A simulation model of mixed traffic flow at non-signalised intersections, based on theShared Space approach

Luuk de Jong
A simulation model of mixed traffic flow at non-signalised intersections, based on the Shared Space approach

THESIS

submitted in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in

TRANSPORT, INFRASTRUCTURE AND LOGISTICS

by

Luuk Erik de Jong

born in Leiderdorp, the Netherlands

TU Delft

Department of Transport & Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Delft, the Netherlands
www.transport.citg.tudelft.nl
Copyright © L.E. de Jong, 2013. All rights reserved.

Cover picture: "artist's impression" of paths under Shared Space conditions (Bézier curves)
A simulation model of mixed traffic flow at non-signalised intersections, based on the Shared Space approach

Abstract

This report deals with conceiving and implementing a traffic flow model for mixed traffic at a non-signalised intersection, in particular one designed according to the Shared Space approach. The attitudes of road users in terms of being polite and taking initiative serve as the most important behavioural input. The modelling process starts from an investigation into the traffic-behavioural theory underlying Shared Space. Then, the state-of-the-art in traffic flow modelling for this particular type of intersection and traffic configuration is introduced. A new conceptual model is explained in the next chapter, followed by a description of the implementation of this model into a simulation model, written in Matlab. This implementation is used in a face validity analysis of the model. Furthermore, the implementation is applied in a few cases with varying input variables. The report ends with conclusions. The model helps to analyze and quantify the impact of considering road traffic as a process of social interaction with explicit negotiation about priority and accelerations.

Thesis committee:

Chair: Prof. dr. ir. S.P. Hoogendoorn, Faculty CEG
Supervisor: Dr. ir. W. Daamen, Faculty CEG
Committee member: Prof. dr. K.A. Broekhuis, Faculty TPM
Preface

This report is the result of a prolonged thesis project. This project forms the last phase of the Master of Science programme in Transport, Infrastructure and Logistics at Delft University of Technology.

The topic of this thesis report is the modelling of mixed traffic flow on intersections inspired by the Shared Space approach. Originally, I chose this topic for two reasons. The first reason was that I had the ambition to build a pioneering traffic flow model. This would give me the chance to show that I could learn a programming language and use it in a model. The second reason was that I was attracted to Shared Space due to its supposed rejection of existing traffic paradigms. In retrospect, one can argue about the tenability of either reason; adjusting an existing traffic flow model would have given quicker results, and the Shared Space approach may have been less revolutionary than it seemed to me then.

Thanks to my family for keeping me relatively sane, as well as fed and clothed, while working on this thesis. Thanks to the members of my graduation committee, especially Winnie Daamen, for their patience and constructive criticism.

Luuk de Jong
Leiden, March 2013
Contents

Preface .................................................................................................................................................. iii

Contents ............................................................................................................................................... v

List of Figures .................................................................................................................................. vii

List of Tables .................................................................................................................................... viii

Summary ............................................................................................................................................ 1

1 Introduction ..................................................................................................................................... 7

  1.1 Problem definition and project objective ............................................................................... 7

  1.2 Research question .................................................................................................................... 8

  1.3 Methodology ............................................................................................................................ 8

  1.4 Report structure ..................................................................................................................... 9

2 Shared Space theory ....................................................................................................................... 11

  2.1 Shared Space as a design process .......................................................................................... 11

  2.2 Social behaviour .................................................................................................................... 12

  2.3 Risk attitude .......................................................................................................................... 13

  2.4 Relation with Sustainable Safety .......................................................................................... 14

  2.5 Model requirements ............................................................................................................... 16

3 State-of-the-art in traffic flow modelling ......................................................................................... 19

  3.1 Classification of traffic flow models ...................................................................................... 19

  3.2 Selected models .................................................................................................................... 21

  3.3 Comparison of models .......................................................................................................... 24

    3.3.1 Criteria and possible scores ............................................................................................ 25

    3.3.2 Scored comparison .......................................................................................................... 26

    3.3.3 Analysis of comparison results ....................................................................................... 27

  3.4 Conclusion .............................................................................................................................. 28

4 Conceptual traffic model ............................................................................................................... 29

  4.1 Conceptual model diagram ..................................................................................................... 29

  4.2 Movement of road users ......................................................................................................... 32

    4.2.1 Distance, speed and acceleration .................................................................................. 32

    4.2.2 Relative and absolute position ...................................................................................... 33

  4.3 Negotiation between road users ............................................................................................. 35

    4.3.1 Path conflicts ................................................................................................................ 36

    4.3.2 Preferred trajectory ....................................................................................................... 39

    4.3.3 Detection of potential conflicts ...................................................................................... 39
List of Figures

Figure 2.1 Relations between road system elements relevant for Shared Space ................................................................. 12
Figure 4.1 Conceptual model diagram .......................................................................................................................... 29
Figure 5.1 Screenshot of the blink GUI ......................................................................................................................... 55
Figure 5.2 Overview of GUI input panels ........................................................................................................................ 56
Figure 5.3 Screenshots of GUI simulation control panel ................................................................................................ 56
Figure 5.4 UML diagram of program classes .................................................................................................................. 58
Figure 5.5 Simulation model flow diagram ..................................................................................................................... 60
Figure 5.6 Diagrams of a non-priority square and a priority intersection .......................................................................... 62
Figure 5.7 Flow diagram within generation process ......................................................................................................... 65
Figure 5.8 Illustration of a generic Bézier curve ................................................................................................................. 68
Figure 5.9 Flow diagram within negotiation process ...................................................................................................... 70
Figure 5.10 Decision tree of determining negotiation result ............................................................................................. 71
Figure 5.11 Screenshot of visualisation and explanation of its elements ............................................................................. 72
Figure 6.1 Eight traffic configurations ............................................................................................................................ 76
Figure 6.2 Average speed and total throughput as functions of traffic demand in configuration 1 ................................. 80
Figure 6.3 Average speed and total throughput as functions of traffic demand in configuration 2 ................................. 80
Figure 6.4 Average speed and total throughput as functions of traffic demand in configuration 3 ................................. 82
Figure 6.5 Precedence of primary and secondary road users in configurations 4 to 8..................................86
Figure 7.1 Boxplots of average speed values per case, grouped by modality...........................................94
Figure 7.2 Boxplots of TET values per case, grouped by modality..........................................................94
Figure 7.3 Boxplots of average speed values for case 2, grouped by modality and input............................96
Figure 7.4 Boxplots of TET values for case 2, grouped by modality and input..........................................96
Figure 7.5 Boxplots of average speed values for case 3, grouped by modality and input............................97
Figure 7.6 Boxplots of TET values for case 3, grouped by modality and input...........................................97

List of Tables

Table 3.1 Scored comparison of existing traffic flow models........................................................................26
Table 4.1 Sequence of acceleration options for two cooperative road users without precedence...........44
Table 4.2 Sequence of acceleration options for two non-cooperative road users without precedence..44
Table 4.3 Sequence of acceleration options for one road user without precedence..................................44
Table 4.4 Sequence of acceleration options for two road users with precedence.....................................46
Table 4.5 Sequence of acceleration options for one road user who takes precedence...........................46
Table 4.6 Sequence of acceleration options for one road user while other takes precedence...............46
Table 5.1 Non-internal input variables..................................................................................................52
Table 5.2 Main internal input variables..................................................................................................53
Table 5.3 Simulation control variables..................................................................................................53
Table 5.4 Main output variables............................................................................................................54
Table 6.1 Precedences in configurations 4 to 8 with initiative and politeness at 100%...............................83
Table 6.2 Precedences in configurations 4 to 8 with initiative and politeness at 0%.................................85
Table 7.1 Input variables for the four cases............................................................................................89
Table 7.2 Traffic intensities for the four cases..........................................................................................90
Table 7.3 Probabilities of equal means for average speed and TET values for case 1 to 4...............90
Table 7.4 Probabilities of equal means for population segments in cases 2 and 3.................................98
Table I.1 Modality-specific internal input values.....................................................................................113
Table I.2 Minimum headways of individual comfort zones.................................................................114
Table I.3 Minimum sideways of individual comfort zones.....................................................................114
Il semble que la perfection soit atteinte non quand il n'y a plus rien à ajouter,
mais quand il n'y a plus rien à retrancher.

Antoine de Saint-Exupéry, Terre des Hommes
Summary

The objective of this research project is to analyze the traffic behaviour that the Shared Space approach assumes to enforce in a traffic space designed according to its principles, and to determine the impact of this behaviour on traffic performance and safety, isolated from location-specific elements. Thus, the main research question in this thesis project is:

How does the Shared Space approach perceive road users to behave on a non-signalised intersection and how would that impact traffic performance and safety?

Answers to this question are sought by means of a new conceptual model and its implementation in a simulation model. Subsequently, the research question has been divided in sub-questions in this direction. They deal with (1) traffic-behavioural hypotheses, (2) modelling methods in current scientific literature, (3) building a new model in this thesis, (4) output variables on traffic performance and safety and (5) the results of the new model for these output variables.

Consequently, the working process of this thesis project consists of eight steps: (1) defining the problem, (2) studying the Shared Space philosophy and defining its main hypotheses, (3) researching and evaluating current traffic flow modelling approaches, (4) formulating a traffic flow model, (5) implementing the model, (6) analyzing the validity of the model, (7) applying the model to a specific case and (8) deriving conclusions. Each of these steps is captured in its own chapter.

Shared Space is, if anything, a road design process. It has a vision on the road network, but more so on the functions of public spaces and on the role of stakeholders in designing them. Public spaces are assumed to be multifunctional. Thus, traffic behaviour and the organisation of traffic control should not severely restrict other functions, such as shopping, meeting and resting. It cannot take too much space and should fit in visually and mentally. It is the role of a multidisciplinary design team to create a road environment that helps to enforce appropriate traffic behaviour, partly by road design.

Shared Space distinguishes between (1) social behaviour, consisting of unfocused, unpredictable and relatively slow movements without programme, (2) traffic behaviour, which is focused, predictable, fast and programmed, and (3) social traffic behaviour, a supposedly dangerous hybrid of the other two types of behaviour. No evidence is provided for this distinction, nor for the alleged communication between socially-behaving road users by means of eye contact.
Social behaviour could sometimes overrule established traffic rules. This shift may lead to a reduced level of experienced safety. Shared Space pioneers expect that this will help to improve the actual safety levels, based on (reverse) risk compensation: road users will take more care when the traffic situation is perceived as unsafe. The most obvious way of reducing this perceived risk is reducing speed. The danger of a high subjective lack of safety is a decreasing acceptance of the road scheme, cumulating in an unintended lower use of the road.

Shared Space contrasts with Sustainable Safety, the inspiration for current Dutch traffic safety policy, in many ways, despite agreeing on the vulnerability and fallibility of road users and the importance of road design in influencing behaviour: Shared Space intends to replace rule-based behaviour with reason, while Sustainable Safety prefers automatic execution of traffic tasks. The former seeks only homogeneity in speed, not in modality, and uses lack of predictability as a tool to improve safety.

The theoretical study has led to a set of five requirements to a simulation model needed to optimally analyze Shared Space traffic: it should (1) be applicable to at least an intersection, (2) accommodate different modalities, including pedestrians, cyclists and motorised traffic, (3) represent roadspace and movements on it, (4) model the impact of the road environment and (5) contain a form of conscious decision-making, thus accommodating the potential deviation from established priority.

In scientific literature, a large number models can be found that were built with the intention of simulating a non-signalised intersection with heterogeneous traffic. Many diverging methodologies have been applied to model the interaction between road users, resulting in gap-acceptance models, cellular automata, conflict-point models, car-following models, social force models and a model based on utility-optimisation. Several models have been selected to be studied in more detail, having been classified by their level of detail, the simulated traffic decisions and their scale of application. They are compared using the five requirements established above.

Gap-acceptance methods have limited spatial representation and are, like conflict point methods, inflexible, but they do provide an explicit decision-making process. Cellular automata are fast, easy to adjust and open to heterogeneity, but do not incorporate the road environment. Car-following models seem to be valuable only for mid-block road sections. Utility-optimisation models tick all the right boxes, but they are particularly complex. Force models are almost as good, but they lack the explicit decision-making of utility-optimisation models. In particular, the single model specifically aimed at Shared Space is a force model (Anvari et al., 2012). It contains several “forces” that, combined, fully determine a road user's movements. As there is no deliberate traffic decision-making by the road user, it could pass for a model of any mixed-traffic intersection, without much impact of Shared Space.
In this thesis project, a new conceptual model is proposed. It emphasises the dynamic relation between two fundamental traffic processes, negotiation and movement. Negotiation between road users on the basis of their conflicting trajectories is supposed to result in accelerations for all. These accelerations determine the road users’ speeds and positions, using ordinary numerical kinematic equations. Road users of all modalities are supposed to be involved in the negotiation process, assuming sufficient communication to clarify intentions.

The conceptual model defines two behavioural variables for every road user: an initiative factor and a politeness factor. The initiative factor determines whether the road user, during negotiating, would like to take precedence even if it does not have priority. Initiative is grounded on a road user’s risk attitude, and is assumed to be required to overcome the tendency to solve a potential conflict by adhering to prescribed priority. The politeness factor impacts whether the road user will offer or accept that the other road user will proceed despite its not having priority. Politeness originates in the social component that the Shared Space approach assumes that exists in traffic interaction.

Road users are assumed to have fixed paths consisting of a number of curve points connected by line elements. The paths are defined to be conflicting if any pair of curve points of different road users is uncomfortably close. In the negotiation process, these path conflicts form an input to calculating if two preferred trajectories have a potential conflict within a certain time horizon. If so, both road users can have alternative acceleration patterns, leading to alternative trajectories, which can also be tested for potential conflicts. The influence of the two behavioural variables initiative and politeness lies in the range and sequence of possible acceleration patterns that a pair of conflicting road users is prepared to consider. If one road user is already in the conflict zone, fewer acceleration options need to be tested.

The model is implemented as the simulation model blink, using Matlab, which is available, suitable and easy to learn, as the programming environment. The program has a graphical user interface (GUI). The program uses a combination of programming paradigms: it is both object-oriented, as it consists of instances of various classes that communicate with one another, and procedural, since the objects perform calculations for all road users at once (communication between objects in Matlab is slow).

The simulation program has different categories of input variables: (1) non-internal variables, which are all user-defined, such as road dimensions, traffic-behavioural characteristics and simulation variables, (2) internal variables, such as modality-specific physical dimensions and kinematic characteristics of road users and (3) simulation control variables (speed and refresh period). Non-internal input variables can be adjusted either through the GUI or by a text file. Any value calculated by the model can be considered output. The most important output variables may be trajectories and
speeds of the road users. Output data are visualised by the GUI, but can also be extracted as a MAT-file.

The program consists of a number of processes, which are run either every simulation run or every timestep. The first process is the initialisation of the road environment. In the simulation model, this is always a four-arm intersection with either a priority road or priority from the right. The position of road users on this intersection impacts their preferred speed level. The next processes are the calculation of speeds and positions of the present road users and the removal of road users who have arrived at their destination. After that, we come to the generation of road users on the basis of a random arrival pattern. It considers the arrival of platoons or groups of road users, rather than individual road users. The process also gives every road user an individual path, based on a Bézier curve, and searches for all conflicts of this path with the paths of others. During the negotiation process, the simulation program determines new accelerations on the basis of searching foreseen conflicts for various trajectories. The final process is the visualisation of the movements in the GUI.

The model’s validity has been analyzed on the basis of simulations of eight traffic configurations. Each configuration consists of another traffic flow or combination of traffic flows, ranging from a single flow of cyclists to a continuous series of priority conflicts involving lorries and pedestrians. Three aspects, related to the interaction between road users, have been taken into account: following behaviour, conflict handling and the impact of the variables initiative and politeness.

For all three studied aspects, the simulation results are largely as expected for moderate traffic demand. Most following conflicts are solved realistically at moderate levels of intensity, with an occasional overreaction. The observed relation between traffic intensity and average speed is plausible up to road capacity. The capability of the model to facilitate overtaking is limited. The simulations provide realistic ratios of precedence for priority and non-priority traffic. Most priority conflicts are solved adequately. Road users are quick to decelerate in case of a conflict, but also eager to accelerate if possible. The model does not show the impact of road users negotiating as a collective. An adjustment of the levels of initiative and politeness has an impact on the ratio of precedences for the priority and non-priority traffic flows, reducing the dominance of priority rules in determining which road user goes first, which is in line with the Shared Space approach. On the whole, the model’s face validity seems sufficiently warranted for use in this thesis.

The simulation model is applied to determine the impact of the shares of initiative and politeness on some indicators for an intersection’s performance and safety. Various simulations have been run with changing behavioural variables. Four cases have been defined, each with alternative percentages of the road user population inclined to take initiative or be polite. There are two extreme cases: one in which
no one is taking initiative or being polite and one in which every road user is doing so. Another case sets all the percentages at 50 percent, yet another case varies by modality: motorised traffic is relatively polite, slow traffic is taking initiative more often. All other variables have been kept constant. The studied output variables are the average speed and the Time Exposed to critical TTC (TET) value.

The output results of the case application give no indication that increased initiative and politeness would lead to a higher average speed or a lower TET value. This would suggest that the process of resolving potential conflicts remains a zero-sum game in terms of travel speed, but also that safety would not be significantly impacted. Other statistical tests suggest a significant correlation between being inclined to take initiative and experiencing a higher average speed and a lower TET value. For the behavioural variable of politeness, such a both logical and significant correlation could not be found. Obviously, these observations all need to be taken with the caveat that they are based on a specific set of traffic intensities and finite samples of output variables.

The Shared Space approach can be modelled as a concept and implemented as a simulation program for heterogeneous traffic on a generic intersection. The pioneers of the Shared Space approach allege that it would have an impact on traffic performance and safety, but the model results do not back this up, since the approach seems to have an impact on a minority of traffic conflicts.

This thesis project poses a cautious argument in favour of modelling Shared Space traffic, rather than in favour of the Shared Space approach itself. It shows a way to represent some of Shared Space’s behavioural paradigms in a conceptual and a simulation model, which is needed for ex ante evaluation of a Shared Space scheme. Due to lack of data, the simulation program cannot be used to discard or accept the Shared Space approach for a particular traffic situation.

Various recommendations for further work can be formulated. Firstly, the model could be refined and extended, for example by replacing fixed paths by an iterative pathfinding process. Secondly, the model could be extended into a genuine agent-based model. In the current simulation, the road users themselves are no objects, due to limitations of Matlab. If they were, the negotiation process could also be made more sophisticated. A third recommendation for further work would be a calibration of the current model using actual traffic data. This could be succeeded by a more thorough validation process. The final potential follow-up to this thesis is the challenging of the fundamentals of Shared Space, such as with respect to communication, subjective safety and the impact of the road environment. Answering questions about these topics is important policy-wise as it helps to determine for which situations Shared Space will be effective in improving traffic performance and safety.
1 Introduction

In this chapter, we start with a short description of the problem at hand and define a research objective. Research questions for this master thesis project will be established, as well as a description on the methodology used. The chapter ends with an outline of the report’s structure.

1.1 Problem definition and project objective

Over the last decades, national traffic safety policy in the Netherlands has led to a large reduction in road casualties. It becomes increasingly more difficult to reduce these numbers even further. Not only do safety measures sometimes tend to reduce spatial quality, they may also lead to significant risk compensation behaviour that diminishes the intended safety gains, often at the expense of the safety of the most vulnerable road users.

Over twenty years ago, traffic engineer Hans Monderman started working on what is known now as the “Shared Space” approach. Determined to improve road safety in a couple of Frisian villages, he designed new road lay-outs that reduced rather than increased the amount of signs and signals, while trying to match the design of the street with its environment. The approach was successful in reducing speeds and casualty numbers. Monderman was also involved in urban Shared Space schemes in Drachten and Haren. Other towns in the Netherlands have followed, such as Tiel and Haarlem. Through international governmental cooperation, the approach has also been introduced in countries such as Denmark and the United Kingdom.

Shared Space is somewhat unique in triggering low-speed but not completely predictable interactions between road users, leading to a sense of disorientation. It is assumed that road users experiencing a subjective lack of safety will be very careful. Thus, objective traffic safety is supposed to be enhanced. This contrasts with the current Dutch “Sustainable Safety” policy which focuses on predictability and homogeneity. This may be the reason why the scope of Shared Space traffic schemes has been largely limited to smaller towns in the north of the Netherlands.

The objective of this research project is to analyze the behaviour that, in the Shared Space approach, road users are assumed to exhibit when moving in a traffic space designed according to Shared Space principles and to determine the impact of this type of behaviour on traffic performance and safety, isolated from location-specific elements.
1.2 Research question

The main research question in this master thesis project is:

How does the Shared Space approach perceive road users to behave on a non-signalised intersection and how would that impact traffic performance and safety?

This research question can be divided in various sub-questions:

1. What are the traffic-behavioural hypotheses underlying the Shared Space approach?

2. Which methods, presented in scientific literature, have been applied to model non-signalised traffic intersections and what is their use with respect to the Shared Space approach?

3. How can we model generic traffic in a road environment based on Shared Space?

4. What are relevant output variables for analyzing the impact on traffic performance and safety of behaviour assumed under Shared Space conditions?

5. How does traffic behaviour under Shared Space affect these output variables?

1.3 Methodology

We aim at gaining insight into traffic behaviour under the conditions set within the Shared Space approach and more generally into the character of non-signalised mixed traffic flow, through the development of a traffic flow model. The preparations to formulate and implement this model, as well as the application of it, are an essential part of the research process. The research project will be carried out in eight steps. These are:

1. Defining the problem
2. Studying the Shared Space philosophy and defining its main hypotheses
3. Researching and evaluating current traffic flow modelling approaches
4. Formulating a traffic flow model
5. Implementing the model
6. Analyzing the validity of the model
7. Applying the model to a specific case
8. Deriving conclusions

Step 1 has led to the writing of the original research proposal, which has been reworked for the first chapter of this report. The steps 2 and 3 are important building blocks for setting up a traffic flow model. Step 2 concerns the theoretical foundations of Shared Space, that we are going to analyze through building the model. Step 3 consists of making an inventory of existing traffic flow models presented in literature that may give useful insights for our own model.

Step 4 is the actual formulation of the model. A set of mathematical algorithms will be developed, which together form a model describing the interactions between road users and their environment and between one another. These algorithms will be partly derived from traffic flow models that were studied during step 3. In step 5, these algorithms will be implemented in a set of Matlab scripts.

Step 6 consists of an analysis of the model’s behaviour for various traffic situations, in order to judge its face validity. This may also tell us more about the wider applicability of the Shared Space approach. After that, step 7 provides a generic case study using the model’s implementation, resulting in quantitative answers on non-signalised traffic. During step 8, we answer the research questions defined in section 1.2, and formulate conclusions and recommendations with respect to road design and traffic safety policy as well as future development of the traffic flow model.

1.4 Report structure

The structure of this report closely resembles the eight steps defined in the previous section. Chapter 2 deals with Shared Space and its hypotheses. Chapter 3 then continues with state-of-the-art traffic flow models in literature, most often either concerning mixed or non-signalised traffic flow (while we are aiming at combining these two characteristics). In chapter 4, the results from these two chapters are applied, by establishing a new conceptual traffic model. In chapter 5, this model is implemented in Matlab. Chapter 6 deals with the model’s face validity, while chapter 7 is about a generic case study. After that, the research questions will be answered and conclusions will be derived, both in chapter 8.
2 Shared Space theory

The Shared Space approach is a relatively recent innovation, and therefore cannot boast a large body of academic research dedicated to its foundations and effects. Most sources publicly available are either policy documents or articles in popular magazines. Over the past years, the approach has been applied under various traffic conditions, widening its theoretical basis. It remains a difficult issue to describe how the interaction between road users is perceived in the Shared Space approach.

In this chapter, the principles of Shared Space are laid out and related to traffic behaviour. Firstly, the Shared Space approach is presented as a design process. After that, the specific topics of social behaviour and risk attitude are connected with Shared Space. The next section compares the Shared Space approach with the Sustainable Safety approach. The chapter concludes with a set of requirements to the traffic flow model that is needed to analyze Shared Space traffic behaviour.

2.1 Shared Space as a design process

Shared Space is a road design process, rather than a specific set of design guidelines (Reid et al., 2009). It stretches the importance for the government of forming a strong vision about its road network but also of consulting inhabitants and other stakeholders (Fryslan, 2005). The vision serves to determine which roads and intersections will have traffic as the dominant function and which locations will be considered to be transformed into a more public space. Part of the Shared Space approach is that in such a public space, all spatial functions, such as shopping, meeting and resting, are treated as equals. During the subsequent design process, carried out by a holistic design team, a functional design will be made. Finally, this design is implemented with particular attention for materials and street objects. It is assumed that this multidisciplinary approach leads to spatial quality (a pleasant public space) and democratic quality (commitment and involvement of all stakeholders).

The consequence of considering an intersection as a public space is that the organisation of traffic control (signs and signals) as well as the traffic behaviour itself must be such that other functions are not severely restricted. This means that communication to road users on how to behave is bound to certain conditions. It cannot take much road space and it should fit visually and mentally with the road surroundings. Traffic signals, but especially the queues that accompany them, typically take too much space to fit in a multifunctional public space. That is why, in many Shared Space schemes, much of the motorised traffic that used the intersection may need to be diverted to other routes, since the new road
design may not be able to handle that amount of traffic, or only with significant hindrance to other, mainly recreational, spatial functions.

Without traffic signals or other drastic traffic control measures possible, the burden of imposing certain traffic behaviour upon the road users comes down to the quality of the road design. This is illustrated by Figure 2.1. It is the role of the multidisciplinary design team to create a road environment that helps to enforce appropriate traffic behaviour. Such an environment can be partially created by road design (road width and pavement types), but also by other factors, such as historical and social context of the public space. These factors are often hard to grasp for traffic engineers, but the Shared Space approach often puts much effort in applying them. Also, the emphasis on the location-specific design frequently leads to alterations to the road environment during its use, for example to protect pedestrians or discourage on-street parking. This shows the essence of observing the behaviour of road users after implementation to see if the design functions as expected.

### 2.2 Social behaviour

The Shared Space approach also offers strong statements about the type of behaviour that should be encouraged or could even be expected on intersections designed with its proposed process. Fryslan (2005) makes a distinction between three types of traffic behaviour:

1. **Social or public behaviour**, consisting of unfocused, unpredictable and relatively slow movements, which are guided by people's feelings at that particular time, without a clear predetermined programme

---

*Figure 2.1 Relations between road system elements relevant for Shared Space*
2. (Regular) traffic behaviour, which is focused, predictable, fast and programmed
3. Social traffic behaviour, a combination of the first two types of behaviour.

These types are supposed to be observed in the corresponding parts of the traffic system: social behaviour in the public realm, traffic behaviour on the highway and social traffic behaviour in the transitional zones. This distinction of different categories in behaviour by road users seems artificial and without evidence. It is a definition of what the Shared Space pioneers consider to be social behaviour, rather than an observation of actual behaviour of people in public spaces. Pedestrians in a railway station running for a train are definitely focused, even though they are in a public space.

Fryslan (2005) signals the confusions between road users that may arise under the banner of social traffic behaviour. Road users could expect different types of behaviour from one another based on their own persona, motive for travelling or interpretation of the road environment. This is surprising since some of the Shared Space schemes, for example in Drachten, focus on this dangerous intermediate zone between traffic space and public space. The use of the Shared Space approach probably has more to do with using a perceived lack of safety to enforce safe behaviour, as explained in the next section.

The Shared Space approach also claims that the interaction between road users to solve potential conflicts happens by means of eye contact. To make that possible, speeds are supposed to be very low, that is below 30 km/h. On the other hand, Reid et al. (2009) write that there are no convincing data that the majority of road users make eye contact at all. The authors assume that car drivers react on the pedestrians' behaviour rather than direct communication.

### 2.3 Risk attitude

Shared Space aims at creating social behaviour of road users, replacing and adding to rules and regulations established by the local government. This shift in regulation may lead to a reduced level of experienced safety. The Shared Space pioneers expect that this will help to improve the actual safety levels, based on (reverse) risk compensation. Risk compensation occurs when road users, experiencing a safer traffic situation, start performing more risky behaviour. Thus, the effect of safety-improving measures may be reduced. In the case of reverse risk compensation, it is expected that road users will take more care when the traffic situation is perceived as unsafe. The most obvious way of reducing this perceived risk is reducing speed. Then, a road user has more time, if necessary, to react to potential conflicts. One could say that lowering the experienced level of safety is a way to artificially increase the mental load of a road user to a level where it needs to slow down to feel sufficiently safe again.
In the Shared Space approach, risk compensation is assumed to be a part of the mechanism to make road users perform safer behaviour. As such, it is not the objective of a Shared Space scheme to reduce subjective safety, but accepted as a means to influence behaviour. One could even argue that the transparency of Shared Space reflects objective safety levels better than overregulated traffic spaces that seem safer than they are in reality.

Some scientists suggest that the level of risk that road users are willing to take will not change by means of safety measures or law enforcement (Wilde et al., 2002). This is called risk homeostasis. It is suggested that, in order to make traffic safer, (financial) incentives should be offered to crash-free drivers. This would lead to their “resetting their risk thermostats”. Risk homeostasis theory and its evidence are subject to strong discussion. In that light, the Shared Space approach does seem to try to influence the road users’ risk thermostat by appealing to the social feelings of humans towards one another, thus breaking the conventions of the neutral road environment.

The danger of a high subjective lack of safety is a decreasing acceptance of the road scheme, cumulating in an unintended lower use of the road. This is undesirable from both a utilitarian and an ethical point of view. It is not useful, because the positive impact intended by the road design is diminished. It is not ethical, because public spaces are only public when no citizen is excluded.

2.4 Relation with Sustainable Safety

The Sustainable Safety vision, introduced by the Dutch traffic safety institute SWOV, has been an inspiration for Dutch national traffic safety policy since the 1990s (Wegman & Aarts, 2006). This vision is used here as a foil to characterise the innovation in policy argued by the Shared Space approach. Attention will be paid to both the behaviour of road users and the design of infrastructure.

With respect to traffic behaviour, Sustainable Safety focuses on reducing traffic incidents, either due to a mistake or a conscious offence of traffic regulations. It presumes that the probability of dangerous behaviour is at the lowest level when traffic tasks are performed automatically. That means that safe behaviour should not be enforced on the basis of reason or rules, but by a road environment that stimulates road users to perform the expected, safe behaviour. It appears that the Shared Space approach is equally unsatisfied with rule-based behaviour but instead considers the use of reason in the performance of traffic tasks as an alternative. The Sustainable Safety vision considers this alternative to be particularly prone to errors as well, with relatively severe consequences.
Although the road designs resulting from applying either of the two approaches may differ, the assumptions underlying them are similar to a large extent. Both assume the road design to be of great importance in influencing the road users’ behaviour. Also, both recognise the vulnerabilities and fallibilities of humans. Nevertheless, more than Sustainable Safety, Shared Space expects road users, despite their flaws, to behave in a constructive manner as well.

The five principles of the (revised) Sustainable Safety policy are functionality, homogeneity, predictability, forgivingness and state awareness (Wegman & Aarts, 2006). We shall define each of these five, and describe how they relate to the design philosophy of the Shared Space approach.

The principle of functionality is reflected in the requirement that every road has a single function, being part of a hierarchical road network of connection, distribution and access roads. The original small-scale Shared Space approach, applied in small villages and on former through roads, was mainly meant for access roads. Now that it is also used for more intensively used roads and intersections, which could be described as distributive, there is a danger that the hierarchy in the road network does not match with the expected behaviour of road users. It is remarkable that the original idea of Shared Space to separate social behaviour and traffic behaviour seems to have been relinquished, as this is the most important element for which it differs from sustainable safety.

Homogeneity is defined as equality in speed, direction and mass of vehicles, in particular at medium and high speeds. At low speed, which is the main domain of Shared Space, this principle can be interpreted in another way. Because the speeds are low, direction and mass of vehicles do not have to be harmonised. If Shared Space is capable to lower speeds for mixed traffic effectively, this would match with Sustainable Safety without a problem.

The principle of predictability concerns the consistency and continuity of the road design, which in turn should also lead to predictable behaviour of road users. The relation of this principle to Shared Space depends on what can be understood as predictable. The design of a Shared Space intersection would lead to social behaviour. That is in itself a good prediction. At the operational level, it does not predict traffic behaviour that well, simply because the lack of predictability is part of the philosophy.

Forgivingness stands for the prevention or limitation of injury in case of conflicts or mistakes. This implies both a forgiving physical road environment and forgiving social behaviour, especially anticipation of one another’s behaviour. Houtenbos (2009) defines social forgivingness as:
The willingness to anticipate on potentially unsafe actions of another road user and to act in such a way that negative consequences of a potentially unsafe action are prevented or at least limited.

She also argues that, due to the removal of road elements such as signs and markings, Shared Space offers more “interaction space” to road users. This would enhance forgiving behaviour and would improve safety.

The principle of state awareness reflects the importance of road users being able to judge their own capability to participate in road traffic, particularly with respect to their (driving) experience or current state of mind (alcohol, drugs, fatigue). Shared Space adds the ability to judge the capability and attitude of other road users as an important factor.

2.5 Model requirements

This theory chapter concludes with establishing a set of requirements to a traffic flow model needed to analyze Shared Space traffic. These requirements are based on the description of the Shared Space approach in this chapter. They reflect the road environment, traffic configurations and traffic processes that need to be incorporated. The choice for these particular requirements is based on three criteria:

- They are requirements to simulation models, rather than to their underlying modelling concepts. Any conceptual model could be applicable to Shared Space as long as it does not prevent the derived simulation model from fulfilling the requirements. If it does, the proposed modelling concepts are not in accordance with the Shared Space approach.
- Secondly, they are restricted to evaluating modelling choices, rather than simulation output. For example, it is more important to know that the model allows for varying speeds than to see that the speeds do not vary that much. That is because, in this phase of the research, the study of the capabilities and limitations of the modelling concepts is the first priority.
- Together, they must, as much as possible, constitute a full range of mutually independent modelling choices, meaning that all kinds of combinations of scores for these requirements are feasible. This will show the differences between the models as clear as possible.

Traffic situation

Shared Space, as a design philosophy, can be applied to mid-block road sections as well as to intersections. These two traffic situations have a diverging modelling focus. On mid-block road sections, the only possible conflicts between road users are longitudinal (maybe save pedestrian crossings). On intersections, the focus is more on lateral conflicts, often regulated by a form of traffic
control. One can argue that Shared Space is mostly concerned with influencing traffic control, i.e. the application of priority rules. Consequently, this results in the model requirement that the model should be applicable to intersections. This does not mean that all models dealing with longitudinal conflicts are discarded as irrelevant, since longitudinal conflicts can occur on intersections as well. It does mean though that the model to which this thesis project leads needs to cover an intersection.

Different modalities
One of the main issues of the Shared Space approach is that road users of all modalities are accommodated by the traffic system. Although Shared Space argues for a system of main roads, unsuitable for slow and local vehicular traffic as well, traffic heterogeneity is seen as a pronounced characteristic of the Shared Space approach. In terms of a model requirement, this obviously leads to the demand for mixed traffic flows. In the case of the Netherlands, this would mean the inclusion of pedestrians, cyclists and car users at minimum, since they form the bulk of the traffic flows. Lorries and buses could be added as well, because, despite their smaller flows, their conflicts with other road users can have a great impact due to their different size and acceleration properties.

Representation of space
Under Shared Space road design, road users often move quite close to one another. In most of its schemes, there are no lanes for individual road users. Compared with conventional traffic, it is thus more important to describe the positions and movements of road users in detail, in particular laterally. The ambiguity of priority rules only adds to that, since the relative positions of road users will more often determine who goes first. This leads to the model requirement that both the roadspace and the movements on it are represented realistically. This can be either continuous or discrete. This requirement leads to the disqualification of models that represent an entire intersection as one queue.

Impact of road environment
An assumption of the Shared Space approach is that the behaviour of road users can be influenced by the road environment. On itself, that is a trivial statement. What is meant here is that social behaviour of road users towards one another can be enforced by the furnishing of the roadspace as a public space. For example, road users will reduce speed if they have to drive past a terrace full of people, some of which they may be acquainted with. Obviously, this could be modelled in diverging ways. Still, it can be seen as a requirement to the model that, in some way, the road environment is accommodated to play a role in traffic decisions. Ceteris paribus, a traffic decision could have a different outcome depending only on the road user’s position within the roadspace.
Decision-making process

Compared to conventional traffic safety policy, the Shared Space approach sees conscious decision-making by road users with respect to their interaction as advantageous, rather than as sub-optimally safe. It argues that road users should have the freedom to give and take priority on the basis of factors such as the weather and the perceived vulnerability of pedestrians. Rather than adhering to prescribed traffic rules, road users should be able to decide on their own more often. (How this conscious behaviour really works is not made clear at all.) As a model requirement, this means that the decision-making process, for example with respect to their acceleration or direction of movement, should be made explicit as much as possible, so that differences between road users in their decisions can be introduced easily. This may include a clear distinction between determining the physical options of the road user and deciding which option would be preferred. In any case, the model must show that road users make deliberate decisions during their movement, because that is when the difference between road users with respect to social behaviour and risk assessment comes to the front.
3 State-of-the-art in traffic flow modelling

In this chapter, a number of traffic flow simulation models from literature are studied, to give a general overview of the state of the art in relevant simulation modelling as well as to serve as valuable input for a new model for traffic under Shared Space conditions. In the first section, it is explained how relevant and educational models have been selected. The second section introduces the selected models and discusses their methodologies. In the third section, the models are compared with one another on the basis of criteria related to Shared Space traffic. These criteria have been derived at the end of chapter 2. The chapter concludes with determining whether a new traffic model is needed.

3.1 Classification of traffic flow models

There is an almost infinite amount of traffic flow models available, in all kinds and sizes and with all kinds of objectives and motives in mind. This pack of models needs to be structured according to certain characteristics in order to select those that are relevant and educational to this research. Various different classifications have been proposed, three of which are explained here. These three are chosen for two reasons. Firstly, these classifications are commonly used in scientific articles. Every author describes his model using these terms, thus facilitating its use for classification. Other classifications may require information that is not included in the model descriptions, which are often quite concise. Secondly, these classifications provide a framework for determining which models can be expected to have sufficient affinity to traffic in a Shared Space to warrant closer investigation.

One important classification is according to the level of detail, proposed by, amongst others, Hoogendoorn & Bovy (2001). They propose a distinction between (sub)microscopic, mesoscopic and macroscopic (vehicular) traffic flow models. In microscopic models, the individual road users and their interaction are studied. In contrast, macroscopic models describe models as an aggregate flow. Mesoscopic models are a combination of the two, determining the behaviour of individual road users on the basis of aggregate relationships. Submicroscopic models are described as an extension of microscopic models by including control behaviour and sub-part functioning of the vehicle in its focus.

Daamen (2004) splits the classification of the level of detail into two: traffic representation (individual road users or aggregate traffic flow) and the type of behavioural rules (individual or collective). She has found existing (pedestrian) models for all four property combinations, three of which seem to closely resemble microscopic, mesoscopic and macroscopic models.
A second way to classify models is by determining which choices made by road users are studied. Hoogendoorn & Bovy (2004) distinguish three levels of choices (originally for pedestrians): *strategic* (departure time and activity pattern), *tactical* (activity scheduling, activity area and route) and *operational* (walking behaviour). A final way to classify models is according to its scale of application (Hoogendoorn & Bovy, 2001), i.e. the physical dimensions of the traffic situation that is included in the model, ranging from an intersection or a stretch of road to an entire city.

These classifications are now used to define which models to take into account and which not:

- **Level of detail**: in the Shared Space approach, road users are perceived as individuals with their own characteristics and decision-making. That is why the search is limited to models in which the traffic flow consists of individual road users, whose behaviour is determined individually. This means that the search is limited to (sub)microscopic models.

- **Level of choices**: it is clear that Shared Space may have an impact on all of the three choice levels. In this thesis, the focus is on the interaction between individual road users, which is the most pronounced at the operational level. Therefore it is essential that the selected models incorporate operational choices. Whether actical and strategic choices are also included is of minor importance and is not used to select or discard a model.

- **Scale of application**: generally, the Shared Space approach does not define its scale of design, but it is limited to (semi-)public spaces. The operational choices that are studied play out mostly at the level of a single intersection or stretch of road. Thus models with this limited scale of application are preferred. Larger-scale models will be discarded when it is clear that the large scale leads to too simple behavioural assumptions at the level of a single intersection. These classifications are not fully independent of one another, so, more often than not, if a model cannot pass the first requirement, it would also fail to meet one or both of the other criteria.

To limit the number of models even further (to those being actually relevant, rather than expected to be relevant), additional conditions are applied. In order to be considered relevant in this project, a traffic flow model must at least partly reflect traffic conditions associated with Shared Space. That is why a model should account for at least one of these two basic traffic characteristics:

- Heterogeneity within the population of road users, in terms of behaviour (risk attitude, priority choices) or with respect to variety in modalities (for example various vehicle types).
- Free movement for at least one modality; that is, not bound to a particular route or zone within the total space available for traffic.

These conditions are chosen because they can be seen as the two most important factors why traffic under Shared Space conditions is relatively unpredictable compared with conventional traffic (such as
when using traffic signals). Therefore, the ability of a model to represent this unpredictability is a good indicator for its ability to represent Shared Space traffic conditions and its value in this study.

Obviously, in case of the model representing an intersection, it should always provide the opportunity to simulate non-signalised traffic interaction. Traffic signals do not suit Shared Space, because they take too much space and prevent most of the sought-after social interaction between conflicting flows.

### 3.2 Selected models

The selection process has resulted in a group of 17 traffic flow models described in scientific journals between 1995 and 2012 that fulfill our selection criteria. Generally, they have been found with Google Scholar, using keywords such as “mixed traffic” and “unsignalised intersection”, and by looking for other articles in the references of the articles already found. The article of Anvari et al. (2012) has been found by a specific search using the main author’s name, since I have spoken to her in person. This and several other models have been studied after the simulations for this thesis project were finished, but this does not impact the outcome of this state-of-the-art chapter. It should also be noted that several articles that appeared to be interesting could not be studied, due to having no access to the journal.

To have a clear overview of all the relevant models, they are classified according to their type of modelling approach to the interaction between road users, in order of ascending complexity. Most models share their approach with several other models, thus they are presented simultaneously. The distinguished approaches are gap-acceptance, cellular automaton, conflict points, car-following, social forces and utility-optimisation. The classification of the models into these different approaches is not conventional and may show some overlap between approaches. It is mainly based upon common sense and upon close reading of the model descriptions, in order to provide as much insight as possible into the similarities and differences between the models.

The availability of modelling approaches is also an issue. This collection is not an exhaustive list of all possible approaches, but it comprises a good variety of them. There are two possible reasons for other approaches being left out. The first one is their failure to pass the requirements of the previous section. Another reason can be that no recent literature about them could be found.

**Gap-acceptance model**

The first model is by Kaysi & Alam (2000) and determines traffic behaviour at non-signalised intersections by means of a gap-acceptance approach. This means that a road user on a minor road
needs a sufficiently long time period between vehicles on the main road to cross. The authors acknowledge the weaknesses of this method and try to improve it, mainly by differentiating between drivers on the basis of their risk attitude. In addition, they account for a learning effect in the sense that yielding drivers, while waiting, become better at estimating the time gap required for crossing.

Cellular automata

The three models by Ruskin & Wang (2002), Liu et al. (2005) and Thanh & Hoai (2010) also use gap-acceptance methods, but based on a minimum required distance. That is because all three are cellular automata (CA). This type of models contain a set of general rules of behaviour, stating in logical terms which cells of a grid, representing the road space, are occupied by a road user. The interaction between road users basically contains of waiting for a gap in the conflicting flow of a sufficient number of cells. The first two models differentiate between road users in terms of risk attitude. Thanh & Hoai (2010) take the heterogeneity one step further by including multiple modalities.

Vasic & Ruskin (2011) have also developed a CA for heterogeneous traffic. Their main innovation is the use of different cell shapes for turning traffic, rather than the conventional rectangular grid. This requires the model to remember conflicting cells and determine a certain distance before that point at which the road user becomes aware of the possibility of a conflict and may need to decelerate.

Another CA model is proposed by Lan et al. (2010): an alternative traffic flow model for mixed traffic, focusing on erratic driving behaviour of motorcycles. Unfortunately, the model cannot handle traffic on intersections. The authors use the model to derive fundamental diagrams for mixed traffic.

Conflict-point models

Two models (Trinadha Rao & Rengaraju (1997, 1998) and Wang et al. (2009)) have been found that propose to represent interaction between road users on an intersection as a chain of conflict points. Compared with gap acceptance, there is no requirement for a preset priority rule. Each time there are at least two vehicles in conflict, a formula is used to calculate which vehicle would be given way in a real traffic situation (for example first come, first served).

The two models differ with respect to the spatial representation of driving patterns. Trinadha Rao & Rengaraju (1997,1998) use fixed trajectories for each particular route on an intersection, making it easy to predict potential conflicts. In their model, conflicting vehicles cannot enter the intersection at the same time. Wang et al. (2009) have defined each route on an intersection as a sequential occupation of points. Thus, conflicting vehicles can move on an intersection simultaneously as long as they do not occupy the same point.
The conflict point approach has also been used in various models aimed at calculating the capacity of a non-signalised intersection. Taking a totally analytical approach, they calculate the probability of road users arriving at a conflict point (almost) simultaneously and the subsequent delay. From this, a theoretical capacity is derived. A good example of this is by Prasetijo & Ahmad (2012). This model is not used for the comparison in the next section, because it is not microscopic.

Car-following models

The models of Oketch (2000), Cho & Wu (2004) and Arasan & Koshy (2005) use another distinctive approach. These three models all originate in car-following models, and are only applicable for mid-block road sections. Basically, all vehicles that are not in free flow adjust their driving behaviour to the vehicle ahead, in order to keep a safe headway. In theory, car-following models can be used with all kinds of vehicles. Two out of these three do facilitate variety in vehicle and behaviour characteristics, the model of Cho & Wu (2004) is limited to a motorcycle flow. To a varying extent, algorithms that simulate the decision to overtake the leading vehicle have been incorporated into the models; in particular into that of Oketch (2000), which uses fuzzy logic methods to evaluate options.

Social force models

The next approach for modelling interaction between road users can be found in social force models, in which the movements of either pedestrians or vehicles are directed by forces exercised upon them by other road users or physical objects. The resulting force vector determines the direction and magnitude of acceleration. A revolutionary model within this group is that of Helbing and Molnár (1995), which in itself is a spatial representation of Lewin’s concept of social fields (which seeks to explain group dynamics). It is a pedestrians-only model that, although described as ‘simple’ by the authors, demonstrates complex spatiotemporal patterns such as lane formation. In Helbing et al. (2001), this model was explored further with respect to such features of self-organisation, including trail formation in rough terrain.

In their model, Wang & Wu (2003) take the concept of force vectors to mixed traffic flow. This flow is divided in motorised, non-motorised and pedestrian traffic. These sub-flows have limited interaction. Within each lane, there is an elaborate set of mathematical formulas for calculating accelerations. Xie et al. (2009) have basically done the same thing, but for a non-signalised intersection. Their article contains an extensive sensitivity analysis for a share of the variables used in their formulas.

Huang & Wu (2008) have built a traffic model that claims to incorporate all the important choices that a road user makes, including operational choices. The model part for the operational side is based upon the social forces model as well. It seems to be suitable for all kinds of intersections. An additional
article (2008b) elaborates upon the path planning of cyclists. This process is translated into a combination of a fuzzy logic control algorithm, which judges potential paths on the basis of its hazards, efficiency, comfort directness, and a social forces model for the actual acceleration decision. The model in this additional article is not included in the next section, because it seems to be incomplete.

The only model in this comparison specifically built for simulating Shared Space traffic is by Anvari (2012). She applies a social force model, containing a driving force, an interaction force and a socio-repulsive force. The latter force represents the extra distance that pedestrians keep from cars, even if no physical contact is to be expected. For other situations, the interaction force keeps road users apart realistically already. The driving force depends on a distance potential field that gives the direction of the shortest distance to the desired position. Surprisingly, the model does not seem to show much impact from the Shared Space approach. It could pass for a model of any mixed-traffic intersection.

Utility-optimisation model
The final selected model is Nomad, a pedestrian model by Hoogendoorn (2001). Its approach is based on utility-optimisation, meaning that individual road users are expected to move such that their destination is reached under a minimum of discomfort. The model not only simulates operational walking behaviour, but also activity scheduling and route choice. Many of the concepts used in force models can also be found in this utility-optimisation model. For example, the avoidance of each other by means of repulsive vectors is a close resemblance. The two modelling approaches have subtly different ways of optimizing their acceleration level and direction. While a social force model finds a directing force as the sum of all forces, a utility-optimisation approach tries to find the acceleration for which the utility of the road user is the highest.

3.3 Comparison of models

In this section, the models are compared on the basis of criteria that reflect the specific features of Shared Space traffic. These criteria have been introduced in chapter 2. First, the possible outcomes for these criteria are discussed. This is followed by the table of scores itself and an analysis of the results. Whether or not a model proves of use for this research does not mean that it is a bad model. It may suit its purpose as intended by the authors very well.
### 3.3.1 Criteria and possible scores

In this sub-section, the criteria and possible scores are stated. Also, the preferred and acceptable scores (with respect to optimally modelling traffic as perceived by Shared Space) are explained.

**Criterion 1 Traffic situation**

The easiest criterion to identify in a model is the traffic situation. There are three possible scores: intersection, mid-block (parallel flow, no crossing traffic) and both. In chapter 2, it has already been stated that the model should at least be applicable to an intersection, because the ambiguity in traffic rules that Shared Space promotes mainly concerns crossing traffic flows. Therefore the scores intersection and both are acceptable (the other models can still be instructive examples). The fact that a model has the score both suggests that the authors of the model have used a flexible mathematical formulation that could be developed further. This would be the preferred result for this criterion.

**Criterion 2 Different modalities**

This criterion deals with the extent to which different modalities can be included. In theory, the possible scores are all combinations of all possible combinations of all possible modalities. In practice, there are models that include a single mode (pedestrians, cars, motorcycles), only vehicles or all modalities. The last score means that pedestrians, cyclists and car drivers are included. In Shared Space, all types of vehicles, both motorised and non-motorised (bicycles), as well as pedestrians, are accommodated. This implies that all modalities is the preferred score for this criterion.

**Criterion 3 Representation of space**

The model should represent positions and movements realistically. Various ways of modelling them can be found in literature, ranging from no spatial representation at all to a continuous two-dimensional plane. Between these two extremes, there are a number of discrete options: square cells, cells of variable size, conflict points and longitudinal strips. Another option is to establish fixed trajectories. The desired result for the detailed analysis of Shared Space would be a continuous two-dimensional plane representation. The discrete options are acceptable on the condition that the elements are not so large that the representation becomes too coarse. The option of fixed trajectories can be identified as one-dimensional continuous, which would be partially realistic. The only unacceptable option is no spatial representation at all, since this clearly does not fulfill the stated requirement.

**Criterion 4 Impact of road environment**

It has already been argued that in Shared Space, the relation between the road and its environment is very important with respect to the expected traffic behaviour. It is very difficult to model, and it would
be good to know if existing models are able to capture this relation in some way, for example by defining social areas (with more social traffic behaviour) or by distinguishing attractive and repulsive road boundaries. The possible scores for this requirement are yes and no. Obviously, the preferred score would be yes. The fact that the studied relation is, although important, quite poorly defined within the Shared Space approach means that scoring a no cannot be particularly disqualifying.

Criterion 5 Explicit decision-making process

For this final criterion, the main issue is whether the models are capable of simulating decision-making processes (such as route choice) such that we can separate mental processes from physical restrictions. Often, model algorithms integrate these into one set of behavioural formulas. Instead, it would be better to have a model in which the choices of road users have been made explicit. The possible scores for this criterion are simply yes and no, and the preferred score would be yes.

3.3.2 Scored comparison

Below, the scores of the seventeen models with respect to the five criteria have been put together.

Table 3.1 Scored comparison of existing traffic flow models

<table>
<thead>
<tr>
<th>Method</th>
<th>Authors</th>
<th>Situation</th>
<th>Modalities</th>
<th>Space</th>
<th>Environment</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap</td>
<td>Kaysi &amp; Alam (2000)</td>
<td>int</td>
<td>car</td>
<td>non</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>ca</td>
<td>Ruskin &amp; Wang (2002)</td>
<td>int</td>
<td>car</td>
<td>cel</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>ca</td>
<td>Liu et al. (2005)</td>
<td>int</td>
<td>veh</td>
<td>cel</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>ca</td>
<td>Thanh &amp; Hoai (2010)</td>
<td>both</td>
<td>veh</td>
<td>cel</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>ca</td>
<td>Vasic &amp; Ruskin (2011)</td>
<td>both</td>
<td>veh</td>
<td>vcl</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>ca</td>
<td>Lan et al. (2010)</td>
<td>mid</td>
<td>veh</td>
<td>cel</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>con</td>
<td>T. Rao &amp; Rengaraju (1997,98)</td>
<td>int</td>
<td>veh</td>
<td>trj</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>con</td>
<td>Wang et al. (2009)</td>
<td>int</td>
<td>all</td>
<td>pnt</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>cfm</td>
<td>Oketch (2000)</td>
<td>mid</td>
<td>veh</td>
<td>str</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>cfm</td>
<td>Cho &amp; Wu (2004)</td>
<td>mid</td>
<td>mot</td>
<td>pla</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>cfm</td>
<td>Arasan &amp; Koshy (2005)</td>
<td>mid</td>
<td>veh</td>
<td>pla</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>for</td>
<td>Helbing &amp; Molnár (1995)</td>
<td>both</td>
<td>ped</td>
<td>pla</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>for</td>
<td>Wang &amp; Wu (2003)</td>
<td>mid</td>
<td>all</td>
<td>pla</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>for</td>
<td>Xie et al. (2009)</td>
<td>int</td>
<td>veh</td>
<td>pla</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>for</td>
<td>Huang &amp; Wu (2008)</td>
<td>both</td>
<td>all</td>
<td>pla</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>for</td>
<td>Anvari et al. (2012)</td>
<td>both</td>
<td>all</td>
<td>pla</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>utl</td>
<td>Hoogendoorn (2001)</td>
<td>both</td>
<td>ped</td>
<td>pla</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
3.3.3 Analysis of comparison results

From a conceptual point of view, a gap-acceptance method is relatively inflexible. It can only be applied for intersecting vehicular traffic and has a limited spatial representation. Extension of the model towards inclusion of other traffic situations than yielding priority to main road traffic is impossible. On the upside, this decision-making process can be made explicit, and thus it can be formulated with quite some sophistication. In that sense, it is a primitive version of the decision-making process presumed in Shared Space conditions. Overall, models based on gap-acceptance methods seem to have very limited value for simulating Shared Space traffic.

Cellular automata are very promising with respect to Shared Space traffic, but the current models do not fulfill all the criteria, in particular the environment inclusion criterion. If this deficiency were solved, a CA model could be a very valuable tool: fast, easy to adjust, accepting heterogeneity and using logical rules for decisions. Note that the grid of cells must not be too coarse for the sake of pedestrians.

Conflict point methods, like the gap-acceptance method, have been applied to intersections only. In theory, they could be used for mid-block road sections, although that may not be so informative. Conflict point models can be used to include all modalities. Unfortunately, the interaction between these modalities is limited to determining who will occupy a certain area first. At the same time, the trajectories of all road users are fully prescribed and have no variation. Considering a lack of conceptual flexibility equal to that of gap-acceptance-based models, conflict point models are also not suitable for analyzing Shared Space.

Car-following models, in contrast to many of the other models, have a more refined way of defining space and spatial movements. Although applicable for all types of vehicular traffic and even capable of
describing decision-making processes, the models are inadequate with respect to modelling crossing traffic flows, which is absolutely essential in this research. The potentially erratic paths of all kinds of road users would be very difficult to match with the car-following algorithms.

Force models are the first type of models which the impact of the road environment could be implemented in. The methodology has a wide applicability with respect to traffic situation and composition. The most important disadvantage of this group of models for our analysis is that the movements of road users are mostly a result of each others’ movements. The lack of personal deliberation in deciding on one’s trajectory appears to hinder the implementation of mental processes that are presumed to exist in road users operating under Shared Space conditions.

A utility-optimisation model, in this case represented by Nomad, is a very flexible model, but that strength is also its weakness: it is a complex model, with a lot of unknowns that need to be calibrated before use. It seems possible to make it applicable for vehicular traffic and in all kinds of traffic situations and manoeuvres. It is one of the few models in which modelling of the road environment seems feasible. A final strong point is the model’s implementation of decision-making processes, which appears to be the best of all models analyzed in this comparison.

3.4 Conclusion

Various types of models have been introduced, with very diverging characteristics. No model presented here has fulfilled all criteria to suit Shared Space traffic. A utility-optimisation model would best suit the requirements of modelling Shared Space traffic, but its drawback is its relatively high complexity. This is particularly problematic since this thesis project will not feature significant calibration of simulation parameters. Nevertheless, there is still need, and room, for another, less complex, model that tries to adhere to the Shared Space approach. The rest of this report is devoted to the attempt at conceiving and implementing such a model. It may not instantly tick all the boxes, but hopefully the study of existing models in this state-of-the-art will be of use in developing and implementing it.
4 Conceptual traffic model

In this chapter, a conceptual traffic model is introduced. The relevant behavioural relations and assumptions are explained. The Shared Space philosophy is included in this model by means of introducing independent initiative and politeness variables in the model. The implementation of the conceptual model in a simulation model and a numerical simulation program is treated in chapter 5.

4.1 Conceptual model diagram

The first step in the construction of a traffic model is the development of a conceptual model. The conceptual model can be seen as a framework that combines the theoretical foundations of Shared Space and the practical requirements of a traffic flow model, thus establishing a vision upon traffic processes inspired by the Shared Space approach. Figure 4.1 shows the conceptual model diagram.
The conceptual model diagram emphasises the dynamic relation between negotiation and movement, which are assumed to be the two fundamental traffic-behavioural processes in a public space. Any road user is perceived to continuously observe whether it needs to negotiate before moving on, and when it has moved on, it needs to negotiate in order to continue to move in safety. The diagram shows that the negotiation process results in determining an acceleration value. This acceleration obviously determines speed and position of the road user. The calculated preferred future trajectory of the road user (together with the trajectories of all the other road users) forms an input for the negotiation process, during which a new acceleration value is determined. The (mathematical) relations between all these variables will be further explored in the sections 4.2 (movement) and 4.3 (negotiation).

Negotiation fulfills a central role in the conceptual model, but the term is only occasionally mentioned in the Shared Space literature. Being a design philosophy, the Shared Space approach focuses much more on the road design. The supposed behavioural patterns in a public space are barely worked out beyond a hypothetical level. One of the 'lessons' mentioned by Fryslan (2005) is that road users, if they have to share the roadspace and there is no regulated priority, have to negotiate the right of way by slowing down and making eye contact. It is not made clear neither whether this is always true nor whether this leads to significantly better traffic operations. Since social interaction between road users depends heavily upon effective communication, the way in which this communication is performed, whether by eye contact or through accelerations or in any other way, could be considered of great importance. A lack of communication could result in dangerous situations.

For the sake of studying the implications of the Shared Space theory upon traffic behaviour and performance (the main research question), we assume that there is always sufficient communication between road users to make their intentions clear to one another. This choice is justified if speeds are low and the road environment is clear, that is without visual obstacles. This conceptual model will be implemented for a spacious urban intersection, so these requirements can reasonably be expected to be fulfilled. This assumption is also connected to the heterogeneity of the population of road users. Factor et al. (2007) expect that larger social and cultural diversity in the population may cause road users to have different interpretations of the same traffic situation and diverging driving repertoires, leading to more confusion and, possibly, more accidents. This means that low heterogeneity is effectively another assumption of the conceptual model, since it is supposedly a requirement for sufficient communication (to avoid 'social accidents').

The Shared Space approach tries to emancipate the more dependent modalities (Fryslan, 2005). That is why the model perceives each road user to be an independent decision-maker, regardless of modality. Every road user is seen as a unique individual with its personal characteristics. With that in

30
mind, the model assumes identical relations, and therefore formulas and algorithms, for road users of all modalities. The included individual characteristics of road users primarily deal with their personal attitudes with respect to the interaction with other road users.

The conceptual model reflects the Shared Space philosophy by defining two behavioural variables for every road user. The first one is an initiative factor that determines, during negotiating with other road users in case of a potential conflict, whether the road user would like to take precedence even if it does not have priority. Initiative is grounded on a road user’s risk attitude. In the context of a negotiation, we assume that a sense of initiative is needed to overcome the tendency to solve a potential conflict by adhering to prescribed priority. Thus, it resembles the inclination (or lack thereof) of people to deal with the perceived lack of safety on the intersection by offering alternative ways to solve conflicts.

The second behavioural variable is the politeness factor that impacts whether the road user will offer or accept that the other road user will proceed despite its not having priority. Politeness originates in the social component that the Shared Space approach assumes that exists in traffic interaction. In a negotiation, it is important that one sometimes gives way if that would have a high value for the other.

In this conceptual model and its implementation in chapter 5, the initiative and politeness variables are presented as booleans. Thus, variety in simulation results would be rooted in the percentages of road users taking initiative or being polite, rather than in the level of initiative and politeness in a single road user. These percentages can be seen as the extent to which the road environment is successful in promoting these types of behaviour, which the Shared Space approach sees as both beneficial to overall traffic performance and spatial quality and possible to change by road design. How this promotion actually works is not defined in the conceptual model. Neither the road design nor in a wider sense the road environment is explicitly included in the conceptual model. That does not mean that it can have no impact upon the modelled traffic behaviour, only that its role is defined in the implementation, and often implicit in other modelling choices. In the simulation program, the road environment has an impact upon the road users’ speeds and paths. This is explained in chapter 5.

In the context of this model, politeness and initiative are supposed to widen the array of options for road users to solve mutual traffic conflicts. Alternatively, not being prepared to show politeness and initiative can reduce a road user’s ability to solve potential conflicts with the most satisfactory result for itself and for other road users. Consequently, a lack of initiative could be as detrimental to the intersection’s performance as a lack of politeness, even though it may be meant as altruistic.
4.2 Movement of road users

In this section, the relations between the distance, speed, acceleration and position variables are explained, represented by mathematical equations. Forming the “movement” side of the conceptual model, these equations are in essence numerical approximations of general kinematic relations.

4.2.1 Distance, speed and acceleration

The main kinematic variables is the distance that a road user has travelled. The general equation for this distance is:

\[ s_i(t+1) = s_i(t) + v_i(t) \cdot \Delta t + 0.5 \cdot a_i(t) \cdot (\Delta t)^2 \]  

(4.1)

with:

- \( s \) total distance travelled
- \( i \) individual road user
- \( t \) current time
- \( v \) speed
- \( a \) acceleration
- \( \Delta t \) time step

None of these variables are represented as (two-dimensional) vectors, since the distance is defined as a scalar. Note that formula (4.1) is a numerical approximation of the distance variable, that assumes that the acceleration and speed at time \( t \) do not change significantly during the next time step period. This assumption is involved in the equation for calculating the current speed as well:

\[ v_i(t+1) = v_i(t) + a_i(t) \cdot \Delta t \]  

(4.2)

We also assume that the speed cannot be negative, nor that it can be higher than a certain maximum speed. These assumptions with respect to speed are made to limit the range of the acceleration of the road user. During the negotiation process, this will reduce the number of distinguishable (discrete) options for the level of acceleration. In general, this is the range of the acceleration:

\[ v_{i,max} \geq v_i(t+1) \geq 0 \rightarrow (v_{i,max} - v_i(t)) / \Delta t \geq a_i(t) \geq -v_i(t) / \Delta t \]  

(4.3)
Since the model restricts the domain of acceleration (and deceleration) with a maximum acceleration and a maximum deceleration (i.e. a minimum acceleration), the full acceleration domain becomes:

\[
\min (a_{i,\text{acc,max}}, (v_{i,\text{max}} - v_i(t)) / \Delta t) \geq a_i(t) \geq \max (a_{i,\text{dec,max}}, -v_i(t) / \Delta t)
\]  \hspace{1cm} (4.4)

These boundaries are treated as physical, i.e. accelerations outside this domain are not possible. The choice of the acceleration or deceleration value individually or on the basis of interaction with other road users is separated from that, and this choice process is treated in the next two sections.

### 4.2.2 Relative and absolute position

The most important explicit assumption underlying the conceptual model is that the model does not account for the possibility that the paths of road users can change during their movements. In the presented algorithms, paths are treated as a pre-defined, fixed variable. Road users have the power to continually adjust the value of their acceleration, but not its direction. Effectively, this prevents any path change. Although the added load of calculations caused by variable paths would be considerable, it is not the reason for sticking to fixed paths. The problem is that it would introduce new questions about how this path change actually works and which variables are involved in triggering it. Without observations of social interaction in a Shared Space scheme or a solid foundation of path change in the Shared Space theory, it would be preferred to stick to a simple approach. An observation of Van der Boomen (2006) seems to confirm that that may be plausible: he claims that cyclists in China change their paths only slightly, compensating that with a fairly low speed and low levels of acceleration.

The distance of a road user is assumed to be travelled along a certain curve on the intersection. This curve consists of \(n+1\) points, connected by \(n\) straight arc elements (numbered from 1 to \(n\)). For the negotiation calculations in the next section, we need to determine a road user’s position relative to these curve points. For example, a relative position of 7.5 means that a road user is halfway between the seventh and eighth curve points. This is equal to being halfway on the seventh arc element. With this formula, a road user's relative position \(r\) on the curve at a certain time instant \(t\) can be defined:

\[
[r_i(t)] = \lfloor r_i(t) \rfloor + \{r_i(t)\}
\]  \hspace{1cm} (4.5)

with:

- \(r_i(t)\) relative position on curve
- \([r_i(t)]\) current arc element (integer)
- \(\{r_i(t)\}\) relative position on current arc element (range \([0,1)\))
This formula may seem trivial, but it is not: the two terms on the right-hand side of the equation need to be calculated separately and added to find the left-hand term. But before we can determine the current arc element, we first need to know the accumulated arc length up to any of the \( n+1 \) points that describe the curve. This is described in this formula:

\[
L_i(k) = \begin{cases} 
0 & \text{for } k = 1 \\
\sum_{m=2}^{k} d(\vec{Q}_{i,m-1}, \vec{Q}_{i,m}) & \text{for } k = 2, 3, \ldots, n + 1
\end{cases}
\]  

(4.6)

with:
- \( k \) specific curve point
- \( L_i(k) \) total arc length up to point \( k \)
- \( d(\vec{A}, \vec{B}) \) distance between two points \( A \) and \( B \) (scalar)
- \( \vec{Q}_{i,m} \) two-dimensional position vector of \( m \)th point on curve

Obviously, the accumulated arc length for the first point is zero. For the subsequent points, the formula gives a value that is equal to a summation of distances between the previous points on the curve. This calculation is only valid under the assumption that these are straight arc elements.

Now that the accumulated arc lengths are established, the right-hand side terms of equation (4.6) can be calculated as well. The first term, the number of the current arc element, is equal to the number of the last point that the road user has passed. This number can be determined with this formula:

\[
[r_i(t)] = \max\{ k \in \{1, 2, \ldots, n + 1\} : s_i(t) \geq L_i(k) \}
\]  

(4.7)

with:
- \( n \) total number of arc elements
- \( n + 1 \) total number of curve points

Thus, the current arc element is the last element for which the starting point has a lower accumulated arc length than the current distance. If the travelled distance \( s_i(t) \) is larger than any arc length value \( L_i(k) \), the road user is at the end of the curve and should be excluded from the next time step.

The relative position on the current element can be calculated by this formula:

\[
|r_i(t)| = \frac{s_i(t) - L_i([r_i(t)])}{d(\vec{Q}_{i,[r]}, \vec{Q}_{i,[r]+1})}
\]  

(4.8)
In words, this formula says that the road user's relative position on the current element is equal to the current distance subtracted with the curve's accumulated arc length up to the last curve point passed, divided by the length of the current element. This, again, leads to a dimension-less quantity.

The scalar value of a road user's relative position can be used to approximate its absolute position in the form of a two-dimensional position vector by means of this weighted-average formula:

\[
\vec{X}_i(t) = (1 - |r_i(t)|) \cdot \vec{Q}_i(|r_i(t)|) + |r_i(t)| \cdot \vec{Q}_i(|r_i(t)| + 1)
\]  

(4.9)

with: \(\vec{X}_i(t)\) two-dimensional vector of current absolute position

In the same way, a road user's direction of movement (tangent) can be approximated. In order to do that, one first needs to approximate the direction of movement at the curve points (see section 4.3.1 for that). Both a road user's absolute position and its direction of movement can be seen as derivative quantities which are no input to the negotiation algorithms. Their only virtue is as input to the visualisation process, which is explained in some detail in section 5.8. On the other hand, the relative position of road users will prove to be essential in the processes described in the next section.

### 4.3 Negotiation between road users

From a kinematic point of view, negotiation is merely determining an acceleration. But for a traffic flow model, determining the acceleration may be the single most important process. In this conceptual model, the negotiation part contains most of the model's intelligence (i.e. algorithms not based on kinematics or book-keeping), in particular with respect to conflict detection and acceleration choice.

The negotiation process in the model is dynamic: the road users try to find the best solution to their mutual conflict under continually changing circumstances. Even with limited degrees of freedom, the problem becomes complex rather easily. The already mentioned assumption of fixed paths helps to keep the complexity limited. Also, the negotiation algorithm does not calculate whether a solution is 'optimal'. What it does is take specific acceleration patterns, derive positions and check for foreseen conflicts. Thus, it should come up with a likely solution that should avoid or mitigate the conflict. The approach can be characterised as discrete and deterministic, since the chosen accelerations are from a limited set of options and fully dependent on the traffic situation and personal characteristics. This heuristic is intended to give viable solutions with limited calculations.
4.3.1 Path conflicts

A requirement for the negotiation process is that road users know at which relative position a conflict is feasible. This is the case if the paths of two road users cross each other or at least are uncomfortably close. Finding such path conflicts requires an extensive algorithm with many intermediate variables. In this sub-section, the algorithm to get from path definition to path conflict matrix is formulated.

The first intermediate variable is the direction of movement of a road user at the \( n+1 \) curve points, expressed as the angle of the path’s local tangent line and approximated by this formula:

\[
\theta_i(k_i) = \begin{cases} 
\text{atan2}(y_i(2) - y_i(1), x_i(2) - x_i(1)) & \text{for } k_i = 1 \\
\text{atan2}(y_i(k_i+1) - y_i(k_i-1), x_i(k_i+1) - x_i(k_i-1)) & \text{for } k_i \in 2,3,\ldots,n \\
\text{atan2}(y_i(n+1) - y_i(n), x_i(n+1) - x_i(n)) & \text{for } k_i = n+1 
\end{cases} 
\]  

with:
- \( \theta_i(k_i) \) direction of movement at curve point
- \( (x_i(k_i), y_i(k_i)) \) coordinates of curve point

The advantage of using the \text{atan2} function instead of the usual tangent is that its period is a full circle, which causes that the \( \theta \) value also indicates a direction (making the tangent line into a vector).

Assuming that a road user’s physical occupation is rectangular and that its front is always orthogonal to its direction of movement, the positions of a road user’s four vertices can be calculated:

\[
\vec{V}_i(k_i) = \vec{Q}_i(k_i) + C_{i,1} \cdot \sin(\theta_i(k_i)) + C_{i,2} \cdot \cos(\theta_i(k_i)) 
\]  

with:
- \( \vec{V}_i(k_i) \) matrix of position vectors of road user’s vertices
- \( C_{i,1}, C_{i,2} \) physical dimensions of road user from base point

The road user’s base point is the point for which the travelled distance (formula 4.1) and absolute position (formula 4.9) have been defined, its point of impact. This may be the centre of the rectangle, the centre of the front side or any other point on the road user’s central longitudinal axis. The terms \( C_{i,1} \) and \( C_{i,2} \) are matrices that contain the distances between the vertices of the road user’s rectangle and its base point, when \( \theta_i \) is \( \pi/2 \) rad and 0 respectively. Often, the resulting vertex positions will be calculated as a combination of these two extremes.
The position of a road user becomes important for detecting conflicts only when compared to the position of another road user. This formula gives the relative distance of the vertices of the detected road user \(i\), from the point of view of the detecting road user \(j\):

\[
\vec{D}_{j,i}(k_j, k_i) = \vec{V}_i(k_i) - \vec{Q}_j(k_j)
\]  

(4.12)

with:

- \(j\) other individual road user (observer)
- \(\vec{D}_{j,i}(k_j, k_i)\) matrix of relative distance vectors of vertices of \(i\)

The relative distances resulting from (4.12) are still in the (x,y)-plane. Since the margins that the detecting road user \(j\) requires are in a different coordinate system, its axes being the direction of movement (longitudinal) and orthogonal to that (lateral), we need to linearly transform the relative distances to this alternative coordinate system. This is done by applying these formulas:

\[
\vec{D}_{j,i}(k_j, k_i)_{\text{long}} = \vec{D}_{j,i}(k_j, k_i)_{x} \cdot \cos(\theta_j(k_j)) + \vec{D}_{j,i}(k_j, k_i)_{y} \cdot \sin(\theta_j(k_j))
\]  

(4.13)

\[
\vec{D}_{j,i}(k_j, k_i)_{\text{lat}} = \vec{D}_{j,i}(k_j, k_i)_{x} \cdot \sin(\theta_j(k_j)) - \vec{D}_{j,i}(k_j, k_i)_{y} \cdot \cos(\theta_j(k_j))
\]  

(4.14)

with:

- \(\vec{D}_{\text{long}}, \vec{D}_{\text{lat}}\) linear transformations of distance matrix
- \(\vec{D}_{x}, \vec{D}_{y}\) partitions of original distance matrix

Now that the distances between the road users are determined and put in the right format, we need to find the values to test them, which are the minimal required distances to have no interference:

\[
\vec{B}_{j,i} = \begin{bmatrix}
B_{\text{front}} \\
B_{\text{rear}} \\
B_{\text{left}} \\
B_{\text{right}}
\end{bmatrix} = \begin{bmatrix}
M_{\text{head}}(j, i) + p_j \cdot l_j \\
-(M_{\text{head}}(i, j) + (1-p_j) \cdot l_j) \\
-(M_{\text{side}}(j, i) + .5 \cdot w_j) \\
M_{\text{side}}(j, i) + .5 \cdot w_j
\end{bmatrix}
\]  

(4.15)

with:

- \(\vec{B}_{j,i}\) minimal required distance vector, required by \(j\)
- \(M_{\text{head}}(j, i)\) headway margin matrix (\(j\) following, \(i\) leading)
- \(p_j\) proportion of length between front and base point
- \(l_j\) length of road user \(j\)
- \(M_{\text{side}}(j, i)\) sideways margin matrix
The headway and sideway margin matrices, as well as the length and width values, will depend on the modalities of the road users involved. The proportion of length $p$ can be any value from zero (base point is at the front) to one (base point is at the rear). (In the implementation within this report, this value is taken as .2, the base point being roughly located near the steering axis of a vehicle.)

This formula represents the test for a path conflict for a single vertex of road user $i$:

$$ c_{j,i}(k_j,k_i) \left|_v \right. = \begin{cases} 1 & \text{if (} B_{\text{front}} \geq \bar{D}_{j,i}(k_j,k_i)_{\text{long},v} \geq B_{\text{rear}} \land \bar{D}_{j,i}(k_j,k_i)_{\text{lat},i} \leq B_{\text{right}}) \\ 0 & \text{otherwise} \end{cases} \quad (4.16) $$

with:
- $c_{j,i}(k_j,k_i)$ path conflict value at curve point (boolean)
- $v$ specific vertex number of $i$, from set $\{1,2,3,4\}$

If there is any vertex of $i$ within the minimal distance from $j$ or vice versa, both road users will record a path conflict for that particular combination of curve points, which can be summarised as:

$$ \left( \sum_{v=1}^{4} c_{j,i}(k_j,k_i) \left|_v \right. + \sum_{v=1}^{4} c_{i,j}(k_i,k_j) \left|_v \right. \right) > 0 \Rightarrow c_{j,i}(k_j,k_i) = c_{i,j}(k_i,k_j) = 1 \quad (4.17) $$

This formula confirms that the full matrices $c_{j,i}$ and $c_{i,j}$ are each other’s transpose.

Occasionally, the paths of road users may cross without this algorithm noticing so. This can happen, for example, when two lorries have orthogonally crossing paths with distances between curve points significantly smaller than the lorry lengths: when they are both halfway on the intersection, the lorries will certainly have a physical overlap, but since there are no vertices of one road user within the minimal required distance of the other, the algorithm will not detect this overlap.

To avoid this, the binary matrix that contains all potential conflict booleans must be adjusted: any intermediate zeroes in the matrix will be considered ones. For example, in a certain row of ten conflict values, only the third and sixth entries are ones. That means that the fourth and fifth entries must be changed from zero to one as well. The potential problem with this method is that it may be too aggressive in declaring potential conflicts when there is none, leading to unnecessary decelerations. As long as the curves contain only a single turning movement, this risk seems to be fairly low.
4.3.2 Preferred trajectory

In general, every road user determines its preferred acceleration pattern on its own and finds out whether the resulting preferred trajectory would cause a conflict with another road user. For these preferred trajectories, two important choices have been made. Firstly, that every road user has a desired (normal) speed that can vary over its path. That implies that a road user may prefer to slow down even when there is no other traffic. A second important choice is that every road user has preferred acceleration and deceleration values that are used under non-conflict circumstances, being more comfortable than maximum acceleration and deceleration (for more urgent circumstances).

The formula to calculate the acceleration or deceleration to adhere to the individual normal speed:

\[ a_i(t) = \min(a_{\text{acc, norm}, i}, \max(a_{\text{dec, norm}, i}, (v_{\text{norm}, i(t)} - v_i(t))/\Delta t)) \]  

Using this formula with (4.2) and (4.1), the entire preferred trajectory of every road user can be predicted. Note that the speed norm is itself dependent on the travelled arc length.

After that, the formulas (4.5) to (4.8) must be applied to determine the relative positions of the road users. These relative positions are used as input in determining the weighted conflict values for all pairs of preferred trajectories, which is the treated in the next sub-section.

4.3.3 Detection of potential conflicts

The preceding sub-sections have introduced quantities that serve as input to the conflict detection process treated in this sub-section. The essence of this process is to look for conflicts between the preferred trajectories and, if one arises, to administer the need for alternative trajectories.

In the model, every road user also has its own horizon for which it is able to detect expected conflicts. This horizon is expressed as a time period. A minimum time period for all road users can be defined, but it can be as long as the time to reduce speed to zero if that is longer:

\[ h_i(t) = \max(h_{\text{min}}, \frac{c \cdot v_i(t)}{a_{\text{max, dec}}}) \]  

with: \( h_i(t) \) time horizon

39
If a road user does not detect a conflict within its personal time horizon, it will take the calculated acceleration or deceleration value. (This can easily be zero if normal speed has already been reached.) Thus, the road user’s time horizon comes down to a critical Time-to-Collision (TTC) value; the model could predict conflicts even if beyond this horizon, but the road user does not act upon them.

All road users search for conflicts individually: with which road users can it expect a conflict in the foreseeable future? In the model, this is represented by calculating a weighted conflict value for any pair of road users, for every time step within its time horizon, using the current relative positions on the curve as weights for the conflict values at the four closest curve point combinations:

$$c_{j,i}(r_j(t), r_i(t)) = \sum \left( \begin{array}{c} \left[ 1 - \left\{ r_j(t) \right\} \right] \\ \left[ r_j(t) \right] \end{array} \right) \times \left( \begin{array}{c} \left[ 1 - \left\{ r_i(t) \right\} \right] \\ \left[ r_i(t) \right] \end{array} \right) \times \left( \begin{array}{c} c_{j,i}(\left\{ r_j(t) \right\}, \left\{ r_i(t) \right\}) \\ c_{j,i}(\left\{ r_j(t) \right\}, \left\{ r_i(t) \right\} + 1) \end{array} \right) \times \left( \begin{array}{c} c_{j,i}(\left\{ r_j(t) \right\} + 1, \left\{ r_i(t) \right\}) \\ c_{j,i}(\left\{ r_j(t) \right\} + 1, \left\{ r_i(t) \right\} + 1) \end{array} \right)$$

(4.20)

For the sake of clarity, this sum has been formulated as an element-by-element multiplication.

Since the path conflict matrices of both road users are each other’s transpose, both road users will find the same conflict values for all time steps during the interaction between their trajectories:

$$c_{i,j}(r_i(t), r_j(t)) = c_{j,i}(r_j(t), r_i(t))$$

(4.21)

Subsequently, this conflict value needs to exceed a certain threshold value $c_{\text{min}}$ to have the interaction between the two road users be labelled as a potential conflict:

$$c_{j,i}(r_j(t), r_i(t)) > c_{\text{min}}$$

(4.22)

Like the conflict values themselves, the threshold value can have any value from zero to one. The lower the threshold, the more conservative the model is in declaring the traffic situation conflict-free (or the more aggressive in assuming a potential conflict). A value of zero would mean that any overlap of a close combination of curve points would require a renewed negotiation. A value of one would mean that there is never a conflict, since the conflict value can never exceed this. In the implementation of chapter 5, a threshold value of .2 is used, which seems a fair value. If only one of the four closest
combinations of curve points gives a path conflict (i.e. has a value of one), roughly half of the [0,1] by [0,1] domain of all the combinations of relative positions will give a conflict with this threshold value.

It is important to understand that the two road users involved in a potential conflict may not have the same time horizon, which makes it possible that one road user detects the potential conflict and the other does not, even if its conflict value would be high enough to warrant action. This means that any implementation of this model should account for a traffic situation in which only one of the road users is prepared to take action. Obviously, if this road user is not successful, it is likely that the other road user, at one time or another, will find the potential conflict within his own horizon as well.

The meaning of the conflict value mainly lies in the severity of the overlap between the road user's personal spaces. Once the threshold value has been exceeded, its precise value is no longer important; there is a potential conflict. The urgency of the conflict, i.e. whether it requires an action on a short notice, and how strong that action must be, will be better reflected by the time-to-conflict value.

The model assumes that the road users do not take action if the threshold is not exceeded. If it is exceeded, the only way to handle the potential conflict is by adjusting the acceleration pattern of one or both road users. This process is explored in the next sub-section.

### 4.3.4 Adjustment of acceleration

The previous sub-section has resulted in a list of all potential conflicts currently foreseen by any road user present. In this final sub-section, we deal with the remainder of the negotiation algorithm, which focuses on resolving all of them for the current time step. In particular, the different acceleration options and the possible sequences of testing them need to be accounted for.

The conflicts are resolved in descending order of urgency: the conflict that is projected to happen first (i.e. has the shortest time-to-conflict) is handled first. What does 'handling' mean? It means that one or both road users pick an alternative acceleration pattern. These patterns are used to re-calculate the future trajectories of both road users and, subsequently, their mutual conflict values. For this, the equations from section 4.2 and sub-section 4.3.3 are applied. If the mutual conflict values are below the threshold value, the foreseen conflict is supposed to be 'handled' by assigning the new acceleration value to both of the road users involved in this conflict for the current time step. If the mutual conflict values (within the appropriate time horizon) are still above the threshold, one or more alternative combinations of acceleration patterns can be tested in similar fashion. If there is still no solution after
testing these acceleration patterns, the condition for accepting an alternative can be relaxed: it is an adequate solution to the conflict if the first exceedence of the threshold value occurs at a later time than under the original trajectories, which would mean that the conflict has become less urgent.

The remainder of this sub-section deals with the possible sequences of testing and, potentially, accepting alternative acceleration patterns. The differences between them originate in three factors:

- Defined precedence: if two road users have interfering paths, and one of them enters the potential conflict zone, it is not possible for the other road user to go first, even if it has priority. The model distinguishes between two situations when determining a logical acceleration pattern: the one in which theoretically both road users could still go first (precedence has not been defined) and the one in which one road user has gone first (so precedence has been defined). The algorithm varies significantly for these two situations, since a following road user is much more restricted in its acceleration options than a leading road user.

- Number of road users with no established acceleration: any potential conflict in the model is always between two road users, but one of them may not have the conflict within its time horizon, or may have established its acceleration in solving a more urgent conflict. The single remaining road user can only change its own acceleration, even if it has priority.

- Initiative and politeness variables: if there are still two road users available for negotiation, their initiative and politeness variables may have an impact. If, and only if, the road user with priority is polite and the other road user tends to take initiative, the two road users may decide that the road user with priority will yield to the other, if the traffic situation is such as to make this an adequate way of handling the potential conflict.

The last factor in particular shows that priority rules are an important element of the algorithm, despite the reputation of the Shared Space approach as doing away with priority. In the Netherlands, national priority rules are valid under all conditions, even if the road design does not make them clear very well. Also, most of the road users apply them, so we are in no position to leave them out. Generally, priority rules establish which road user has the advantage in getting sufficient space for moving on, which means that he is least impacted by a potential conflict.
The sets of alternative acceleration patterns may contain three options:

- Braking every time step until a road user’s speed is zero (moderate or strong deceleration);

0 Adhering to preferred trajectory in the current time step (zero or moderate acceleration or deceleration), directly followed by constant speed (zero acceleration) (for one-sided potential conflicts, the acceleration is set at zero for the current time step as well);

+ Strongly accelerating in the current time step, followed by continuous zero acceleration.

It should be remembered that these acceleration patterns are only intended for and valid during negotiations. They do not enforce certain accelerations upon a road user beyond the current time step! In the next time step, the entire process is repeated: all road users determine their desired trajectory (again). In particular in case of high traffic intensities, the traffic situation can be expected to be very dynamic. A road user may turn out to accept totally different accelerations every few time steps.

The first and third options have been formulated as to be two widely diverging negotiation outcomes, while the second option is close to keeping the status quo for one’s own trajectory. The options are clearly not symmetrical; the option to keep braking is much more disadvantageous than the option to accelerate is advantageous. This difference is legitimate: in a real traffic situation, a single conflict can lead to a road user's full halt but it cannot lead to an equivalently higher speed for another road user, since he may encounter other potential conflicts on the intersection. As such, the proposed patterns of acceleration are the farthest-apart options that still constitute realistic driving behaviour.

The Tables 4.1 to 4.6 provide an overview of all sequences of acceleration combinations. They will repeatedly be cited in the discussion below. The conditions under which an option is accepted is reflected in its symbol in the table:

① the option satisfies the strict condition that the potential conflict is avoided;

① the option only satisfies the less strict condition that the potential conflict is delayed;

0 the default option if no other option has been accepted. There may be more than one default option, of which the one with the strongest delaying effect is chosen.

The number of an option refers to its position in the sequence. Option 1 will be tested before option 2.
### Table 4.1 Sequence of acceleration options for two cooperative road users without precedence

<table>
<thead>
<tr>
<th>Road users</th>
<th>Options</th>
<th>Priority road user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding road user</td>
<td>-</td>
<td>1 5 9 13b</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>3 7 4</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>10 12 13a 2 6</td>
</tr>
</tbody>
</table>

### Table 4.2 Sequence of acceleration options for two non-cooperative road users without precedence

<table>
<thead>
<tr>
<th>Road users</th>
<th>Options</th>
<th>Priority road user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding road user</td>
<td>-</td>
<td>1 5</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>2 4</td>
</tr>
</tbody>
</table>

### Table 4.3 Sequence of acceleration options for one road user without precedence

<table>
<thead>
<tr>
<th>Road users</th>
<th>Options</th>
<th>Single road user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>~</td>
<td>1 4 7a 2 5 7b 3 6 7c</td>
</tr>
</tbody>
</table>
Negotiation without defined precedence

When theoretically both road users could still go first, the model gives the road user with priority the first-mover advantage. If this road user can prevent a conflict by decelerating or accelerating, this solution is chosen and the conflict is considered resolved. The other road user will temper its deceleration or acceleration accordingly. This is visible in the Tables 4.1 and 4.2 as options ① and ②. If this does not prevent a conflict, the issue of initiative and politeness comes into play. Only if the road user with priority is polite and the road user without priority likes to take initiative, the other road user is offered to try to resolve the conflict by decelerating or accelerating (Table 4.1). Again, if this behaviour resolves the conflict, this solution is chosen and the road user with priority will conform to it. If it does not, all four options now mentioned are again tested as solutions, the condition being that they at least postpone the conflict. If none of these solutions is accepted, a combination of one road user accelerating and one road user decelerating is offered. If this configuration again neither solves the conflict, nor helps to postpone it, the only alternative is that the road user without priority chooses deceleration or acceleration on the basis of which makes the conflict the least urgent. In this case, the priority-having road user will help to solve this conflict by taking the opposite acceleration pattern.

The model does not offer strong acceleration or deceleration for both road users simultaneously as viable options (the upper left and lower right corners of Table 4.1). Strong acceleration is very unlikely to be a feasible solution since both road users will then only end up faster at their mutually conflicting positions (it is not impossible if one road user is able to accelerate significantly more). On the other hand, deceleration for both road users will almost always fulfill the condition of avoiding the potential conflict, but it is a trivial solution: neither will ever get to their destination if this continues to be the best negotiation result! The danger of including this option is that it turns out to be so attractive that several conflicts are 'solved' this way, leading to stagnation or total gridlock. This is an illustration of the need in traffic flow models to always provide sufficient incentive to road users to keep moving.

If the road user with priority is not polite or the road user without priority does not like initiative, the road user without priority is offered to decelerate or accelerate if that postpones the conflict (Table 4.2). If that does not work, this road user will decelerate by default.

If one of the two road users involved in the conflict has its acceleration already determined, the algorithm becomes much simpler, as can be seen in Table 4.3. No matter the priority, the remaining road user can choose between deceleration, acceleration or even constant speed and take whatever option avoids or, later on, delays the conflict. The option of deceleration is tested first because this potential conflict could be single-sided because it is outside the other road users’s time horizon; this would make it sensible to assume that the other road user is not reducing speed or even speeding up.
Table 4.4 Sequence of acceleration options for two road users with precedence

<table>
<thead>
<tr>
<th>Road users</th>
<th>Options</th>
<th>Preceding road user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding road user</td>
<td>-</td>
<td>① ② 5</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>③ ④</td>
</tr>
</tbody>
</table>

Table 4.5 Sequence of acceleration options for one road user who takes precedence

<table>
<thead>
<tr>
<th>Road users</th>
<th>Options</th>
<th>Road user taking precedence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>~</td>
<td>① ⑤a ② ⑤b</td>
</tr>
</tbody>
</table>

Table 4.6 Sequence of acceleration options for one road user while other takes precedence

<table>
<thead>
<tr>
<th>Road users</th>
<th>Options</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding road user</td>
<td>-</td>
<td>② ⑤b</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>① ⑤a</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>
Negotiation with defined precedence

If one road user goes first, priority plays no role anymore. The options of the following road user, but also those of the leading road user, are reduced (see Table 4.4). In the case of both road users still free to decide upon their acceleration, there are only three options: one is that the following user decelerates, two is that the leading user accelerates and three is that option one and two happen simultaneously. Even if none of these options passes the test, option three is still the outcome, as it is the option that leads to a maximum distance between the two road users.

If one of the road users has a fixed acceleration already, the number of options is again small, as can be seen in the Tables 4.5 and 4.6. Depending on whether the remaining road user is leading or following, the set of options consists of a constant speed (acceleration zero) and acceleration (when leading) or deceleration (when following). This road user is able to optimise the outcome for itself alone (the other road user has effectively bowed out of this negotiation). If neither of the two options helps to avoid or postpone the outcome, the option is chosen that makes the conflict the least urgent.
5 Model implementation

In this chapter, the focus is on the implementation of the model in a simulation model and then in a working program. This implementation is named blink (after the blink of an eye that a negotiation between road users usually takes). First, some of the choices that were made during programming are accounted for. After that, the input and output variables of the simulation are introduced, accompanied by an explanation on how to feed input data into the simulation (which is primarily by means of a graphical user interface). Also, the structure of the program is explained. The simulation model is presented in the form of a model flow diagram. The model is broken down into smaller process elements which are explained separately. These include initialisation, generation and negotiation.

5.1 Programming

In this section, some of the choices with respect to the programming of the simulation model are accounted for: why has it been constructed in this way and what has been the impact on the simulation process. The program itself will be explained further on in this chapter.

5.1.1 Programming in Matlab

The model is implemented using the numerical computing environment Matlab. Equivalently, one could say that the blink program is coded in the numeric programming language Matlab. The decision to use Matlab is based on several reasons. Firstly, it is easy to learn (at least at the start). Secondly, it is designed for handling large matrices, and these will be abundant in blink. Thirdly, a student version is provided by the university at no cost.

During programming, other advantages and disadvantages of Matlab have come up. As for the advantages: it turns out to be a very flexible language, so it can handle diverging tasks, although not always as elegant as one would hope. Another plus is its excellent documentation, which includes examples and help functions. The main drawback of Matlab in this project is its low performance in terms of speed for object-oriented programming, which is treated in more detail in the next section.
5.1.2 Programming paradigms

The program uses a combination of programming paradigms, because each of these paradigms has characteristics that help to make my program well-organised, easily adaptable and quick to run. By combining them, the intention is to reach an optimum of these properties. On the one hand, the program has object-oriented (OO) features. It consists of instances of classes that communicate with one another and that hold all elements of the traffic model in methods. Also, the program itself is a class: an instance of the program is generated every time that it is opened. On the other hand, the program also contains elements of modular programming. Many calculations are performed through separate functions. In general, they perform simple tasks with a limited number of input and output variables. For these tasks, they do not need access to object properties. Letting these functions have this access would violate the principle of encapsulation, a characteristic of OO programming.

In addition, features of procedural programming have been added. As mentioned, the main drawback of using Matlab for OO programming is its lack of performance in terms of calculation speed. It seems that calling for object methods takes a disproportional amount of time. During these time periods, no other calculations are performed! The chosen way to neutralise this is to consolidate all road users into one road user meta-object. Thus, at each step in the simulation, only one object will be called, instead of all road users individually. This meta-object’s methods have to be written in such a way as to accommodate calculations for all road users present in the simulation. These calculations are performed simultaneously (vectorised) as frequently as possible, to minimise calculation times. Sometimes calculations must be performed sequentially, for example when accessing cell arrays.

Accessing object properties, as opposed to methods, also takes a lot of time, especially in the case of cell arrays. In the blink program, this last delay has been reduced by defining many object properties as internal variables within the method, particularly those used in for- and while-loops. Because of their complex and often sequential algorithms, containing many definitions of internal variables, one could argue that the meta-object’s methods are procedural functions disguised as methods. This leads to higher calculation speeds but compromises OO’s advantage of simple data management.

5.2 Managing input and output data

In this section, the main input and output variables are presented. Also, the ways in which the user of the simulation program will be able to adjust some of the input parameters are explained: the graphical user interface and an input data file. At the end of this section, the output of data is treated.
5.2.1 Input and output variables

The program requires an extensive amount of input variables. A part of those can be defined by the user of the program through the graphical user interface or the input data file. Another set of required variables cannot be changed in any way except by changing it in the program code itself (the internal input variables). The justification for this is that these variables are relatively independent from the studied traffic situation or a Shared Space road design. For example, the length of a car is not impacted by the road it drives on. Typically, they are not the variables that are measured in traffic counts.

In addition, the simulation model has a pair of simulation control variables, that have a direct influence on the calculation processes of the simulation and the animation, but not on the content of the simulation itself. As for the output data, the current program collects only output data that is needed within the context of this thesis report. It should not be difficult to save more data from simulation runs in a similar manner (by adding more lines of code). In the next few paragraphs, a large number of input and output variables are explained in more detail.

Non-internal input variables

The user-defined, thus non-internal, input variables (see Table 5.1) can be categorised into three groups. The first one deals with the intersection, and consists primarily of the road dimensions, the priority situation and the intersection type. Considering that the simulation model is only concerned with a four-armed intersection, the intersection type can be either a standard intersection or a square. Many of the pioneering Shared Space schemes involve squares, so it is logical to incorporate this type. The dimensions of such a square are additional user-defined input variables. With respect to the priority situation, the choice is between priority to the right and the establishment of a primary (and secondary road). These are the only two possible priority situations in the Netherlands.

The second group of non-internal input variables deal with the road user populations. First of all, this concerns their intensities, by means of origin-destination matrices for the modalities pedestrian, cyclist, car and lorry. Secondly, there are variables for their collective behaviour: the grouping factor and the platooning factor. The use of these variables is explained in section 5.6.1. Thirdly, the percentages of road users inclined to take initiative or be polite. These behavioural variables have been introduced in the previous chapter. The way in which they are used is further explained in section 5.7.

The third and final group of non-internal input variables contains simulation variables, amongst which the number of runs, the simulation time, the time step and the random seed. Less usual variables are the Bézier step, which defines the precision of the road users’ paths (explained in section 5.6.2), and
the fast mode variable, which determines whether or not there is an on-screen animation. As a rule, no animation means quicker calculations, especially when traffic intensities are low.

Table 5.1 Non-internal input variables

<table>
<thead>
<tr>
<th>Variable(s)</th>
<th>Domain</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road dimensions</td>
<td>Non-negative</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Priority situation</td>
<td>1 or 2</td>
<td>-</td>
<td>1 Priority to the right, 2 Primary road</td>
</tr>
<tr>
<td>Intersection type</td>
<td>1 or 2</td>
<td>-</td>
<td>1 Standard Intersection, 2 Square</td>
</tr>
<tr>
<td>Square dimensions</td>
<td>≥ Widths of roads</td>
<td>m</td>
<td>Only applicable if intersection is a square</td>
</tr>
<tr>
<td>Traffic intensities</td>
<td>Non-negative</td>
<td>/h</td>
<td>Preferably zero for origin = destination</td>
</tr>
<tr>
<td>Grouping factor</td>
<td>[0,1)</td>
<td>-</td>
<td>For pedestrians and cyclists only</td>
</tr>
<tr>
<td>Platooning factor</td>
<td>[0,1)</td>
<td>-</td>
<td>For cars and lorries only</td>
</tr>
<tr>
<td>Initiative share</td>
<td>[0,100]</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Politeness share</td>
<td>[0,100]</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Number of runs</td>
<td>Any positive integer</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Simulation time</td>
<td>Any positive number</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>Time step</td>
<td>Any positive number</td>
<td>s</td>
<td>Preferably in the order of .1 s</td>
</tr>
<tr>
<td>Bézier step</td>
<td>(0,1)</td>
<td>-</td>
<td>Preferably in the order of .05 – .1</td>
</tr>
<tr>
<td>Random seed</td>
<td>Non-negative integer</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Fast mode</td>
<td>1 (Yes), 0 (No)</td>
<td>-</td>
<td>If in fast mode, the GUI shows no picture.</td>
</tr>
</tbody>
</table>

Internal input variables

Table 5.2 shows the most important internal input variables. The most obvious internal variables are the modality-specific physical dimensions (derived from Dutch road design norms) and kinematic variables of the road users, including maximal and normal speeds, accelerations and decelerations. These kinematic variables have been roughly estimated for the various modalities.

Other important input variables are the minimal headways and sideways between road users, defining someone's “comfort zone” and used for detecting conflicting paths, and a minimum time horizon for detecting expected conflicts. This time horizon can be seen as the lower limit for a road user’s critical Time-To-Conflict; conflicts are only detected if they are expected to occur within this time period.

Since the internal input variables cannot be found in the user-defined input files, their values used in this project have been collected and accounted for in an annex at the end of this report.
Table 5.2 Main internal input variables

<table>
<thead>
<tr>
<th>Variable(s)</th>
<th>Domain</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road user dimensions</td>
<td>Any positive number</td>
<td>m</td>
<td>Length and width for each modality</td>
</tr>
<tr>
<td>Minimum time horizon</td>
<td>Any positive number</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>Minimum headways</td>
<td>Non-negative</td>
<td>m</td>
<td>May differ for each following &amp; followed combination of modalities</td>
</tr>
<tr>
<td>Minimum sideways</td>
<td>Non-negative</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Maximum speed</td>
<td>Any positive number</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td>Normal speed</td>
<td>Any positive number</td>
<td>m/s</td>
<td>May differ for intersection versus incoming and outgoing roads</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>Any positive number</td>
<td>m/s²</td>
<td></td>
</tr>
<tr>
<td>Normal acceleration</td>
<td>Any positive number</td>
<td>m/s²</td>
<td></td>
</tr>
<tr>
<td>Maximum deceleration</td>
<td>Any positive number</td>
<td>m/s²</td>
<td>Negative sign is left out for convenience</td>
</tr>
<tr>
<td>Normal deceleration</td>
<td>Any positive number</td>
<td>m/s²</td>
<td></td>
</tr>
</tbody>
</table>

Simulation control variables
The simulation program has two simulation control variables (see Table 5.3). Both of them are only used when the simulation is not run in fast mode, meaning that there is on-screen visualisation. The first one is speed, which is expressed as a proportion of the simulation time. The second variable, the refresh period, determines when a new image for the visualisation needs to be generated. Obviously, a smaller period will lead to a more natural animation, its lower limit being the length of one timestep.

Table 5.3 Simulation control variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Domain</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>.25, .5, 1, 2 or 4</td>
<td>-</td>
<td>Animation speed compared to real-time</td>
</tr>
<tr>
<td>Refresh period</td>
<td>Any positive integer</td>
<td>timestep</td>
<td>Time between new animation images</td>
</tr>
</tbody>
</table>

Output variables
Basically, any value calculated by the simulation model could be considered output. The series in Table 5.4 is limited to the variables related to the identity and movements of individual road users. The identity of road users is defined by their modality and their individual initiative and politeness factors. The use of these behavioural factors are further explained in section 5.7. The movements of the road users are established by their path (time-independent route coordinates), trajectory (position at particular times), speed, acceleration and angle. One can say that these output variables, except the angle, together form a road user’s state, describing its full behaviour in relation to the model.
In chapter 7, an additional pair of output variables will be introduced, namely the average speed and the total time for which a road user expects conflicts, i.e. detects a conflict within the critical TTC. These variables are used to study the impact of varying initiative and politeness shares.

**Table 5.4 Main output variables**

<table>
<thead>
<tr>
<th>Variable(s)</th>
<th>Domain</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modality</td>
<td>1, 2, 3 or 4</td>
<td>-</td>
<td>1 Pedestrian, 2 Cyclist 3 Car, 4 Lorry</td>
</tr>
<tr>
<td>Initiative factor</td>
<td>-1 or 1</td>
<td>-</td>
<td>-1 No initiative, 1 Initiative</td>
</tr>
<tr>
<td>Politeness factor</td>
<td>0 or 1</td>
<td>-</td>
<td>0 Not polite 1 Polite</td>
</tr>
<tr>
<td>Path</td>
<td>Within intersection</td>
<td>m</td>
<td>Two-dimensional position vectors</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Within intersection</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>Non-negative</td>
<td>m/s</td>
<td>Limited by maximum speed</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Any real number</td>
<td>m/s²</td>
<td>Limited by max acceleration/deceleration</td>
</tr>
<tr>
<td>Angle</td>
<td>[0,2π)</td>
<td>rad</td>
<td>Mainly used for animation</td>
</tr>
</tbody>
</table>

**5.2.2 Graphical user interface**

The graphical user interface (GUI) is the most visible part of the blink program. It functions as an easy way to manage the input data and the simulation process itself, to watch an animation of the simulation results (i.e. moving road users on the screen) and to extract output data for further analysis.

The blink GUI has been constructed programmatically. That means that all properties and dimensions of the GUI can be deduced from lines of code. This code forms an integral part of the blink simulation program. The GUI can be easily adapted, if required, during the design and construction process.

In Figure 5.1, a screenshot of the GUI is shown. On the left side are three input panels, one of which is visible at a certain time. These three input panels hold all controls to adjust the non-internal input parameters. At the foot of the GUI is a simulation control panel to play, pause and stop the simulation and determine its speed and refresh period. It also contains the name of the current input data file, which is `inputblink.txt` by default. The menu bar at the top contains the menu “Input file” menus to load, save and close input data files and the menu “Output file” to save an output file of a finished batch of simulation runs. Data files will be further explained in the sections 5.2.3 and 5.2.4.
Figure 5.2 shows the three input panels in a row, showing all non-internal input variables. It should be noted that all four modalities have a separate input panel, which can be changed by a secondary switch at the top of the panel. The panels of the pedestrians and cyclists are slightly different from the panels of the other modalities, due to their having a grouping factor rather than a platooning factor.

The dynamic nature of the control panel can be seen in Figure 5.3. Before running, the Play button is clearly visible. While running the simulation, it can be seen that this is also the Pause button. While the simulation is paused, it again shows "Play". On the other hand, the Stop button stays the same, apart from being inactive when there is no running or paused simulation that could be stopped. Equal to the Play/Pause and Stop buttons, the speed and refresh period controls are quasi-continuously monitored by the simulation model. That means that the user has the opportunity to change these variables at any time, even while the simulation is running.
Figure 5.2 Overview of GUI input panels

Figure 5.3 Screenshots of GUI simulation control panel
5.2.3 Data input by text file

For a more structured data input than typing the desired input values in the GUI, the simulation model accommodates the loading and saving of input data by means of a simple text file. In order to be interpreted correctly by the simulation model, this text file must adhere to specific guidelines with respect to lay-out, naming of variables and possible values of the variables. The template of such a text file has been added as an appendix to this report.

When initialising the blink simulation program, a default input file is used (inputblink.txt). This file contains input values for all the boxes and tables in the GUI's input panels. If the program is unable to find or read this file, it uses arbitrary internal values to fill in the GUI. After initialisation of the program, it is possible to load a different input file (through the menu bar). Alternatively, it is possible to change input values in the GUI itself and then save these in either the default input file or a new text file. The simulation program automatically saves all input values in the currently used input file, if any of them has been changed, at the start of a set of simulation runs.

5.2.4 Data output management

Managing output data from the simulation consists of two steps. The first step is to store the data during the simulation runs. The second step is to save the data to a file before running a new simulation or closing the program. The second step can be taken care of by clicking "Output file" in the GUI's menu bar after the simulation is finished, and then save the current output file under a chosen name in a chosen directory. Not saving the output data at that time means that they are lost (although the exact same file contents can be generated when using the same input variables). The output file is a MAT-file, which implies that one needs the Matlab program to view and analyze its contents.

In the current version of the simulation program, the first step may require a bit more work. Although the storage of simulation data into arrays of the program's main objects is comprehensive, the storage of these data into larger arrays that can be accessed afterwards has been restricted to those variables that are needed for this report. This has been done to keep the program as clear as possible. It would be up to the program user to add more code in order to transfer the sought-after data to these arrays as well. More importantly, the user needs to construct a matlab program that structures these arrays and may help to derive aggregate variables or perform statistical operations. The program file used for the statistical analyses in chapter 7 may prove useful in this endeavour.
5.3 Program structure

The program consists primarily of a set of class definitions, and also contains a number of separate functions. In this section, the classes are introduced, starting with the most abstract and finishing with the most concrete class. It should be noted that none of the classes fully represents an entity in the real world. Their structure is moulded towards their role in the computer program. It is more important that their behaviour by interaction is realistic than that they are realistic entities themselves.

5.3.1 Classes

The first class is the blink class. An instance of this class is made when the program is started. The constructor method of this class also calls the separate method fguiblink, which builds the graphical user interface. This function will feature further in this section and in the next section. The blink class holds the fsimrunner method, which is active continuously during the simulation. Every run, this method creates an instance of the simulator class, the second class. The simulator object serves as an intermediary between the blink object and other objects. It receives messages from blink and sends messages to others. It is responsible for communication in a single run only.

The third class is the generator class. Four instances of this class are generated each run, one for each modality covered by the model. The fourth and final class is the roaduser class. This is the meta-class of road users that was mentioned in the previous section. All four generator instances and the roaduser class are created through the constructor method of the simulator class. Under normal OO programming conditions, the generator objects would create new instances of the roaduser class. Since there is only one roaduser object, which is created straightaway, the generators are left with notifying,
rather than creating, the roaduser object that a new road user has arrived (giving its modality, origin and destination). The roaduser object has a method called fcreate, which changes an entry in a couple of matrices saved as object properties.

Other methods of the roaduser class perform other steps in the traffic interaction model of the previous chapter: creating a path and detecting potential conflicts for each new road user, changing positions, “accommodating” negotiations and adding and removing road users for each new timestep.

All classes mentioned in this section are subclasses of the handle class. This is a condition in Matlab for instances of these classes. The motivation for that is as follows. The objects generated from these four class definitions have to communicate with one another. Therefore, they need to be able to refer to one another, acknowledging them as unique objects. Metaphorically speaking, the relation between these objects resembles a posh cocktail reception: you cannot talk to one another if you have not been introduced, for example by the party host. For this communication to work, these classes must to be subclasses of the handle class. That is because Matlab defines typical OO behaviour such as notifying and listening as generic methods of this handle class.

5.3.2 Functions

The most prominent separate function of the program is fguiblink, which contains the codes for constructing the GUI. For the greater part, the code is taking care of creating graphical objects within the GUI, such as buttons and editable boxes. Matlab’s graphics objects have special features, that distinguish them from objects used in OO programming. They have a fixed set of properties matching their type and style. When programming a graphics object, one adjusts the values of these properties to give the object the right appearance and functionality.

Many of the graphics objects in the GUI require callback functions: functions that are called for example when clicking a button or changing the selection in a menu. In blink, they are mostly involved in the loading, changing or saving of input data. These callbacks are required to be separate functions (that is, separate from the fguiblink function) because they must be accessible for their associated graphics objects, even when fguiblink is not run. It is allowed though, as well as convenient, to keep them in one file with fguiblink, to avoid having fifteen different function files. Thus, the function file is named fguiblink, but it contains fifteen different functions.
Figure 5.5 Simulation model flow diagram
5.4 Simulation model flow diagram

In the model flow diagram (Figure 5.5), we can see that the traffic model contains two loops, preceded by collecting input variables and followed by calculating output variables. The seven main processes that are executed each timestep are quite different, ranging from changing a single variable (the time) to a group of complicated sub-processes. The two most elaborate processes, generation of new road users and negotiation of accelerations, are broken down in separate sub-process flow diagrams (Figures 5.7 and 5.9). Visualisation, although not a part of the conceptual model in chapter 4, is included in this model flow diagram, since it is fully integrated in the simulation program.

From these flow diagrams, it shows that, in this model, road users have a position, a speed, an acceleration and a status of being either in a queue, present or done. Also, they move within a certain road environment. Many of the relations between these variables and the calculations within the processes will be explained in the rest of this chapter. The calculation of positions and speeds of the road users is excepted from that, since this has already been explained to a great extent in chapter 4.

5.5 Initialisation

By definition, the initialisation process consists of the tasks that have to be carried out before the simulation calculations can begin. In the blink simulation program, a distinction can be made between tasks meant to prepare for an entire batch of simulation runs and tasks that need to be repeated prior to every single run. The second group of tasks mainly concerns the generation of new instances of the simulator, generator and roaduser classes, replacing the instances of the previous run. The interdependencies of these classes have been described in section 5.3.

In preparation for the entire batch of simulation runs, the input values have to be loaded from the GUI's input panels and sometimes saved to the current input file. Also, a diagram of the intersection has to be put in the GUI, in case an animation is required. In section 5.5.1, diagrams of the intersection are presented, accompanied by an explanation on the role of the road environment in the simulation. As an extension to that, section 5.5.2 goes into the simulation's dealings with priority rules. Although the Shared Space approach is not always clear on this topic, priority must be included in the model.
Figure 5.6 Diagrams of a non-priority square (above) and a priority intersection (below)
5.5.1 Road environment

The traffic moves on a two-dimensional intersection of two perpendicularly crossing roads, as is shown in Figure 5.6. These roads can have pavements and separate lanes for cyclists. The intersection consists of either the intersecting parts of the two roads or a larger square, the centre of which is the intercept of the middle lines of the two roads. The two halves of a road need not have the same dimensions. Setting a dimension at zero means that that lane is not present. Setting all dimensions for one direction at zero means that the intersection is reduced to a T-intersection. The model does not accommodate obstacles such as lane dividers or traffic humps. Separate cycle lanes and pavements for pedestrians are available for the in- and outgoing streets, but not on the intersection or square itself.

In two ways, the lay-out of the intersection has an impact upon the traffic behaviour. Firstly, it influences the paths that the road users will take: the dimensions of the intersection form the outer bounds of the paths and many of them are actual input in the creation of paths. Although the simulation model does not strictly forbid paths being outside the roadspace, the methodology of constructing paths is such that it becomes very unlikely. This methodology is explained in section 5.6.2.

Secondly, the intersection lay-out influences the traffic behaviour with respect to the speeds. As is mentioned in Table 5.2, the normal speeds to which road users tend to adhere may vary depending on the road user's position within the total roadspace. It is realistic to assume that vehicles on the intersection itself reduce their speed, since this is the location of most conflicts and least predictability of the traffic situation. In contrast, the incoming and outgoing roads are less stressful and could allow for a higher speed. For pedestrians, it can be argued that the opposite may be the case: being the most vulnerable road users, they may hurry up a bit more on the intersection to shorten the time period during which they are most exposed to the risk of a conflict with a vehicle.

It should be noted that the normal speeds are identical for all road users of a single modality. This is a simplification that would seem to have the most impact upon the frequency of expected conflicts between road users of the same modality. The justification for this simplification can be that Shared Space schemes typically aim at reducing and harmonising speeds. This should lead to relatively low speed differences already. Also, the focus of the simulation is on lateral rather than longitudinal conflicts, hence the choice for simulating an intersection. It can be argued that for lateral conflicts, the avoidance of conflicts depends greatly on the ability to accelerate or decelerate, thus deviating from the normal speed. The acceleration and deceleration pattern is covered comprehensively by the model.
5.5.2 Priority rules

Under the Shared Space philosophy, priority rules may sometimes seem to be left out, or at least kept vague or disguised. Still, they always apply, which implies that Shared Space intersections without any form of priority simply do not exist in the Netherlands. That is why the regular priority rules must be included in the simulation model. Then, it is up to individual road users with priority to decide whether or not to take that priority or yield, based on the current traffic situation.

In the simulation model, priority rules are incorporated by determining, for each combination of road users presently on the intersection, whether the rules apply and, if so, who has priority. This algorithm is executed each time that a new road user arrives, comparable to someone who arrives at a party and shakes everyone's hand. The simulation model accommodates two different priority rules. The established priority rule is assumed to be either priority from the right or priority for the primary road. If there is a primary road, it is always assumed to be in the north-south direction. Both the options of a square and an intersection lay-out can have either priority arrangement in the model. In reality, the presence of a square may be more correlated with the lack of a primary road.

If no priority rule exists, such as between pedestrians, priority is only assigned in case of a conflict. This assignment depends on the respective origins and destinations and on the distance travelled. If the two road users have the same origin or destination, resulting in a side conflict, the road user that is the farthest ahead receives priority. If this condition does not hold, the road user that has the least distance travelled receives priority. That is because many of these conflicts concern two vehicles from opposite origins both turning left, for which this is the logical priority decision.

5.6 Generation of road users

After the initialisation process, a loop of calculation processes is walked through every time step. One of those processes is the generation process, which consists of generating new road users and adding them to the intersection if there is space for them. This process is presented in Figure 5.7. It can be seen in this diagram that new road users are always first added to a queue, and then wait for room on the intersection. Obviously, if the interarrival time of road users with that modality and from that origin is considerably longer than the simulation's time step, and there is only a limited share of road users moving in a platoon or group, the likelihood of staying in the queue for even one time step is low.

In chapter 4, the assumption that road users have fixed paths that cannot be changed during their
journey across the intersection has already been mentioned. It is based on the decision to keep the model light and, as much as possible, free from traffic-behavioural claims for which this research has no data. The impact of this assumption is in two ways. Firstly, overtaking behaviour could become less likely for pedestrians and cyclists, and generally impossible for cars and lorries. This is of minor concern, because the real-life occurrence of road users overtaking on an intersection is low (being very dangerous) and because, as mentioned in section 5.5.1, speeds are already harmonised by the model, thus marginalising overtaking intentions. Secondly, the choice of fixed paths reduces the opportunities for road users to avoid conflicts. Instead of a combination of changes in speed and changes in direction as in reality, the model only accommodates changes in speed.

The traffic situation for which the choice of fixed paths may have the biggest impact is when queues develop on the intersection (for example on the secondary road). Under normal circumstances, right-turning cyclists or pedestrians may pass this queue on the right, but the simulation does not accommodate that. On the other hand, a Shared Space scheme is often intended to create continuously flowing traffic. That would mean that passing on the right becomes less of an issue.

---

**Figure 5.7 Flow diagram within generation process**
5.6.1 Traffic flows and arrival pattern

There are four modalities defined: pedestrians, cyclists, car users and lorry users. These can have their origins and destinations in all four directions. In theory, the model should be able to handle the case that origin and destination are the same, but this has not been considered during its construction. It is no problem to leave any of the possible OD-pairs empty (as in the case of a one-way road).

Pedestrians and cyclists often travel in small groups, instead of as an individual. The model accommodates this by generating groups of road users simultaneously, with identical origin and destination. For cars and lorries, a similar but not identical pattern of collective movement can be found. They can form platoons caused by speed differences, as there is rarely room for overtaking. The road users in this platoon will have the same origin but not necessarily the same destination.

In traffic simulations, the exponential distribution is often used to generate random values for the time between independent arrivals of road users on the intersection. This is equivalent to a Poisson distribution for the number of arrivals within a certain time period. In case of groups of users travelling together or forming platoons, arrivals of individual users cannot be considered independent, but the arrivals of these groups still can. That is why the model generates random interarrival times between the groups of users from an exponential distribution.

The size of these groups of users must also be determined at random. In theory, it ranges from 1 to infinity. The chosen approach is to use a fixed probability for each modality that a road user is followed by a road user of the same modality. If so, this follower again has the same probability of being followed, etcetera. The sequence of constant probabilities of “success” leads to a geometric probability distribution. This is a distribution that is discrete and that has no memory: the probability of adding another member to the group stays the same, no matter how large the group already is.

Note that, to calculate the expected (mean) interarrival time between groups, the inverse of the traffic flow must be divided by the expected (mean) number of road users in the group. Also note that the model accommodates unimodal groups and platoons only. So a platoon of for example a lorry followed by three cars cannot be generated. Obviously it can be observed in the model if the arrival times of the next platoons for these modalities (for this origin) are close to each other.

In Figure 5.7, it can be seen that newly-generated road users are first added to a virtual queue. In theory, every waiting road user has its own queue, because this condition of available space is reviewed for every user. In practice, road users of the same origin and modality will share a queue,
with cars and lorries merging their queues as well. In many cases, newly-generated road users will leave their queue directly after their generation if they are not in a group.

5.6.2 Path generation

The paths are a combination of straight lines while travelling on the incoming and outgoing roads and a Bézier curve for the intermediate curve on the intersection. Some of the coordinates of a path are identical for all road users with the same origin or destination (and sometimes modality), others are variable within certain bounds. For example, the lateral position of pedestrians on an incoming road varies over the entire width of the pavement, save for the outer pieces measuring half of the pedestrian’s width, as to prevent the user from walking in the gutter or against buildings... A uniform distribution is used to determine the exact lateral position of the pedestrian if the pavement is wider than himself. The same applies for cyclists. If there are no pavements or cycle lanes, pedestrians and cyclists will have to use the road and are supposed to stay as far to the right as possible.

The reasons for using unique individual paths (if permitted by the road dimensions) are twofold. In the first place, the Shared Space approach emphasises the importance of individual traffic decisions over prescribed ones, and determining its position is one of the fundamental decisions of a road user. Also, adding variety to the paths brings some randomness to the initial positions of road users entering into a negotiation process. This should lead to the varied negotiation results that Shared Space presumes.

The Bézier curve is a particular curve that uses a set of ‘control points’ that the curve adheres to without necessarily running through it (see Figure 5.8). There are three reasons for using Bézier curves in this model. The first one is the ease to change their form by using random numbers for a part of the control points coordinates. The second reason is the similarity of these curves to the clothoid curve. In other words: the control points can be chosen as to create a curve with a gradually decreasing and increasing radius. Thirdly, the tangents of the curve at the starting point and at the finishing point are easy to fit with the straight lines for the incoming and outgoing roads. The tangent at the starting point is a line through the starting point and the first control point, while the tangent of the curve at the finishing point runs through the finishing point and the last control point.
The simulation model presented here uses Bézier curves with a starting point, a finishing point and only two control points. The positions of these four points determine the shape and position of the entire curve, as can be seen in this formula:

$$\vec{Q}(u) = (1-u)^3 \vec{P}_0 + u(1-u)^2 \vec{P}_1 + u^2(1-u)\vec{P}_2 + u^3 \vec{P}_3, \quad u \in [0,1]$$

with:
- $\vec{Q}$ Bézier curve vector
- $u$ curve domain
- $\vec{P}_0$ starting point position vector
- $\vec{P}_1$ position vector of first control point
- $\vec{P}_2$ position vector of second control point
- $\vec{P}_3$ finishing point position vector

The reason for using two control points rather than any other number is that it seems to be the lowest number of points for which a 90 degree turn can be modelled realistically. Having only one control point leads to a too simplistic curve, while any number of control points higher than two can make a curve more complicated but not necessarily more realistic.

The lack of a formula of the curve in the form of $y = f(x)$ is a drawback of a Bézier curve. This is not a major problem, as an alternative numerical method to represent positions on the path is used. The path is represented by a set of two-dimensional coordinates, between which the road user moves on straight line elements. This approximation thus has a smaller total distance than the original curve. The difference depends on the number of elements in the approximation.
The path itself is the collection of points through which the base point of the road user travels. As mentioned in chapter 4, in the model implementation, this point is assumed to be in the front half of its physical space, as to resemble the location of the steering axis. Although pedestrians have no axes, their base point is also located in their front half. A less realistic point concerns lorries. The model does not have the capability to simulate turning movements with wheels steering. That means that the rear of vehicles, in particular that of lorries, may swing wildly. This may be avoidable by using more sophisticated formulas, but these have not been derived or included.

The angle of movement of the road users relative to the 'north', which is primarily used for the visualisation of the simulation, is calculated as the weighted average of the tangents of the two path points between which the user moves at that time instant. Each of these tangents is derived as the arctangens of the quotient of the north-south distance and the east-west distance between the two closest path points. The tangents of the first and last path points are considered equal to the tangent of the closest curve element, which is always a multiple of \( \pi/2 \).

If the calculated travelled arc length is larger than the actual total length of the curve, the road user is removed from the intersection, and given the 'done' status instead of the 'present' status. It will no longer be taken into account by other road users when detecting potential conflicts.

In the model implementation, the detection of conflicting paths is performed directly after a new road user is admitted to the traffic space. The mathematical equations of this process have been treated extensively in section 4.3.1. Every road user keeps records of all other road users with conflicting paths and of all its own coordinates involved in such a conflict.

### 5.7 Negotiation

One of the cornerstones of the Shared Space philosophy is that road users under threat of conflict will enter into negotiations to determine who will proceed and who will slow down, not necessarily respecting established priority rules. In the model, this negotiation process has been reflected in a complex algorithm to determine all accelerations, which has been explained in section 4.3. Basically, it is a series of tests for individual road users and for their foreseen interaction to judge whether a certain acceleration or deceleration helps to avoid a conflict or reduce its impact. This algorithm is less a negotiation itself than an algorithm to determine the likely outcome of a negotiation. It tries to give a logical, deterministic outcome of the negotiation process based on the planned trajectories.
Figure 5.9 shows the flow diagram of the negotiation process. The first step of the negotiations is that all road users determine their preferred accelerations and find out whether conflicting trajectories can be expected. For these preferred trajectories, two important choices have been made. The first one is that every road user has a normal speed, to which it tries to adhere, for every part of its curve. This has already been mentioned in sub-section 5.5.1. A second important choice is that all modalities have a normal acceleration and a normal deceleration, as opposed to a maximum acceleration and a maximum (in absolute terms) deceleration. The normal values are used under non-conflict circumstances and for less urgent potential conflicts, as they are supposed to be more comfortable than maximum acceleration and deceleration (which are used under more urgent circumstances).

For every road user, it needs to be tested whether following the preferred trajectory would lead to one or more conflicts with other road users. Chapter 4 has explained the mathematical equations to transform a set of trajectories to a set of foreseen conflicts within someone’s time horizon. Road users that do not foresee a conflict may use their preferred acceleration.

The other road users are transferred to another sub-process. This negotiation of alternative accelerations sub-process is shown in Figure 5.10. It repeatedly refers to the Tables 4.1 to 4.6 from the previous chapter. These tables contain the sequences of acceleration options that the implementation needs to explore, classified by established precedence, number of road users involved and mutual cooperation (initiative and politeness variables) of the two road users.
As has already been explained in sub-section 5.5.2, all potential conflicts that need to be handled in this sub-process must have a priority arrangement. That is because the tested acceleration patterns of priority road users and yielding road users are not identical. Since the implementation establishes the priority between road users only when necessary, the "determine priority" sub-process is shown in Figure 5.10 as making a short loop back to the "All conflicts handled?" decision point.

Figure 5.10 Decision tree of determining negotiation result
Figure 5.11 Screenshot of visualisation and explanation of its elements
It should be noted that the implementation does not guarantee that road users, despite handling their potential foreseen conflict, will never collide or enter one another's comfort zone. The simulation does not formally acknowledge existing conflicts, since physical overlap of road users is neither registered nor made impossible. In the end, the accepted accelerations are intended to be a deterministic answer to a complex and unpredictable traffic situation.

5.8 Visualisation

The last process before finishing a calculation time step, assuming that the calculations are not executed in the fast mode, is visualising the simulation results in the axes of the GUI. This consists of removing parts of the previous visualisations that are no longer accurate and adding new elements based on the calculations performed during the current time step.

The screenshot in Figure 5.11 shows that the axes of the GUI contain various dynamic elements, amongst which the current position of the present road users (the rectangles), their current speeds (the numbers next to the rectangles) and their trajectories up to this time step (the lines). Each time step, the old positions and speeds are removed and replaced by the current ones. That is also the case with the current simulation time in the lower left corner of the axes. It should be noted that the colours of the current speed numbers give an indication of the current accelerations of the road users. Black means zero, green positive, red moderately negative (normal deceleration) and purple stands for the maximum deceleration, only used for a very urgent conflict.

The visualisation of the trajectories is organised differently. Rather than replacing the current trajectories, an extra element is added to the axes. Thus, the seemingly continuous curve consists of many curve elements. These elements need not be straight lines themselves; any intermediate set of coordinates of the individual preferred path (Bézier curve) will form a point on the curve element. In that way, the visualised curve is identical to the covered trajectory in the simulation.

Once the road user is finished, i.e. it has covered a longer distance than the length of its preferred path, the simulation model no longer calculates its further movement. Its position and speed are no longer visible. From then on, every timestep, the oldest element of the curve is removed from the axes. After a time period as long as the road user's total stay on the intersection, the last element is removed.

When a simulation run finishes, all positions, speeds and trajectories are removed from the axes. If a new run is initialised, the axes’ run number is added up by one and the simulation time is back at zero.
6 Face validity analysis

In this chapter, the face validity of the model is analyzed. This means that it will be assessed, in broad terms, whether the simulation model works according to expectations. In this case, the model is expected to show generic traffic behaviour suiting a Shared Space road environment. Various traffic configurations will be fed into the program, in order to give both a qualitative judgment with respect to the appearance of the simulated traffic behaviour and a quantitative analysis of the relations between various traffic variables. Most of the input variables used do not change between the configurations, such as the physical dimensions of the road users. The traffic situations are intended to give an impression of the model's capabilities, not to make a sensitivity analysis of all variables involved.

In the first section, the criteria for the analysis are explained: which elements of traffic behaviour and which variables are taken into account? The next section introduces the eight traffic configurations that will be used for observations. The observations themselves, including selected output values, are presented in the third section. This is followed by a conclusion in the fourth and final section.

6.1 Criteria for face validity

In this section, three criteria for sufficient face validity are defined. All three criteria deal with the interaction between road users, rather than with isolated individual traffic behaviour. The rationale of this choice is, firstly, that simulating the interaction between road users is the most challenging task for the model and, secondly, that negotiation is the traffic process for which the strongest impact of the Shared Space approach is supposed to be found. These are the three criteria:

Criterion 1 Realistic moving and following behaviour
Road users tend to keep or speed up to their preferred speed if they can, whereas encountering slower road users in the same direction may require overtaking or adhering to a lower speed. As overtaking is only rarely possible in this simulation model due to overlapping fixed paths, many road users may have to moderate their speed. The model gives all road users of the same modality an identical preferred speed, so as long as there are no disruptions (including decelerations to give way), speeds may be kept fairly high. The higher the traffic intensity, the higher the probability of disruptions becomes. That is why it can be expected, both in reality and in the model, that increasing traffic flows will lead to a lower speed and a stagnating throughput of the intersection.
Figure 6.1 Eight traffic configurations (pedestrians in green, cyclists in red, cars in blue, lorries in dark blue)
Criterion 2 Realistic handling of priority conflicts
Ideally, road users give way when it is required and do not give way if they have priority or if they can leave the conflict zone before another road user arrives. Obviously, there are more ambiguous, multi-interpretable traffic situations feasible, leading to road users offering different strategies to solve a conflict. It is fair to say that the Shared Space approach actively encourages the creation of road environments in which many traffic conflicts are ambiguous. Translated to a face validity criterion, the simulation output should reflect that road users recognise and adhere to priority rules, but keep an open mind to other outcomes if that fits better with the current traffic situation. There is no particular ratio between adherence and non-adherence to qualify for face validity, so it depends on the particulars of a traffic situation which outcomes are realistic.

Criterion 3 Significant impact of changes in level of initiative and politeness upon conflicts
Apart from the priority situation and the road users' paths and kinematics, the conceptual model assumes that the handling of potential conflicts is also impacted by the levels of initiative and politeness. The simulation model must show this impact in a significant and realistic way in order to be considered face valid. If this impact is not found, this may be due to the Shared Space approach not working as supposed or the simulation model not following the approach correctly.

A judgment of the model's performance on these three criteria can be pronounced in, at least, two ways. On the one hand, it is possible to take a look at the visualised model output, i.e. the on-screen movements of simulated road users, and give a qualitative assessment of its level of reality. This could relate to issues such as acceleration and deceleration patterns, traffic jams and breakdowns, physical implausibilities and the impact of the fixed route choice on the occurrence of conflicts. Another option is to collect output data and perform quantitative analyses on them, in order to see if the relations between variables, such as traffic intensity and speed, match with expectations. In this chapter, in particular section 6.3, both methods are used simultaneously.

6.2 Configurations

In total, eight different configurations are defined. An overview of them is provided in Figure 6.1. These eight have been chosen for two reasons. Firstly, they are supposed to offer a wide range of traffic situations, in particular amongst the possible modalities. Secondly, they must suit the three criteria for face validity as introduced in the previous section; there are configurations in which longitudinal conflicts are dominant (in order to study following behaviour) and configurations with more attention for crossing traffic flows (to study priority behaviour and the impact of initiative and politeness).
The first three configurations all have no priority conflicts. The only possible conflicts in them are rooted in road users having roughly identical paths for a part or the whole of their route. The first configuration contains only cyclists from one origin, all going straight ahead. Configuration 2 adds some variation to that by introducing a destination split. Half of the traffic flow is supposed to head straight on, with the rest equally divided over the two other directions. These proportions have been chosen to reflect that, as a rule, most traffic tends to go straight on, while still allowing for all possible flows to occur at a significant level. With low intensities for certain OD-pairs, the actual destination split would vary greatly between simulation runs, with the risk of volatile aggregated output variables. Configuration 3 adds another novelty: it contains traffic flows consisting of both cars (90%) and lorries (10%), going in all directions. Since the two modalities have diverging kinematical characteristics and preferred speeds, their interference can be expected to be more complex than in the first two cases.

These first three configurations lead to negotiation processes in which, without an exception, the precedence of one road user before the other has already been established. That means that only a part of the negotiation algorithm is applied. In the configurations 4 to 8, the algorithm is fully used. Also, every modality is included at least once in a priority conflict in these configurations.

Configuration 4 consists of perpendicular two-way flows of cars all going straight ahead on a priority intersection. Configuration 5 also contains road users of only one modality: cars from one direction all intend to go straight ahead, while cars from the opposite side all take a turn to their left. Although this technically does not qualify as a priority rule, the Dutch traffic regulations clearly state that the traffic flow going straight ahead must go first in this traffic situation.

In configuration 6, only straight-going pedestrians and lorries are involved. The lorries come from the right, the pedestrians from the left, so the lorries have priority. The seventh configuration is partly the same, with cyclists coming from the right and cars from the left. Only this time, both modalities have destination splits, using the same proportions as in the configurations 2 and 3. This means that there are three locations for potential conflicts rather than one. In the eighth and final configuration, right-turning cars are supposed to give way to straight-going pedestrians with the same origin as the cars. Again, this is technically not a priority conflict, but there is an established rule to handle it.

Overall, the configurations 4 to 8 provide a wide range of possible conflicts between road users with diverging characteristics, exactly as the Shared Space approach propagates.
6.3 Observations and analysis

In this section, the simulated traffic behaviour in the eight traffic configurations is studied. This is done both by basic observation and by collecting and analyzing values of appropriate traffic parameters.

6.3.1 Moving and following behaviour

For the aspect of moving and following behaviour, the focus is on the first three configurations. For each of the three configurations, the observations and analyses are put here separately.

Configuration 1: groups of cyclists from one side, all going straight ahead
A significant number of cyclists enter the system as part of a group. Under limited traffic intensity, these groups have a low probability of interfering with one another. Within the group, the cyclists have an obvious impact on one another’s acceleration pattern, in particular when the leading vehicle reduces its speed close to the intersection. Since the following vehicle is not yet as close to the intersection, its desired speed has not changed yet, making this an urgent foreseen conflict. The deceleration of the following vehicle is at the maximum value, while the leading vehicle only slows down with normal deceleration. After a few timesteps, the following vehicle accelerates again, slowly.

It would be interesting to know the effect that these patterns of deceleration and acceleration have on the average speed and the capacity of the intersection. In order to collect output data on this, the simulation has been run for a range of traffic intensities. Figure 6.2 shows plots for the average speed of the cyclists (blue line) and the total throughput of the intersection (transparent bars) as a function of the potential traffic demand. Every bar represents one simulation of two runs of five minutes of simulation time each. One can see that the throughput increases steadily, although not evenly, with traffic demand until close to 4000 cyclists per hour. At that point, the total throughput comes close to 600 cyclists over ten minutes, which would be equivalent to an intensity of 3600 per hour. Increasing the intensity any further simply leads to a higher stack of cyclists waiting to enter the intersection, which is only allowed if there is a space available. In this respect, the model seems to work as expected.

The average speed diagram in Figure 6.2 shows that disruptions seem to be limited for traffic intensities up to 2000 cyclists per hour. This is more than can reasonably be expected on the average Shared Space intersection. Surprisingly, the average speed is higher for unrealistically high intensities. This seems to be accompanied by frequent physical overlap between road users, which would lead to the conclusion that the model does not give realistic results for very high intensities.
Figure 6.2 Average speed and total throughput as functions of traffic demand in configuration 1 (cyclists)

Figure 6.3 Average speed and total throughput as functions of traffic demand in configuration 2 (pedestrians)
The model does not facilitate cyclists riding alongside one another, since the cycle lane is not wide enough. But even if the lane was wide enough, cyclists would still not be able to consciously choose a path that would allow for riding alongside one another possible, let alone overtaking. The cyclists should have been assigned very diverging paths by chance, not by choice, to make that possible. At face value, the lack of cyclists riding together makes their behaviour less realistic.

Configuration 2: pedestrians from one side, going in all directions

Due to the higher width of the pavement, some pedestrians are able to walk in pairs for parts of their trajectories. Where their paths interfere, for example during turns, they may tend to take more distance from each other (one of the two decelerates). It is clear that these pedestrians have no relation with each other; they merely tolerate each other as long as their trajectories do not interfere.

All pedestrians have the same origin here, but they need not have the same destination if not part of one group. Consequently, tangential conflicts are foreseen. The resolution of these conflicts by the model seems fine, though a bit arbitrary. That is logical, since they have no priority rules among them.

Figure 6.3 shows the plots for average speed and total throughput as a function of the potential traffic intensity going with configuration 2. The maximum capacity of the intersection seems to lie at approximately 2000 pedestrians per hour. Remarkably, the speed reduction for increasing intensity levels is quite small. This may be related to the fact that pedestrians have a higher preferred speed in the middle of the intersection than on the incoming and outgoing roads, and thus have a short period with acceleration and then deceleration. This may alleviate rather than cause following conflicts. It may also be related to the observation that all pedestrians decelerate directly upon entering the intersection. Apparently, the negotiation algorithm considers the minimum distance between pedestrians that the arrival algorithm uses too small for safety. This deceleration slows down the entering of the next pedestrians waiting in the stack, which also moderates the traffic flow.

Configuration 3: cars and lorries from one side, going in all directions

Cars and lorries have different normal speeds, so sometimes cars need to slow down to harmonise their speed with lorries. Normally, this would be an issue for the mid-block road sections. In this model, cars and lorries only form a platoon if their arrival times are, by chance, close. For higher traffic intensities, this is obviously more likely to happen. The single-modality platoons are inserted in the same stack of road users waiting to enter the intersection, which is as far as their mixing goes.

In this first appearance of lorries, one notices that their turning movements, especially to the right, are very basic. The paths of all road users are based on a set of coordinates and their tangents, and not on
two axes and steering-wheels at the front. In this configuration, this does not matter at all, since there is no traffic on other lanes. If there was, this excessive swaying out could lead to conflicts.

Figure 6.4 shows the average speed and throughput data for configuration 3. Compared with the two previous figures, the results seem to be less robust. This seems to be caused by a combination of two factors. Firstly, the mixing of modalities is likely to cause much more disruptions in the traffic flow than were present in the previous two configurations. Secondly, of all modalities, car and lorry are the heaviest, thus the slowest to accelerate and decelerate. That means that these modalities will have the most difficulty to smoothen out flow disruptions, leading to further deceleration upstream.

For the combination of cars and lorries, the maximum capacity seems to be in the order of 2000 vehicles per hour, under ideal circumstances and without any other traffic. In real-life non-signalised urban traffic with low speeds, this level of intensity is unlikely to occur. For lower intensities, the model seems to work as expected. Occasionally, road users seem to decelerate more than is needed, but they do solve their conflicts in a correct manner.

Figure 6.4 Average speed and total throughput as functions of traffic demand in configuration 3 (cars and lorries)
6.3.2 Handling of priority conflicts

The aspect of handling conflicts, involving priority and negotiation, requires attention to the configurations 4 to 8. Again, qualitative observations of traffic behaviour are mixed with a modest quantitative analysis on the basis of plain book-keeping. Every configuration is simulated for two runs of five minutes of simulated time each. For this total of ten minutes, it is recorded for every occurring priority conflict which road user (eventually) goes first. This is either the primary road user (the one which has priority) or the secondary road user (the one which the rules require to give way). As was mentioned in section 6.1, the consideration of face validity does not come with a specific ratio between the number of precedences for the primary road user and that of precedences for the secondary road user. It is also important that the modelled negotiation process itself is performed realistically.

Configuration 4: cars coming from all sides, all going straight ahead

This is the first configuration involving traffic from more than one side, hence the need for priority rules. Defining the north-south route as the priority road, most of the foreseen conflicts are indeed solved by deceleration of the cars on the east-west route. In Table 6.1, the number of precedences for both traffic flows can be found (for all five configurations). Clearly, the cars on the primary road go first in most of the cases (54 times). In some cases, traffic on the secondary road is allowed to go first (17 times). Nevertheless, occasional queues on the incoming lanes of the secondary road can be observed.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Primary flow</th>
<th>Number of precedences</th>
<th>Secondary flow</th>
<th>Number of precedences</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Cars on primary road</td>
<td>54</td>
<td>17</td>
<td>Cars on secondary road</td>
</tr>
<tr>
<td>5</td>
<td>Cars going straight</td>
<td>32</td>
<td>5</td>
<td>Cars turning left</td>
</tr>
<tr>
<td>6</td>
<td>Lorries going straight</td>
<td>14</td>
<td>7</td>
<td>Pedestrians crossing</td>
</tr>
<tr>
<td>7</td>
<td>Cyclists from the right</td>
<td>39</td>
<td>4</td>
<td>Cars from the left</td>
</tr>
<tr>
<td>8</td>
<td>Pedestrians going straight</td>
<td>28</td>
<td>14</td>
<td>Cars turning right</td>
</tr>
</tbody>
</table>

The queues on the secondary road can become a problem for incoming traffic. If an incoming car cannot reduce speed fast enough, it may physically overlap a preceding vehicle. Almost always, the following car will come to a stop anyway, and can only accelerate after the leading vehicle has moved away again. One could say that these vehicles adhere to a first in, first out policy.

In case of a conflict, the cars reduce speed fairly quickly, sometimes maybe too much. Most road users seem very keen on getting back to speed if possible though. A gridlock of cars seems to be very rare, which is good, but this comes at the price of the occasional overlap of crossing vehicles.
Configuration 5: cars from opposite sides, one straight ahead, one turning left
Just like in the previous configuration, the cars in these flows are well aware of who should go first, and adhere to it in most cases. In the analyzed simulation runs, the primary road user has gone first in 32 cases, the secondary road user in only 5 cases. Again, queues of more than two cars are building up a few times. The left-turning vehicles all take slightly different paths. This seems very close to reality.

It happens a few times that two cars from opposite sides slow down, even when they are not on the intersection. That is caused by their left sides being too close to each other. If the paths had not been fixed, they would have moved to the centre of their respective lanes to avoid this side conflict. It has only a limited impact on the negotiations on the intersection itself.

Configuration 6: groups of pedestrians coming from the west, lorries coming from the south
In this configuration, the lorries are supposed to go first, and this happens frequently. It seems that only when a pedestrian gets as far as blocking a lorry's path, the lorry will yield. This results in a 2:1 ratio of precedence for the primary and secondary road user (14 to 7 precedences). In reality, a group of pedestrians assembling on the verge of the intersection may convince the lorry driver to brake. This impact of acting as a collective cannot be found in the behaviour of the pedestrians in the model. That is because the simulation model sees every conflict as involving only two road users.

Configuration 7: cars coming from the west, cyclists coming from the south
In contrast with the previous one, the slower and more vulnerable modality has priority in this configuration. Again, even with maximum inclination for politeness and initiative, the number of conflicts where priority is given away is very low: cars are allowed to go first only 4 times, while cyclists retain their priority 39 times. Simultaneously occurring conflicts are very rare, thus the model has no difficulty determining which conflict is the most urgent. The foreseen conflicts are resolved easily. Even though the cyclists have priority, some of them tend to slow down to approximately half the normal speed on the intersection. But that does not mean that they do not go first.

Configuration 8: cars turning right, pedestrians going straight ahead, all from one side
In the final configuration, the cars again have to give way, this time to crossing pedestrians. The model is very clear in pushing the car to take the first acceptable gap, even if there is a much larger gap coming up later. Over the two simulation runs, a pedestrian is counted to go first 28 times, while a car has gone first 14 times. This is a much more even distribution than in the previous configuration, which may be related to the larger initial speed difference between cars and pedestrians: with their relatively high speed, cars may be able to push themselves through the flow of slow pedestrians. At very low speeds, pedestrians may have an advantage due to their stronger ability to accelerate.
It is interesting to notice that the flow of pedestrians makes the calculations very slow. Not only are there a lot of pedestrians in the system to begin with, but they also seem to need quite a lot of calculation time individually. This may be caused by the calculation of their trajectories; with such a low speed, the completion of their trajectories to the maximum arc length takes a lot of timesteps.

6.3.3 Impact of initiative and politeness

Up to this point, the face validity analysis has been based on the observations and output values of simulations of eight traffic configurations, always under the assumption that the shares of initiative and politeness in the population of road users are optimal (100%). To isolate the impact of these levels upon the simulation results, the same simulations need to be run again, with only these percentages adjusted. For a maximum contrast, the new shares of initiative and politeness are set at 0%. Even then, the differences between the two sets of simulations are difficult to distinguish for two reasons.

The first reason is that, for many conflicts, the levels of initiative and politeness do not play a role at all, i.e. they are not used by the algorithm in that particular case. For example, their impact is solely on conflicts for which no precedence has been defined yet. That implies that simulating the configurations 1 to 3 would not lead to any other outcome. The configurations 4 to 8, which all deal with conflicts between different flows, are suitable for this part of the analysis. Secondly, even if the input variables are used, that does not mean that the chosen strategy to solve the conflict would be significantly different if they had a different value. Rather than describing individual conflicts qualitatively, the face validity analysis consists of, again, counting the precedences for the primary and secondary road users and compare them with the previous set of counts.

The precedence counts of the five remaining configurations are in Table 6.2. The road users in the primary flow have much more precedences than those in the secondary flow, with no ratio below 3:1. This would indicate that with limited options for negotiation, adherence to priority rules is the norm.

<table>
<thead>
<tr>
<th>Config</th>
<th>Primary flow</th>
<th>Number of precedences</th>
<th>Secondary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Cars on primary road</td>
<td>64</td>
<td>Cars on secondary road</td>
</tr>
<tr>
<td>5</td>
<td>Cars going straight</td>
<td>38</td>
<td>Cars turning left</td>
</tr>
<tr>
<td>6</td>
<td>Lorries going straight</td>
<td>17</td>
<td>Pedestrians crossing</td>
</tr>
<tr>
<td>7</td>
<td>Cyclists from the right</td>
<td>39</td>
<td>Cars from the left</td>
</tr>
<tr>
<td>8</td>
<td>Pedestrians going straight</td>
<td>43</td>
<td>Cars turning right</td>
</tr>
</tbody>
</table>
On themselves, the precedence values in this table seem realistic, but to be an indication of face validity, they must be compared with the values of Table 6.1. For an easier comparison, the numbers of the two tables have been combined into a bar graph, which is shown in Figure 6.5.

Figure 6.5 Precedence of primary and secondary road users in configurations 4 to 8, with initiative and politeness at both 100% or 0%

Please note that the bars for each configuration need not be of equal length. After all, the resulting precedence in a conflict may influence the existence of another conflict. For example, there is a single cyclist with initiative yielding to an infinite platoon of cars with priority. Then, the number of conflicts, which is the length of the bar, is equal to the number of cars taking priority plus one for the first car that decides to give way to the cyclist. So while the total number of road users having passed the intersection does not change, the number of negotiations can. That is why, even though the traffic flows for both sets of simulation runs are (almost) equal, the numbers of precedences may be different.

Overall, the effect of high initiative and politeness levels seems to be, for several configurations, that the established priority has become a bit less dominant in determining which road user goes first. This is in line with the assumptions of the Shared Space approach. The change in precedence of the primary traffic flow is particularly high in the configurations 4 and 8. In configuration 6, the precedence of the secondary traffic flow is almost nonexistent if the initiative and politeness shares are reduced to 0%. For the two other configurations, the differences between the two bars are marginal.
6.4 Conclusion

In this chapter, simulations of eight traffic configurations have been carried out with the intent of analyzing the model’s face validity, in particular with respect to the interaction between road users. Following behaviour, conflict handling and the impact of the variables initiative and politeness have been taken into account, both by simple observation and quantitative analysis of the output results.

The observations with respect to following behaviour show that most longitudinal conflicts are solved realistically at moderate levels of intensity, with an occasional overreaction. The relations of the potential traffic intensity with the average speed and the realised traffic throughput are plausible up to a realistic maximum capacity of the roadway. The capability of the model to facilitate overtaking is limited, but this was known before running any simulation. In real life, overtaking on the intersection itself is less common than on mid-block road sections, which are not part of the simulation.

The analysis of simulated priority conflicts gives realistic ratios of precedence for priority and non-priority traffic in all five traffic configurations. Although observations of individual negotiations may result in an occasional raised eyebrow, most priority conflicts are solved adequately. Road users are quick to decelerate in case of a conflict, but also to accelerate if possible. Since all conflicts are viewed as involving only two road users, the impact of road users negotiating as a collective is not present.

With respect to initiative and politeness, the quantitative analysis shows for the majority of the simulated traffic configurations that adjustments in their values do have an impact on the ratio of precedences for the priority and non-priority traffic flows. Having a population of road users that is more inclined to take initiative and give way to other road users reduces the dominance of priority rules in determining which road user goes first, which is in line with the Shared Space approach.

On the whole, the model’s face validity seems sufficiently warranted to use the model further in this thesis. For all three studied aspects, the simulation results are largely as expected for realistic traffic demand. In the next chapter, the simulation model is used to determine the impact of the shares of initiative and politeness on some indicators for the performance and safety of a generic intersection.
7 Model application

In the previous chapter, the simulation has been applied at a small scale, in order to judge its face validity. In this chapter, the blink simulation program is used to determine the impact of changing the behavioural variables of the model on the performance and safety of a generic intersection. In the first section, four different cases are introduced. After that, the output variables are explained. The results of the simulation are presented and analyzed in the third section, both in statistical and traffic-related terms. The last section of this chapter formulates conclusions on the model’s applicability.

7.1 Four cases and its input variables

There are four different cases that will be studied. The only distinction between these are the values of the traffic behaviour variables: the share of road users taking initiative and the share of road users inclined to being polite. The values are shown in Table 7.1. The variation of these variables is intended to reflect to which extent the population of road users adheres to the traffic behaviour associated with Shared Space. As has been explained in chapter 4, the model does not get into the question of how this behaviour comes to be at that level. This can be caused by either a change in the road environment, such as a new road design, or a change in the underlying characteristics of road users, for example caused by an information campaign. A combination of these two kinds of changes could be that a share of the population avoids the intersection due to a lack of subjective safety.

<table>
<thead>
<tr>
<th></th>
<th>Case 1: all 0%</th>
<th>Case 2: all 50%</th>
<th>Case 3: variation</th>
<th>Case 4: all 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Initiative</td>
<td>Politeness</td>
<td>Initiative</td>
<td>Politeness</td>
</tr>
<tr>
<td>Pedestrians</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>40</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Cyclists</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Cars</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>80</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Lorries</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>90</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

The rationale of these four cases is as follows. There are two extreme cases, in which either no road user adheres to Shared Space traffic behaviour, or all of them (case 1 and 4, respectively). In between these two cases, there is a case (case 2) in which half of the road users is polite and half of the road users likes to take initiative. These two variables are independent of each other, so a road user can have either of the four combinations of these two. In this case, every combination holds approximately
a quarter of the road users, so only a quarter of the road users would be behaving as the Shared Space approach would intend them to. Other road users may be too restrained or antisocial to do so.

In addition, there is a case (case 3), for which the percentages of the input variables differ by modality. These values are intended to provide realistic traffic behaviour, in which motorised traffic is supposed to act more restrained by means of having relatively few road users taking initiative and relatively many being polite. For non-motorised traffic, it is the opposite: fewer road users showing politeness, more road users taking initiative. This distribution is based on the overall vision of the Shared Space approach of giving slow traffic a better position in negotiations about priority. (Whether or not this works out in reality the way it was intended is another matter.) The sum of the input variables in case 3 has been kept the same as in case 2 (100 % per modality), in order to specifically look for the impact of relative variations in the input variables, rather than that of a rise of their sum.

Other than the behaviour variables, all variables have been kept constant for the sake of an optimal comparison between the cases. This includes the traffic intensities and the dimensions of the intersection, and even the random seed. The traffic intensities have been put in Table 7.2. These traffic intensities are chosen with the intention of them being neither too low for any significant potential conflict nor too high for optimal functionality of the algorithm. The latter means that, if it is too high, there is a chance that the simulation model will not be able to handle such an amount of traffic without gridlock, as has been found in the previous chapter. The intersection is a square (20 by 25 metres) and priority is given to road users coming from the right. Pedestrians only have priority over vehicles when going straight ahead while the vehicle is turning. All the four roads have cycle lanes and pavements.

### Table 7.2 Traffic intensities for the four cases

<table>
<thead>
<tr>
<th>O\D</th>
<th>Pedestrians</th>
<th>Cyclists</th>
<th>Cars</th>
<th>Lorries</th>
</tr>
</thead>
<tbody>
<tr>
<td>/h</td>
<td>N E S W</td>
<td>N E S W</td>
<td>N E S W</td>
<td>N E S W</td>
</tr>
<tr>
<td>N</td>
<td>0 15 30 15</td>
<td>0 30 60 30</td>
<td>0 30 90 30</td>
<td>0 6 18 6</td>
</tr>
<tr>
<td>E</td>
<td>15 0 15 30</td>
<td>30 0 30 60</td>
<td>30 0 30 60</td>
<td>6 0 6 12</td>
</tr>
<tr>
<td>S</td>
<td>30 15 0 15</td>
<td>60 30 0 30</td>
<td>90 30 0 30</td>
<td>18 6 0 6</td>
</tr>
<tr>
<td>W</td>
<td>15 30 15 0</td>
<td>30 60 30 0</td>
<td>30 60 30 0</td>
<td>6 12 6 0</td>
</tr>
</tbody>
</table>

Is it problematic that the simulation is only performed for a single set of traffic intensities and intersection dimensions? The behaviour variables only play a role in resolving potential conflicts, so to respond to this question, it must be analyzed how varying traffic flow intensities and intersection dimensions would impact the occurrence and nature of such conflicts. Logically, higher traffic intensities may lead to a higher frequency of potential conflicts, but in particular of complicated ones,
with more than two road users involved. Since the simulation model algorithm always searches for the lowest TTC between two road users to determine accelerations, it can be argued that the algorithm approaches all conflicts as if concerning only two road users. The third (or fourth) road user in this conflict cannot influence the accelerations of the others. This results in a higher likelihood of a sub-optimal acceleration. This has the potential of making the simulation results less robust. In that sense, the model could have problems with complicated potential conflicts. These conflicts may lead to unpredictable outcomes, thus compromising its validity.

With respect to intersection dimensions, the main connection between these and potential conflicts is through the generation of fixed trajectories. It appears that the assumption of fixed paths becomes less realistic if there is more roadspace for road users to deviate from their preferred trajectory. On the other hand, if the intersection is more spacious, the trajectories that the simulation algorithm prescribes can also be further apart, which helps to reduce the occurrence of potential conflicts, particularly tangential conflicts. Also, there is a definite lower bound for the dimensions of the incoming and outgoing roads, as they must allow for passing traffic from opposite directions.

On the whole, it cannot be ruled out that changing the non-behavioural input variables, especially upwards, would change the relations between input and output variables. At the same time, the simulation model algorithm may perform less realistically under different input. Thus, keeping these input values will give the outcomes of these simulations the highest possible value. By performing a number of batches of simulation runs and comparing the aggregated results, it is possible to formulate cautious answers to some of the research questions with respect to the Shared Space philosophy.

7.2 Studied output variables

One of the research sub-questions is to determine which output variables could be applied to study the impact on traffic performance and safety of traffic behaviour according to Shared Space. The following two output variables are proposed:

**Average speed**

The first one is the road user’s average speed, defined as a road user’s total travelled distance, divided by the time between the moment the road user enters the incoming road into the intersection and the moment that it has left the outgoing road from the intersection. This calculated average speed is slightly biased towards the speed on the outgoing road. The reason for this is the discrete nature of the simulation time. In the model, the road user is considered to be near or on the intersection as long as
its total travelled distance is not longer than the length of its prescribed trajectory. At its generation, a road user’s travelled distance is zero. Every time step, the simulation model calculates the total travelled distance of every road user, compares those with every road user’s trajectory length and, on that basis, determines which road users are finished and, thus, must be thrown out. By definition, the total travelled distance of a removed road user has been equal to the prescribed trajectory length sometime during this final time step. The exact moment is unknown to the model, and is approximated by taking the current simulation time. That means that the total travel time of the road user is rounded up. The extra added time and the extra added travelled distance are included in the average speed calculation. Since these time and distance additions do not concern the movement on the intersection itself, the inclusion of them results in the found average speed value being an approximation, with a slight bias towards the speed in the last time step. If the time step is kept small, the bias will also be small. With a time step of only .1 s, the bias is of minor importance.

**Time Exposed to critical TTC**

The second output variable is the Time Exposed to critical TTC (TET) value for all road users. Minderhoud & Bovy (2001) propose this quantity as a measure of the safety of an intersection. For each road user, it is the sum of all the time intervals during which its TTC is lower than its critical value. It is assumed that a road user in such a situation acts to increase this TTC, for example by decelerating. In this chapter, the TET concept is translated to the accumulated time during which a road user detects at least one potential conflict. That implies that a road user’s individual time horizon in the simulation model is equated to the critical TTC as used in the article. Equivalently, detecting a potential conflict within this time horizon forces a road user to act, in this simulation model by negotiating.

The reasons for using these two variables, apart from suiting the domains of performance and safety, are that they are easy to understand, can be calculated with little effort and allow for comparison, not only between the four cases, but also between the modalities.

### 7.3 Simulation results and analysis

The results of the simulation are presented and analyzed in two ways. First, the aggregated output of the four cases is compared for each modality. This would help to answer whether or not the value of the behavioural variables has an impact on the overall traffic performance and safety. After that, the cases in which the behavioural variables are not either 0 or 100 percent, namely the cases 2 and 3, are studied in more detail. For these cases, the population of road users is divided into those who are polite and those who are not, and into those who take initiative and those who do not, looking for an
impact upon for the output variables, again for each modality separately. This is accompanied by a statistical and traffic-related analysis, which will help to draw conclusions in the next section.

Statistics from real-life Shared Space schemes do not provide a uniform basis for a hypothesis of the results of this simulation. Quimby & Castle (2006) provide collision numbers before and after the implementation of Shared Space in, amongst other towns, Oosterwolde and Drachten, which show no significant reduction or increase in safety. More recent numbers provided by Gerlach et al. (2008) show a mixed image. Safety seems to have been improved at the Laweiplein roundabout in Drachten and in the Haren town centre, but gotten worse at another location in Drachten, the De Drift-Torenstraat-Kaden intersection, which has a road design similar to the simulated intersection.

With respect to speed, Reid et al. (2009) summarise the evidence as mixed and scattered. It is not clear why speeds in some areas are reduced more strongly than in others, but it is suggested that site-specific factors play a major role. In this application, these factors have been left out deliberately.

Every case is simulated for a total of 120 minutes, consisting of one batch of 12 runs of 10 minutes of simulated time. Considering the time period of a single run and the temperate traffic flows, it seems acceptable to have no warming-up period. Frequently during the simulation, there are no potential conflicts to resolve due to low traffic intensities. One could say that every run starts during such a low.

### 7.3.1 Comparison between cases

In this section, the comparison between the cases consists of two steps. Firstly, the results are presented in the form of two sets of boxplots. Secondly, these results are analyzed using a series of statistical tests. What is tested, repeatedly, is the hypothesis that, for each modality, the output values in the four cases are so close that they can be expected to have the same mean. This would lead to the conclusion that the behavioural input variables have no significant impact on the output variables.

The following two figures are the two sets of boxplots for the two output variables. In Figure 7.1, the average speed values have been collected and grouped, first by modality, then by case. In the same way, Figure 7.2 contains the grouped TET values of all road users. The first four boxplots of both figures are the output values of pedestrians, the second four those of cyclists, the next four those of car drivers and the final four are the output values of lorries. Every set of four plots for a single modality relates to the four cases as presented in section 7.1 (case 1: behavioural variables all at 0 %; case 2: all at 50 %, case 3: variation and case 4: all at 100 %).
At first sight, the box plots for each modality seem very much alike. These box plots alone would suggest no significant impact of the output variables. It is remarkable that the worst-scoring case (lowest average speeds, highest TET values) seems to be case 3, since this is the supposedly most realistic case of the four, although the differences are quite small.

For the statistical tests, the concept of the Student's t-test is used. As already stated, this test determines whether two samples can be expected to have the same mean. The Student’s t-test is a more generic case of the t-test that can be used for testing samples drawn from a normal distribution. In the case of these output values, there clearly is no (approximated) normal distribution.

The Student’s t-test involves a certain test statistic, calculated on the basis of the samples. Generally, the larger the value of this statistic, the more different the data sets are, and the more likely that they have different means. The essence of the test is to determine if the test statistic is so large that the
probability that both samples are derived with the same mean is significantly low. This is assumed to be equivalent to a significant probability that the two samples have been drawn with different means.

In Table 7.3, the probabilities that two samples have the same mean are summarised. The probabilities of equal means for the average speed values have been put in the lower (light-grey) triangles, and those for the TET values have been put in the upper (medium-grey) triangles. Obviously, there are four different table segments for the four different modalities in the simulation.

### Table 7.3 Probabilities of equal means for average speed and TET values for case 1 to 4

<table>
<thead>
<tr>
<th>Mod</th>
<th>Pedestrians</th>
<th>Cyclists</th>
<th>Cars</th>
<th>Lorries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>.65</td>
<td>.84</td>
<td>.54</td>
<td>.13</td>
</tr>
<tr>
<td>2</td>
<td>.46</td>
<td>.81</td>
<td>.88</td>
<td>.18</td>
</tr>
<tr>
<td>3</td>
<td>.81</td>
<td>.62</td>
<td>.69</td>
<td>.78</td>
</tr>
<tr>
<td>4</td>
<td>.33</td>
<td>.82</td>
<td>.48</td>
<td>.27</td>
</tr>
</tbody>
</table>

Lower triangle (light-grey): average speed values
Upper triangle (medium-grey): TET values

Assuming that the input variables have a significant impact upon the mean of the output variables, the difference in mean should be the most pronounced when comparing the cases with the most diverging input values. In other words, the probability of equal means should be lower for a comparison of the cases 1 and 4 than for a comparison of the cases 2 and 3. The results in Table 7.3 do not match this expectation. The greatest difference (still only approximately 90% significant) is between the cars in case 2 and in case 3, which is one of the least likely places to find one. Moreover, with so many values in the table (seemingly close to random), there is a high probability of finding a false positive.

The outcome of the statistical tests is that the differences in mean amongst the average speed samples and amongst the TET samples are not significant. Therefore, the input variables can be considered to have no significant impact on the mean of the overall output variables. In traffic-related terms, this would imply that, according to the simulation results, the percentages of road users being polite or taking initiative do not significantly impact the average performance and safety of the intersection. As the tests are only concerned with the means of the samples, it is theoretically possible that the input variables have an impact on the distribution of the output variables. This could result in diverging standard deviations. The boxplots in the Figures 7.1 and 7.2 give no indication that this is the case.
7.3.2 Impact of behavioural variables within cases

In the previous sub-section, the focus has been on the overall performance and safety of the intersection as a function of the behavioural input variables of initiative and politeness. This sub-section deals with the impact of input variables within the population of road users. Even though the means of output samples from different cases are not significantly different, these samples may still show that it matters for a road user to be inclined to be polite or take initiative, possibly at the expense or for the benefit of other road users. For this, the results of the cases 2 and 3 will be studied in more detail, since these are the cases with a heterogeneous road user population.

The Figures 7.3 through 7.6 contain the boxplots of the output results of the individual road users in the cases 2 and 3. The first two figures represent case 2, while the latter two are from case 3. For each set of two figures, the first figure contains the box plots for the average speed values, the second figure those for the TET values. Within every figure, the left-hand half contains the initiative-related boxplot pairs, while the right-hand half holds the politeness-related boxplot pairs. Every pair of boxplots represents a single modality for that characteristic and output variable. All pairs have on the left the road users who are inclined to be polite or take initiative (+) and on the right those who are not (-).

![Boxplots of average speed values for case 2, grouped by modality and input (m/s)](image)

*Figure 7.3 Boxplots of average speed values for case 2, grouped by modality and input (m/s)*

![Boxplots of TET values for case 2, grouped by modality and input (s)](image)

*Figure 7.4 Boxplots of TET values for case 2, grouped by modality and input (s)*
Compared to the previous sub-section, these boxplot figures show considerably more variation. This could be interpreted as a distinct impact of changes to the behavioural variables, were it not for the fact that the variations often run both ways. For example, the third and fourth pair of boxplots in Figure 7.5 (the impact of initiative upon average speed values of cars and lorries in case 3) both show considerable difference between initiative and no initiative. However, lacking initiative seems to lead to lower average speeds for cars but higher average speeds for lorries. It is possible that this is realistic (e.g. lorries may be so large that taking initiative may be counter-productive as it could lead to a blockade for all, including the lorry itself), but it is difficult to prove.

Also, the differences are not always consistent between the cases 2 and 3. As for the aforementioned box plot pair, the impact of initiative on the medians for cars and lorries in case 3 is the opposite of that in case 2. This could be related to the fact that the initiative level of a road user can only have an effect if the road user with which it has a potential conflict is polite. In case 3, these polite road users are predominantly other cars (and lorries), since the slow traffic in this case is not so polite. The varying modal split of potentially conflicting road users could be a deciding factor in the impact of the initiative level, but this cannot be derived from these aggregated results alone.
All boxplot pairs in the Figures 7.3 through 7.6 have been tested, again by performing a series of Student’s t-tests. The impact of the behavioural variable is analyzed by calculating the probability of equal means for the samples. In Table 7.4, these probabilities have been collected.

<table>
<thead>
<tr>
<th>Segment input</th>
<th>Pedestrians</th>
<th>Cyclists</th>
<th>Cars</th>
<th>Lorries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output \ Case</td>
<td>Initiative</td>
<td>Politeness</td>
<td>Initiative</td>
<td>Politeness</td>
</tr>
<tr>
<td>2 3 2 3</td>
<td>.08 .08 .51 .52</td>
<td>.90 .07 .17 .78</td>
<td>.17 .00 .33 .95</td>
<td>.03 .40 .04 .67</td>
</tr>
<tr>
<td>Average speed</td>
<td>.13 .09 .64 .49</td>
<td>.98 .13 .75 .85</td>
<td>.88 .01 .11 .94</td>
<td>.06 .73 .30 .59</td>
</tr>
<tr>
<td>TET value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are several values in Table 7.4 that suggest unequal means of the particular samples. On the whole, the initiative variable seems to have more impact than the politeness variable. The probabilities of equal means seem slightly lower for the average speed results than for the TET results.

With respect to the initiative variable, it is clear that the the probabilities of equal means are lowest when the box plots show that taking initiative is correlated with a higher average speed and a lower TET value. This seems to hold for all modalities. This correlation would indicate that road users take initiative in order to speed up, which seems to be a realistic assumption.

The politeness-related probabilities of equal means in Table 7.4 are considerably higher than the initiative-related ones. The only apparently significant difference is in the average speeds of lorries in case 2. The impact of politeness suggested by this pair of samples is the opposite of the (insignificant) impact found for the same pair in case 3. It is also hard to explain why an impolite road user would not give way to other road users if doing so would increase its speed. As mentioned before, the effect may be related to the lorry being so large as to block the intersection, reducing everyone's speed including its own. Another explanation could be a disproportional impact of one or more outlier values in the samples, since the traffic volumes of lorries are quite low compared to the other modalities.

7.4 Conclusion

In this chapter, the blink simulation model has been applied to gauge the impact of varying initiative and politeness levels within the road user population upon the traffic performance and safety of the intersection. The output variables that represent this traffic performance and safety are the average speed and the TET (Time Exposed to critical TTC) values. They have been presented by means of boxplots and compared using a series of Student’s t-tests.
One of the basic arguments in favour of Shared Space is that it would be beneficial in terms of speed and safety for all road users. The results from the simulation model do not give an indication for that. Instead, they would suggest that, at unsignalised intersections, the process of resolving potential conflicts between road users remains very much a zero-sum game. In other words: the reduced waiting time for one road user comes at the expense of another road user. Simultaneously, the results also give no indication that the safety, as represented by the TET samples, is significantly influenced by increased levels of initiative or politeness across the road user population. This outcome would not be out of line with empirical evidence. Safety statistics have suggested that safety does not change significantly in many Shared Space traffic schemes, measured in the number of reported accidents.

The statistical tests suggest a significant correlation between being inclined to take initiative and experiencing a higher average speed and a lower TET value. For the behavioural variable of politeness, such a both logical and significant correlation could not be found. Obviously, these observations all need to be taken with the caveat that they are based on a specific set of traffic intensities and finite samples of output variables.
8 Conclusions and recommendations

The final chapter of this report contains the overall conclusions and recommendations based on the entire thesis report and the development of the simulation model and relating to the research questions as defined in chapter 1. In the first section, findings during the process are recapitulated. This is followed by conclusions on these findings in the next section. The third section deals with implications for science and practice. Finally, recommendations for future work are formulated.

8.1 Findings

The findings are summarised by means of formulating a concise answer to the five sub-questions stated in chapter 1. Combined, these should also answer the main research question.

What are the traffic-behavioural hypotheses underlying the Shared Space approach?

The Shared Space approach can be summarised by four underlying hypotheses:

• In traffic, there is a distinction between social behaviour (unfocused, unpredictable, slow and without clear programme) and traffic behaviour (the opposite). Shared Space assumes that the road environment makes clear to a road user what type of behaviour is expected. Social traffic behaviour is a combination of these two that should be avoided as much as possible.

• Traffic in a public space is considered as a social activity in which all road users should be taken into account. In the Shared Space approach, this results in heterogeneous traffic: the road environment welcomes all modalities, including pedestrians, cyclists and motorised traffic.

• Road users are expected to perform safer traffic behaviour when perceiving the road environment as relatively unsafe (reverse risk compensation). This assumption leads the Shared Space approach to argue for a sufficiently unpredictable traffic situation.

• In the Shared Space approach, conscious decision-making is seen as an legitimate alternative to both automatic and rule-based traffic behaviour. Road users are encouraged to work out conflicts to mutual benefit, thus deviating from established priority rules.
Which methods, presented in scientific literature, have been applied to model non-signalised traffic intersections and what is their use with respect to the Shared Space approach?

The literature provides various models for heterogeneous traffic without traffic signals, such as gap-acceptance models, cellular automata, conflict-point models, car-following models, social force models and a model based on utility-optimisation. Generally speaking, most of these models contain elements that suit the Shared Space approach, such as a continuous representation of the road space or an elaborated decision-making process. It is very rare to see that these elements are combined. Only one model (Anvari et al., 2012) has been conceived with Shared Space in mind, but it does not seem to fulfill all requirements that the Shared Space approach poses.

How can we model generic traffic in a road environment based on Shared Space?

The thesis presents a conceptual model that supposes negotiation to be a main traffic process by matching the current traffic situation with a feasible negotiation result, under the assumption of fixed paths. Needless to say, there are many other possible conceptual models (and implementations).

What are relevant output variables for analyzing the impact on traffic performance and safety of behaviour assumed under Shared Space conditions?

For the model application, two output variables have been defined. The first one is the average speed, the second one is the TET (Time Exposed to critical TTC (Minderhoud & Bovy, 2001)) value. The latter variable is a safety indicator. In this model, it is equal to the total duration of time during which a road user foresees any conflict with another road user. The average speed, while obviously an indicator of safety, also represents the performance of the intersection: a high average speed for all groups of road users would indicate that potential conflicts are dealt with effectively.

How does traffic behaviour under Shared Space affect these output variables?

In the simulation model, traffic behaviour under Shared Space is represented by two behavioural variables: the levels of initiative and politeness in the population. The output results of the model application do not suggest a statistically significant impact of these input variables on either of the two output variables. They do suggest that road users with initiative would have a higher average speed and a lower TET value. For politeness, such a correlation could not be found.
8.2 Conclusions

Shared Space aims at promoting safe and efficient interactions between road users through a subjectively unsafe but social traffic situation. In itself a very difficult design task, it is also difficult to model an approach that is based on local circumstances that are different at each location or even on each day. It may be concluded that the Shared Space approach can be modelled as a concept and implemented as a simulation program. Many features from its theory can be found in the simulation, such as the equal treatment of road users with diverging modalities and the possibility of individual decision-making. Basic conventions of movement and negotiation apply, and these can, combined with established priority rules, be transformed into algorithms that give realistic outcomes for speeds and acceleration patterns. It has become a fairly generic model, so in order to apply it for any given intersection, the model user has to spend a lot of effort to construct a suitable implementation of it.

The pioneers of the Shared Space approach allege that it would have an impact on traffic performance and safety, but the model results do not back this up. Of course this could be due to limitations of the model, but even so, one can reasonably expect that the approach has a limited effect if it has only an impact on a minority of traffic conflicts. This should not be detrimental to the successes of the Shared Space approach in involving stakeholders and creating high-quality public spaces.

8.3 Implications for science and practice

Since the simulation model is built with very limited quantitative data, its users would not be in the position to either discard or accept the Shared Space approach for a particular traffic situation on the basis of this model alone. In that sense, this thesis is unlikely to have a direct impact. That is not to say that the simulation model will not have implications for research in the long run.

This thesis project poses a cautious argument in favour of modelling Shared Space traffic, rather than in favour of the Shared Space approach itself. It shows a way to represent some of Shared Space's behavioural paradigms in a conceptual and a simulation model. This is encouraging in the sense that much of the research on Shared Space up to now has been ex post, i.e. after the implementation of a Shared Space scheme. To carry out an ex ante evaluation of a scheme, i.e. a prediction of its impacts, a simulation model is required. Hopefully, this thesis has provided some building blocks for it. In particular, the concept of negotiation, while definitely not originating in this thesis, deserves more attention than it currently receives, since it may be wider applicable than in Shared Space alone.
8.4 Recommendations for future work

There are at least four things that could be done to follow up on this thesis project. Firstly, the proposed conceptual model, and subsequently its implementation, could be refined and extended to include more elements of Shared Space traffic behaviour and road design. There are several assumptions, which have kept the simulation model quick to calculate and not too complex, that could be substituted for more elaborate interpretations. First of all, the fixed route choice of road users could be changed into an iterative process, in which both the value and the direction of the acceleration are determined. Consequently, the knowledge of other road users about a road user's path (and one's own path) can only be considered as an expectation for the moment, and no longer as a certainty. This implies that, in case of conflicting flows, the detection of path conflicts must be performed from scratch every time step. It may also be necessary to change the negotiation process algorithm, depending on whether the results of this algorithm are sufficiently robust under the changing path coordinates.

Related to the previous point, the destination choice of a road user is considered public knowledge in the current simulation model. In reality, other road users try to predict this choice, looking for clues in the road user's movement, appearance and conscious communication. The limited time horizon used in the simulation is an easy way to represent the limits to this prediction of one another's behaviour. It would be recommended to include this variability in information, but under the condition that the conscious and unconscious communication between road users is also included in the model.

A second follow-up to this thesis project could be to study the impact of transforming the simulation model into a genuine agent-based model. The current simulation model is object-oriented, but the road users themselves are no objects, due to Matlab's slow performance for this type of objects. If the road users had been objects, the simulation would have needed additional programming in order to have the objects communicate smoothly with one another and with the simulator. Also, which road user object would be allowed to update its acceleration first, and what would be the impact of this priority? It could be important to know if this change in programming has an impact on the simulation results.

Once the simulation model is agent-based, it can be feasible to implement a more sophisticated negotiation process. The current algorithm can be considered as determining the most likely outcome of the negotiation, rather than simulating the negotiation process itself. It could be relevant to study the impact of introducing probabilistic elements in the model, leading to subjective instead of objective acceleration decisions. For this, basing the model on utility optimisation should be contemplated.
The third thing that could be done as a follow-up is a calibration of the current model or possibly of an improved version of it. This could be succeeded by a more thorough validation process. The main requirement to a calibration is obvious: traffic data. Even a calibration of just the current model would require observations of positions, speeds, accelerations and behaviour towards priority rules. More complicated traffic behaviour, such as path adjustments, would seem to require even more data, this time focused on a road user’s internal continuous decision process. The easiest way to get hold of such data may be by installing equipment in a road user’s vehicle and analyze its movement changes. No wonder that this has not been a part of this thesis project...

The final potential follow-up to this thesis is the most far-reaching. The conceptual model of this thesis is an interpretation of the established theoretical framework of the Shared Space approach. I have tried to do justice to what I consider its fundamentals, but what the approach really needs is the challenging of its fundamentals. The behavioural hypotheses of Shared Space provide many opportunities for this: how does the road environment trigger road users to change their behaviour? How do road users communicate? What makes them slow down? What is the impact of heterogeneity on safety? Is the cooperation between road users still effective with higher traffic flows? What happens if priority rules are left out completely? What if Shared Space only works because of residual good traffic behaviour? Is a lack of subjective safety a sustainable strategy in the long term, or do people get accustomed to it?

The answers to these questions should have implications on the policy level. A continued success of Shared Space will depend on the ability of enthusiastic pioneers to take away doubts on its applicability beyond the current pilot schemes. The obvious way is by strengthening the theoretical basis of Shared Space, maybe more than in this conceptual model taking into account the relation between social traffic behaviour and road design. In that way, we will be better able to determine in which situations Shared Space may be the most effective in improving traffic performance and safety.
References


Annexes
I Values for internal input variables

Modality-specific variables

A large part of the internal input variables differs by modality, but is the same for all road users of that modality. The values of these variables have been collected in Table I.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Pedestrian</th>
<th>Cyclist</th>
<th>Car</th>
<th>Lorry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>m</td>
<td>.50</td>
<td>1.90</td>
<td>4.74</td>
<td>10.40</td>
</tr>
<tr>
<td>Width</td>
<td>m</td>
<td>.75 (1.00)</td>
<td>.75 (1.00)</td>
<td>1.77</td>
<td>2.62</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>m/s</td>
<td>1.4</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Normal speed (midblock)</td>
<td>m/s</td>
<td>1.2</td>
<td>4</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Normal speed (intersection)</td>
<td>m/s</td>
<td>1.4</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>m/s²</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Normal acceleration</td>
<td>m/s²</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
<td>.5</td>
</tr>
<tr>
<td>Maximum deceleration (abs)</td>
<td>m/s²</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Normal deceleration (abs)</td>
<td>m/s²</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

The length and width values of the vehicles are based on the standards for Dutch road design. The speed, acceleration and deceleration values are rough values, chosen by the author. The main motivation is to have clear distinctions between the modalities in their kinetic properties.

Due to being close to the kerb (cyclists) or, potentially, the façades of buildings, cyclists and pedestrians have been assumed, during the generation of their paths, to have a higher width. This should not affect the detection of path conflicts or, subsequently, the negotiation process.

Other input variables

There are a couple of other important internal input variables:

- **Minimum time horizon**: this variable is a lower limit for the time period (relative to the current time) that a road user is able or willing to detect potential conflicts in. As mentioned in chapter 5, that implies that it also can be seen as the lower limit of a road user’s critical time-to-collision (TTC). The value of the minimum time horizon in this simulation is set, after a bit of trial-and-error, at 3 seconds. It was found that, using this value, the road users would anticipate potential conflicts sufficiently early to be able to avoid it, thus ensuring a smooth traffic flow.
Tables of minimum headways and sideways: for the detection of conflicting paths, the simulation model determines for every curve point whether any vertex of either road user is within the other's comfort zone. This comfort zone consists of the physical occupation of roadspace (the dimensions of which are given in Table I.1) with margins on all four sides of the road user.

The margins on the front and rear, the minimum headways, are presented in Table I.2, while the margins on the sides, the minimum sideways are collected in Table I.3. Again, these values are rough estimates, chosen by the author. The rationale of their values is that larger, faster road users keep more distance to preceding road users than vice versa. Conversely, vulnerable road users are assumed to accept smaller distances before them because they have lower speeds and would be able to come to a halt within a shorter distance. For the minimum sideways, there is no difference between leading or following, hence the table's diagonal symmetry.

### Table I.2 Minimum headways of individual comfort zones

<table>
<thead>
<tr>
<th>Minimum headway (m)</th>
<th>Leading road user</th>
<th>Pedestrian</th>
<th>Cyclist</th>
<th>Car</th>
<th>Lorry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Following road user</td>
<td>Pedestrian</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Cyclist</td>
<td>0.7</td>
<td>0.7</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Car</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Lorry</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

### Table I.3 Minimum sideways of individual comfort zones

<table>
<thead>
<tr>
<th>Minimum sideway (m)</th>
<th>Road user being detected</th>
<th>Pedestrian</th>
<th>Cyclist</th>
<th>Car</th>
<th>Lorry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detecting road user</td>
<td>Pedestrian</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Cyclist</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Car</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Lorry</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

114