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Modelling Shared Space

An organized chaos

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Modelling Shared Space: an organized chaos

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Abstract

Increased traffic pressures in the city of Amsterdam are leading to a lack of space for cyclists and pedestrians. In search of creative solutions the municipality of Amsterdam has chosen to implement a Shared Space area next to the ferry docks at Amsterdam Central Station. This research has sought to simulate and analyze the movements and interactions of the users of this Shared Space, by developing an Agent Based Model. In order to gain insight into the amount of people the Shared Space can handle, a number of real-life scenarios were tested, varying in agent densities, ratios and traveling directions. The main results suggest risks of unacceptably low average velocities are greater than risks of increasing amounts of agent conflicts.

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1. Introduction

1.1 Background

The city of Amsterdam faces major challenges in the coming years. More residents, jobs and visitors will lead to an increase in mobility in and around Amsterdam, and to greater pressures on valuable public space (Gemeente Amsterdam, 2013).

Amsterdam is growing and getting busier. More and more inhabitants, tourists and students are populating the city, while simultaneously, the number of jobs, businesses and events are increasing. This bustle has repercussions on the roads and cycle paths. Especially within the A10 traffic ring, the pressure on public space is increasing rapidly. The cycle paths are getting busier, as more and more elderly people use bicycles and many children cycle to school. The number of mopeds owned by Amsterdam residents has also risen; from 8,000 in 2007 to 32,000 in 2015 (Gemeente Amsterdam, 2018).

It is impossible to imagine Amsterdam without bicycles, and cycling has been gaining popularity in Amsterdam for years. At the beginning of the 21st century cyclists were responsible for about a *quarter* of all traffic movements. In 2018 already *one third* of all movements was done by bike, making it by far the most used mode of transport in the city; around 80 percent of Amsterdam residents aged 12 years and older own a bicycle. In 2017, 835.000 Amsterdam residents cumulatively undertook 665.000 bicycle trips every day. As the number of residents is expected to reach approximately 900.000 in 2025, the number of cyclists is also expected to further incline. Additionally, the number of mopeds and scooters in Amsterdam has been growing over the years: in 2018, the city counted around 58.000 vehicles with a moped license plate (Gemeente Amsterdam, 2018).

All these pressures on the public space are leading to lack of space for cyclists and pedestrians. This lack of space in the center of town is becoming a critical factor that is leading to a higher number of conflicts among pedestrians and cyclists. However, one of the highest priorities of the municipality of Amsterdam is avoiding traffic accidents, and where space is scarce and expensive, the search for creative solutions pays off.

1.1.1 Shared Space at Amsterdam Central Station

On the 21st of November 2015 the Shared Space next to the ferry docks at Amsterdam Central Station was opened. On this so-called ‘slow traffic square’ (*langzaamverkeerplein*) no cars are allowed. However, the remaining traffic enters the area from many different sides: from the cyclist/pedestrian tunnel underneath the station, from both sides of the *De Ruijterkade*, and from the ferries at the north side arriving from the other side of the *IJ* river. Because of the high traffic intensity, the concept of Shared Space was chosen as an optimal solution safe unwinding of the intersecting traffic flows.

The area was transformed from a traffic centered design into a Shared Space; a free-for-all area without traffic lights and signs (figure **1.1**), over which approximately 21.000 cyclists and moped drivers, and 18.000 pedestrians were to pass on a daily basis (Gemeente Amsterdam, 2016).

Figure 1.1 Overview Shared Space area

The idea of ‘shared’ traffic space is not new; the Shared Space concept was conceived more than thirty-five years ago by Hans Monderman, a traffic engineer from the Netherlands. The basic idea of a Shared Space is a traffic space without features such as curbs, road surface markings, traffic signs, and traffic lights. At the center of the Shared Space concept lies the recognition of people’s ability to be able to resolve general traffic conflicts themselves, if treated as intelligent citizens (Clarke, 2006). A Shared Space is one in which “all street users move and interact in their use of space on the basis of informal social protocols and negotiations” (Hamilton-Baillie, 2008:166).

In February of 2016, About three months after the Shared Space was installed, the Municipality of Amsterdam carried out a project evaluation which concluded that –compared to the previous situation– the new setup had led to a *decrease* of traffic conflicts and accidents in this area. Measurements done both before and after the introduction showed a reduction of traffic conflicts by a factor of eight (Het Parool, 27/08/2016). *Het Parool* (27/02/2016) published an article titled: *Ongelooflijk, maar er gaat niks mis in Shared Space* [Incredibly, nothing goes wrong in Shared Space]. This title says a lot about the preconceptions about the project that existed at the time, and about the success the Shared Space had actually become.

1.1.2 Problem statement

The Shared Space at Amsterdam Central Station is not the first of its kind, however, the amount of traffic that passes through makes it unique. During the afternoon and rush hours, the space is crossed by approximately 2000 cyclists and 1700 pedestrians per hour, making it one of the most crowded areas in Amsterdam. People travel in an east to west direction along the *De Ruyterkade* (figure **1.2 A**), or in a north to south direction as the Shared Space functions as an extension of the ferry docks (figure **1.2 B**). In November of 2017 the number and capacity of ferries travelling to and from Central Station was increased in order to handle the crowds at peak moments. The amount of traffic moving across the Shared Space will likely grow further, as future forecasts

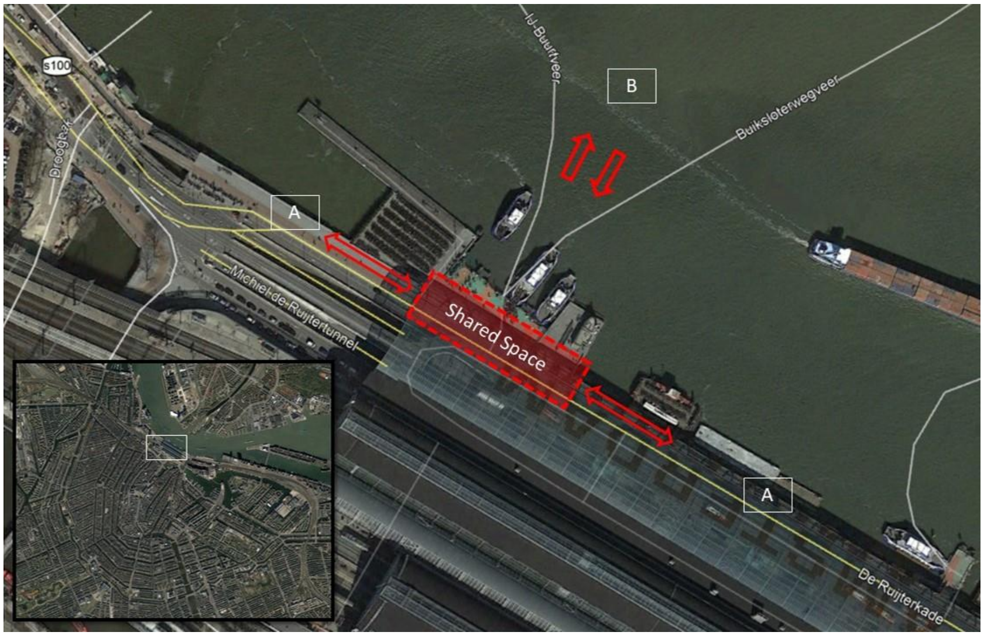


Figure 1.2 Shared Space area, satellite image

predict a steady increase of passengers travelling through Central Station and across the *IJ* channel (Municipality of Amsterdam, n.d.).

In 2016, in order to provide insight into the workings of the Shared Space, the Municipality of Amsterdam chose to perform a conflict observation in order to analyze to what extent safety inside of the Shared Space is guaranteed and whether or not interventions were needed.

These observations showed that despite increasing crowdedness the transformation of the area into a Shared Space had led to a *decrease* of incidents and conflicts. While the realization of the Shared Space initially brought up feelings of unsafety, measurements prove the environment to be safer than before. It seems there is a certain order to the perceived chaos, and in this sense, the Shared Space can be considered as a system in a dynamic equilibrium.

However, these observations did register the occurrence of precarious situations and conflicts between users of the Shared Space, especially during rush hours, and the question arises to what extent the Shared Space will be able to cope with increasing pressures in the future. As crowds continue to grow, the system could reach a ‘tipping point’ –a situation in which the state of the Shared Space becomes one of crowdedness or chaos– leading to an increase in agent conflicts and accidents.

Despite the emerging popularity of the shared space concept, limited studies have investigated the interaction behavior of active road users in such facilities (Alsaleh et al., 2019). While with the rise of the concept of Shared Space in the eighties and nineties, a significant number of studies have been conducted regarding the subject, the majority of these focus on the implications of Shared Space for the vulnerable street users such as the visually impaired (i.e. Havik et al., 2015; Melis-Dankers, 2012).

This research project aims to contribute to existing research on Shared Space through the process of Agent based Modeling (ABM). As ABM has proven especially useful in addressing the difference between individual’s actions on the micro level and behavioral patterns that arise on the macro scale (Bruch & Atwell, 2015), this modelling technique offers the opportunity to approach Shared Space as a system, determined by individual agents choices and behaviorisms.

1.2 Objectives

The main objective of this research is **to simulate and analyze the movements and interactions of Shared Space users at Amsterdam Central station, by developing an Agent Based Model**. The model is meant to be useful in simulating a number of real-life scenarios, varying in agent densities, ratios and traveling directions. In this way more insight can be acquired into the amount of people the Shared Space can handle, and what can be considered as desirable, or problematic agent ratios. For calibration and validation purposes, the model will be populated with an existing, measured dataset, provided by the Municipality of Amsterdam.

1.2.1 Research questions

To better understand the dynamics between agents in Shared Spaces, the interactions between pedestrians, cyclists and moped drivers in the Shared Space at Amsterdam CS are simulated through developing an Agent Based Model (ABM). This leads to the following research question:

RQ ***How can the dynamics within the Shared Space environment at Amsterdam Central Station (CS) be analyzed and understood, by simulating agent dynamics using an Agent Based Modelling technique?***

A number of theoretical and methodological sub-questions form the framework/basis of the project. These question will be answered in the course of chapter **2** and **3**.

SQ 1 ***What is Shared Space, and what are its most important features?***

SQ 2 ***How can Agent Based Modelling be used to better understand agent dynamics within Shared Spaces?***

SQ 3 ***How can the agent dynamics within the Shared Space environment at Amsterdam CS be converted into a set of rules?***

After the model is realized, a number of interpretative sub-questions are answered in paragraph **3.3** and chapter **4**:

SQ 4 ***To what extent do the model patterns compare to measured (real-life) patterns?***

SQ 5 ***What kind of agent densities and ratios can lead the system to reach a 'tipping-point' – a state of over crowdedness and/or chaos?***

1.3 Scope

The design of the Shared Space at Amsterdam Central Station, and the unique agent composition within the area, make this research a challenging and innovative endeavor. It is therefore essential to clarify its scope and limitations.

The final version of the Shared Space model should be able to generate close-to-realistic patterns in terms of the number and location of conflict incidents within the Shared Space, as well as the trends in average agent velocities at different intensities. However, it is necessary to keep in mind that the uniqueness of the traffic area means that the findings and conclusions determined through this research, only apply for the Shared Space at Amsterdam Central Station, and merely serve as an indication for predicting dynamics in other Shared Spaces.

Furthermore, the empirical data used for model evaluation – the 2006 municipal conflict observation report – can be considered as anecdotal data; while it is indicative of the number of agents and conflict incidents in the area, the number of measurements is not great enough to be able to provide for definite statistical conclusions.

Thus, while the Shared Space model is meant to be used to replicate agent interactions established through empirical data, the scenarios analyses should be considered as a guide for future research, but not as a definite quantitative truth.

1.4 Study area

This thesis focuses on the Shared Space located behind Amsterdam Central Station. It is a plain, even surface with a coverage of approximately 60m by 20m, functioning as a traffic square for pedestrians, cyclists and moped drivers (figure **1.3**). The square is essentially part of the *De Ruyterkade* (**1.3 A**), which is an important traffic artery running east to west along the *IJ* channel. In the 2016 edition of the *Fiets Telweek*, an annual report on the state of cycling in the Netherland, the *De Ruyterkade* proved to be Amsterdam's busiest, and the Netherland's fourth busiest cycling lane (Fietsersbond, 2016). Adding to this, in a north to south direction, the Shared Space functions as an extension of the ferry docks (**1.3 B**), which provide a steady in- and outflow of people travelling between *Amsterdam Noord* on the one hand, and the Central Station and city center on the other. Further contributing to the crowdedness are the many shops, cafés and restaurants located on the ground floor of the station (**1.3 C**), as well as the taxi stand positioned next to the station (**1.3 D**). As the Shared Space lies at the heart of these points of interest and traffic flows, it is home to a few of the most crowded square meters in the Netherlands.

Figure 1.3 Study area

1.5 Relevance

This research on the Shared Space at Amsterdam Central Station is both socially and scientifically relevant.

1.5.1 Social relevance

Amsterdam, and especially it's city center, never in history had to deal with the current amount of people and traffic passing through its streets. The crowds around the IJ channel are a prime example of this; the number of people travelling to and from the northern part of Amsterdam is expected to increase from 46.000 now to 80.0000/110.000 in 2030 (Municipality of Amsterdam, n.d). An ever increasing amount of tourists, combined with a steady population growth begs for smart design of public spaces and traffic flows. A better understanding of the dynamics within Shared Spaces can assist urban planners and policy makers in assessing current traffic situations, and determining suitable Shared Space locations in the future.

1.5.2 Scientific relevance

The situation at Amsterdam CS is described as a Shared Space, and it is constructed similarly to the original Shared Space design; a free-for-all traffic square without traffic lights, signs or curbs, through which road users have to negotiate rights of way among themselves. However, while the Shared Space at Amsterdam CS is conceptually similar to more 'traditional' Shared Spaces, in technical terms it can be considered as a one-of-a-kind traffic design.

While the majority of Shared Space designs include cars, one of the most important features of the Shared Space at Amsterdam CS is the absence of motorized vehicles other than moped-drivers. The area is designed for cyclists and pedestrian traffic, in which mopeds are considered as 'guests' in pedestrian area, and are required to maintain the 15 km/h speed limit. This agent composition makes modelling more challenging, as the behavior of cyclists and pedestrians has found to be much more complex than that of car drivers, because their interaction and degrees of freedom in decision making are less guided by rules and regulations and therefore harder to predict.

While mutual interactions between pedestrians (see Helbing & Molnár, 1998), and interactions among cars, cyclists, and pedestrians (Anvari et al., 2016; Pascucci et al., 2015) have been extensively researched, the exclusive presence of cyclists and pedestrians (and the occasional moped), in combination with the (extremely) high traffic intensity makes this research a unique endeavor.

Another feature that makes the study area unique, is the constant arrival and departure of ferries at the IJ channel docks, causing a continual flow of agent groups entering the Shared Space. As a ferry arrives at the docks, a *wave* of agents travels through the Shared Space, and as ferries depart, agents travel in the opposite direction in pursuit to board the ferry in time.

While these technical aspects of the Shared Space make the study area unique, this research can primarily be considered scientifically relevant because it is to the authors knowledge the first to simulate, and analyze, a car-free Shared Space environment, using an Agent Based Modelling approach.

1.6 Overview

Chapter **1** has provided an introduction to this research; describing the study area and formulating objectives. Going forward, chapter **2** presents a theoretical framework; describing Shared Space and Agent Based Modeling (ABM) as concepts, and introducing the Social Force Model, which forms the theoretical foundation of this modelling exercise. Chapter **3** presents the methods used; the conceptual model, the technical implementation and model calibration. In chapter **4** a number of traffic scenarios are tested and analyzed, experimenting with different agent intensities and distribution points. The most important conclusions of the scenario analysis are summarized in chapter **5**. In chapter **6**, research limitations and further recommendations are discussed.

2. Theoretical framework

This chapter presents a theoretical framework for this research. Paragraph **2.1** describes Shared Space as a concept: it's history and functionality; paragraph **2.2** discusses a number of modelling approaches in general, and Agent Based Modeling (ABM) in particular; paragraph **2.3** describes the Social Force Model, which forms the theoretical foundation of this modelling exercise. The most important conclusions of this chapter are summarized in paragraph **2.4**.

2.1 From separated flows to Shared Spaces

Shared Space was developed in the early 1980s, and first realized by Hans Monderman in a number of small towns in the Dutch province of Friesland. In trying to keep the streets safe without an appropriate budget, Monderman came up with the idea of removing road signs and markings, so to create a flat surface across which all different modes of transportation were to negotiate rights-of-way amongst themselves. The absence of any traffic controls increased driver awareness, forcing them to slow down (PPS, 2008). The minimization of demarcation elements and traffic devices caused the perceived level of risk to increase, leading users to a more respectful and precautionary behavior (Hamilton-Baillie, 2008:166).

After successful first attempts, numerous pilot-projects in the field of Shared Space were carried out in the Netherlands during the following couple of decades. At present time, there are a great number of international examples of cities and municipalities that have implemented schemes based on Shared Space principles (NHL, n.d.).

The separation of traffic flows through the use of curbs, road crossings and traffic signs is commonly accepted and widely implemented. However, there is growing evidence that this separation can in some occasions actually *increase* the risk to pedestrians and cyclists. In some situations, the removal of barriers, signs and road markings not only makes a more pleasant urban environment, but also slower, more careful and less congested traffic (Clarke, 2006). On motorways and busy highways, where the purpose of traffic is simply to move along a single road, it is still necessary to use traditional separation tools such as traffic lines. However, in a more complex urban traffic environment, with its multitude of functions, these demarcations become more redundant (Clarke, 2006).

One of the greatest downsides of designing with a purely technical approach has been the increased ‘messiness’ of public spaces; uniformities, road signs and other installments have turned many public spaces into ‘traffic areas’. As a result many of these spaces have lost their identity (NHL, n.d.). An important difference between these more traditional designs and Shared Spaces is the focus on social aspects rather than technical aspects of traffic in the latter. Individuals within a Shared Space become an integral part of the social and cultural context. As a result, traffic behavior is controlled by everyday norms of behavior (Clarke, 2006). Thus, fundamental to the functioning of Shared Spaces is a more human way of traffic interaction. The absence of traffic rules and certainties in this sense increases personal responsibility and mutual cooperation; individuals are expected to coordinate their movements among themselves (NHL, n.d.).

“Rather safety with uncertainty, than accidents with clarity”

One of the cornerstones of the Shared Space concept is to promote interaction, and to increase eye contact between road users. The assumption is made that traffic speed reduces whenever individuals do not explicitly obtain, or are obliged to grant right of way. Furthermore, it is assumed that road users within Shared Spaces show mutual respect.

In a Shared Space environment, it is desirable to heighten road users’ level of attention, and to limit traffic speed as much as possible. As a direct result of the lay-out of the Shared Space, road users develop an awareness of the presence of human activities, which in turn leads to a form of insecurity or uncertainty among road users. This level of uncertainty causes a general change in road use, resulting in objectively safer behavior (NHL, n.d.). Essentially, the idea is not to take away the insecurity and uncertainty that individuals within a Shared Space experience, but rather to use it; this insecurity is in this sense vital to the success of Shared Spaces (NHL, n.d.).

2.2 Agent Based Modeling

2.2.1 From macro to micro

In order to understand traffic dynamics in urban environments, computer simulations are used to develop models. A common type of traffic modelling is a macro-approach (Antonini et al., 2004). These are models that do not zoom in on the individual agent, but regard traffic as flows with a small number of defining parameters. While traffic modelling is mostly focused on this macro-scale of flows of people between places, modelling can also be focused on the micro-scale. Microscopic traffic models describe the movement of individual agents and attempt to simulate crowd dynamics by considering the choices made by individuals (Porter et al., 2017).

A common approach to identify how people spatially interact over time is by using an Agent Based Model (ABM) (Batty, 2001). Agent-based models can be defined as *“computer programs in which artificial agents interact based on a set of rules and within an environment specified by the researcher”* (Bruch & Atwell, 2015). These models have over time emerged as suitable alternatives to more aggregate and more geometric approaches to spatial modeling, one of the most important reasons for this being the ability of these models to treat individual events as unique classes whose behaviorisms can be simulated explicitly (Batty, 2001).

Agent Based Models (ABM) are a unique type of models. While they can represent systems as big as (in theory) the universe, they are categorized as micro-level models; in which every agent is an autonomous entity. The understanding of an ABM system is not derived from understanding the behavior of a single agent but by understanding their behavior as a collective (Hall and Virrantaus, 2016).

Agent Based modelling thus seems to be a very suitable simulation method for researching agent interaction within the Shared Space environment; for the main part because of agents’ capacity for autonomous acting and the link between micro and macro patterns.

2.2.2 Stochastic simulation

Most phenomena in real world situations, such as pedestrian interaction and conflict avoidance within the Shared Space environment, are partly subject to a degree of chance (randomness). These occurrences thus require **stochastic simulation**. In stochastic simulations, variable values are randomly generated in order to model randomness and chance. The result is that no two runs with the same variable configuration results in the same model output. The Shared Space Model will include a number of stochastic variables; this degree of chance within the model prevents agents from always make the same decision.

2.3 Social Force Model

Another important type of microscopic models, are so-called Force Based Models, in which pedestrians are individual entities that moved by attractive of repulsive forces. An important research done by Helbing & Molnár (1998) describes pedestrian interactions in the context of a *Social Force model*. Helbing & Molnár (1998) suggest that the motion of pedestrians can be described as if they would be subject to 'social forces'. In their paper *Social Force model for pedestrian dynamics*, Helbing & Molnár state that temporal changes of pedestrian velocities are described by a (measurable) vectoral quantity that can be interpreted as a social force. This force represents the effect of the environment on the behavior of a pedestrian; a quantity describing the individual's motivation to act, which evokes either acceleration or decelerations forces within pedestrians, as a reaction to perceived external information. In this sense, a pedestrian acts as if he/she would be subject to external forces (Helbing & Molnár, 1998).

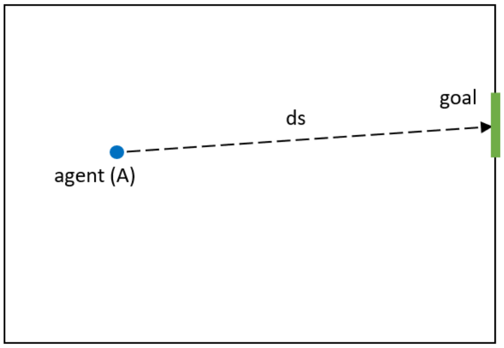
Helbing & Molnár describe the *Social Force* model through formulating pedestrian behaviors into a set of equations, describing the main effects that determine pedestrian motion (table **2.1**).

1A	A pedestrian wants to reach his/her destination as comfortable as possible, therefore, the shortest possible route will be chosen. These destinations (or goals) can be more accurately described as gates or areas rather than points. The pedestrian will constantly steer to the nearest point within the corresponding area.
1B	In the process of pedestrian deceleration due to hindrances/obstructions, a deviation develops between the actual velocity and the desired velocity. This leads to a certain relaxation time before the pedestrian again meets his/her desired velocity. It is also important to note that a maximum accepted velocity for pedestrians exists.
2A	Pedestrian movement is influenced by other pedestrians. Each pedestrian has a personal private sphere. Pedestrian A feels increasingly uncomfortable the closer he/she approaches another (unfamiliar) pedestrian (B). This other pedestrian generates a repulsive effect, the impact/strength of which is dependent on the general pedestrian density and the desired velocity of pedestrian A.
2B	Pedestrians also keep a certain distance from the borders of buildings, walls, obstacles etc. These borders also generate a repulsive effect for pedestrians.
3	Similarly to the repulsive effect, pedestrians are sometimes attracted to other persons (friends, street performers etc.), or objects (window displays, signs etc.). These attractive effects work similar to, but in the opposite direction of the repulsive effects; pedestrians tend to group together instead of disperse.

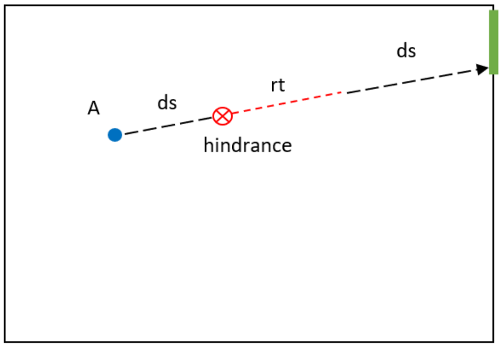
4	Both the attractive and the repulsive effects only hold for situations that are perceived in the desired direction of motion. Situations located behind a pedestrian will have little to no influence on their movements in space.
5	Fluctuations from the pedestrian behavior as described above, are possible. Fluctuations can stem from (1) ambiguous situations in which two or more behavioral alternatives are equivalent, or (2) fluctuations arise from accidental or deliberate deviations from the usual rules of motion.

Table 2.1 Social Force rules, adapted from Helbing & Molnár

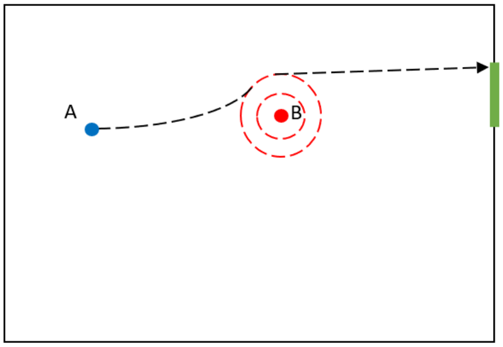
1A. SHORTEST ROUTE. An agent chooses the shortest route to his or her destination. These destinations (or goals) can be more accurately described as gates or areas, rather than points. The agent will constantly steer to the nearest point within the corresponding area. If unhindered, agents travel with a certain desired velocity (ds). It is also important to note that a maximum accepted velocity for each agent group exists.



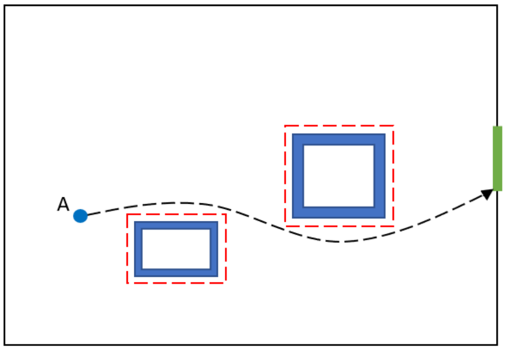
1B. RELAXATION TIME. In the process of agent deceleration due to hindrances/obstructions, a deviation develops between the actual velocity and the desired velocity. This leads to a certain relaxation time (rt) before the agent again meets his/her desired velocity.



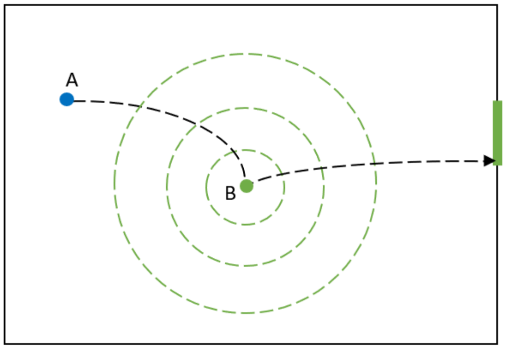
2A. REPULSIVE EFFECT. Agent movement is influenced by other agents. Each agent has a personal private sphere. Agent A feels increasingly uncomfortable the closer he/she approaches another (unfamiliar) agent (B). This other agent generates a repulsive effect, the impact/strength of which is dependent on the general agent density and the desired velocity of agent A.



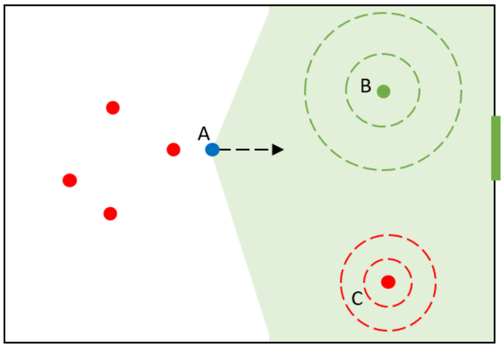
2B. BORDERS. Agents also keep a certain distance from the borders of buildings, walls, obstacles etc. These borders also generate a repulsive effect for agents.



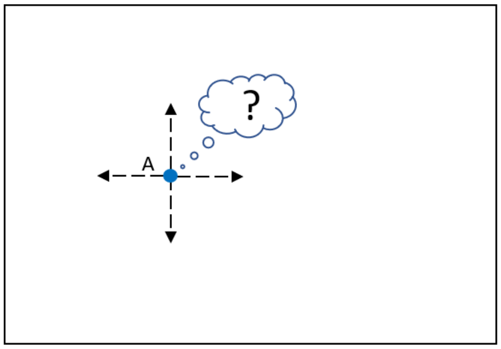
3. ATTRACTIVE EFFECT. Similarly to the repulsive effect, agents are sometimes attracted to other persons (friends, street performers etc.), or objects (window displays, signs etc.). These attractive effects work similar to, but in the opposite direction of the repulsive effects; agents tend to group together instead of disperse.



4. FIELD OF VIEW. Both the attractive and the repulsive effects only hold for situations that are perceived in the desired direction of motion. Situations located behind an agent will have little to no influence on their movements in space.



5. FLUCTUATIONS. Fluctuations from the agent behavior as described above, are possible. Fluctuations can stem from (1) ambiguous situations in which two or more behavioral alternatives are equivalent, or (2) fluctuations arise from accidental or deliberate deviations from the usual rules of motion.



2.4 Summary

This chapter has sought to built a theoretical foundation on which the rest of the research is built. First, the concept of Shared Space as a novel traffic solution was described, answering the first sub-question (SQ 1): *What is Shared Space, and what are its most important features?*

Second, Agent Based Modelling was presented as a suitable method for approaching the research problem, mainly because of the agents’ capacity for autonomous acting and the link between micro and macro patterns. Lastly, the Social Force Model was introduced as a theoretical starting point for developing the Shared Space Model.

With this, chapter 2 has also answered the second sub-question (SQ 2): *How can Agent Based Modelling be used to better understand agent dynamics within Shared Spaces?*

3. Methodology

Based on the theory about Shared Spaces, Agent Based Models and the Social Force model, a Shared Space model will be developed. This chapter will entail the development process, spanning the conception, implementation and evaluation of the model. In paragraph **3.1**, the *conceptual model* is presented and the various assumptions and modelling choices are discussed. Paragraph **3.2** describes the technical *implementation* of the model, including the modeling software of choice, the spatial dataset used, and the modelling process. In paragraph **3.3**, the model is evaluated, using data from the report: "*Monitoringsonderzoek Gedeelde Ruimte Amsterdam CS*", retrieved from the Municipality of Amsterdam. In this section, a sensitivity analysis is performed in order to determine which model variables are the most influential in producing model output.

Figure 3.1 Overview Shared Space area

3.1 Conceptual model

3.1.1 Overview

This research aims to analyze behavior within the Shared Space at Amsterdam Central Station, by simulating individual agents using an Agent Based Modeling (ABM) approach. Agents show certain behavior concerning movement and interaction, which is captured in a number of concepts largely drawn from the Social Force model (Helbing & Molnár, 1998). However, the model is different from the existing Social Force model in a number of ways. First of all, while Helbing & Molnár's model was designed to describe the self-organization of *pedestrian* behavior, the Shared Space model further attempts to incorporate the movements of *cyclists* and *mopeds*. Second, while Helbing & Molnár's model accurately describes agent movement and interaction, it does not attempt to describe *conflicts* between agents; the latter being one the main focuses of the Shared Space model. Furthermore, due to modelling restrictions, a number of choices were made with regards to agent interaction, which will be addressed in paragraph **3.1.7**. Table **3.1** shows which effects from the Social Force model were captured in the Shared Space model, and which effects were not implemented.

	Social Force model	Shared Space model
1A	Shortest route	✓
1B	Relaxation time Maximum velocity	✓
2A	Repulsive effect	✗
3	Attractive effect	✗
4	Field of view	✓
5	Fluctuations	✓

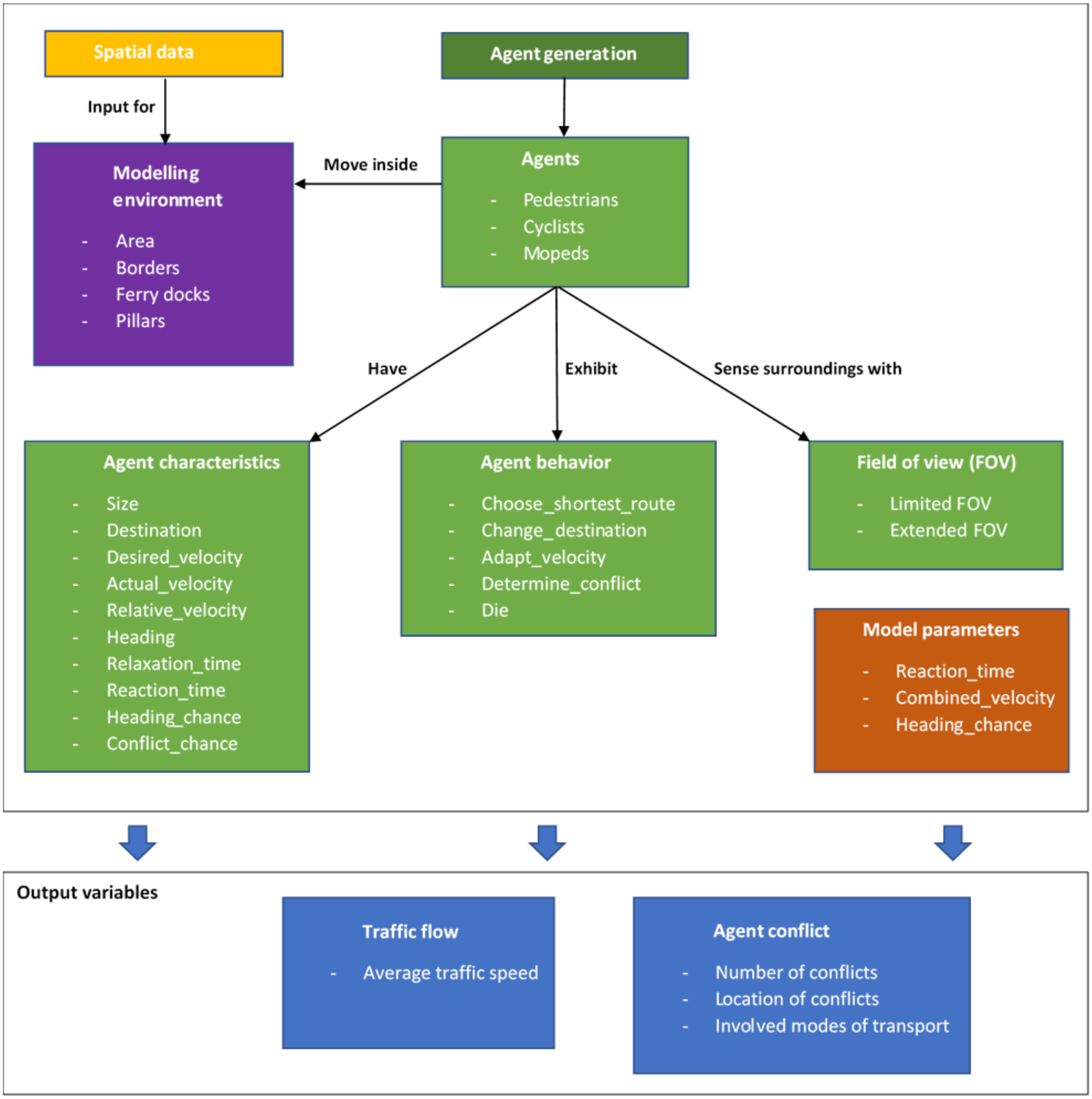
Table 3.1 From Social Force to Shared Space

Agents travel through the Shared Space area, choosing the shortest route to their destination. Agents interact with the environment and with each other; changing course when a solid object is in their trajectory, and slowing down when other agents are blocking their way. Agents have heterogeneous dispositions with regard to the way they react to other agents, some being more prone to slow their pace than others. The repulsive and attractive effects as presented by Helbing & Molnár were omitted from the final Shared Space model due to unsatisfactory results. Instead, agent conflict was modelled by implementing a number of stochastic variables into the model. With every model step, a chance is calculated which determines whether or not a conflict occurs between two agents in case of an intersection, based on their velocity and heading. These effects only hold for situations that are perceived in the desired direction of motion.

The following sections will further explain the preliminary assumptions behind the model's agents, environment, characteristics and interactions.

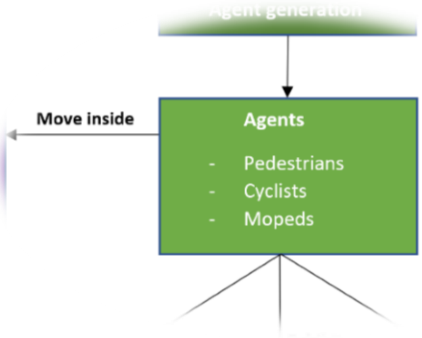
Conceptual model, schematic

Presented below is a schematic representation of the conceptual model. Paragraph **3.1.2** up to **3.1.9** further describes each of these building blocks.



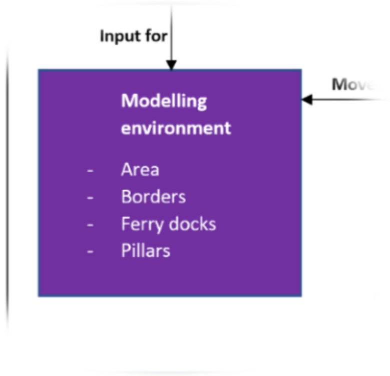
Scheme 3.1 Conceptual Model

3.1.2 Agents



Three type of agents are distinguished in the model. The agents in the model represent individual **pedestrians**, **cyclists** and **mopeds**. While in reality the area is also frequented by other road users such as handicapped vehicles and skateboarders, these agent types are omitted from the model due to their limited numbers. Around 21.000 cyclists and moped drivers, and 18.000 pedestrians enter and leave the area on a daily basis, these numbers are reproduced within the modelling environment.

3.1.3 Environment



The modelled environment is the area through which agents move and interact. The Shared Space **area** is a trapezium-shaped area with a coverage of approximately 60m by 20m (Figure **3.2**). The dimensions of the area are reproduced in the modeling environment. Agents enter the shared space area from, and exit the area at nearly all of its **borders**. Pedestrians enter and leave the area along its entire perimeter. Bicyclists and moped-drivers travel in an east to west direction along the *De Ruyterkade*, or in a north to south direction as the Shared Space functions as an extension of the **ferry docks**: a number of ferry waiting areas (green) and ferry boarding areas (red) bordering the *IJ* river. Several solid **pillars** are situated within the area, functioning to support a part of the roof of the station building. These pillars form an obstruction for the agents when moving through the area.

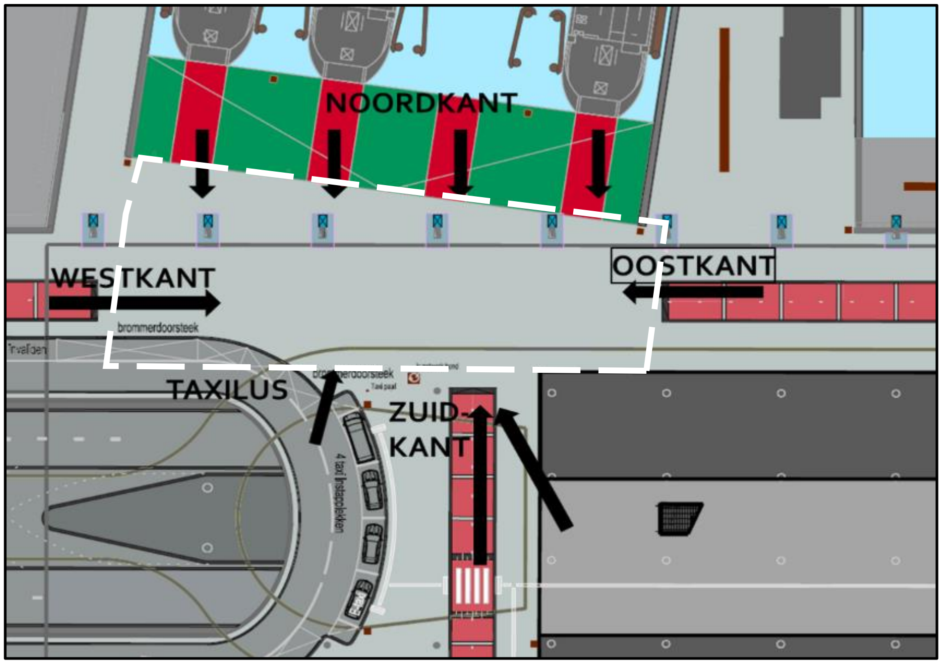
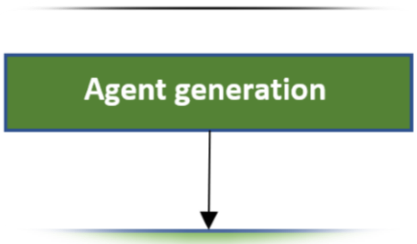


Figure 3.2 Shared Space environment

3.1.4 Agent generation



The Shared Space area is one of the busiest areas in the Netherlands. Pedestrians, cyclists and mopeds enter the Shared Space from the north, south, east and west constantly. It is unfeasible to attempt to simulate the exact number of agents and their exact points of entrance. However, for modelling purposes, an approximation is made of the number of agents per agent type, as well as their general points of entrance. Information about agent numbers and entrance points is extracted from five different sources. *First*, by visiting and observing the research area; *second*, by examining (moving) images of the research area; *third*, by consulting the report "Update Nota Veren" (Gemeente Amsterdam, 2016), which includes measured numbers of ferry travelers; *fourth*, by consulting the online Amsterdam ferry timetable (reisinfo.gvb.nl), and *fifth*, by consulting the report "Monitoringsonderzoek Gedeelde Ruimte Amsterdam CS" (Gemeente Amsterdam, 2016), a conflict observation report from 2016 in which the numbers of visitors and conflicts within the Shared Space area were registered through the use of camera footage and counting and tracking sensors.

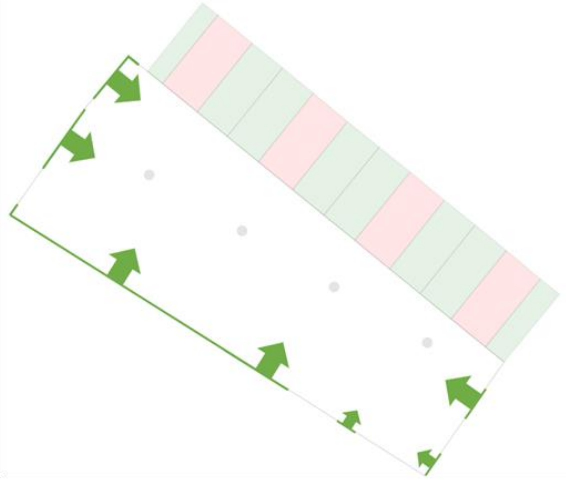
Regarding the generation of agents, agents either (1) enter the Shared Space from the *city side*; along the southern, eastern, and western borders of the Shared Space, or agents (2) enter the area from the *IJ river side*, after disembarking from one of the ferries docking at the northern border. This section describes the modelling choices regarding the generation of agents from both sides. The specific technical implementation of these modelling choices is set out in paragraph **3.2.2**.

Agent generation: city side

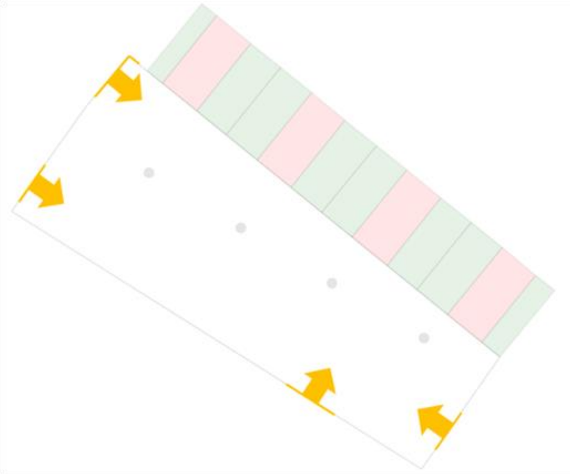
The main influx of agents from the *city side* is caused by the hordes of people exiting Amsterdam Central Station, but also by the constant stream of pedestrians, cyclists and mopeds entering the area from the several footpaths and bicycle paths.

Travelers enter the area from the city side in a constant stream, and this is simulated in the model. The border of the modelled area is built up out of separate line segments, each of which 'release' agents into the area at regular intervals. Every few model steps an agent spawns from one of these edges along the south, east and west borders, before moving into the Shared Space. The number of model steps between each generated agent can be adjusted manually.

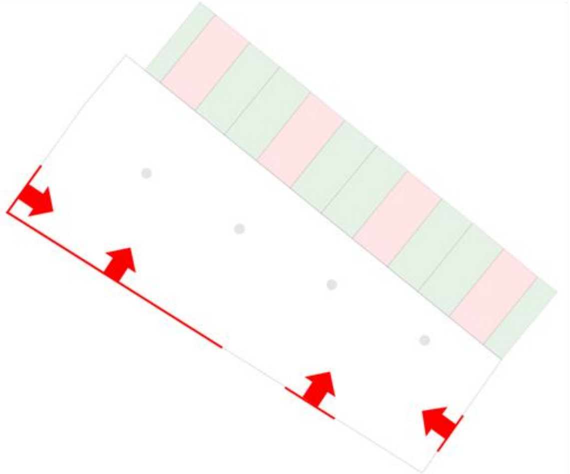
Not all line segments are generation points for all three agent species. Some of the borders represent incoming footpaths, some represent bicycle paths, and agents can also enter the area through the bicycle shed or the taxi stand. Figure **3.3** shows along which edges agents are generated, per agent species.



Pedestrians enter the shared space area from almost all sides. Multiple footpaths lead into the area, and pedestrians also appear from the taxi stand on the southeast, and the bicycle parking space on the north east side of the shared space.



Cyclists enter the shared space through four different entrance gates: three bicycle paths leading into the shared space, and the bicycle parking space on the northeastern side.



Mopeds enter the shared space area through the same three bicycle path- entrances, and also appear from the taxi stand on the southeastern side of the area.

Figure 3.3 Agent generation: city side

Agent generation: IJ-river sides

In contrast to the constant and gradual traffic inflow of agents from the city side, the influx of agents from the *IJ-river side* is caused by the periodical arrival of ferries from Amsterdam Noord. Agents disembark from the ferries in groups, and enter the area in *waves* of agents.

Regarding the generation of agents from the ferry docks, the same modelling principles apply. However, instead of individuals spawning every couple of model steps, agents of all three species spawn in *groups* that represent loads of ferry passengers (Figure **3.4**). These agent groups are generated every couple of minutes in one of the four red boarding areas, depending on where a ferry arrives.

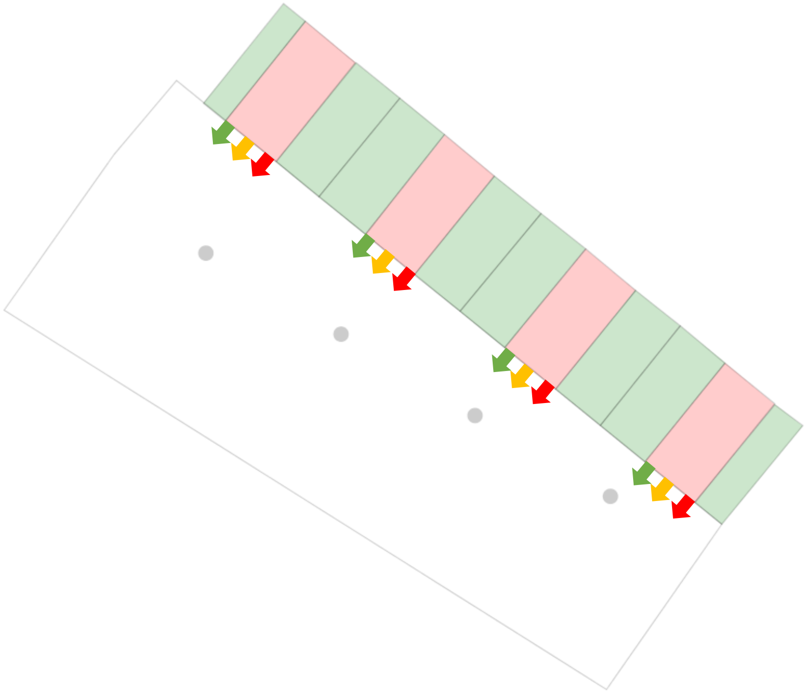
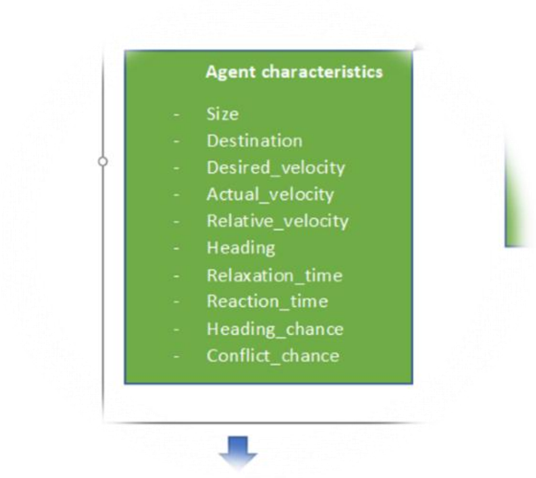


Figure 3.4 Agent generation: IJ-river side

3.1.5 Agent characteristics



Once generated, agents have certain unique *characteristics*;

Agent size

Agents –especially cyclists and mopeds-drivers– are rarely circular-shaped. However, in the 2D modelling environment, agents are represented as circles with different *sizes*. Each agent takes up a certain amount of space within the area, and the space an agent takes up in the area directly influences the chance of this agent intersecting another agent. The size of the agents relative to each other and relative to the modelled environment is approximated by using camera footage; pedestrians are 0.5m in diameter, cyclists 0.8m in diameter, and mopeds have a diameter of 1.0m. Within the modelled environment, agents of the three different species are represented as colored circles.

Destination

Each agent has a travel *destination* (figure **3.5**). An agent's travel destination or goal is conceptualized as a point beyond the borders of the Shared Space area. An agent is travelling either towards one of the green waiting areas or red boarding areas, the taxi stand, the bicycle stand or towards one of the bicycle- or footpaths leading away from the area.

The entrance gates as previously illustrated in Figures **3.3** and **3.4** are also target destinations for agents of the same species; *pedestrians* can leave the area at all edges except for the bicycle paths, *cyclists* can leave the area at the three bicycle paths and the bicycle parking space, and *mopeds* can leave the area at the bicycle paths and the taxi stand.

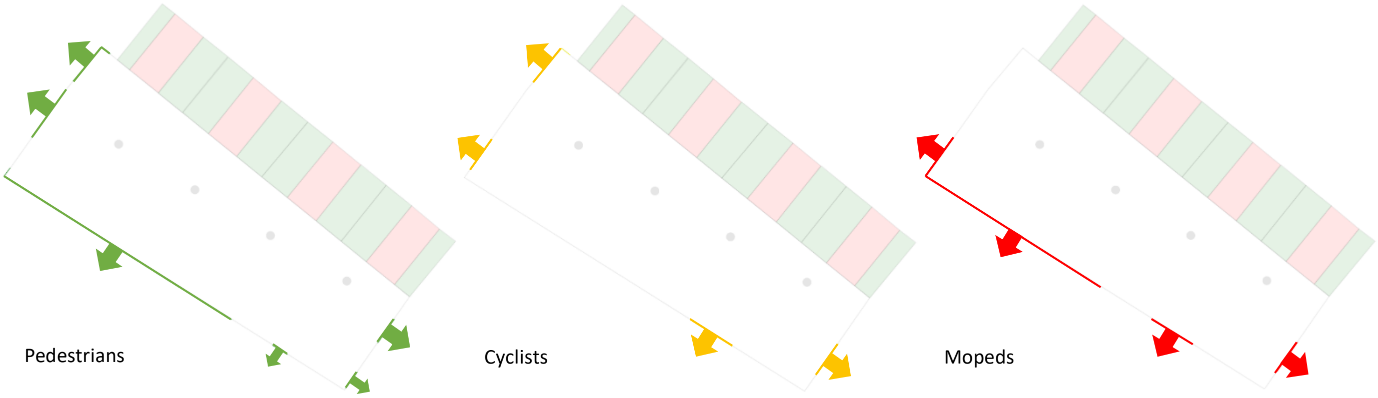


Figure 3.5 Agent travel destinations: City side

Desired velocity

Each agent has a certain ***desired velocity***. This is the velocity when no other agents are in the trajectory. Gehl & Svarre (2013) find urban pedestrian walking speeds ranging between 2,5 and 7,5 km/h. Kassim et al. (2020) find minimum and maximum measured cycling speeds varying between lows of approximately 4 to 7 km/h, and highs of approximately 35 to 36 km/h. However, the majority of riders were found travelling at relatively moderate speeds ranging from 8 to 24 km/h. Within the Shared Space however, it is accepted that most cyclists slightly adapt their speed even before entering the traffic area, which indeed shows when observing camera footage. Within the Shared Space environment, a choice is therefore made to set cyclists minimum and maximum speeds at 5 and 22 km/h, respectively. Mopeds are considered as ‘guests’ in pedestrian area, and are required to maintain the 15km/h speed limit. However, again, camera footage of the Shared Space environment shows deviations from the rule, and moped velocities are also set between 5 and 22 km/h. Table **3.2** summarizes the minimum and maximum speeds.

An agent’s desired velocity is a randomly chosen value between the maximum and minimum velocity thresholds. Tests were run to ensure agent speeds are proportionate to the modelled environment; for example, an agent with a velocity of 10 km/h needs approximately 21.5 seconds to cross the Shared Space area in east to west direction (60m).

Agent type	Maximum desired velocity (km/h)	Minimum desired velocity (km/h)
Cyclist	22	5
Pedestrian	7.5	2.5
Moped	22	5

Table 3.2 Maximum and minimum desired velocities

Actual velocity

An agents ***actual velocity*** is its real-time speed. When no other agents are in its trajectory, an agent’s actual velocity is similar to its desired velocity. Whenever an agent interacts with others, its actual velocity changes. In this context it is important to realize that while an agent’s velocity *cannot* exceed the maximum desired velocity, it *can* fall below the minimum desired velocity, during interaction with other agents

An agents actual velocity influences the chance the agent is involved in a conflict with another agent; this will be further illustrated in paragraph **3.1.7**.

Heading

Every agent has a certain ***heading***, between 0 and 360 degrees; see Figure **3.6**. In this example the pedestrian (green) has a heading of 224.2°, the cyclist (yellow) has a heading of 13.5° and the moped (red) has a heading of 186.9°. An agent’s heading determines the chance it is involved in a conflict with another agent; this will be further illustrated in paragraph **3.1.7**.

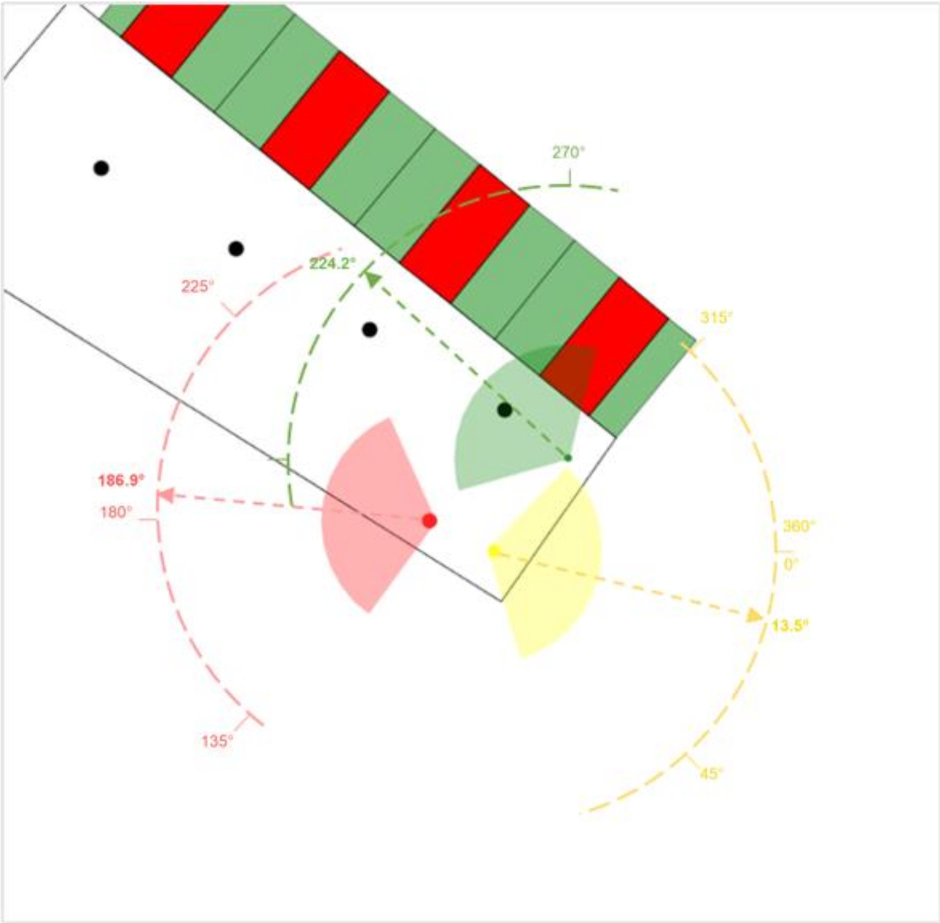


Figure 3.6 Agent heading

Relaxation time

When other agents are in its trajectory, an agent slows down and it takes some time before reaching its desired velocity again. Helbing & Molnár call this ***relaxation time***. Every agent has a certain relaxation time-value, which is dependent on the number of other agents within its pathway. In the Shared Space model, an agent's relaxation time is a value between 0.1 and 1.0. The greater the number of other agents in an agent's way, the lower its relaxation time-value; this will be further illustrated in paragraph **3.1.7**.

Reaction time

It would be unrealistic to presume that all agents react to the presence of others in the same fashion. Young, local people are expected to be alert and accustomed to busy traffic and bicycles, while tourists, elderly people and toddlers are examples of vulnerable road user groups. Some agents are quick to react to a potential conflict situation, while others need more time to slow down. In order to implement these different reaction styles into the model, each agent is assigned an additional value which translates to their ***reaction time***. An agent's reaction time is a measure that is used to create a certain level of variety within agent's ability and proneness to react to other agents. Every agent has a unique reaction time-value, which is party dependent on this agent's relaxation time; this will be further illustrated in paragraph **3.1.7**.

Heading chance

In the Shared Space model, whenever two agents intersect, both agent's heading determine the chance a conflict occurs. An agent's heading relative to that of the nearest other agent determines its ***heading chance***. Every agent has a heading chance-value which ranges from 0.0 to 1.0. The higher the heading chance, the higher the probability of conflict in case of an intersection; this will be further illustrated in paragraph **3.1.7**.

Combined velocity

An agent's velocity, in combination with that of its potential conflict partner, is determinative for whether or not an accident occurs in case of intersection. This is captured in a ***combined velocity***-value, which ranges from 0.0 to 1.0. The higher the combined velocity, the higher the probability of conflict in case of an intersection; this will be further illustrated in paragraph **3.1.7**.

Conflict chance

Whenever two agents intersects, and both their velocities are great enough, a ***conflict chance***-value is calculated. This conflict chance-value is a product of a *heading chance*-value and a *velocity chance*-value*.* This will be further illustrated in paragraph **3.1.7**.

3.1.6 Field of view

Field of view (FOV)

- Limited FOV
- Extended FOV

As presented in Helbing and Molnár's Social Force Model: an agent's behavior is only based on situations that are perceived in the desired direction of motion. Anything outside the agent's ***field of view*** does not influence the agent. A field of view is the overseeable area in front of an agent. In reality, a field of view is 3-dimensional, as it has a horizontal (left-right), vertical (top-down) as well as a viewing extent (depth). However, in this model the field of view represents a 2-dimensional surface area comprised of a horizontal viewing aspect and a viewing depth.

Horizontal viewing aspect

Humans have a slightly over 200-degree forward-facing horizontal arc of their visual field, which is called the *total* visual field. However, our *binocular* field of vision –the region where both eyes can see together– is smaller. This region of stereo vision is limited to a 120-degree forward-facing arc (Stanford, 2019), see Figure **3.7**. Within the busy Shared Space environment, it is likely agents are anticipating whatever is right in front of them, while whatever is happening in the corners of the eyes is less of interest. Therefore, within the Shared Space model agents use a binocular 120-degree visual field.

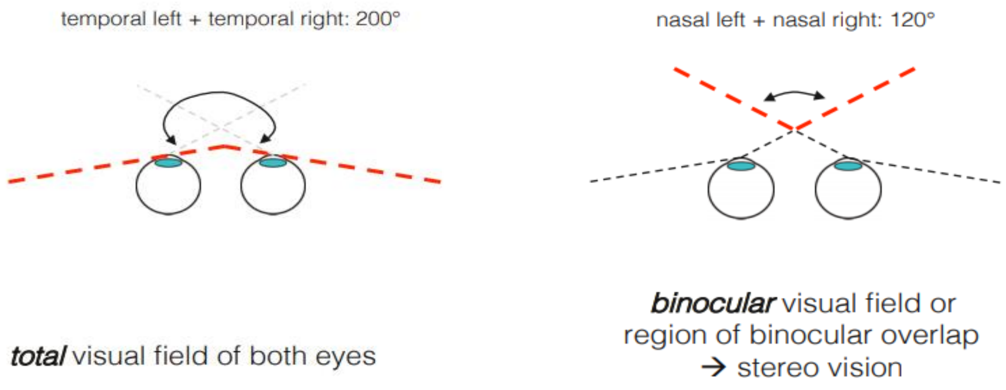


Figure 3.7 Human visual field

Viewing extent

While the extent (depth) of human vision can reach many kilometers, the extent of vision is in this model much more limited. An agent is unlikely to anticipate actions of agents that are very far away. The ***viewing extent*** is the distance an agent is perceiving while deciding in which direction and at what velocity to move, and is set at 15 meters within the model.

Extended and limited field of view

The combination of the forward facing horizontal view radius (in degrees) and the viewing extent, or viewing depth (in meters) creates a *cone* geometry that represents an agent's personal ***field of view***. An agent's velocity and movement is affected by the presence of objects and other agents inside this field of view, see paragraph **3.1.7**. For modeling purposes, every agent is assigned *two* fields of view: an *extended* and a *limited* field of view, which both have different functionalities. The extended field of view is used to sense and avoid the inanimate pillars within the area, while the limited field of view is used to adapt to the presence of other moving agents. Figure **3.8** visualizes the two different cones separately.

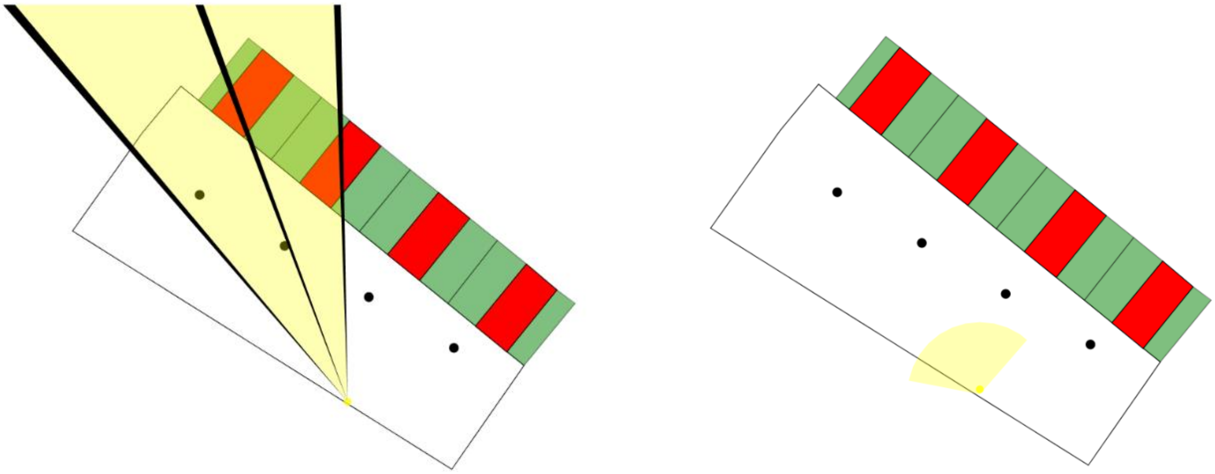


Figure 3.8 *Extended* field of view (left), and *limited* field of view (right)

3.1.7 Agent behavior

Choosing the shortest route

An agent knows where to go as soon as it enters the Shared Space area. It's destination is a point on one of the line segments on the area border. Just like in the Social Force Model, in order to reach the destination as quickly as possible, an agent will constantly steer to its predetermined goal. However, there are two types of obstructions that can intersect an agent's trajectory; either (1) one of the four pillars, or (2) one of the other agents. Agents temporarily change their travel destination in order to circumvent pillars, and agents adapt their velocity when confronted with other agents.

Changing destination

As an agent enters the Shared Space area, it uses its extended field of view to assess its route, while steering towards its goal. If a pillar is in its trajectory, an agent will start adapting at an early stage, by adjusting its route gradually. If a pillar is in the way, the agent temporarily chooses a new target and moves towards it, until there is no more barrier between the agent and its original target. After this, the agent moves to its original target without perturbations. By choosing this modelling technique, agents retain a close-to-realistic trajectory. The technical implementation and visualization of this process can be found in paragraph **3.2.2**.

Adapting velocity

Step 1: relaxation time

In line with Helbing & Molnár's Social Force Model, in the process of deceleration due to hindrances or obstructions, a deviation develops between an agent's *desired* velocity and its *actual* velocity. In laymen's terms: when other agents are in its trajectory, an agent slows down and it takes some time before reaching its desired velocity again. Helbing & Molnár call this *relaxation time* and conceptualize it as a literal measurement of time. However, in the Shared Space model, an agent's relaxation time is dependent on the number of agents within its field of view, and conceptualized as a value between 0.1 and 1.0. An agent with no other agents within its field of view has a relaxation time value of 1.0. For every new agent within the field of view, the relaxation time *decreases* by a decimal;

$$\textbf{\textit{Relaxation time}} = 1.0 - \frac{number\ of\ agents\ within\ field\ of\ view}{10}$$

Example: *Number of agents within field of view =* ***3***

$$\textbf{\textit{Relaxation time}} = 1.0 - \frac{\mathbf{3}}{10} = \mathbf{0.7}$$

Step 2: actual velocity (1)

In the modelling environment, every agent starts off with its own *desired* travelling velocity. When other agents emerge in its field of view, its relaxation time-value decreases and so does its *actual* velocity. An agents actual velocity is thus a function of its desired velocity and its relaxation time;

Actual velocity = $desired\ velocity\ *\ relaxation\ time$

Example: *Desired velocity:* ***13.4 km/h***

Relaxation time: ***0.7***

Actual velocity*:* $(13.4 * 0.7)$= ***9.83 km/h***

Step 3: reaction time

Reaction time is an agent characteristic that creates a certain level of variety within the agent group, regarding the ability and proneness of agents to react to other agents. The *higher* an agent's reaction time-value, the more it slows down when confronted with other agents. An agent's *reaction time* is a value between 0.0 and 1.0, and is a product of (1) the *Reaction*-value ***R***, and (2) the *relaxation time*;

Reaction time = $(R * relaxation\ time)$

An agent's ***Reaction*-value *(R)*** is a randomly assigned value anywhere between 0.0 and 1.0 and is unique for each agent;

R = $rnd\big((X),(Y)\big)$ *(where X and Y are both between 0.0 and 1.0)*

During model verification, the lower (X) and upper (Y) threshold values of *R* are adjusted manually. This has an effect on the volatility of reaction time-values within agent group. In the example below a random value between **0** and **30** percent of an agent's relaxation time is used (**X** = 0.0; **Y** = 0.3).

Example: *Relaxation time:* ***0.7***

R = $rnd\big((0.0),(0.3)\big)$ = *(for example)* ***0.17***

Reaction time = $(0.17 * 0.7)$ = ***0.119***

Step 4: actual velocity (2)

Finally, an agent's actual velocity is the product of its desired velocity, relaxation time and reaction time:

Actual velocity = $\big(desired\ velocity * (relaxation\ time - reaction\ time)\big)$

Example: *Desired velocity:* ***13.4 km/h***

Relaxation time: ***0.7***

Reaction time = $(0.17 * 0.7)$ = ***0.119***

Actual velocity = $\left(13.4 * (0.7 - 0.119)\right)$ = ***7.79 km/h***

Determining conflict

What is considered to be a traffic conflict between two agents remains open to interpretation. What is experienced as a conflict situation for agent A, might not be for agent B. Also, a conflict can vary between a quick change in direction, breaking and swerving, up to more obvious conflict situations such as (high speed) collisions. For modelling purposes, certain choices were made in determining when agent interaction results in a conflict.

In Helbing and Molnár‘s Social Force Model, agents have their own personal private sphere and are subject to *attractive* and *repulsive* effects. While actual conflict is not incorporated in the Social Force model, in theory, these attractive and repulsive effects would be determinative for the occurrence of conflict situations. In this Social Force model, an agent feels increasingly uncomfortable the closer it gets to another agent, and conflict is actively avoided by adjusting direction when moving within each other’s private sphere.

In the first version of the Shared Space Model, an attempt was made to incorporate these attractive and repulsive effects into the model. However, due to modelling constraints and unsatisfactory results these effects were omitted from the final model. A choice was made to model agent conflict through an alternative method; by allowing agents to maintain their original heading, and calculating a *conflict chance* in case of intersection. Whenever two agents intersect, and both their velocities are great enough, a *conflict chance*-value is calculated. Whenever this conflict chance-value exceeds a certain ***conflict threshold (Ct)***, a conflict occurs. This process is described in the following section.

Involved modes of transport conflict

It is accepted that every agent type can get into a conflict situation with any other agent type. One exception exists: pedestrians cannot get into a conflict situation with other pedestrians; their combined velocity is too low. This leaves five sets of possible conflict partners (Table **3.3**).

Involved modes of transport
Cyclist – cyclist
Cyclist – pedestrian
Cyclist – moped
Moped – pedestrian
Moped – moped

Table 3.3 Conflict partners

Prerequisite 1: Intersection

In the modeling environment, a conflict is only possible when two agents *intersect*, see Figure **3.9**. This is a prerequisite for the occurrence of a conflict. However, an intersection alone is not sufficient for a conflict. Whether a conflict actually occurs, further depends on the *velocity and heading* of both involved agents.

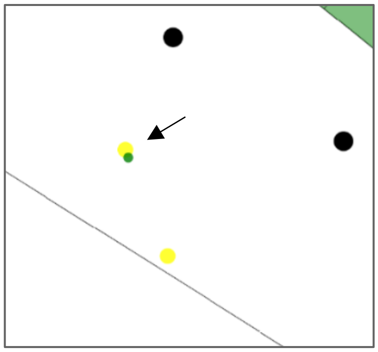


Figure 3.9 Agent intersection

Prerequisite 2: Minimum combined velocity

Velocity is a decisive factor in the occurrence of agent conflicts. When agents interact at low velocities, this is not regarded as a conflict situation. The combination of an agent's own velocity and that of its potential conflict partner (the nearest other agent) is called *combined velocity*, and is determinative for whether or not an accident occurs, in case of intersection. A *minimum* combined velocity is thus a prerequisite for an agent conflict; the two velocities combined are required to exceed a certain ***velocity threshold* (*Vt)*** before the model calculates a conflict chance. In order to take account of all three different agent groups, travel velocity-values are used which are relative to the maximum velocity of the agent in question, which results in a value between 0.0 and 1.0. Whenever this *combined velocity* exceeds the velocity threshold, a *conflict chance* is determined.

Conflict chance

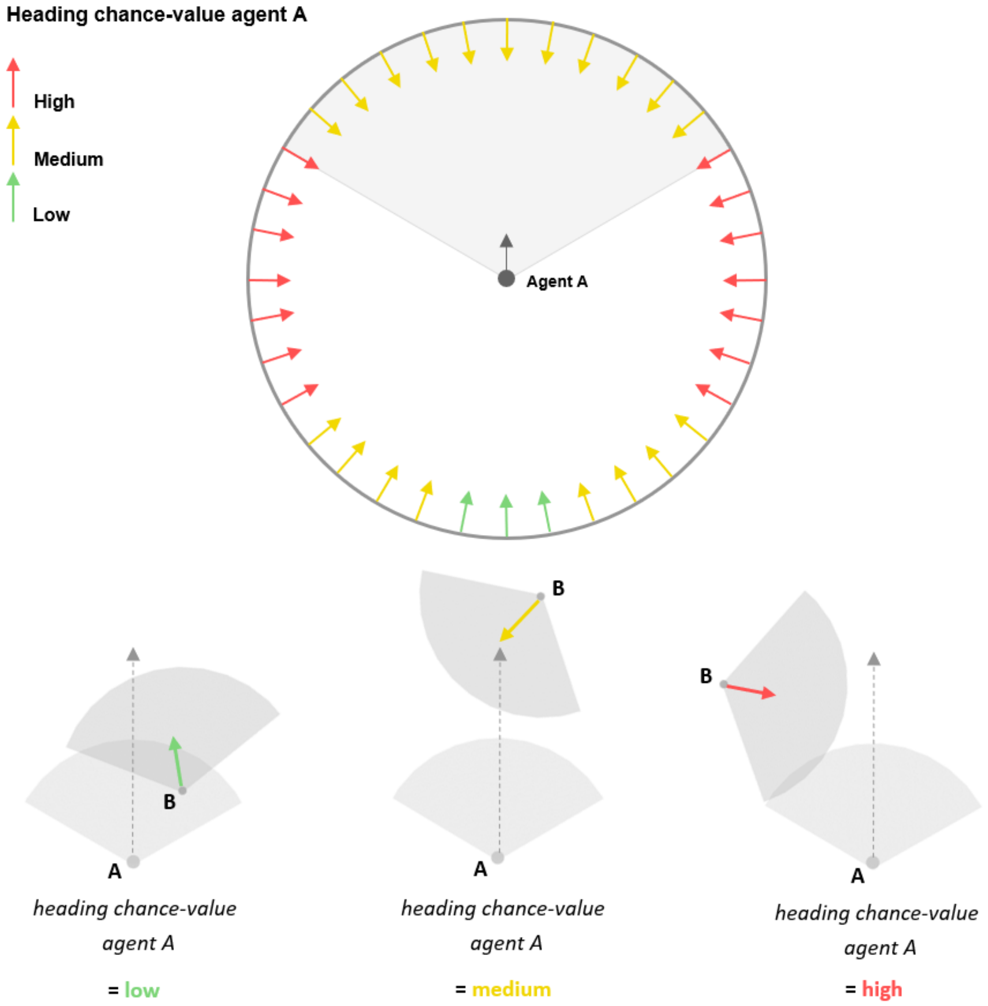
Within the Shared Space model, two agents can only cause a conflict whenever (a) both agents intersect; and (b) their combined velocity exceeds the velocity threshold. If these criteria are met, a *conflict chance* is calculated. This does not yet mean a conflict takes place; weather a conflict actually takes place depends on the magnitude of the conflict chance, which is determined by the *heading* and *velocity* of both involved agents. The following assumptions are made:

- The more perpendicular the angle between both agent's headings is, the greater the chance of a conflict occurring. This is captured in a variable we call *heading chance*, which has a value ranging between 0.0 and 1.0.
- The greater the combined velocity of both involved agents, the greater the chance of a conflict occurring. This *velocity chance*-value ranges between 0.0 and 1.0.

Heading chance

The angle between the heading of agent A and that of its nearest neighbor determines the *heading chance-value* of agent A. This is a value between 0.0 and 1.0. The more perpendicular the angle between both agent's heading is, the greater the heading chance-value of agent A.

Figure **3.10** illustrates this; the arrows around agent A represent potential agents approaching at various angles. The heading chance-value of agent A is the greatest when the angle between its own heading and that of its closest neighbor is close to a 90 degrees (red arrows). Its heading chance-value is the smallest whenever the two agents are travelling in the same general direction (green arrows).



heading chance-value agent A = low

heading chance-value agent A = medium

heading chance-value agent A = high

"The more perpendicular the angle between both agent's heading is, the greater the heading chance-value of agent A."

Figure 3.10 Heading chance-value

Combined velocity

The higher the speed, the greater the chance of conflicts. The *combined velocity*-value is a result of the velocity of both agents relative to their maximum speeds; see the example below;

Combined velocity: $\left(\frac{Velocity\ agent\ A}{Max\ velocity\ agent\ type}+\frac{Velocity\ agent\ B}{Max\ velocity\ agent\ type}\right)*\ 0.5$

Example:

Maximum velocity cyclists: **25 km/h**

Maximum velocity mopeds: **15 km/h**

Agent A: **Cyclist** travelling at **15.5 km/h**

Agent B: **Moped** travelling at **10.2 km/h**

Combined velocity: $\left(\frac{15.5}{25}+\frac{10.2}{15}\right)*\ 0.5=\mathbf{0.65}$

Velocity chance

Before implementing the *combined velocity-value* into the final formula, this variable is turned into a stochastic variable; the *velocity chance*. The *velocity chance*-value is a randomly assigned value, anywhere between 0.0 and the combined velocity-value. On average, higher combined velocities thus lead to higher velocity chance-values.

Calculating the conflict chance

An agent's *conflict chance*-value is a value between 0.0 and 1.0, and is a product of it's *heading chance*-value (0.0 – 1.0), and it's *velocity chance*-value (0.0 – 1.0). This leads to the following equation:

Conflict chance: $\Big((Cw * heading\ chance)+\big((1-Cw)*\ velocity\ chance\big)\Big)$

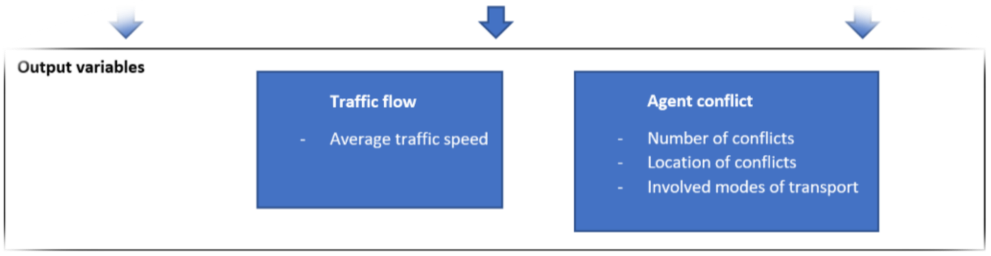
*The **conflict weight**-value **(Cw)*** is a value that represents the **weight** of both the heading chance-value and the velocity chance-value in determining the conflict chance-value; if Cw = 0.5, both values contribute equally to the conflict chance-value.

Ultimately, whenever the conflict chance-value exceeds the *conflict threshold (Ct)*, an agent conflict occurs and registered in the model.

Dying

Whenever an agent reaches its destination at the edge of the Shared Space area, its final action is to *die* and disappear from the model.

3.1.8 Model output



The Shared Space model delivers a number of model outputs, which can be categorized into two sections; **traffic flow** and **agent conflict**:

Traffic flow

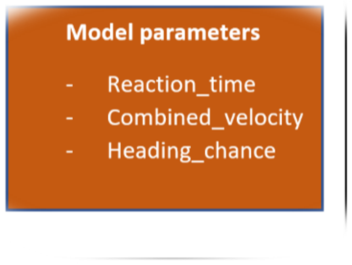
The concept of Shared Space is built around the idea that road users slow down and anticipate other agents. However, whenever speeds fall below a certain level, the functionality of the traffic area becomes questionable.

The **traffic flow** within the Shared Space model is measured trough calculating the *average traffic speed* of all agents in the area.

Agent conflict

The second measurable model output is **agent conflict**. This includes (1) the number of conflicts, (2) their locations, and (3) the involved agent types.

3.1.9 Overview of variables



Model parameters

- Reaction_time
- Combined_velocity
- Heading_chance

The former section has set out to describe the concepts and assumptions made within the Shared Space model. It has successfully attempted to formulate an answer to sub-question 3 (SQ 3): *How can the agent dynamics within the Shared Space environment at Amsterdam CS be converted into a set of rules?*

This paragraph presents an overview of the most important independent variables within the model, and whether they are kept constant, or function as model parameter during either (1) the process of verification or (2) the scenario analysis. In chapter **3.3,** the model is verified by conducting a sensitivity analysis. In the progress of model verification, a number of variable values are kept constant, while others function as model parameters. After the model is validated, several traffic scenarios are tested and analyzed in chapter **4**. During this scenario analysis, a different set of variables function as model parameters. In table **3.3** all the relevant model variables are set out, along with their (baseline) value, their influence within the model, their information source (if applicable), and their role as model parameter.

	Variable	Value	Influence in model	Source	Model parameter during:
Agent generation	**Agent spawning frequency**	651 – 5.314 per hour	Influences: average agent velocity and total number of conflicts	Gemeente Amsterdam, 2016	Model validation (chapter 3.3) & Scenario analysis (chapter 4)
	Agent ratio	cyclists 58% pedestrians 35% mopeds 7%			Scenario analysis (chapter 4)
	Agent spawning distribution*	north – south – east – west*	Unknown		
Agent characteristics	**Desired velocity thresholds (km/h)**	cyclists: 5 – 22 pedestrians: 2.8 – 7.2 mopeds: 5 – 22	Influences: chance of agent conflict	(Source)	Kept constant
	Agent destination distribution*	north – south – east – west*	Unknown	Gemeente Amsterdam, 2016	
	Agent size (2D diameter)	cyclists: 0.8 m pedestrians: 0.5 m mopeds: 1.0 m	Influences: chance of agent intersection -> chance of agent conflict		
	Viewing extent	15 meters			Kept constant

Field of view	**Viewing aspect (forward facing)**	120 degrees	Influences: relaxation time-value -> agent velocity -> chance of agent conflict	Stanford, 2019	Kept constant
Agent behavior	**R** (Reaction time-value)	$rnd\big((X),(Y)\big)$ (between 0.0 – 1.0)	Influences: agent velocity during interaction.		Model validation (chapter 3.3) & Scenario analysis (chapter 4)
	Vt (Velocity threshold)	Between 0.1 – 1.0 Baseline value = 0.5	Influences: conflict chance; if the combined velocity exceeds this threshold, a conflict chance is calculated.		Model validation (chapter 3.3)
	Cw (Conflict weight: heading vs velocity)	Between 0.1 – 1.0 Baseline value = 0.5	Influences: conflict chance; if **Cw = 0.5**, heading and velocity contribute equally to the *conflict chance*-value.		Model validation (chapter 3.3)
	Ct (Conflict threshold)	Between 0.1 – 1.0 Baseline: 0.75	Influences: number of conflicts.		Kept constant

*The distribution of agent spawning and destination points is set out in chapter **3.3**

Table 3.4 Model variables and parameters

3.2 Implementation

3.2.1 Software choices

GAMA

When looking at the requirements for choosing which software to use in the modeling process, the best option is *GAMA (1.7)*. The programming language used by GAMA is *GAML*, a high-level agent-oriented language dedicated to the definition of agent-based simulations (http://gama-platform.org). This software has several advantages above others; while GAML is based on other object-oriented languages like Java or C++, it is more intuitive than those for a non-experienced programmer. Furthermore, the platform is specifically made for complex GIS data (shapefiles) which can function as agents and also as environments for agents to move in. The toolkit makes it possible to let the agents move within a geometry including coordinates and computing e.g. distance travelled (Taillandier et al, 2012).

GAMA is a free, open-source tool, and it has a broad documentation, manuals, tutorials and model examples which allows beginning users to get acquainted with the software rapidly. Also, the platform facilitates carrying out multiple simulation runs at once and it allows for inspecting the agents during the simulation, essential for monitoring, processing and saving output data.

Excel

Microsoft Excel is a spreadsheet developed by Microsoft for Windows, macOS, Android and iOS. It features calculation, graphing tools, pivot tables, and programming languages. All model data output from GAMA is saved in Excel format. The data captured in these sheets is presented as charts.

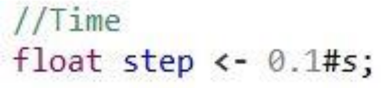
ArcGIS Pro

ArcGIS Pro is a professional desktop GIS application from Esri. It can be used to visualize and analyze data and to create 2D maps and 3D scenes. During the modelling process, ArcGIS Pro is used to (1) prepare data (shapefiles) to use as input for the model in the GAMA modeling environment, and (2) to visualize model output; heatmaps were created by running output shapefiles through the ArcGIS Pro ‘Kernel Density’-tool.

3.2.2 Modelling process

3.2.2.1 Time

Within the GAMA modelling environment, every **10** model steps (or cycles) represent **1** real-world second.



```
//Time
float step <- 0.1#s;
```

3.2.2.2 Agents

The agents in the model represent individual pedestrians, cyclists and mopeds. In the GAMA modelling environment, *inheritance* is used; the three agent types are defined as *sub-species* of a *main* parent species. All three agent types show similar behavior, which is defined in the main species code section. However, by choosing this model architecture, different agent types can be modelled as separate groups with unique characteristics.

3.2.2.3 Environment

In order to reproduce the architecture of the study area, and to implement it into the model in Gama, a range of Shapefiles was created using ArcGIS Pro. A total of (33) files were created and assigned a geographic location; (16) polygons and (17) lines, which together form the geometric input for the model in the Gama modelling environment. Figure **3.11** shows the resulting model layout in GAMA.

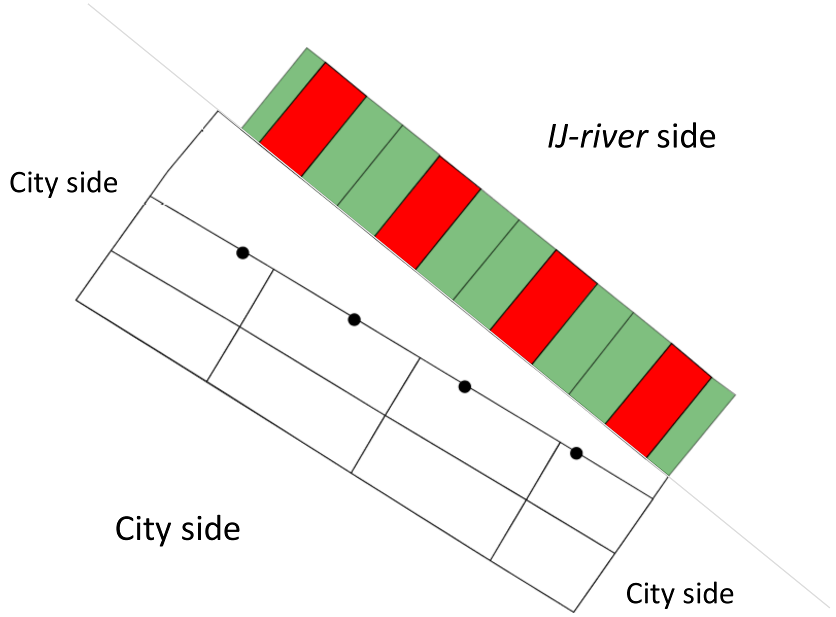


Figure 3.11 Modelling environment in GAMA

3.2.2.4 Agent generation

Pedestrians, cyclists and mopeds enter the Shared Space at regular intervals. For each of the agent species, a unique *spawning frequency* exists. By determining how much model cycles pass before another agent of the same species is generated, this parameter regulates the amount of agents per hour.

All sixteen line segments that make up the edges of the Shared Space are placed in a list. Then, for each agent species, a *source probability list* determines the chance an agent is generated on a particular line segment. Every couple of model cycles (based on the spawning frequency), an agent belonging to one of the three agent species is generated. This new agent is instructed to ‘choose’ one of the line segments from the list, according to the probability distribution, and to then be generated on a random point on this line.

Figure **3.12a** shows one agent of each species being generated at one of the line segments, during the first model cycle. Figure **3.12b** shows the moment a ferry unloads its passengers; multiple agents are generated before heading into the Shared Space.

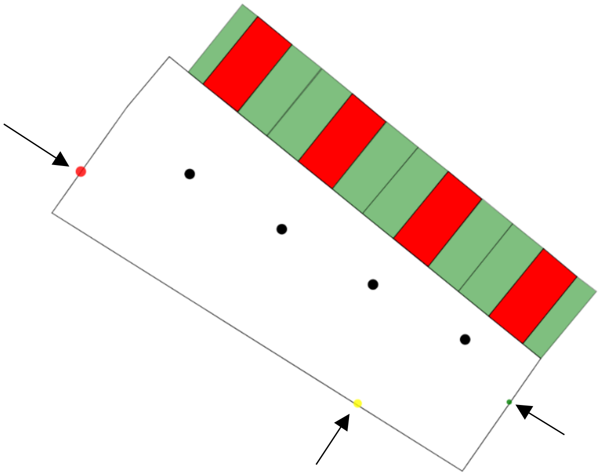


Figure 3.12a Agent generation from city side

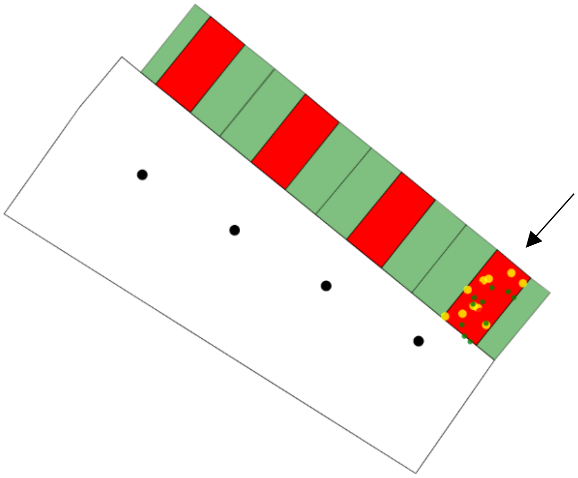


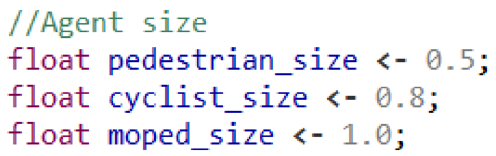
Figure 3.12b Agent generation from IJ-river side

3.2.2.5 Agent characteristics

Once generated, agents have certain unique *characteristics*;

Agent size

Each agent takes up a certain amount of space within the area. The data used to create the modelling environment is geographically referenced. This allows for the use of accurate agent sizes within the code:



```
//Agent size
float pedestrian_size <- 0.5;
float cyclist_size <- 0.8;
float moped_size <- 1.0;
```

Destination

When an agent is generated, a *target location* for that agent is assigned simultaneously. Similar to the method of choosing a spawning location, a *target probability list* determines the chance an agent's target is located on a particular line segment. Again, not all line segments function as target areas for all three agent species.

Agents that enter the Shared Space from one of the ferries are very unlikely to board one of the ferries again. Therefore, agents that spawn in any of these four boarding areas are assigned a target line segment from a separate list; one in which the ferry waiting areas and ferry boarding areas are omitted.

Desired velocity

In the model, an agent's *desired velocity* is determined by choosing a random (rnd) value between the *maximum* and *minimum* desired velocities; see example below:

```
//Desired cyclist velocity
float desired_velocity <- rnd(min_cyclist_velocity,max_cyclist_velocity);
```

3.2.2.6 Field of view

Every agent has two separate fields of view; an *extended* and a *limited* field of view. Both fields are modelled similarly. Every model step an agent's perception is updated, by creating two

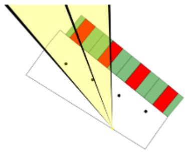
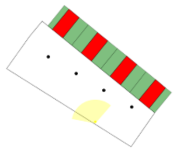
Field of view	Heading range	Perception distance	Result
Extended	°20 (left) + °20 (right) = °40 total	120 meter	
Limited	°60 (left) + °60 (right) = °120 total	15 meter	

Table 3.5 Field of view; extended and limited

forward facing cone-geometries, with predetermined *heading range* and *perception distance* values (table **3.5**).

3.2.2.7 Agent behavior

Shortest route + changing destination

As an agent enters the Shared Space area, it uses its extended field of view to assess its route, and steer towards its goal. If a pillar is in its trajectory, an agent will start adapting at an early stage, by adjusting its route gradually. Figure **3.13** shows the process of an agent circumventing a pillar. During the *first* model cycle, the agent's middle antenna intersects one of the pillars (A). Based on the location of the center of the pillar relative to the middle antenna, the agent chooses a new *temporary* target (B), which is the location where the outer antenna intersects the edge of the Shared Space area. During the *second* cycle, the agent travels towards this new target (C). During the *third* cycle the agent regains its original target, and the process repeats itself until the agent's trajectory no longer intersects the pillar; in this example this point is reached during cycle 9. In the remaining cycles the agent travels towards its intended target unhindered and eventually arrives at one of the ferry docks during cycle 65 (equating to 6,5 seconds). After reaching its destination at the edge of the Shared Space area the agent dies.

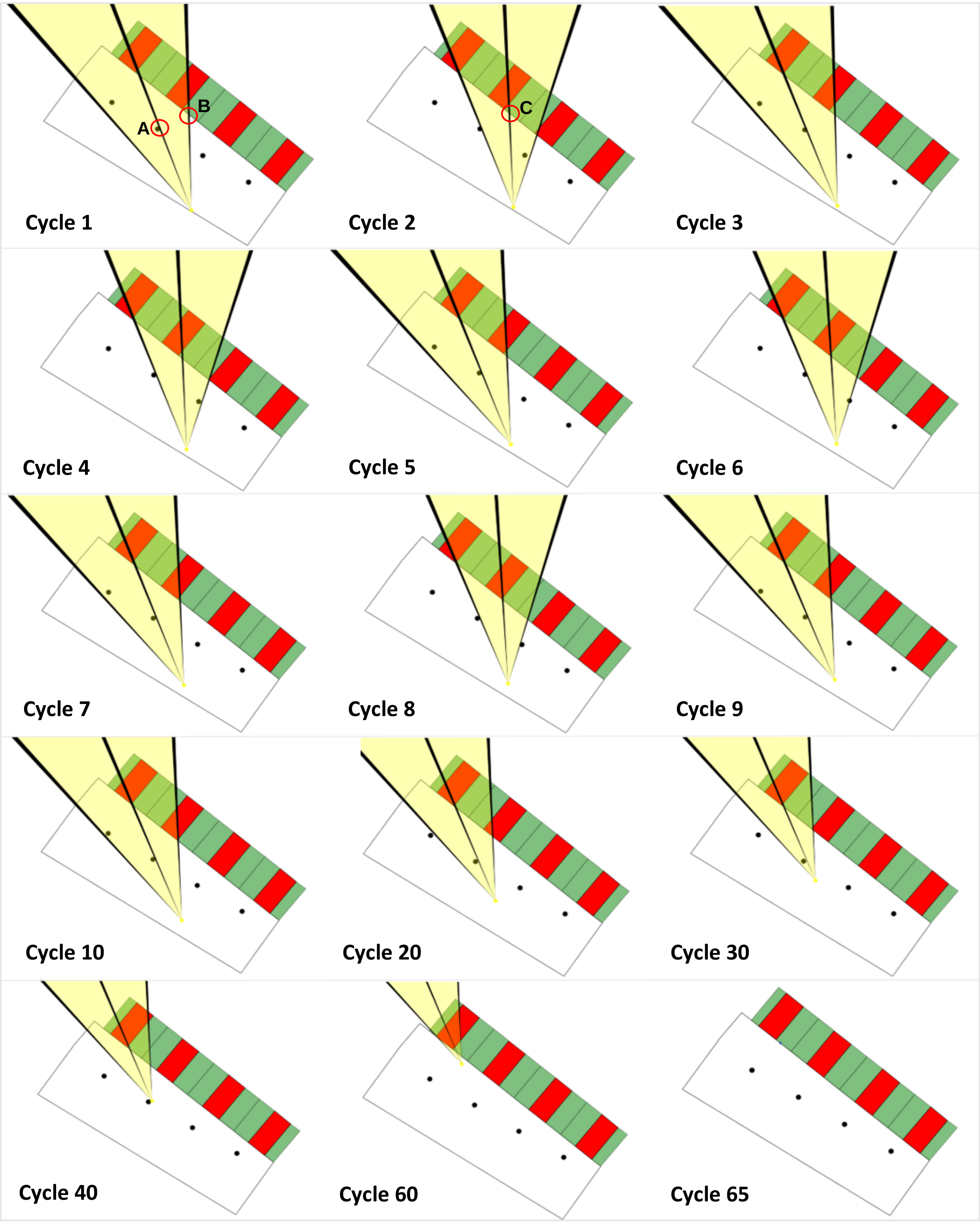


Figure 3.13 An agent circumventing a pillar

A = pillar, **B/C** = new temporary target

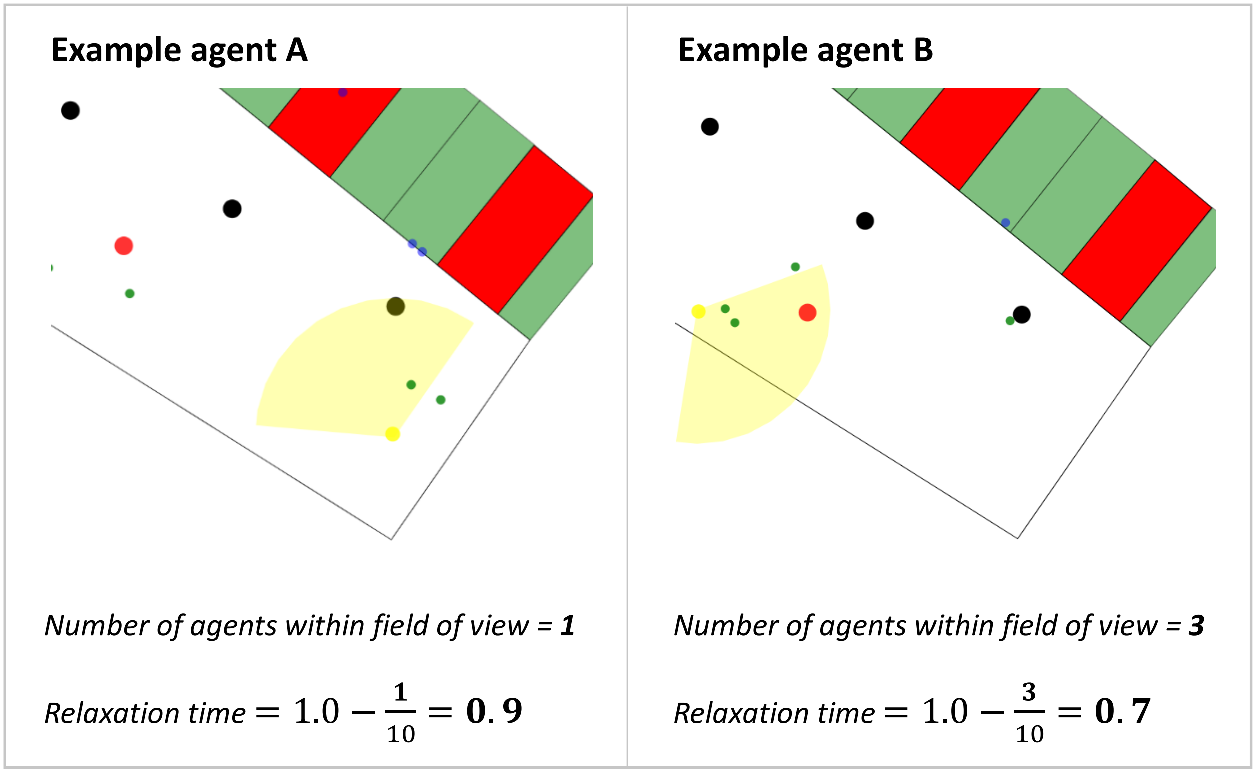
Adapting velocity: step 1

For every new agent within the field of view, an agents *relaxation time* decreases by a decimal:

$$\textbf{\textit{Relaxation time}} = 1.0 - \frac{number\ of\ agents\ within\ field\ of\ view}{10}$$

Agent **A** has **one** other agent within its field of view; this means that its relaxation time is decreased by **1** decimal.

Agent **B** has **three** other agent within its field of view; this means that its relaxation time is decreased by **3** decimals.



Example agent A

*Number of agents within field of view = **1***

$$\textit{Relaxation time} = 1.0 - \frac{\mathbf{1}}{10} = \mathbf{0.9}$$

Example agent B

*Number of agents within field of view = **3***

$$\textit{Relaxation time} = 1.0 - \frac{\mathbf{3}}{10} = \mathbf{0.7}$$

Figure 3.14 Adapting velocity: step 1

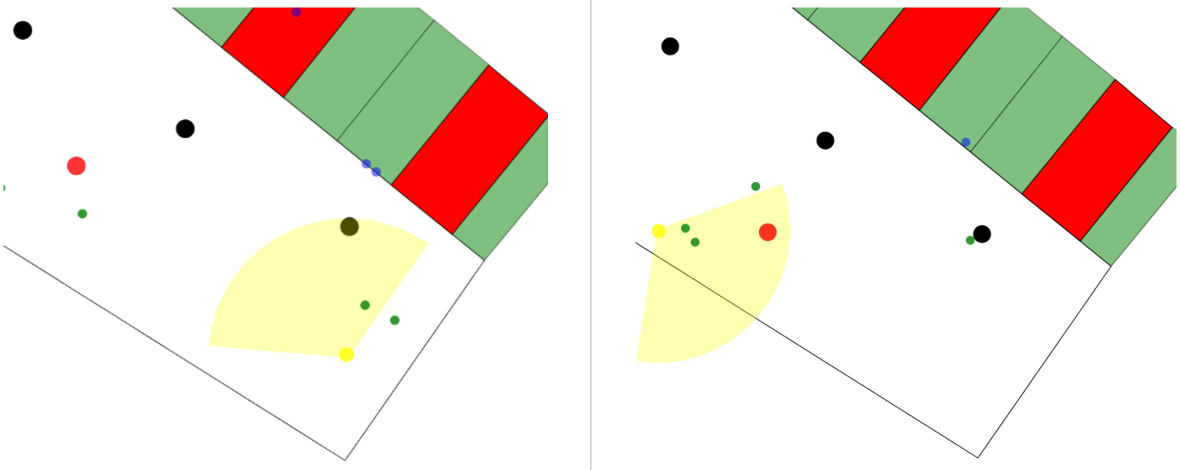
Adapting velocity: step 2

An agents new velocity is a function of its *desired velocity* and its relaxation time;

Actual velocity = $desired\ velocity\ *\ relaxation\ time$

The desired velocity of agent **A** is 17.2 km/h; multiplied by its relaxation time (0.9) = ***15.48 km/h***

The desired velocity of agent **B** is 13.4 km/h; multiplied by its relaxation time (0.7) = ***9.83 km/h***



Example agent A

Desired velocity: ***17.2 km/h***

Relaxation time: ***0.9***

*Actual velocity: 17.2 * 0.9 =* ***15.48 km/h***

Example agent B

Desired velocity: ***13.4 km/h***

Relaxation time: ***0.7***

*Actual velocity: 13.4 * 0.7 =* ***9.83 km/h***

Figure 3.15 Adapting velocity: step 2

Adapting velocity: step 3

An agent's *reaction time* is a value between 0.0 and 1.0, and is a product of (1) the Reaction-value R, and (2) the relaxation time;

Reaction time = $(R * relaxation\_time)$

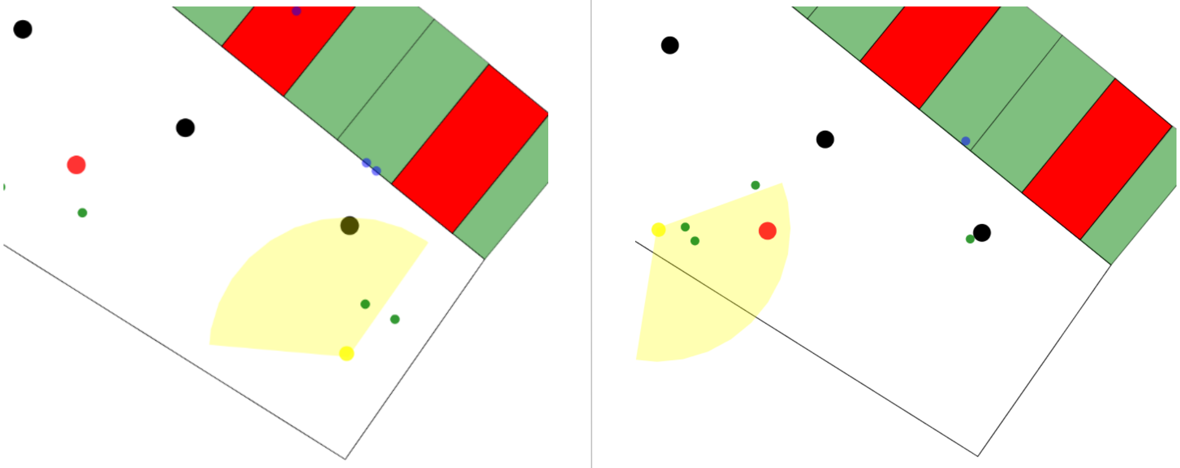
R = $rnd((X),(Y))$ *(where X and Y are both between 0.0 and 1.0)*

Agent **A** has an R-value of **0.25**; multiplied by its relaxation time (0.9) = ***0.225***

Agent **B** has an R-value of **0.17**; multiplied by its relaxation time (0.7) = ***0.119***

Example agent A

Example agent B



Relaxation time: ***0.9***

R = ***rnd****((0.0),(0.3))* *= (for example)* ***0.25***

Reaction time *= (0.25*0.9)* ***= 0.225***

Relaxation time: ***0.7***

R = ***rnd****((0.0),(0.3))* *= (for example)* ***0.17***

Reaction time *= (0.17*0.7)* ***= 0.119***

Figure 3.16 Adapting velocity: step 3

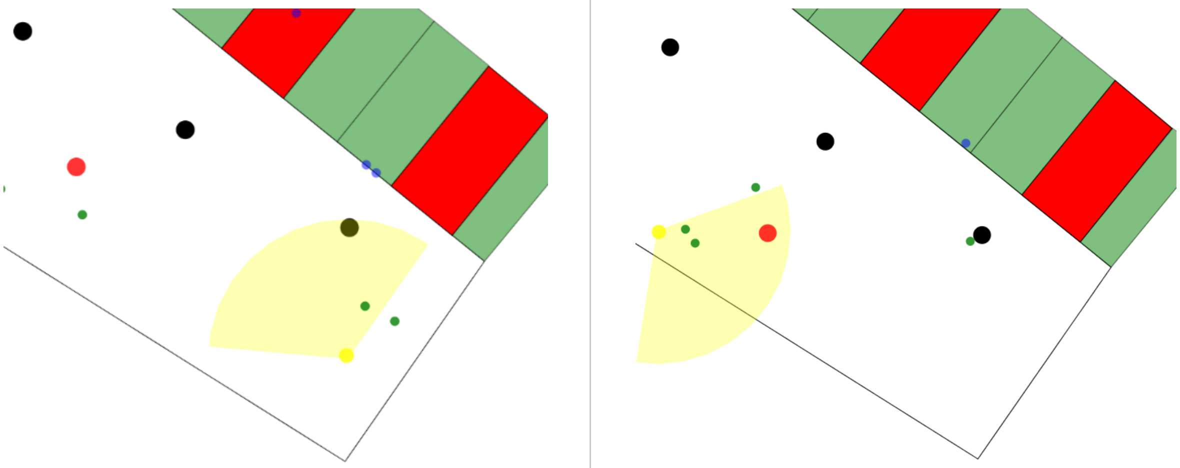
Adapting velocity: step 4

An agent’s actual velocity is the product of its desired velocity, relaxation time and reaction time;

Actual velocity = $(\mathit{desired\ velocity} * (\mathit{relaxation\ time} - \mathit{reaction\ time}))$

Agent **A:** desired velocity (17.2) * (relaxation time (0.9) - reaction time (0.225)) = ***11.61 km/h***

Agent **B:** desired velocity (13.4) * (relaxation time (0.7) - reaction time (0.119)) = ***7.79 km/h***



Example agent A

Desired velocity: ***17.2 km/h***

Relaxation time: ***0.9***

Reaction time: ***0.225***

Actual velocity*:*

$(17.2 * (0.9 - 0.225))$ = ***11.61 km/h***

Example agent B

Desired velocity: ***13.4 km/h***

Relaxation time: ***0.7***

Reaction time: ***0.119***

Actual velocity*:*

$(13.4 * (0.7 - 0.119))$ = ***7.79 km/h***

Figure 3.17 Adapting velocity: step 4

Determining conflict

Conflict chance flowchart

With every agent step a series of calculations is performed, in order to arrive at a *conflict chance.* If this conflict chance exceeds the conflict threshold (Ct), a conflict occurs. Figure **3.18** describes the process of determining whether or not a conflict occurs within the model:

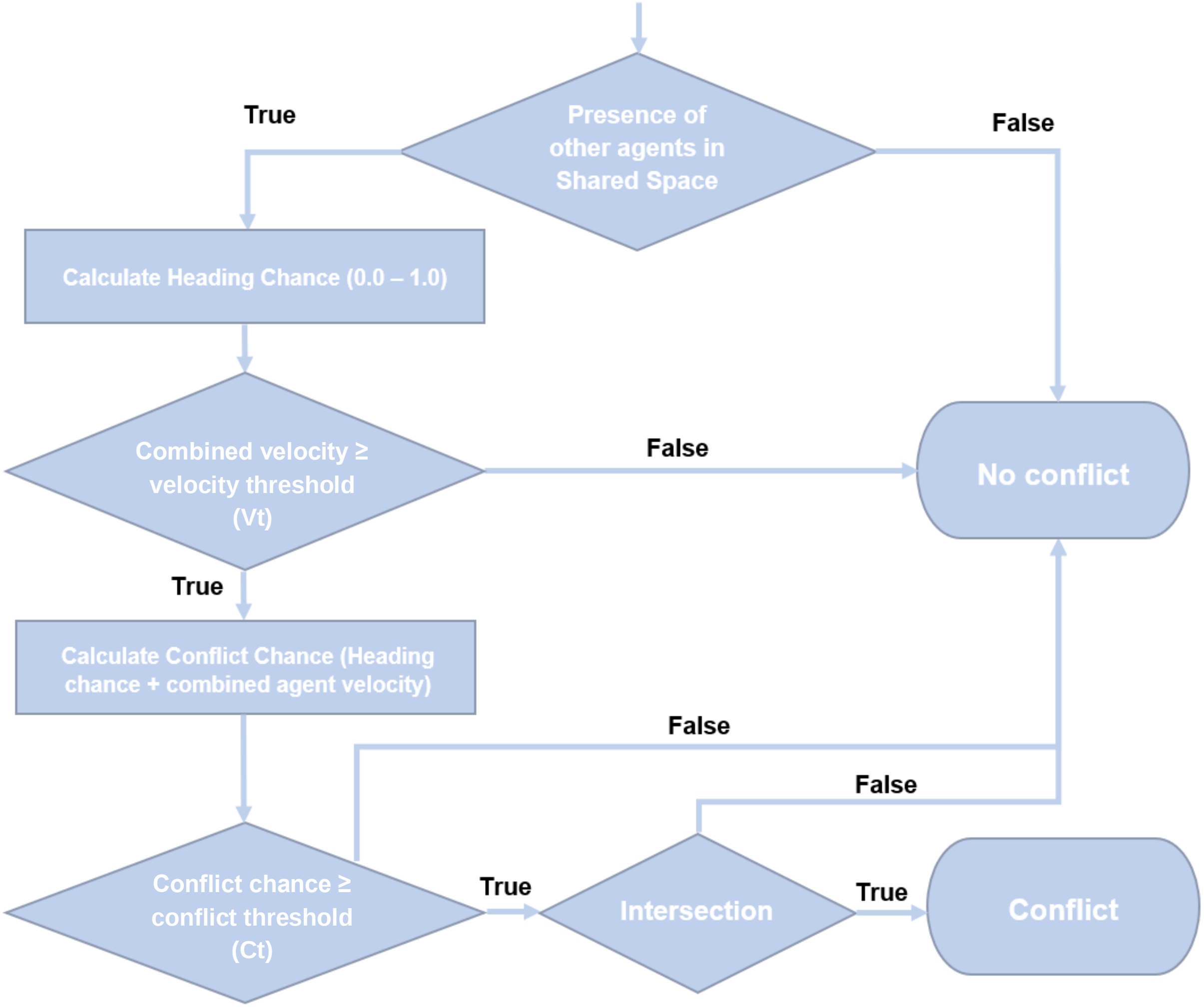


Figure 3.18 Conflict chance flowchart

3.3 Evaluation

The empirical dataset used during model calibration consists of measurements of the Shared Space done by *DTV Consultants* in cooperation with, and commissioned, by the *Municipality of Amsterdam*.

Paragraph **3.3.1** contains a description of the conflict observation done by the municipality; both the measurement process and results.

In paragraph **3.3.2** a sensitivity analysis is conducted. During calibration, model parameters are measured (or estimated), and adjusted on the basis of an empirical dataset. This process will be one of trial and error; the parameters are adjusted after testing the model, after which the parameters are again adjusted. This process goes on until the system is as close as possible to representing reality.

3.3.1 Measurement process

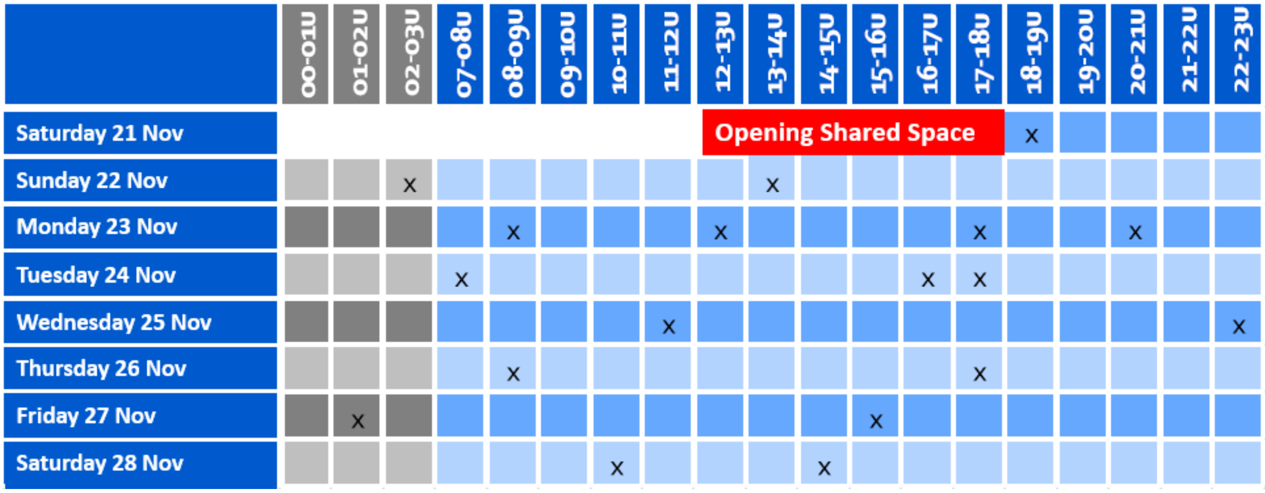
Because the Shared Space traffic design had not earlier been implemented in the city of Amsterdam, the municipality decided to monitor the functioning of the area during the first three months after the official opening.

In order to provide insight into the workings of the Shared Space, the Municipality of Amsterdam chose to perform conflict observations in the area. The purpose of these observations was to analyze whether safety inside of the Shared Space was guaranteed and whether or not interventions were needed. The monitoring report was developed by the research and knowledge department of the Municipality of Amsterdam (*V&OR, team Onderzoek en Kennis*)

For the analysis of traffic conflicts in the Shared Space, camera footage was used. In order to monitor the traffic flows in the area (agent numbers and ratios), counting and tracking sensors were used.

3.3.1.1 Measurement moments

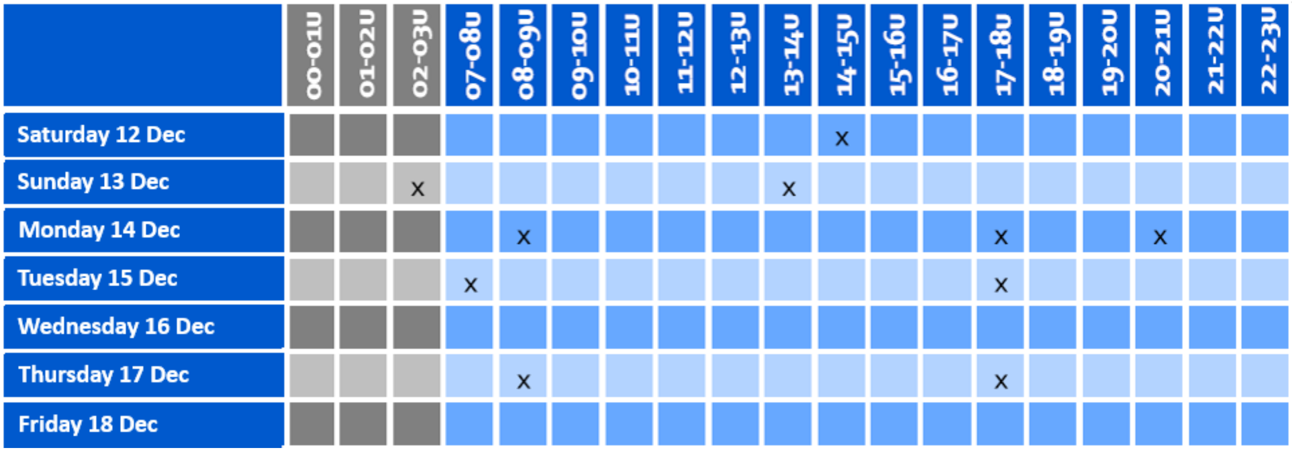
The monitoring was done between the 21st of November 2015 and the 21st of February 2016. In this period *three* separate conflict observations were made; in the 1st, 4th and 12th week after the opening of the area. Per week, a number of hours was chosen to perform conflict analysis on. During this first week, 18 hours were chosen for analysis, spread out over the days of the week and the hours of the day (table **3.6a**).



	00-01u	01-02u	02-03u	07-08u	08-09u	09-10u	10-11u	11-12u	12-13u	13-14u	14-15u	15-16u	16-17u	17-18u	18-19u	19-20u	20-21u	21-22u	22-23u
Saturday 21 Nov									Opening Shared Space						x				
Sunday 22 Nov			x							x									
Monday 23 Nov					x				x					x			x		
Tuesday 24 Nov				x									x	x					
Wednesday 25 Nov								x											x
Thursday 26 Nov					x									x					
Friday 27 Nov		x										x							
Saturday 28 Nov							x				x								

Table 3.6a 1st week

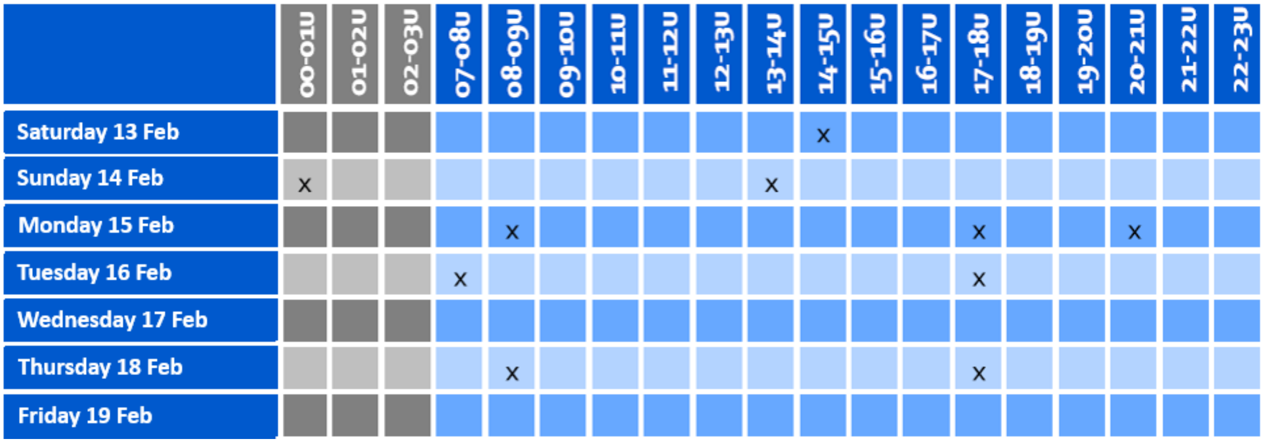
In the second measurement, conducted during the fourth week after the Shared Space was introduced, 10 hours were chosen for conflict analysis (table **3.6b**). These 10 hours were also analyzed in the first measurement week in order to be able to compare results. The lion's share of the chosen hours were rush hours, because the chance of traffic conflicts occurring was expected to be higher in these periods. A number of non-peak hours were also included.



	00-01u	01-02u	02-03u	07-08u	08-09u	09-10u	10-11u	11-12u	12-13u	13-14u	14-15u	15-16u	16-17u	17-18u	18-19u	19-20u	20-21u	21-22u	22-23u
Saturday 12 Dec											x								
Sunday 13 Dec			x							x									
Monday 14 Dec					x									x			x		
Tuesday 15 Dec				x										x					
Wednesday 16 Dec																			
Thursday 17 Dec					x									x					
Friday 18 Dec																			

Table 3.6b 2nd week

In the third measurement, conducted during the twelfth week after the Shared Space was introduced, again, 10 hours were chosen for conflict analysis. For comparative purposes, the same hours that were monitored during the second measurement were also chosen for the third measurement (table **3.6c**).



	00-01U	01-02U	02-03U	07-08U	08-09U	09-10U	10-11U	11-12U	12-13U	13-14U	14-15U	15-16U	16-17U	17-18U	18-19U	19-20U	20-21U	21-22U	22-23U
Saturday 13 Feb											x								
Sunday 14 Feb	x									x									
Monday 15 Feb					x									x			x		
Tuesday 16 Feb				x										x					
Wednesday 17 Feb																			
Thursday 18 Feb					x									x					
Friday 19 Feb																			

Table 3.6c 3rd week

3.3.1.2 Measured elements

A conflict analysis was performed over the 38 hours as specified in the section above. The following elements were registered through camera footage:

- *number* of conflicts;

- *severity* of conflict;

- *involved modes of transport* of conflict;

- *cause* of conflict;

- *location* of conflict;

During the conflict observation, the *severity* of a traffic conflict was determined by using the DOCTOR-method (Dutch Objective Conflict Technique for Operation and Research). This method is used for identifying the seriousness of a conflict and is based on a five-point scale (table **3.7**).

Class	Definition
1	Careful breaking, swerving or other anticipating behavior when the chance of a collision occurring is low.
2	Controlled breaking or swerving in order to avoid a collision, with limited time to maneuver.
3	Powerful breaking, rapid change of course or stopping in order to avoid a collision, resulting in a near-accident.
4	Emergency stop or powerful swerving in order to avoid a collision, resulting in a near-accident or a light collision
5	Emergency intervention, followed by a collision

Table 3.7 DOCTOR-method

The conflict occurrences that fall within classes 1 and 2 can be seen as controlled, anticipating traffic behavior. Because these behaviorisms are considered to be inherent to the working of the Shared Space, they were not regarded as conflicts. Thus, in the municipal research, only the occurrences within classes 3, 4 and 5 were registered and analyzed.

In the Shared Space model, the result of an interaction between two agents is either a conflict or no conflict; no further distinction is made in terms of conflict severity. Therefore, during model verification, all conflicts registered during the municipal conflict analysis (class 3, 4 and 5) are treated as equal.

In the municipal conflict analysis an attempt was made to determine the *cause* of each conflict. However, due to the subjective nature of this exercise, the cause of conflicts is not captured within the Shared Space model.

This leaves us with *three* measured elements that will be used during verification:

- *number* of conflicts;

- *involved modes of transport* of conflict;

- *location* of conflict;

During model verification, for each of these three elements a comparison is made between (1) the results of the municipal conflict observation and (2) the Shared Space model output.

Traffic intensity and ratio

Through the use of cameras and laser systems, *traffic counts* were performed on all the traffic entering and leaving the Shared Space area from the eastern, western and southern borders. The influx and outflow of traffic to and from the ferry docks at the northern border was based on counts done in September of 2015, during the *Ferryboat Monitoring Research*.

Because the automatic counting-software was only able to distinguish between pedestrians and two-wheelers (and not between bicycles and mopeds), a *visual* sample count was performed in order to determine the proportion of both moped drivers and cyclists among two-wheelers. In order to objectively determine the bicycle/moped ratio, these counts were performed on different times of the day throughout the week.

3.3.1.3 Results

Number of conflicts

During 38 analyzed hours, a total of **24** conflicts were identified inside the Shared Space.

Conflict partners

The majority of the 24 registered conflicts played out between cyclists among themselves. Cyclists were involved in 87,5% of all conflicts. Pedestrians were involved in 29% of all conflicts. Mopeds were also involved in 29% of all conflicts. See table **3.8**.

Involved modes of transport	Conflicts	Percentage
Cyclist – cyclist	13	54,5 %
Cyclist – pedestrian	4	16,5 %
Cyclist – moped	4	16,5 %
Moped – pedestrian	3	12,5 %
Total	**24**	**100 %**

Table 3.8 Conflict partners

Conflict locations

In order to register the location of every conflict, a virtual raster was used, dividing the Shared Space area into separate cells (figure **3.19**).

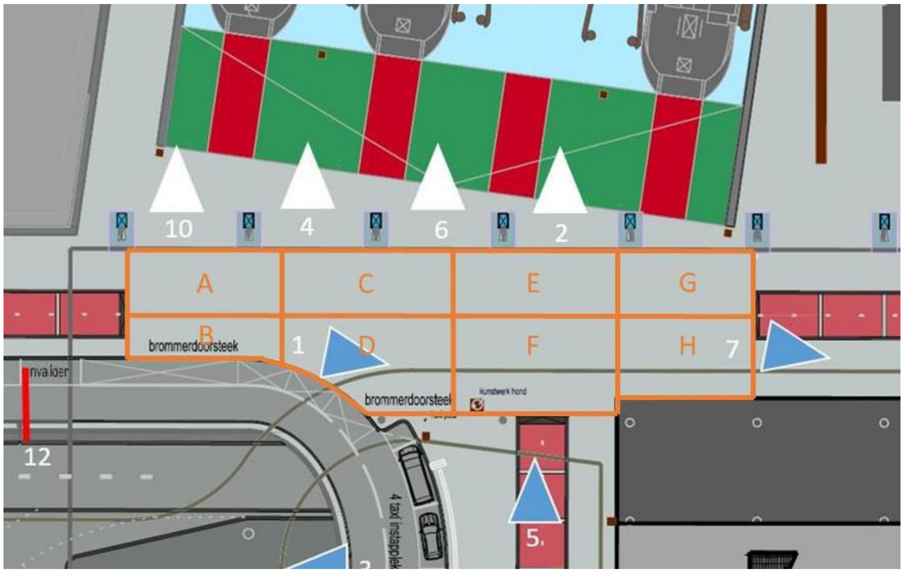


Figure 3.19 Shared Space raster

Raster cell	Conflicts	Percentage
A	1	4,2 %
B	-	-
C	1	4,2 %
D	2	8,3 %
E	4	16,5 %
F	11	46 %
G	3	12,5 %
H	2	8,3 %
Total	**24**	**100 %**

Table 3.9 Conflict

By far the most of the 24 registered conflicts in the Shared Space took place inside of cell **F**. This is the cell where the bicycle lanes would intersect if they were to continue in a straight line. Table **3.9** shows the number and percentage of conflicts per raster cell.

Conflicts and traffic intensity

In order to be able to relate the conflicts to the traffic intensity inside of the Shared Space area, traffic counts were carried out. During the conflict measurements, the traffic intensity varied between 651 and 5.314 visitors per hour. Figure **3.20** shows the traffic intensities of the 38 analyzed hours, as well as the number of conflicts that took place during those hours. Each spheroid represents one analyzed hour. The hours during which no conflicts were registered are displayed in blue. The hours during which 1 or more conflicts were registered are displayed in different shades of red. The size of the spheroid corresponds to the number of conflicts during that hour.

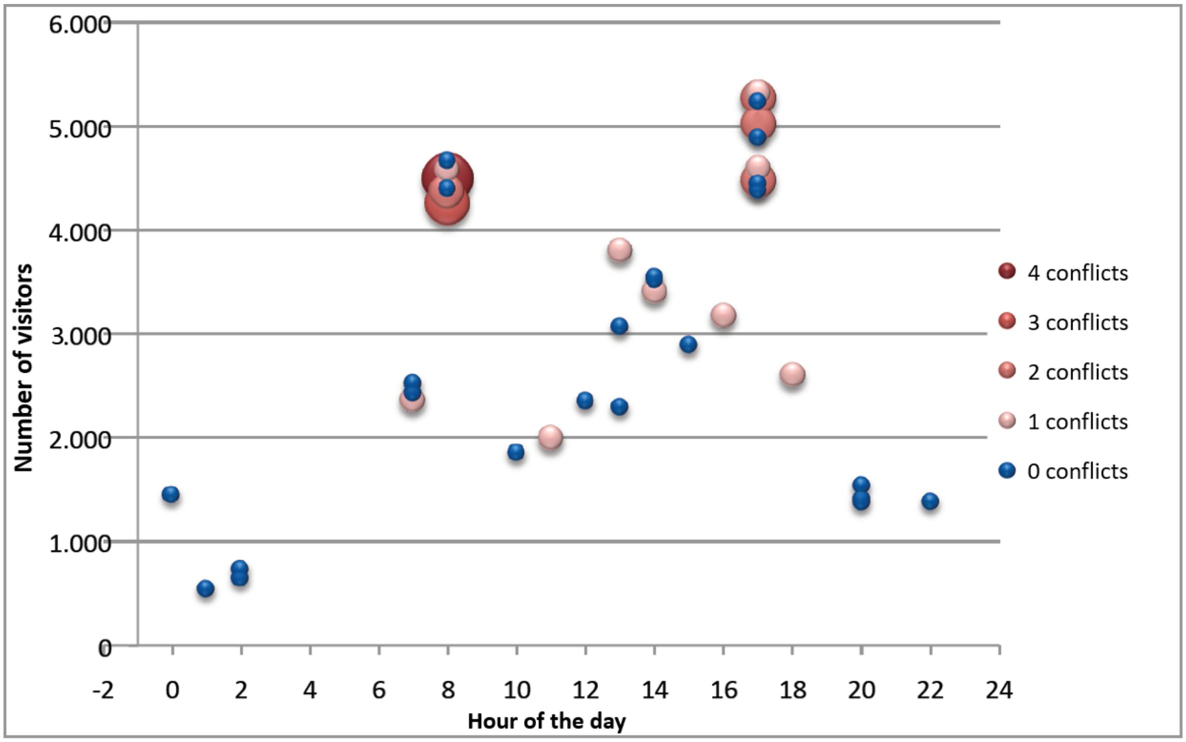


Figure 3.20 Conflicts and traffic intensity

The relationship between the number of agents and the number of conflicts within the Shared Space is not linear. There are a number of hours during which the measurements show high traffic intensities, but no conflicts. However, a certain pattern can be distinguished:

- While high traffic intensities (≥ 4000 visitors) where registered in less than 40% of the measured hours, 75% of all conflicts took place during these hours.
- All of the hours during which more than one conflict was registered, are hours in which the number of visitors was higher than 4 thousand.
- During hours with traffic intensities between 2 and 4 thousand visitors (medium traffic intensity), a maximum of 1 conflict was registered.
- During low intensity hours, with less than roughly 2 thousand visitors, no conflicts were registered.

This leads to a general expected pattern regarding the relationship between the number of agents and the number of conflicts within the Shared Space model, see table **3.10**:

Number of agents per hour	Expected number of conflicts per hour	Expected *average* number of conflicts per hour*
0 - 2000	0	0
2000 - 4000	0 – 1	0.4
4000 - 5314	0 – 4	1.2

Table 3.10 Expected number of conflicts

*These average values are based on the average number of conflicts measured within each traffic intensity category.

It is expected that the Shared Space model output shows the same patterns, in terms of the distribution between conflict partners, the location of conflicts, and the number of conflicts per hour in relation to the traffic intensity.

3.3.2 Sensitivity analysis

3.3.2.1 Method

A number of parameters are kept constant throughout the entire process; examples are *agent size, agent viewing aspect and extent,* and the *conflict threshold*. Certain other parameters are excluded from sensitivity analysis, but will be tested during the scenario analysis in chapter **4**, examples of these are *desired velocity*, *agent ratio* and the distribution of *agent spawning and destination points*. During sensitivity analysis however, **three** parameters are tested: *reaction time*, *velocity threshold* and *conflict weight* (see table **3.11**).

R (Reaction-value)	$rnd((X),(Y))$ (between 0.0 – 1.0) Baseline value-range = (0.2, 0.4)	Influences: agent velocity during interaction. The higher the **R**-value, the more an agent slows down during interactions.
Vt (Velocity threshold)	Between 0.1 – 1.0 Baseline value = 0.5	Influences: conflict chance; if the combined velocity exceeds **Vt**, a conflict chance is calculated.
Cw (Conflict weight: heading vs velocity)	Between 0.1 – 1.0 Baseline value = 0.5	Influences: conflict chance; if **Cw = 0.5**, heading and velocity contribute equally to the *conflict chance*-value.

Table 3.11 Parameters tested during sensitivity analysis

The effect of these three variables in determining model output is tested by means of a 'one-at-a-time' (OAT) sensitivity analysis. This means that the variations on a parameter are applied while all other variable values are kept constant (using the baseline value). For all three parameters, **two** variations are tested (a low and a high value); leading to **six** different variable configurations in total. The number of agents per run is a randomly generated value, somewhere between the lowest and highest measured agent count (between 651 and 5.314 agents). The model is run 75 times per variable configuration.

After conducting the sensitivity analysis, the results are presented and discussed before choosing which parameter configuration lies closest to reality. Going forward, this configuration is then kept constant during the process of scenario analysis in chapter **4**. Within this context it is important to realize that the most desired parameter configuration is one that produces a close-to-realistic number of agent conflicts, while also keeping an acceptable mean agent velocity.

Reaction time (R)

The *reaction time* (as presented in paragraph **3.1.7**) determines the degree to which an agent reacts (slows down) when confronted with other agents. While each agent's reaction-value (**R**) is unique and randomly generated, all values fall within a lower and upper threshold, somewhere between **0.0** and **1.0**. During the sensitivity analysis, these reaction time thresholds are adjusted, in order to determine the parameter's influence within the model. During **configuration 1** the R-value is kept **low**; the lower and upper threshold values are set at respectively **0.0** and **0.2**. This configuration will lead to a relatively *high* average agent velocity. During **configuration 2** the R-value is kept **high**; the lower and upper threshold values are set at **0.4** and **0.6**. This configuration will lead to a relatively *low* average agent velocity. During both configurations, the remaining two parameters (*velocity threshold* and *conflict weight*) are kept constant, at their baseline values.

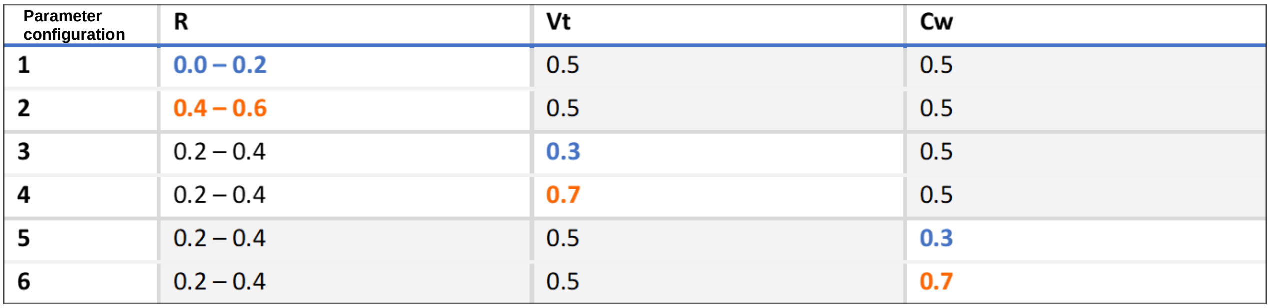
Velocity threshold (Vt)

Within the Shared Space model, two agents can only cause a conflict whenever their combined velocity exceeds the *velocity threshold*. The level at which this threshold (**Vt**) is set, determines the amount of agents that qualify for calculating a conflict chance. During **configuration 3,** the Vt-value is kept **low**, and is set at **0.3**. During **configuration 4,** the Vt-value is kept **high**, and is set at **0.7**. During both configurations, the remaining two parameters (*reaction time* and *conflict weight*) are kept constant, at their baseline values.

Conflict weight (Cw)

The *conflict weight-value* (**Cw**) is a value that represents the weight of both the heading chance-value and the velocity chance-value in determining the conflict chance-value; at the baseline value of **0.5**, both parameters contribute equally to the conflict chance-value (both 50 percent). During **configuration 5**, the Cw-value is set at **0.3**; in this configuration, the heading chance determines only 30 percent of the conflict chance-value, while the velocity chance determines the other 70 percent. During **configuration 6,** the Cw-value is set at **0.7**; in this configuration, the heading chance determines 70 percent of the conflict chance-value, while the velocity chance determines just 30 percent. During both configurations, the remaining two parameters (*reaction time* and *velocity threshold*) are kept constant, at their baseline values.

Table **3.12** presents an overview of all six parameter configurations during the process of sensitivity analysis.



Parameter configuration	R	Vt	Cw
1	**0.0 – 0.2**	0.5	0.5
2	**0.4 – 0.6**	0.5	0.5
3	0.2 – 0.4	**0.3**	0.5
4	0.2 – 0.4	**0.7**	0.5
5	0.2 – 0.4	0.5	**0.3**
6	0.2 – 0.4	0.5	**0.7**

Table 3.12 Overview of configurations during sensitivity analysis

3.3.2.2 Results

Configuration 1

During the first model configuration, agents are assigned a low *reaction time*-value (0.0 – 0.2). The remaining two parameters (*velocity threshold* and *conflict weight*) are kept constant, at their baseline values of both (0.5). Figure **3.21** shows the resulting number of agent conflicts; each of the 75 blue dots represent one model run. The data show that this configuration leads to a relatively **high** amount of agent conflicts (up to 25/30 conflicts per hour).

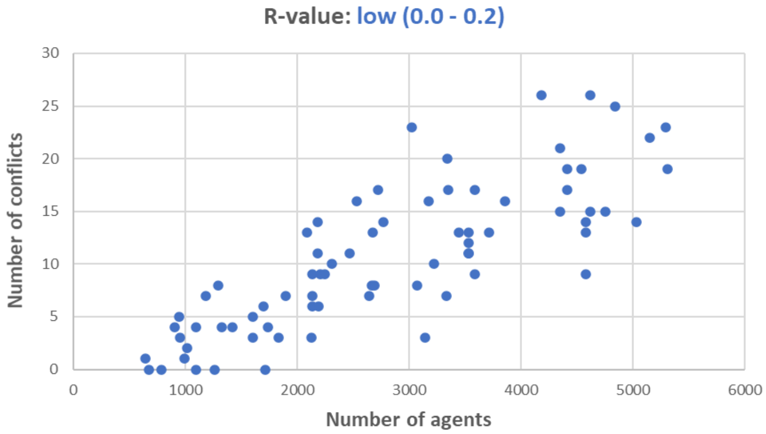


Figure 3.21 **Configuration 1**: number of conflicts and traffic intensity

Because a low R-value causes agents to retain the greatest part of their desired velocities; average travelling speeds are relatively high and traffic flows remain smooth, even during peak agent intensities (see figure **3.22**). These increased agent velocities are at the same time the cause of the high amount of conflicts; in case of intersection, the higher the combined speed, the greater the conflict chance. In figure **3.23** the average agent velocity during a full model run is presented, using a sample of three runs (low, medium and high agent velocity). Again, it is clear that this configuration leads to relatively high agent velocities, even at peak moments during high intensity runs (such as the unloading of a ferry).

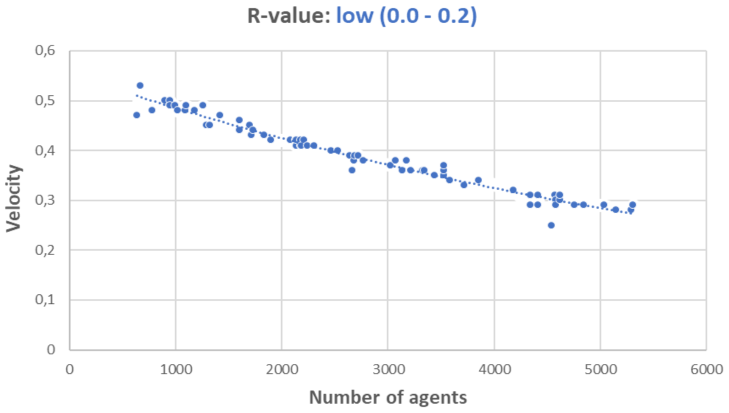


Figure 3.22 **Configuration 1**: traffic intensity and average agent velocity

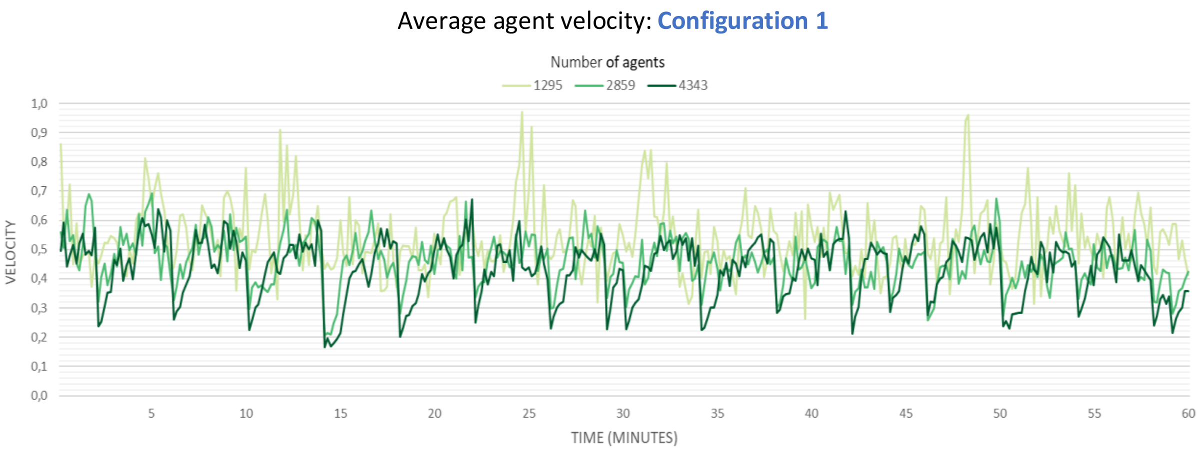
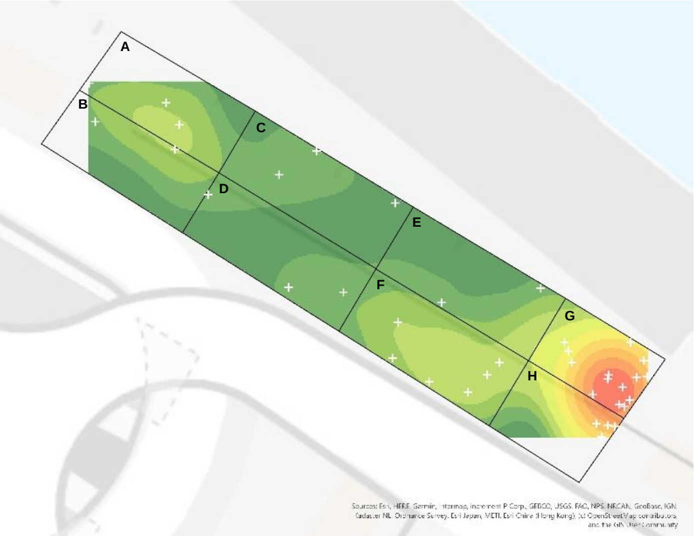


Figure 3.23 Configuration 1: average velocity during run; sample of three runs



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.24 Configuration 1: conflict locations, sample of three runs

Conflict locations

Figure **3.24** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell G.

Conflict partners

Cyclist - Cyclist	**24**	**65 %**
Cyclist - Pedestrian	**9**	**25 %**
Cyclist - Moped	**3**	**7 %**
Moped - Pedestrian	**1**	**3 %**
Moped - Moped	**0**	**0 %**

Configuration 2

During the second model configuration, agents are assigned a high *reaction time*-value (0.4 – 0.6). Again, the remaining two parameters (*velocity threshold* and *conflict weight*) are kept constant, at their baseline values. Figure **3.25** shows the resulting number of agent conflicts; each of the 75 red dots represent one model run. In comparison to model run 1, this configuration clearly leads to a lower amount of agent conflicts (max. 11 conflicts per run). However, the number of agent conflicts is overall still significantly higher than measured during the municipal conflict observation.

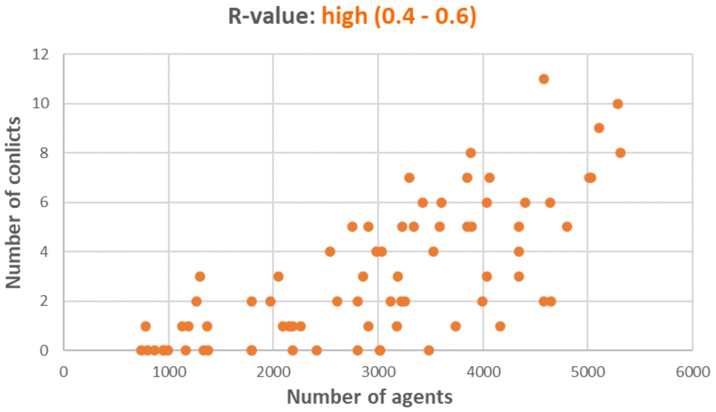


Figure 3.25 Configuration 2: number of conflicts and traffic intensity

Because a high R-value causes an agent to severely lower it's speed in case of interaction, this model configuration leads to low average travelling velocities, especially during busy hours. Figure **3.26** shows the average agent velocity during all 75 runs; a notable drop in the average velocity can be observed around the 3.500 / 4.000 agent-mark.

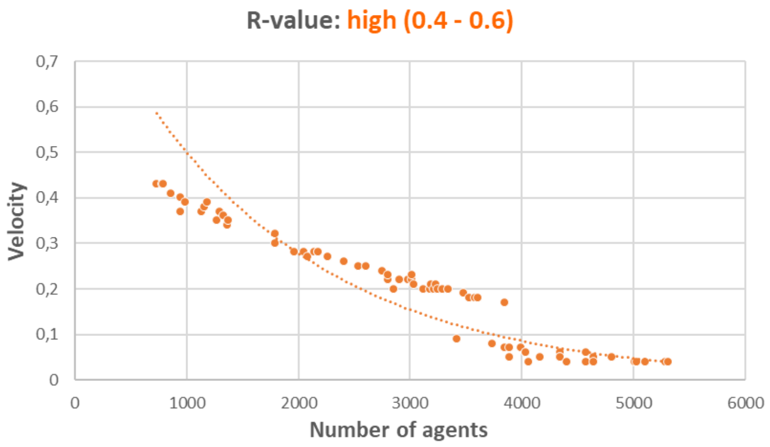


Figure 3.26 **Configuration 2**: traffic intensity and average agent velocity

This is even more clearly illustrated in figure **3.27** which shows the average agent velocity during a full model run, using a sample of three runs (low, medium and high agent velocity). This graph shows a tipping point in average agent velocity, at around 15 minutes into the run. While the average agent velocity during the low- and medium-intensity runs (lighter green lines) continues to follow the same pattern, the line representing the average velocity during the high-intensity run (dark green) is not able to "recover" from the stagnation and stays below the 10 percent line after this moment in time.

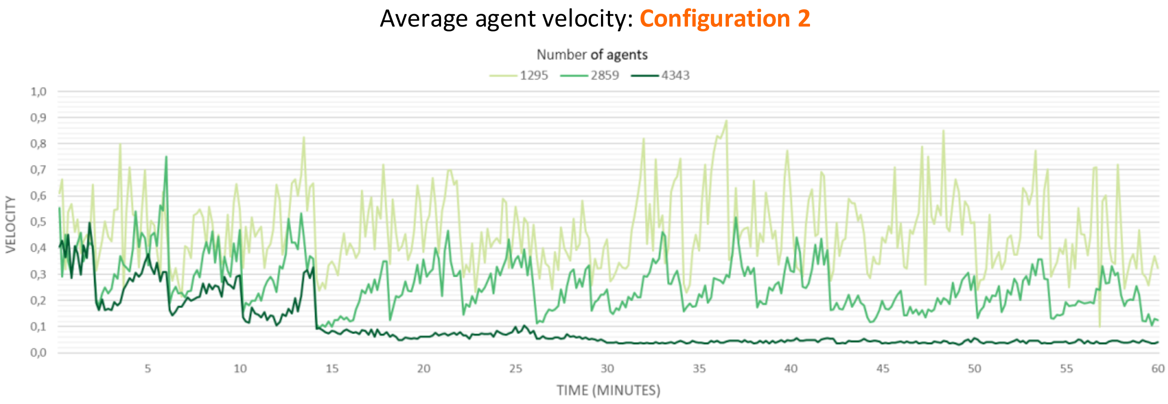
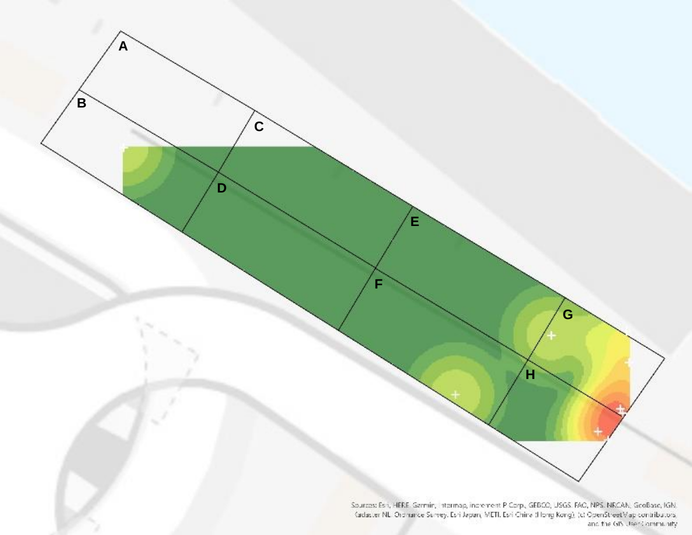


Figure 3.27 **Configuration 2**: average velocity during run; sample of three runs

Altogether, this parameter configuration leads to (extremely) low agent velocities, especially at peak moments during runs with high agent intensities.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.28 **Configuration 2**: conflict locations, sample of three runs

Conflict locations

Figure **3.28** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell G & H.

Conflict partners

Cyclist - Cyclist	**3**	**34 %**
Cyclist - Pedestrian	**4**	**44 %**
Cyclist - Moped	**1**	**11 %**
Moped - Pedestrian	**1**	**11 %**
Moped - Moped	**0**	**0 %**

Configuration 3

During model configuration 3, agents are assigned a low *velocity threshold*-value. The remaining two parameters (*reaction time* and *conflict weight*) are kept constant, at their baseline values of respectively (0.2 – 0.4) and (0.5). A low velocity threshold means that in case of agent intersection, a lower (combined) velocity is required in order to calculate the conflict chance. Figure **3.29** shows the resulting number of agent conflicts. Each of the 75 blue dots represent one model run; this configuration leads to a maximum of 14 conflicts per hour. While in comparison to the first two model runs the output of this parameter configuration is more balanced, combining a relatively low number of agent conflicts with an acceptable average agent velocity (figure **3.30** and **3.31**), the number of conflicts is still significantly higher than measured during the municipal conflict observation.

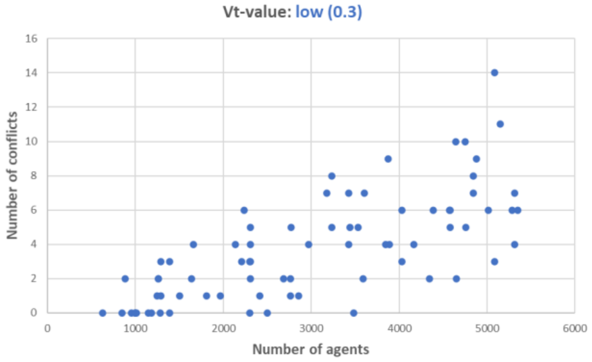


Figure 3.29 Configuration 3: number of conflicts and traffic intensity

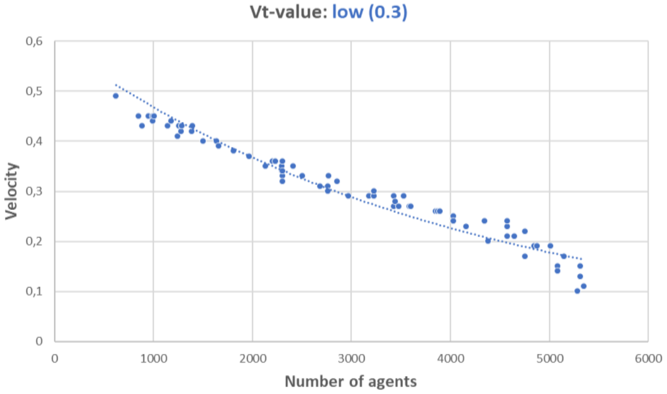


Figure 3.30 Configuration 3: traffic intensity and average agent velocity

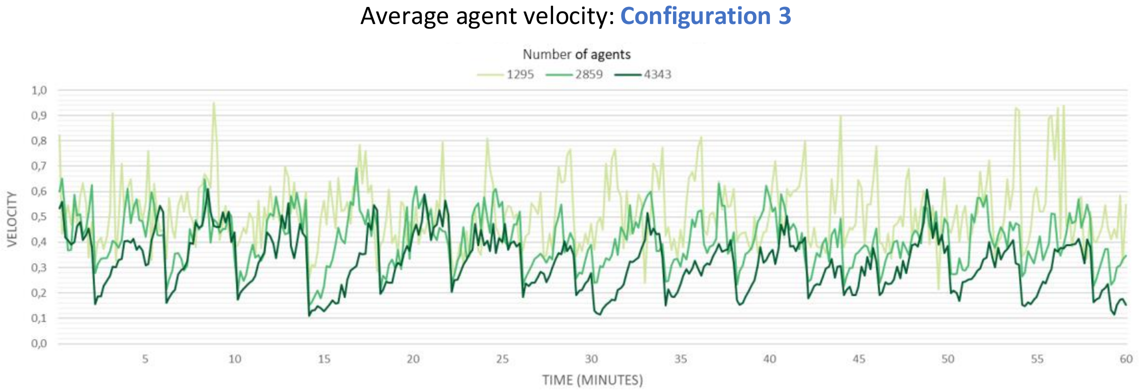


Figure 3.31 Configuration 3: average velocity during run; sample of three runs

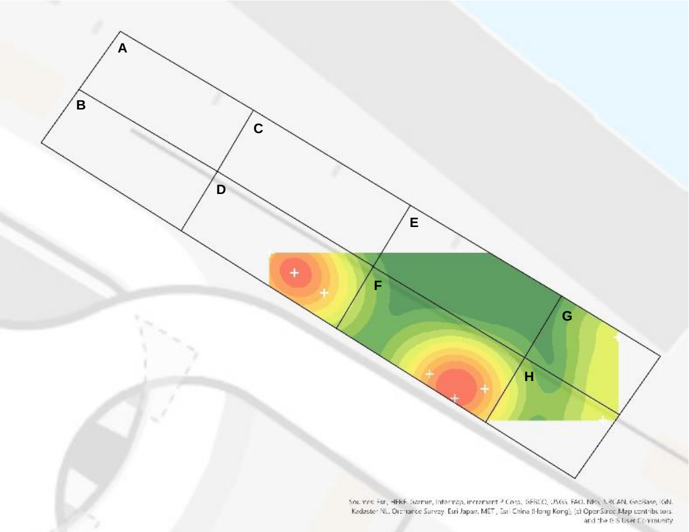


Figure 3.32 Configuration 3: conflict locations, sample of three runs

Conflict locations

Figure **3.32** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell D & F.

Conflict partners

Cyclist - Cyclist	**1**	**12.5 %**
Cyclist - Pedestrian	**2**	**25 %**
Cyclist - Moped	**1**	**12.5 %**
Moped - Pedestrian	**4**	**50 %**
Moped - Moped	**0**	**0 %**

Configuration 4

During model configuration 4, by applying a high *velocity threshold*-value of 0.7, an even lower average number of conflicts per model run is achieved, while maintaining acceptable average speeds. Figure **3.33** shows the resulting number of agent conflicts; each of the 75 red dots represent one model run. Similarly to configuration 3, the remaining two parameters (*reaction time* and *conflict weight*) are kept constant, at their baseline values. While average agent velocities show an acceptable trendline (figure **3.34** and **3.35**), the number of conflicts produced with this parameter configuration (max 9 per hour) is however still too high.

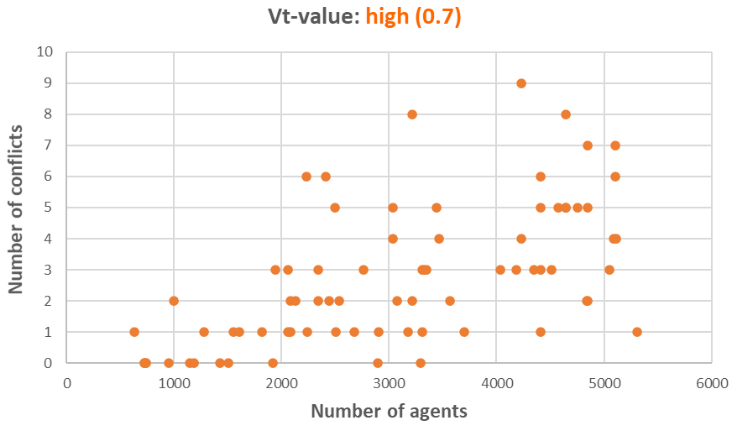


Figure 3.33 **Configuration 4**: number of conflicts and traffic intensity

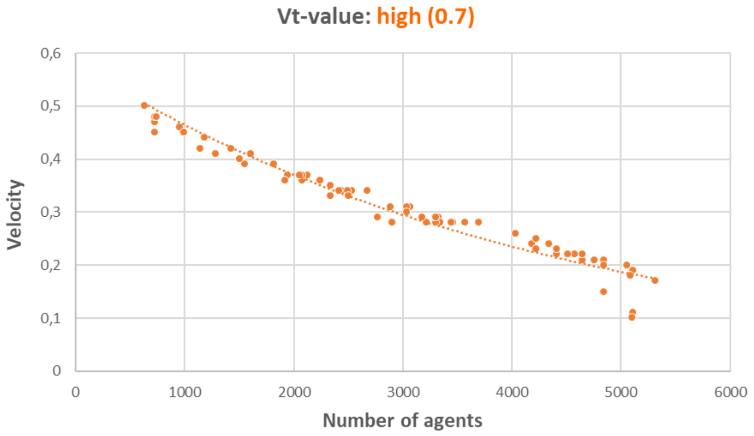


Figure 3.34 **Configuration 4**: traffic intensity and average agent velocity

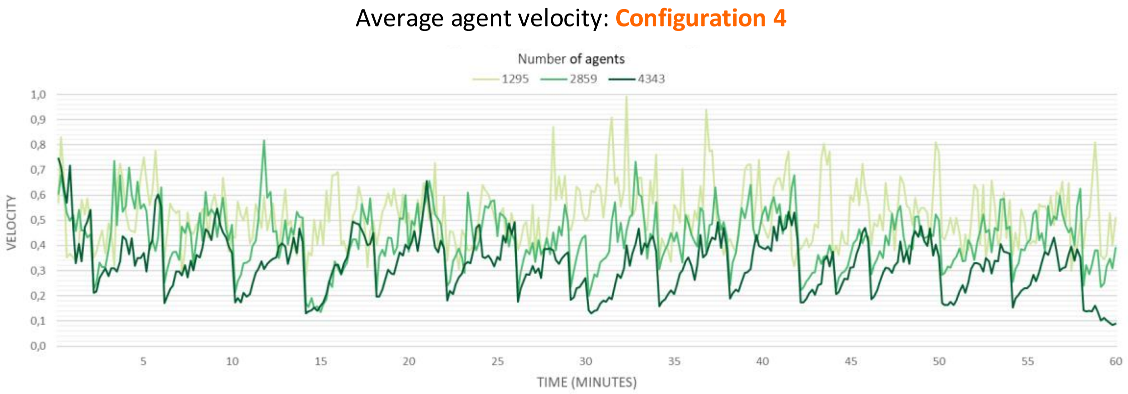
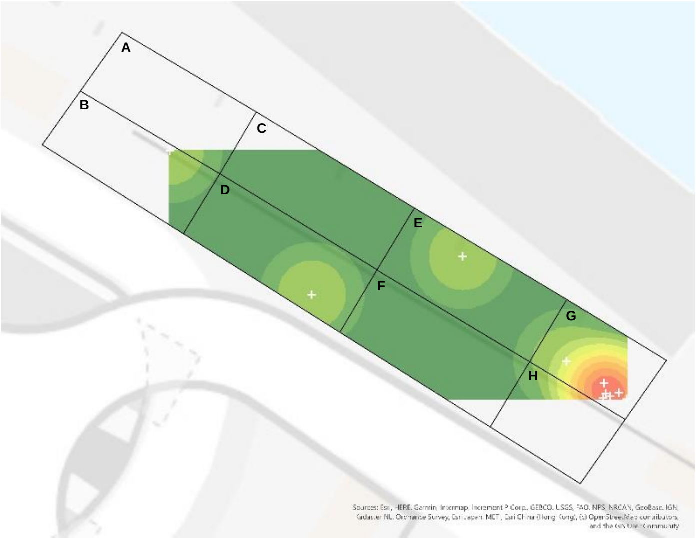


Figure 3.35 **Configuration 4**: average velocity during run; sample of three runs



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.36 **Configuration 4**: conflict locations, sample of three runs

Conflict locations

Figure **3.36** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell G.

Conflict partners

Cyclist - Cyclist	**5**	**50 %**
Cyclist - Pedestrian	**4**	**40 %**
Cyclist - Moped	**0**	**0 %**
Moped - Pedestrian	**1**	**10 %**
Moped - Moped	**0**	**0 %**

Configuration 5

During the fifth model configuration, agents are assigned a low *conflict weight*-value (0.3). The remaining two parameters (*reaction time* and *velocity threshold*) are kept constant, at their baseline values of respectively (0.2 – 0.4) and (0.5). In this configuration, an agent's heading is determinative for just 30 percent of the conflict chance, while it's velocity determines the other

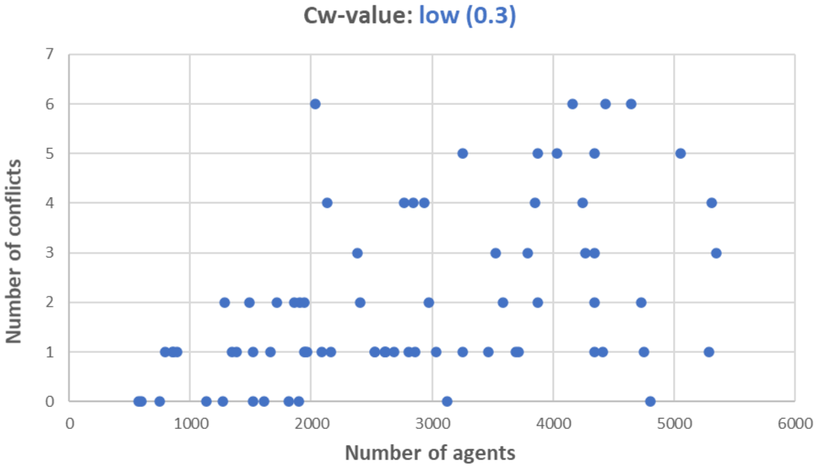


Figure 3.37 **Configuration 5**: number of conflicts and traffic intensity

70 percent. Figure **3.37** shows the resulting number of agent conflicts; each of the 75 blue dots represent one model run.

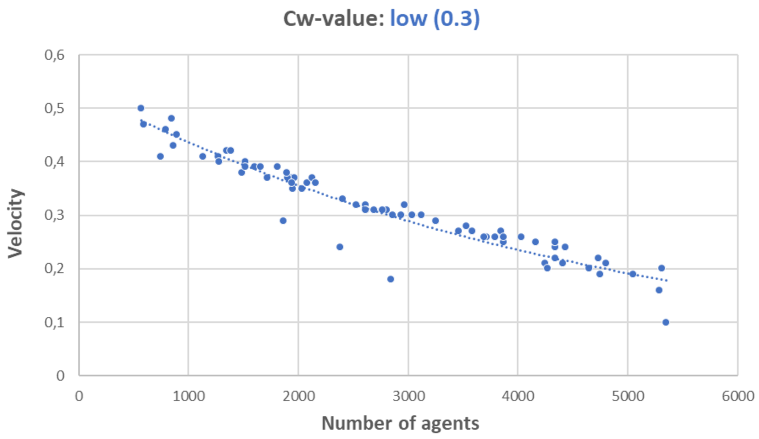


Figure 3.38 Configuration 5: traffic intensity and average agent velocity

The output produced with this parameter configuration shows strong similarities to the conflict data measured during the municipal conflict observation; the number of measured conflicts per hour does not exceed 6, and the average agent velocities remain at acceptable levels (figure **3.38**). However, while this configuration produces a close-to-realistic model output; the average number of conflicts is still slightly above measured levels. Particularly the lower- and medium intensity runs (≤ 4000 agents) are on average still producing too much conflict instances: up to 5/6 conflicts instead of 0/3 conflicts per hour. Also, as figure **3.38** and **3.39** show, while velocities remain at acceptable levels, at high intensity moments the data show negative outliers which

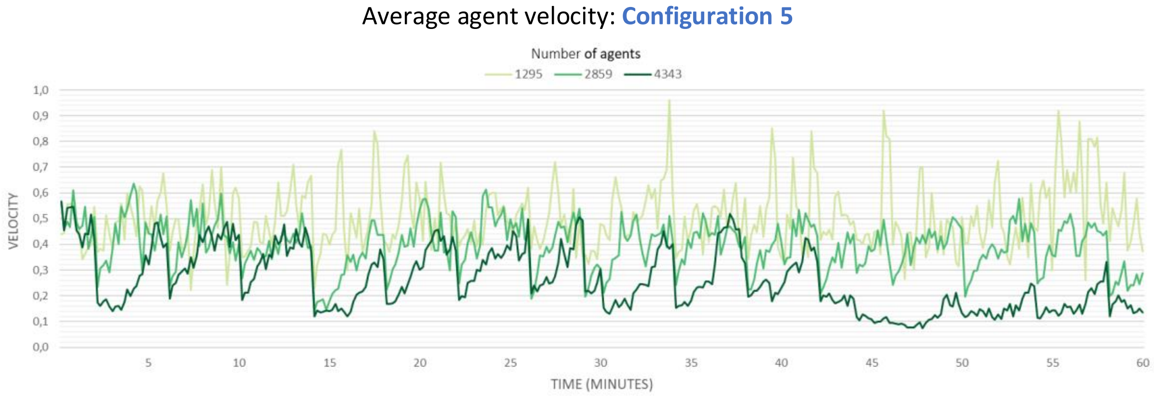
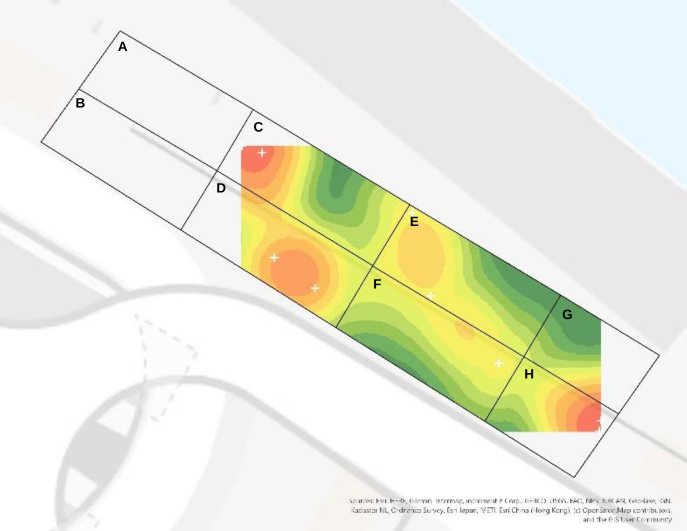


Figure 3.39 Configuration 5: average velocity during run; sample of three runs

suggest the system could be close to a tipping point similar to that demonstrated during the second model configuration.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.40 Configuration 5: conflict locations, sample of three runs

Conflict locations

Figure **3.40** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, conflicts are equally divided over Cells C, D, F, E and H.

Conflict partners

Cyclist - Cyclist	**3**	**33 %**
Cyclist - Pedestrian	**4**	**45 %**
Cyclist - Moped	**0**	**0 %**
Moped - Pedestrian	**2**	**22 %**
Moped - Moped	**0**	**0 %**

Configuration 6

During the sixth model configuration, agents are assigned a high *conflict weight*-value (0.7). The remaining two parameters (*reaction time* and *velocity threshold*) are again kept constant. In this configuration, an agent's heading is determinative for 70 percent of the conflict chance, while it's

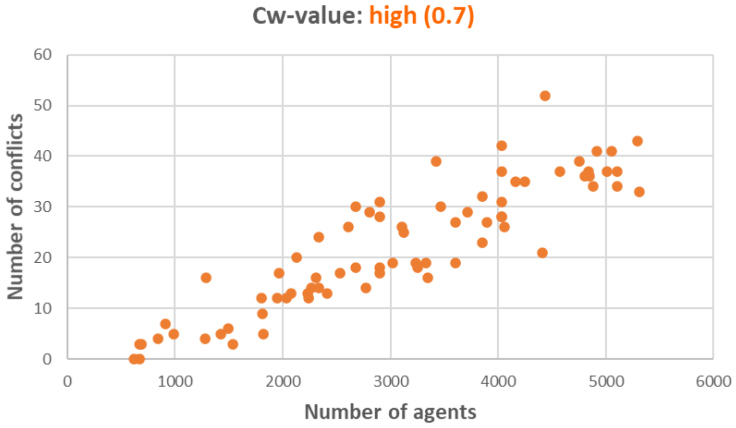


Figure 3.41 Configuration 6: number of conflicts and traffic intensity

velocity determines the other 30 percent. Figure **3.41** shows the resulting number of agent conflicts; each of the 75 red dots represent one model run. Figures **3.42** and **3.43** show the average agent velocity per run.

Figure **3.41** shows a clear rise in the average number of conflicts per hour, when compared to the output of configuration 5, with maximum conflicts numbers reaching into the forties and fifties. This means that within the Shared Space model, an agent's heading in relation to others is far more decisive in determining whether or not a conflict takes place than it's velocity.

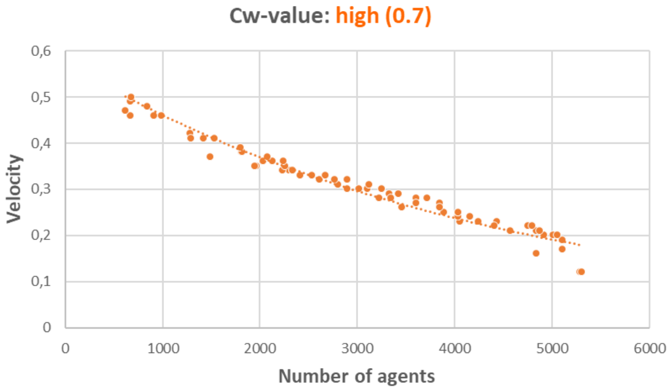


Figure 3.42 **Configuration 6**: traffic intensity and average agent velocity

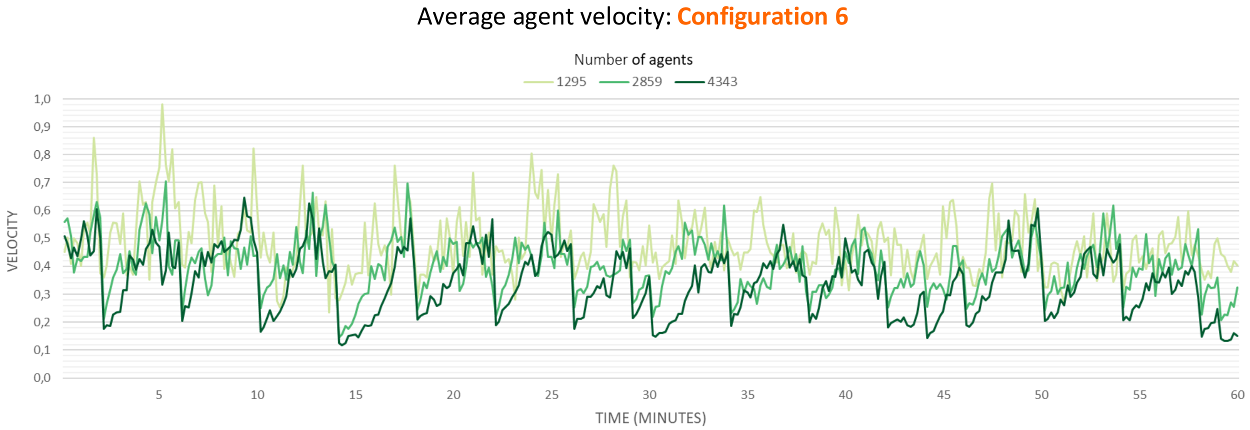
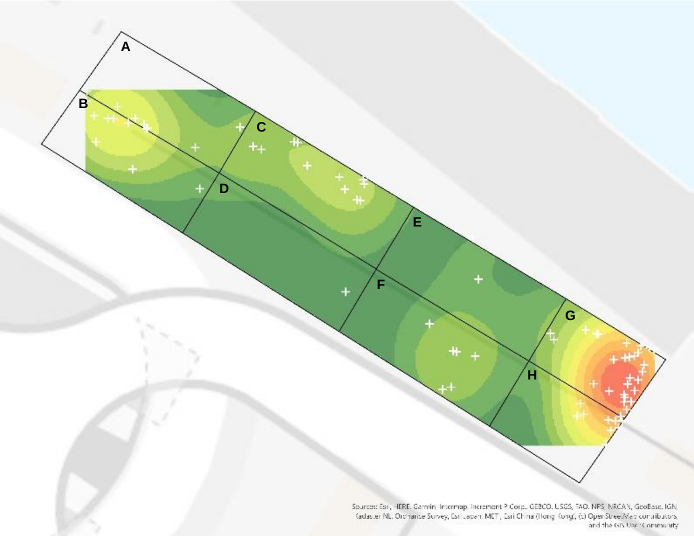


Figure 3.43 **Configuration 6**: average velocity during run; sample of three runs

While figure **3.42** and **3.43** show average agent velocities remaining at acceptable levels, this model configuration clearly produces too much conflicts per hour.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.44 **Configuration 6**: conflict locations, sample of three runs

Conflict locations

Figure **3.44** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell G.

Conflict partners

Cyclist - Cyclist	**61**	**83 %**
Cyclist - Pedestrian	**8**	**11 %**
Cyclist - Moped	**4**	**6 %**
Moped - Pedestrian	**0**	**0 %**
Moped - Moped	**0**	**0 %**

3.3.2.3 Sensitivity analysis: conclusion

After testing six different parameter configurations, and running a total of (6*75 =) 450 hours, this section summarizes the sensitivity analysis results. Also, an optimal parameter configuration is presented in going forward into the process of scenario analysis in chapter **4**.

Configuration 1 and 2

During the first two parameter configurations the influence of the *reaction time*-value (R-value) was tested. By running both a low and a high R-value configuration, a deeper understanding was gained of the effect and weight of this variable within the model. Both the low R-value configuration (0.0 – 0.2) and the high configuration (0.4 – 0.6) lead to desirable as well as undesirable effects within the model.

Number of conflicts and agent velocity

The advantage of using a low R-value is the preservation of a high degree of traffic flow within the model. Because agents only marginally reduce their speed during interactions, the average agent velocity during model runs is relatively high. This means that even at peak moments during high intensity runs (such as the unloading of a ferry), velocities do not fall below undesirable levels.

These increased agent velocities are at the same time the disadvantage of using a low R-value; in case of intersection, the higher the combined speed, the greater the conflict chance, which leads to an unacceptably high amount of conflicts.

Using a high R-value has exactly the opposite effect; while the number of conflicts per run comes close to desirable numbers, the average agent velocities are too low. In fact, during peak agent intensities, this configuration causes the model to tip over into a state in which the Shared Space is “clogged” with agents that are unable to reach acceptable speeds.

Conflict locations and partners

When looking at the locations within the Shared Space where the conflicts took place, both configuration 1 and 2 show the majority of conflicts occurring near the eastern border of the area, in cells G and H. This spatial distribution of conflict locations does not resemble the spatial pattern of conflicts measured during the municipal conflict observation, and especially the severe clustering of conflicts in cell G during configuration 1 indicates an imbalance between parameters, causing spatially inaccurate output data.

Regarding conflict partners, the agent types involved in conflicts during configuration 1 and 2 are found to be quite similar to the distribution of conflict partners measured during the municipal conflict observation; most conflicts played out between cyclists among each other.

Configuration 3 and 4

During parameter configuration 3 and 4, the influence of the velocity threshold-value (Vt) was tested. By running both a low (0.3) and a high (0.7) Vt-value configuration, a deeper understanding was gained of the effect and weight of this variable within the model.

Number of conflicts and agent velocity

In comparison to the first two model runs, both the low, as well as the high Vt-value configurations lead to greater balance in the model output, combining a relatively low number of agent conflicts with an acceptable average agent velocity. This result however, is mainly due to usage of the baseline R-value (0.2 – 0.4), and less the consequence of changing the conflict threshold.

During the fourth, high Vt-value configuration, the lowest-yet average number of conflicts per model run was achieved, while maintaining acceptable average speeds. However, the number of conflicts is still significantly higher than measured during the municipal conflict observation.

Conflict locations and partners

When assessing the locations within the Shared Space where the conflicts took place, the output of configuration 3 shows a very different spatial pattern in comparison to that of configuration 4. While, similar to the first two configurations, configuration 4 show the majority of conflicts occurring near the eastern border of the area, in cells G and H, the conflicts resulting through configuration 3 shows a more balanced spatial distribution, with conflicts occurring either in cell D, F or G. This result shows a lot more similarities to the spatial distribution of conflicts measured by the municipality.

Regarding conflict partners, the agent types involved in conflicts during configuration 4 are, again, relatively similar to the distribution of conflict partners measured during the municipal conflict observation; most conflicts played out between cyclists among each other. During configuration 3, however, a deviation from this trend can be noted; no less than half of the registered conflicts during the sampled runs played out between mopeds and pedestrians.

Configuration 5 & 6

During parameter configuration 5 and 6, the influence of the conflict weight-value (Cw) was tested. By running both a low (0.3) and a high (0.7) Cw-value configuration, a deeper understanding was gained of the effect and weight of this variable within the model.

Number of conflicts and agent velocity

A significant contrast is noted between the output of both configurations, particularly regarding the amount of agent conflicts. While the high Cw-value configuration leads to an excessive amount of conflicts (up to 40 / 50 conflicts per hour), the low Cw-value configuration leads to a far lower number. The output produced with this parameter configuration shows strong similarities to the conflict data measured during the municipal conflict observation; the number of measured conflicts per hour does not exceed 6, and the average agent velocities remain at acceptable levels.

Conflict locations and partners

When looking at conflict locations, again, great variation in spatial distributions can be noted between configuration 5 and 6. Similarly to the output produced during configuration 1,2 and 4, configuration 6 leads to the majority of conflicts occurring near the northeastern border of the area, in cells G and H. Configuration 5 on the other hand shows a more balanced spatial distribution; with locations more evenly spread out over cells C, D, E, F, G and H.

Regarding conflict partners, the output of both parameter configurations are relatively similar to the empirical data; most conflicts are played out either between cyclists among each other, or cyclists and pedestrians.

Configuration 7

Based on the results acquired during configuration 1 to 6, and separately tested during (X) model runs, a **seventh** parameter configuration is presented.

Firstly, regarding the R-value, we can conclude that both the low (0.0 – 0.2) as well as the high (0.4 – 0.6) parameter configurations lead to unsatisfactory results. The result is either a higher than acceptable amount of conflicts, or a lower than acceptable level of agent velocity. Considering both the advantages, and especially the disadvantages of both parameter configurations, the choice is therefore made to keep the R-value at its baseline value of (0.2 – 0.4).

R = 0.2 – 0.4

Secondly, regarding the velocity threshold-value (Vt), it can be concluded that this parameter is not of great influence within the model. An explanation lies in the following. By setting the Vt-value at its lower level of 0.3, a far greater number of potential conflicts is calculated. However, whether or not this in fact results in a conflict is still dependent on an agents conflict chance-value. In other words: in a situation in which two agents with a combined velocity-value of 0.3 intersect, a conflict chance is calculated. However, this conflict chance-value will in this example rarely be high enough to sufficiently contribute to a conflict occurrence. By setting the Vt-value at it’s higher level of 0.7, however, it seems that a percentage of potential conflicts is actually “skimmed” off the top, leading to a decrease in conflict numbers. Therefore, the Vt-value is set at 0.7.

Vt = 0.7

Thirdly, the conflict weight-value (Cw) has proven to be pivotal in determining the model output. A high Cw-value (0.7) leads to an unacceptably high number of conflicts, while a low Cw-value (0.3) shows promising results. To clarify: after two agents have reached a combined velocity that exceeds the velocity threshold, an agent’s heading in relation to others is far more decisive in determining whether or not a conflict takes place than its remaining extra velocity. In this Cw-value configuration of (0.3), an agent’s heading chance determines ‘only’ 30 percent of the total conflict chance-value, leading to a low number of conflicts. Therefore, a choice is made to set the Cw value even lower, at 0.2.

Cw = 0.2

Using the parameter configuration as presented above, the model is run an additional twenty-five times. Figure **3.45** shows the resulting number of agent conflicts per run; each of the green dots represent one model run.

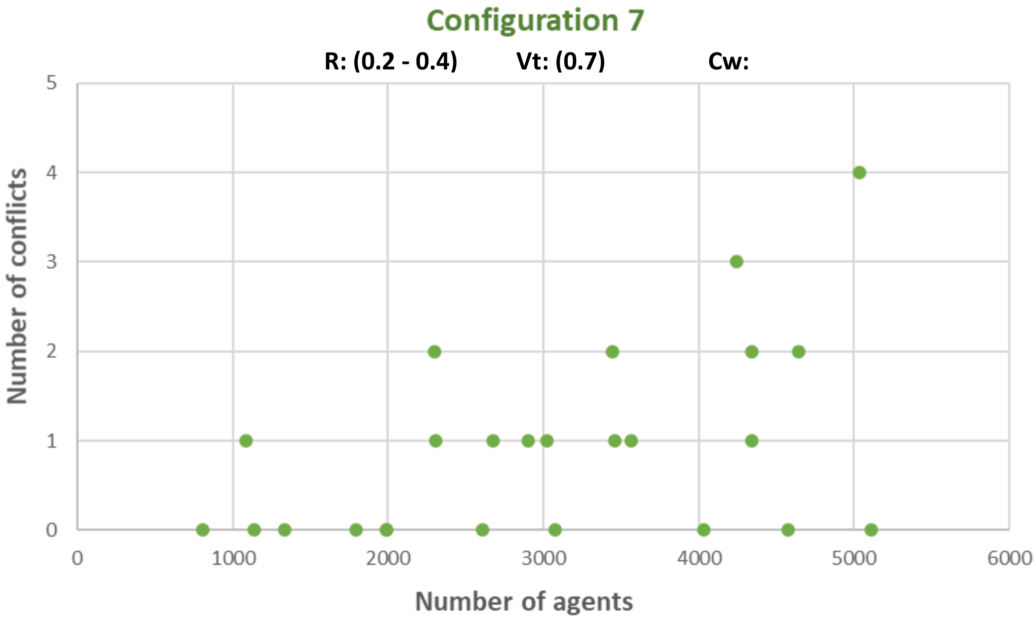


Figure 3.45 **Configuration 7**: number of conflicts and traffic intensity

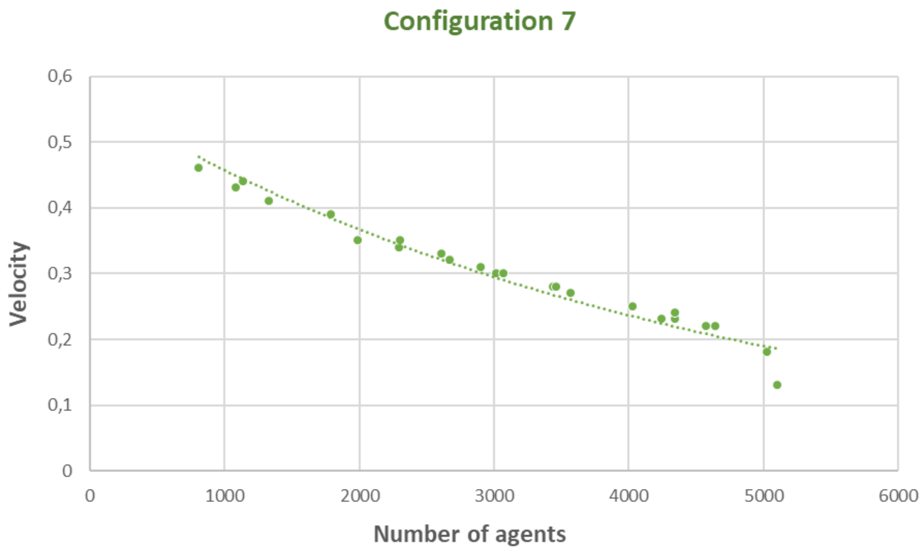


Figure 3.46 **Configuration 7**: traffic intensity and average agent velocity

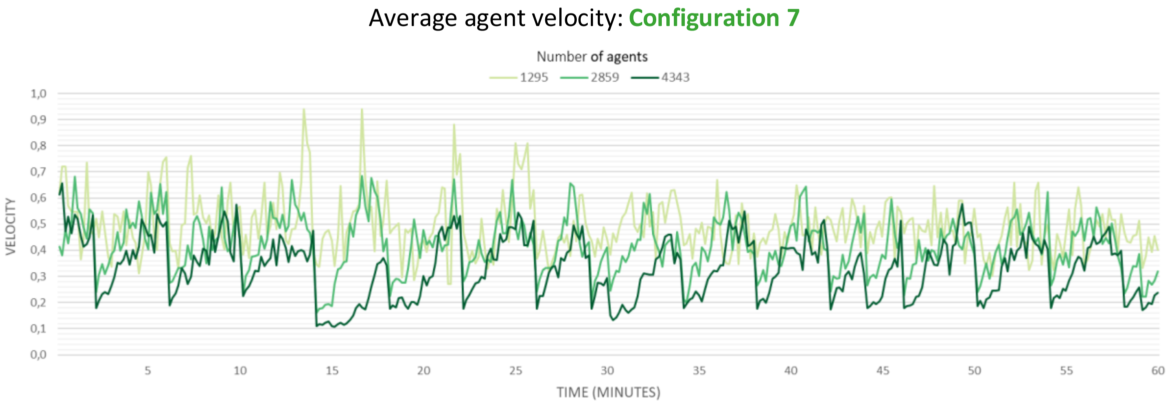
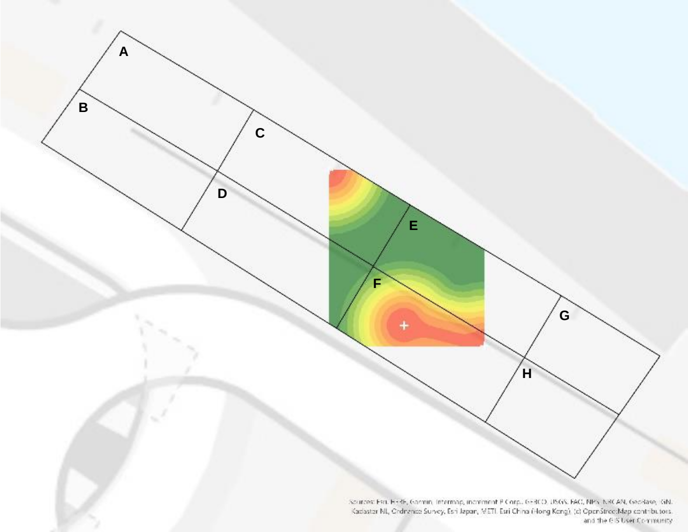


Figure 3.47 **Configuration 7**: average velocity during run; sample of three runs

As figure **3.45**, **3.46** and **3.47** show, we have arrived at a parameter configuration that meets our requirements, and produces a number of conflicts comparable to the results from the municipal conflict observation while retaining acceptable average agent velocities. At low intensities with less than 2000 agents per hour, hardly any conflicts are noted. At medium intensities, between 2000 and 4000 agents per hour, between zero and two conflicts are measured. During high-intensity hours with more than 4000 hours, the number of conflicts varies between zero and four conflicts. These numbers quite accurately match the number of conflicts measured during the conflict observation.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.48 **Configuration 7**: conflict locations, sample of three runs

Conflict locations

Figure **3.48** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell F.

Conflict partners

Cyclist - Cyclist	0	0 %
Cyclist - Pedestrian	3	100 %
Cyclist - Moped	0	0 %
Moped - Pedestrian	0	0 %
Moped - Moped	0	0 %

3.4 Summary

In this chapter, an attempt has been made to get a feeling of the functioning of the various parameters within the Shared Space model. The original 6 tested parameter configurations all came with advantages and disadvantages, but through the process of sensitivity analysis a clear overview was created, and on the basis of acquired information an optimal configuration was found (configuration 7).

This parameter configuration has resulted in a close-to-realistic model output; the number of conflicts per run has proven to quite accurately match the output as measured during the municipal conflict observations. Furthermore, during this final configuration, a “healthy” pattern in agent velocities was observed. While at peak moments (the unloading of a ferry) during high intensity runs, speeds dropped considerably, average agent velocities remained clear of approaching a tipping point.

Regarding the spatial distribution of conflict locations, it is a challenging exercise to accurately account for the cause of variation among spatial output between different variable configurations.

A number of the tested parameter configurations produced a very unbalanced distribution of conflict locations. The conflicts during these runs were often clustered in large numbers within the outer easternmost regions of the modeling area, primarily within cells G and H.

However, during the final configuration, conflict locations showed a balanced pattern; equally divided over cells C, F and E; which quite accurately matches the spatial distribution presented in the municipal data. It is however important to note that the spatial data acquired through this small sample of runs merely serves as an indication of where conflicts take place, but cannot be considered to be statistically significant.

Altogether, this chapter has been able to quite extensively answer the fourth sub-question (SQ 4): *To what extent do the model patterns compare to measured (real-life) patterns?*

In the next chapter (**4**), two plausible scenarios are tested while maintaining this parameter configuration.

4. Scenario analysis

In this chapter, agent behavior is researched in two different scenarios, with respect to the number of agents entering the Shared Space, but also the entry point distribution. First the scenarios are introduced, and second, put in action through running the calibrated model with two different settings.

4.1 Scenarios

As Amsterdam is growing to be a more popular tourist destination every year, and the number of residents is also steadily inclining, it is safe to presume that the Shared Space area will become even more crowded over time. Furthermore, the northern part of Amsterdam is growing even more in demand; with more residents, but also more café's, festivals and other third spaces popping up every year. The last couple of years the municipality of Amsterdam has increased the number of ferry services across the IJ-river, and it is predicted that this trend will follow through in the coming years. It is therefore reasonable to test scenarios in which we include an increased amount of Shared Space visitors, but also one in which the percentage of visitors entering from Amsterdam Noord (from the ferry docks) is increased.

4.1.1 Scenario 1: More agents

In the first scenario tested, the overall number of Shared Space visitors is increased, while keeping the same entry point distribution. This means more agents spawn from all entry points. The maximum number of agents registered per hour during the municipal conflict observation was 5314. In this analysis the number of agents is increased, and is set anywhere between 5314 and 7000 agents per hour. The model is run **15** times; each of the green points represents one model run. When looking at the output of Scenario 1, two things become clear. Firstly, looking at figure **4.1**, while the number of agents per run is significantly higher compared to the model runs done during the sensitivity analysis, the average number of conflicts per hour does not dramatically increase. Thus, when using this parameter configuration, an stark increase in agent numbers does not lead to much more conflicts. At the same time, when we look at the results presented in figure **4.2** and **4.3**, these additional numbers of agents lead to extremely low agent velocities. The effect of these additional agents on agent speeds is best visualized in figure **4.3**;

during all three of the sample runs, the average speeds reach a tipping point, and fall below acceptable speeds at approximately 15 minutes into the run.

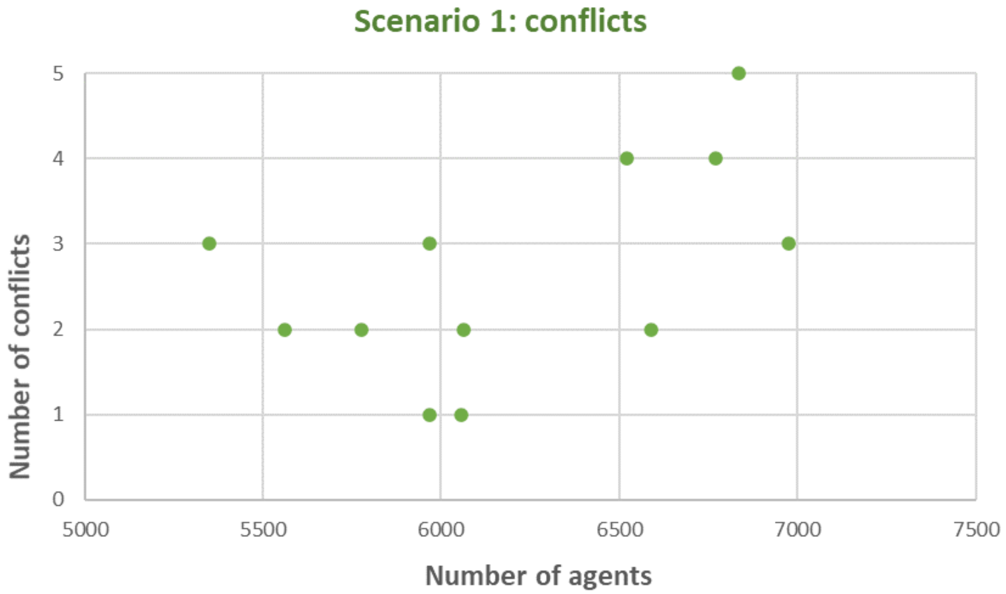


Figure 4.1 Scenario 1: number of conflicts and traffic intensity

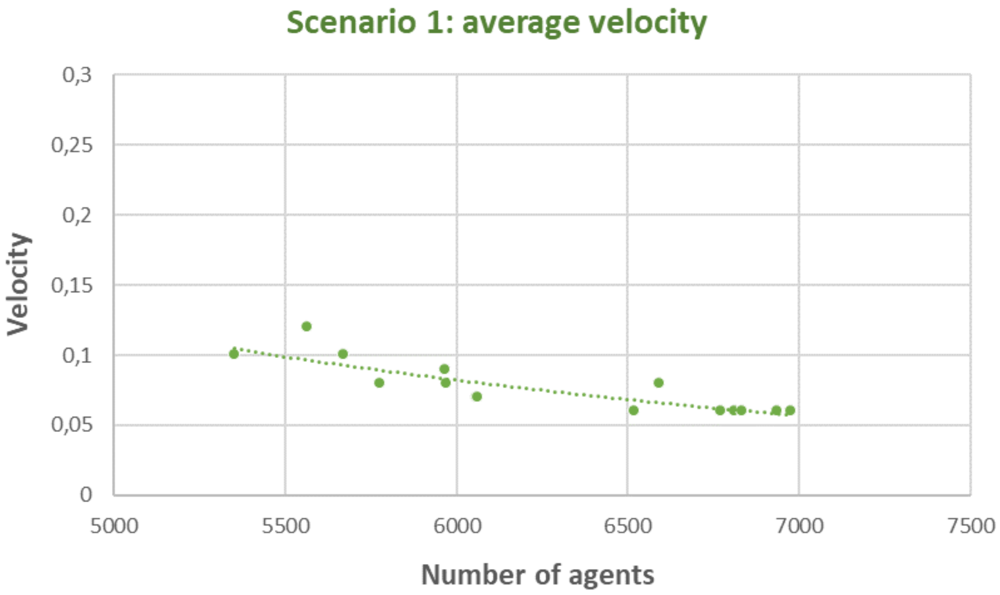


Figure 4.2 Scenario 1: average velocity and traffic intensity

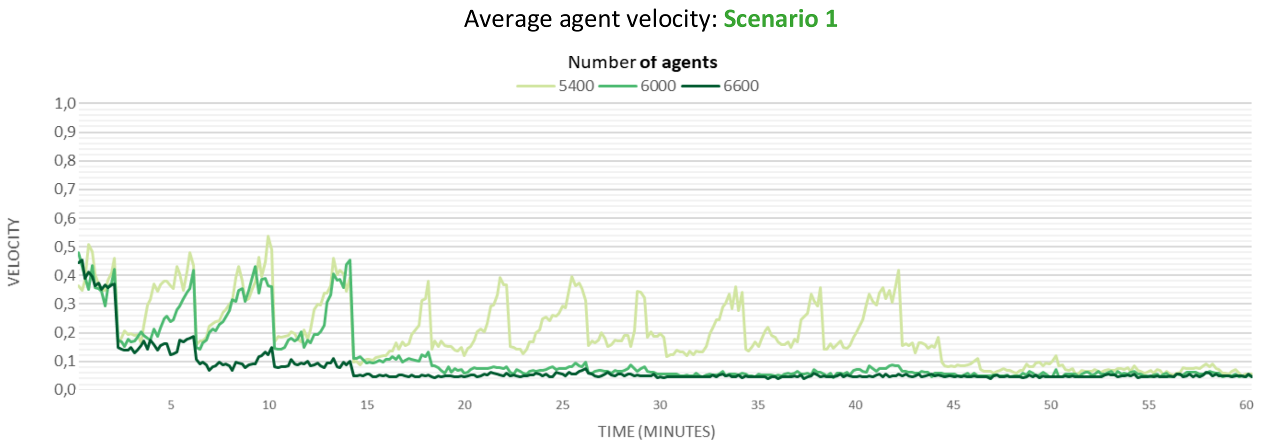


Figure 4.3 **Scenario 1**: average velocity during run; sample of three

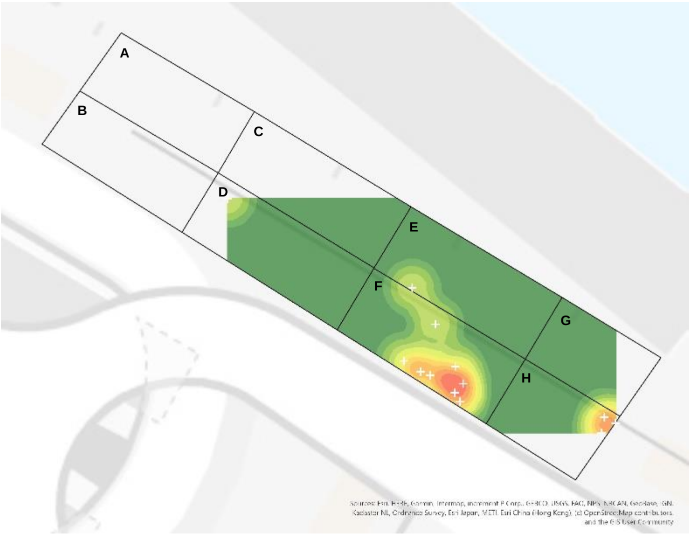


Figure 4.4 **Scenario 1**: conflict locations, sample of three runs

Conflict locations

Figure **4.4** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell F.

Conflict partners

Cyclist - Cyclist	**1**	**7.5 %**
Cyclist - Pedestrian	**11**	**85 %**
Cyclist - Moped	**0**	**0 %**
Moped - Pedestrian	**1**	**7.5 %**
Moped - Moped	**0**	**0 %**

4.1.2 Scenario 2: Increased traffic from Amsterdam Noord

In the second scenario tested, the percentage of Shared Space visitors entering the area from the northern border (the ferry docks) is increased, while keeping the total number of agents at original values. Traffic counts have shown that at the moment, approximately 38 percent of all Shared Space visitors enter the area from the northern edge. During the second scenario

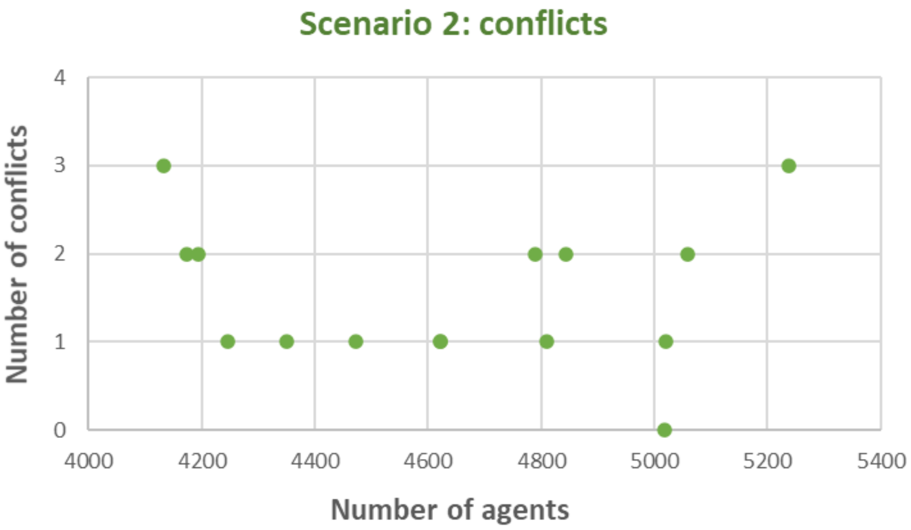


Figure 4.5 Scenario 2: number of conflicts and traffic intensity

analysis, however, this percentage is increased to 57 percent. Because our interest lies in agent interaction during hours with high-agent densities, the minimum number of agents per run is set at 4000. The model is run 15 times; each of the green dots represents one model run.

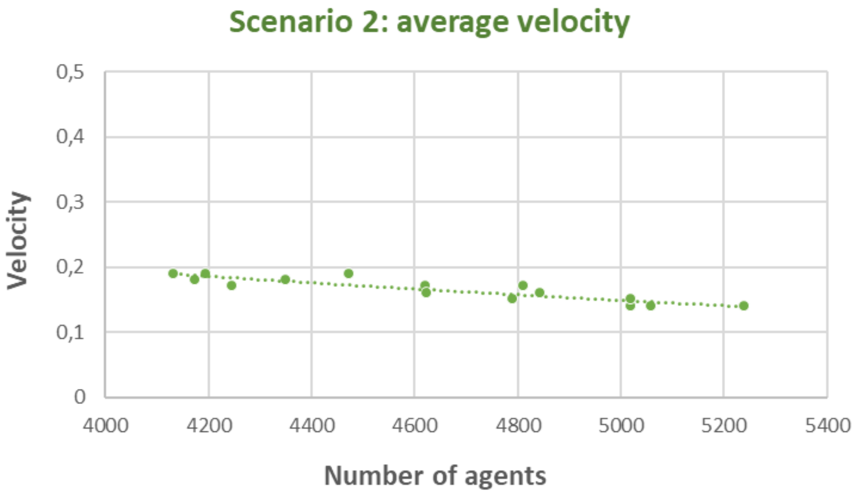


Figure 4.6 Scenario 2: number of conflicts and traffic intensity

When looking at the output of Scenario 2, we notice two things. Firstly, when looking at resulting agent conflicts in figure **4.5**, we can see that increasing the percentage of agents arriving from the ferries has not led to an increase in conflict occurrences. In fact, compared to the results obtained during the sensitivity analysis, a slight decrease in the average number of conflicts per hour is noted in this scenario. Furthermore, when looking at the average agent velocities in figure **4.6** and **4.7**, we can conclude that while speeds during peak moments (the unloading of a ferry) are low, the plot does not suggest a tipping point being reached. Also, when observing the results shown in figure **4.6,** it is notable that unlike all previous model runs, the average velocities between low-, medium-, and high intensity runs do not show distinct differences.

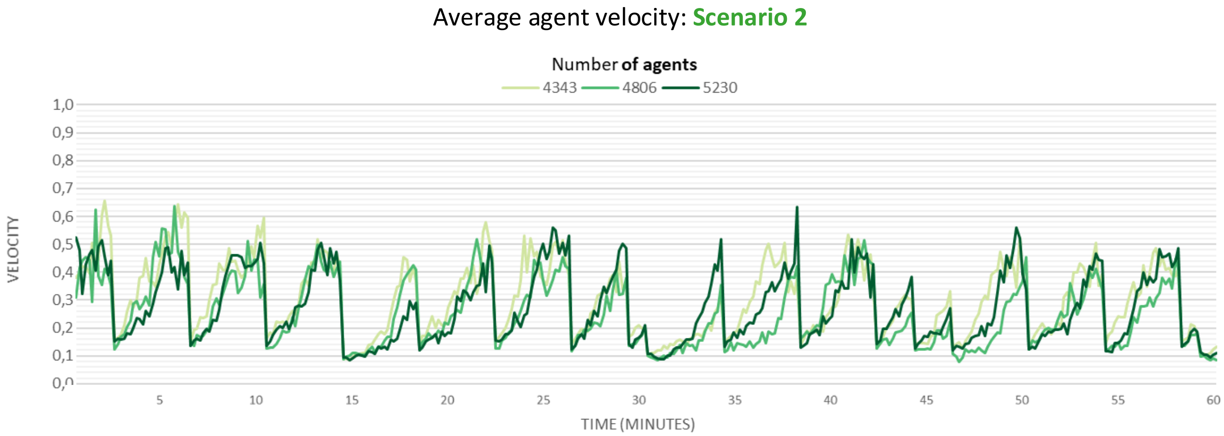


Figure 4.6 Scenario 2: average velocity during run; sample of three

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 4.7 Scenario 1: conflict locations, sample of three runs

Conflict locations

Figure **4.7** shows the locations of all the conflicts registered during the same three sample runs. In this model configuration, most of the conflicts took place in Cell F.

Conflict partners

Cyclist - Cyclist	**0**	**0 %**
Cyclist - Pedestrian	**2**	**66 %**
Cyclist - Moped	**0**	**0 %**
Moped - Pedestrian	**1**	**34 %**
Moped - Moped	**0**	**0 %**

4.2 Summary

Chapter **4** has sought to test our calibrated Shared Space model on scenarios that are not at all far from realistic in the (near) future. During the first scenario, the experimentation consisted of increasing total agent numbers. While the number of agent conflicts did not drastically increase, these additional agents caused average agent velocities to dip below a certain “point of no return”, or “tipping-point”, after which agents were unable to reach acceptable speeds. During the second scenario, the percentage of agents arriving from the ferries at the northern edge of the area was increased. This did not lead to more conflicts, and also has a limited effect on the average agent velocity.

Regarding the spatial distribution of conflict locations, the following can be concluded. In contrast to the output of some of the configurations in the sensitivity analysis, the conflicts registered in both scenarios generally match the locations as measured by the municipality. However, it is fair to note the limited amount of conflict instances that lead us to this observation.

All in all, this chapter has provided us with a comprehensive answer to sub-question 5 (SQ 5): *What kind of agent densities and ratios can lead the system to reach a ‘tipping-point’ –a state of over crowdedness and/or chaos?*

5. Conclusion

Our research question: “How can the dynamics within the Shared Space environment at Amsterdam Central Station (CS) be analyzed and understood, by simulating agent dynamics using an Agent Based Modelling technique?” can be addressed as such:

The dynamics within the Shared Space have been vigorously analyzed. Agent-based modelling has presented itself as a suitable method for describing agent behavior, conflict occurrence and changes in velocities, within the Shared Space environment. Altogether, this modelling endeavor has turned out to circle around a precarious balance between agent speed, agent heading, and distributions of entry points. In finding a balance between the theoretical footing of Helbing and Molnár’s Social Force principles, as described in the conceptual model, and the modelling restrictions at hand, various modelling choices have led to a functioning model that is configured in such a manner that it produces close-to-realistic conflict output.

However, to get more specific, within this Shared Space model a number of concrete conclusions can be made.

- Within the Shared Space model, **agent velocity** is primarily decisive for producing agent conflicts; as agent velocities fall below certain levels, the chance of conflicts occurring is diminished;
- However, whenever two conflict partners have reached a certain combined speed, their **heading** in relation to one another becomes the decisive factor in producing a conflict;
- Increasing total agent numbers within the Shared Space area well into the 5- and 6-thousands has not proven to lead to more conflicts;
- However, as the number of agents within the Shared Space exceeds the 5000/5500 agent-per-hour mark, average velocities drastically drop, causing the model to reach a **tipping point**, after which the Shared Space “clogs up” with agents that are unable to reach acceptable speeds;
- Increasing the percentage of agents arriving from the ferries at the northern edge of the area does not lead to more conflicts, and also has a limited effect on the average agent velocity;
- The results from this Shared Space research show that when increasing agent numbers, and/or changing the distribution of agent entry points, the risk of unacceptably low

average velocities (clogging up), is greater than the risk of increasing the amount of agent conflicts.

- Regarding the spatial distribution of conflict locations, the following is noted. A number of the tested parameter configurations produced a very unbalanced distribution of conflict locations. The conflicts during these runs were often clustered in large numbers within the outer easternmost regions of the modeling area, primarily within cells G (and H) (figure **5.1**).
- This corner of the Shared Space is generally the most cluttered; it is located on the crossroads of (1) a large number of agents entering the area from the eastern cycle- and footpath, and (2) one of the two most important ferry unloading areas. Camera footage has indeed proven this corner of the Shared to be the most busy. However, the municipal conflict observation has shown this cell (G) was only accountable for 12.5 percent of all measured conflicts; while most of the conflicts were measured in Cell F (46 percent). An explanation for this discrepancy lies in the following;
- As we can already conclude that within this area generally the most intersections among agents take place, the parameter configurations that led to the patterns as observed in figure **5.1** either: (1) caused an agent intersection to "too easily" turn into a conflict, or (2) caused a percentage of agents to move with such a low velocity that during overlap between two agents, agents intersect ("touch") each other more than once, leading to multiple conflict chance calculations per interaction.

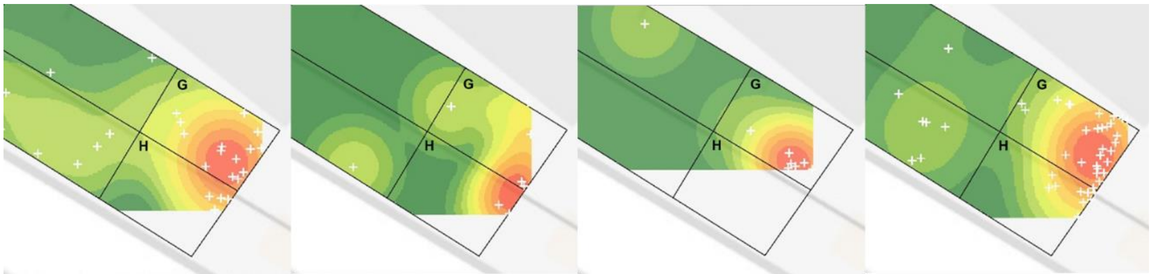


Figure 5.1 Clustering of conflicts locations

- However, when examining the conflict output of the scenario analysis, a more balanced spatial distribution presents itself (figure **5.2**). While still some degree of clustering is noted, the conflict locations are much less focused on the outer border-areas, slightly more distributed over the whole area, and a far greater percentage of the conflicts fall within cell F. The spatial conflict-distribution in this sense shows a far greater similarity to the conflict locations measured during the municipal observation.

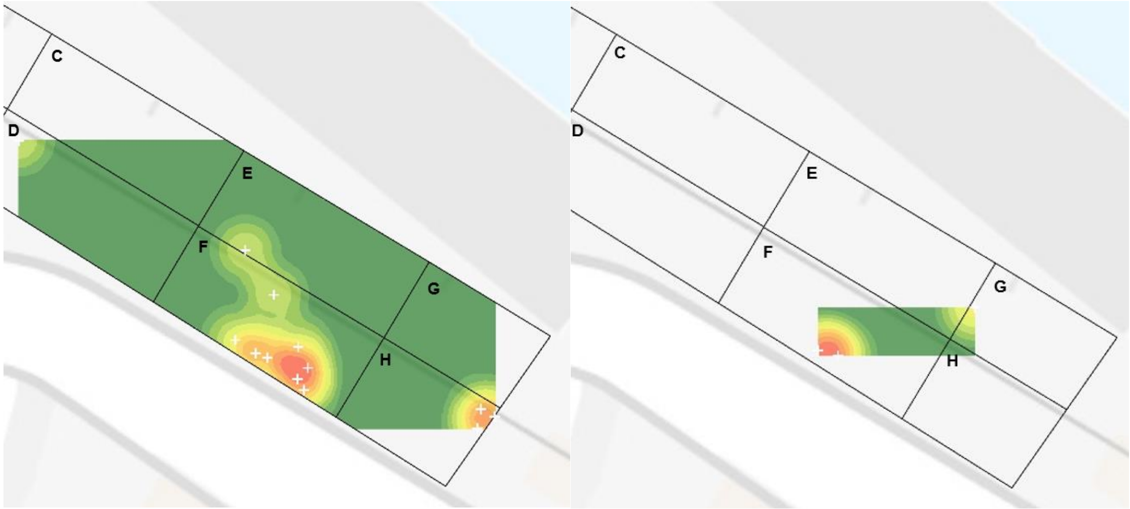


Figure 5.2 Clustering of conflicts locations; scenario 1 (left), and 2 (right)

6. Discussion

When it comes to Shared Spaces, there aren't a lot of fixed rules. An inventory of Shared Spaces in the Netherlands has shown that the difference in environmental and compositional characteristics of Shared Spaces make it impossible to use an overall definition of the appearance or functionality of a Shared Space location.

The Shared Space area behind Amsterdam Central Station is as unique a location as it gets. A lot of the traffic rules that apply for the greater part of the city (or country) become obsolete, as people are left to rely on their own judgment.

While the municipal monitoring research does grant some insight into the number of registered conflicts and traffic intensities, the conflict observation only included a limited number of observed hours. This research thus offers an insight into similar traffic situations by using an Agent Based Approach, but it does not grant us quantitatively accurate output data.

Furthermore, while Helbing and Molnár's Social Force Model provided a stable foothold on which to build the rest of the model, a large part of the model is based on uncertain parameter values that could disproportionally impact results; even inaccurate models can produce accurate output. Therefore, some hesitation regarding model interpretation is appropriate.

However, we can surely conclude that as traffic pressures keep growing, somewhere in the near future a tipping point in some form will be reached. In seeking to contribute to potential future Shared Space research, it can be recommended to (1) expand and diversify empirical data sources used in for model validation, and (2) improve modeling techniques, especially with respects to improving realistic agent traveling paths.

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