iTLCs. Because there are multiple types of TLCs, and multiple choices in the current market for these types, one example of a iTLC is provided for those control methods. The optimisation process for Flowtack is described, based on known technical specifications and members of the Flowtack team at RoyalHaskoningDHV.

In the next block, TLCS & Equity, the example controllers are decomposed to a set of principles that describe the rules and techniques of CCOL and Flowtack in more detail. This is where equity and control theory come together. *How* these principles work is found in documentation like (Wilson, 2006) and (Kant, Hut, & Wolfrat, 2019). The intentions and consequences of the iTLC principles are analysed under the assumption that the resulting effects are the reasons for implementing the principles at the traffic light controller. Then, the principles are linked with a generalised axiom from the ethical theories that these principles agree with. It is possible that there is no link at all between the selected ethical theories and the iTLC principles, but it is also possible that there are multiple links. The link between ethics and iTLC principles is now explicitly stated.
Identifying *how* ethical theories are implemented with principles helps to determine *what* could be improved or adjusted in the experimental part of this thesis. Furthermore, by comparison of the ethical background of different iTLCs, certain ethical theories that are *relatively* over- or under-represented indicate how equity on the iTLC has developed over time. Insight in the principles and the explicit link with ethics opens the discussion on differences between TLCs and the impact on equity.

Selection of a equity measurement method

The performance of recent developments in the field of signalised intersection control have previously been evaluated with the use of performance indicators like *safety*, *throughput*, *logic*, *emissions*, *intersection capacity*, *average delay* and *promotion of active modes - and public transport* (Willekens, 2020) (Ranjitkar, Shahin, & Shirwali, 2014). These performance indicators originate from the evaluation of conventional Traffic Light Controllers and have been repeated for the evaluation of recently developed TLCs, that optimise based on these performance indicators. While different methods can be measured by the same performance indicators, since they are eventually impacting the outcome of on the same road situation, it is the question whether the optimised performance indicator is still a relevant measure. This emphasizes the need for (a) new measure(s).

A measure of equity is necessary in this research, in order to measure whether the following experiments cause an improvement of equity or not. The definitions of equity that have been elaborated in the first block of the methodology are key to find a measure fit to evaluate the performance on equity. Since there are multiple definitions of equity, multiple measures are required. Since the definitions of equity are rather complex, a main -non nuanced- axiom can be made explicit with a mathematical indicator. Literature is consulted to see how equity has previously been measured in the field of traffic / transport. Some literature has been explicitly linked to the definition of equity that its equity measures refer to, however, not all literature has done this explicitly. To find measures for the definitions of equity that are selected in this thesis, the measures from literature are now explicitly linked to the definition of equity that these measures apply to. This creates an oversight of measures, ethical theories and their sources, which is then used to find a collection of measures that represent each of the chosen definitions of equity.

Simulation experiments

With known definitions of equity, a measure to assess the level(s) of equity and knowledge of traffic light controllers and control theory, it is time to experiment with the traffic light controller in a simulation environment, with the goal of improving the equity performance. A simulation experiment is chosen, because simulations visualises the behavior and automatically measures the delay of all road users. Real life experiments on this scale would come with safety issues and risk of creating congestion. The simulation experiment is performed with the available simulation software at RoyalHaskoningDHV, namely Aimsun, provided with an existing intersection and realistic flow and arrival rates. Additionally, Flowtack comes with certain settings that influence the objective function and can be modified conveniently. Some trial and error experiments are performed initially in order to gain insight in . This insight, together with theoretical knowledge from the previous chapters, is used to construct hypotheses for experimental settings.

The experimental settings are created with the explicit goal of improving equity. Weight functions are tested based on different function shapes, that either might be interesting, or just to prove whether the results behave in an expected way. On the other hand, multiplication factor settings in Flowtack are constructed based on reason, trial and error. More details about the experiment setup can be found in Chapter 6.

Validation

When experimental settings improved equity, by the defined definitions and measures of equity, these settings are validated. A validation is necessary because traffic control is rather complex, one intersection is not the other. The validation is also performed to find if there are any unforeseen factors that might have impacted the results. The validation is performed with experimental settings that are created in the same way as the settings that generated the best results in the simulation experiment and differs in the simulation environment (intersection layout & origin-destination flow). A different environment, logically, leads to different results with- and without the proposed settings for improving equity. New referential scenarios are needed, and the experimental settings are validated if the course of the shift in results stays similar for the different validation scenarios.

Another form of validation is implicitly performed by regular communication with experts in the fields of traffic management and simulation modelling. Intermediate results are presented to supervisors and experts in order to gain feedback on the experiment, which leads to extra experiments and deeper understanding of *why* these results were found. This form of validation is an on-going process during the entire experimental phase (2nd main body of this thesis). More details about the validation can be found in Chapter 6.

3

Ethics

This literature review includes literature on various ethical theories, regardless of traffic related theory. The theories that are discussed in this chapter will be used as input for Chapters 4 & 5 and sets the definitions of equity that will be referred to in the rest of this document. A summary of the discussed ethical theories is presented at the end of this chapter.

3.1. Ethical theories

The study of ethics is about 2500 years old, as Confucius and Socrates are considered its founding fathers for Eastern and Western ethics (Yu, 2005). Throughout the years, many philosophers have documented their ethical theories, creating a wide range of theories. Names like Spinoza (1632-1677), Kant (1724-1804), Hegel (1770-1831), Marx (1818-1883), Nietzsche (1844-1900), Sartre (1905-1980) and Rawls (1921-2002) are some examples of influential philosophers one might have heard about. Baumane-Vitolina, Cals, and Sumilo (2016) distinct three main groups of ethical theories: teleological, deontological and virtue ethics. Teleological theories originate from the Greek 'telos', translated to 'an end'. The end is the consequence of an action and not the action itself, thus in teleology the consequence of the action determines whether the action is ethical. On the contrary, deontology originates from the word 'deon', which means 'duty' in Greek. The duty, or motivation to act, is key for ethical behaviour in deontology, rather than the consequence in teleology. Lastly, virtue ethics focuses on desired personal traits that are behaviour related (Baumane-Vitolina et al., 2016). Personal traits are out of the scope of this research, therefore virtue ethics are left out of consideration in this chapter. Some teleological and deontological theories will be discussed.

A selection of ethical theories is made out of Van Wee and Roeser (2013)'s earlier research where ethical theories are combined with cost-benefit based ex ante evaluation. This selection should cover a broad spectrum of ethical theories, including teleological and deontological theories. The theories that were mentioned in this research are contextualism, contractarianism, utilitarianism, deontology and egalitarianism.

Van Wee and Roeser (2013) mentions contextualism as a non-monistic theory, which means this theory consists of various ethical considerations instead of one single moral principle. This makes contextualism a very interesting alternative, yet more complex than monistic theories. Due to time constraints, this theory will be cast aside for further research.

Contractarianism is another interesting theory, based on the idea that every member of the community should sign the imaginary contract. This means that every individual has to agree. A strong mechanism to achieve agreement can be compensation for those that wouldn't agree in the first place. Yet, compensation is out of the scope of this project because it involves individuals, thus contractarianism is cast aside.

This leaves three ethical theories from Van Wee and Roeser (2013) that will be elaborated in this chapter are: utilitarianism, deontology and egalitarianism. A fourth interesting ethical theory is added as it was identified as an interesting theory for intersection control: sufficientarianism. This theory has been elaborated in Lucas et al. (2016). The main concept of the above mentioned ethical theories will be elaborated. This is followed up by a brief summary, stating the key principles of justice for each ethical theory, defining equity. Ethics involves more than just equity, however the aim of this literature review is to define equity.

3.1.1. Utilitarianism

Utilitarianism is an altruistic form of teleology, where *the end justifies the means* (Van Wee & Roeser, 2013). There are 2 forms of utilitarianism, the classic ’act utilitarianism’ and the newer ’rule utilitarianism’. Both forms of utilitarianism will be discussed in this paragraph, starting with act utilitarianism.

Act-utilitarianism can be described by three basic rules (Åqvist, 1969):

1. An action ought to be done, if and only if its consequences are better than those of every alternative;
2. an action is right, if and only if its consequences are at least as good as those of every alternative;
3. an action is wrong, if and only if its consequences are worse than those of some alternative.

The definition of ’better’ in this formulation has been clearly described by Harsanyi (1977). He describes the above mentioned rules as the maximisation of ’social utility’. Utility can then be approached in a hedonistic way by the means of the total amount of pleasure, or a Moorean way where social utility is measured by the total amount of ’mental states of intrinsic worth’. The hedonistic approach assumes that pleasure is the only motivation for humans to act. In order to find the societal utility, the sum of the pleasure can be used. Moore’s definition of utility however, differs for each person, as every person has different and situational needs in order to achieve their objective mental state of intrinsic worth. To calculate societal utility regarding to the latter principle, the arithmetic mean is used instead of the sum. The sum and arithmetic mean are mathematically equivalent when the amount of persons in the equation remain constant (Harsanyi, 1977).

Arithmethic mean:

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i$$

Maximisation of social utility can, in classic act-utilitarianism, mean that someone could be disadvantaged over others if this generates more utility for society as a whole. To put this concept to an extreme, if a lie leads to more happiness in certain circumstances, a utilitarian is morally right to lie. This is controversial, as lying can be considered unjust in any kind of situation, following deontological theory (next section).

Harrod (1936) revised utilitarianism because of, how Goodin (1995) describes it, the ”Limits of reason” (p. 17). Furthermore, utilitarians would be considered unreliable when they always lie if that leads to better societal consequences. The essence of the problem is stated by Harrod (1936) as ”There are certain acts which when performed on n similar occasions have consequences more than n times as great as those resulting from one performance” (p. 148). The Kantian theory obligates truthfulness, as it is morally right to always be truthful, this will be elaborated in the next section, ’Deontology’. Harrod (1936) has embodied the Kantian principle into the utilitarian theory, creating the concept now called rule-utilitarianism. To fall back to the previous example, the rule-utilitarian does not condemn all lies, but the lie would be justified so that if the total loss of confidence would not exceed the disutility of truthfulness in all circumstances. The correct moral rule should be defined in such a way that it would create the highest societal utility in the long run. Utilitarian moral rules will always have exemptions for situations of emergency or exceptional cases (Harsanyi, 1977).

3.1.2. Deontology

Deontology is a collection of moral principle based ethical theories. If a judgement is not solely dependent on consequences, Gaus (2001a) states that the theory behind this judgement is then considered deontological. Based on this definition, the above described rule-utilitarianism is could be considered a deontological theory, because a rule-utilitarian will not act upon the optimal consequences when the moral rule/principle rejects the act (Gaus, 2001a). To find a better understanding of moral principles, we move to key deontological philosopher Immanuel Kant. Kant stated that moral principles need to be universally and unconditionally valid: the categorical imperative (Van Wee & Roeser, 2013). The categorical imperative does not need argumentation in order to establish, it is rather obvious to rational humans. Kant's formulated three categorical imperatives (Robinson, 2019):

1. Formula of autonomy or universal law
2. Formula for the respect of the dignity of persons
3. Formula of legislation for a moral community

The first formula implies that the moral rules we decide to live by must be intended by us to be universal: apply to everyone. The second formula says we cannot use people as a means to our end, we must treat people as an end in themselves. The third formula means that all rules we create should harmonise with a kingdom of ends, where every person in the kingdom is subject of the universal laws.

Discussion whether moral rules are absolute or not divides the deontological philosophers. Some moral 'fanatics' say that moral rules can not be broken under any circumstances, regardless of the consequences. Other deontologists state that exceptions to moral rules are evident, as not all moral rules weigh the same if one has to chose between breaking two moral rules (Gaus, 2001a).

Actually, deontology is so broad, Gaus (2001b) concludes his article with ten different influential ways in which deontology has been understood:

1. "as an ethical theory in which the right does not maximise production of the good;
2. as an ethical theory admitting considerations of justice;
3. as a moral theory that advances absolute moral commands or prohibitions;
4. as an ethical theory such as Prichard's in which duties and obligations are justified independently of the concept op good;
5. as an ethical theory such as Gauthier's moral contractualism, in which the concept of the right is not defined in terms of a substantive notion of the good;
6. as an ethical theory according to which our values and conceptions of the good presuppose justified moral principles;
7. as an ethical theory which would have us hold that we have reasons to respect as well as to promote value;
8. as an ethical theory founded on, or giving a large role to, the concept of respect for persons;
9. as an ethical theory which gives pride of place to moral rules;
10. as an imperatival ethical theory." (Gaus, 2001b, p. 11)

No deontological theory conforms to all ten definitions. Because of the broadness of deontology, even act-utilitarianism can be considered deontological conform definition 2 and 10, and rule-utilitarianism conforms 1, 9 and 10 (Gaus, 2001b).

3.1.3. Egalitarianism

Egalitarianism has a closer connection to deontology than utilitarianism, because it is based on moral considerations especially in the topics of justice and fairness. However, egalitarianism falls under the group of teleological theories, as it measures the ends, rather than the intention. Egalitarianism originates from the french word 'égal', which means 'equal'. Just like previously shown in deontology, there are multiple egalitarian views. John Rawls, Amartya Sen and Martha Nussbaum are leading egalitarian philosophers, their views will be elaborated in this chapter.

Rawls (2009) has created his own ethical theory based on a self-developed thought experiment. In this experiment, the subject uses the 'original position' as its base for developing moral principles of justice and fairness. The original position is a perspective reached by imagining an unborn impartial state, where the subject has no idea about its future social status. Ignoring social status and personal interests is called the 'veil of ignorance'. Using this thought experiment, Rawls states, rational human beings will develop maximin principles: benefiting the least advantaged of society. A second important result from Rawls thought experiment is that certain primary social goods are needed in order to have a fair society (Van Wee & Roeser, 2013):

- ”Basic liberties, including freedom of association;
- Freedom of movement and choice of occupation;
- Powers and prerogatives of offices and positions of responsibility;
- Income and wealth;
- The social bases of self-respect.” (Van Wee and Roeser, (2013), p. 7)

Crocker (1977) argues that the maximin principle is not necessarily pure egalitarian, as not everyone is treated equal: the initially least advantaged are now advantaged over the initially slightly better advantaged. Four other mathematical examples of egalitarian distribution are stated by Crocker (1977), which are interpreted as:

1. an upper boundary for absolute differences;
2. an upper boundary for relative (percentage) differences;
3. an upper boundary for the relative improvement between initially least- and most advantaged;
4. a boundary for absolute increase for the initially least advantaged, but allowing increase of relative differences.

The above principles are very material based, as fairness is based on the distribution of goods. However, philosophers Sen & Nussbaum have a different view on egalitarian fairness. Instead of the distribution of goods, they think that the 'capabilities' should be distributed equally (Van Wee & Roeser, 2013). Nussbaum (2003) describes capabilities as ”What people are actually able to do and to be” (p. 33). Sen & Nussbaum stated that distribution of *goods* is an inadequate way of judging equality, because not every person has the same *needs*. This is caused by diversity in: person, environment, social climate and relational perspective. For example, a handicapped person generally needs different goods than an able bodied person (Van Wee & Roeser, 2013).

Moreover, Nussbaum (2003) listed ten capabilities, with in mind that each person is treated as an end itself, just like deontologist Kant stated in his second formulation of the categorical imperative. The ten central human capabilities (shortened the explanation) according to Nussbaum (2003):

1. **Life** - No premature death or reduction of life quality to not-worth-living;
2. **bodily health** - Physical, reproductive health and shelter;
3. **bodily integrity** - Secure from any type of violence;
4. **senses, imagination and thought** - Education and freedom of choice and speech in artistic and religious matter;
5. **emotions** - True emotions, not forced by fear or anxiety;
6. **practical reason** - Ability to form a concept of good or bad, and ability to critically reflect on life;
7. **affiliation** - Ability to live with and toward others and social bases of self respect and nonhumiliation;
8. **other species** - Being able to to live with concern for and in relation to flora and fauna;
9. **play** - Being able to enjoy recreational activities;
10. **control over one's environment** - Political participation and material property and privacy.

To strengthen this theory, Sen notes that research in the field of happiness shows that an increase of an already wealthy person's wealth, does not increase his/her happiness. This conflicts with any type of conventional measure of utility, 'goods' or Willingness to pay. Thus, equalising capabilities should be considered for a new measure of equity (Van Wee & Roeser, 2013).

3.1.4. Sufficientarianism

Sufficientarianism comes from the word ’sufficient’, enough. The main principle of this ethical theory is to bring all persons in a society above a certain threshold for their basic needs, such as Rawls primary social goods stated above in the egalitarianism section. Other than the boundaries stated earlier by Crocker (1977), a sufficientarian boundary only sets a minimum boundary for the distributed goods.

Arneson (2007) states 2 important rules that explain sufficientarianism:

1. **The Headcount Claim**, the number of persons with sufficient goods should be maximised;
2. **The Negative Thesis**, there are no distributive criteria when everyone has access to sufficient goods.

A simple example of the headcount claim is constructed to clarify how it works: Distributing €3 over 3 children, with a threshold value of €1.50 (price for ice cream). Option 1: each kid receives €1 euro, which is insufficient to buy ice cream. Option 2: two kids receive €1.50 euros and 1 kid receives nothing. The headcount claim from the sufficientarian point of view would lead to option 2. The negative thesis can be explained with an abundance of money, where every kid would get sufficient money to buy 1 ice cream and the distribution of the abundance of money does not matter.

Criticism on sufficientarianism is found in Arneson (2007). These critics are based on the fact that sufficientarianism would benefit those who are close to the threshold in small amounts by large numbers instead of those far from the threshold by large amounts. Other critics focus on the negative thesis, because it leads to indifference of equity above the threshold.

Shields (2020) recently published a new idea in response to the criticism on sufficientarianism: pluralism. A pluralist would accept the importance of non-sufficientarian principles, on top of sufficientarianism. This way, the indifference from the negative thesis can be overcome by the addition of for example egalitarian principles after sufficient has been reached.

3.1.5. Summary of ethical theories

Four ethical theories have been elaborated in this chapter: utilitarianism, deontology, egalitarianism and sufficientarianism. It has been made clear that there are different branches with different views within these theories. Even though there are many different views, the fundamentals of the theories are identified and summarised in Table 3.1.

Table 3.1: Ethical theories and fundamental principle(s) of equity, summarised.

Theory	Fundamental principle(s) of equity	Obtained by
Utilitarianism	Utility maximisation, greatest good for the greatest group. Only consequences matter.	Optimising total utility
Egalitarianism	Veil of ignorance, benefit the least advantaged in society. Distribution of capabilities.	Maximin principle
Sufficientarianism	Everyone has right to a sufficient level their basic needs.	Headcount claim, negative thesis
Deontology	Categorical imperative, moral rules apply to everyone. Human dignity is central.	Moral constraints

4

Ethics in traffic light control

This chapter starts with a short overview of control theories. These theories are rather general for anything that includes a controller that influences a process. A signalised intersection manages traffic, thus can be covered by control theory with a controller and a process. What in this research is referred to as a intelligent traffic light *controller* (iTLC), is the controller that corresponds with the controller block of control theory. This contradicts with other documents (Fløan, Looijen, Smit, & Hiddink, 2016), where the controller from control theory would be referred to as an Intelligent Transport System application (ITS), whilst 'iTLC' refers to the hardware on the intersection (including traffic lights and detection).

In the subsequent section, the principles that are implemented in iTLCs are linked with corresponding ethical theories, for example iTLCs CCOL & Flowtack. These links are made to identify *how* equity is currently implemented in iTLCs. The similarities and differences in ethical background of those controllers will be highlighted in this chapter's conclusion.

4.1. Control theory

Control theory describes the input, output and process of a system, emphasizing *how* these characteristics influence each other. Control theory is relevant in order to understand how different TLCs influence / manage the real world traffic situation on the intersection. A few general definitions that are important to understand control theory are listed:

- *Controller*, the decision maker that uses information (*desired behavior*) as inputs and sends out its decisions as *control signals*
- *Desired behavior*, the desired outcome of the *process*, comes in form of control laws (restrictions)
- *Control signals*, the output of a decision maker that will be sent to the process
- *Process*, the response of the 'real-world' system to the combination of control signals and disturbances
- *Process behavior*,
- *Disturbances*, inputs to the *controller* or the *process* that cannot be influenced by the controller (external influences), but do effect the outcome (van Lint et al., 2014)

Three generic control methods are explained and linked to the field of signalised intersection control, starting with a basic control method: feedforward control, to then add more complexity: feedback control & model predictive control (MPC).

Feedforward control

Feedforward control methods solely react to disturbances and predefined desired behavior. Data regarding to the current state and/or output of the system is not used for the controller's decision making process (van Lint et al., 2014).

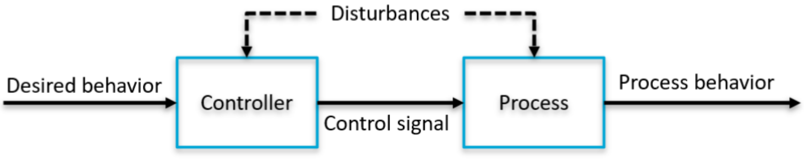


Figure 4.1: Feedforward control structure in a block diagram, adapted from (van Lint et al., 2014)

On a signalised intersection, such feedforward control is used by fixed time control. Fixed time control uses historical flow data and the conflict matrix[1], to distribute green time in a fixed cycle for a fixed sequence of stages[2]. The Webster formula[3] is used to find the optimal cycle time and corresponding green times for each stage, based on the historical flow data and capacities (Knoop et al., 2019).

The desired behavior of such a fixed time control system is to have the stages take turns, based on the predefined schedule. An important disturbance to the controller is time, as the controller can adjust the schedule to the corresponding time of day, which is the control signal. The process includes the management of traffic on the intersection using predefined cycles.

Feedback control

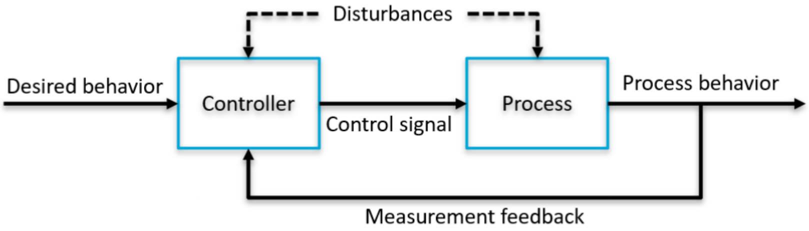


Figure 4.2: Feedback control structure in a block diagram, adapted from van Lint et al. (2014)

Feedback control adds a feedback measurement of the process behavior back to the controller in the block diagram, as depicted in Figure 4.4 (van Lint et al., 2014).

On an intersection, such feedback control is used by fully actuated control. Fully actuated control uses a fixed sequence of conflicting directions, just like fixed time control. However, fully actuated control makes use of real-time detection of road users, in order to decide whether a green phase[4] should be extended, truncated or entirely skipped. The use of phases instead of stages reduces the internal lost time[5] considerably (Knoop et al., 2019). Figure 4.3 shows the phases that are used in fully actuated control. This shows that there are various possibilities to adjust the green phase, relative to a fixed green duration in fixed time stage control. Fully actuated control is the state of the art in the Netherlands, CCOL is a typical fully actuated control application that is applied as the controller in the block diagram.

In the fully actuated **CCOL** controller, the measurement feedback consists of a loop detector that measures whether there is traffic present at its current direction in the cycle. The presence of traffic means that the current green phase could be extended and the lack of traffic means that the corresponding green phase will be skipped or truncated to move on to the next direction. The process in this block

---

[1] Conflicts on an intersection are movements that would collide when given green light simultaneously. Conflict groups are combinations of directions with mutual conflicts that do not conflict each other (Knoop et al., 2019).

[2] A stage is a group of non-conflicting directions that are granted green at the same time. The sequence of stages is repeated every cycle and a direction can be placed in multiple stages if it does not conflict with the other directions in those stages (Knoop et al., 2019).

[3] Calculates an optimum cycle time per conflict group based on the internal lost time, total vehicle flow rate and total saturation flow rate. The Webster formula uses empirical factors for this optimisation and assumes the arrival of vehicles randomly Poisson distributed (Knoop et al., 2019).

[4] A phase structure uses individual conflicts of directions to prolong the green time of a direction during a next, non-conflicting direction's turn. The length of each green phase can be different in each cycle (Knoop et al., 2019).

[5] Internal lost time is calculated per conflict group and consists of the sum of the time that it takes for a driver to react on green, the yellow time that is not used and the clearance time between conflicting movements.

signal	colour	signal phase
🟥	red	Red before request
	red	Red after request
🟩	green	Advance green
	green	Fixed green
	green	Waiting green
	green	Exetension green
	green	Parallel green
🟨	yellow	Yellow time
🟥	red	Red before request - next cycle

Figure 4.3: Phase cycle, adapted from Knoop et al. (2019)

diagram corresponds to the management of traffic by adjusting the green phase to the measured situation. Note that this feedback is limited to the lanes that currently are in the green phase, the presence of traffic on other lanes does not influence the controller decision. Viti and Van Zuylen (2010) described in more detail how the vehicle actuated control system interacts with the measurements of detector loops. The presence of traffic is in this case a disturbance input to the process. The controller decides based on control laws and feedback measurements on the presence of traffic in the current lane, whether a green phase should be extended, truncated or skipped.

Model predictive control

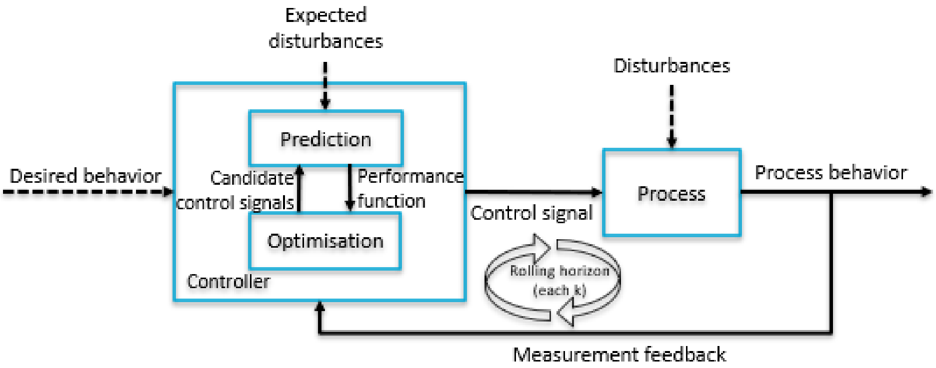


Figure 4.4: Model predictive control structure in a block diagram, adapted from (Knoop et al., 2019)

The block diagram for MPC is similar to that of feedback control, as it also includes a feedback loop between the controller and the process. However, the MPC controller uses both prediction and optimisation for its decision making, which differs from the previous controllers.

The controller uses feedback input of the system state $x(k)$ as a whole for its optimisation. This means that, rather than measuring whether there is traffic present in the current green phase in order to decide by control laws how to act, the model predictive controller uses the presence of vehicles at all directions, estimated arrivals by measurements of the current state, to predict the optimal solution for this situation over a future time horizon N, for every time step of k. This updating time horizon is called the *rolling horizon*. The prediction state $\hat{x}(\tilde{k})$ for time step $k \leq \tilde{k} \geq k+N$ with control signal plans $u(k), ..., u(k+N)$. The controller searches for a control signal u, which optimises objective function J by its best prediction state $\hat{x}(\tilde{k})$ (Knoop et al., 2019).

Various versions of objective function J can create various types of controllers within the MPC type of control. An objective function that optimises green times within a given sequence or cycle, with average flow predictions, can for example be used as input to optimise the Webster formula, instead of the historical flow data input (in feedforward control). An example of a whole different type of controller is Flowtack (Humblet, 2020).

Flowtack is an example of and iTLC, practised in the Netherlands, that uses a block diagram such as that of the MPC. However, an MPC-version of the previously mentioned CCOL controller *would* optimise cycles by varying the cycle time and green time duration of the predetermined sequence of green phases. Instead, Flowtack optimises the sequences and the green times structure-free. Structure-free refers to the freedom of defining the sequences without being limited by the rule of creating a cycle: there are *no cycles* in Flowtack. This means that, unlike the other types of controllers, this controller can interchange green light between 2 directions - even when there is presence of traffic on the other directions - if this is found 'optimal' for the that situation. There is no documentation in mathematical format of Flowtack's operations. A rough description of Flowtack is made in the following paragraphs, in order to to clarify the prediction- and optimisation processes. A list of definitions is created for clarification of the variables used in this description:

- J, the objective function, defines *what* is optimised
- k, frequency or time step for which the objective function updates its solution. Order of magnitude 1 second. $k \in K$.
- n, rolling horizon N is divided into a number of time steps n. Every time step n, control plan u can decide whether direction j is granted green or not. Adjustable variables, order of magnitude N = 400 seconds, n = 0.2 second. $n \in N$.
- i, individual road user i. $i \in I$.
- $j(i)$, direction j on the intersection where individual road user i queues. $j \in J$
- $u_j(k)$, the optimisation variable, control plan u defines whether direction j is planned red or green; 0 or 1. The amount of control plans that are tried for each optimisation step k depends on the amount of possible solutions, order of magnitude 100 - 30.000.
- $w_i(n)$, accumulated waiting time for road user i previous to the starting time $n = 0$ of time step k.
- $f(w_i(n))$, weight function (curve shaped) for each road user, with the weight factor (w/s) on the y-axis and waiting time (s) on the x-axis.
- $\beta_{j(i)}$, a multiplication factor (-) that is direction- and road user type dependent.

To decide the optimal control solution, Flowtack uses an objective function J, which updates approximately every second (time step k). This objective function finds an optimal solution for a control plan $u_j(k)$, which is the optimisation variable that is tested with a decision tree. Within the optimisation, N defines the time horizon; how far the optimisation looks ahead.

Figure 4.5 shows the the timeline which includes the arrival time of road user i at left side, optimisation starting point k somewhere in the middle and time horizon N on the right side. The accumulated waiting time for $n = 0$, $w_i(n = 0)$, is the time that road user i has waited prior to optimisation time step k. Time horizon N is divided into sections of n seconds, for each of which control plan $u_j(k)$ can change its signal. One could imagine that a time horizon of 400 seconds in steps of 0.2 seconds leads to a countless number of possibilities for the decision tree. Therefore, the decision tree is pruned, leading to the order of magnitude of 100-30.000 options of $u_j(k)$[6].

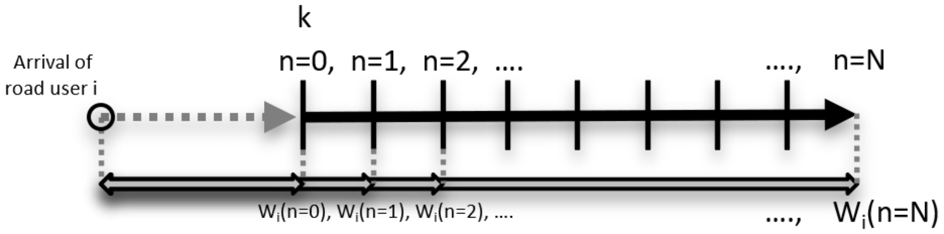


Figure 4.5: Timeline

---

[6] Details about how this decision tree works can not be disclosed in this thesis.

For each time step n, a weight for each waiting road user $i \in I$ is added to the optimisation. The weight that is added over time step n is defined by weight function $f(w_i(n))$, which is dependent of the time that road user i has already waited before time step n. That waiting time is referred to as the accumulated waiting time $w_i(n)$ in Figure 4.5. The accumulated waiting time is defined, because a vehicle could have been already waiting when time step k starts, or it can arrive after time step k starts, which means it has not been delayed yet. Thus, the accumulated waiting time defines the location of road user i on the weight function $f(w_i(n))$ of a time step n, over which the weighted delay is summed in the objective function.

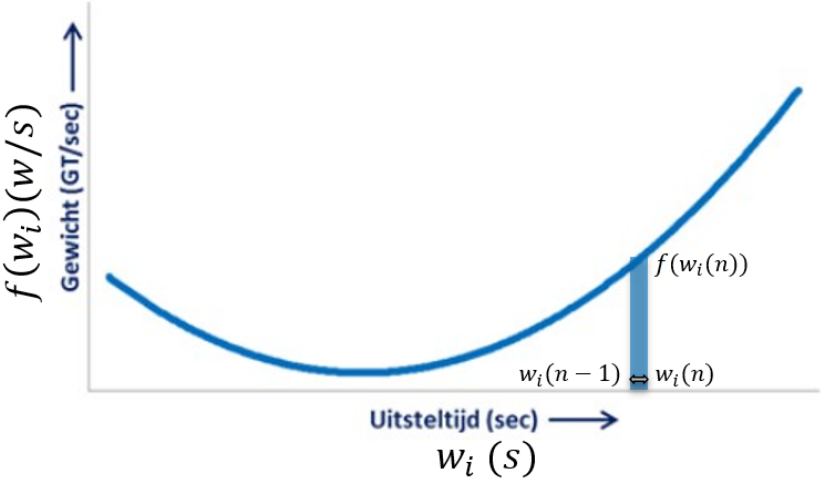


Figure 4.6: Weight function $f(w_i(n))$, time dependent weight factor (w/s) on the vertical axis, and expected delay (s) on the horizontal axis. Also known as 'Badkuip curve' or 'Bathtub curve', adapted from Kant et al. (2019)

Weight function $f(w_i(n))$ is depicted in Figure 4.6. The marked area in this Figure shows the weight accumulation per second (w/s) on the vertical axis for time step n with an accumulated waiting time $w_i(n)$ for road user i. $w_i(n-1)$ is the waiting time at which previous time step $n-1$ ended. Furthermore, a direction or road user type can be granted a multiplication factor, which multiplies the whole block of weight depicted in Figure 4.6.

Flowtack sums the weight of each road user and each time step that this road user was waiting. Then multiplies this with a corresponding multiplication factor, and finally minimises this by trying various control plans $u_j(k)$. The following equation describes the optimisation function:

$$J = min_{u_j(k)} = \sum_{i}^{I} \sum_{n}^{N} \beta_{j(i)}\, f\big(w_i(n)\big)\, \big(w_i(n) - w_i(n-1)\big)$$

Equity in a block diagram

Now the block diagrams for feedforward, feedback and MPC are elaborated with traffic light controller examples, it is interesting to identify the locations in a block diagram where equity-related principles could be applied. The MPC is the most complex and complete block diagram, therefore this block diagram is used as a reference for locating equity in the block diagrams.

To start, equity could be the optimisation goal of a controller. In MPC, this means that equity finds itself at objective function J, where equity is to be maximised by testing variable control plans. As objective, equity is required to be explicitly defined, because an outcome for a 'level' of equity needs to be predicted with mathematical relations, testing the impact of variable control plans on the level of equity. Another place to implement equity into the block diagram is found in control laws, via the desired behavior input. These control laws can consist of system boundary conditions, restrictions or other forms of desired control behavior. Desired behavior can result in different types of candidate control signals or different behavior at the performance function.

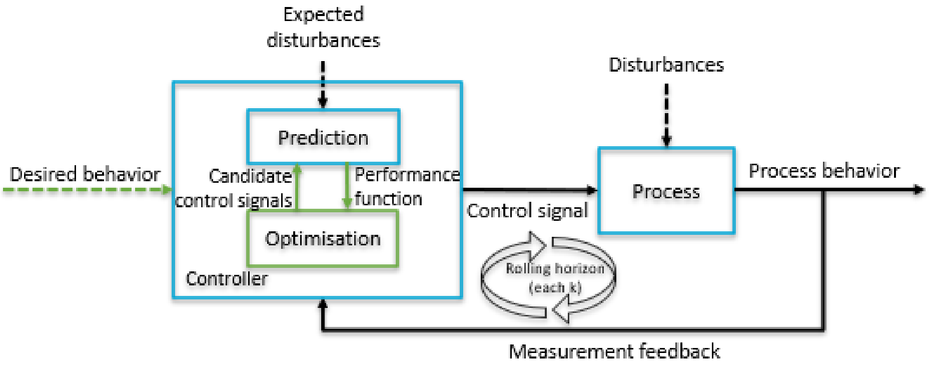


Figure 4.7: Locations for implementations of equity, on the MPC block diagram

Figure 4.7 shows the locations where equity-related principles can be implemented in green. Note that in feedforward and feedback control, the option to implement equity is limited to desired behavior, which can still influence the control scheme. With a predefined control structure in feedforward- and feedback control, a form of optimisation finds it place in the Webster formula, outside of the block diagram. Changes to this formula could be another alternative to implement equity goals.

On the other hand, Flowtack does make use of changes in the performance function and control input measures, as weights are added in order to influence the optimisation outcome in a desired, equitable, way. However, equity is not implemented explicitly as its optimisation objective, settings within the performance function are tuned to improve equity, implicitly.

Conclusion

The main difference between feedforward and feedback control is the caused by the provision of information on the current state of the system in the feedback controller, which allows the controller to be reactive. The MPC uses a similar block diagram to that of the feedback controller, however, due to predictions and optimisation based on these predictions, the MPC is proactive, rather than reactive. Currently, the feedback controller and MPC controllers are preferred over feedforward controllers in practice for iTLCs in the Netherlands, because these controllers are able to respond to the situation. Most intersections in the Netherlands are equipped with a feedback controller, rather than the feedforward fixed time controller. MPC-like controllers are rarely implemented, as this control technique is fairly new in the market of iTLCs.

Fixed time (feedforward) control will not be taken into account in the following section, because this control structure is not a desired type of control anymore. The following sections elaborate on the principles that are key to CCOL and Flowtack, as examples of feedback control and *structure-free* model predictive control. Being structure-free is added to Flowtack's description, because this characteristic is rather unique to Flowtack and not covered by the definition of MPC. The principles are subsequently linked to the ethical theories that correspond with the effects and/or intentions of adding these principles. Most of the upcoming principles can be identified as control laws: inputs of desired behavior.

4.2. Linking iTLC principles to ethics

In the following section, a link of control theory will be made with intersection control and examples of iTLCs in practise are given. Because each iTLC could work differently, this chapter uses 2 examples of iTLCs to show *their* specific principles. These principles are presumed to be added with a certain reason, or intention: an improvement of a performance of some kind. In the following sections, the principles of the iTLCs are linked with the different the ethical theories that it currently implicitly corresponds with. The effects or consequences of the principles are elaborated, after which the implicit intention of the principle can be identified and linked with ethics.

4.2.1. Feedback control: CCOL principles

A first and very important principle in CCOL is that it uses **cycles**. Working with cycles ensures turn based events, meaning there is a constant sequence of **phases**, with the difference from stages in a fixed time control that the duration of the phase is variable. These phases are based on combinations of conflict groups, and the sequence of the conflict groups is predefined. However when no traffic is detected in CCOL, the corresponding phase will be omitted. Cycles are implemented in the first place, because the function of a TLC is to provide safe crossing for all directions, avoiding conflicts.
The basic idea of a cycle can be identified as an *egalitarian* principle: all directions are served with the same frequency. However, some directions might have multiple occurrences in one cycle when they either have little conflicts with other directions, or when prioritised. Prioritisation will be discussed later this section. Using **phases** instead of stages, reduces the internally lost time. This allows for more optimal solutions, reducing unnecessary delay. Thus, some *utilitarian* aspects are present within the cycles too.

An added principle that influences the cycles, is the **maximum cycle time**. The maximum cycle time provides a threshold for the duration of 1 cycle. If no maximum cycle time was implemented, one main flow of vehicles could claim a very long green time, causing the conflicting directions to wait longer than acceptable. A maximum cycle time of 120 seconds is currently implemented in the Netherlands (Wegenwiki, 2017). The implementation of a maximum cycle time can be seen as either sufficientarian or deontological, depending on the argumentation. The maximum cycle time implicitly provides a maximum waiting time equal to the maximum cycle time if the queue can be processed within 1 cycle. The exception to this is at an over-saturated intersection, where it can take multiple cycles for a waiting vehicle to cross.
Creating a maximum waiting time comes closest to a *sufficientarian* idea, as it creates a maximum threshold for something that is undesired. On the other hand, one can argue that it is undesirable to long cycle times because of the risk that road users might ignore red light if cycles take too long, which is unsafe. In that case, it can be argued that a maximum cycle time is a moral constraint due to its function to limit waiting time, which suits the *deontological* theory.

Also, a **maximum green time** is implemented. The maximum green time makes sure to switch between phases after a certain amount of time, even if more upcoming traffic is detected. However, CCOL can reset the maximum green time once, when a new vehicle triggers the detector during a waiting green phase (see Figure 4.3). Thus, in 1 cycle, the maximum green time can be used twice for the same direction. The real maximum of green time is therefore twice the value of the maximum green time. The value that is used to determine the maximum green time is found by multiplying the optimal green time for a fixed time controller by factor 1.2 - 1.4, depending on the number of phases (2 - 5) of the TLC (Wilson, 2006).

When no maximum green time would be implemented, one conflict group could receive an unbalanced amount of green time compared other directions. Thus, to consider a maximum green time, implies a consideration between sufficient green time for the current phase versus the need for green time within this cycle of next phase(s). The maximum green time draws a threshold line between these two considerations, and ensures the cycle continues. however, drawing a maximum threshold for the green time does not help the least advantaged directly (which would be sufficientarian), it actually limits those who would otherwise be advantaged. Thus, having such a mechanism can be identified *egalitarian*.

In contrast to the maximum green time, a **minimum green time** is implemented. The minimum green time guarantees about 5-6 seconds of green. This minimum is implemented in order for the waiting road user(s) to react on the light switch and safely cross the intersection. The minimum green time prevents disco light effects[7], which is important for the credibility of the TLC. The minimum green time starts counting after the initial vehicle(s) has left and no newly arriving vehicles are detected, or when a prioritised vehicle on a conflicting direction arrives (Knoop et al., 2019). Without a minimum green time, the green light on a TLC would not be trustworthy as it could switch before you react. In CCOL, the *fixed green time* phase includes the minimum green time. Another function of the minimum green time is to clear the detectors, in order to be able to detect new incoming vehicles. A minimum green time value of about 6 seconds is often used, which corresponds to the clearance of 2 queued vehicles[8](Knoop et al., 2019).

The minimum green time can be seen as a categorical imperative type of principle as it revolves around human factors. It would be wrong to have no minimum green time, as humans have a certain amount of reaction time. The categorical imperative corresponds to a *deontological* principle. However from the sufficientarian point of view, the minimum green time could be implemented as a threshold for a minimum amount of vehicles having to be able to cross at once, before CCOL decides whether to proceed or stop that green phase. Thus, the minimum green time guarantees a certain amount of road users that can cross, which matches the headcount claim from *sufficientarianism*.

Furthermore, **priority** can be granted. Fixed pre-timed control can not extend green phases or add green phases. Therefore, prioritisation in fixed pre-timed TLCs is executed by adding multiple green phases for the prioritised direction(s) within the cycles. This could be practised in actuated control too, however, in CCOL priority is generally granted to vehicles that can check in their arrival. Such priority is granted to public transport (busses). On check-in, the prioritised vehicle will receive green light as soon as possible. Conflicting directions currently are in the green or yellow phases will be cut off after the minimum green and yellow time, switching as soon as possible to the prioritised direction. Intersection layout plays a role here, as public transport either has its own lane, or shares its lane with other vehicles. In a shared lane, other vehicles could obstruct the prioritised vehicle to move through, the intersection has process the queue first. It is usually preferred to have a public transported dedicated lane for prioritised intersections.

Priority for public transport or emergency services is accepted within *every ethical theory* in this research. It can be stated that prioritisation of these vehicles create more utility, whilst it is also morally right to prioritise them and these vehicles need more priority than the other road-users. From egalitarian point of view it could be argued that public transport is accessible for everyone, therefore it is a choice to not use it and its priority. For emergency services, everyone would want them to have priority when they are the ones that need it. In sufficientarianism, the threshold for emergency services or public transport can be set at a higher level than that of other road users.

---

[7] Disco light effect at an intersection happens when green and red interchange rapidly (Knoop et al., 2019).

[8] With the number of vehicles in the queue between the detectors 'n', headway 2 seconds and drive-off lag 2 seconds, the fixed green phase will be (2 + n*2) seconds.

Another way to prioritise with CCOL is by using **conditioned priority**. Conditioned priority only grants priority when the prioritised vehicle actually needs it. An example could be a bus that needs to catch up with its schedule (would be prioritised), versus a bus that is ahead of schedule (would not be prioritised) (Wilson, 2006).
Conditioned priority fits especially the *utilitarian* theory, because prioritising a bus that is driving ahead of schedule would create less utility than prioritising a bus that is behind on schedule. Theoretically, there could be potential to apply other conditions like whether the bus is full or empty or whether the conflicting directions are congested or not. Potential boundary conditions for conditioned prioritisation correspond with the other ethical theories. However, CCOL is not known for using other conditions.

Due to the slow deceleration of heavy vehicles, heavy vehicles are known to drive through yellow/red light if the traffic light switches too late for them to stop. As a solution to this, priority can be granted to **heavy vehicles**, increasing not only the safety on the intersection, but also reducing the environmental impact, comfort & costs. Where a check-in is needed for conditioned priority, heavy vehicle priority can be organised by road detection placement about 300 m before the intersection, identifying heavy vehicles by vehicle length, as function of time and speed. This type of priority can only be realised if the direction in which the prioritised heavy vehicles are detected, is already in the green phase at the moment of detection. The detected heavy vehicle will cause CCOL to extend the current green phase and delay the yellow phase (Wilson, 2006).
Heavy vehicle prioritisation fits well within the *utilitarian* theory. It is driven by practical reasons, including the disutility of costs & environmental impacts and the utility of comfort & safety. However, the safety argument for heavy vehicles prioritisation can be considered *deontological*, as it is a moral value to increase the safety for human beings by avoiding red light crossing.

Coordination between different CCOL intersection is generally used to create green waves [9]. It could - in other words - be considered a form of prioritisation, specifically made for platoons on the main road. CCOL uses the *advance green* phase for coordination, as mentioned in Figure 4.3. Advance green aligns the green phases of the main road on multiple intersections. Advance green also suggests confidence to the incoming platoon to accelerate as they will pass through the coming intersection as well. However, coordination comes with the cost flexibility.
One reason to implement coordination is to prevent backlash of a traffic jam from one to another close by intersection. A reason for coordination between close by intersections is safety, as accelerating traffic will not always anticipate to stop soon after driving away, preventing red light crossing. Green waves for through roads are on the other hand mainly implemented to improve the throughput of vehicles on the through road, which is usually the biggest amount of vehicles. Preventing backlash and improving throughput are *utilitarian* reasons, focused on the greater good for the biggest group. The safety reason can be identified *deontological*, where preventing unsafe situations for human beings should be a moral value, as previously stated when prioritising heavy vehicles.

Table 4.1 shows an overview of the above elaborated CCOL principles, effects and links with ethical theories. Note that all of the elaborated ethical theories are represented by the principles that are used by CCOL. Where egalitarian ideas stand at the base of (ensuring) cycles, adding a maximum cycle time makes it sufficientarian. Safety related principles are identified deontological, and priority and coordination are principles identified as utilitarian. It is also important to note that some of the described principles are always present because they are evident for the iTLC, whilst other principles are added more incidentally. CCOL's principles that are always active are the cycles, cycle time, maximum- and minimum green time. Priority and coordination is only used when appropriate.

4.2.2. Structure-free model predictive control: Flowtack principles

Flowtack fits in the model predictive control type of controllers. As a result, rather than using cycles, Flowtack is **structure-free**. This means that Flowtack can freely choose a sequence of following directions that acquire green phase. The choice to implement a structure-free optimisation rather than an optimisation that uses cycles, is made because of the increased agility of structure-free control: losing control laws regarding sequences leads to more possible (quantity), thus more optimal (quality)

---

[9] A green wave coordinates multiple intersection in such a way that a platoon of vehicles can pass all intersections without having to stop / with minimum delay. Coordination is usually implemented on intersections that are located close to each other or are part of a through road (Wilson, 2006)

Table 4.1: Link between CCOL's principles and ethical theories

Principle	Effect	Corresponding ethical theory
Cycles	Sequence-based events & phases	Egalitarianism / Utilitarianism
Maximum cycle time	Waiting time	Sufficientarianism / Deontology
Maximum green time	Constraint to the distribution of green	Egalitarianism
Minimum green time	Constraint to the distribution of green	Deontology / Sufficientarianism
Priority	Exceptions to the standard cycle	All
Coordination	Fixed control for platooning	Utilitarianism / Deontology

solutions. This agility especially seems to pay off during off-peak-hours, due to irregular and limited demand, because cycles in saturated conditions is already very efficient. Flowtack seems to adapt well to the irregular flows (Kant et al., 2019).
The principle of using **structure-free** optimisation causes increased agility of the optimisation process of Flowtack. Optimal solutions are in the greatest interest of the greatest group, thus this principle is linked to *utilitarianism*, which corresponds with maximisation of utility.

Data from detectors and vehicle to road side communication is currently used for the **minimisation of (weighted) vehicle loss hours** [10]. A minimisation of VLHs is chosen as optimisation goal, because this is how the performance of the Flowtack is mostly measured: via key performance indicators, like VLHs.
A minimisation of VLHs equals a maximisation of utility: VLHs are disutility for the road user. Thus, this principle is *utilitarian*.

Weights are added to the VLHs minimisation in Flowtack. The weights are relative from one to another, and can come in form of a multiplication factor or a weight propagation function. Weights were added in order to protect the minority from waiting for an unlimited amount of time if the majority is much bigger. A multiplication factor or increasing weight function can help minor road user to become more 'weighty' to the optimisation process over time (Kant et al., 2019). More detail about the weight function and multiplication factors that are currently applied in Flowtack is found in Chapter 6.
Currently, the weights are used to help the minority that otherwise experiences most delay. Helping the minority some at the cost of the majority corresponds to *egalitarianism*. However, the increasing weight function indirectly creates a maximum waiting time. As the weight increases faster over time, at some tipping point this road user will be favoured over other road users with smaller weighted VLHs. This tipping point equals a soft maximum waiting time. The maximum waiting time was earlier identified as *sufficientarian*.

Priority can be given by adjusting the weights for specific road users or directions. Examples of possible weight priority are increasing the initial weight, which impacts the chance of having to stop and increasing the steepness of weight propagation over time, which impacts the delay once already stopped. Priority can be adjusted road user specific and per direction. Thus, the toolkit of weights is not only used for the optimisation goal, it is also used to define priority between different road users or directions on the intersection. Currently, Flowtack prioritises emergency services and public transport with enormous weights to ensure green at all times. Depending on local policies, examples of other priority are cyclists and side roads.
Where priority was identified predominantly utilitarian in CCOL, the priority mechanism can be implemented in different ways in Flowtack. Actually, not-implementing weight factors would be purely utilitarian, since the optimisation goal will find the least total vehicle loss hours. And as mentioned in the

---

[10] vehicle loss hours (VLH) are defined as the sum of the time for vehicles that have to wait at the intersection. Thus, 1 vlh could mean 60 vehicle had to wait for 1 minute at the intersection, or any combination of vehicles and minutes that add up to 1 vlh.

paragraph above, the some weight settings lead to a more egalitarian optimisation process. However, this was covered by the previous principle of weights. The priority of emergency services and public transport was linked with every ethical theory, as it is done for Flowtack.

The next principle is that Flowtack implements **no maximum green time**, in contrast to CCOL. Because Flowtack uses increasing weight for waiting vehicles as a soft maximum waiting time, it is not necessary to implement a strict maximum green time. Waiting vehicles get their turn based on the optimisation of weighted VLHs, and the weighted VHLs implicitly create a maximum green time, but only if other traffic is present and waiting long enough.

Thus, not implementing a maximum green time can be very efficient when there is very little traffic present on side roads, which corresponds with *utilitarianism*. From another point of view, it can be argued that losing the urge of moving on in the sequence and instead providing green while possible, is relatively person centered. If there are no other persons, there is no need for a maximum green time, and even if there are other persons, the maximum green time should not be restricted, instead, their maximum waiting time should be restricted. Such reasoning identifies best as a moral rule, a categorical imperative from *deontology*. Expanding this thought, when a maximum waiting time is restricted, but the maximum green time is not, this means that the optimisation should supply sufficient (maximum waiting time) for everyone, but indifference of the distribution any further than that. This is conform the negative thesis, which makes this principle *sufficientarian* as well.

Another principle that is used in Flowtack is the **topology** of the intersection. The topology of the intersection includes factors like its clearance times, detector locations and infrastructure design. Using the topology allows the algorithm to optimise more adequate for specific intersections (Kant et al., 2019). The topology fine tunes some factors and constraints that are used in the optimisation process, therefore the topology is mainly used for *utilitarian* reasons.

Predicted **information** can be shared from Flowtack to the road users. Flowtack updates the most optimal solution for the intersection every second, which makes informing the road users about their waiting time quite hard, as it can be updated and changed right after the road user has been informed (Kant et al., 2019).

Informing road users is mainly done for better understanding of the situation and acceptance to wait. Informing road users allow them to choose more carefully how to act, it respects the dignity of persons, Kant's second categorical imperative as elaborated in Section 3.1.2. Thus, informing the road users is identified as a *deontological* principle.

Information also goes the other way around, as an input for the iTLC. This information comes from a combination of detectors and mobile data. Faulty detector data could lead to unacceptable situations in the iTLC, where the conventional TLC is less sensitive to these faults. When a detector is in fault state, the iTLC switches to another algorithm, turning off the detection for the according direction and automatically generating requests for this direction once every minute, called **detection replacement**. This ensures the faulty direction will gain green light at some point, even though detection is broken and it is unknown whether or how many vehicles are present (Kant et al., 2019).

Using this detection replacement over *not* using it, could lead to a higher total utility based on the amounts of vehicles in the faulty direction, but it could just as well lead to a lower total utility when there is no traffic present at the faulty direction. It can be argued that because of the latter, this principle is not utilitarian. However, a well functioning iTLC has a *duty* to let all traffic flow through, even if detection is faulty. With such a point of view, this principle is *deontological*. Lastly, this principle is identified *egalitarian*, because this mechanism distributes the capability of gaining green light: When no detection replacement is implemented, the faulty direction would lose the capability of gaining green light.

Currently, the main input information for the iTLC consists of detectors, because of the low penetration rate of mobile date (only 3% of the road users were Flitsmeister users in the Deventer case study (Willekens, 2020)). However, the quality of the detection data dependents on the presence and location of detectors. This causes an inequality for road users depending on their orientation on the intersection, where some might or might not be detected.

In a future where all data about incoming vehicles is available via mobile data, this situation becomes more *egalitarian*, because participation in the optimisation algorithm is not dependent on the presence of detectors. Not only can this be considered more egalitarian, it is potentially also more *utilitarian*, because accurate data will allow for more accurate optimisation, increasing the total utility.

Table 4.2: Link between Flowtack's principles and ethical theories

Principle	**Effect**	**Corresponding ethical theory**
Structure-free	Agile, adapts to the situation	Utilitarianism
Vehicle loss hours minimisation	Decrease of total waiting time	Utilitarianism
Weights	Waiting time	Egalitarianism / Sufficientarianism
Priority	Privilege for directions or vehicles	All
No maximum green time	Less restrictions	Utilitarianism / Deontology / Sufficientarianism
Topology	Intersection integration	Utilitarianism
User information	Acceptance	Deontology
Detection replacement	Ensures traffic flow on faulty directions	Deontology / Egalitarianism

Table 4.2 shows the principles of the iTLC Flowtack, their effects and the corresponding ethical theories. It is important to note that there is some connection between different aspects. Where the vehicle loss hours minimisation is utilitarian, adding weights to the optimisation makes it sufficientarian. Just as the CCOL principles in the previous section, all elaborated ethical theories are also represented in Flowtack's principles. It is (again) important to note that some of the described principles are always present because they are evident to the iTLC, whilst other principles are added more incidentally. Flowtack's evident principles are structure-free, VLH minimisation, weights, no maximum green time and the topology. Currently, user information is limited, and both detection replacement and priority are rather incidental.

4.3. Conclusion

All ethical theories are represented in the tables of CCOL and Flowtack. However, a glance on Tables 4.1 and 4.2 shows that egalitarian principles are represented more by CCOL than Flowtack. The opposite applies to utilitarianism, as utilitarian principles are represented more by Flowtack than CCOL. The main cause for this difference in ethical design between the two iTLCs can be found in the first section of this chapter, as one iTLC uses structure-free MPC optimisation, whilst the other uses feedback control with control laws for sequences. All of the following principles are built around the base of these differences: an MPC needs different principles to function desirable in the real world than a feedback controller.

Deontology is mainly found in principles that are added because of safety and human factors and sufficientarianism has been found mainly in restricting (threshold creating) principles of both iTLCs.

Flowtack's principle of adding weights to the optimised VLHs feels like its strongest principle for bringing egalitarianism and sufficientarianism into the rather utilitarian MPC Flowtack. How the weights principle works and how it impacts equity within Flowtack will be elaborated in Chapters 6 & 7.

Repeating research question 1:

”How are ethics implicitly implemented in the current iTLCs?”

This Chapter concludes that the ethical theories are currently implicitly implemented via principles that are listed in Tables 4.1 and 4.2. All of the ethical theories have some form of representation in the iTLCs via those principles, and *how* they are linked is explained through the intentional effects of the principles on the iTLC or the road user.

Side note: Willekens (2020) studied the effects of Flowtack versus CCOL for a network of 3 intersections located in Deventer, the Netherlands. This study was performed with real life data and showed that Flowtack causes significant improvement for performance indicators like VLHs, maximum- and average delay. Even though Willekens (2020) does not mention equity as one of the performance indicators, the results of this report show that Flowtack scores well on utilitarian measures compared to CCOL, which substantiates the conclusion that utilitarian principles are better represented by Flowtack than CCOL. Additionally, the absence of equity emphasizes the significance of the next Chapter, where performance indicators for equity are selected.

5

Measure of equity

To continue with research question 2[1], a measure of equity is needed to find whether equity has been improved or not. This chapter aims to find a measure of equity, however since equity has multiple interpretations, multiple measures are expected. Due to the nature of deontology, which measures by the intention rather than the consequences, deontology is cast aside for the measurements of equity. Thus, this chapter will define a measure for equity based on the definitions of equity from the teleological theories that are elaborated in Chapter 3: utilitarianism, egalitarianism & sufficientarianism.

This chapter starts with a literature section that shows how equity has been measured previously in the field of (i)TLCs & transport, in chronological order. The measuring methods of the studies that are mentioned in the literature section are then linked to the definitions of equity that are measured in by those methods. This link is new for some of the studies, whilst for other studies, the link with ethics might have already been discussed. This chapter ends with a selection of those methods for measuring equity that will be used in this research.

5.1. Literature

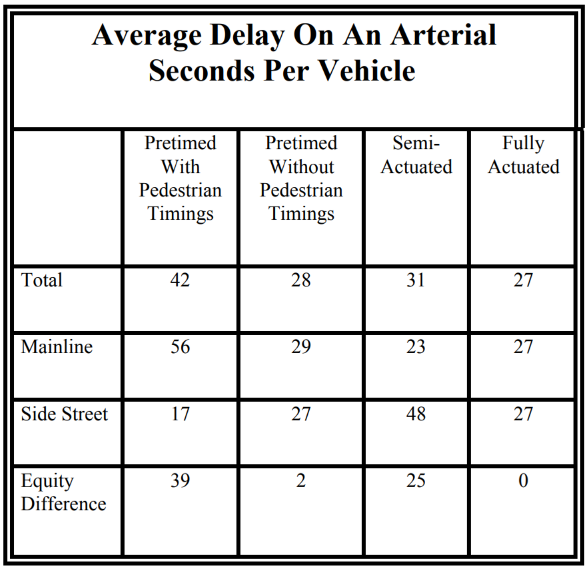
Yarger (1993) described the difference in equity between a semi- and fully actuated TLC. The fully actuated TLC is equipped with detectors at all directions, whilst the semi actuated TLC only has detection on side roads, leaving the main road undetected. Both TLCs use cycles that follow a fixed sequence of green phases, where green phases can be passed when no traffic is detected. The measure for equity in this document defined as *the absolute difference in average delay between the main road and the side road*, as depicted in Figure 5.1.

A next study measured equity and efficiency of a ramp metering system. Ramp metering uses traffic lights to control the flow of traffic that merges onto a freeway. The challenge of the on-ramp of a saturated highway can be shortly described as a dilemma of choosing between congestion on the highway due to weaving at critical highway capacity, or congestion at the on-ramp, possibly backfiring to urban area. Kesten et al. (2013) compared the efficiency and equity of different ramp metering systems versus no ramp metering system. Speed and delay was measured and processed into various statistical indicators like range, variance, Gini, as shown in Figure 5.2. These indicators were used to measure the equity performance of the ramp metering systems versus no ramp metering system. Kesten et al. (2013) measured the efficiency, separately from equity, by the total travel time, delay, stops, speed, and their averages.

The previously mentioned Gini coefficient has been elaborated by Lucas et al. (2016). This study elaborates how the Gini coefficient can be used to evaluate accessibility in a quantitative way for transport policies. The Gini coefficient can be calculated from cumulative distribution curves, such as the well-known Lorenz curve, often used to depict the distribution of income of countries. Figure 5.3 shows such a distribution of a 'good' over a population, with in this case accessibility as the distributed good. The

---

[1] Research question 2: *"How to improve equity in an iTLC, according to various ethical theories?"*



Average Delay On An Arterial Seconds Per Vehicle

	Pretimed With Pedestrian Timings	Pretimed Without Pedestrian Timings	Semi-Actuated	Fully Actuated
Total	42	28	31	27
Mainline	56	29	23	27
Side Street	17	27	48	27
Equity Difference	39	2	25	0

Figure 5.1: Equity measure by absolute difference between the average delay on the main road and the side road. Adapted from Yarger (1993)

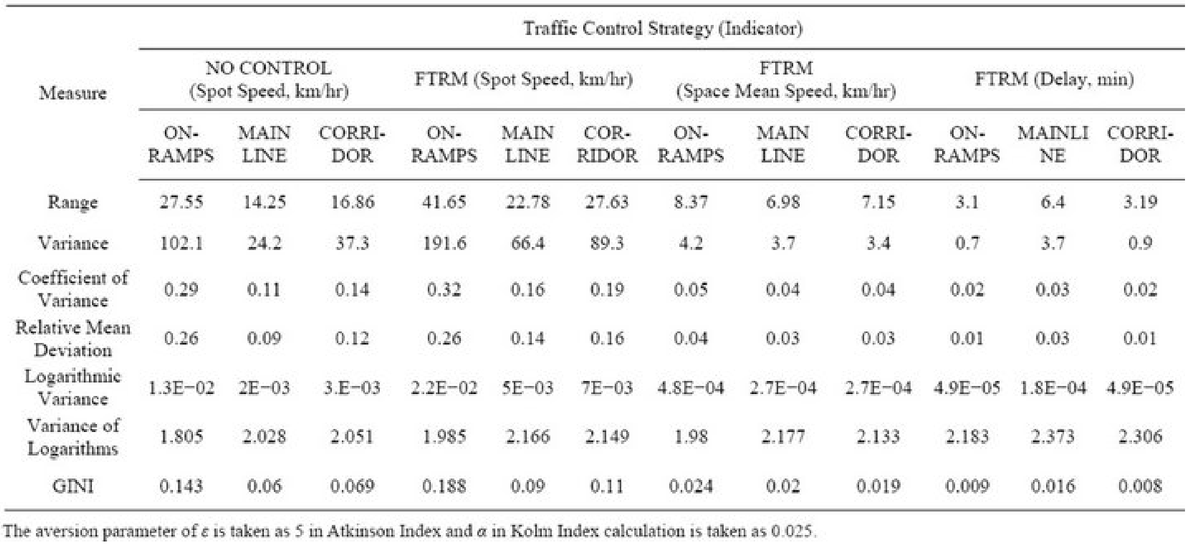
diagonal line, or equal distribution line, shows indicates when the distributed good is evenly distributed over the whole population. This means that 10% of the population owns 10% of the distributed good, 20% of the population owns 20% of the distributed good etc.
The Lorenz curve however, shows the realistic distribution of a good over the population. The Gini coefficient follows from dividing the area between the equal distribution line and the Lorenz curve through the area under the equal distribution line. This results in a normalized coefficient that represents a maximum unequal distribution when it has a value of 1, and a perfect equal distribution when it has a value of 0. Lucas et al. (2016) suggested that this coefficient could be used with journey time on the y-axis.

A variation of use of the Gini coefficient could be to implement a threshold value. Point Xs in Figure 5.3 shows a chosen threshold value for the measured good. This line shows the amount of social exclusion, people who did not make it to the threshold value. The threshold value could be set at a desired minimum or maximum of the good (accessibility).

Another study showed an equity measurement for the back pressure controller: an event-based optimisation algorithm that originates from queuing algorithms for wireless communication. The back pressure controller optimises using both upstream, and downstream information to calculate the pressure on the availability of space on each direction of the intersection (Li & Jabari, 2019). Wu et al. (2017) proposed an improvement of the back pressure controller by adding a delay-based decision variable. Wu et al. (2017)'s study compared the 'fairness' of the proposed delay-based back pressure controller versus a queue-based back pressure controller.

Wu et al. (2017) argues that the theoretical queue-based back pressure could be improved by making the decision variable delay-based, adding spatial limitations and defining & using the network capacity as guidelines. They showed that the delay-based back pressure controller performed better in terms of fairness, when using *Jain's fairness index* and the probability that a *threshold-value for delay* is exceeded. Jain's fairness index is a dimensionless index between 0 and 1 which is independent for scale, with the value of 1 referring to equal distribution. Jain's fairness index is calculated by the formula as shown in Figure 5.4, dividing the squared sum of the delays by the sum of the squared delays multiplied by the amount of participants (Jain, Chiu, & Hawe, 1984). This fairness index originates, just like the back pressure controller, from the field of computer engineering.

A recent study of Liang et al. (2020) identified the trade-off between efficiency and equity for a traffic signal control algorithm that works with connected-vehicles and minimises the delay per cycle (Guler, Menendez, & Meier, 2014) based on this connected vehicle data and prediction data for non-connected



Measure	Traffic Control Strategy (Indicator)											
	NO CONTROL (Spot Speed, km/hr)			FTRM (Spot Speed, km/hr)			FTRM (Space Mean Speed, km/hr)			FTRM (Delay, min)		
	ON-RAMPS	MAIN LINE	CORRI-DOR	ON-RAMPS	MAIN LINE	COR-RIDOR	ON-RAMPS	MAIN LINE	CORRI-DOR	ON-RAMPS	MAINLINE	CORRI-DOR
Range	27.55	14.25	16.86	41.65	22.78	27.63	8.37	6.98	7.15	3.1	6.4	3.19
Variance	102.1	24.2	37.3	191.6	66.4	89.3	4.2	3.7	3.4	0.7	3.7	0.9
Coefficient of Variance	0.29	0.11	0.14	0.32	0.16	0.19	0.05	0.04	0.04	0.02	0.03	0.02
Relative Mean Deviation	0.26	0.09	0.12	0.26	0.14	0.16	0.04	0.03	0.03	0.01	0.03	0.01
Logarithmic Variance	1.3E−02	2E−03	3.E−03	2.2E−02	5E−03	7E−03	4.8E−04	2.7E−04	2.7E−04	4.9E−05	1.8E−04	4.9E−05
Variance of Logarithms	1.805	2.028	2.051	1.985	2.166	2.149	1.98	2.177	2.133	2.183	2.373	2.306
GINI	0.143	0.06	0.069	0.188	0.09	0.11	0.024	0.02	0.019	0.009	0.016	0.008

The aversion parameter of ε is taken as 5 in Atkinson Index and α in Kolm Index calculation is taken as 0.025.

Figure 5.2: Equity indicators for speed and delay at ramp metering traffic control. Adapted from Kesten et al. (2013)

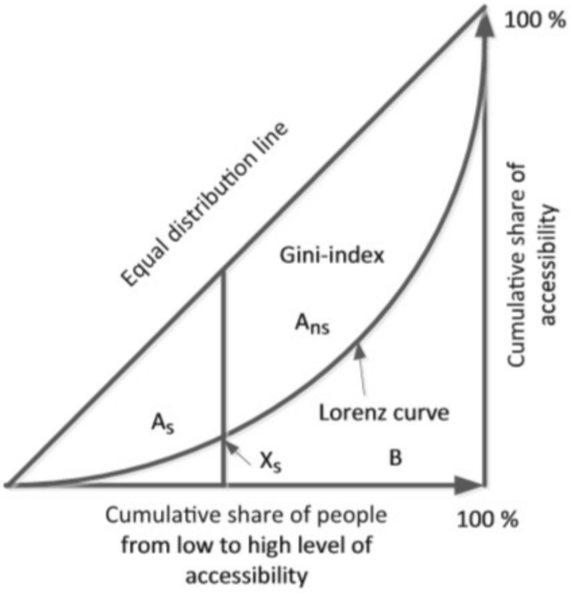


Figure 5.3: The Gini coefficient (or index), adapted from Lucas et al. (2016)

vehicles. Liang et al. (2020) used a cumulative percentage delay versus the cumulative percentage of vehicles (equals the Lorenz curve as elaborated in the previous paragraphs) to show the distribution of delay. The Gini index was calculated from these 'Lorenz' curves and plotted versus the average delays, as depicted in Figure 5.5. Their experiment was performed for multiple hard-programmed maximum delay threshold values and these thresholds for maximum delay were plotted on the same graph.

Liang et al. (2020)'s study shows in Figure 5.5 that a higher threshold value leads to a worse distribution of delay (higher Gini coefficient), and a better average delay. The steepness of the graph implies the trade of between the Gini coefficient and the average delay. Figure 5.6 shows that these curves vary for different flows on the network, which mean that an improvement of the Gini coefficient costs less average delay for a relatively quiet intersection. On the other hand, a relatively crowded intersection starts off with a better Gini coefficient but has a worse trade-off for improvement when looking at the costs in average delay.

$$f(\vec{d} = [d_1, d_2, ..., d_M]) = \frac{\left(\sum_{i=1}^{M} d_i\right)^2}{M \sum_{i=1}^{M} (d_i{}^2)}.$$

Figure 5.4: Jain's index formula. With d_i the delay for vehicle *i* and *M* the total number of vehicles. Adapted from Wu et al. (2017).

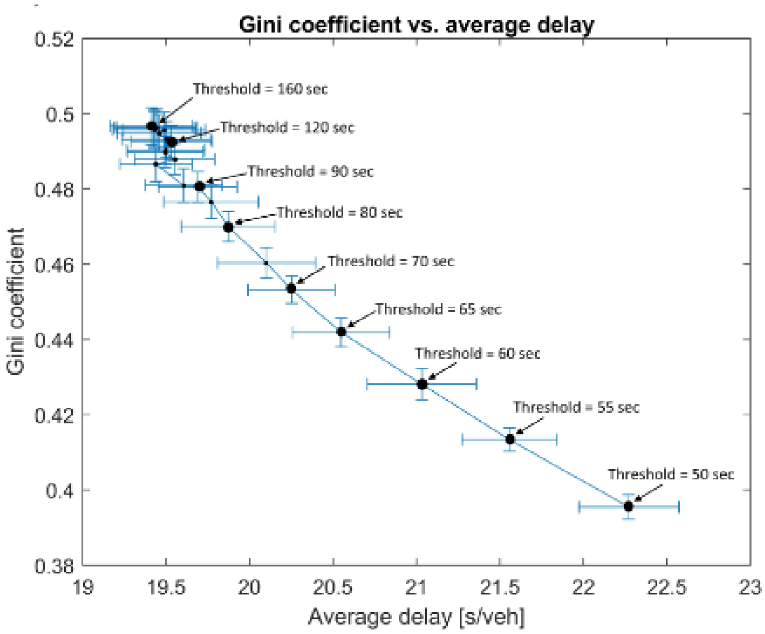


Figure 5.5: Gini coefficient versus average delay, for different maximum delay thresholds. Adapted from Liang et al. (2020).

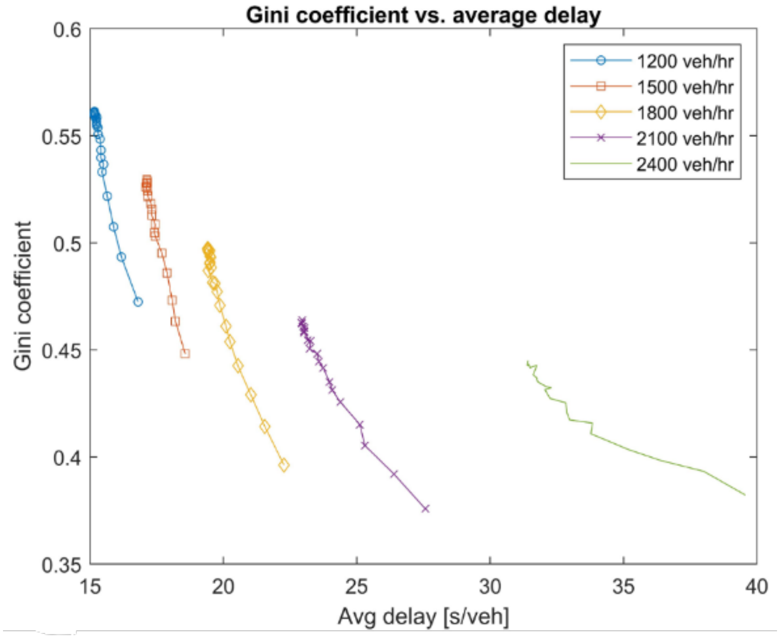


Figure 5.6: Gini coefficient versus average delay, for different maximum delay thresholds and intensities. Adapted from Liang et al. (2020).

5.2. Link with ethics

In this section, the literature of the previous section is summarised by extracting the measurement methods. These measurement methods are then linked to the type of equity that it measures by the different definitions of equity from the teleological theories (utilitarianism, egalitarianism and sufficientarianism) that were elaborated in Chapter 3.

Yarger (1993) took the average delay for the main roads and subtracted the average delay on the side road from it, leading to an equity difference expressed in seconds. Using the average delay matches *utilitarianism*, because the biggest group determines where the average will be. A lower average delay implicates a better situation for the biggest group. However, distinguishing the main road from the side roads does add some form of distributive equity that comes closer to *egalitarianism*, as from this point of view, the equity difference in average delay would be 0 for a perfectly egalitarian distribution of the 'good' (delay). However, this method does not seem sophisticated enough to measure egalitarianism from the road user's point of view, because the distribution within the average of one direction can be unfair, whilst the average delay remains appears the same.

Secondly, Kesten et al. (2013) created a Table with statistical indicators, including the delay and Gini coefficient. Their measures were split up in 2 tables, 1 showing 'efficiency' performance and the other showing 'equity' performance. In this research, the efficiency table matches *utilitarianism* due to the average and total performance indicators, which says more about the performance for the majority of the population than the performance for the minority of the population. Then there is the equity table, which contains statistical information about the variance, deviation and the Gini. These are all indicators for the distribution of the goods, which fits *egalitarianism*.

Next, Lucas et al. (2016) Uses a cumulative distribution curve, Gini coefficient and thresholds for social exclusion as equity measures for accessibility. These methods were developed from egalitarian & sufficientarian points of view, as elaborated by the authors of this study.

Wu et al. (2017)'s study used Jain's index, which is actually very similar to the Gini coefficient. Where the Gini coefficient determines distributive equity by a number from 0 to 1 with 0 for perfect distributive equity, Jain's index also determines distributive equity by a number from 0 to 1, although Jain's index refers to perfect distributive equity with a value of 1. Jain's index is therefore identified as a measure for *egalitarian* equity.

Last but not least, Liang et al. (2020) presented the average delay on the x-axis of a graph, with the Gini coefficient for the distribution of delay on the y-axis of that graph and a threshold for maximum delay within the graph. However Liang et al. (2020) did not explicitly mention the ethical theories in this study, this study delivers a method to measure utilitarianism, egalitarianism and sufficientarianism in a single graph.

The average delay measure corresponds to *utilitarianism* because the average shows information about the majority rather than the minority, as elaborated in the previous paragraphs. The Gini coefficient is an *egalitarian* measure (Lucas et al., 2016). *Sufficientarianism* was finally represented as a threshold value in the graph for a maximum delay that was accepted for each simulation.

Table 5.1 summarises the measurement methods per study from the previous section, and links those methods to the ethical theory of which equity is measured. as explained above. Note that all sources regarding signalised intersections use some statistic value of delay to assess equity.

Table 5.1: Summary of equity measures literature linked to ethical theories

Source	Method(s)	Measures corresponds with (ethical theory)
Yarger (1993)	Average delay per lane	Utilitarianism / Egalitarianism
Kesten, Ergun and Yai (2013)	Table with statistical indicators (incl. Delay & Gini)	Utilitarianism / Egalitarianism
Lucas, Van Wee and Maat (2016)	Cumulative distribution curve (Lorenz curve) / Gini / Threshold (Social exclusion)	Egalitarianism / Sufficientarianism
Wu, Ghosal, Zhang and Chuah (2017)	Jain's fairness index	Egalitarianism
Liang, Guler and Gayah (2020)	Average delay / Gini coefficient / Maximum delay	Utilitarianism / Egalitarianism / Sufficientarianism

5.3. Equity measurement selection

A selection of methods for measuring equity is selected in this section. Due to the different definitions of equity for various ethical theories, equity can not be measured by merely a single indicator. Therefore, a combination of different measures seems appropriate.

As shown in Table 5.1, Liang et al. (2020) provides a measure for all 3 ethical theories that have been chosen in this research: utilitarianism, egalitarianism and sufficientarianism. With the Gini coefficient on the y-axis and the average delay on the x-axis, this graphical display of the data clearly shows the trade-off between Utilitarianism and Egalitarianism. Sufficientarianism is presented as a threshold for maximum delay that the plotted data point satisfies to. The other sources stated in Table 5.1 also shows methods similar to Liang et al. (2020)'s, however not all equity measures in 1 graph. An advantage of using the cumulative distribution (Lorenz) plot, as described by Lucas et al. (2016), is that it shows the actual distribution rather than only providing a dimensionless vague number (Gini coefficient). However, just a cumulative distribution lacks the absolute numbers of delay.

For example, a Lorenz curve could be very egalitarian (close to the line of equality), however the absolute income of the country with this egalitarian curve could be very low, meaning everyone has a low (maybe not even sufficient) income. To translate this to traffic control, a congestion could lead to higher delay for everyone, resulting in a more equally distributed Lorenz curve. Reducing the Lorenz curve to a Gini coefficient, allows the this data to be combined with context data (average, maximum), which is important to judge its performance.

Thus, this thesis will use Liang et al. (2020)'s method, where utilitarian and egalitarian measures are presented on the x- and y-axes. Adding the average delay on the x-axis in a plot with the Gini coefficient on the y-axis, adds the context that is necessary in order to use the Gini coefficient, as explained in the example above. A decrease of the Gini coefficient is translated to an improvement of egalitarian equity and a decrease of the average delay is translated to an improvement of the utilitarian equity. Decreasing the maximum delay will be seen as an improvement of sufficientarian equity. This thesis does not define a boundary definition for sufficient, however, a level of sufficientarianism can be identified by stating the maximum measured delay that has been experienced. The links of Liang et al. (2020)'s measures with the ethical theories that have been identified in this chapter are depicted in Figure 5.7.

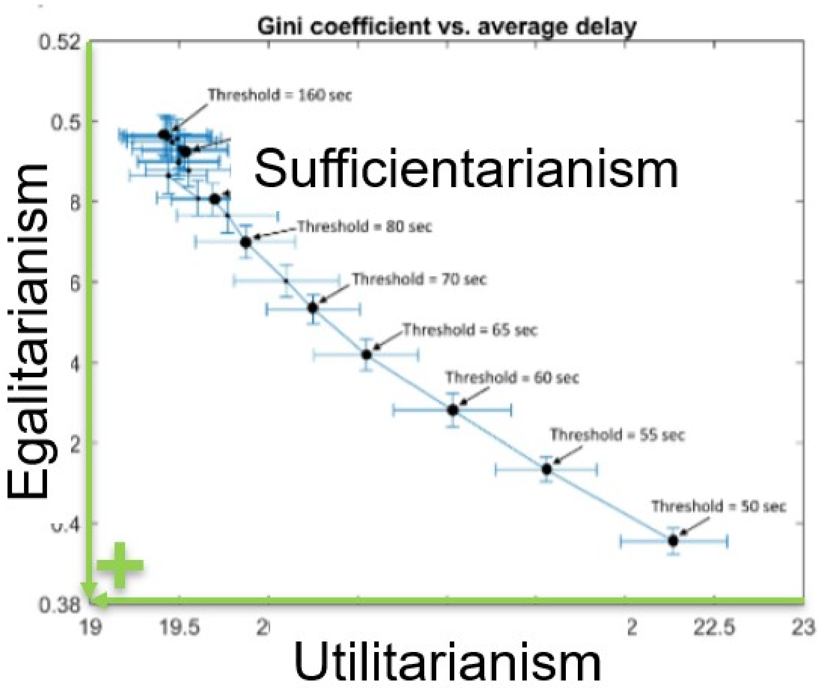


Figure 5.7: The equity measures selected for this research. Utilitarianism on the x-axis, measured by average delay. Egalitarianism on the y-axis, measured by Gini coefficient. Sufficientarianism stated on plot, measured by maximum delay. Original Figure adapted from Liang et al. (2020), added link with ethical theories and positive effects on the axes.

6

Simulation experiment setup

To find out how equity can be influenced by the settings of Flowtack, an experiment to test those settings is performed. This experiment is performed in a simulation environment, because a real world experiment would take too much time and might create unacceptable situations. Different scenarios with substantiated settings are tested for each experiment. The output data of these experiments will eventually be processed to show the equity measures defined in Chapter 5. This chapter elaborates the **how** and **what** questions for the simulation experiments.

6.1. Simulation setup

How the experiment is performed and with what software is elaborated in this section. This section starts with the simulation environment, followed up by Flowtack as iTLC, how these 2 programs are linked and finishes with the process from simulation data to equity measures in excel.

6.1.1. Simulation environment: Aimsun

Simulation software Aimsun, which stands for advanced interactive microscopic simulator for urban and non-urban networks, is used as a replacement of the real world. An Aimsun model works with supply- and demand data. Supply data refers to everything related to the infrastructure and attributes that define the way people move in the model and demand is defined by Origin-Destination Matrices per road user type and time interval (Casas, Ferrer, Garcia, Perarnau, & Torday, 2010).

Supply

The A050 intersection in Deventer is used, as this intersection is quite complete. It is a signalised intersection that consists of a main road with 2 side roads, 2 cyclist / pedestrian cross-overs and a shared bus lane, as depicted in Figure 6.1. The upper side road connects a high school and a police station to the main roads, hence relative small flow of vehicles and bigger flow of cyclists. The bottom side road connects to a residential area and some industry.

For a validation experiment, intersection 'Rotterdam 97190' was used. This intersection layout was already available in Aimsun and is depicted in Figure 6.2. Other than intersection A050 in Deventer, this intersection consists of 12 directions for vehicles, and has no pedestrian cross overs, only one cyclist cross over. Directions from the North and South sides of this intersection have one extra lane for straight-ahead traffic relative to the East and West sides.

Demand

Demand data for intersection A050 in Deventer was already available for RoyalHaskoningDHV (HaskoningDHV, 2021). Measured average flows for working days in March 2019 were provided. The demand data for the evening peak between 16:00 and 18:00 was also provided, and is used for this experiment. This data varies from flows of about 1400 veh/h on the main roads to about 10 veh/h on a side road, the Origin-Destination matrices can be found in Appendix B.1.2. 10% of the flow is simulated to be trucks (5% heavy and 5% light trucks). For active modes, 25 pedestrians per hour per direction have been

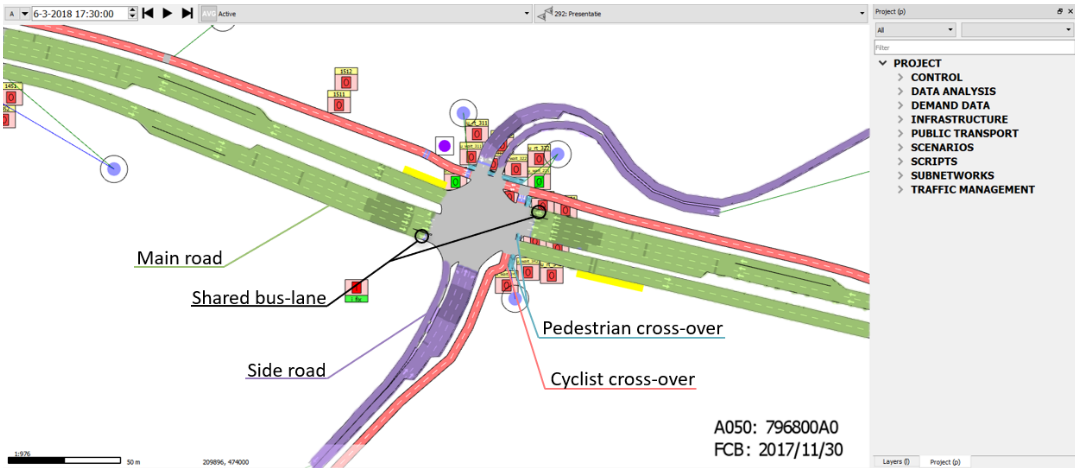


Figure 6.1: Intersection layout in Aimsun of A050 Deventer

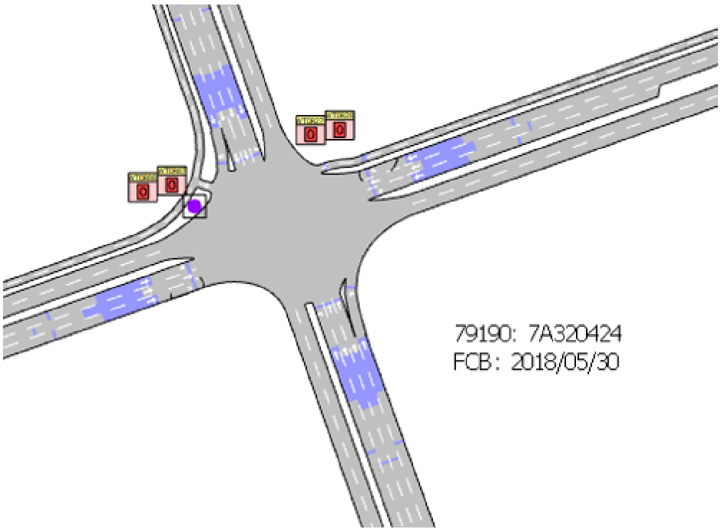


Figure 6.2: Intersection layout in Aimsun of Rotterdam 97190

generated on both pedestrian cross-overs and about 200 cyclists per hour per direction have been generated on the bicycle path parallel to the main road, and about 30 cyclists per hour from and to the bottom side road. The OD matrices and some more details can be found in Appendix B.1.2.

Originally intersection 97190 consists of mainly trucks traffic due to its location at the port of Rotterdam between 2 Maasvlaktes. However, for this validation experiment, details about real demand on the intersection are ignored, and car traffic has been simulated instead. The active modes are not generated in this experiment, which makes this intersection more different from the A050 in Deventer.

For the purpose of validation, 3 origin-destination matrices have been constructed for intersection Rotterdam 97190. The total flow is kept at 3600 veh/h because approximately such a total flow has been measured in Deventer on the A050 as well. This flow is kept the same, because a lower amount would generate a less interesting situation as there will be little traffic, and a higher flow would possibly generate traffic jams, which creates a distorted picture about the Gini coefficient, as explained in Chapter 5. The distribution of flow over the directions on the intersection is varied per scenario, starting with a perfectly equal distribution of cars on each direction. The second validation scenario uses an OD matrix with a slight inequality in the distribution of traffic flow, varying with factor 6 from highest main road flow to the lower side road flows. The last OD matrix uses a flow distribution similar to that of the intersection at Deventer, where only a hand full of vehicles is simulated at the side roads with a very dominant flow on the main road. The OD matrices can be found in Appendix B.1.2.

6.1.2. Traffic light controller: Flowtack

Flowtack decides for the in Aimsun simulated traffic lights when to switch the color, based on real-time data, which is simulated again in Aimsun for this experiment. This data is collected by loop detectors under the roads and so called Cooperative Awareness Messages (CAM), which is data about incoming vehicles from apps, *Flitsmeister* for example. As elaborated in Section 4.1, Flowtack uses all input data to predict the total delay for all the road users on the intersection for different control plans. However, it is not just the delay that plays a role for the final decision, the performance function is influenced by *weights*, defined by a weight function $f(w_i(n))$ and multiplication factors $\beta_{j(i)}$. Settings of Flowtack allow to influence the **weight function**, **multiplication factors per road user type** and **multiplication factors for intersection directions**. Figure B.7 from Appendix B.1.3 shows what these settings look like and how they can be adjusted.

The same definitions from Chapter 4 are used, with Objective function J. These are repeated below:

$$J = min_{u_j(k)} = \sum_{i}^{I} \sum_{n}^{N} \beta_{j(i)}\, f\big(w_i(n)\big) \Big(w_i(n) - w_i(n-1)\Big)$$

- J, the objective function, defines *what* is optimised
- k, frequency or time step for which the objective function updates its solution. Order of magnitude 1 second. $k \in K$.
- n, rolling horizon N is divided into a number of time steps n. Every time step n, control plan u can decide whether direction j is granted green or not. Adjustable variables, order of magnitude N = 400 seconds, n = 0.2 second. $n \in N$.
- i, individual road user i. $i \in I$.
- $j(i)$, direction j on the intersection where individual road user i queues. $j \in J$
- $u_j(k)$, the optimisation variable, control plan u defines whether direction j is planned red or green; 0 or 1. The amount of control plans that are tried for each optimisation step k depends on the amount of possible solutions, order of magnitude 100 - 30.000.
- $w_i(n)$, accumulated waiting time for road user i previous to the starting time $n = 0$ of time step k.
- $f(w_i(n))$, weight function (curve shaped) for each road user, with the weight factor (w/s) on the y-axis and waiting time (s) on the x-axis.
- $\beta_{j(i)}$, a multiplication factor (-) that is direction- and road user type dependent.

Weight function

As mentioned, Flowtack's settings allows adjustments to be made in the weight function. The weight function for road-users is influences the performance function of the optimisation and thus the resulting optimal control plan. The horizontal axis of the weight function depicts the delay of one road user, and the vertical axis depicts the weight that this road user gains per second of delay.

A simple example of a weight function is a horizontal line, with a value of 1.0. Such a weight function results in a situation where each delayed road-user gains 1 unit of weighted delay per second *(w/s)* that he/she would be delayed. However, the standard weight function that is used at the moment is referred to as the 'badkuip curve' in Dutch, which means bathtub curve. This curve is depicted in Figure 6.3. Such a function shape is implemented, because it decreases the gain of weight when a vehicle has already stopped, which helps to prevent disco light effects [1] (Kant et al., 2019). After this dip in the curve, the function ascends, which makes it so that this waiting road user becomes more weighty (important) in the optimisation process. This up-going tail is implemented to prevent undesirable long delay, if possible. Thus, the weight function describes in some way the *importance of time* for a delayed/waiting road user at the intersection.

---

[1] Disco light effect at an intersection happens when green and red interchange rapidly. This is the reason that minimum green times are implemented in other TLCs (Knoop et al., 2019).

Thus, the bathtub curve is a interpretation of the importance of time for this road user. The theory behind such a bathtub shape is that a road user would not mind waiting for a bit once stopped, however no road user is willing to wait for too long, hence the build up of importance over time. The dip in the curve also serves to have not-stopped road users drive on, reducing the amount of stops at the intersection, because the weight to stop non-delayed road users is higher than to have shortly waiting road user wait for a bit longer. The shape of the bathtub curve from Figure 6.3 is actually approximated by a set of time and weight values for simplicity, resulting in a discrete version of the continuous curve. Appendix B.1.3 shows the discrete version of the bathtub curve that is currently implemented.

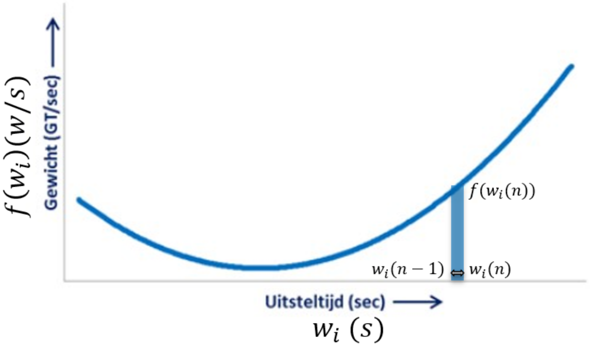


Figure 6.3: Bathtub or 'Badkuip' curve as weight propagation function, weight factor on the vertical axis, expected delay on the horizontal axis. Minimum weight found at about 10 seconds of delay, maximum weight found at around 100 seconds of delay. Adapted from Kant et al. (2019)

Multiplication factors for road user types

Next, there is the multiplication factors for road user types and directions, $\beta_{j(i)}$. These multiplication factors multiply the weight function as a whole by this factor. Thus, multiplication factor 2 creates a situation where the importance of the regarding road user is that of exactly 2 road users with factor 1, if they arrived at the same point (so they are at the same location of the weight function).

The multiplication factor for road user types is mainly used in the current situation for prioritising emergency vehicles, public transport and active modes. Emergency vehicles and public transport get a very high β via a Signal Request Message (SRM), which guarantees priority over the other road users on the intersection regardless of the built up total weight at other directions.
Additionally, the active modes (pedestrians & cyclists) are actually given a higher weight in the current situation at the A050 in Deventer. Where trucks and cars have a β_{veh} of 1, the pedestrians have a β_{ped} of 4 and the cyclists a β_{cyc} of 2. These factors are not implemented to prioritise the active modes over other modes, this is implemented as a compensation for the detection blindness of active modes. The detection blindness for pedestrians is caused by the fact that the detector is merely a button at the intersection. When the button is pressed, it remains unknown how many pedestrians are waiting, and other than the other road users at the intersections that are observed by both loop detectors and CAM, pedestrians are observed rather late: when already waiting at the intersection. The detection blindness of cyclists is less severe than that for pedestrians, because there are some loop detectors to detect incoming cyclists. However, these detectors have a hard time distinguishing a number of cyclists from a single cyclist when they cycle close/next to each other.

Multiplication factors for intersection directions

The multiplication factors for intersection directions work in the same mathematical way as that of the road user types. However, the reason for implementing these multiplication factors in the current settings of Deventer are different. These settings are implemented mainly because of policy goals and expert experience in the field of intersection management. Examples of this are a higher β for a main cycling path as a policy goal and a higher weight for a side road to lower the maximum delay experienced by those who tend to experience high delays (expert experience). The current settings are shown in Figure B.7, Appendix B.1.3.

Weight function per road user type or direction

It is possible to create a weight function for each road user type or direction on the intersection, instead of a general weight function for all road users. Currently, this is not implemented because of the philosophy of Flowtack, where the settings are meant to be elementary and general rather than complex. During the following experiment, the effects of the weight function and multiplication factors are explored, thus going into detailed settings like this is not for this thesis.

6.1.3. Communication, latency and reproducibility

For this experiment, Flowtack and Aimsun are linked to work together. Aimsun generates the road users and sends the simulated detection data to Flowtack. Then Flowtack's algorithm uses this data to decide for the intersection which traffic light is granted green light, and Flowtack sends back this information to Aimsun for it to execute Flowtack's decisions. Both communication steps between Aimsun and Flowtack are sent over the internet. This causes the arrival of a message to be delayed by the latency of the network at that time, which is very variable.

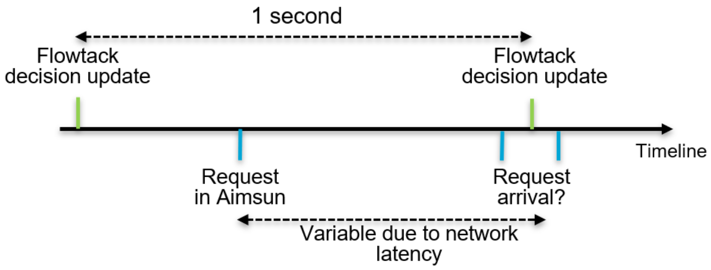


Figure 6.4: Communication between Aimsun and Flowtack and the impact of latency of the network on it.

Figure 6.4 shows how the latency of the network could possibly influence the outcome of the optimisation process. Flowtack updates the solution approximately every second, which is shown with the green bars on the timeline. At some point in time, which is always the same point in time due to the random seed being set, a vehicle request from Aimsun comes in via CAM or loop detector. Then, this request is sent over the network to Flowtack. However, if the message arrives in Flowtack before the decision update, the outcome of the decision might be different than when it arrives after the decision update. This creates a situation where the results of this experiment are not exactly reproducible. To overcome this, every experiment has to be repeated a few times (5x mostly) to show whether the differences in the results are consistent.

6.1.4. Data collection and processing in Excel

Aimsun delivers the data from its simulation in SQLITE format. This format is transferred to excel format by RoyalHaskoningDHV's Transport Tools function for Aimsun. Every vehicle in the simulation is tracked and a lot of data about every vehicle is stored in the excel file. This data consists of indicators like air pollution (PM), emissions (CO2, NOx), amount of stops (-), stop time (s), vehicle loss hours (h), delay (s), speed (km/h), travel time (s), queue lengths (veh) and more. All data is available per car, per direction on the intersection and in total amounts. Only the delay data for each road user is extracted from these excel files, because this is all that is necessary to create the defined equity measures of average delay, maximum delay and Gini coefficient, from Chapter 5.

In Excel, some basic function are used in order to find the average delay and the maximum delay of one experiment. The data is then rounded up to deci-seconds (10^{-1} s, initially provided in 10^{-4} s) and sorted, because that much detail is not necessary and increases the number of unique data points significantly. Next, the unique values are counted and a cumulative frequency from small to high delay values is created. This sets up for the Lorenz curve data points created with x values for cumulative share of the population and y values for the cumulative share of the delay. The Lorenz curves are not necessarily plotted, the area under the Lorenz curve is needed and can be defined based on these data points. With a known area under the Lorenz curve and a known area of 0.5 under the perfect equality line, the Gini coefficient can easily be computed.

Finally, each experiment delivers 3 data points: the average delay, maximum delay and Gini coefficient. As each experiment is repeated a few times, multiple points are plotted. The average point of all data points is also determined for easier comparison. Appendix B.1.4 shows how the excel functions are used to create these equity measures and explains the steps.

6.2. Experimental settings

Each experiment has been performed with the supply and demand as described earlier this chapter. The simulation time starts at 17:00 and ends at 17:30, which is within the evening peak for which the OD matrices were defined. 3% CAM data was generated by the road users which is a representative number for the CAM data that is currently generated in Deventer (Willekens, 2020), these road users allow Flowtack to make more accurate decisions.

The experiments are divided into 3 groups, based on the Flowtack settings that can be adjusted: Weight function settings, road user type settings and directional settings. The goal of these experiments is to find out whether adjusting these settings can improve equity. A fourth experiment combines some of the findings from these three experiments to see whether different settings add up in a desired way. Since Flowtack was identified more utilitarian than the conventional, cycle-based iTLCs like CCOL, in Chapter 4, the challenge for this experiment is to find settings for Flowtack that increase its egalitarian and sufficientarian measures, rather than looking to make Flowtack even more utilitarian. Each of the following experiments consist of scenarios with certain Flowtack settings, and each scenario consists of a set of simulation runs of 30 minutes to show whether there is consistency in the results.

The experiments are followed up by a validation of the scenario(s) with the best results, with the goal of showing that the corresponding settings also perform as intended on an intersection with a different layout and flow distribution.

6.2.1. Hypotheses

Before the experiments are conducted, hypotheses are constructed. The settings for the experiments with Flowtack can be adjusted to infinite combinations, therefore a careful selection of settings for the experiments is necessary. The hypotheses support the structure and selection of settings by explaining what is expected from the experiments. Research question 2 is repeated:

> ”How to improve equity in an iTLC, according to various ethical theories?”

Various definitions and measures for equity have been elaborated in Chapters 3 & 5: utilitarianism by average delay, egalitarianism by Gini coefficient and sufficientarianism by maximum delay. The following experiments are performed in order to find how these forms of equity are influenced by the settings in the iTLC Flowtack, aiming for improvement of equity on the levels of egalitarianism and sufficientarianism. The selection for an improvement of egalitarianism and sufficientarianism is made, because Flowtack seemed to be predominantly utilitarian compared to cycle-based TLC as concluded in Chapter 4. Furthermore, Liang et al. (2020) showed that when using those measures of Gini coefficient in combination with average and maximum delay, that there is a correlation between the results that show lower maximum delays result in lower Gini coefficients and higher average delays. Thus, updating the research question and research goal can be updated with the current knowledge, substantiated with the conclusion of principles of equity in Chapter 4 and results from previous research that shares the same measures, as elaborated in Chapter 5.

The weight of a road user accumulates over time and is influenced by the weight function, thus the weight function defines this road user’s priority in the optimisation process.
Hypothesis 1a: A weight function that increases over time is expected to favour the road users that would otherwise have been disadvantaged -in terms of delay- over time, at the cost of road users that would have otherwise been advantaged.
Using the measures for equity, it is expected that the weight function results in a lower Gini coefficient at the cost of an increase in average delay.

Additional hypotheses can be created for weight function shapes other than the gradually increasing.
Hypothesis 1b: A weight function that stays constant over time is expected to treat all individual road users equally, thus favouring larger groups of individuals over smaller groups of individuals.
Using the measures for equity, it is expected that the weight function results in a lower average delay and a higher maximum delay and Gini coefficient.

To test whether the weight function can be altered to perform in an undesired way, one more similar hypothesis is constructed, using a linearly decreasing weight function, which means that the road user gains less priority over time once delayed.

Hypothesis 1c: A weight function that decreases over time is expected to lead to more inequity: (dis)advantaging the already (dis)advantaged.
Using the measures for equity, it is expected that the weight function results in a worse Gini coefficient.

Furthermore, there are settings that are road user type specific. A high multiplication factor for a certain road user type improves the weight -thus the priority- of that road user type.
Hypothesis 2a: It is expected that when road user type specific settings are adjusted in favour of currently -in terms of delay- disadvantaged road users, the relative disadvantage cancels out.
It is expected that the results show that the share of the total delay for the disadvantaged road users should become more equal to their share in the total population.

and vice versa
Hypothesis 2b: It is expected that when road user type specific settings are adjusted in disadvantage of currently -in terms of delay- favoured road users, the relative advantage cancels out.
It is expected that the results show that the share of the total delay for the advantaged road users should become more equal to their share in the total population.

Directional settings generate a multiplication factor per direction on the intersection. It is assumed that the layout of the intersection can advantage some directions over other directions, due to the varying number of conflicts at each direction.
Hypothesis 3: It is expected that adjusting the directional settings can compensate for (dis)advantaged directions.
Using the measures for equity, it is expected that this results in a lower Gini coefficient and maximum delay, at the cost of a higher average delay.

When the experiments are separately performed and multiple independent settings led to improvement of equity conform egalitarianism and/or sufficientarianism, these settings can be combined with the intention to find even better results. For example, when certain weight function settings leads to a lower maximum delay and certain directional settings do too, combining those settings would lead to an even lower maximum delay. Following the principle of 1 + 1 > 1.
Hypothesis 4: The performance of independent settings is expected to cumulate when combined.

Furthermore, the settings that are currently used in Flowtack are somewhat general and somewhat tuned for the intersection, but similar settings of Flowtack are currently implemented and performing as desired on multiple intersections.
Hypothesis 5a: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators when implemented on another intersection.

Other than cycle-based TLCs, event-based TLCs are functioning independent of the flow composition, which leads to Hypothesis 5b.
Hypothesis 5b: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators for different flow compositions.

Last but not least there are currently settings implemented that are intersection specific for A050 at Deventer. These settings consist of multiplication factors for directions: The conflicting traffic with the main cycling path gets a lower multiplication factor and the main cycling path and one side road received higher multiplication factors. It is assumed that this side road with the lowest flow experienced the highest delay.
Hypothesis 6: It is expected that helping a minor direction with a higher multiplication factor in the current settings lowers the maximum delay.
Using the measures for equity, it is expected that this results in a lower maximum delay.

6.2.2. Experiments

The following experiments are performed to judge whether the previously stated hypotheses are true or false. Additional reasons for specific settings are elaborated partly in this section, and partly in Appendix B.2. The numbering of the intersection directions is standard, Appendix B.2 shows this numbering with a Figure and some explanations.

Experiment 0: Reference scenario A and current settings
In order to measure the effects of the adjustments in Flowtack's settings on equity, a reference scenario is created. This scenario is created by simplification of the current settings. The reasoning and operations behind the current settings are already elaborated earlier in this chapter, in section 6.1.2. This section shows the numeric values, and the reasoning for the reference scenario to be different from the current settings.

Table 6.1: Flowtack's current settings at the A050 in Deventer

Current settings	**Weight Function $f(w_i(n))$**
	See Figure 6.3
Road user type	**Multiplication factor β_i**
Cyclists	2.0
Pedestrians	4.0
Directions	**Multiplication factor β_j**
02 & 03	1.5
04 & 12	0.8
22 & 81	1.2

Table 6.1 shows the settings that are currently used. Since a weight function is needed for reference, it is chosen to keep the weight function as it currently is for the reference scenario. Under perfect conditions for reference, all settings would be set to 1.0 to minimise any influences on the objective function of Flowtack. However, the road user type weights are chosen to remain as they are, because these settings are used to compensate for *detection blindness*. Therefore, it is chosen to keep these road user type specific settings in the reference scenario. This means that only the directional settings of this reference scenario are different from the current settings, as shown in Table 6.2. While adjusting the settings in the following 3 experiments, the results of the simulation with the settings of this reference scenario is used for reference. Every experiment only adjusts 1 type of settings at a time, leaving the other settings from the reference unmodified.

Table 6.2: Reference scenario A settings

Reference scenario A	**Weight Function $f(w_i(n))$**
	See Figure 6.3
Road user type	**Multiplication factor β_i**
Cyclists	2.0
Pedestrians	4.0
Directions	**Multiplication factor β_j**
all	1.0

By running both sets of settings, a comparison of reference scenario A and the current settings can be made. hypothesis 6 will be tested by this experiment.
hypothesis 6: It is expected that helping a minor direction with a higher multiplication factor in the current settings lowers the maximum delay.

Experiment 1: Weight function settings
The shape of the weight function is varied in this experiment, keeping the road user type weights and directional weights unchanged. Variations of function shapes that are used as concepts for the implemented weight functions in this experiment are shown in Figure 6.5, the actual implementation of the weight functions is elaborated in Appendix B.2. More non-linear shapes could have been tested, however, due to time constraints this research has limited itself to these functions. Function shapes B and D of this experiment test for hypothesis 1a, function shape E for hypothesis 1b and function shape C for hypothesis 1c.
Hypothesis 1a: A weight function that increases over time is expected to favour the road users that would otherwise have been disadvantaged -in terms of delay- over time, at the cost of road users that

would have otherwise been advantaged.
Hypothesis 1b: A weight function that stays constant over time is expected to treat all individual road users equally, thus favouring larger groups of individuals over smaller groups of individuals.
Hypothesis 1c: A weight function that decreases over time is expected to lead to more inequity: (dis)advantaging the already (dis)advantaged.

Table 6.3: Experiment 1 settings

Experiment 1	**Weight Function** $f(w_i(n))$
	Varies
Road user type	**Multiplication factor** β_i
Cyclists	2.0
Pedestrians	4.0
Directions	**Multiplication factor** β_j
all	1.0

For explanatory reasons, *Function E* is elaborated first, the horizontal line. The weight propagation of a road user remains the same during the delay of this road user. This means that the road user's actual weight for the optimisation process increases linearly. In this scenario, a long delayed road user's time is equivalent to a short delayed road user's time, and multiple road user's will always be advantaged over a single road user.

Function B is linearly increasing, which should mean that a long waiting road user's seconds count heavier in the equation than a shortly waiting road user's seconds at all times. This forces the optimisation process to the advantage of the road user's with longer waiting times. In the implementation of this scenario, the tub of the bathtub curve was preserved, and after the tub, the weight function becomes linear. This choice was made to make this scenario a bit more realistic One long waiting road user can in this case even be advantaged over a few other shortly waiting / just arriving road users, if the difference in weight propagation is big enough. Such a principle is perceived fair under the definitions of egalitarianism and sufficientarianism.

Function C shows a weight function that is linearly decreasing. A linearly decreasing weight propagation function still increases the actual weight, however with smaller step sizes when delayed longer. This function creates a scenario where waiting vehicles are disadvantaged over non-waiting vehicles. The cost of delaying a moving vehicle for a few seconds is higher than the cost of having the already delayed vehicle wait for a longer time. This effect increases the maximum delays. Such a weight function does not make sense. However, it is an interesting experiment to check whether the impact of such a weight function on the measured performances of equity is as expected.

Function D shows the same function as Function A in Figure **??**. The idea behind this curve is to implement the same curve differently, varying the steepness of the curve. The curve that is currently implemented is actually more steep at the end than depicted in Figure **??**, therefore a curve that comes closer to this shape is implemented in scenario D.

Experiment 2: Road user type settings
As explained in the first part of this chapter, the current multiplication factors for active modes (cyclists and pedestrians) are implemented to compensate for the lack of proper detection, rather than granting priority to active modes. For this reason, it is chosen to limit the experiments with these settings down to a single experiment.

To find out whether the active modes are (dis)advantaged over the other road users due to the combination of detection blindness and their increased multiplication factor, the vehicle loss hours (VLH) of the active modes are now compared to the total VLH of all road users and the flow of these active modes is compared to the total flow. An egalitarian form of equity would be to balance the share of the active mode's population to their share of the vehicle loss hours.

Even though both the cyclists and the pedestrians have higher multiplication factors than the other road users in reference scenario A, currently pedestrians are still disadvantaged, whilst the cyclists seem to be very advantaged, as shown in Table 6.4. The ratios between the share of VLH and the

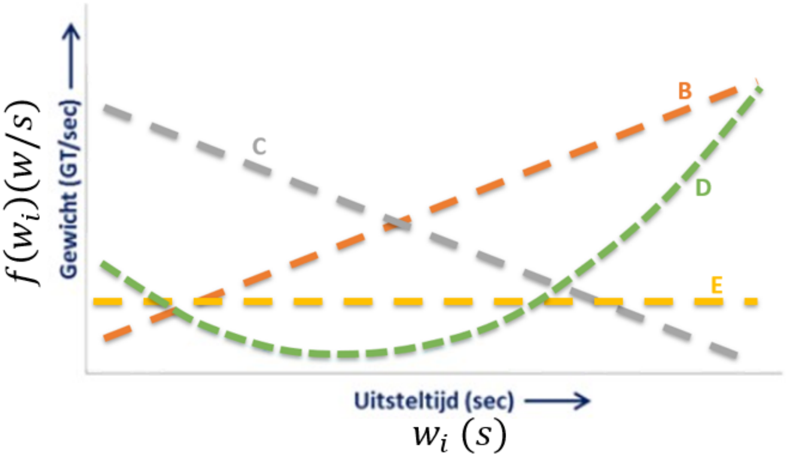


Figure 6.5: Various function concepts as basis for weight function $f(w_i(n))$. Weight factor on the vertical axis, expected delay on the horizontal axis.

share of population is then multiplied with the weight multiplication factor of these modes, resulting in a multiplication factor of 0.8 for cyclists and 5.8 for pedestrians.

Table 6.4: Vehicle loss hours and flows in percentages for cyclists and pedestrians for 6 simulation runs of reference scenario A

%VLH bike	5.33	%VLH ped.	4.22
%Flow bike	13.53	%Flow ped.	2.92
VLH:Flow bike	**0.39**	**VLH:Flow ped.**	**1.44**

The resulting settings for the road user type experiment are presented in Table 6.5. In this experiment, pedestrians are the disadvantaged road users that are favoured, testing hypothesis 2a. Simultaneously, Hypothesis 2b is tested on the cyclists in this experiment. The equity measures as mentioned in Chapter 5 do not measure equity between different road user types. This additional information is required in the results of this experiment to answer the hypotheses. Thus, Table 6.4 will be extended for scenario AM.

Hypothesis 2a: It is expected that when road user type specific settings are adjusted in favour of currently -in terms of delay- disadvantaged road users, the relative disadvantage cancels out.

Hypothesis 2b: It is expected that when road user type specific settings are adjusted in disadvantage of currently -in terms of delay- favoured road users, the relative advantage cancels out.

Table 6.5: Experiment 2 settings

Experiment 2	**Weight Function $f(w_i(n))$**
	A
Road user type	**Multiplication factor β_i**
Cyclists	0.8
Pedestrians	5.8
Directions	**Multiplication factor β_j**
all	1.0

Experiment 3: Directional settings

In this experiment, the settings for cyclists and pedestrians are reset to those of reference scenario A. Only the effects of the directional factors is tested. However, the A050 intersection has a lot of possible variations for the directional settings as there are 21 directions [2] to define a multiplication factor for. This experiment was created more in an iterative way rather than having a predefined plan. The iterations

---

[2] 11 directions for vehicles, 4 directions for cyclists, 4 for pedestrians and 2 for busses, however these bus lanes are shared with other vehicles

steps can be found in Appendix B.2, and their intermediate results are presented in Appendix C. This experiment will test Hypothesis 3.
Hypothesis 3: It is expected that adjusting the directional settings can compensate for (dis)advantaged directions.

Paying attention to the cyclists during the simulation runs of experiment 2 led to the realisation that other factors than just weight for specific modes play a role in the (dis)advantaging of these modes: the amount of conflicts with other directions. When paying attention to especially the cyclists during the simulation runs, it was noted that the main cyclist route (directions 22 and 81 of Figure B.12 in Appendix B.2) had a little amount of conflicts, as it only conflicts with traffic from and to one of the side roads. The other cross over for cyclists conflicts with the main road, but there is a relatively small amount of cyclists on this direction. This causes the cyclists to seem more advantaged over other road users at the intersection due to the position of the cross over. The pedestrians share these routes (and conflicts) with the cyclists, however the pedestrians are equally distributed over both cross overs, whilst the cyclists are mainly using the this main direction. This difference in the distribution explains why pedestrians seem to be disadvantaged and cyclists seem to be advantaged, even though the similarity in routes.

The first iteration scenario of this experiment is implemented purely based on the conflict matrix [3] of intersection A050. This iteration is referred to as scenario conflict factor (CF). *During the run* of scenario CF, the next iteration was created. Namely after the realisation that one conflict does not equal another conflict in terms of how the road user is delayed by the conflicts. A conflict with a big flow on it will generate more delay for you than a conflict that barely has any flow on it. Thus, the weight of a conflict should depend on the flow on this conflict: the opposers. However from road user A's point of view, there are also directions that have no conflict with road user A's direction, including road user A's own direction. If these non-conflicting directions are occupied, these other road users basically 'help' road user A to get green light: the supporters. Iteration 2: scenario weighted conflict factors (WCF) divides the amount of opposers by the amount of supporters, which leads to new multiplication factors per directions.

However, during the simulation of scenario WCF, another flaw was recognised. This flaw is best explained with road user A expecting support from road user B, whom has no conflict with road user A. Meanwhile, road user B expects support from road user A. This means that the multiplication factor in scenario WCF becomes smaller for both road users, due to each other. However, road user A did not expect road user B to has its multiplication factor reduced, and vice versa. So eventually, both road users expected to be supported a certain amount by one another, however the actual amount of support is lower due to the correlation between the road users. This correlation causes the weighted conflict factors to become more extreme than they should be, low values become lower and high values become higher. To solve such a problem is not within the scope of this thesis. A rather practical solution to reduce extreme values is the square root operator. Thus, the final iteration of this experiment is referred to as scenario sqrt, where the square root of the multiplication factors of scenario WCF is taken. The formula for the multiplication factor β_j for every direction of j is stated:

$$\beta_j = \sqrt{\frac{C_j}{S_j}}$$

- β_j, a multiplication factor (-) that is direction dependent.
- C_j, the amount of conflicting road users (opposers) for direction j.
- S_j, the amount of non-conflicting road users (supporters) for direction j, including the amount road users at direction j.

The results of this formula are found in Table 6.6.

---

[3] The conflict matrix of an intersection shows which directions have 'conflicts'. A conflict is when two directions would clash if both receive green light at the same time.

Table 6.6: Experiment 3: settings for scenario sqrt

Experiment 3	Weight Function
	A
Road user type	**Multiplication factor**
Cyclists	2.0
Pedestrians	4.0
Directions	**Multiplication factor**
02	3.7
03	2.4
04, 11	0.4
05	0.3
06	1.1
07	0.9
08	2.2
09, 24, 83	1.6
10, 31, 32	0.1
12	1.0
33	0.7
34	0.8
81	0.2

Experiment 4: Combination of 'best' settings
In order to test Hypothesis 4, the 'best settings' scenario is created from the selection of scenarios from Experiments 1, 2 and 3 with the most egalitarian / sufficientarian results. A final run will be performed which will be referred to as scenario combi, the combination of settings that both lead to an improvement in egalitarian and/or sufficientarian equity.
Hypothesis 4: The performance of independent settings is expected to cumulate when combined.

Last but not least, a **validation experiment** is added to test the best settings for hypotheses 5a and 5b. The best settings could be scenario combi or one of the other scenarios of the previous experiments, if Experiment 4 does not lead to better settings. This validation will show whether these best settings have the same impact on another intersection, with other flow compositions. The corresponding supply and demand that are used for this validation experiment were already elaborated in Section 6.1.1. In order to test these best settings, a new reference scenario is required for each of the OD matrices. The settings of reference scenario A are used for the reference scenarios of the validation, the settings of the best settings scenario will be selected after experiments 1-4 are finished. This creates a set of 6 scenarios that are used for validation, as depicted in Table 6.7.
Hypothesis 5a: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators when implemented on another intersection.
Hypothesis 5b: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators for different flow compositions.

Table 6.7: Validation scenarios

Validation experiment Rotterdam 97190	Validation reference scenario A	Validation best settings scenario
Validation OD matrix 1	VA1	V1
Validation OD matrix 2	VA2	V2
Validation OD matrix 3	VA3	V3

6.2.3. Overview of hypotheses and experiments

An overview of the link between the hypotheses, experiments and scenarios is given in Table 6.8.

Table 6.8: Overview of hypotheses, experiments and scenarios

Hypotheses	About	Experiment	Scenario(s)
Hypothesis 1a	Increasing weight function	1	B, D
Hypothesis 1b	Constant weight function		E
Hypothesis 1c	Decreasing weight function		C
Hypothesis 2a	Road user type specific compensation	2	AM
Hypothesis 2b	Road user type specific compensation		
Hypothesis 3	Direction specific compensation	3	sqrt
Hypothesis 4	Cumulating settings	4	combi
Hypothesis 5a	Similar effects on different intersection	Validation	VA
Hypothesis 5b	Similar effects with different flow compositions		V ’best’
Hypothesis 6	Current settings	0	A

7

Simulation experiment results & Analysis

This chapter presents the results from the experiments as set out in Chapter 6 with the equity measures as described in Chapter 5. This chapter starts with the results of experiments 0-3, then briefly introduce experiment 4, shows its results and ends with a validation experiment. An analysis of the results is mixed in to either confirm or reject the hypotheses. Unexpected results will be highlighted and an interpretation of what might cause such unexpected results is listed.

7.1. Initial experiments

This section includes experiments 0, 1, 2 and 3. Each of the experiments tests how one particular type of settings can influence the equity on the intersection. The hypotheses from the previous chapter are tested and either confirmed or rejected. Analysis of the results and explanation of unexpected effects/behavior are provided in this section. This section ends with a conclusion of experiments 1 to 3 and a selection of the most interesting settings that would lead to a new scenario for experiment 4, in which those settings are combined.

Experiment 0: Reference scenario A and current settings

Figure 7.1 shows the results of experiment 0. The blue dots in this Figure indicate the results for 6 runs of reference scenario A, and the green crosses indicate the results for 5 runs with the current settings. Note that the axes of the Figure are customised to zoom in on the details. The data points from multiple simulation runs of 1 scenario create a cluster of results that indicate how these settings perform. For these plotted data points the average is calculated, and lines are drawn towards this average in order to indicate the center of the cluster of results.

The cluster of results for these scenarios overlap, and it can be seen that the Gini coefficient for the scenarios has an average value of 0.74 and the average delay is also approximately 12.5s for both scenarios. Hypothesis 6 [1] expects that the current settings lead to a lower maximum delay, as the intention of the current settings is to help the side road. The current settings are set as they are, because experience in the field of traffic control tells that the side road is a direction that typically experiences most delay. By reducing the maximum delay relative to reference scenario A by 10 seconds, hypothesis 6 is **confirmed**.

Reference scenario A is represented in each of the results of the following experiments, presenting these exact same data points.

Experiment 1: Weight function settings

The results of experiment 1 are found in Figure 7.2. Note that the blue dots that indicated reference scenario A in Figure 7.1 also indicate this scenario in Figure 7.2. The axes are widened to fit in the results of the other scenarios.

---

[1] *Hypothesis 6: It is expected that helping a minor direction with a higher multiplication factor in the current settings lowers the maximum delay.*

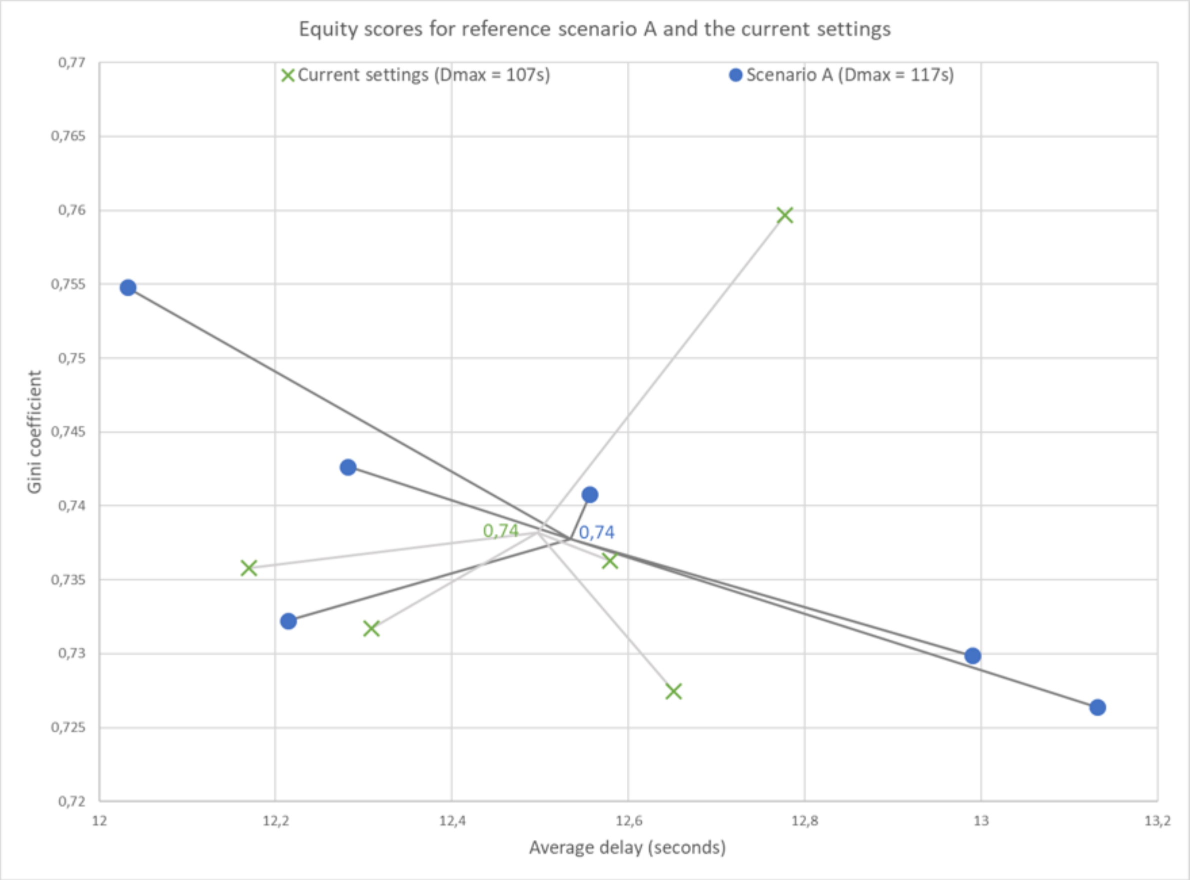


Figure 7.1: Results of experiment 0: Current settings and reference scenario A

The results of scenario B are very promising, as these results score relatively well on all indicators of equity, even though the numeric differences in average delay and Gini coefficient look small. Almost all data points are located below those of the reference scenario and the average delay tends to be slightly higher.

Hypothesis 1a[2] seems to be **confirmed** by scenario B, because favouring the disadvantaged leads to lower average delay and when doing this at the cost of the advantaged, this should lead to a better (lower) value for the Gini coefficient. Both of these expectations are met as the maximum delay drops by 23 seconds and the Gini coefficient drops by 2%.

Even though scenario D is also a curve that increases, the results from scenario D do **not match** hypothesis 1a, because scenario D's Gini coefficient remains the same as that of the reference scenario. This can be explained by scenario D's curve being relatively similar to that of scenario A: only a gradual increase of weight in the weight function between 70-100 seconds is added (visualised in Appendix B.2 Figure B.17). The maximum delay for scenario D does show the desired effect, where it drops by 11 seconds relative to reference scenario A.

It is remarkable that the average delay of scenario D seems to be on the higher side (on average), when comparing it to the reference, whilst the average delay of scenario B is arguably located on the lower side of the reference. This could be caused by the spread between the different runs that occurs due to the latency problem as described in Section 6.1.3, or by other factors within Flowtack that are not known. Scenario B scores arguably better on the average delay, which is an unexpected result. Such a result can be explained because the optimisation process of reference scenario A is being forced to make non-optimal solutions when a delayed road user approaches the "wall of weight" at 100 seconds.

---

[2] *Hypothesis 1a: A weight function that increases over time is expected to favour the road users that would otherwise have been disadvantaged -in terms of delay- over time, at the cost of road users that would have otherwise been advantaged.*

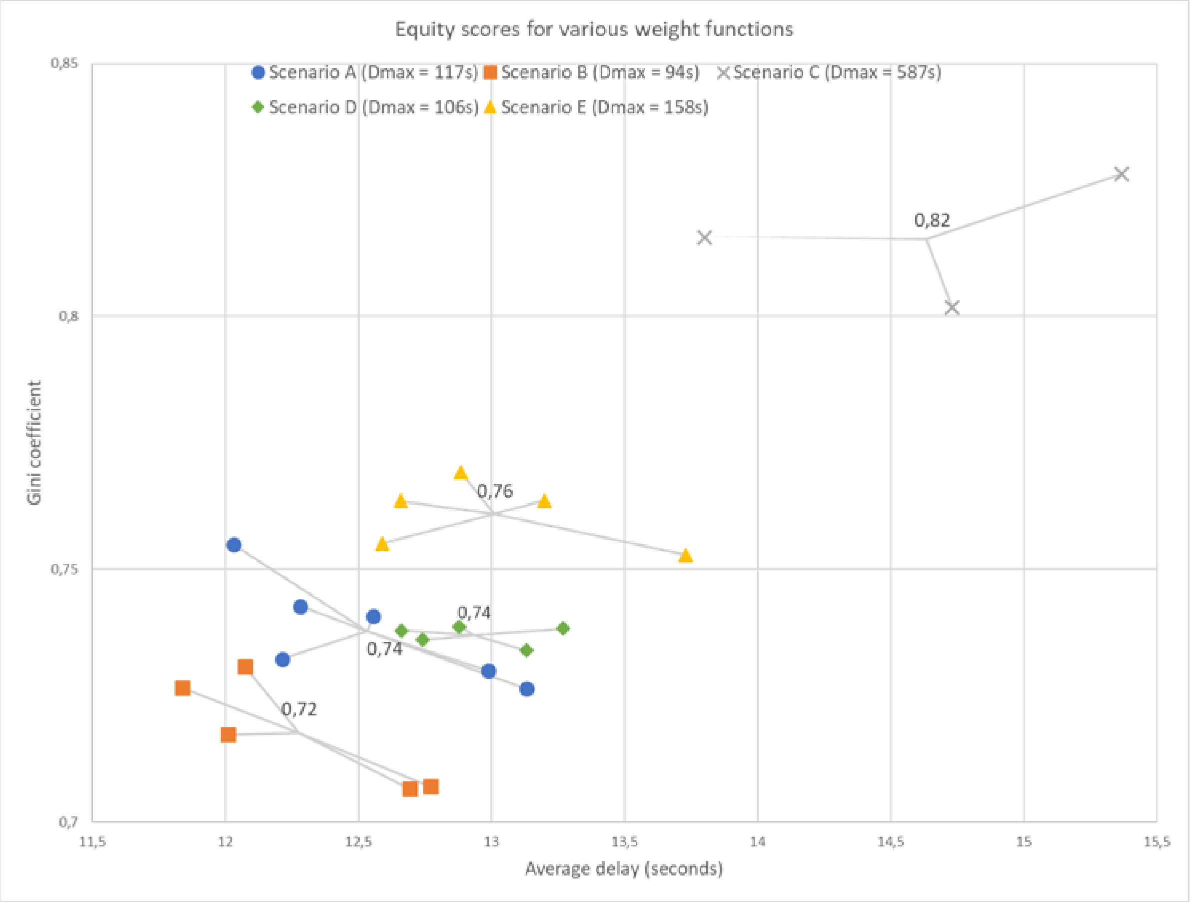


Figure 7.2: Results of experiment 1: Reference scenario A, and weight function scenarios B, C, D & E

This wall of weight can be seen as a tipping point that changes the decisions that are made drastically. The decisions that are made because of these tipping point can be far from optimal. For example, when a platoon is just arriving while the ”wall of weight” is about to be hit by a waiting vehicle on a conflicting direction, this waiting vehicle could get priority over the platoon of vehicles. However, it is not only undesirable to stop the platoon for this waiting vehicle, it is also undesirable to have the waiting vehicle wait for much longer. Therefore, it might have been more optimal to have granted green to this waiting vehicle earlier. A gradually increasing weight does not cause such a tipping point or ”wall of weight” and stimulates an earlier movement of the waiting vehicle.

Scenario E can be linked to Hypothesis 1b[3], because scenario E uses a weight function that is a straight line. Hypothesis 1b’s expectation matches the definition of the utilitarian form of equity: the greatest good for the greatest group. Scoring worse on the maximum delay and the Gini coefficient matches the expectation of a straight weight function, however, the average delay is actually worse by half a second than that of the reference scenario, which is in **counter to the expectation** with respect to hypothesis 1b.

This result could be implicitly caused by the absence of a temporary decline (dip) at the lower levels delays. This dip was preserved in scenarios A, B and D and left out in scenarios C and E. Without such a dip, the disco light effect (see section 6.1.2) is not prevented. Thus, the traffic light switches between green and red more often and every switch requires yellow time and clearance time[4]. The additional clearance times from the disco light effect could lead to these higher average delays.
Even though the counter intuitive result can be explained, hypothesis 1b is **not confirmed**.

---

[3] *Hypothesis 1b: A weight function that stays constant over time is expected to treat all individual road users equally, thus favouring larger groups of individuals over smaller groups of individuals.*

[4] Clearance time is the time that it takes to cross the intersection. This time is required between red of one direction and green of the next (conflicting) direction and is implemented for safety reasons (Knoop et al., 2019)

On the contrary, scenario C does not suffer at all from the disco light effect. Scenario C stimulates waiting, as stopping a driving vehicle will have a high cost since its weight starts high, however having a stopped vehicle wait for longer results in lower costs. This weight function is rather ridiculous, but it shows very well whether the weight function behaviors as expected. A maximum delay of 586s equals almost 10 minutes, a Gini coefficient that corresponds to a very unfair distribution and an average delay that is also increased. This **matches the expectation** of hypothesis 1c[5].

Experiment 2: Road user type settings

Experiment 2's results are shown in Table 7.1. These results are the average values for the 6 runs of reference scenario A and 5 runs of scenario Active Modes (AM), which data can be found in Appendix C.1. The Figure with equity scores can be found in Appendix C.1.

Table 7.1: Vehicle loss hours, flows and the ratio between those in percentages for cyclists and pedestrians scenarios A and AM

Cyclists	Scenario A	Scenario AM	Pedestrians	Scenario A	Scenario AM
%VLH	5.33	6.34	%VLH	4.22	3.75
%Flow	13.53	13.45	%Flow	2.92	2.92
VLH:Flow	**0.39**	**0.47**	**VLH:Flow**	**1.44**	**1.28**

The ratios in Table 7.1 show that the proposed settings for scenario AM do impact the ratio of VLH:Flow in a way that this ratio comes closer to 1.0. A value of 1.0 indicates a balanced scenario (at least, on average, between modes), which corresponds with egalitarianism. For example, when 10 % of the total road users experience 10% of the total delay, the VLH:Flow ratio for these road users is 1.0 and such a data point is on the line of equality in the Lorenz curve. Both Hypotheses 2a[6] & 2b[7] are **somewhat confirmed**. In scenario A, the pedestrians are the disadvantaged, who's multiplication factor increases from 4.0 to 5.8 in scenario AM, whilst the cyclists are the initially advantaged, who's multiplication factor now decreases from 2.0 to 0.8 in scenario AM. The relative (dis)advantage in scenario AM does become smaller for both road user types as the ratios are now closer to 1.0, however, the relative (dis)advantage is not entirely cancelled out because those values are still in advantage of the cyclists and in disadvantage of the pedestrians.

Zooming in on the cyclists, who went from a multiplication factor that was twice as high as that for vehicles to one that was lower than vehicles whilst suffering from detection blindness, it is remarkable that they remained relatively advantaged. This is peculiar, as this is quite a significant change in the multiplication factor, for a limited change in results. As explained in the experiment setup of experiment 3 in the previous chapter, it is not just multiplication factor for the road user type that plays a role here as these cyclists are relatively well off due to the small amount of conflicts and potentially the settings for co-requestsA co-request is a request for green by a direction that has the same (or less) conflicts as the direction that currently has green. and co-extensions[8].

Correcting hypotheses 2a & 2b: Yes, road user type specific settings can be used in order to compensate for (dis)advantage, leading to egalitarian equity. However, the impact is limited as other settings also play a role.

Experiment 3: Directional settings

Figure 7.3 shows the result of experiment 3. In order to get to scenario sqrt, multiple iterations were performed as described in the previous chapter. This section focuses on the results of the last iteration scenario rather than the results of the previous iterations, which are elaborated in Appendix C C.1.

The results of experiment 3 stand out on the Gini coefficient, with the drawback of a higher (about 2 seconds) average delay. The intention of the scenario was to compensate for (dis)advantages caused

---

[5] *Hypothesis 1c: A weight function that decreases over time is expected to lead to more inequity: (dis)advantaging the already (dis)advantaged.*

[6] *Hypothesis 2a: It is expected that when road user type specific settings are adjusted in favour of currently -in terms of delay-disadvantaged road users, the relative disadvantage cancels out.*

[7] *Hypothesis 2b: It is expected that when road user type specific settings are adjusted in disadvantage of currently -in terms of delay- favoured road users, the relative advantage cancels out.*

[8] A co-extension is an extension of a green phase for a direction that has the same (or less) conflicts as another direction which green phase is being extended. This means co-extension will extend this green phase even though no road users are detected.

by the flow distribution over the directions and the amount of conflicts due to the intersection layout. This means that those who initially experienced a high delay due to these causes, now experience a lower delay at the cost of those who experienced low/no delay, which fits under egalitarianism. This type of compensation also has the effect of extreme values becoming less extreme, thus lowering the maximum delay, which fits under sufficientarianism. Hypothesis 3[9] is **confirmed**.

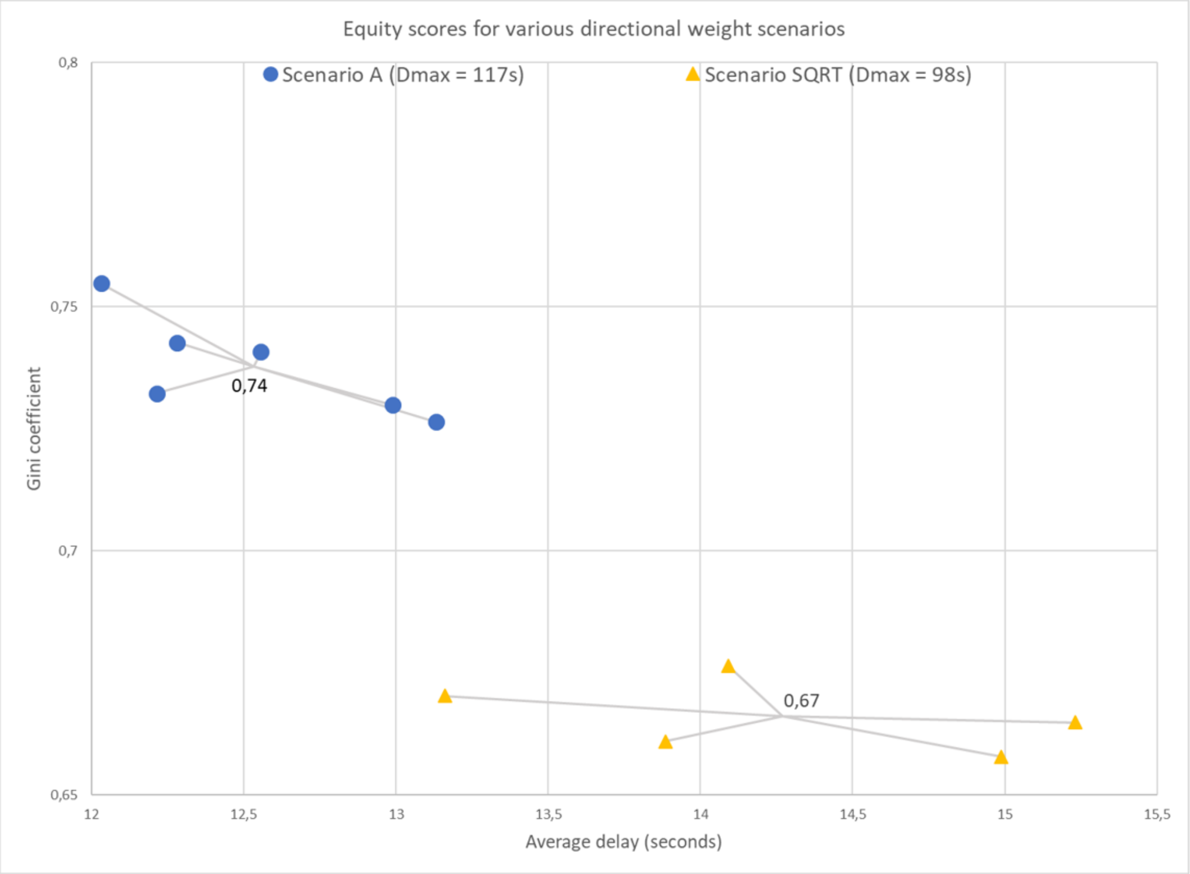


Figure 7.3: Results of experiment 3: Reference scenario A and scenario sqrt - square root of flow weighted conflicts as multiplication factor for each direction

Conclusion

From experiments 1-3 the first conclusion that can be drawn that interactions on an intersection are rather complex and changing certain software related settings can have impact on the outcome but does not always act as expected because of (explainable) other factors that also influence the outcomes. These factors can be other settings that can be changed, or mechanisms of the intersection that can not be changed with settings.

From the results of **experiment 1**, weight function scenario B shows dominant results, better in all cases than all the other weight functions scenarios. Looking back at the research question and the later established goal of improving equity by the definitions by egalitarianism and/or sufficientarianism, scenario B is the only weight function in experiment 1 that improves both. **Experiment 2** shows that vehicle type settings can influence (egalitarian) equity between different road user types. However, the actual impact on the results is limited. **Experiment 3** consists of only 1 scenario that shows exactly the improvement of egalitarianism and sufficientarianism that was expected, even though taking the square root was only a practical solution rather than solving the correlation problem that was elaborated in the experiment setup of experiment 3 (previous chapter).

The hypotheses that were answered in the previous experiments are summarised in Table 7.2.

---

[9] *Hypothesis 3: It is expected that adjusting the directional settings can compensate for (dis)advantaged directions.*

Table 7.2: Hypotheses results from experiments 0-3

Hypotheses	About	Confirmed?	Reason
Hypothesis 1a	Increasing weight function improves egalitarianism	Partly	Little change in results due to little change in settings
Hypothesis 1b	Constant weight function improves utilitarianism	No	No dip, leads to disco light effect and clearance time
Hypothesis 1c	Decreasing weight function leads to inequity	Yes	-
Hypotheses 2a & 2b	Egalitarian settings lead to egalitarian results	Partly	Limited impact, Other factors intervene
Hypothesis 3	Directional settings can compensate: egalitarianism	Yes	-
Hypothesis 6	Lowering max delay: sufficientarianism	Yes	-

Scenario B of experiment 1 and scenario sqrt of experiment 3 could create an interesting combination for follow up experiment 4. scenario AM of experiment 2 is passed for the last experiment, because its impact on the equity indicators were negligible and would increase the complexity of analysing the results of follow up experiment 4.

7.2. Combination experiment

It was concluded from experiments 1-3 that scenario combi will consist of the combined settings: weight function $f(w_i(n))$ from scenario B and directional multiplication factors β_j of scenario sqrt. The results of this experiment are compared to those of the previous experiments, in order to determine which of those scenarios has the most egalitarian and/or sufficientarian results.

Experiment 4: Combination of 'best' settings

This final simulation experiment has been performed with the settings of scenario combi, the combination of scenario B and scenario sqrt. The corresponding settings are displayed in Table 7.3.

Table 7.3: Experiment 4: settings of weight function scenario B and directional scenario sqrt combined to scenario combi

Experiment 4	**Weight Function**
	B
Road user type	**Multiplication factor**
Cyclists	2.0
Pedestrians	4.0
Directions	**Multiplication factor**
02	3.7
03	2.4
04, 11	0.4
05	0.3
06	1.1
07	0.9
08	2.2
09, 24, 83	1.6
10, 31, 32	0.1
12	1.0
33	0.7
34	0.8
81	0.2

The results of using these settings are shown in Figure 7.4. The results of scenarios B and sqrt are copied into this scenario, to quickly see whether the principle of 1 + 1 > 1 from hypothesis 4[10] applies. Figure 7.4 shows that the Gini coefficient of scenario combi is indeed better than either of the separate scenarios. The same is seen for the maximum delay, where both scenarios B and sqrt caused the maximum delay to be lower, the maximum delay of scenario combi is even lower. A similar effect is observed for the average delay, where the value of a positive effect (scenario B, slightly lower average delay) and a negative effect (scenario sqrt, higher average delay) combined end up somewhere in the middle. Hypothesis 4 is **confirmed**.

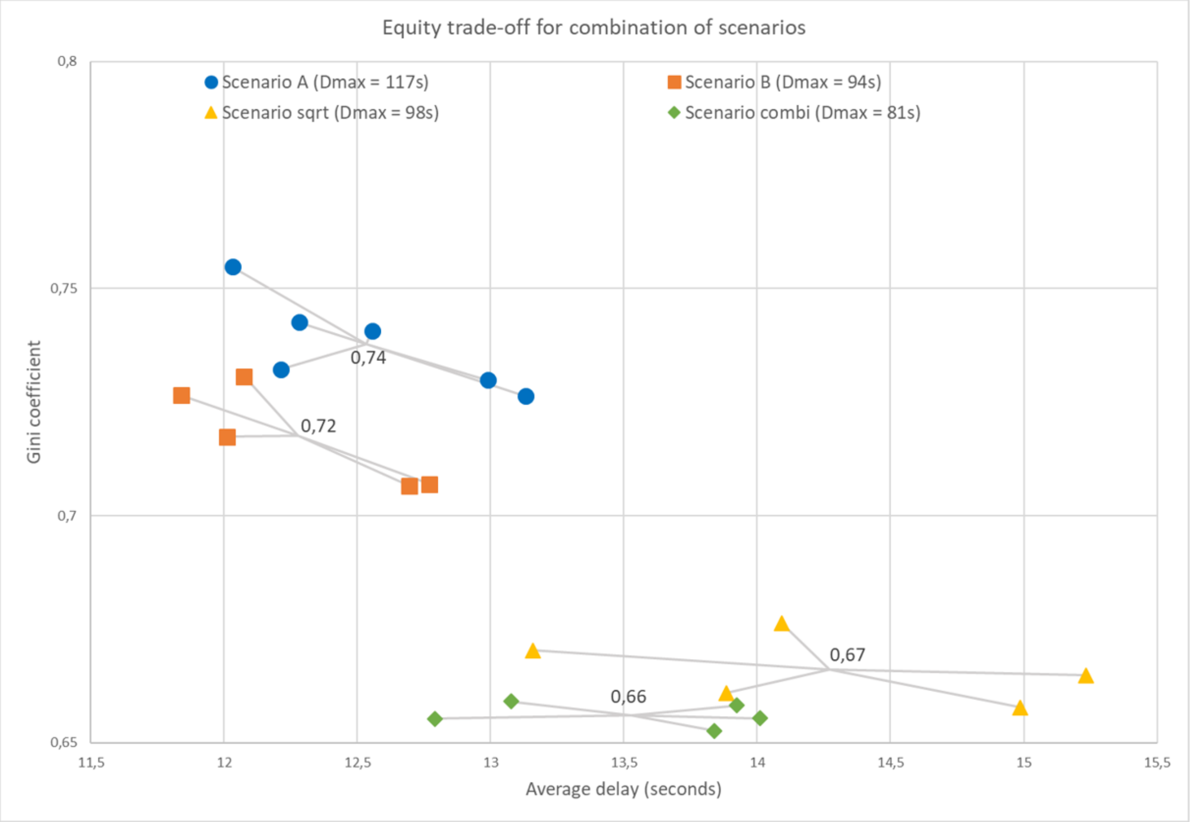


Figure 7.4: Results of experiment 4: Reference scenario A, scenario B, scenario sqrt and scenario combi

Best scoring scenario

The 'best' scenario, with the most egalitarian and sufficientarian scores, from experiments 1-4, can now be identified as scenario combi. This scenario has the lowest Gini coefficient, and the lowest maximum delay. A trade-off to get to these scores is observed, as these results come at the cost of some average delay. The next section will validate whether these settings can be implemented on another intersection, for different flows (defined by a set of 3 OD matrices).

---

[10] *Hypothesis 4: The performance of independent settings is expected to cumulate when combined.*

7.3. Validation

The validation experiments are performed to validate the results of the best scenario in terms of egalitarianism and / or sufficientarianism: scenario combi. This validation is performed in order to show that the settings generate comparable results of the equity performance of another intersection with different flows. This means explicitly that on a different intersection, for different flows, scenario combi will score better on egalitarianism & sufficientarianism, and worse on utilitarianism than the corresponding reference scenario, conforms hypotheses 5a[11] & 5b[12]. However, the absolute value of this trend may differ from Experiment 4, because the capability of improvement in equity measures is very situational to the flow.

Validation experiment settings

The 3 OD matrices, as mentioned in Chapter 6 and found in B.2, create 6 validation scenarios: 3 reference scenarios and 3 combi scenarios. For reference, the same settings as reference scenario A of experiment 0 are used: weight function A & all directional values at 1.0. The road user type specific weights remain undefined in for the validation, and no cyclists or pedestrians are simulated during this validation scenario opposed to the previous experiments.

The combined settings scenario in the validation experiment use weight function B, from Figure 6.5 Chapter 6. The directional settings are **dependent on the flow distribution** in the OD matrix, since the flow and intersection layout influence the multiplication factor. Thus, 3 sets of directional settings are created in the same way these settings were created for scenario sqrt in Experiment 3.

The settings for the validation scenarios combi are generated by the same method as the directional settings of experiment 3. The resulting settings are stated in Table 7.4. The OD matrices, opposer matrices and supporter matrices that were created to produce these settings can be found in Appendix C. Other than for intersection A050 in Deventer, direction 1 on Rotterdam 79190 refers to the right-turning traffic from the East to the North, and this count increases clockwise around the intersection. Appendix C.1.3 shows the link between the cardinal directions and the intersection directions in the opposer and supporter matrices for each direction.

Note that the directional factors that are created for OD matrix 1 are either 1 for straight ahead traffic and left turning traffic, or 0.4 for right turning traffic. Because when all flow is equal and the intersection layout is symmetrical, weighing the conflicts by the flow cancels each other out.

Table 7.4: Directional settings for validation scenario combi 1, 2 and 3.

Validation scenario	**Reference**	**combi OD 1**	**combi OD 2**	**combi OD 3**
Weight Function	A	B	B	B
Directions	**Mult. Fact.**	**Mult. Fact.**	**Mult. Fact.**	**Mult. Fact.**
1	1.0	0.4	0.5	0.8
2	1.0	1.0	1.3	2.9
3	1.0	1.0	1.3	2.3
4	1.0	0.4	0.4	0.3
5	1.0	1.0	0.8	0.3
6	1.0	1.0	1.0	0.9
7	1.0	0.4	0.5	0.7
8	1.0	1.0	1.3	3.1
9	1.0	1.0	1.3	2.5
10	1.0	0.4	0.4	0.3
11	1.0	1.0	0.8	0.3
12	1.0	1.0	1.0	1.0

---

[11] *Hypothesis 5a: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators when implemented on another intersection.*

[12] *Hypothesis 5b: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators for different flow compositions.*

Validation results

The results of the validation are presented in Figure 7.5. This Figure contains 6 scenarios, of which 3 reference scenarios and 3 best settings combination scenarios.

OD matrix 1 had an equal flow on all directions. The results of the scenarios that were created with this OD matrix (the crosses in Figure 7.5) shows an improvement of 12 seconds in maximum delay and about 4% in Gini coefficient. The average delay is increased somewhat.

OD matrix 2 had a slightly unequal flow composition, and led to the result (the diamonds in Figure 7.5) that the improvement of the Gini coefficient is better than that of OD matrix 1. The maximum delay is decreased by 14 seconds and the average delay remains the same.

OD matrix 3 had a very unequal flow composition, like the one in Deventer. This validation (the triangles in Figure 7.5) shows that the Gini coefficient is reduced enormously compared to that of OD matrices 1 & 2, by about 15%. Also the maximum delay is reduced by a considerable 26 seconds. However, this improvement of egalitarianism and sufficientarianism comes at a higher cost of utilitarianism than that of the other OD matrices, about 2.5 seconds.

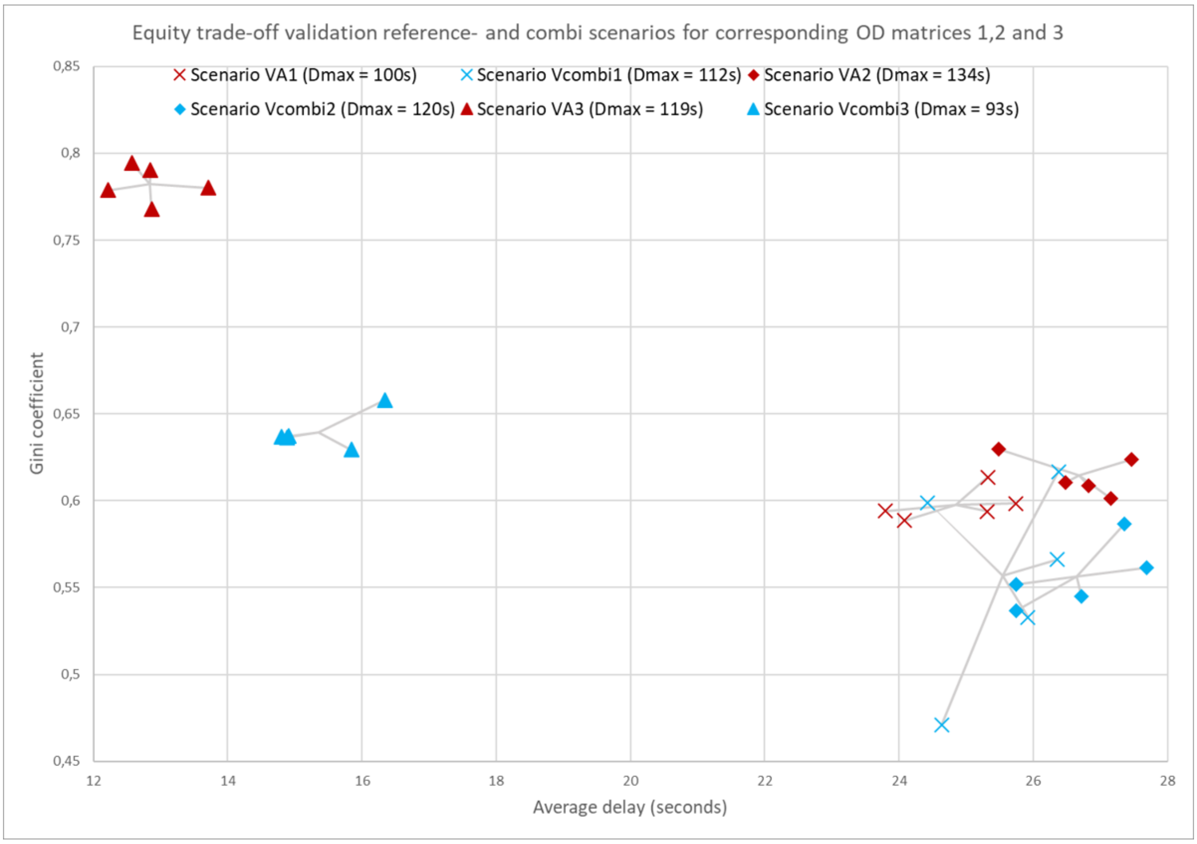


Figure 7.5: Results of the validation: Reference scenario VA1-3 and scenario Vcombi1-3 for each matrix. In red the reference scenarios, and in blue the combi settings scenarios.

Thus, the more unequal the flow composition of the OD matrix, the more gain can be generated on egalitarianism by implementing the settings of scenario combi, even on another matrix. The same counts for the potential gain in sufficientarianism. Only the results for OD matrix 2 show no costs for the improvement in egalitarianism and sufficientarianism, since the average delay remains the same. However, just like on the intersection in Deventer, the validation scenarios with other OD matrices did create the improvement in egalitarianism & sufficientarianism at the cost of utilitarianism. Whether hypothesis 5b[13] could be confirmed can be argued, since a similar negative effect on the utilitarian

---

[13] *Hypothesis 5b: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators for different flow compositions.*

measure was not found in OD 2. Hypothesis 5a[14] is **confirmed**, as OD 3 shows that a similar flow on a different intersection does generate similar effects.

7.4. Conclusion

The combination of weight function B and directional factors based on conflicts, flow and a correction leads to a more egalitarian and sufficientarian iTLC. Flowtack, which was identified as relatively utilitarian, shows the ability to compensate for the loss of egalitarianism and sufficientarianism in the principles (cycles, maximum green time), by the means of adjusting its settings. Where a set sequence, or maximum green time are *hard* control laws, Flowtack's weight function seems to be more of a *soft* boundary to reach those goals. An example of a soft boundary in Flowtack is found in the steep increase of the original weight function in the reference scenario, when a road user is delayed for 100 seconds. In this case, a soft boundary of 100 seconds maximum delay is used, which can be exceeded if traffic demand on the intersection is very unbalanced in favor of other directions. Otherwise, the relatively high weight will push this road user to priority over the others.

The validation of this experiment shows that the *positive effects* on the equity measures of scenario combi are preserved, when implemented on another intersection with different flow compositions. The potential gain in Gini coefficient (egalitarianism) of applying scenario combi's settings, increases when the flow composition (OD matrix) becomes more unequal (and realistic).

A summary of the answers on hypotheses 4, 5a and 5b is presented in Table 7.5 and an oversight of the results of all experiments performed in this chapter is provided in Figure 7.6.

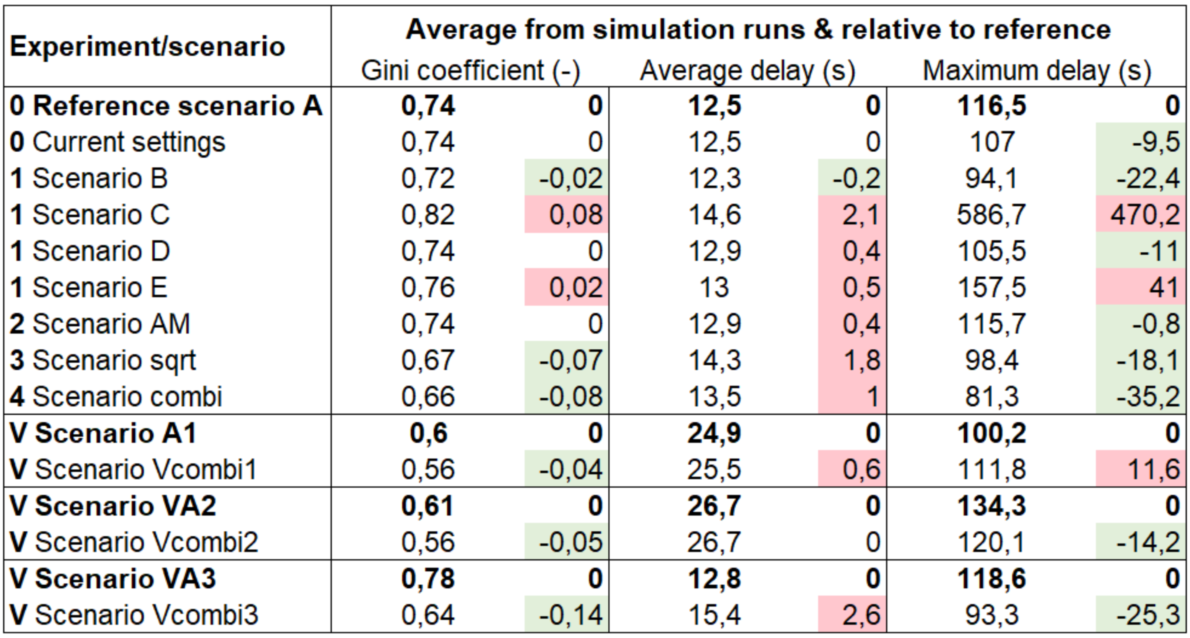
Table 7.5: Hypotheses results from experiment 4 and validation

Hypotheses	**About**	**Confirmed?**	**Reason**
Hypothesis 4	Cumulating settings	Yes	-
Hypothesis 5a	Similar effects on different intersection	Yes	-
Hypothesis 5b	Similar effects with different flow compositions	Yes	-

This summary of the results shows the relative impact on equity, of all experiments and presented scenarios, to the corresponding reference scenario in color. This table shows clearly that the magnitude of improvement in the Gini coefficient increased over the validation scenarios. One exception is found in the maximum delay of validation scenario 1, as its maximum delay increases instead of decreases. The reason for this exception is presumed to be caused by the fact that the initial weight function was, in this case (Validation scenario 1), more effective in reducing the maximum delay because of its shape and the flow composition of the scenario. The shape increases the weight factor from 1 to 10 at 100 seconds, thus stimulating the optimisation to avoid delay longer than 100 seconds, whilst the proposed weight function (B) is more effective at increasing a single road user's weight to gain advantage over the larger group. In this validation scenario, the flow composition was equally distributed over the directions, such that there is no single road user or a main road with bigger groups.

---

[14] *Hypothesis 5a: When using the found (combination of) settings that lead to the most egalitarian and/or sufficientarian measures of equity, similar settings are expected to lead to similar effects on the equity indicators when implemented on another intersection.*



Experiment/scenario	**Average from simulation runs & relative to reference**					
	Gini coefficient (-)		Average delay (s)		Maximum delay (s)	
0 Reference scenario A	**0,74**	**0**	**12,5**	**0**	**116,5**	**0**
0 Current settings	0,74	0	12,5	0	107	-9,5
1 Scenario B	0,72	-0,02	12,3	-0,2	94,1	-22,4
1 Scenario C	0,82	0,08	14,6	2,1	586,7	470,2
1 Scenario D	0,74	0	12,9	0,4	105,5	-11
1 Scenario E	0,76	0,02	13	0,5	157,5	41
2 Scenario AM	0,74	0	12,9	0,4	115,7	-0,8
3 Scenario sqrt	0,67	-0,07	14,3	1,8	98,4	-18,1
4 Scenario combi	0,66	-0,08	13,5	1	81,3	-35,2
V Scenario A1	**0,6**	**0**	**24,9**	**0**	**100,2**	**0**
V Scenario Vcombi1	0,56	-0,04	25,5	0,6	111,8	11,6
V Scenario VA2	**0,61**	**0**	**26,7**	**0**	**134,3**	**0**
V Scenario Vcombi2	0,56	-0,05	26,7	0	120,1	-14,2
V Scenario VA3	**0,78**	**0**	**12,8**	**0**	**118,6**	**0**
V Scenario Vcombi3	0,64	-0,14	15,4	2,6	93,3	-25,3

Figure 7.6: The equity results of all experiments, average value of Gini coefficient, average delay and maximum delay for multiple simulation runs per scenario on the left and on the right the relative change to the associated reference scenario.

8

Discussion & conclusion

This chapter starts with a discussion sections, which includes a reflection of the results. This discussion will be taken into account for the conclusion of this thesis.

8.1. Discussion

This discussion reflects on the results of this thesis. Because this thesis includes 2 research questions, this discussion is split up in 2 subsections, one of which covers Chapters 3 & 4 and the other covers Chapters 5, 6 & 7.

8.1.1. Ethics & Control theory

The ethical theories that have been covered are by far not all ethical theories that were available. Van Wee and Roeser (2013) mentioned contextualism & contractualism as interesting theories, and in the process of looking for literature, theories like relativism & virtue ethics seemed interesting as well. The selection of theories may have or may not have impacted the course of this research. However, for this project's scope, these 4 theories seem relevant and broad. To substantiate why these ethical theories are relevant, Liang et al. (2020) have, by coincidence, used the measures of equity that correspond to these ethical theories, in their isolated intersection control study on efficiency versus equity.

Using ethical theories to define iTLC principles in practise is new. However, studies in the field of autonomous driving do show some ethical considerations of priority in situations where everyone travels by autonomous vehicles, which is a field of study close to this one. Mladenovic and McPherson (2016) proposed a method for individual priority indexes for each road user in an autonomous vehicle, with a trade-off of social justice and efficiency being fundamental for the design. Social justice finds its way into - what is identified as - egalitarianism in this research, via John Rawls. Efficiency on the other hand was identified as utilitarianism in this research. This confirms the use of egalitarianism and utilitarianism as interesting theories for the traffic management problem. In addition, where Mladenovic and McPherson (2016) is one step ahead in time by designing traffic management systems for fully autonomous driving vehicles without the need for traffic light control, *this thesis* focused more on the development and clarifications of the present day techniques.

For control theory, feedforward control (FFC), feedback control (FBC) and model predictive control (MPC) are used in order to explain the main differences in traffic controllers that are used with fixed time control, fully actuated control and structure-free, Flowtack. Due to limit of time, only CCOL, as fully actuated FBC, and Flowtack, as structure-free MPC have been elaborated. Adding the elaboration and identification of ethical background of fixed time FFC would have been more complete picture, possibly pushing CCOL relatively in more utilitarian corner with Flowtack. However, Flowtack remains relatively utilitarian with regards to CCOL, therefore the following simulation experiment goal of improving equity on by the other definitions of egalitarianism & sufficientarianism, would not have changed if older traffic light controllers would have been elaborated in this chapter.

8.1.2. Equity measures & simulation experiment

Van Wee and Roeser (2013) and Lucas et al. (2016) show that the addition of ethical theories to the now commonly used - mainly utilitarian - Cost-Benefit Analysis in the Netherlands, are key to include equity in decision making. Measures for equity according to various ethical theories, including utilitarianism, egalitarianism and sufficientarianism are explicitly elaborated in these studies. However, the measurement method provided by Liang et al. (2020) provided more insight to the trade-off between the different ethical theories, which shows useful for the experiments. These measures were selected for this thesis as the measures for utilitarianism, egalitarianism and sufficientarianism. Relative to the ethical theories, these measures seem quiet blunt. An excuse to accept this bluntness, is that most philosophers argue about right or wrong, life and death, which makes the issues very complex: there is not a single definition of equity, not even per ethical theory. On the other hand, a practical measure needs a clear definition. Traffic light control is complex too, however, it does not cause discussions about life or death and to some extent right or wrong. The challenge on the intersection is rather practical, which requires the practical, but blunt, measures as provided in Chapter 5.

Liang et al. (2020) used these measures to show the impact of varying the maximum delay thresholds, flow and the penetration rate of connected vehicles. The experiments in this research have some similarities, but are in essence very different. The algorithm that was used by Liang et al. (2020) was able to set absolute thresholds for the maximum delay in the optimisation problem, where Flowtack does this in a soft way by changing weights in the settings. The maximum delay is an input in the Liang et al. (2020)'s study, whilst it is an output measure in this thesis. Furthermore, this thesis does not vary the amount of connected vehicles. It uses a number of 3% of connected vehicles for its simulations, which is a representative number for the current situation on the roads (Willekens, 2020). Liang et al. (2020) show a positive impact on the Gini coefficient with lower threshold values of the maximum delay, whilst lower thresholds do cause a negative effect on the average delay. This can also be seen in this thesis's experiments, where improvement of the Gini coefficient often (but not always) moves along with an improvement of the maximum delay at the cost of the average delay (the exception has been elaborated in the results).

Another reason for the differences in results can be found in the reproducibility of the results that were created in this thesis. Due to the latency, the results actually varied during each run, even though settings remain the same and the simulated population is generated with the same random seed. How latency impacts these results is elaborated in Chapter 6. Because of this latency error, this thesis performed every experiment a number of times, creating a cluster of results, which could fade the correlation between the measures that were found in Liang et al. (2020)'s study.
The objective of this research was to *measure* and *improve* equity of an iTLC. Because Flowtack was specified as mainly utilitarian by the first part of this thesis, this research goal was fine-tuned in the process to improve egalitarian & sufficientarian equity. The results in Chapter 7 show that this is achieved with the settings of experiment 4: scenario combi. The imprecise reproducibility does not matter in this case, because even though the spread of data points, they are clustered in results that show little to no overlap. In the real world, the reproducibility and latency would not cause a problem to measure equity, which would make the outcome of these measures more solid.

The 3 performance indicators for utilitarianism, sufficientarianism and egalitarianism - average delay, maximum delay and Gini coefficient - show that an improvement from 0.74 to 0.66 on the Gini coefficient and reducing the maximum delay from 117 to 81 seconds, brings the average delay (on average) up from 12.5 to 13.5 seconds in experiment 4. A following question rises: is this result desired from the road user's perspective?
The most intuitive indicators are the average delay and the maximum delay. Feedback from experts from sustainable mobility at RoyalHaskoningDHV brought up that the perceived delay of road users does not necessarily equal the measured delay. This session showed that minor delay is generally perceived close to the actual delay, whilst major delay is generally perceived as longer than the actual delay. This means that the gain of lowering the maximum delay by 35 seconds would be perceived more positive than the actual 35 seconds, whilst the extra second in average delay might pass unnoticed. This means that the eTLC in this case, would be perceived positive by the road users.
On the contrary, if given a choice to the Dutch road user, who is generally an individualist, the greater group of road users is expected to choose utilitarianism over egalitarianism or sufficientarianism, because this will benefit this group. A popular saying in the Netherlands to support such a choice: ”Time

is money". Note that this statement is heavily generalised and not supported by research. However, it can be a counter argument to take into account for the discussion whether an eTLC is desired or not. As a matter of fact, every person has his/her own perspective on equity, hence the wide range of ethical theories.
Next, the Gini coefficient is not as intuitive as the average and maximum delay, because this is a dimensionless number that says 'something' about the distribution of delay in this research. An improvement in Gini coefficient means that the least-advantaged are now relatively closer in the distribution to the most-advantaged. However, this does not necessarily equal an absolute improvement in delay for the least-advantaged, as this improvement of Gini can also be reached by lowering the advantage of all the advantaged. For example, traffic jams would lead to very egalitarian results, because in the case of traffic jams, all road users experience a significant delay.

From the experiments, experiment 3 shows that there is some form of correlation when defining the multiplication factors for directions: When one direction expects a certain amount of support from another non-conflicting direction, the actual support is lower because the other direction's multiplication factor was lowered because it was expecting a certain amount of help as well. This correlation problem has been tackled by tackling the outcome, which becomes more extreme, via the square root operator, rather than tackling the cause of the correlation. For now, this solution has provided the improvement in equity that was looked for, thus this method was sufficient for this thesis. However, if ever to be implemented, a more elegant solution would be to apply a different method that doesn't suffer from correlation.

An interesting point of discussion is found in the detection blindness. Due to this inaccuracy and inconsistency of detection, inequality is generated between road users. More accurate detection allows for better anticipation of the arriving road user, advantaging this road user over a road user that can not be accurately - or is rather late - detected. This problem has been pointed out earlier in Chapter 6, where the current settings for pedestrians and cyclists seem to be implemented to compensate for this detection blindness. These settings for pedestrians and cyclists were empirically estimated to function as desired and it was chosen for this thesis to keep those settings as they are. These inconsistencies are real-world problems, looking back, it was not necessary to implement such real-world problems into this thesis' simulation experiment in Aimsun. This option has been overlooked in the experiment setup. These compensating factors might have blurred the actual results of the simulation experiments in this thesis.
Ideally, the timing between detection and arrival would be equal, accurate and consistent for each type of road user on every direction.

Last but not least, -a little bit off topic, but nevertheless one of the most important issues nowadays-sustainability. This thesis did not tackle sustainability issues. Looking back at this thesis, Flowtack does show potential to account for sustainability goals via the weight function. However, reaching sustainability goals via the intersection creates a paradox. When stimulating road users to cycle instead of taking the car, cyclists are generally prioritised, which causes vehicles to be stopped more often. However, stopping vehicles increases the emissions, whilst stopping cyclists does not create additional emissions.

8.2. Conclusion

This thesis explicitly connected ethics and control theory, based on a combination of literature of both topics. From this explicit connection, this thesis concludes that Flowtack, as example of a structure-free Model Predictive Control iTLC, is identified as rather utilitarian compared to CCOL, which is an example of a conventional feedback controller, whilst CCOL is identified is rather egalitarian compared to Flowtack. Even though, all ethical theories find some representation in both iTLCs. Together, this answers research question 1.

Furthermore, measures for equity based on utilitarianism, egalitarianism & sufficientarianism have been defined. These measures allowed this thesis to measure an improvement in egalitarian and sufficientarian equity, by successfully adjusting Flowtack's settings in simulation experiments. This answers research question 2.

Adding the two research parts of this thesis up leads to the conclusion that a choice between a more egalitarian/sufficientarian eiTLC and the currently utilitarian iTLC is provided for traffic engineers and policy makers. This choice can now be explicitly substantiated by a combination of ethical theories, control theory, principles in iTLCs.

Pragmatically, identification and measurement of equity in the first part of this thesis, are the means to an end: more equitable traffic light control, part 2 of this thesis. In terms of scientific contribution, the explicit identification of the link between traffic control & equity is of value. Explicitly using definitions of equity from various ethical theories in intersection control, leads to a deeper understanding of the reason behind certain principles.

On one side, the ethical part of this discussion pointed out that all individual have their own ethical perspective on equity. The perception of delay plays a considerable role in how the equity trade-off will be made by road users. On the other hand, policy makers consider criteria like time of day (peak / off-peak), location (industrial / residential), etc in order to make this equity trade-off. On the other side, the signalised intersection is controlled by a discrete controller in a continuously changing, and complex environment.
The combination of the above mentioned ethical- and technical difficulties add another layer of complexity. Nevertheless, this thesis has made the first steps to explicitly connect the complex topics of equity & traffic control.

Only time will tell whether the ambition to *”create awareness of ethics in the world of traffic light control”* will be achieved. By telling the story of this thesis at TU Delft and the Transport & Planning department of RoyalHaskoningDHV, discussion on this topic has already been encouraged. Furthermore, the proposed method for equitable settings shows that the ethics-based iTLC (eiTLC) is technically feasible. A remaining challenge for now is to find both societal- and political feasibility, from road users' and policy makers' perspective.

9

Recommendations

This chapter contains some recommendations based on the discussion and conclusion of this thesis. Starting with recommendation for further research, followed up by recommendations for implementations in practise.

9.1. Further research

- A timeline of developments in intersection management, linked to equity. This puts the principles and different control methods in perspective of time.
- The experiments of this research were performed with Flowtack. However, it would be interesting to see how CCOL settings can be adjusted in order to improve equity by the same measures, and compare the equity scores that the different technologies are able to achieve.
- The correlation problem from experiment 3 was not solved, instead, a rather practical solution was used in this thesis. Further research could come up with another method in order to benefit the least advantaged, that does not have this correlation problem.
- Instead of implementing equity by control laws that adjust the objective function, actual optimisation of equity. This could theoretically be done by expressing the average delay and maximum delay in a value of 0 (good) to 1 (bad), just like the Gini coefficient, with as objective function a minimisation of the sum of these coefficients. Additionally, multiplication factors can be added to determine a relative weight between the equity coefficients.
- Equity research on a networks level. In addition contractarianism could be added as ethical theory, which could lead to principles like delay compensation for road users.
- Using the *perceived* delay in order to find the impact of this thesis' eTLC settings on road users. Such a research focuses on the human factors of the intersection. The perception of the Gini coefficient would be a nice addition (see discussion, the Gini coefficient requires context).
- The impact of loop detection on equity. Liang et al. (2020) has already researched the impact of the penetration rate of connected vehicles on the intersection, however, the impact of the moment of detection by loop detector should be important if the penetration rate of connected vehicles is low. Due to detection blindness, multiplication factors of respectively 4 and 2 are currently implemented for pedestrians and cyclists. This implies that the difference in moment of detection and actual arrival at the intersection has a significant enough impact on the level of service to the road user to implement these compensation factors.
- A sensitivity analysis for the impact on equity of changing Flowtack's settings by quantity and absolute numbers, rather than the ideological approach of this thesis.

9.2. Implementation in practise

- A market analysis to find out the political and societal feasibility of the eTLC.
- Weight function B seemed to score (slightly) better on all performance indicators of equity. If this is validated to be true for various other intersections and flow composition, this would be an argument to apply this weight function in general.
- Where in simulation, the OD matrices of year-average peak hours for the intersection are used to create the eTLC settings per direction, in real life, real-time data could be used in order to find the amount of conflicting and non-conflicting road users per direction, updating the directional factors every x hours.
- Dynamic settings over the day, this creates the opportunity for policy makers to choose a desired form of equity fit for the situation. This could for example be, utilitarian during peak hour and egalitarian/sufficientarian way during off-peak.
- Inform policymakers at municipalities and provinces that Flowtack can adjust its settings to conform to different ethical views. Policymakers will need insight in the trade off between utilitarianism and egalitarianism / sufficientarianism.
- Stimulation of mobile (CAM) data by informing the road users about the impact of detection on the optimisation, which is substantiated by other research (Liang et al., 2020) (Guler et al., 2014).

References

Åqvist, L. (1969). Improved formulations of act-utilitarianism. *Nous*, *3*(3), 299–323.

Arneson, R. (2007). Distributive justice and basic capability equality:“good enough” is not good enough. In *Capabilities equality* (pp. 27–53). Routledge.

Baumane-Vitolina, I., Cals, I., & Sumilo, E. (2016). Is ethics rational? teleological, deontological and virtue ethics theories reconciled in the context of traditional economic decision making. *Procedia Economics and Finance*, *39*, 108–114.

Casas, J., Ferrer, J., Garcia, D., Perarnau, J., & Torday, A. (2010). Traffic simulation with aimsun. In *Fundamentals of traffic simulation* (pp. 173–232). Springer.

Crocker, L. (1977). Equality, solidarity, and rawls’ maximin. *Philosophy & Public Affairs*, 262–266.

Dynniq. (2021). *Overzichtsplaatje deventer a050.*

Farah, H. (2018). *Lecture slides ctb3370 - geometrical design of roads and railways.*

Fløan, I., Looijen, H., Smit, P., & Hiddink, J. (2016). *Intelligente verkeers regel installatie (ivri) – fase 1.* Retrieved from `https://www.ivera.nl/wp-content/uploads/2016/01/Deliverable-F-iTLC-Architecture-v1.2.pdf`

Gaus, G. (2001a). What is deontology? part one: orthodox views. *Journal of Value Inquiry*, *35*(1), 27.

Gaus, G. (2001b). What is deontology? part two: Reasons to act. *Journal of Value Inquiry*, *35*(2), 179.

Goodin, R. (1995). *Utilitarianism as a public philosophy*. Cambridge University Press.

Guler, S., Menendez, M., & Meier, L. (2014). Using connected vehicle technology to improve the efficiency of intersections. *Transportation Research Part C: Emerging Technologies*, *46*, 121–131.

Harrod, R. (1936). Utilitarianism revised. *Mind*, *45*(178), 137–156.

Harsanyi, J. (1977). Rule utilitarianism and decision theory. *Erkenntnis*, *11*(1), 25–53.

HaskoningDHV, R. (2021). *Interne data.*

Humblet, B. (2020). *Flowtack, optimale doorstroming: vlotter verkeer, schonere steden.* Retrieved from `https://www.royalhaskoningdhv.com/nl-nl/nederland/specials/flowtack`

Jain, R., Chiu, D., & Hawe, W. (1984). A quantitative measure of fairness and discrimination. *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*.

Kant, M., Hut, G., & Wolfrat, H. (2019). *Functionele specificatie flowtack* (Tech. Rep.). HASKONINGDHV NEDERLAND B.V.

Kesten, A., Ergün, M., & Yai, T. (2013). An analysis on efficiency and equity of fixed-time ramp metering. *Journal of Transportation Technologies*, *3*.

Knoop, V., Hegyi, A., Salomons, M., van Lint, H., Yuan, Y., & Landman, R. (2019). *Traffic flow modelling & control*. Delft: Delft University of Technology.

Li, L., & Jabari, S. (2019). Position weighted backpressure intersection control for urban networks. *Transportation Research Part B: Methodological*, *128*, 435–461.

Liang, X., Guler, S., & Gayah, V. (2020). An equitable traffic signal control scheme at isolated signalized intersections using connected vehicle technology. *Transportation Research Part C: Emerging Technologies*, *110*, 81–97.

Lucas, K., Van Wee, B., & Maat, K. (2016). A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches. *Transportation*, *43*(3), 473–490.

Mladenovic, M., & McPherson, T. (2016). Engineering social justice into traffic control for self-driving vehicles? *Science and engineering ethics*, *22*(4), 1131–1149.

Nussbaum, M. (2003). Capabilities as fundamental entitlements: Sen and social justice. *Feminist economics*, *9*(2-3), 33–59.

Ranjitkar, P., Shahin, A., & Shirwali, F. (2014). Evaluating operational performance of intersections using sidra. *The Open Transportation Journal*, *8*(1).

Rawls, J. (2009). *A theory of justice*. Harvard university press.

Robinson, R. (2019). Kant’s categorical imperative and moral duties. In *Imperfect duties of management* (pp. 11–38). Springer.

Shields, L. (2020). Sufficientarianism. *Philosophy Compass*, *15*(11), 1–10.

Stone, T. (2016). *A complete history of the traffic signal.* Retrieved from `https://www.traffictechnologytoday.com/features/a-complete-history-of-the-traffic-signal.html`

Talking Traffic, P. (2019). *Hoe staat het met de ivri?* Retrieved from `https://www.talking-traffic.com/nl/nieuws/hoe-staat-het-met-de-ivri`

van Lint, H., Hoogendoorn, S., van Zuylen, H., Hegyi, A., Bliemer, M., & Pel, A. (2014). *Integrated and coordinated networkmanagement*. Delft: Delft University of Technology.

Van Wee, B., & Roeser, S. (2013). Ethical theories and the cost-benefit analysis-based ex ante evaluation of transport policies and plans. *Transport reviews*, *33*(6), 743–760.

Viti, F., & Van Zuylen, H. (2010). A probabilistic model for traffic at actuated control signals. *Transportation Research Part C: Emerging Technologies*, *18*(3), 299–310.

Wegenwiki. (2017). *Cyclustijd.* Retrieved from `https://www.wegenwiki.nl/Cyclustijd`

Willekens, M. (2020). *Flowtack in deventer - verkeerskundige evaluatie* (Tech. Rep.). DTV Consultants B.V.

Wilson, A. (2006). *Handboek verkeerslichtenregelingen*. Ede: CROW.

Wu, J., Ghosal, D., Zhang, M., & Chuah, C. (2017). Delay-based traffic signal control for throughput optimality and fairness at an isolated intersection. *IEEE Transactions on Vehicular Technology*, *67*(2), 896–909.

Yarger, B. (1993). Fully actuated vs. semi-actuated traffic signal systems. *Yarger Engineering, Indianapolis*.

Yu, J. (2005). The beginning of ethics: Confucius and socrates. *Asian Philosophy*, *15*(2), 173–189.

A

Appendix A

This Appendix contains a summary of this thesis, written as a research paper.

Identifying-, measuring- and experimenting with equity in intelligent Traffic Light Control

O. Hendriks, J.W.C. van Lint, J.A. Annema, A. Hegyi, M.C. Verkaik-Poelman, G. Hut, M.S. Jesus

Delft University of Technology, TIL5060 Transport, Infrastructure & Logistics thesis

Abstract. A new generation of intelligent Traffic Light Controllers uses Model Predictive Control to minimise delay at signalised intersections. The conventional cycle of set sequences of green phases is dropped for optimisation purposes. This research uses the ethical theories utilitarianism, egalitarianism, sufficientarianism & deontology to define equity. An explicit connection of these ethical theories and technical principles of conventional traffic light controller CCOL & new generation traffic light controller Flowtack, has been provided to identify the change in ethical landscape, from predominantly egalitarian towards relatively utilitarian. Performance indicators for equity in traffic control are defined based on earlier research. Multiple setting changes in Flowtack are proposed and tested in simulation experiments with Aimsun. These experiments show that adjusting Flowtack's objective function can improve the equity scores according to egalitarianism & sufficientarianism, at the cost of the equity score of utilitarianism. The best results are validated using various flow compositions on an alternative intersection. As a result, the gain in equity by the proposed settings becomes greater, as the flow composition becomes more uneven.

1 Introduction

There are 5500 signalised intersections in the Netherlands (Talking Traffic, 2019). The key function of the signalised intersection is to *safely* and *efficiently* manage the flow of traffic. Most of the signalised intersections are equipped with an intelligent Traffic Light Controller (iTLC) that runs with set sequences, or cycles. The most common iTLC in the Netherlands uses (fully) actuated control, which allows the controller to react on detected traffic.

A new generation of iTLCs, that can anticipate on incoming traffic flows, is now being developed and tested. This new generation iTLCs do not necessarily follow a cycle pattern or particular sequences, instead, it controls in a structure-free order of directions, and optimises the sequence and time of the control plan for green phases. This allows the new generation of iTLCs to respond more freely on the measured and anticipated traffic, which creates opportunities for even more efficient intersection control.

However, loss of cycle structure in intersection control rises questions. When efficiency is the objective in development of newer techniques, will the new generation of iTLCs still be fair? Cycles ensure a frequency of turns, where the new generation of iTLCs do not ensure this. An example of this problem is given by a side road on an intersection with a single road user on it, who has to wait for a very busy main road during peak hour. The conventional iTLC guarantees this road user a turn within one cycle. However, without cycles it is probably optimal to let this road user wait until peak hour is over. This however, is an unacceptable long waiting time. On the other hand, prioritising this single road user would not be fair to the big group of road users that then would have to stop. Thus, somewhere in between these 2 extremes. The relevant question to ask with the present development and opportunities is: "What is acceptable - or what is *fair*?"

This question has occupied philosophers in the study of ethics plenty of years. The study of ethics is about 2500 years old, as Confucius and Socrates are considered its founding fathers for Eastern and Western ethics (Yu, 2005). Throughout the years, many philosophers have documented their ethical theories, resulting in a wide range of theories. Spinoza (1632-1677), Kant (1724-1804), Hegel (1770-1831), Marx (1818-1883), Nietzsche (1844-1900), Sartre (1905-1980) and Rawls (1921-2002) are some examples of influential philosophers one might have heard about.

This paper merges control theory with the study of ethics, by decomposing the iTLC system into principles that can be linked with an underlying ethical theory. The ethical backgrounds of CCOL and Flowtack, as examples of a conventional- and a new generation iTLC, will be explicitly defined in the following Section. With knowledge of how ethics are implemented in these systems, a simulation experiment will be performed. The objective of this simulation experiment will be to show whether the level of equity (or fairness) can be improved by adjusting settings in Flowtack.

2 Ethics, control theory & performance indicators

2.1 Definitions of equity

Four ethical theories are selected from Van Wee and Roeser (2013) and Lucas, Van Wee, and Maat (2016): utilitarianism, egalitarianism, sufficientarianism & deontology. These theories cover a broad spectrum of perspectives on the definition of equity (Van Wee & Roeser, 2013).

Utilitarianism concerns the maximisation of utility, which can be translated to maximisation of profit or social value (Åqvist, 1969), (Harsanyi, 1977). Equity is thus defined as the summed up utility for all members of the population that produces the greatest possible utility, in other words, the greatest good for the greatest group.

Egalitarianism strives towards equality of goods and capabilities, based on an individual's needs (Rawls, 2009), (Nussbaum, 2003), (Van Wee & Roeser, 2013). Rawls (2009) argues that goods should be distributed in such a way that they are of the greatest benefit to the least-advantaged individuals in society, also known as the Maximin principle. Crocker (1977) extended this idea with upper boundaries for both absolute and relative differences between a population's wealth.

Sufficientarianism argues that everyone has the right for a sufficient amount of basic needs. Arneson (2007) uses two rules for explanation of equity: the headcount claim & the negative thesis. The headcount claim says we should maximise the number of people that have sufficient goods. Once every individual has reached this sufficiency, no other constrictions to the distribution of goods are desired, according to the negative thesis.

Deontology defines what is right or wrong by the intention of the action, rather than the consequence(s) (Gaus, 2001). This ethical theory uses moral rules, which should be universal, apply to everyone. The individual is key and should always be respected as a person (Robinson, 2019).

2.2 Equity in control theory

Multiple control methods have been applied in signalised intersection control. Three relevant control methods are (1) feedforward control (FFC), (2) feedback control (FBC) and (3) model predictive control (MPC) (van Lint et al., 2014). FFC solely reacts on disturbances and predefined desired behavior. An iTLC that uses the FFC methodology is known as fixed time control, where the disturbance is the time of day (morning-peak, evening-peak, off-peak) and the desired behavior is a predefined cycle schedule, with green duration calculated by Webster's formula, based on historical flow (Knoop et al., 2019). Next, a form of FBC is known as fully actuated control. The feedback loop allows the controller to react on detected vehicles at the intersection. The feedback controller still makes use of a set sequence within the cycles, the main difference with FFC is that the amount of green time can be adjusted based on the amount of detected vehicles at the direction who's turn it is.

MPC has the same control structure as feedback control, besides the process within the controller. The MPC uses feedback data of all directions, in order predict and find the optimal solution from candidate control signals (Knoop et al., 2019). An MPC could optimise the Webster-cycle times with this method. However, example MPC iTLC Flowtack does not use cycles. Instead, the sequence of green phases is an additional degree of freedom in the optimisation process.

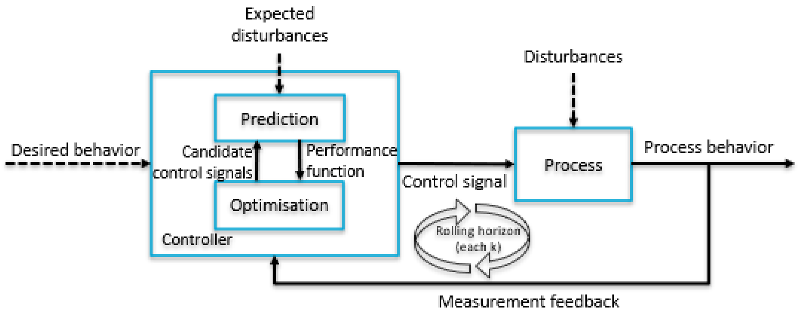


Fig. 1. Model predictive control structure in a block diagram. Adapted from van Lint et al. (2014)

Figure 2.2 shows the MPC structure. Without the prediction and optimisation blocks within the controller and the rolling horizon, this would be a regular FBC. Additionally, removing the measurement feedback would result in FFC.

The desired behavior input of the controller includes control laws. This is where equity currently finds its place in the block diagrams. Control laws of example FBC iTLC CCOL, mostly revolve around the principle of having cycles, such as boundary conditions for the duration of a cycle or green phase (Wilson, 2006). On the other hand, the control laws in MPC iTLC Flowtack focus more on having influence on the optimisation via the performance function and the candidate control signals. An example principle in Flowtack is that it uses a weight function in order to weigh the importance of delayed road users.

Due to the main difference in principle build up by the principles of either using cycles or using structure-free optimisation, *Flowtack is identified relatively utilitarian* compared to CCOL, whilst *CCOL is identified relatively egalitarian* compared to Flowtack. Even though the cycles can be optimised based on Websters formula, which can be identified utilitarian, cycles ensure a maximum amount of spread in the distribution of delay by having a fixed occurrence of directions, which corresponds with the egalitarian idea. On the other hand, optimisation without the use of cycles ensures a control plan that minimises disutility (equals maximisation of utility), namely, the average delay. Additional principles are added in both iTLCs, corresponding to all other mentioned ethical theories.

Table 1 shows a number of principles that are used in CCOL & Flowtack, the consequence/effect that they have on the intersection or road user, and the theories that this correspond with. Deontology is mainly found in principles that are implemented for safety and acceptance reasons, where utilitarianism is mainly found in principles that increase the flow of traffic and egalitarianism & sufficientarianism mainly involves principles that lead to upper and/or lower boundary conditions.

Table 1. Connection between iTLC principles and ethical theories

CCOL principles	**Effect**	**Corresponding ethical theory**
Cycles	Sequence-based events & phases	Egalitarianism / Utilitarianism
Maximum cycle time	Waiting time	Sufficientarianism / Deontology
Maximum green time	Constraint to the distribution of green	Egalitarianism
Minimum green time	Constraint to the distribution of green	Deontology / Sufficientarianism
Priority	Exceptions to the standard cycle	All
Coordination	Fixed control for platooning	Utilitarianism / Deontology
Flowtack principles		
Structure-free	Agile, adapts to the situation	Utilitarianism
Minimisation of vehicle loss hours	Reduces total delay	Utilitarianism
Weights	Waiting time	Egalitarianism / Sufficientarianism
Priority	Privilege for directions or vehicles	All
No maximum green time	Less restrictions & lower internal lost time	Utilitarianism / Deontology / Sufficientarianism
Topology	Intersection layout integration	Utilitarianism
I2V information	Acceptance	Deontology

2.3 Performance indicator for equity

A performance indicator for equity is proposed based on the equity definitions from the above mentioned ethical theories. Because deontology concerns the intention rather than the consequence, no measure for deontology will be proposed. Liang, Guler, and Gayah (2020) has measured the equity- and efficiency performances of an iTLC at a signalised intersection by the Gini coefficient and the average delay, while varying the maximum delay as control law. The Gini coefficient is a dimensionless number from 0 to 1 that indicates perfect equality in the distribution of delay if the value is 0, and perfect inequality if the value is 1 (Lucas et al., 2016). This implicates that road users all experience the exact same delay if the Gini coefficient would be 0, or one group of road users experienced all the delay (never got to cross), whilst another group of road users didn't have any delay at all if the Gini coefficient would be 1. The average delay was referred to as efficiency by Liang et al. (2020) & Kesten, Ergün, and Yai (2013), however in this paper the average delay represents equity, by the definition of utilitarianism. If the average delay decreases, the total delay (disutility) also decreases, and minimisation of disutility equals maximisation of utility: utilitarianism.

3 Case study: Flowtack in Deventer

Flowtack has been identified rather utilitarian, therefore, the settings of Flowtack are adjusted in a simulation experiment in order to find whether the performance indicators for equity by the definitions of egalitarianism & sufficientarianism can be improved. Adjusting Flowtack's settings, requires some insight in the objective function that Flowtack uses for its optimisation. The following objective function has been composed, based on documentation from Kant, Hut, and Wolfrat (2019).

$$J = min_{u_j(k)} = \sum_{i}^{I} \sum_{n}^{N} \ \beta_j \ f\big(w_i(n)\big) \ \Big(w_i(n) - w_i(n-1)\Big)$$

- J, the objective function, defines *what* is optimised
- k, frequency or time step for which the objective function updates its solution. $k \in K$.
- n, rolling horizon N is divided into a number of time steps n. Every time step n, control plan u can decide whether direction j gets green light. $n \in N$.
- i, individual road user i. $i \in I$.
- $j(i)$, direction j on the intersection where individual road user i queues. $j \in J$
- $u_j(k)$, the optimisation variable, candidate control plan u defines whether direction j is planned red or green; 0 or 1. The amount of candidate control plans that are tried out in each optimisation step k depends on the amount of possible solutions.
- $w_i(n)$, accumulated waiting time for road user i previous to the starting time $n = 0$ of time step k.
- $f(w_i(n))$, weight function (curve shaped) for each road user, with the weight factor (w/s) on the y-axis and waiting time (s) on the x-axis.
- β_j, a multiplication factor (-) that is direction dependent.

Every time step k, a look-a-head of N seconds is used to predict the delays for every road user i, of candidate control signal $u_j(k)$. This is then weighted via a multiplication factor β_j and weight function $f(w_i(n))$ in the objective function, to find the lowest outcome of the sum of weighted delay. The lowest outcome of the objective function is the optimal control signal $u_j(k)$ that is sent to the

control device on the intersection. The accumulated waiting time $w_i(n)$ defines the location for each delayed road user i on the x-axis of weight function $f(w_i(n))$ for each time step n. Figure 3 shows how the accumulated waiting time defines the location of one road user i on the weight function $f(w_i(n))$ for a time step n, over which the weighted delay is summed in the objective function.
Currently, the weight function is referred to as the Bathtub curve, after its shape. This shape has been implemented, because of the assumption that once a vehicle is stopped, the road user wouldn't mind waiting for a certain amount of time. The drop of weight at the beginning initiates such behavior. However, no road user is willing to wait for too long, hence the build up of weight over time. Another effect of the dip in the curve is that it reduces the amount of stops at the intersection, because the cost to stop non-delayed road users is now higher than than that of the road users in the dip of the curve.

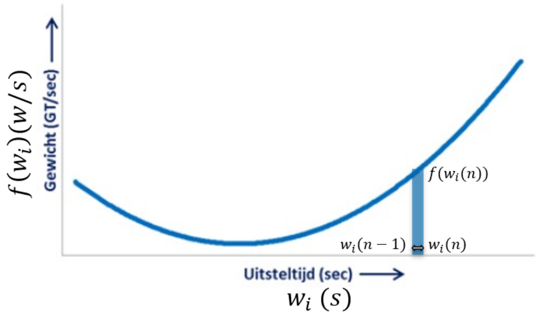


Fig. 2. Weight function $f(w_i(n))$, time dependent weight factor (weight/s) on the vertical axis, and expected delay (s) on the horizontal axis. Also known as 'Badkuip curve' or 'Bathtub curve', adapted from Kant et al. (2019)

3.1 Experiment setup

Simulation software package Aimsun is used with the isolated intersection A050 from the Deventer network, supplied by RoyalHaskoningDHV. The demand data (origin-destination matrices) used for the simulations are for an average evening peak hour, based on real life pre-COVID-19 pandemic data, from 2019. The traffic flow on a single direction varies between 1400 on the main road veh/h to about 10 veh/h on a side road, with a total of 3600 veh/h on the intersection. No congestion occurred during these simulations.

The settings that can be adjusted in the simulation experiment are $f(w_i(n))$ & β_j. Initially, a run with the current settings has been performed, and a reference scenario has been created from those settings, using the current weight function $f(w_i(n))$ and resetting all β_j to a value of 1.0, to reduce any effects other than that of a bathtub curve shaped function. A number of weight functions $f(w_i(n))$ are tested, based on the concepts as depicted in Figure 3.

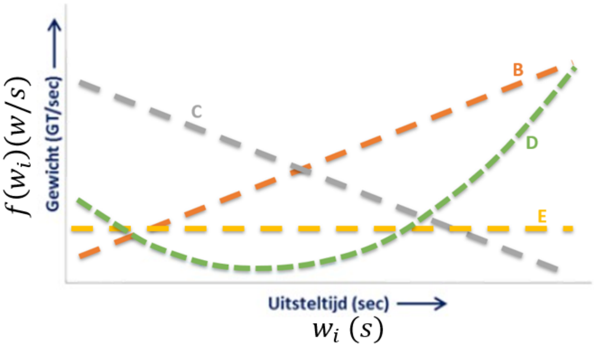


Fig. 3. Various function concepts as basis for weight function $f(w_i(n))$. Weight factor on the vertical axis, expected delay on the horizontal axis.

Next, the β_j are determined. A method to calculate the β_j is created from the philosophy of improving equity, based on egalitarian and sufficientarian definition. Egalitarian philosopher Rawls (2009) argued that goods should be distributed in a way that they are of the greatest benefit for the least-advantaged, thus in this case, weight should be distributed to benefit the least-advantaged road users on the intersection. Due to the weighted-delay optimisation, the amount of road users i on direction j implicitly defines the delay that these road users will experience with respect to road users on other directions, via the accumulated sum of their weight. Additionally, the amount of road users on non-conflicting directions of direction j also add to the advantage of direction j towards the conflicting directions. Using the same reasoning, conflicting directions oppose direction j to be advantaged. Therefore, the advantage of a direction, relative to that of other directions, has been defined as:

$$\frac{C_j}{S_j}$$

- C_j, the amount of conflicting road users (opposers) for direction j.
- S_j, the amount of non-conflicting road users (supporters) for direction j, including the amount road users at direction j.

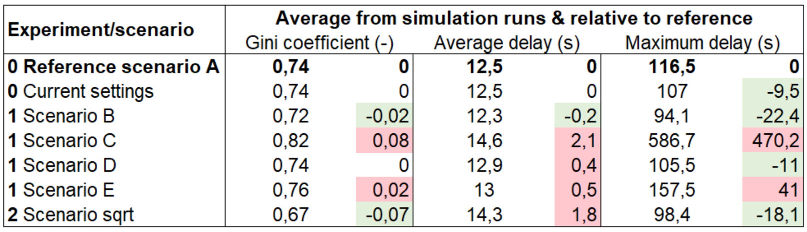
However, a correlation issue is identified in this method: the amount of C_j & S_j for direction j come from weighted directions themselves, thus do not actually give the expected amount of resistance and support for direction j. This correlation problem magnifies the extremes of this solution, therefore the square root operator is applied as a pragmatic solution to reduce the extremes. This results in the following formula:

$$\beta_j = \sqrt{\frac{C_j}{S_j}}$$

- β_j, a multiplication factor (-) that is direction dependent.

3.2 Results

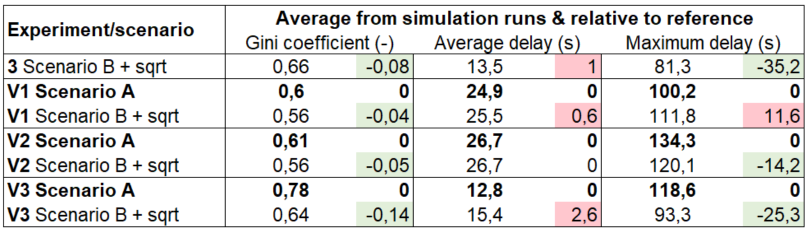
The results of the simulation experiments are presented in Table 4.



Experiment/scenario	Average from simulation runs & relative to reference					
	Gini coefficient (-)		Average delay (s)		Maximum delay (s)	
0 Reference scenario A	**0,74**	**0**	**12,5**	**0**	**116,5**	**0**
0 Current settings	0,74	0	12,5	0	107	-9,5
1 Scenario B	0,72	-0,02	12,3	-0,2	94,1	-22,4
1 Scenario C	0,82	0,08	14,6	2,1	586,7	470,2
1 Scenario D	0,74	0	12,9	0,4	105,5	-11
1 Scenario E	0,76	0,02	13	0,5	157,5	41
2 Scenario sqrt	0,67	-0,07	14,3	1,8	98,4	-18,1

Fig. 4. The equity results of experiments 0, 1 and 2. Showing the average value of Gini coefficient, average delay and maximum delay for multiple simulation runs per scenario on the left side and the relative change to the associated reference scenario on the right side (in color).

Scenarios B and sqrt are the most promising scenarios, showing the best improvement of Gini coefficient and maximum delay for egalitarian & sufficientarian equity. A linearly increasing weight function implies an increase of importance over time, which logically decreases the maximum delay and Gini coefficients, as it pushes the 'disadvantaged' more quickly to have more weight. This weight function will be tested in combination with the proposed β_j in experiment 3.



Experiment/scenario	Average from simulation runs & relative to reference					
	Gini coefficient (-)		Average delay (s)		Maximum delay (s)	
3 Scenario B + sqrt	0,66	-0,08	13,5	1	81,3	-35,2
V1 Scenario A	**0,6**	**0**	**24,9**	**0**	**100,2**	**0**
V1 Scenario B + sqrt	0,56	-0,04	25,5	0,6	111,8	11,6
V2 Scenario A	**0,61**	**0**	**26,7**	**0**	**134,3**	**0**
V2 Scenario B + sqrt	0,56	-0,05	26,7	0	120,1	-14,2
V3 Scenario A	**0,78**	**0**	**12,8**	**0**	**118,6**	**0**
V3 Scenario B + sqrt	0,64	-0,14	15,4	2,6	93,3	-25,3

Fig. 5. The equity results of experiments 3, V1, V2 and V3: the combination- and validation scenarios

Table 5 shows the result of experiment 3, which covers the combination of these settings. The settings of experiment 3 had an even more positive impact on the

Gini coefficient and maximum delay, and are validated with scenarios V1, V2 and V3. The validation scenarios are performed on another intersection layout, with a total flow of 3600 veh/h. However, the difference between the validation scenarios is that V1 has an equal flow input on each direction of the intersection, where V2 varies the flow from 50-300 veh/h between side- and main roads and V3 varies the flow from 5-700 veh/h between side- and main roads. These results show that the settings of scenario B + sqrt still improve egalitarian & sufficientarian equity on another intersection with various flow compositions, except for a situation with equal flows on all directions. The maximum delay of the referential settings are lower, because these settings use the original weight function, with a steep increase of weight at a delay of 100 seconds. This causes a virtual maximum delay, where any road user who reaches this wall will be prioritised. Weight function B did not have this virtual maximum. This validation showed that the amount of gain is dependent on how unequal the flows are on different directions of the intersection.

4 Conclusion & further research

This research combined the complex fields of control theory & ethics to explicitly identify Flowtack as relatively utilitarian & CCOL as relatively egalitarian. Furthermore, performance indicators for equity, based on utilitarianism, egalitarianism & sufficientarianism are defined. These performance indicators allowed an improvement in egalitarian and sufficientarian equity to be measured, by successfully adjusting Flowtack's settings in simulation experiments. Validation of these settings showed that the gain in equity by the proposed settings becomes greater, as the flow composition becomes more uneven.

This research concludes that it is technically feasible to improve equity in an egalitarian & sufficientarian way. It is up to the traffic engineers and policy makers to choose between egalitarianism, sufficientarianism and utilitarianism. Their choices can now be explicitly substantiated by a combination of ethical theories, control theory and principles in iTLCs.

It is recommended to further look into the *perception of delay* of road users. This puts the results of the simulation experiment more into the perspectives of road users and sheds light on the societal feasibility of adjusting equity.

Furthermore, the political feasibility of adjusting equity needs further research. The function of an intersection is expanded by policies like prioritising cyclists and green waves, the question that follows concerns how these policies interact with the performance of equity.

Last but not least, this research limited itself to an isolated intersection with a number of four ethical theories. This research could be extended by adding ethical theories and looking to network level instead. Looking at network creates new opportunities to measure- and improve equity. An example could be to use *contractualism* as an ethical theory and use compensation of weight for initially disadvantaged road users, giving them priority on the following intersection.

References

Åqvist, L. (1969). Improved formulations of act-utilitarianism. *Nous*, *3*(3), 299–323.

Arneson, R. (2007). Distributive justice and basic capability equality:"good enough" is not good enough. In *Capabilities equality* (pp. 27–53). Routledge.

Crocker, L. (1977). Equality, solidarity, and rawls' maximin. *Philosophy & Public Affairs*, 262–266.

Gaus, G. (2001). What is deontology? part one: orthodox views. *Journal of Value Inquiry*, *35*(1), 27.

Harsanyi, J. (1977). Rule utilitarianism and decision theory. *Erkenntnis*, *11*(1), 25–53.

Kant, M., Hut, G., & Wolfrat, H. (2019). *Functionele specificatie flowtack* (Tech. Rep.). HASKONINGDHV NEDERLAND B.V.

Kesten, A., Ergün, M., & Yai, T. (2013). An analysis on efficiency and equity of fixed-time ramp metering. *Journal of Transportation Technologies*, *3*.

Knoop, V., Hegyi, A., Salomons, M., van Lint, H., Yuan, Y., & Landman, R. (2019). *Traffic flow modelling control.* Delft: Delft University of Technology.

Liang, X., Guler, S., & Gayah, V. (2020). An equitable traffic signal control scheme at isolated signalized intersections using connected vehicle technology. *Transportation Research Part C: Emerging Technologies*, *110*, 81–97.

Lucas, K., Van Wee, B., & Maat, K. (2016). A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches. *Transportation*, *43*(3), 473–490.

Nussbaum, M. (2003). Capabilities as fundamental entitlements: Sen and social justice. *Feminist economics*, *9*(2-3), 33–59.

Rawls, J. (2009). *A theory of justice.* Harvard university press.

Robinson, R. (2019). Kant's categorical imperative and moral duties. In *Imperfect duties of management* (pp. 11–38). Springer.

Talking Traffic, P. (2019). *Hoe staat het met de ivri?* Retrieved from https://www.talking-traffic.com/nl/nieuws/hoe-staat-het-met-de-ivri

van Lint, H., Hoogendoorn, S., van Zuylen, H., Hegyi, A., Bliemer, M., & Pel, A. (2014). *Integrated and coordinated networkmanagement.* Delft: Delft University of Technology.

Van Wee, B., & Roeser, S. (2013). Ethical theories and the cost-benefit analysis-based ex ante evaluation of transport policies and plans. *Transport reviews*, *33*(6), 743–760.

Wilson, A. (2006). *Handboek verkeerslichtenregelingen.* Ede: CROW.

Yu, J. (2005). The beginning of ethics: Confucius and socrates. *Asian Philosophy*, *15*(2), 173–189.

B

Appendix B

This Appendix is written to support Chapter 6 experiment setup. The structure of that Chapter is preserved in this Appendix.

B.1. Software

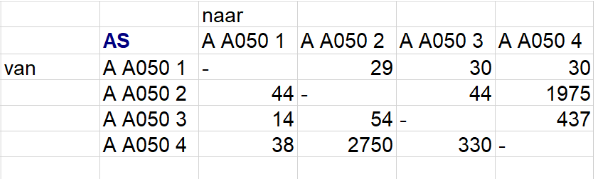
This section shows additional information for Aimsun, Flowtack and Excel. This includes origin-destination matrices, Flowtack settings with a corresponding weight function translation and excel function elaborations.

B.1.1. Aimsun Supply

The supply that is used for the experiments was delivered as a whole network, including multiple intersections that are currently using Flowtack in Deventer. Because this thesis limits itself to 1 intersection, the other intersections are cut out of the simulation. This is simply done by creating new production- and attraction Zones for each cardinal direction of the intersection. No other modifications were needed on the supply side.

B.1.2. Aimsun Demand

This section shows the OD matrices that are used as demand data in Aimsun. In these tables, the numbers 1-4 refer to the 4 cardinal directions of the intersection, where the rows of the matrix define the production of road users from these Zones, and the columns of the matrix define the attraction of road users to these Zones. Direction 1 refers to the North location, counting clockwise. To limit this experiment the single A050 intersection, the OD matrices for all other production- and attraction Zones are deleted, meaning no traffic will be produces around the other intersections.

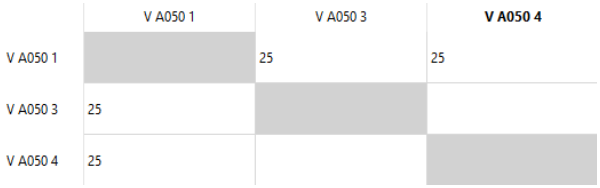


		naar			
	AS	A A050 1	A A050 2	A A050 3	A A050 4
van	A A050 1	-	29	30	30
	A A050 2	44	-	44	1975
	A A050 3	14	54	-	437
	A A050 4	38	2750	330	-

Figure B.1: **2 hour** origin-destination matrix for car traffic at intersection A050 at Deventer, data adapted from (HaskoningDHV, 2021)

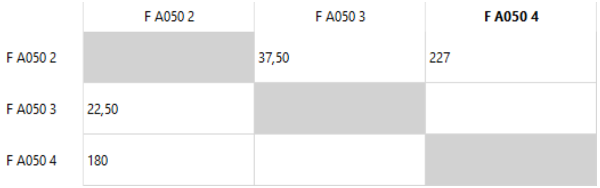
Note that Figure B.1 shows 2 hour data, whilst Figures B.2 and B.3 show single hour data. For the experiment, the OD matrix of Figure B.1 is multiplied by 0.9, because 10% of these vehicles is generated as trucks in a separate OD matrix. Because one scenario run was defined as 30 minutes, the OD matrices of trucks and vehicles are then multiplied by 0.25, whilst the OD matrices for active modes are halved.

In the real world, there might be pedestrians and cyclists wanting to move between directions 3 and 4,



	V A050 1	V A050 3	**V A050 4**
V A050 1		25	25
V A050 3	25		
V A050 4	25		

Figure B.2: 1 hour origin-destination matrix for pedestrians at intersection A050 at Deventer, data adapted from (HaskoningDHV, 2021)

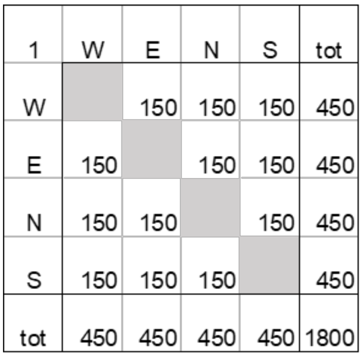


	F A050 2	F A050 3	**F A050 4**
F A050 2		37,50	227
F A050 3	22,50		
F A050 4	180		

Figure B.3: 1 hour origin-destination matrix for cyclists at intersection A050 at Deventer, data adapted from (HaskoningDHV, 2021)

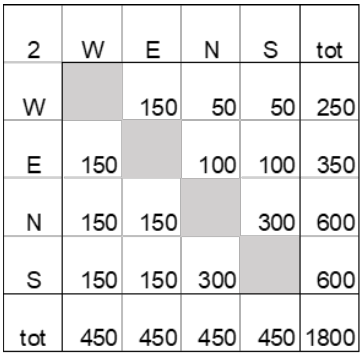
having to double cross. However, to keep the simulation supply data more simple in this experiment, it is chosen to generate pedestrians and cyclists only for the sake of crossing the intersection rather than creating a realistic travel pattern, hence the blank spaces in the OD matrices for active modes.

For validation on the Rotterdam 79190 intersection, 3 OD matrices are created by this thesis' author, varying the distribution of traffic over the directions. These OD matrices are shown in Figures B.4, B.5 and B.6. Only car traffic is simulated on this intersection, this causes the cyclist path to be virtually non-existing. Note that North and South are simulated to be main roads with these OD matrices, with East and South as its side roads in OD2 and OD3. This matches the layout of the intersection: an extra lane for the directions N-S and S-N.



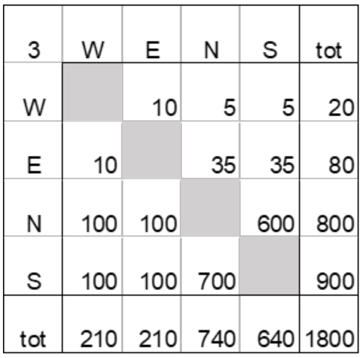
1	W	E	N	S	tot
W		150	150	150	450
E	150		150	150	450
N	150	150		150	450
S	150	150	150		450
tot	450	450	450	450	1800

Figure B.4: OD matrix 1



2	W	E	N	S	tot
W		150	50	50	250
E	150		100	100	350
N	150	150		300	600
S	150	150	300		600
tot	450	450	450	450	1800

Figure B.5: OD matrix 2



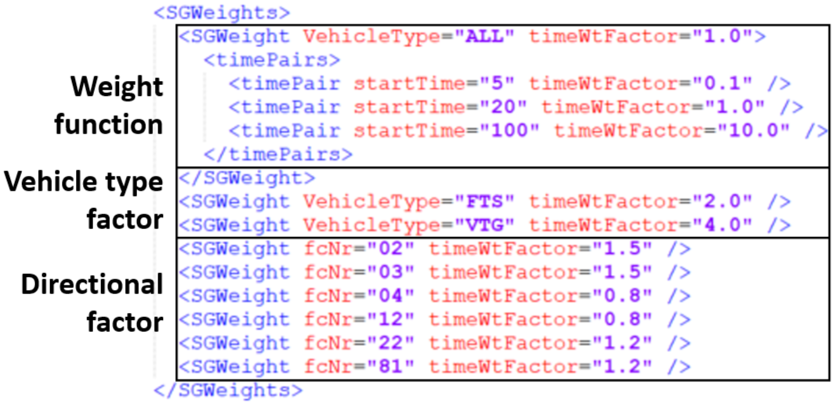
3	W	E	N	S	tot
W		10	5	5	20
E	10		35	35	80
N	100	100		600	800
S	100	100	700		900
tot	210	210	740	640	1800

Figure B.6: OD matrix 3

B.1.3. Flowtack's weight function

The settings that can be adjusted in Flowtack look as depicted in Figure B.7. This Figure shows the settings that are currently used at the A050 intersection in Deventer. The weight function- and road user type settings have proven to perform well by trial and error and are composed by experts in the field of traffic management from RoyalHaskoningDHV. The directional factors are mainly defined by policy of the municipality: prioritising the main cycling route and helping the side roads a bit to decrease their delay.

A translation of the weight function in Figure B.7 is visualised in Figure B.13. The dotted line is plotted to show how it could be a smooth bathtub shaped curve, however, the actual plot is rather angular.



```
<SGWeights>
<SGWeight VehicleType="ALL" timeWtFactor="1.0">
  <timePairs>
    <timePair startTime="5" timeWtFactor="0.1" />
    <timePair startTime="20" timeWtFactor="1.0" />
    <timePair startTime="100" timeWtFactor="10.0" />
  </timePairs>
</SGWeight>
<SGWeight VehicleType="FTS" timeWtFactor="2.0" />
<SGWeight VehicleType="VTG" timeWtFactor="4.0" />
<SGWeight fcNr="02" timeWtFactor="1.5" />
<SGWeight fcNr="03" timeWtFactor="1.5" />
<SGWeight fcNr="04" timeWtFactor="0.8" />
<SGWeight fcNr="12" timeWtFactor="0.8" />
<SGWeight fcNr="22" timeWtFactor="1.2" />
<SGWeight fcNr="81" timeWtFactor="1.2" />
</SGWeights>
```

Figure B.7: The settings in Flowtack that can be adjusted by adding/removing lines and changing the numeric values: weight function, road user type weight factor and direction weight factor.

Figure B.8

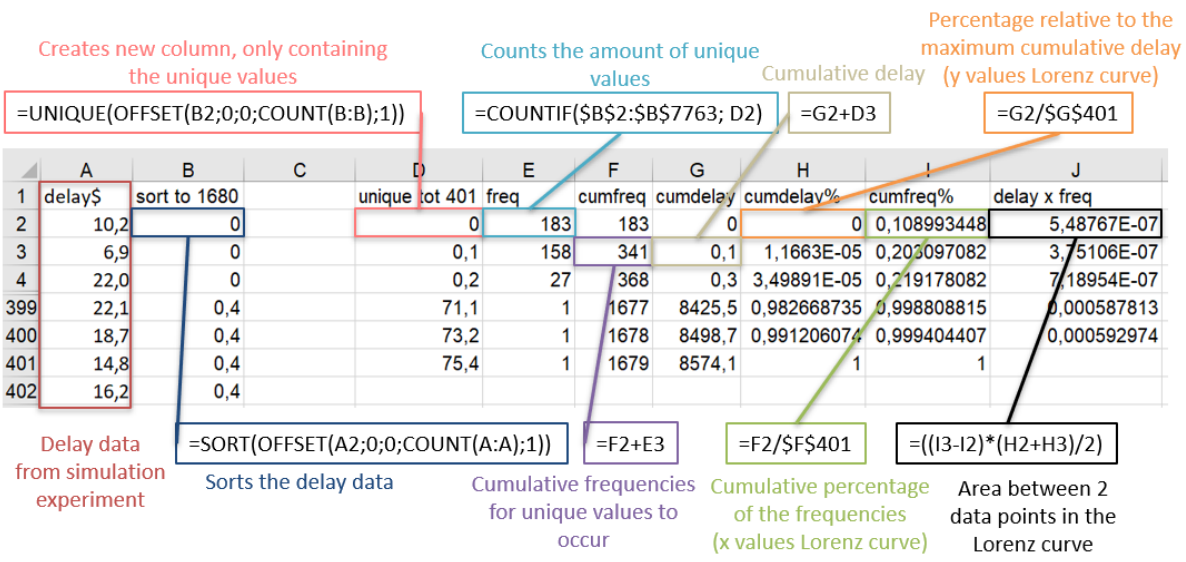
B.1.4. Data processing in Excel

RoyalHaskoningDHV's tool is used to read the SQLITE file that Aimsun creates into Excel. One column with delay data per vehicle is copied for further processing in excel, as shown in Figure B.9. This initial data is pasted on column A and consists of 1680 rows, meaning that 1680 road users crossed the intersection in this experiment. Before this data is processed, the data is reduced from 4 decimals to 1 decimal by turning on Excels function: File, Options, Advanced, Set precision as displayed.

Column B shows the same data of 1680 rows sorted from small numbers to big numbers. This is necessary to later link the correct cumulative percentage of the road users to the delay they have experienced. Column C is left empty, because the following columns will have a different number of rows, depending on the number of unique values in column B, these unique values are created in column D. Column E shows the frequency that each unique value in column D is found in column B. In order to create the cumulative percentage for these numbers, column F creates a cumulative of this frequency, and column I divides the cumulative frequencies by the maximum cumulative frequency, which creates a set of values between 0 and 1 that could be used for the x-axis of a Lorenz curve. Column G creates the cumulative delays from the unique delay column D, after which this is divided by the maximum cumulative delay to create a new set of values between 0 and 1 that could be used for the y-axis of a Lorenz curve. The Lorenz curve plot is not necessary to find the Gini coefficient, however this plot can be made easily from this data to check whether the results are plausible. Figure B.10 shows an example of such a Lorenz curve.

Column J in Figure B.9 approximates the area under the Lorenz curve, by multiplying the difference between 2 x values (width) by the average y value between 2 data points (height). Figure B.11 sums column J, resulting in the total area under the Lorenz curve. Since the axes on of these plots are both restricted between the values of 0 and 1, the total area of the rectangle is 1. Thus, half of this area, the area under the line of equality, is 0.5 and given as the value of M2. Subtracting the area under the Lorenz curve from the area under the equality line gives the area between both curves: value N2. The Gini coefficient equals this area between the curves, however it is divided by the area under the equality line in order to make it a value between 0 and 1, where a value of 0 represents perfect equality: everyone has the exact same delay. A Gini value of 1 represents a Lorenz curve that follow the axes: 1 person has all delay and 1 person has no delay.

The average and maximum values can easily be extracted from the data without any steps. The bottom 3 values in Figure B.11 represent the quantitative measures of 1 simulation for respectively egalitarianism, utilitarianism and sufficientarianism.



Creates new column, only containing the unique values

=UNIQUE(OFFSET(B2;0;0;COUNT(B:B);1))

Counts the amount of unique values

=COUNTIF($B$2:$B$7763; D2)

Cumulative delay

=G2+D3

Percentage relative to the maximum cumulative delay (y values Lorenz curve)

=G2/$G$401

	A	B	C	D	E	F	G	H	I	J
1	delay$	sort to 1680		unique tot 401	freq	cumfreq	cumdelay	cumdelay%	cumfreq%	delay x freq
2	10,2	0		0	183	183	0	0	0,108993448	5,48767E-07
3	6,9	0		0,1	158	341	0,1	1,1663E-05	0,203097082	3,75106E-07
4	22,0	0		0,2	27	368	0,3	3,49891E-05	0,219178082	7,18954E-07
399	22,1	0,4		71,1	1	1677	8425,5	0,982668735	0,998808815	0,000587813
400	18,7	0,4		73,2	1	1678	8498,7	0,991206074	0,999404407	0,000592974
401	14,8	0,4		75,4	1	1679	8574,1	1	1	
402	16,2	0,4								

Delay data from simulation experiment

=SORT(OFFSET(A2;0;0;COUNT(A:A);1))

Sorts the delay data

=F2+E3

Cumulative frequencies for unique values to occur

=F2/$F$401

Cumulative percentage of the frequencies (x values Lorenz curve)

=((I3-I2)*(H2+H3)/2)

Area between 2 data points in the Lorenz curve

Figure B.9: Excel formulas explained, read from left to right. Shows the first- and last 3 rows of data for columns D-J.

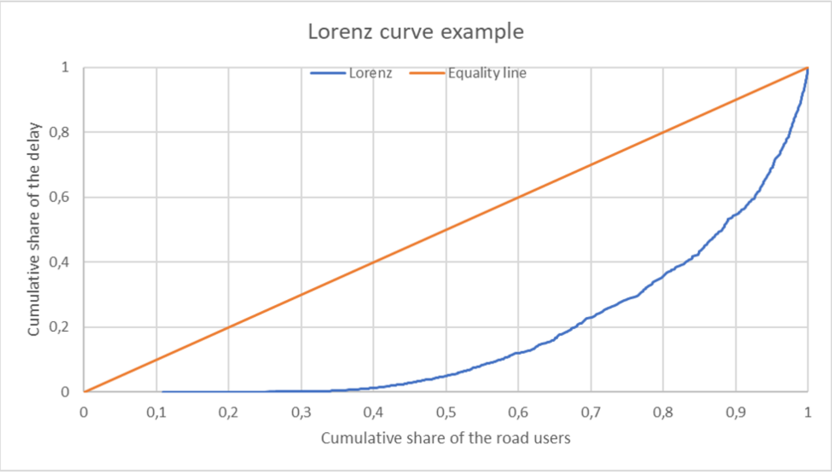
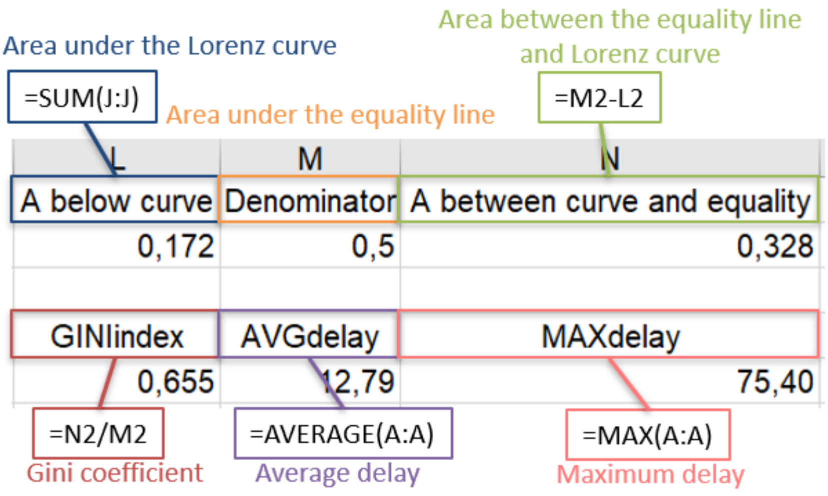


Figure B.10: Lorenz curve plotted from columns H and I from Figure B.9



Area under the Lorenz curve

=SUM(J:J)

Area under the equality line

Area between the equality line and Lorenz curve

=M2-L2

L	M	N
A below curve	Denominator	A between curve and equality
0,172	0,5	0,328
GINIindex	AVGdelay	MAXdelay
0,655	12,79	75,40

=N2/M2

Gini coefficient

=AVERAGE(A:A)

Average delay

=MAX(A:A)

Maximum delay

Figure B.11: Excel results from data, plus explanation

B.2. Experimental settings

This section includes an elaboration of the settings for the scenarios of each experiment and how these settings were created. At the end of this section, a validation experiment is elaborated starting with a new Aimsun supply & demand and then repeated settings.

The standard numbering of an intersection is used, these are depicted in Figure B.12. The directions for cars are numbered from 1 to 12, in this specific case directions 1 and 2 are however combined on a single lane, thus regarded to as direction 2. Directions 45 and 51 regard to a shared bus lane, 22, 24, 81 and 83 refer to cycling paths and 31, 32, 33, and 34 pedestrian cross overs. Note that the orientation of this Figure is upside down compared to the Aimsun orientation, the North is at the bottom side of Figure B.12.

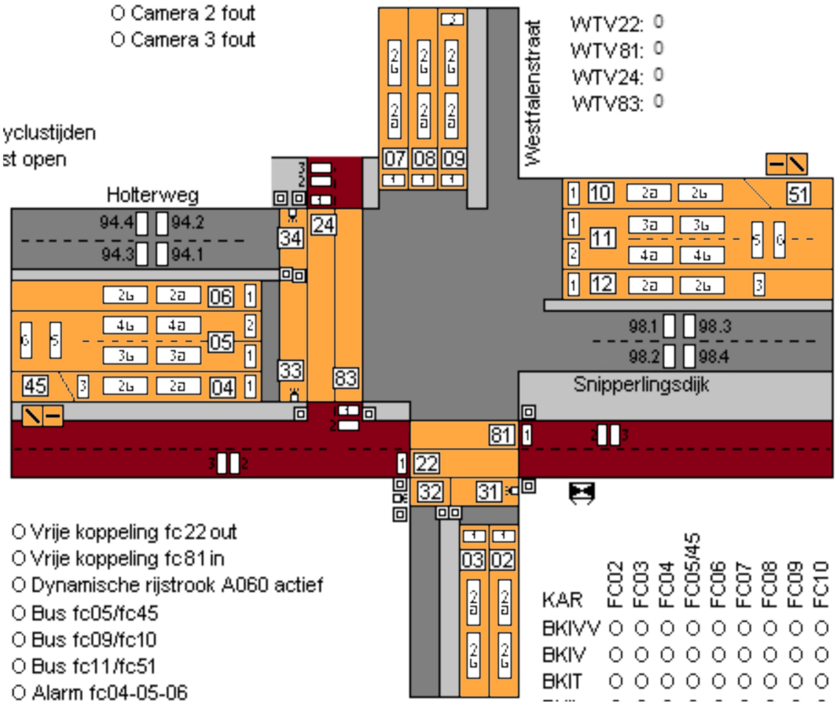


Figure B.12: Intersection layout Deventer A050 (Dynniq, 2021)

B.2.1. Experiment 0: Reference scenario and current settings

The current settings are already elaborated and shown in Figures B.7 and B.8. The only difference with the current settings, is that the directional factors in Figure B.7 are now deleted from the code (which means they are all 1).

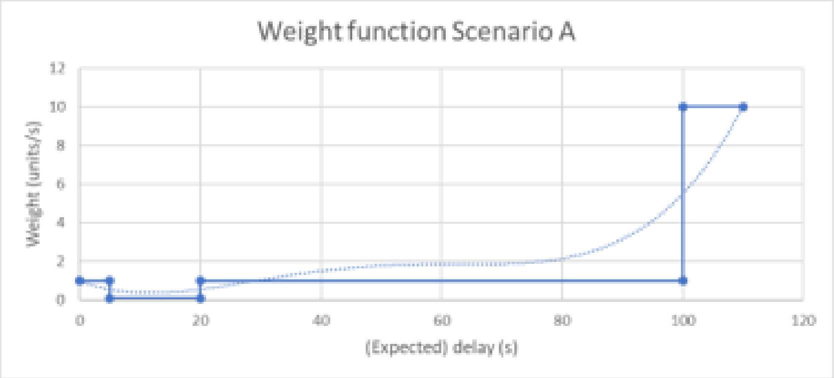


Figure B.13: Weight function of the current settings and reference scenario A

B.2.2. Experiment 1: Weight function settings

The reasoning for the weight function settings is found in Chapter 6. This section elaborates how the weight functions are actually implemented in Flowtack. Figure B.14 shows the conceptual weight functions as defined in the main document. This appendix section shows how these concepts are actually implemented in Flowtack.

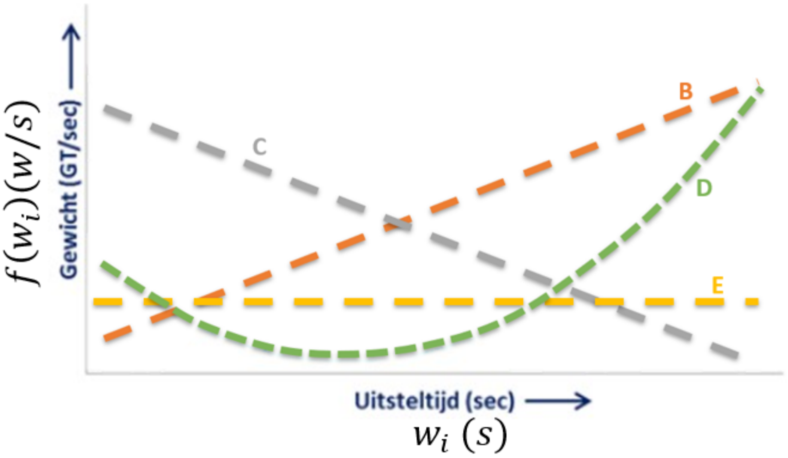


Figure B.14: Various function concepts as basis for experimental weight functions. Weight factor on the vertical axis, expected delay on the horizontal axis.

Flowtack builds its functions based on combinations of weight and time data which it uses as reference points for the weight function. For time in between those points, Flowtack uses the latest value, which means horizontal lines are drawn until a new reference point is defined. Currently, the weight function consists of 4 of these data points, which results in the 'curve' is rather rectangular. After the last data point, the weight function remains horizontal, meaning after a delay of 100 seconds the weight remains 10 for this road user in scenario A. The curves that are created for this experiment will have time steps of 5-10 seconds to approximate the conceptual weight functions. Note that Figures B.13, B.15, B.16 and B.17 have a dashed line through the data that approximates the curve that is followed.

The weight function for scenario B builds up from the tub, that originates from the bathtub curve, towards a stairs shape that approximates the straight line from the concepts. The exact data of this curve is shown in Table B.1 and Figure B.15 shows a visualisation of this weight function.

Table B.1: Time and weight values in Flowtack's settings for the weight function of scenario B.

Start Time (s)	Weight (units/s)
0	1
5	0.1
10	0.3
15	0.6
20	1.0
30	2.1
40	3.3
50	4.4
60	5.5
70	6.7
80	7.8
90	8.9
100	10.0

The weight function for scenario C decreases every 10 seconds with 1 weight unit/s. This approximates the linear function with a stairs shape again. A vehicle that is delayed for 10 seconds from the start

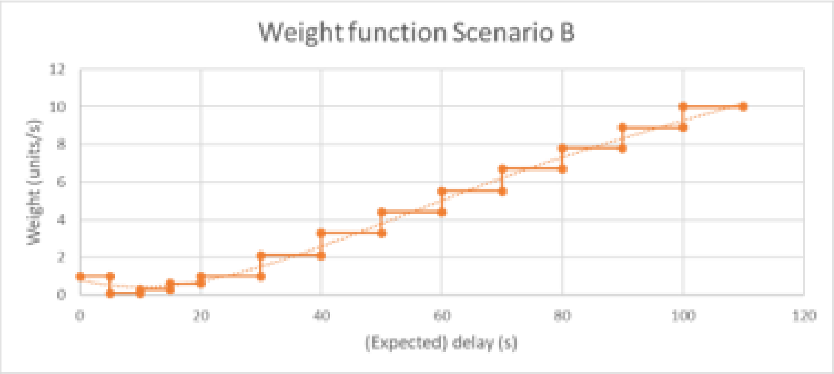


Figure B.15: Weight function for scenario B

has a total weight of 110 units in this approximation function, where this vehicle would have 105 units of weight if this shape would be a perfect straight line. This difference is fairly small, therefore it is presumed unnecessary to add more detail in the weight function. Table B.2 shows the input data for weight function C and Figure B.16 shows a visualisation of this weight function.

Table B.2: Time and weight values in Flowtack's settings for the weight function of scenario C.

Start Time (s)	**Weight (units/s)**
0	11.0
10	10.0
20	9.0
30	8.0
40	7.0
50	6.0
60	5.0
70	4.0
80	3.0
90	2.0
100	1.0

The weight function for scenario D is similar to that of scenario A. The idea of this curve is to add more detail to the curve of scenario A, in order to make it more smooth like the conceptual curve. A few steps are added between 10 seconds of delay and 20 seconds of delay, to more smoothly get out of the tub, and instead of a jump from weight 1.0 to 10.0 at 100 seconds, this jump becomes more gradual in scenario D as it starts at 70 seconds. Table B.3 shows the input data for weight function D and Figure B.17 shows a visualisation of this weight function.

Table B.3: Time and weight values in Flowtack's settings for the weight function of scenario D.

Start Time (s)	**Weight (units/s)**
0	1.0
5	0.1
10	0.3
15	0.6
20	1.0
70	1.5
80	3.0
90	5.0
100	10.0

The straight line weight function of scenario E can very easily be implemented in Flowtack. However, a threshold value has to be implemented to stop so-called 'fase bewaking', which resets Flowtack if

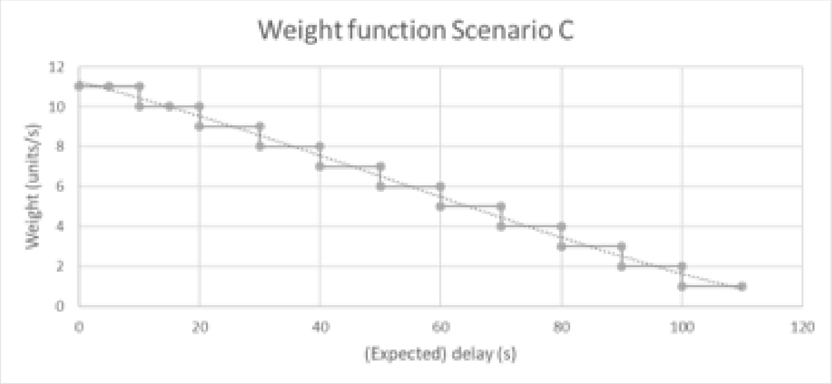


Figure B.16: Weight function for scenario C

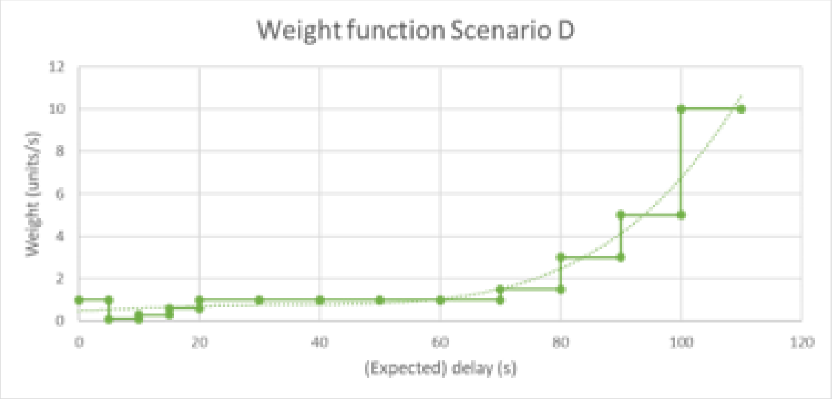


Figure B.17: Weight function for scenario D

a detector is occupied by the same vehicle for too long. Table B.4 shows the input data for weight function D and Figure B.18 shows a visualisation of this weight function.

Table B.4: Time and weight values in Flowtack's settings for the weight function of scenario E.

Start Time (s)	**Weight (units/s)**
0	1.0
180	20

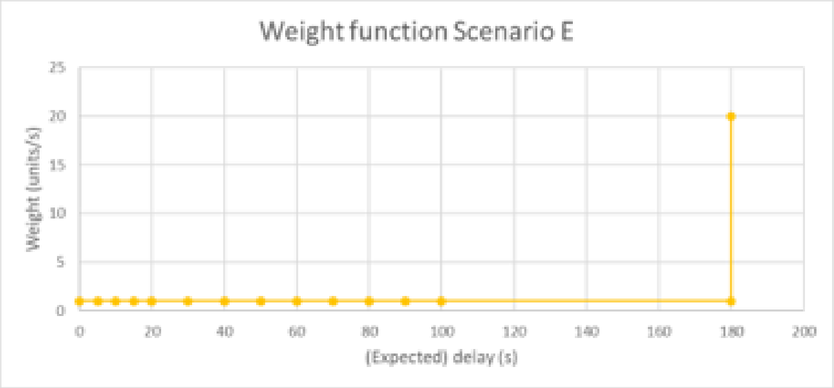


Figure B.18: Weight function for scenario E

B.2.3. Experiment 2: Road user type settings

For the road user type settings, one experiment is performed with the settings for the active modes: cyclists and pedestrians. These modes have currently been given multiplication factors to compensate for detection blindness. However, the impact of such multiplication factors on fairness was not taken into account. To find the impact of these multiplication factors on fairness, the multiplication factors are tuned in a way that should bring the inequity of road user types closer to each other.

Table B.5: Vehicle loss hours and Flow for cyclists, pedestrians and all road users (including cyclists and pedestrians) for 6 runs of reference scenario A.

Scenario A	**VLH bike**	**VLH pred.**	**VLH tot.**	**Flow bike**	**Flow ped.**	**Flow tot.**
Run 1	0.28	0.22	5.70	226	49	1679
Run 2	0.28	0.32	5.62	227	49	1682
Run 3	0.34	0.23	6.09	227	49	1669
Run 4	0.34	0.21	6.05	227	49	1676
Run 5	0.31	0.24	5.73	226	49	1681
Run 6	0.31	0.26	5.81	227	49	1667
Total	**1.87**	**1.48**	**35.00**	**1360**	**294**	**10054**

Table B.5 shows the results VLH and Flow per mode for 6 runs of reference scenario A. This data is generated to automatically in Aimsun, therefore no additional actions are needed other than reading the sqlite file in excel. The sum of all numbers are used to calculate the percentages as stated in Table B.6. This table shows that 13.53 % of the road users are cyclists, who altogether experienced 5.33 % of the VLHs (equivalent to 5.33 % of the delay). In contrast to the pedestrians, who count for 2.92 % of all road users and experience 3.75 % of the VLHs. The ratio of VLH percentage and the percentage of the flow creates a number that is 1 if both are equal, lower than 1 shows road users that are advantaged over the other road users, and higher than 1 means that these road users are disadvantaged relative to the total.

Table B.6: Vehicle loss hours and flows in percentages for cyclists and pedestrians for 6 simulation runs of reference scenario A

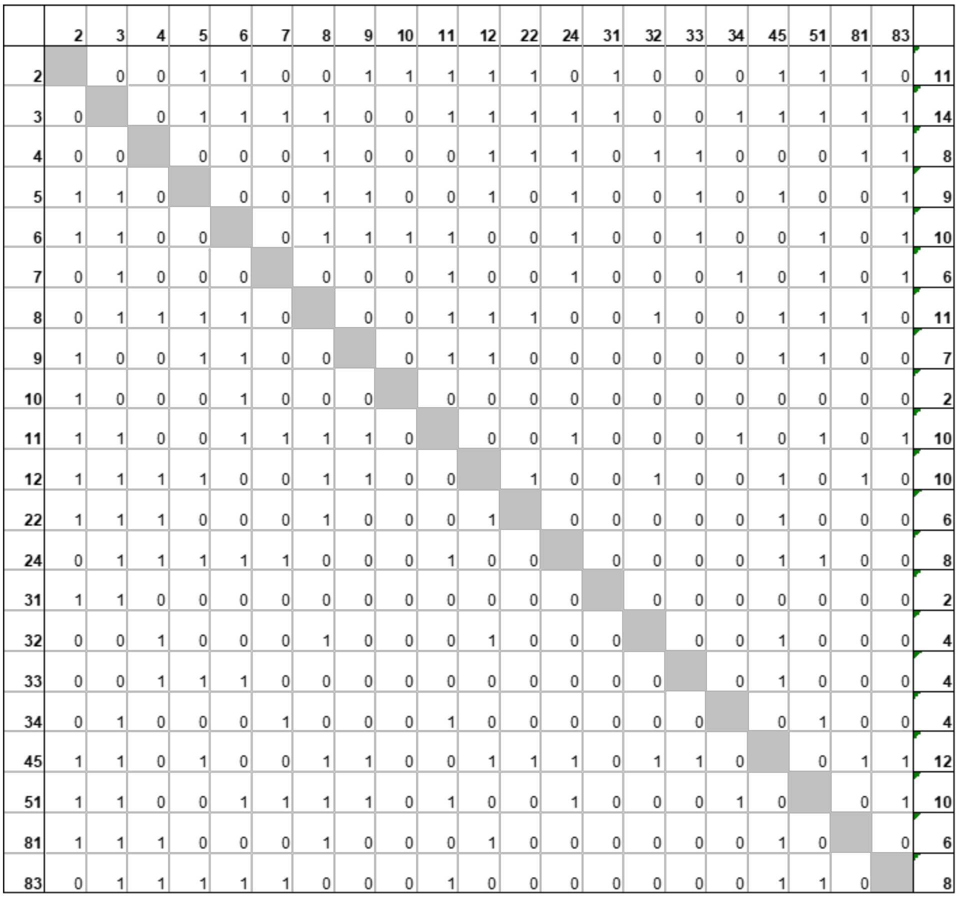
%VLH bike	5.33	%VLH ped.	4.22
%Flow bike	13.53	%Flow ped.	2.92
VLH:Flow bike	**0.39**	**VLH:Flow ped.**	**1.44**

This experiment aims to bring the VLH percentage of active modes closer to their flow percentage, a ratio of 1.0, as this implies a more egalitarian situation between the modes on this cross section. To do this, the current multiplication factors of scenario A are multiplied by the corresponding ratios of VLH:Flow in percentage. This results in new multiplication factors of 0.8 and 5.8 for respectively cyclists and pedestrians for the scenario AM (Active Modes).

B.2.4. Experiment 3: Directional settings

This experiment includes multiple iterations based on the results of the earlier iterations. The focus of this Appendix section is to show how the settings were created, the intermediate results of all scenarios are found in Appendix **??**. The argumentation behind the different iteration scenarios has been elaborated in Chapter 6 and is shortly repeated in this section.

Because the amount of conflicts influences how one direction can be (dis)advantaged, it is decided to link the amount of conflicts per direction to the directional multiplication factors. The conflict matrix is extracted from Flowtack's internal file in which the clearance times [1] are stated only for conflicting directions. This conflict matrix can be found in Figure B.19. Figure B.12 shows the numbering of the directions on intersection A050, which are also used in this conflict matrix. Numbers 02-12 refer to vehicle lanes, the 20s & 80s numbers refer to cyclist cross overs, the 30s numbers refer to pedestrian cross overs, and the 40s and 50s numbers refer to shared bus lanes.



	2	3	4	5	6	7	8	9	10	11	12	22	24	31	32	33	34	45	51	81	83	
2		0	0	1	1	0	0	1	1	1	1	1	0	1	0	0	0	1	1	1	0	**11**
3	0		0	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	**14**
4	0	0		0	0	0	1	0	0	0	1	1	1	0	1	1	0	0	0	1	1	**8**
5	1	1	0		0	0	1	1	0	0	1	0	1	0	0	1	0	1	0	0	1	**9**
6	1	1	0	0		0	1	1	1	1	0	0	1	0	0	1	0	0	1	0	1	**10**
7	0	1	0	0	0		0	0	0	1	0	0	1	0	0	0	1	0	1	0	1	**6**
8	0	1	1	1	1	0		0	0	1	1	1	0	0	1	0	0	1	1	1	0	**11**
9	1	0	0	1	1	0	0		0	1	1	0	0	0	0	0	0	1	1	0	0	**7**
10	1	0	0	0	1	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	**2**
11	1	1	0	0	1	1	1	1	0		0	0	1	0	0	0	1	0	1	0	1	**10**
12	1	1	1	1	0	0	1	1	0	0		1	0	0	1	0	0	1	0	1	0	**10**
22	1	1	1	0	0	0	1	0	0	0	1		0	0	0	0	0	1	0	0	0	**6**
24	0	1	1	1	1	1	0	0	0	1	0	0		0	0	0	0	1	1	0	0	**8**
31	1	1	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	**2**
32	0	0	1	0	0	0	1	0	0	0	1	0	0	0		0	0	1	0	0	0	**4**
33	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0		0	1	0	0	0	**4**
34	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0		0	1	0	0	**4**
45	1	1	0	1	0	0	1	1	0	0	1	1	1	0	1	1	0		0	1	1	**12**
51	1	1	0	0	1	1	1	1	0	1	0	0	1	0	0	0	1	0		0	1	**10**
81	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0		0	**6**
83	0	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	1	1	0		**8**

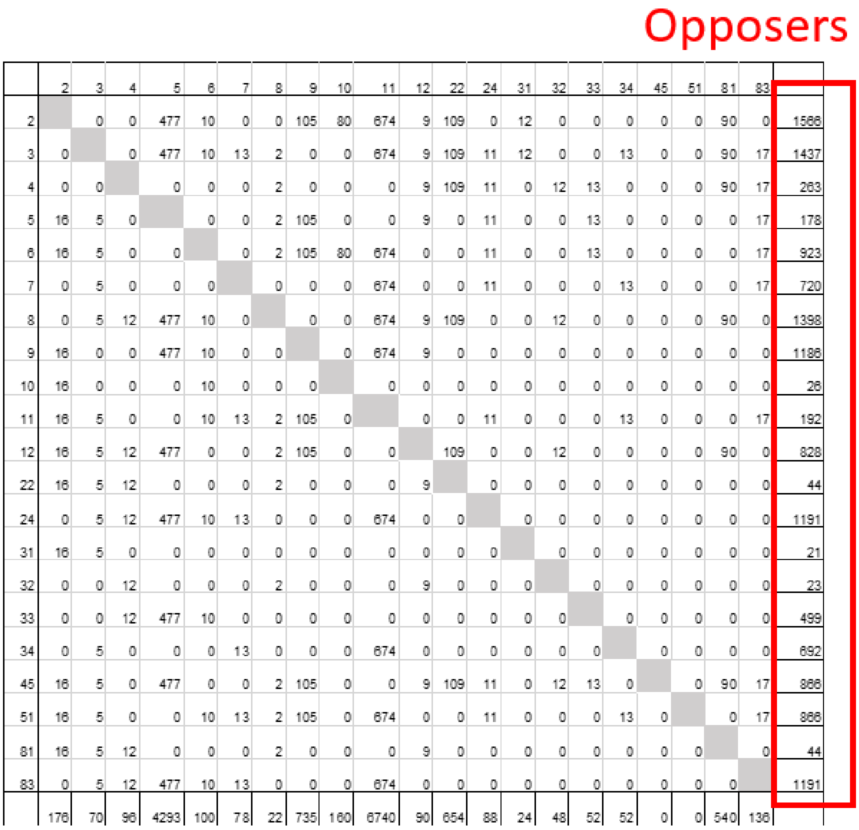
Figure B.19: Conflict matrix of A050 in Deventer, 0 = no conflict, 1 = conflict, direction numbers refer to the directions as depicted in Figure B.12

The sum of all conflicts per direction is found at the right side of the conflict matrix and defines the weights that are used for the vehicles in scenario conflict factor (CF). However, due to the fact that conflicts without traffic are less significant than conflicts with plenty of traffic. The measured flow of reference scenario A has been used as input for a weight on each direction. The number of conflicting road users are counted as opposers in Figure B.20 and the number of non conflicting road users are counted as supporters in Figure B.21. Then, the number of opposers is divided by the number of supporters in order to gain the weighted conflict factor (WCF). The multiplication factors that are used for scenario WCF can be found in Table B.7.

It was observed during these simulation runs of scenario WCF that the extremes of the multiplication

---

[1] Clearance times are the time that is needed between red light for one direction and green for the other, to clear the intersection from traffic that has just passed yellow light before sending conflicting traffic onto the intersection.



	2	3	4	5	6	7	8	9	10	11	12	22	24	31	32	33	34	45	51	81	83	
2		0	0	477	10	0	0	105	80	674	9	109	0	12	0	0	0	0	0	90	0	1566
3	0		0	477	10	13	2	0	0	674	9	109	11	12	0	0	13	0	0	90	17	1437
4	0	0		0	0	0	2	0	0	0	9	109	11	0	12	13	0	0	0	90	17	263
5	16	5	0		0	0	2	105	0	0	9	0	11	0	0	13	0	0	0	0	17	178
6	16	5	0	0		0	2	105	80	674	0	0	11	0	0	13	0	0	0	0	17	923
7	0	5	0	0	0		0	0	0	674	0	0	11	0	0	0	13	0	0	0	17	720
8	0	5	12	477	10	0		0	0	674	9	109	0	0	12	0	0	0	0	90	0	1398
9	16	0	0	477	10	0	0		0	674	9	0	0	0	0	0	0	0	0	0	0	1186
10	16	0	0	0	10	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	26
11	16	5	0	0	10	13	2	105	0		0	0	11	0	0	0	13	0	0	0	17	192
12	16	5	12	477	0	0	2	105	0	0		109	0	0	12	0	0	0	0	90	0	828
22	16	5	12	0	0	0	2	0	0	0	9		0	0	0	0	0	0	0	0	0	44
24	0	5	12	477	10	13	0	0	0	674	0	0		0	0	0	0	0	0	0	0	1191
31	16	5	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	21
32	0	0	12	0	0	0	2	0	0	0	9	0	0	0		0	0	0	0	0	0	23
33	0	0	12	477	10	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	499
34	0	5	0	0	0	13	0	0	0	674	0	0	0	0	0	0		0	0	0	0	692
45	16	5	0	477	0	0	2	105	0	0	9	109	11	0	12	13	0		0	90	17	866
51	16	5	0	0	10	13	2	105	0	674	0	0	11	0	0	0	13	0		0	17	866
81	16	5	12	0	0	0	2	0	0	0	9	0	0	0	0	0	0	0	0		0	44
83	0	5	12	477	10	13	0	0	0	674	0	0	0	0	0	0	0	0	0	0		1191
	176	70	96	4293	100	78	22	735	160	6740	90	654	88	24	48	52	52	0	0	540	136	

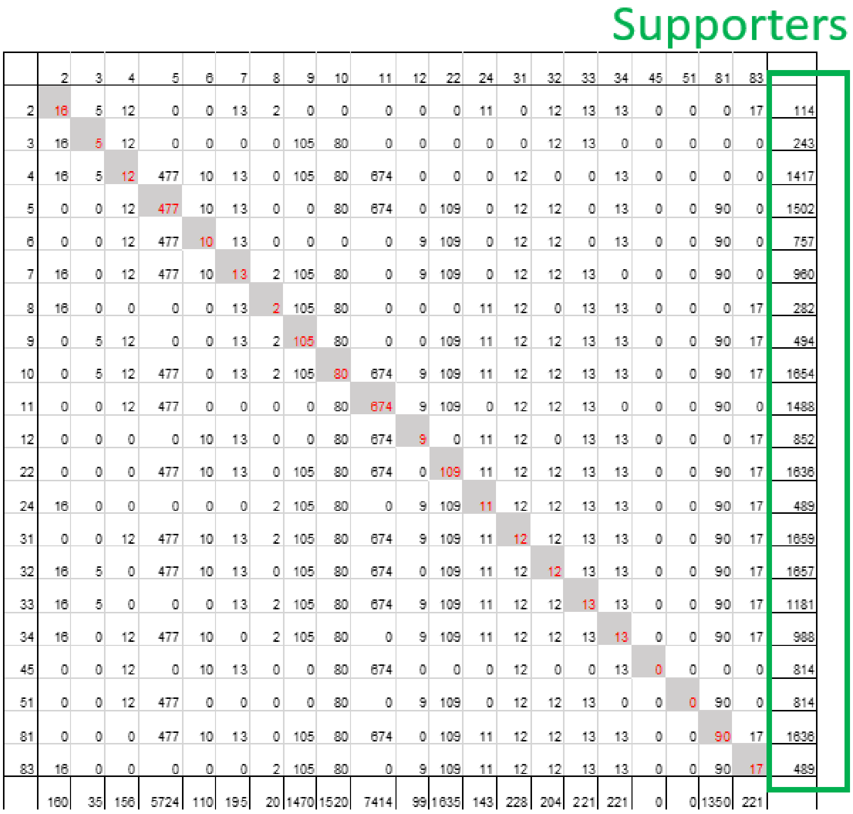
Figure B.20: Opposer matrix, conflicts multiplied by the measured flow on these directions.

factors are probably too high. Table B.7 shows that the multiplication factors vary from 13.7 to 0.01, which causes enormous difference in weight for road users from different directions. For instance, when a road user arrived from one of the directions with a high multiplication factor, all other traffic was stopped to let this vehicle pass, regardless of the amount. This was not the idea behind this scenario, as its purpose was to help those who have little support from the intersection layout and flow with a higher multiplication factor, in order for these road users to experience lower delay. However, the current settings created a situation where these few road users experience no delay at all at the cost of the bigger group of road users.

The extremes in the multiplication factors have to do with the correlation of 2 supporting road users. These road users expect a certain amount of support from other road users, but in reality they receive less support than expected because all their supporter's multiplication factors are lowered due to each other's support. The same happens with the opposers, where a certain amount of resistance is expected but not experienced because the conflicting direction is being corrected for as well. The last scenario iteration corrects for this correlation that causes extremes by manipulation of the extreme values with a square root operator rather than solving the correlation issue. The square root values of scenario WCF's multiplication factors are shown in Table B.7. The formula for the multiplication factor β_j for every direction of j is stated:

$$\beta_j = \sqrt{\frac{C_j}{S_j}}$$

- β_j, a multiplication factor (-) that is direction dependent.
- C_j, the amount of conflicting road users (opposers) for direction j.
- S_j, the amount of non-conflicting road users (supporters) for direction j, including the amount road users at direction j.



	2	3	4	5	6	7	8	9	10	11	12	22	24	31	32	33	34	45	51	81	83	Supporters
2	16	5	12	0	0	13	2	0	0	0	0	0	11	0	12	13	13	0	0	0	17	114
3	16	5	12	0	0	0	0	105	80	0	0	0	0	0	12	13	0	0	0	0	0	243
4	16	5	12	477	10	13	0	105	80	674	0	0	0	12	0	0	13	0	0	0	0	1417
5	0	0	12	477	10	13	0	0	80	674	0	109	0	12	12	0	13	0	0	90	0	1502
6	0	0	12	477	10	13	0	0	0	0	9	109	0	12	12	0	13	0	0	90	0	757
7	16	0	12	477	10	13	2	105	80	0	9	109	0	12	12	13	0	0	0	90	0	960
8	16	0	0	0	0	13	2	105	80	0	0	0	11	12	0	13	13	0	0	0	17	282
9	0	5	12	0	0	13	2	105	80	0	0	109	11	12	12	13	13	0	0	90	17	494
10	0	5	12	477	0	13	2	105	80	674	9	109	11	12	12	13	13	0	0	90	17	1654
11	0	0	12	477	0	0	0	0	80	674	9	109	0	12	12	13	0	0	0	90	0	1488
12	0	0	0	0	10	13	0	0	80	674	9	0	11	12	0	13	13	0	0	0	17	852
22	0	0	0	477	10	13	0	105	80	674	0	109	11	12	12	13	13	0	0	90	17	1636
24	16	0	0	0	0	0	2	105	80	0	9	109	11	12	12	13	13	0	0	90	17	489
31	0	0	12	477	10	13	2	105	80	674	9	109	11	12	12	13	13	0	0	90	17	1659
32	16	5	0	477	10	13	0	105	80	674	0	109	11	12	12	13	13	0	0	90	17	1657
33	16	5	0	0	0	13	2	105	80	674	9	109	11	12	12	13	13	0	0	90	17	1181
34	16	0	12	477	10	0	2	105	80	0	9	109	11	12	12	13	13	0	0	90	17	988
45	0	0	12	0	10	13	0	0	80	674	0	0	0	12	0	0	13	0	0	0	0	814
51	0	0	12	477	0	0	0	0	80	0	9	109	0	12	12	13	0	0	0	90	0	814
81	0	0	0	477	10	13	0	105	80	674	0	109	11	12	12	13	13	0	0	90	17	1636
83	16	0	0	0	0	0	2	105	80	0	9	109	11	12	12	13	13	0	0	90	17	489
	160	35	156	5724	110	195	20	1470	1520	7414	99	1635	143	228	204	221	221	0	0	1350	221	

Figure B.21: Supporter matrix, non-conflicts multiplied by the measured flow on these directions.

Table B.7: Number of conflicts, opposers, supporters, weighted conflict factors and the square root of WCF per direction.

Direction j	**Conflicts**	**Opposers C_j**	**Supporters S_j**	**WCF**	**SQRT**
2	11	1566	114	13.7	3.71
3	14	1437	243	5.91	2.43
4	8	263	1417	0.19	0.43
5	9	178	1502	0.12	0.34
6	10	923	757	1.22	1.10
7	6	720	960	0.75	0.87
8	11	1398	282	4.96	2.23
9	7	1186	494	2.40	1.55
10	2	26	1654	0.02	0.13
11	10	192	1488	0.13	0.36
12	10	828	852	0.97	0.99
22	6	44	1636	0.03	0.16
24	8	1191	489	2.44	1.56
31	2	21	1659	0.01	0.11
32	4	23	1657	0.01	0.12
33	4	499	1181	0.42	0.65
34	4	692	988	0.70	0.84
45	12	866	814	1.06	1.03
51	10	866	814	1.06	1.03
81	6	44	1636	0.03	0.16
83	8	1191	489	2.44	1.56

C

Appendix C

This Appendix is written to support Chapter 7. The structure of that Chapter is preserved in this Appendix.

C.1. Experiment results

This section contains additional information for the results of experiments 1-3, such as the tables that contain the exact data points that were plotted in the Figures of Chapter 7. These tables are found at the end of this Appendix.

C.1.1. Experiment 2: Road user type settings

Figure C.1 shows the equity indicators for scenarios A and AM. Both the Gini coefficient and the maximum delay remain approximately the same for scenario AM. The average delay is on average half a second higher than that of reference scenario A, which is explained by the fact that the higher pedestrian factor causes the vehicles on the main road to wait longer since one of the pedestrian cross overs crosses the main road.

Table C.1 is used to create Tables 6.4, in which the percentages of the totals of these runs in this Table are used to create the VLH:Flow ratios of reference scenario A.

Table C.1: VLHs and Flow for cyclists, pedestrians and the total of all road users (incl. cyclists and pedestrians) for 6 runs of reference scenario A.

Scenario A	VLH bike	VLH pred.	VLH tot.	Flow bike	Flow ped.	Flow tot.
Sc.A.1	0.28	0.22	5.70	226	49	1679
Sc.A.2	0.28	0.32	5.62	227	49	1682
Sc.A.3	0.34	0.23	6.09	227	49	1669
Sc.A.4	0.34	0.21	6.05	227	49	1676
Sc.A.5	0.31	0.24	5.73	226	49	1681
Sc.A.6	0.31	0.26	5.81	227	49	1667
Tot.	1.87	1.48	35.00	1360	294	10054

Table C.2 is used to create Table 7.1, in which the percentages of the totals of these runs in this Table are used to create the VLH:Flow ratios of scenario AM.

Note that the Flow in Tables C.1 & C.2 remains almost constant. Aimsun produces the road users perfectly constant, as the same random seed for the production of road users is used for each experiment (experiment 1-4). The number does vary by a little bit, because they delay data is only known after the road user has crossed. Thus, road users that have not crossed yet due to a different decision by Flowtack can vary the outcome of the Flow by small amounts.

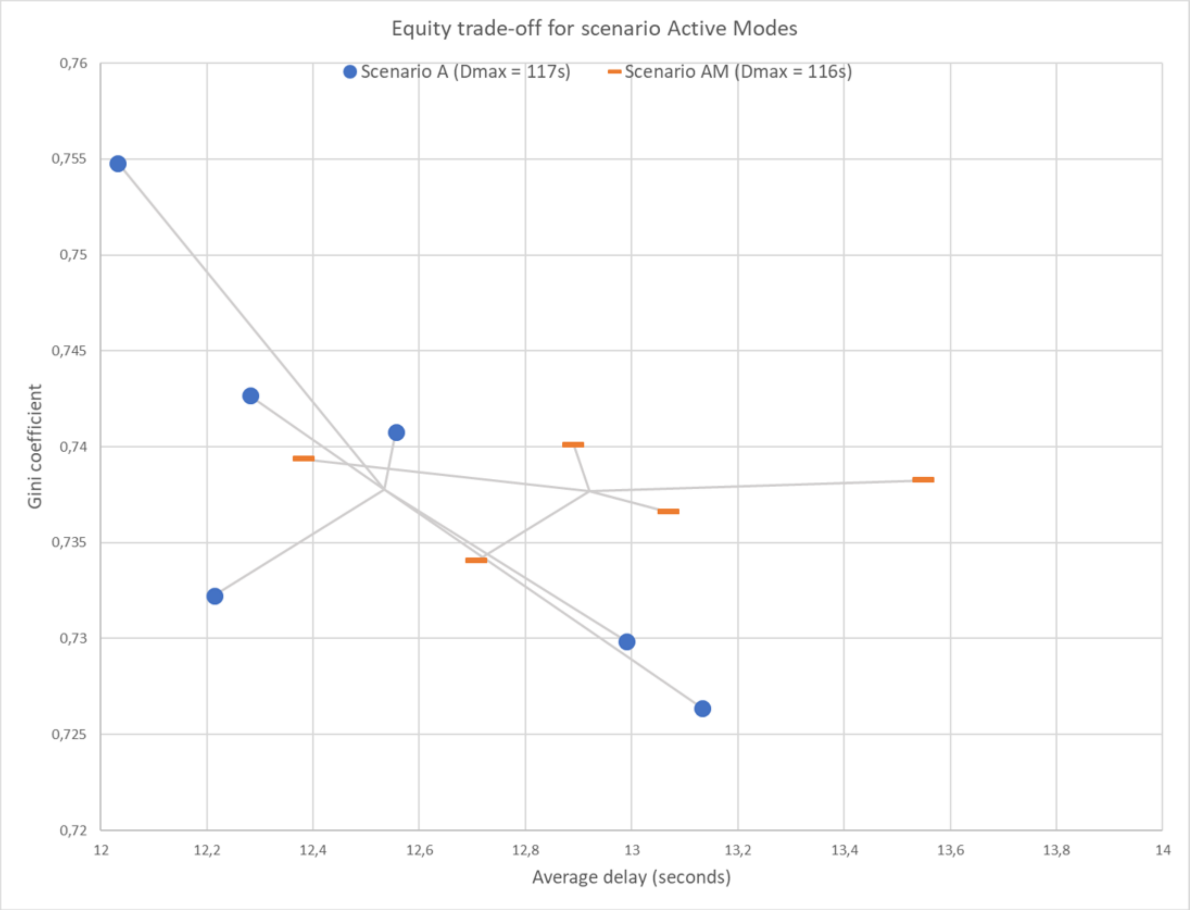


Figure C.1: Results of experiment 2: Reference scenario A and scenario Active Modes (AM)

C.1.2. Experiment 3: Directional settings

The results of the iteration scenarios CF and WCF show why the corrections were made. Scenario CF scores worse on the equity indicators, basically because the conflicts were not weighted, thus generate settings that do not necessarily make sense. Then, scenario WCF weights these settings, but does not take care of the correlation problem. During these simulations, it was seen that the multiplication factors were too extreme, because the side roads were now granted priority over all other vehicles in such a way that these directions never needed to stop. The outcome as depicted in Figure C.2 are logical, as the average delay is almost doubled by making the bigger flows wait on the smaller flows in this scenario. This also has a very positive effect on the Gini coefficient, because the distribution of delay becomes more egalitarian, as more road users are delayed by approximately the same amount of time.

Table C.2: VLHs and Flow for cyclists, pedestrians and the total of all road users (incl. cyclists and pedestrians) for 5 runs of scenario AM.

Scenario A	VLH bike	VLH pred.	VLH tot.	Flow bike	Flow ped.	Flow tot.
Sc.A.1	0.41	0.20	5.76	225	49	1676
Sc.A.2	0.38	0.22	6.02	226	49	1681
Sc.A.3	0.35	0.25	6.33	227	49	1682
Sc.A.4	0.39	0.22	5.92	225	49	1676
Sc.A.5	0.38	0.23	6.10	226	49	1681
Tot.	1.91	1.13	30.13	1129	245	8396

Table C.3: Directional settings for validation scenario combi 1, 2 and 3.

Validation scenario	Reference	combi OD 1	combi OD 2	combi OD 3
Weight Function	A	B	B	B
Directions	**Mult. Fact.**	**Mult. Fact.**	**Mult. Fact.**	**Mult. Fact.**
1	1.0	0.4	0.5	0.8
2	1.0	1.0	1.3	2.9
3	1.0	1.0	1.3	2.3
4	1.0	0.4	0.4	0.3
5	1.0	1.0	0.8	0.3
6	1.0	1.0	1.0	0.9
7	1.0	0.4	0.5	0.7
8	1.0	1.0	1.3	3.1
9	1.0	1.0	1.3	2.5
10	1.0	0.4	0.4	0.3
11	1.0	1.0	0.8	0.3
12	1.0	1.0	1.0	1.0

C.1.3. Validation

The Conflict matrix is the same for each OD matrix, however the amount of opposers and supporters will vary. The conflict matrix is not documented, because the conflicts are implicitly shown in the opposers matrix, where every non-zero value implicates a conflict, since all simulated flows are non-zero. Figures C.3 - C.8 show the opposers and supporters matrices for each OD matrix. The directions count from 1 to 12. North, East, South and West are used rather than the direction numbering in the OD matrices. To clarify the link between the directions, the cardinal directions corresponding to the number codes are added at the bottom of the opposers and supporters matrices.

Table C.3 of Appendix B.1.3 shows the directional multiplication factors for each corresponding OD matrix, created with the multiplication factor formula of scenario sqrt. It is shown in this table that only the right turning traffic in OD 1 is given a lower multiplication factor, where all other multiplication factors remain the same. This is caused by the fact that the amount of conflicts on left-turning traffic equals that of straight-ahead traffic, whilst the right-turning traffic has less conflicts. When all directions generate and attract the same amount of road users, the weighted conflict factor equals the conflict factor, thus the sqrt(WCF) equals the sqrt(CF). The spread of the multiplication factors increases as the OD matrix flows become more unequally distributed. As OD 2's multiplication factors vary between 0.4 & 1.3 and OD 3's multiplication factors vary between 0.3 & 3.1.

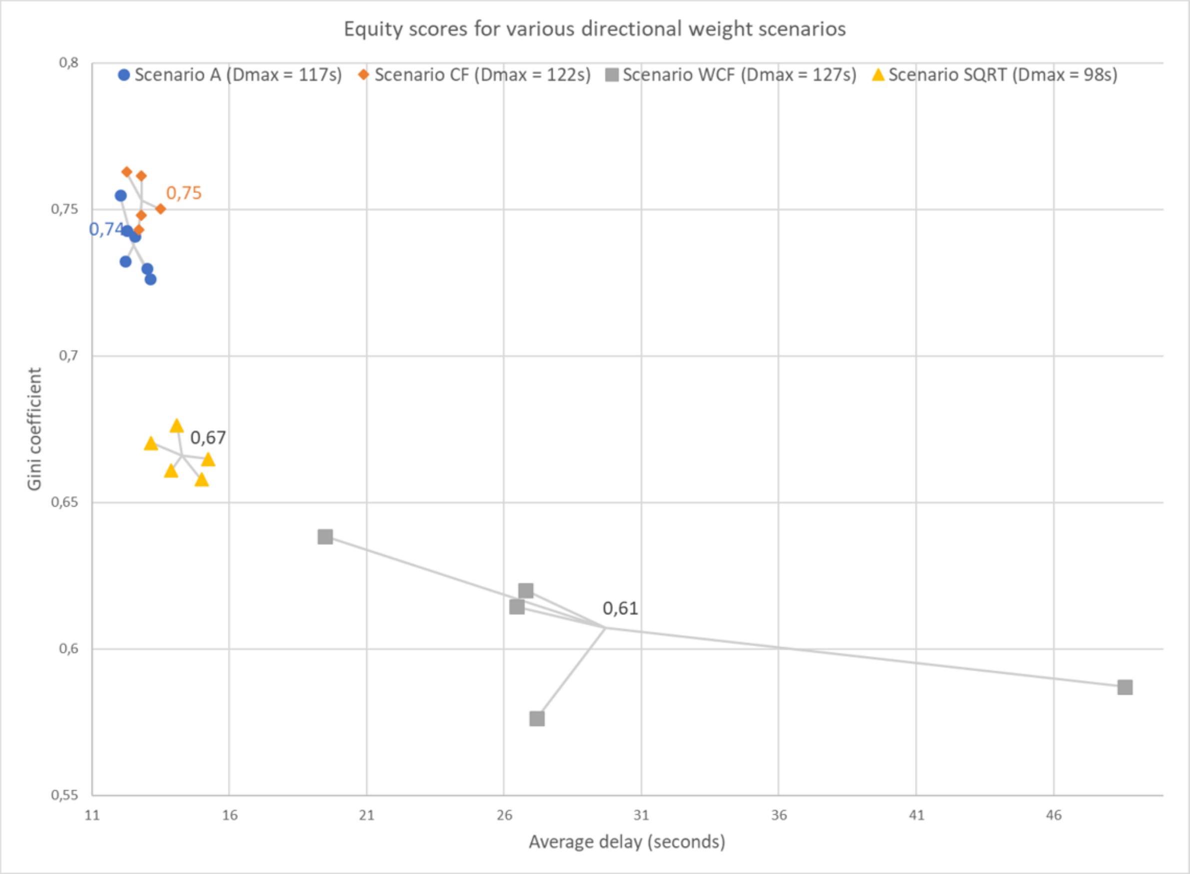
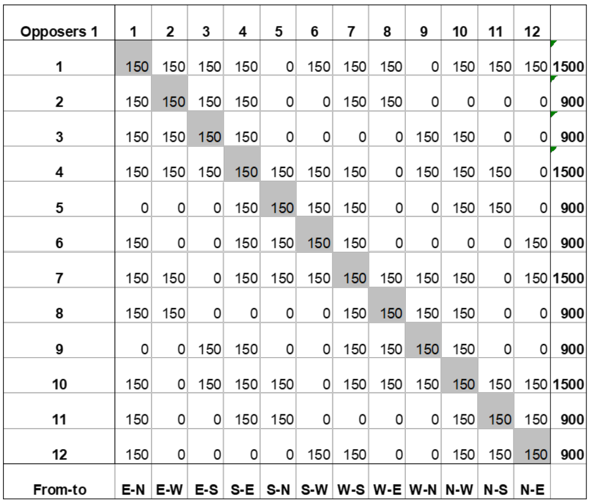
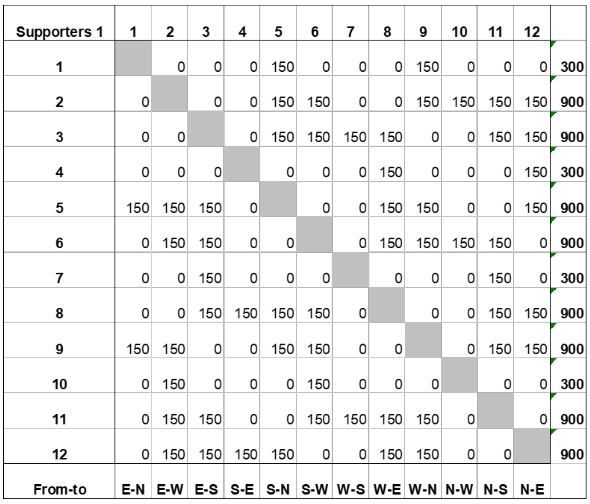


Figure C.2: Results of all iteration scenarios of experiment 3: Reference scenario A, scenario CF, scenario WCF and scenario sqrt



Opposers 1	1	2	3	4	5	6	7	8	9	10	11	12	
1	150	150	150	150	0	150	150	150	0	150	150	150	**1500**
2	150	150	150	150	0	0	150	150	0	0	0	0	**900**
3	150	150	150	150	0	0	0	0	150	150	0	0	**900**
4	150	150	150	150	150	150	150	0	150	150	150	0	**1500**
5	0	0	0	150	150	150	150	0	0	150	150	0	**900**
6	150	0	0	150	150	150	150	0	0	0	0	150	**900**
7	150	150	0	150	150	150	150	150	150	150	0	150	**1500**
8	150	150	0	0	0	0	150	150	150	150	0	0	**900**
9	0	0	150	150	0	0	150	150	150	150	0	0	**900**
10	150	0	150	150	150	0	150	150	150	150	150	150	**1500**
11	150	0	0	150	150	0	0	0	0	150	150	150	**900**
12	150	0	0	0	0	150	150	0	0	150	150	150	**900**
From-to	**E-N**	**E-W**	**E-S**	**S-E**	**S-N**	**S-W**	**W-S**	**W-E**	**W-N**	**N-W**	**N-S**	**N-E**	

Figure C.3: Opposer matrix 1

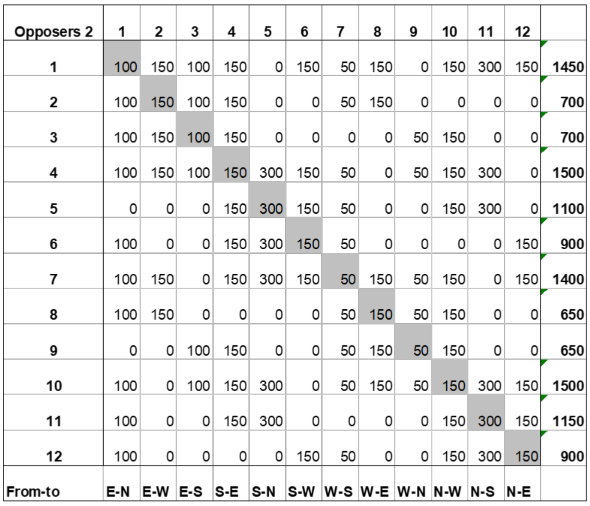


Supporters 1	1	2	3	4	5	6	7	8	9	10	11	12	
1		0	0	0	150	0	0	0	150	0	0	0	**300**
2	0		0	0	150	150	0	0	150	150	150	150	**900**
3	0	0		0	150	150	150	150	0	0	150	150	**900**
4	0	0	0		0	0	0	150	0	0	0	150	**300**
5	150	150	150	0		0	0	150	150	0	0	150	**900**
6	0	150	150	0	0		0	150	150	150	150	0	**900**
7	0	0	150	0	0	0		0	0	0	150	0	**300**
8	0	0	150	150	150	150	0		0	0	150	150	**900**
9	150	150	0	0	150	150	0	0		0	150	150	**900**
10	0	150	0	0	0	150	0	0	0		0	0	**300**
11	0	150	150	0	0	150	150	150	150	0		0	**900**
12	0	150	150	150	150	0	0	150	150	0	0		**900**
From-to	**E-N**	**E-W**	**E-S**	**S-E**	**S-N**	**S-W**	**W-S**	**W-E**	**W-N**	**N-W**	**N-S**	**N-E**	

Figure C.4: Supporter matrix 1

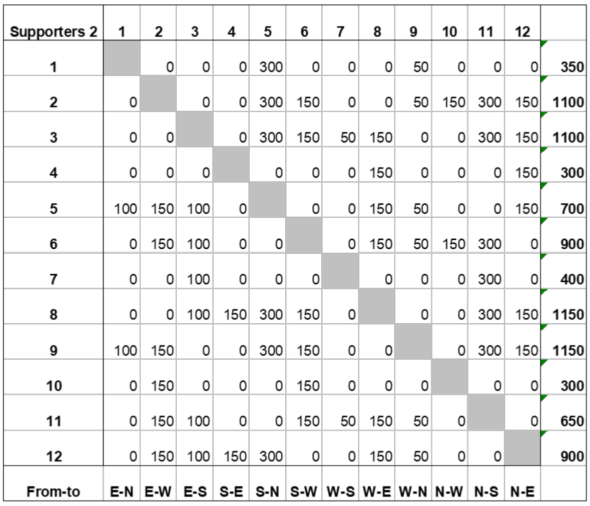
C.1.4. Data points in table form

Tables C.4, C.5, C.6, C.7, C.8, C.9, C.10, C.11, C.12, C.13, C.14, C.15, C.16, C.17, C.18, C.19 and C.20 contain the numeric values of the plotted points in the Figures that contain the equity measures.



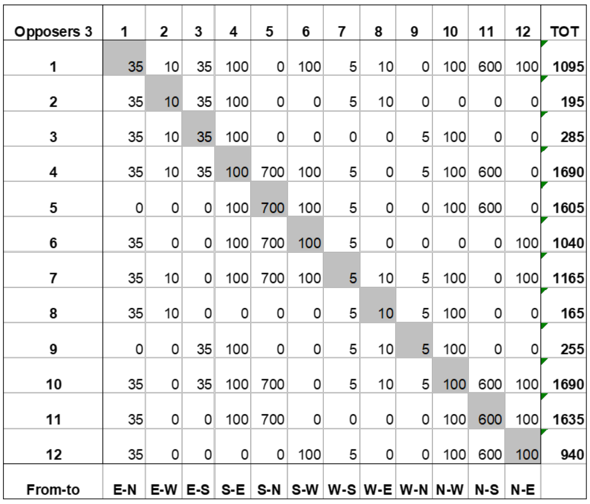
Opposers 2	1	2	3	4	5	6	7	8	9	10	11	12	
1	100	150	100	150	0	150	50	150	0	150	300	150	1450
2	100	150	100	150	0	0	50	150	0	0	0	0	700
3	100	150	100	150	0	0	0	0	50	150	0	0	700
4	100	150	100	150	300	150	50	0	50	150	300	0	1500
5	0	0	0	150	300	150	50	0	0	150	300	0	1100
6	100	0	0	150	300	150	50	0	0	0	0	150	900
7	100	150	0	150	300	150	50	150	50	150	0	150	1400
8	100	150	0	0	0	0	50	150	50	150	0	0	650
9	0	0	100	150	0	0	50	150	50	150	0	0	650
10	100	0	100	150	300	0	50	150	50	150	300	150	1500
11	100	0	0	150	300	0	0	0	0	150	300	150	1150
12	100	0	0	0	0	150	50	0	0	150	300	150	900
From-to	E-N	E-W	E-S	S-E	S-N	S-W	W-S	W-E	W-N	N-W	N-S	N-E	

Figure C.5: Opposer matrix 2



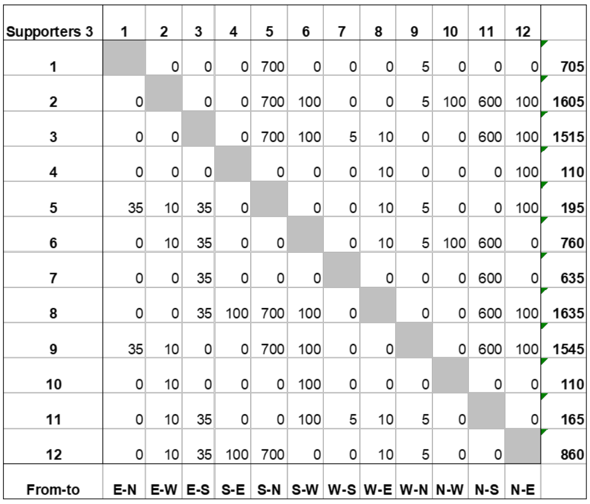
Supporters 2	1	2	3	4	5	6	7	8	9	10	11	12	
1		0	0	0	300	0	0	0	50	0	0	0	350
2	0		0	0	300	150	0	0	50	150	300	150	1100
3	0	0		0	300	150	50	150	0	0	300	150	1100
4	0	0	0		0	0	0	150	0	0	0	150	300
5	100	150	100	0		0	0	150	50	0	0	150	700
6	0	150	100	0	0		0	150	50	150	300	0	900
7	0	0	100	0	0	0		0	0	0	300	0	400
8	0	0	100	150	300	150	0		0	0	300	150	1150
9	100	150	0	0	300	150	0	0		0	300	150	1150
10	0	150	0	0	0	150	0	0	0		0	0	300
11	0	150	100	0	0	150	50	150	50	0		0	650
12	0	150	100	150	300	0	0	150	50	0	0		900
From-to	E-N	E-W	E-S	S-E	S-N	S-W	W-S	W-E	W-N	N-W	N-S	N-E	

Figure C.6: Supporter matrix 2



Opposers 3	1	2	3	4	5	6	7	8	9	10	11	12	TOT
1	35	10	35	100	0	100	5	10	0	100	600	100	1095
2	35	10	35	100	0	0	5	10	0	0	0	0	195
3	35	10	35	100	0	0	0	0	5	100	0	0	285
4	35	10	35	100	700	100	5	0	5	100	600	0	1690
5	0	0	0	100	700	100	5	0	0	100	600	0	1605
6	35	0	0	100	700	100	5	0	0	0	0	100	1040
7	35	10	0	100	700	100	5	10	5	100	0	100	1165
8	35	10	0	0	0	0	5	10	5	100	0	0	165
9	0	0	35	100	0	0	5	10	5	100	0	0	255
10	35	0	35	100	700	0	5	10	5	100	600	100	1690
11	35	0	0	100	700	0	0	0	0	100	600	100	1635
12	35	0	0	0	0	100	5	0	0	100	600	100	940
From-to	E-N	E-W	E-S	S-E	S-N	S-W	W-S	W-E	W-N	N-W	N-S	N-E	

Figure C.7: Opposer matrix 3



Supporters 3	1	2	3	4	5	6	7	8	9	10	11	12	
1		0	0	0	700	0	0	0	5	0	0	0	705
2	0		0	0	700	100	0	0	5	100	600	100	1605
3	0	0		0	700	100	5	10	0	0	600	100	1515
4	0	0	0		0	0	0	10	0	0	0	100	110
5	35	10	35	0		0	0	10	5	0	0	100	195
6	0	10	35	0	0		0	10	5	100	600	0	760
7	0	0	35	0	0	0		0	0	0	600	0	635
8	0	0	35	100	700	100	0		0	0	600	100	1635
9	35	10	0	0	700	100	0	0		0	600	100	1545
10	0	10	0	0	0	100	0	0	0		0	0	110
11	0	10	35	0	0	100	5	10	5	0		0	165
12	0	10	35	100	700	0	0	10	5	0	0		860
From-to	E-N	E-W	E-S	S-E	S-N	S-W	W-S	W-E	W-N	N-W	N-S	N-E	

Figure C.8: Supporter matrix 3

Table C.4: Data input for scenario A

Scenario A	Gini	Avg Delay	Max Delay
1	0.73223	12.21423	113.1
2	0.754779	12.0321	121.3
3	0.726372	13.13223	114.6
4	0.729859	12.9901	114.6
5	0.742657	12.28186	123.8
6	0.740779	12.55609	111.7
AVG	0.74	12.5	116.5167

Table C.5: Data input for current settings

Current settings	Gini	Avg Delay	Max Delay
1	0.731732	12.30874	107.6
2	0.73628	12.5793	103
3	0.727445	12.65167	116.9
4	0.759664	12.77765	105.8
5	0.735814	12.17014	101.4
AVG	0.74	12.5	106.94

Table C.6: Data input for scenario B

Scenario B	Gini	Avg Delay	Max Delay
1	0.730699	12.07564	81.4
2	0.726546	11.84105	95.5
3	0.706597	12.69449	96.5
4	0.707021	12.77097	98.3
5	0.717377	12.01056	99
AVG	0.72	12.3	94.1

Table C.7: Data input for scenario C

Scenario C	Gini	Avg Delay	Max Delay
1	0.815611	13.80155	478.8
2	0.828111	15.36653	597.2
3	0.801823	14.73102	684.1
AVG	0.82	14.6	586.7

Table C.8: Data input for scenario D

Scenario D	Gini	Avg Delay	Max Delay
1	0.735974	12.74122	112.2
2	0.737877	12.66269	103.9
3	0.738259	13.26957	105.6
4	0.738676	12.87894	103
5	0.733916	13.13069	103
AVG	0.74	12.9	105.54

Table C.9: Data input for scenario E

Scenario E	Gini	Avg Delay	Max Delay
1	0.763476	12.65883	149.8
2	0.752807	13.72864	174.2
3	0.755047	12.59081	139
4	0.769215	12.88495	158.3
5	0.763579	13.19875	166.3
AVG	0.760825	13.0124	157.52

Table C.10: Data input for scenario AM

Scenario AM	Gini	Avg Delay	Max Delay
1	0.739348	12.38359	111.6
2	0.740085	12.89114	113.3
3	0.738252	13.54941	122.7
4	0.734067	12.70895	109.6
5	0.736583	13.0702	121.3
AVG	0.74	12.9	115.7

Table C.11: Data input for scenario CF

Scenario CF	Gini	Avg Delay	Max Delay
1	0.762675	12.25959	126.6
2	0.76144	12.7988	120.8
3	0.742938	12.6988	129.2
4	0.750109	13.49413	117.1
5	0.748024	12.7919	117.5
AVG	0.75	12.8	122.2

Table C.12: Data input for scenario WCF

Scenario WCF	Gini	Avg Delay	Max Delay
1	0.62013	26.77837	140.6
2	0.614412	26.46991	107.2
3	0.576299	27.18971	101.7
4	0.638419	19.47379	95.8
5	0.587106	48.59257	189.7
AVG	0.61	29.7	127.0

Table C.13: Data input for scenario sqrt

Scenario sqrt	Gini	Avg Delay	Max Delay
1	0.661027	13.88459	76.3
2	0.670333	13.16008	89.5
3	0.66488	15.23188	103.3
4	0.676398	14.09185	118.1
5	0.657838	14.9874	104.9
AVG	0.67	14.3	98.4

Table C.14: Data input for scenario combi

Scenario combi	Gini	Avg Delay	Max Delay
1	0.655375	12.79023	75.4
2	0.659109	13.076	78
3	0.655418	14.01077	80.3
4	0.658282	13.92262	93.8
5	0.652649	13.83897	79.2
AVG	0.66	13.5	81.3

Table C.15: Data input for Validation reference scenario A - 1

Run VA1	Gini	Avg Delay	Max Delay
1	0.613597	25.32607	103.5
2	0.594098	23.79266	95.1
3	0.598527	25.73558	109.4
4	0.588527	24.07883	86.4
5	0.593793	25.32032	106.7
AVG	0.60	24.9	100.2

Table C.16: Data input for Validation combi scenario - 1

Run Vcombi1	Gini	Avg Delay	Max Delay
1	0.56623	26.35297	121.2
2	0.616773	26.37634	130.3
3	0.598591	24.43034	104
4	0.4709	24.63531	92.9
5	0.532852	25.91988	110.7
AVG	0.56	25.5	111.8

Table C.17: Data input for Validation reference scenario A - 2

Run VA2	Gini	Avg Delay	Max Delay
1	0.629604	25.48373	110.6
2	0.601119	27.16233	115.9
3	0.62353	27.4619	133.4
4	0.610437	26.47726	183
5	0.608501	26.8198	128.4
AVG	0.61	26.7	134.3

Table C.18: Data input for Validation combi scenario - 2

Run Vcombi1	Gini	Avg Delay	Max Delay
1	0.545011	26.71882	104.7
2	0.536729	25.74716	106.1
3	0.561636	27.6858	137.7
4	0.551773	25.74391	115
5	0.58668	27.36247	136.8
AVG	0.56	26.7	120.1

Table C.19: Data input for Validation reference scenario A - 3

Run VA3	Gini	Avg Delay	Max Delay
1	0.768018	12.86643	119.4
2	0.790121	12.84855	119.8
3	0.778736	12.21968	109.9
4	0.794278	12.5773	126.9
5	0.780244	13.7138	116.9
AVG	0.78	12.8	118.6

Table C.20: Data input for Validation combi scenario - 3

Run Vcombi3	Gini	Avg Delay	Max Delay
1	0.636738	14.80288	76.9
2	0.636402	14.88895	102.4
3	0.657914	16.34706	132.7
4	0.637255	14.91199	77.6
5	0.629377	15.84053	76.7
AVG	0.64	15.4	93.3