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Applications of agent based modelling: analysis and simulation of bicycle traffic in urban environments

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Abstract

In the city of Amsterdam, the bicycle is rapidly becoming the most popular method of transportation, and is seen as the solution to congestion, pollution and health problems. A number of improvements have been proposed by the city of Amsterdam, to increase the safety and capacity of the bicycle transportation network. The effect of these improvements will be measured in surveys and path width percentages, creating a knowledge gap on the actual impact of the proposed changes in capacity and safety. Therefor, this thesis research proposes an additional feedback method in the form of an Agent Based Model application of the bicycle network, to calculate the effects of cyclist behavior on the bicycle network load distribution under varying influence of external parameters.

First, the bicycle network is translated to a conceptual Agent Based Model, defining the main components and their interactions of a bicycle network. This conceptual model is implemented in a case study for the city of Amsterdam, which is translated to a model in the GAMA simulation environment.
The simulation model is able to simulate the behavior of 60.000 cyclist agents in the Centrum district of Amsterdam, for a time period between 05:00 and 23:00. Environmental changes are simulated with external parameters on road safety class and occupation of network segments. A change in cyclist behavior in the simulation affects distribution of cyclists on the network.

The accuracy of these results relies heavily on assumed values derived from census data, as data on migration patterns within the city of Amsterdam is non-existent. Comparison of the simulation results with observation based data from the Fietstelweek does however show similarities in cyclist distribution. Agent Based Modeling can therefor be considered an additional tool to investigate the effects of infrastructural changes on a cyclist network, within the boundaries of the available information on cyclist behavior.

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1 Introduction

1.1 Amsterdam: Transportation

Amsterdam is a city with a medieval heart but a modern body. Ancient canals share the city space with state-of-the-art tech start-ups, international art masterpieces are located next to coffee shops and Irish pubs, students lie in parks while businessmen peddle by on their bikes. Amsterdam, as the capital of the Netherlands, has an important, flexible and ever changing role. In early 2017, 835.000 residents lived and worked in the one of the 22 neighborhoods of Amsterdam, making it the largest city in the Netherlands. (Amsterdam, 2017) As the economic heart of the Netherlands, the city of Amsterdam welcomes a variety of companies, ranging from small high-tech start-ups to international business conglomerates. On an educational level, Amsterdam has two universities, and numerous universities of applied science. Furthermore, the city center houses canals, museums and numerous other cultural treasures, which attract 17 million national and international tourists annually, that spend a total of 17 billion EUR in Amsterdam. The combination of all these functions places a demand on transportation networks, which enable all stakeholders to move freely within Amsterdam.

In comparison to other metropolitan cities, Amsterdam has a very distinctive transportation network. Daily commuters do not just rely on foot, car or public transport, but have adopted the bicycle as the main form of transport. In 2015, 36 % of daily transportation was performed by bike, as to 16 % by public transport, 23 % on foot and 24% by car.(Amsterdam, 2017a; Amsterdam, 2013a) In comparison, 3 % of commuters in London choose the bike, and 10 % of commuters in Paris. As a side note, almost 10 % of tourists chooses a bike to explore the city of Amsterdam.(Amsterdam, 2017a)

In the period 1990 – 2015, the share of bicycles as a form of transport increased significantly. By 2015, bicyclists in the inner Ring of Amsterdam formed almost 60 % of all transportation movements.(Amsterdam, 2013a) Traffic by bicycle towards the city centre district increased and resulted in a share of 25 %. In 1990, only 40 % of transportation movements was performed by bike, and only 15 % of movements toward the city centre was performed by bike.(Amsterdam, 2013a) Overall, the number of movements did not increase drastically, but the distribution of mobility choices shows a steady course towards bike and car, and away from public transport. A positive development according to the City of Amsterdam, which considers the bicyclist as an influential force in the ecosystem of the city.

Cyclists are deemed healthier, as physical exercise increases the physical health of citizens. Next to a personal aspect, bikers have no direct CO2 emission, improving the overall climate in the city of Amsterdam. The small footprint of the bike is praised, making the bicycle a rush-hour proof form of transportation and facilitating green logistics, supporting a desired sustainable growth of the city. Last, the bicyclist is praised for its influence on public space, as the bicycle network allows a fine maze of city streets, improving the quality and appeal of public spaces in the city center. (Amsterdam, 2015a)

The growing number of bicycles resulted in a number of negative side-effects. Main bike routes are in peak situations are less and less able to handle the number of bikes, or do not provide a safe environment for bicyclists whilst sharing the road with other road users. Next to this capacity challenge, bicyclists make a spatial claim after finishing their commute, as bikes are placed in the public space, hindering pedestrians and other users of the public space. Last, the behavior of bicyclists leaves room for improvement, with dangerous and unexpected behavior as a main problem. (Amsterdam, 2017a) The city of Amsterdam has recognized the growth of the bike as form of transport, and responds to the developments with the "Meerjarenplan Fiets 2017-2022", a vision on the bike between 2017 and 2022. In the introduction paragraph of the document, three goals are introduced to solve current problems and further strengthen the position of the bike in Amsterdam. A better flow, better storage facilities and better behavior of the bicyclist should form a solution to the current problems, and further strengthen the position of the bicycle as the dominant form of transport.(Amsterdam, 2017a)

1.2 Problem Statement

The document aims to create a network able to support and improve the flow of cyclists on the bicycle network of Amsterdam. A lack of flow, caused by crowded bicycle paths and other obstruction, was identified in questionnaires as the main reason of frustration whilst using a bicycle in Amsterdam. To identify problematic locations, the busiest, most crowded and least spacious bicycle paths and crossings are identified. Faster, more direct, easily recognizable and spacious routes are named as the possible solutions to the overall problem, as these would be able to facilitate a continuous flow of bicycles throughout the day. Reduction of interaction between cars and bicycles, shorter waiting times at traffic lights, are additional solutions which are stated as a positive factor to achieve the goal of a more continuous bike flow. (Amsterdam, 2017a)

Effectiveness of these solutions is monitored by two parameters, which are defined in the Meerjarenplan Fiets. Main indicator of supporting the flow of bicyclists is defined as " 50 % of the bicycle paths has a minimum width of 2,5m" on the parts of the network defined as main routes by 2025. The second indicator is the satisfaction rate of bicyclists with regard to the main bike network. Defined by a surveyed rating, this level should be improved after completion of the infrastructural changes in comparison to the rating determined in 2017. Next to the Meerjarenplan Fiets, the "MobiliteitsAanpak Amsterdam 2030", as well as other exploratory documents, shows a comparable approach, aimed at improving the end-user experience. (Amsterdam, 2017a; Amsterdam, 2011; Amsterdam, 2013a)

Amsterdam sees the bicycle as a green and healthy mobility solution of the future, the answer to numerous mobility problems and an essential structural part of the local economy. (Amsterdam, 2017a; Amsterdam, 2013a) In the current bicycle network, the cyclist is limited by the capacity of the network. Cyclists experience a limited amount of space when using the network, resulting in decreased traffic flow and longer travel times. The city of Amsterdam is responding to these shortcomings in the network and aims to create a durable network, that is able to handle current capacity demand, and able to carry the load of larger volumes of cyclists on the network.

However, the feedback mechanisms used by the city of Amsterdam to monitor the success rate of the proposed plans do not focus on the aspect of network durability. By measuring the satisfaction rate of users and the width of the network, the city of Amsterdam gains knowledge on the end-user satisfaction and the physical aspects of the network. This does not necessarily result in sufficient knowledge to evaluate the overall performance of the network. Simplified, a satisfied cyclist is not necessarily equal to an improved network performance. Although the satisfaction of the cyclist is important, the performance and functioning of the bicycle network should be improved an evaluated on a network scale.
As an example, a widened bicycle path could result in more positive feedback from the user, as it fixes a local flow blockage. However, this positive result on one location could result in an overflow on other locations in the network, which would remain undetected with the current measuring tools. From this perspective, monitoring and designing infrastructural improvements could benefit from additional testing

and feedback mechanisms. The mechanisms should be aimed at monitoring and assessing the role and of the bicycle network as a whole, and should provide insight in the behavior and density of cyclists throughout the day.

Earlier research on traffic flow shows a distinction between two methods, observation and simulation. Observational research relies on measurements form sensors, video-analysis or other inputs, to create input for a behavioral model. A behavioral model enables researchers to determine spatio-temporal relationships based on input values from the network. (Tom Thomas, 2008) Gaining insight in the behavioral pattern of cyclists in Amsterdam could be performed with such quantitative research Although being the most realistic representation of the case, observing the 2.5 million bicycle movements in Amsterdam would be a labor intensive project, and a very costly undertaking.

A case like bicycle mobility in Amsterdam demands a different approach in research. This approach could create a valid assumption on the quantity of bicyclists, the type of bicyclists, their routing choices and the influence of time, whilst not being dependent on subjective values. Agent-based research approaches suit these cases quite well, as Agent Based Modeling and simulation is able to handle geographic, temporal and functional distribution of data. Next to that, Agent Based approaches are able to incorporate the influence of interactions among agents in the system. (Klügl and Bazzan, 2013)

In the research paper "A review on agent-based technology for traffic and transportation", agent-based research methods for transportation networks are reviewed and inventoried, to create an overview of the current applications. Agent-based simulation is able visualize, monitor and validate individuals decisions, but also to assess the impact of all these individual decisions on an overall traffic situations in the network.(Klügl and Bazzan, 2013)
Karima et al., 2012 state in the research paper "Agent-based modeling for traffic simulation" that "Modeling is a powerful tool that allows a designer to observe cause-and-effect relationships in occurrences that happen too slowly or quickly to see; involve danger or safety concerns; occur on a scale too large or too small for study; are not a common occurrence or simply can hardly be realized in real environment with real entities.". In this research paper, modeling is proposed as a tool to predict not only traffic load, but traffic flow as well. Agent-based traffic simulation in urban environments is not a new or unknown technique, as multiple examples show us in scientific literature.

Joubert et al., 2010 created an agent based model to assess the impact of freight vehicles and their infrastructure on the congestion level in a transportation network. On this macro-level, Joubert et al. were able to reconstruct and validate the behavior of heavy freight vehicles with the help of geo-referenced positional data.
Paruchuri et al., 2002 identified macro and micro goals in their conference proceedings “Multi-agent simulation of unorganized traffic”, where the macro goal is defined as the destination, micro goals includes all decisions enabling the agent to reach the macro goal. To realistically simulate agents, decisive capabilities and motivational parameters are identified, which creates a true-to-life representation of network users. Scientific contributions show multiple applications of Agent Based Modeling and Simulation (ABM), in both urban and non-urban environments, and on micro levels and macro levels. (Karima et al., 2012; Joubert et al., 2010) . However, literature also shows that Agent Based Modeling is often used in combination with real-life GNSS data and observations, after the appearance of non-desirable situations in traffic flow patterns. (Klügl and Bazzan, 2013)

A complex problem presents itself in this situation. The city of Amsterdam wishes to promote the adoption of the bicycle as main choice in all forms of inner city transport, but does not provide a bicycle network able to support this development. In this scenario, the city acknowledges the challenges of the current network, which is considered crowded and unsafe by the current users. The city has proposed changes and improvements of the network, which should result in a network that is able to support the current and future use of the bicycle network. From a scientific point of view, the city presents subjective and user-oriented methods to assess the success of the proposed changes, which seem not sufficiently able to measure changes across the network.

These methods contribute to a better overall bicycle experience, but a network wide assessment could further improve the efficiency and usability of the network itself. This assessment can not be performed by means of observation, due to time and financial restrictions, but could be performed with the help of simulation. One of the main methods for behavior based simulation of transportation networks is Agent Based Modeling. Current literature reveals methods focused on pedestrian users or motorized vehicles, but no specific methods for cyclists, especially not on a network scale. As cyclists combine aspects of pedestrians and motorized vehicles, applying this methodology to the cyclists on the bicycle network of Amsterdam could add to the existing knowledge, and increase the understanding of their behavior.

1.3 Research objectives and research questions

The main objective of this research is to develop and demonstrate an Agent Based Model, to explore the effect of varying agent behavior on a bicycle transportation network. Agent Based modeling could form a new method to explore these effects on a cyclist network where observatory methods are to costly and / or labor intensive. In the case of Amsterdam bicycle network, this method could be applied to analyze the current and future state of the bicycle transportation network. This research proposes, researches and validates an Agent Based Model methodology to assess the influence of behavioral factors in cyclists, by applying varying types of behavior to cyclist agents in a modeling environment. This environment is based on the characteristics of the city of Amsterdam, to test the effect of cyclist behavior in a specific situation.

The research focuses on four main questions:

- *What approach is suitable to define a bicycle transportation network in an Agent Based Model?*

- *In what way can routing mechanisms for cyclists be influenced by external variables?*

- *What is the influence of behavioral variables on the bicycle network in the case of Amsterdam?*

- *Is the proposed Agent Based Model for Amsterdam suitable for predictive research on this and other bicycle networks?*

1.4 Reading Guide

Chapter 2 is a review of available scientific literature, to create a solid theoretical basis for the methods used in this thesis research. First, it focuses on Agent Based Modeling in general, ranging from general concepts to more specific applications. Second, the behavior of bicyclists is researched and explained, to identify influencing variables in routing choices.

Chapter 3 describes the general methodology of this thesis research. First, the general methodology to define a transportation network in an Agent Based Model is explained, as well as the inclusion of routing behavior variables. Second, the case study of Amsterdam is introduced. The research area is described, as well general trends in cyclist movements in Amsterdam. Subsequently, the preprocessing steps and necessary variables to define an Agent Based Model for the case study are explained and defined. The chapter continues with an Agent Based Model simulation able to assess the influence of behavioral variables on the number of cyclists in Amsterdam, and their distribution across the network.

A first baseline simulation is performed and shortly discussed with existing cyclist data, to benchmark the model without behavioral influence. After benchmarking the model, the behavioral parameters are applied, of which the results are presented in chapter 4, to assess the sensitivity of the model for these variables.

Chapter 5 contains conclusions on these results, which are discussed in chapter 6. Chapter 7 explains the possibilities and limitations of this model, recommendations for future research and possible implementations.

Related research

2

2.1 Agent Based Modeling

2.1.1 Defining Agent Based Modeling

The use of models is a concept which is well-known to scientists from all branches and disciplines. A model reduces the complexity of reality, to allow analysis the impact of changing external influences on a given system. The overall workings and dynamics of a system can be identified and studied With the help of such models by simplification of mechanisms, and assumptions on the cause-effect relation between input and output parameters. However, in the simplification of systems for the sake of model building the fine detail on the precise functioning of separate elements is lost. Although not necessarily problematic, oversimplification and unjustified approximations can result in skewed models that are not able to universally predict or explain developments within a modeled system.(Bonabeau, 2002; Bandini et al., 2009)

Within the natural sciences, modeling is often equation-based, as the separate steps or phases in natural phenomena can be translated to general equations. As the described processes have a fixed and known number of reactions or trajectories, the model consists of a number of subsequent equations, modeling a phenomenon from input to output. In socio-economic or human systems, agent based modeling has grown in the number of applications in the past decade. Human systems are often too complex to formalize mathematically, making an equation-based approach is less suitable in this research field. (**Helbing2012** ; Bonabeau, 2002)

Agent-Based modeling (ABM) captures a human interaction system as a network of interdependent agents, in which the decisions of the separate agents influence the overall model, next to the defined input parameters. The behavior of agents can then be defined in simple equations, but is often defined in if-then relations rules or logical operations. (Bandini et al., 2009) By adding individual capacities to elements of the model, an ABM is able to not only simulate or predict a system level output, but also allows the study of agent behavior and the effect of decisions on other agents, so called ‘Emergent Phenomena’. As Bonabeau describes it: “Emergent phenomena result from the interactions of individual entities. By definition, they cannot be reduced to the system's parts: the whole is more than the sum of its parts because of the interactions between the parts." ABM is able to simulate, detect and predict the emergence of these phenomena, as it models the behavior and interactions of all separate parts in the system. Furthermore, Agent Based Models are applied in research on complex systems, as the models are modular, flexible and are able to adapt quickly to new developments. (Bonabeau, 2002; Bandini et al., 2009)

The flexibility of ABM has resulted in applications in numerous research fields, ranging from behavioral biology to the urban planning field. Applications can vary, as well as topics, but a shared viewpoint can be identified. The scope of interest is focused on an individual agent, able to make autonomous decisions whilst interacting with other agents within a given space that is shared with these other agents. (Bandini et al., 2009)
When assuming these interactions affect other agents, but also the system as a whole, the result of a complex system is a result of all the agent actions and interactions. To assess the workings and capacities of an Agent Based Model, Bandini et al. introduced a reference model in their research paper "Agent Based Modeling and Simulation: An Informatics Perspective", which aims to capture the common elements of most Agent Based Models. The main reference model proposed in the research consisted of three elements: Agents, Environment and Interaction. Agents are the acting units within a given system, with possible variable behavior specifications. These units function within a given Environment, which supplies influencing trigger signals to the agents and enables the agents to act according to their behavioral specification. Interaction mechanisms influence the Agent behavior in two ways. Directly, by exchanging information between agents that influence decisions, or indirectly, when the actions of an agent alter the environment, and by that influencing the behavior of other agents.

2.1.2 Agent Based Models in transportation research

"The core idea of Agent Based Modeling and Simulation is that, instead of merely describing the overall, global phenomenon, this phenomenon can be rather generated from the actions and interactions of the multi-agent system" (Klügl and Bazzan, 2013).

Transportation studies have become popular applications of ABM technology, as the increasing presence and complexity of transportation create a demand for further insights on both micro and macro level. The efficiency and capacity of traffic systems in modern society influence thousands, if not millions of users on a daily basis. Effects on a macro scale are however influenced by millions of individual user choices on the network. In the paper by Klügl and Bazzan, a number of motivations is identified for using multi-agent system technology in traffic and transportation.

First, the capability of ABM technology to solve problems with agents that are able to act on a local basis. This allows the incorporations of details and constraints on a local level, which would not be captured by a central equation based solution. Second, heterogeneity amongst users can be expressed in ABM, as each element or agents can have specific details if desired. Third, agents and their interactions can be described with “high-level abstractions”, which allows the study of interaction amongst agents. Fourth, Agent Based Models are able to deal with flexibility and changes within a network. Connections within a network can be altered, moved or changed, as agents are able to adapt their behavior accordingly to their environment. Last, Agent Based Modeling allows the researcher to inspect the full development of problem solving mechanisms. A change in the system does not immediately change agent behavior, as agents can be persistent initially. ABM allows researchers to model and study learning behavior in agent behavior and interaction.

Klügl and Bazzan continue with an overview of agent and multi agent technologies for transportation and traffic scenarios. A first separation is made by the authors, with a traffic and transportation simulation section, and a management and control section. Within the scope of this research, the former is applicable to the situation of Amsterdam, and will be used for a first overview of developments and possibilities.

Travel demand simulation

First, Klügl and Bazzan discuss the methods of Agent Based Travel Demand Simulation, which is determined as the first step in Agent Based Traffic Simulation. In this configuration, Agents are used in models to determine what a daily schedule of said agent could resemble, under the given choice parameters. A daily schedule is created with the help of a starting point, locations and trips, after which a model is run to determine the order in which agents will perform their tasks at said locations, incorporating travel time and travel distance. Next to the physical aspect of moving an agent, this paragraph mentions the research on the influential factors for routing and planning. Social influences, ranging from group behavior to social media interactions, have been studied in multiple research examples. The result of this type of research is an insight in the presence, behavior and planning of the agents during a day on their varying activities, which makes the results available for comparison with potentially available empirical evidence. However, this method does not supply information on the traffic flow or intensity on the available networks, and does provide insight in the presence of agents on a given route between their desired locations. In other words, this methodology shows where the agent might go

Simulation of traffic-related choice

The paper by Klügl and Bazzan continues with their second selection in Agent Based Models for traffic systems, traffic related choices. These techniques can range from destination or departure time selection to the position of an agent on a given road section. A distinguishing factor in these applications is the agent choice process, where the agent always selects one option from a set of alternatives. Within traffic-related choice methods, three main directions are indicated. First, the use of Game-theoretic choice models, which base the choice mechanism of and individual on personal gain. Multiple alternatives are offered to the agent, and selection is based on reward. The best alternative is that with the highest reward. Reward is undefined, but could be time saved, speed gained or economic benefits. This singular approach is quite simplistic to resemble agent behavior, but can provide insights when there is a clear information medium or a direct consequence (i.e. financial or other benefit) of an action.

The second concept of traffic-related choice discussed by Klügl and Bazzan is that of network learning, communication and re-routing. In this method a feedback mechanism is introduced, as agents are informed real-time on changes or blockages in the network. As an example the research by Klügl and Rindsfuser is used. In this research, simulated drivers learned about the realistic travel times, to simulate a balanced distribution of load according to a real-world scenario. Next, a part of this network is blocked, whilst agents are navigating across the network on their shortest route to a destination. When approaching the blocked segment, the agent was informed about the blockage and given the opportunity to re-navigate the chosen route, resulting in a load distribution. In comparison to a situation where the blockage was known before the agent started navigating the network, the load distribution was quite different. The moment and level of information about network changes influenced the behavior of the agent on the network.

Complex agent architectures for traffic-related choice are a third variety of traffic-related choice mechanism. In the first two methods, the agents decision making process is based on a single input and has a limited number of predefined reactions. In complex agent architectures, the name illustrates the method, the method and number of decision processes is more complex. Klügl and Bazzan introduced the use of layered agent architecture, in which the navigational decision component is a separate entity, and another layer is used for the actual physical driving of the vehicle. In short, the route choice of said agent is split from the physical position of the road, and rely on separate input variables and preferences. The decisions created in one layer can, but not necessarily have to influence the decision process in the second layer, creating a more complex representation of agent behavior.(Klügl and Bazzan, 2012)

Traffic flow simulation

As final chapter in the simulation part of the paper, agent-based traffic flow simulation is discussed. Traffic flow simulation is deemed necessary when the time granularity is an issue, for instance when the behavior of agents within a system is studied on a minute to minute basis. These models do not necessarily focus on the navigational and routing aspect of agents, but more on the agent behavior whilst moving. With the help of behavioral rules (e.g. distance to other agents, preferred speed etc.) the behavior of large groups of agents within a network can be simulated. The attention to the behavioral aspect of agents allows fine-grained microscopic analysis of agents within a network. As an example, the research of Paruchuri et al. (2002) is mentioned, in which two types of behavior (aggressive and passive) were described in a crossing situation without traffic rules. The methodology of traffic flow simulation models is often more aimed at the reaction and behavior of agents in changing environments, on a close to real-time basis.

2.2 Cyclist behavior

2.2.1 Cyclist status

In the scientific area of transportation and mobility studies, the cyclist takes a special spot between walking and motorized traffic. Over short distances, the bicycle forms a good alternative to motorized traffic, but does not have the polluting side-effects of the motorized vehicle and a positive influence on physical health. The bicycle has a niche between the car and the pedestrian, combining positive elements of both transport modes. Modeling a cyclist is therefor not necessarily comparable to a modeling a pedestrian or motorized vehicle, as the behavior and routing choices of cyclists are influenced by varying physical aspects of a transportation network. This chapter aims to review the results of research on routing behavior of cyclists and identify relevant variables.

2.2.2 Cyclists in non-cyclist oriented societies

The routing mechanism of cyclists has been studied extensively in the past decades, with varying methods and findings. A number of studies was performed in societies with a low modal bicycle share, in this case Canada and the U.S.A..

Tilahun et al. measured cyclist preference for bicycle facilities. Based on a computer based survey among 168 participants, it was derived that cyclists are willing to add extra time to their commute, if this was rewarded with a route that contained better cyclist facilities. The highest rewarded were designated bike lanes, followed by streets without vehicle parking and the off-road separated bike paths. This study was based on surveys with a stated character, specifically defining the trade-off between travel time and facility safety level, without a study of the cyclist movement. (Tilahun et al., 2007)

Hunt and Abraham (2007) studied the influence of external factors on the use of bicycles in Edmonton, Canada. This research covered numerous factors that not only influence the cycling itself, but also the factors influencing the modal share of bicycles in general. The results of this research indicate that cyclist tend to prefer cycling on bicycle lanes or path instead of riding in mixed traffic, making the results comparable to Tilahun et al. (2007) However, the level of cycling experience was also deemed influential, as experienced cyclists indicated a lower presence for dedicated bicycle infrastructure than their inexperienced colleagues. (Hunt and Abraham, 2007)

In an observational study in Portland, Oregon, Dill and Gliebe asked participants about their route choices and preferences when using the bicycle for utilitarian trips, and combined these outcomes with GPS data obtained from the participants cycle trips. Participants placed the highest importance on minimizing distance and routes that consisted of streets with low vehicle traffic volumes. After that, a bicycle lane was identified as positive influence in route selection, next to low waiting times at intersections and traffic lights. As stated by the authors, these four preferences represent two conflicting objectives. On one side, cyclists wish to have a short and fast trip, but this short and fast trip has to meet the safety and network load preferences as well, indicating a constant trade-off between speed, safety and other road users. This research was based on stated preference surveys combined with GPS data, increasing the accuracy of the observed routing preferences. (Dill and Gliebe, 2008)

Broach et al. continued with research on the collected GPS data from the study by Dill and Gliebe, combining this data with the presence of other vehicles on the road sections. This revealed that the value of cyclist specific infrastructure depend on the available infrastructure for cyclists. Overall, cyclists showed a preference for "bicycle boulevards" and separated paths, and valued calm, low volumes streets over bike lanes on busy streets. Separation of other vehicle traffic, either by specific infrastructure or low volume secondary streets seemed to be an influential factor next to the shortest path.

2.2.3 Cyclists in cyclist-oriented societies

The before mentioned research focused on societies with a lower bicycle modal share, mostly in Canada and the USA. In the Dutch and Danish society, the bicycle is less of a niche and often used for daily transport, justifying a review of available literature in these countries.

An important difference between these countries is the role of the cyclist. As an example, in the Netherlands the allowed maximum speed influences the level of cyclist separation, and vice versa. In a study by Schepers et al. (2017), it is described that municipalities in the Netherlands have made common practice of separating bicycle traffic from other traffic depending on the maximum speed for motor vehicles. Such a bicycle oriented approach reduces the need for cyclist to actively search for bicycle infrastructure, and changes the trade-off whilst navigating towards a destination. Furthermore, the lower cycling speed in the Netherlands increases the chance of successfully reacting to a changing situation in every day traffic, reducing the need to actively search for low traffic streets whilst riding a bicycle.(Schepers et al., 2017)

Research performed by the city of Amsterdam presents contrasting choices amongst cyclists when compared to the mentioned research in the U.S.A. and Canada. The abundance of specific bicycle infrastructure shows a negative side, as mentioned in the policy document "Bicycle monitor of the city of Amsterdam" . It mentions that, during rush hour, 55% of cyclists in Amsterdam feels negatively impacted by the presence of other cyclists on bike paths and bike lanes, and 42% of bicycle users in Amsterdam states that they alter their route to avoid crowded bicycle paths. Next to finding and utilizing specific bicycle infrastructure, cyclists look for less crowded streets with a lower volume of other cyclists, next to lower volumes of other traffic. (Amsterdam, 2011)

Snizek et al. mapped bicyclist experiences in Copenhagen, a city with one of the highest levels of bicycles in the world. Based on tracking information and accompanied questionnaires, the relationship between 'positive experience' and the followed path was measured. After statistical analysis, a positive experience was related to smaller roads, cycling facilities and attractive nature environments. Negative experiences come from high density traffic, bus-stops (which was related to the exiting passengers crossing bike paths) and intersections. An interesting advice is the mapping of possible experience hot spots, either positive or negative, to determine locations where bicycle infrastructure can be improved.

2.3 Summary

The related research on Agent Based Modeling applications in transportations provides definitions, use cases, applications, limitations and methods.

In general, an Agent Based Model is deemed as the preferred method when researching complex systems, as an equation based model can oversimplify a complex system, which can lead to loss of detail or unjust model representations. (Bonabeau, 2002; Bandini et al., 2009) An Agent Based Model translates the complex system to a network of interdependent agents, which is influenced by both agents and input variables. These capacities allow the study of agent behavior and emerging phenomena, which are products of agent interaction within a complex system. (Bonabeau, 2002)

An inventory of applications of Agent Based Modeling and Simulation was created by Klügl and Bazzan in 2013. Overall, ABM is presented as a preferred method to study the increasingly complex transportation systems emerging in the modern society. A number of methods are specified in the research, varying in routing and choice levels for the independent agents. In this research, the complex agent architecture, or multi-layered agent architecture is used, as it separates the movement component from the routing decision component, which closely resembles the assumed behavior of a cyclist.

Research on cyclist routing provides results that vary with the research area. Research performed in cities where (utilitarian) cyclists form an exception, indicates that shortest time, shortest path and dedicated cyclist infrastructure are favorable factors in the routing decision, forming a trade-off between speed and safety. Studies in Amsterdam, where the cyclist forms 36% of all utilitarian movements, also indicate a preference towards safe cycling situations and a shortest path. However, the bicycle infrastructure is not necessarily the preferable option whilst navigating the city of Amsterdam, as 42% of cyclists indicate that the high levels of cyclists on dedicated cyclist infrastructure is a reason to recalculate their desired route. (Snizek et al., 2013; Amsterdam, 2011; Schepers et al., 2017; Broach et al., 2011; Dill and Gliebe, 2008)

Based on the related research, this research will develop an Agent Based Model that uses a multi-layered or complex agent architecture, which separately executes movement and routing actions. These actions can, but do not necessarily will influence one another. The routing behavior of the cyclists will be influenced by three parameters, each deemed influential in research on cyclist behavior. Distance, infrastructural safety and the presence of other cyclists will be incorporated in the model, to assess the potential influence of these external parameters.

3 Methodology

The methodology used to perform exploratory research on Agent Based Models for bicycle networks is outlined and explained in chapter 3. As Chapter 2 revealed, both Agent Based Modeling and cyclist behavioral studies show a variety in approaches. First, the general aspects of a suitable Agent Based Model are outlined, followed by the influencing variables of a cyclist. Second, the case study of the city of Amsterdam is explained and defined. Last, a full overview is created of the ABM for the case study, the required input values and the performed experiments. The results are then further discussed in the next chapter, chapter 4.

3.1 Concept

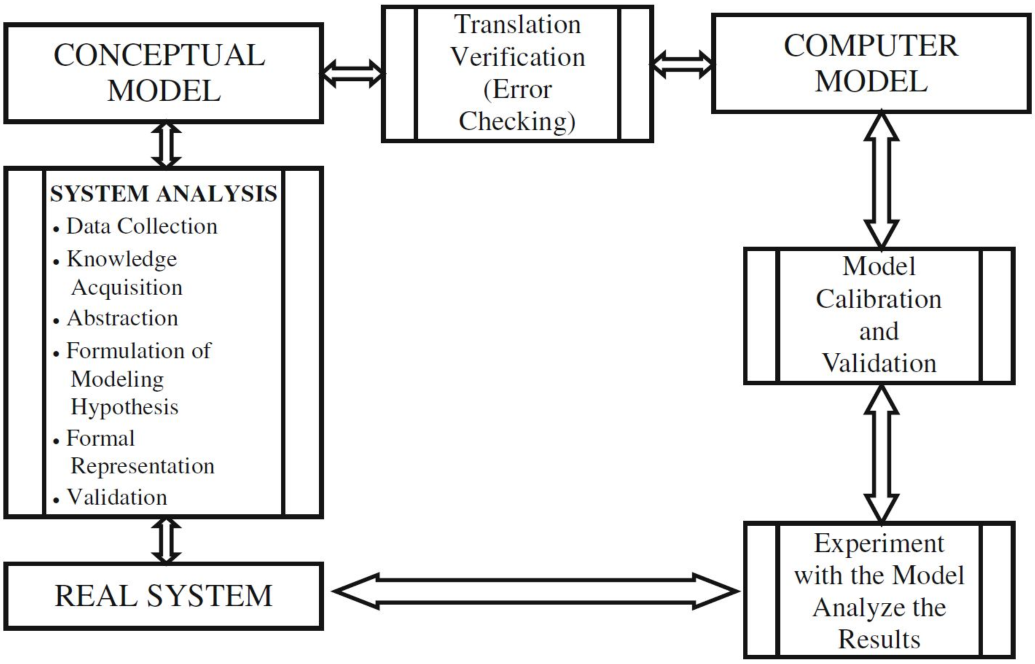

Figure 3.1: Methodological steps of the model-building process (Barcelo, 2011)

This research aims to create a modeled representation of an bicycle transportation network. As described in the problem statement, the scale and complexity of the system do not easily allow a study on the relationship between input variables and output variables of a bicycle network. With the help of an Agent Based model, a device can be created that is able to predict possible output variables, under varying input variables, without using the actual bicycle transportation network. (Barcelo, 2011; Daellenbach, 1995). Figure 3.1 describes methodological steps of a model-buildings process for complex systems by Barcelo (2011).

A System Analysis is the first phase of the model proposed by Barcelo. The main goal of a system analysis is gathering information on the network, allowing the first abstraction of reality and resulting in the conceptual model of the bicycle network or, to follow the definition by Barcelo, a 'real system'. In this research, the method of Barcelo is followed, combined with aspects of methodology by Daellenbach as cited by Barcelo. In this chapter, the bicycle network of Amsterdam will be referred to as 'the real system'

To conceptualize a real system, the real system must be described in a system description. In this knowledge acquisition phase, the cyclist network in the city of Amsterdam is described according to the following specifications (Barcelo, 2011):

1. Activities of the system
2. Boundaries of the system
3. Components, subsystems and stable relationships between components, subsystems or the system
4. External inputs
5. Outputs

At the end of chapter 3.2, the modeling assumptions are formulated, describing the expected workings of the system. The assumptions are supported by the interactions and relationships between separate parts of the model, as described in the system description

The model that is described after these steps, is what Barcelo refers to as the 'conceptual model'. Although based on the network of Amsterdam, this network does not (yet) have input or output variables, it merely describes the concepts derived from the bicycle network. In chapter 3.3, the case study application is described, defining the applicable input variables and desired outputs of the conceptual model. A true-to-life representation of an average day in Amsterdam is created, by defining the number of cyclists on the network on a given time, their origins and their destinations based on collected census data.

A conceptual model and defined case study data are combined to create a simulation model in chapter 3.4, which is created in the GAMA platform. The platform, its workings and the performed experiments are explained, as well as input variables and expected output.

At the end of chapter 3, the bicycle network is conceptualized, applied to a case study, defined in a computer model, validated and prepared for the described experiment, allowing analysis of the results in chapter 4.

3.2 System Analysis

In this subchapter, the main components, characteristics and systems that form the bicycle network of Amsterdam are discussed. An abstract representation of the bicycle network is created by describing five main elements defined by Barcelo,

3.2.1 Activities and boundaries of the system

A bicycle network system has one main activity, as it facilitates the movement of users and goods from origin to destination, on an infrastructure that is available to cyclists. (Amsterdam, 2017a) Cyclists access the network at a starting time, on a start location, define an optimum route according to their preferences, and exit the network when arrived at the desired destination. Whilst the user is moving across the network, the system supplies information to the cyclist on the varying factors of the chosen routes, such as distance, surface resistance, but also the safety situation with signs, physical separations or road markings. The cyclist receives information by scanning their surroundings for other users and preferred infrastructure that could influence the suitability of the selected path from origin to destination.

The system described in the conceptual model will be limited to the bicycle network in the Centrum district of the city of Amsterdam. Centrum has an inflow and outflow of bicycle users from the other city districts like Oost, West and Zuid. Furthermore, the Central Station is the goal of many bicycle users. Next to internal users, the bicycle is also used as the final part of a journey towards Amsterdam with public transport. (Mobiliteitsbeleid, 2017).

3.2.2 Components and relationships

Network

Users move from origin to destination by using the bicycle transportation network, as is the case in Amsterdam. The bicycle network is the network of streets, roads and paths that legally allow the presence of cyclists, as defined in the Dutch road laws. In contrast to other cities and countries, the use of the sidewalk is not allowed. Furthermore, the bicycle can not be used on mixed traffic category roads with a speed above 50 km/h, in which case a separate(d) bicycle path or lane is mandatory. Highways and inter-local roads are non-accessible to cyclists for the same reason. (Schepers et al., 2017) All segments are connected to the network, and are accessible from all parts of the network. As mentioned in the chapter 3.2.1, the network is limited to the Centrum district. A network consists of road segments, which have a level of safety related to the layout of the infrastructure. Presence of other traffic categories, separation from other traffic and general classification of the road define the level of safety of a segment.

Cyclists

In the real system, a variety of cyclists can be identified, on a variety of motives or reasons. In this system, cyclists are classified on their motivation to use the bicycle. In national and local reports, four categories are named in modal split research, defining the motive categories for the use of a given transportation method. Work and business related, education, shopping and recreation are defined as the main motives for using a method of transportation (Amsterdam, 2017b; Mobiliteitsbeleid, 2017).

The work and business and education category share a common characteristic, as these have a defined 'end-time'. Their main goal is to use the network in such a fashion that it produces the fastest route to the destination. Starting times and return times vary per user, but the overall characteristic is the utilitarian motive. Considering this motive, this category has a higher speed whilst moving and aims to find the shortest and fastest path. The routing process is assumed to be influenced by a constant trade-off between the shortest route, the safest route and the calmest route, as indicated in chapter 2.2.

The shopping category is present throughout the day, has a less restricted start time, can end at a given time and arrives within opening hours of commercial venues. Start and end of movements is distributed across the day. The main goal is the shortest path to the desired destination, but at a lower speed, as the need to reach departure deadlines is lower than that of the work and business category. The routing decision process is assumed to be influenced by the distance, safety situation and presence of other cyclists.

The recreational category is one that is less easy to define for the city of Amsterdam, when focused on residents. Reports show that recreational cyclists tend to exit the city, and cover greater distances outside the urban network (Amsterdam, 2015a). The tourist is therefor defined as the recreational group. This group is characterized by renting bicycles from rental locations, use these to visit touristic locations, and return to the original point of rental. As the goal is to discover and enjoy the surroundings in the city of Amsterdam, their speed is considerably lower than the business category or the shopping category, whilst also aiming for a shortest path from destination to destination.

Origins and Destinations

The origin of a cyclist is defined by the category it belongs to. In this system, it is assumed that a cyclist from the work category starts at a residential adress, or comes from outside the Centrum district. On average, work oriented cyclists cycle a distance of 4 kilometers, which results in an origin within the Centrum district, the Centraal Station, or one of the surroundings districts. (Amsterdam, 2017b).

An education oriented cyclist also originates from residential addresses in district Centrum, the surrounding districts or the Centraal Station, as the average distance covered per trip is at 4 kilometers.

A shopping cyclist only originates from a residential address within district Centrum, as the modal split shows that a destination outside a radius of 2 kilometers is often traveled with public transport or the car. (Amsterdam, 2017b) A recreational cyclist originates from a rental location in the Centrum district, as this category does not own a bicycle when visiting the city of Amsterdam.

Destinations of these cyclists are defined by their assigned motives for travel, and vary throughout the categories. A work or education category cyclist has a destination at a business or education location in the Centrum district, in the surrounding districts or the Centraal Station, roughly within a 4 kilometer radius of the cyclists origin.
A shopping cyclist moves towards a commercial location within the Centrum district, as the average distance covered is measured at 2 kilometers, and does not exit this

district.(Amsterdam, 2017b)
The recreational cyclist is bounded not by the actual distance, but a time budget. The tourist has an option to visit a number of attractions, until the rental time budget is spent, or if the tourist decides it had seen enough locations in the Centrum district.

Relationships

The main goal of this model is to predict the possible outcomes of the system, which can not be performed with the four identified main components. To calculate the output, the interactions between the four main components have to be defined, as these interactions define the behavior of the components, and therefor the outcome of the model. Each component, the influence of other system components on said component and influence of said component on other system components is discussed.

First, the work/business and education cyclist, influenced by origin and destination, and the network component. The shortest path is defined by the origin and the destination, combined with the influence of the network safety class. Furthermore, this cyclist is influenced by the presence of other users on the road segments, as the presence of other users can have an influence on the attractiveness of a segment.(Amsterdam, 2011) The work/business and educational cyclist influences the road network, as their presence adds weight to road segments.

The shopping cyclist is influenced by the origin and the destination, as it defines the path it will follow. It is assumed that the shopping cyclist, as it is also a utilitarian cyclist, chooses the shortest path, with a trade-off in safety class and user presence comparable to the business and education oriented cyclist. The shopping cyclist influences the network with its presence, which is translated to added weight for a network segment.

The tourist cyclist is influenced by the origin, possible destinations and the available time. The cyclist chooses the shortest path to the selected location of interest, selects a new location of interest and continues to do so until the end of the rental period is reached. As the main goal of the tourist cyclist is recreational, it is assumed that safety class and presence of other users does not influence the tourist cyclist. When the rental period has ended, the tourist cyclist returns to the original rental location. The presence of the tourist cyclist influences other types of cyclists with the presence on network segments, with an added weight per network segment.

The network influences all cyclists, as it determines the physical distance between origin and destination via the road network. All segments of the network have a physical geometry, which influences the shortest path routing mechanism of all cyclists. Furthermore, the segments are classified to safety levels, resulting in additional weight depending on the type of cyclist. Segments of the network are also influenced by other components, the cyclists, as the presence of cyclists on the network results in an added weight factor, resulting in a variable attractiveness for the business, educational and shopping cyclist.

3.2.3 External inputs & system output

As defined in chapter 2, based on the related research, the main influential parameters for this research were determined to be distance, road safety class and the number of other users on the network, or hereafter: occupation. It is assumed that the defined external inputs influence the number and type of cyclists on the network, as well as their routing mechanism.(Schepers et al., 2017; Dia, 2002; Dill and Gliebe, 2008)

This research focuses on the influence of cyclist routing behavior on the network load, therefor distribution of cyclists across the segments or parts of the road network forms the desired output. Desired output is therefor defined as: the total number of cyclists that have crossed a segment of the network, within a pre-defined time interval.

3.2.4 Modeling assumptions

A model is created to represent the complex system that is the bicycle network of Amsterdam Centrum, based on the system analysis and system definition. The following assumptions, based on the system analysis, support the abstract representation of the bicycle network.

- The system consists of a network, cyclists, origins and destination.
- The network only consists of road segments accessible to cyclists, with a predefined safety class based on available cyclist infrastructure.
- Cyclists are divided in categories, based on the transportation motive. This category influences origin, destination, speed, start time, end time and preferences in weight factors.

- The cyclist path algorithm is sensitive to three factors; the physical distance, the safety class and the number of cyclists on a segment.

- Cyclists in the model move from origin to destination at the start time, and move from destination to origin at the end time. Between and after these movements, the cyclists remain stationary.

- Input variables are defined as the number of cyclists per category, origin, destination, and the sensitivity of the cyclist path algorithm

- Output of the model is defined as: The number of users that passed a network segment, registered per segment, within the desired period of time.

3.3 Case study Amsterdam

The Amsterdam bicycle network is complex, as explained in the introduction and problem statement of this research. Although the bicycle is one of the most popular forms of transportation, the information on cyclists is limited. To test the conceptual model that is described in chapter 3.1 and chapter 3.2, an implementation is created for the bicycle transportation network of Amsterdam. The four main elements of the model (network, cyclist, origin, destination) require inputs, which can not be based on actual measurements or observations, as these do not exist. To examine the influence of road safety classes and user presence on network load, these four factors are set to baseline values. In this case study, an average day in Amsterdam is assumed, to create a baseline for the number of cyclists, their origin and destination, and starting times.

3.3.1 Amsterdam bicycle network

The first phase defines the bicycle network in the Centrum district. In this network, the roads are incorporated where a cyclist is legally allowed to ride. Two network datasets are combined to create a map of all infrastructure available to cyclists. The resulting network is then classified according to the available cyclist infrastructure.

Resources

Two input datasets are used for the creation of the road network, the road network for the City of Amsterdam, and the bicycle route network for the city of Amsterdam.

Both datasets were obtained from the City Data portal by the City of Amsterdam. The original road network is a clip from the Open Street Map database, to which the specific bicycle infrastructure has been added by the Research, Information and Statistics department of the municipality of Amsterdam (OIS). After the creation of the bicycle networks on this OSM based network, the network has been placed back in Open Street Map as additional information for the applicable road segments. The road network dataset contains information on all road segments, but does not contain information on separate bicycle lanes or bicycle segments on the regular road network. The bicycle network dataset consists of all infrastructure dedicated to solely support cyclists, including bicycle segments on the road network. A join of the two datasets is performed to create a single network of all road segments accessible to cyclists in the Centrum district of Amsterdam.

Preprocessing

The first step in preprocessing is the joining of the two spatial datasets. Both datasets contain an Open street Map specific ID (OSM ID) attribute, uniquely identifying the segments in each dataset. In QGIS, the bicycle dataset is joined with the road network dataset, with the latter forming the base layer. Double segments are dissolved into single elements, whilst additional bicycle path segments are added to the road network dataset. Result is a road network for the city of Amsterdam, with added bicycle infrastructure segments and additional bicycle network information for existing segments.
As only the road network for the Centrum district is required for this model, the road network is clipped with a spatial representation of the Centrum district.

Result is a network for the Centrum district, with an attribute table that contains extensive information on each segment. The first selection removes all road segments that are not legally accessible to cyclists, which in this case are highways, footpaths and other pedestrian paths.

Classification

After the preprocessing phase, the road network has a physical length, but has no additional classification. A further classification is performed to indicate the road safety class of each segment, resulting in a weight factor in the later steps of the model. This classification is based on a research by Broach et al. 2011, and is expressed in the following table:

Road class (OSM derived)	Safety class
Secondary w/o bicycle lane	1
Secondary with bicycle lane	2
Tertiary, residential w/o bicycle lane	2
Tertiary, residential with bicycle lane	3
Bicycle lane (non-separated)	4
Bicycle lane (separated)	5

Table 3.1: Segment classification road and bicycle network

Bicycle paths

Network segments are classified based on their safety situation, on a scale from 1 to 5, hereby following the findings by Broach et al. (2011). Cyclists showed a preference for separated infrastructure, followed by other bicycle infrastructure. A separate bicycle path is a path that does not interact with other road users and does not cross other roads. In this case study, a separate bicycle path receives the highest road safety class (class 5). A non-separate bicycle path receives the road safety class 4, as it is comparable to a fully separate path, but has some crossings or other interactions with other road users.

Bicycle lanes

The network contains a number of secondary and tertiary roads, in which the cyclist shares the road segment space with higher volumes of traffic. A number of secondary and tertiary segments have marked bicycle segments, aimed at cyclists, but can be crossed by other road users if there is no cyclist present. Although a physical separation is absent, the reserved space increases the level of safety for the cyclist when using these shared road segments. (Schepers et al., 2017) To reflect this impact, the secondary and tertiary roads are divided in four classes, based on the presence of bicycle lanes.

Mixed traffic

Secondary and tertiary roads without bicycle lanes are awarded class 1 and 2. A secondary road with a bicycle lane is seen as equal to a tertiary road, raising the safety class to level 2. A tertiary road with a bicycle lane is rewarded safety class 3, as it is deemed safer than a regular tertiary road, but not as safe as a bicycle lane in class 4.

The classes are assigned to the segments based on the OSM "HIGHWAY CODE" classification and the presence of bicycle infrastructure, derived from the bicycle network dataset. The classification is added to the attribute table of the network dataset with the field calculator in the QGIS software platform.

Cleaning

After joining, clipping and classifying, the network that is created has a number of unnecessary or doubled attributes, as well as spatial irregularities. The dataset is therefor cleaned of all that is unnecessary for this case study, resulting in a attribute table with OSM ID, a highway class and a road safety class. From a spatial perspective, the presence of secondary roads and bicycle paths forms a challenge. Based on the work by Schepers et al. 2017, it is safe to assume that it is highly unlikely a cyclist is allowed to use a secondary road if a mandatory bicycle path is situated alongside the road. Secondary road segments with an accompanying bicycle path are therefor removed, as these are not accessible to cyclists in the bicycle network. After removal, the connections between the bicycle path and other road segments are checked and corrected. All segments with the highway class "unclassified" are also manually classified and, if not accessible to cyclists, removed from the network.

Preprocessing results

The resulting dataset is a representation of the bicycle network in the Centrum district of Amsterdam. The dataset is a shape file, containing the roads that are legally accessible to cyclists, which attributes are summarized in table 3.2.

Attribute	Type
OSM_ID	Integer
Highway Code	Integer
Length	Float
Road safety class	Integer

Table 3.2: Attributes of the created bicycle network dataset

3.3.2 Amsterdam bicycle users

In this chapter, the cyclists in the case study of Amsterdam are defined. The conceptual model defined four categories, characterized by motive. The number of cyclists per category is calculated from census data provided by the city of Amsterdam, which leads to a first alteration for the education cyclist. As the census data from the city of Amsterdam does not allow valid assumptions on the number, the origin and the destination of the education oriented cyclist, it is therefor assumed that a part of the education cyclist population is represented in the work cyclist, and a part in the shopping cyclist. This case study will therefor define three cyclist categories: the work cyclist, the shopping cyclist and the tourist cyclist.

Work cyclists

On January 1st, 2017, the city of Amsterdam had 835.000 citizens, of which 426.000 are employed. Among these employed citizens, 119.000 citizens work outside Amsterdam and 307.000 work in Amsterdam. It is assumed that 28% of the employed citizens works outside Amsterdam, against 72% that is employed in the city of Amsterdam. The city of Amsterdam offers 527.000 employment positions, of which 271.000 are filled by employees from outside the city of Amsterdam, or 51%. The other 49%, or 256.000 positions, are filled by employees residing in Amsterdam. (Amsterdam, 2017b; Amsterdam, 2018; Amsterdam, 2015a; Mobiliteitsbeleid, 2017) The census data does not provide specific ratios on internal and external employment for the Centrum district citizens, nor the origins of workers in the Centrum District. The general percentages on employment and supply are therefor assumed to be suitable for the Centrum district.

The Centrum district has 103.000 employment positions, which are assumed to all be fulfilled on a daily basis. Based on the census data, 49% of the workers originates from a location within Amsterdam, and 51% originates resides outside the city of Amsterdam. These percentages translate to 50.470 employees that reside within Amsterdam, and 53.230 that reside within Amsterdam. First, the number of work cyclists that lives in Amsterdam and works in Centrum is calculated, followed by the number of cyclists that arrive from outside Amsterdam to work in the Centrum district. Last, the number of cyclists that lives in the Centrum district and works outside Amsterdam is calculated. (Amsterdam, 2018)

Workers residing within Amsterdam

The census data states that in the Centrum, West, Oost and Zuid district, the bicycle has a share of 50% in the daily home-to-work commute. Based on this percentage, roughly 25.235 cyclists arrive from a residential address in Amsterdam to work in the Centrum.

According to the census data, the Centrum district welcomes 25.235 work cyclists from anywhere in Amsterdam. With an average work cycling distance of 5 kilometers in Amsterdam, not all work cyclists necessarily originate from the Centrum district, as this distance could allow cyclists to start their journey in the surrounding districts of West, Oost and Zuid. To replicate this possibility in the case study, it is assumed that the district Centrum, West, Oost and Zuid provide shares of workers to the other districts. Table 3.4 expresses the share per district in their combined working population. The origin of these work cyclists, calculated with their share in the working population, is found in the fourth column of the table.

District	Working Population	Share (%)	Cyclists origin
Centrum	45.800	16	4.169
West	79.800	28,7	7.260
Zuid	74.600	26,9	6.788
Oost	77.100	27.8	7.107
Total	277.300	100.0	25.235

Table 3.3: Working population (share) for each city district, translated to amount of working cyclists originating from each district.

If assumed that these four districts have traveling cyclists between them, the Centrum district has working cyclists that move from a location in Centrum to one of the surrounding districts as well. Under the same distribution, this means that the Centrum district supplies the same 16% of the working population in West, Zuid and Oost, of which 50% travels by bicycle. Result is that 1.958 cyclists origin from Centrum to work in West, 4.270 work in Zuid and 2.549 in Oost, creating a total of 8.777 cyclists moving from Centrum to surrounding districts.

Workers residing outside Amsterdam

The second group is the group that resides outside Amsterdam, but travels to the workplace in Centrum by bicycle. According to the census data, 36% of daily commuters uses the railway system to reach the city of Amsterdam, of which 50% arrives at Amsterdam Centraal Station. For most travelers, the station is not their final destination. An estimation made in the Mobiliteitsbeeld policy document 2017 assumes that 20% of these travelers uses the bicycle to reach their final destination, resulting in roughly 7.700 cyclists that travel from the Centraal Station to their final destination in Amsterdam. As the average distance covered by bike in Amsterdam is 4 to 5 kilometers, it is assumed that the Centrum district is the final destination of these cyclists.

Workers residing in Centrum, working outside Amsterdam

Third, the number of workers that lives in the Centrum but works outside Amsterdam is calculated. Assuming that 28% of the 45.800 employed residents works outside Amsterdam, 12.824 citizens will travel to a destination outside Amsterdam to work each day, of which 36% will use the Centraal Station to travel by train to their work destination. 55% of these commuters uses a bicycle to reach the Centraal Station, resulting in 2.539 cyclists from the Centrum district. (Mobiliteitsbeleid, 2017; Amsterdam, 2018)

Work cyclist definition The total number of arriving work cyclists in Centrum consists of the work cyclists originating from Amsterdam, combined with the work cyclists arriving at the Centraal Station, which creates a total of approximately 33.000 cyclists. The total number of departing work cyclists from Centrum consists of the work cyclists that work outside the district and the work cyclists that work outside Amsterdam, creating a total of approximately 11.316 cyclists. Result is a work cyclist population, moving either in or out of the Centrum district, that consists of approximately 44500 cyclists.

Arriving / Departing	Origin	Destination	Amount
Arriving	Amsterdam	Centrum	25.235
Arriving	Outside Amsterdam	Centrum	7.700
Departing	Centrum	Outside Amsterdam	2.539
Departing	Centrum	Amsterdam	8.777

Table 3.4: Specification of the arriving and departing work cyclists in district Centrum

Shopping cyclists

The Centrum district has 86.500 citizens, of which 74.784 are part of the working population. 45.800 of the working population is employed, leaving 28.984 citizens that do not work. As they are not at a place of employment during daytime hours, it is assumed that they are part of the shopping cyclist group. For this case study, a conservative estimate is made on their daily movements, set at 1 trip per day. Following the same trend as the work cyclist, 50% of the trips by shopping cyclists is performed with a bicycle, resulting in 14.492 shopping cyclists on a daily basis.

Tourist cyclists

The number of tourist cyclists is difficult to define. According to census data, 7,3 million tourists visit Amsterdam per year, translating to 20.000 tourists in Amsterdam on a daily basis. The bicycle is used by 10% of tourists to explore Amsterdam, and with the main attractions located in the Centrum district, it is assumed that this is the number of tourist cyclists on an average day in Centrum. Although the tourist is often named as a disturbing factor in Amsterdam, it is not included as an input variable in this case study. The presence of the tourist cyclist, combined with a low speed, is used to represent the potential disturbance. Increasing or decreasing the number of tourist cyclists could influence the results, but can not be sufficiently supported from the census data at the time of this research (March 2018).

Summary

Based on the census data and motivated assumptions, this case study will simulate the presence of approximately 60.000 cyclists in the Centrum district. These numbers are, within the possibilities of the provided census data, an as accurate as possible assumption on the amount of cyclists on an average day in Amsterdam. Summarizing, the number of cyclists will be defined as:

- 45.800 work cyclists are simulated in this case study, arriving or departing in Centrum.

- 14.500 shopping cyclists are simulated in this case study, moving within Centrum.

- 2.000 tourist cyclists are simulated in this case study, moving within Centrum.

3.3.3 Origin & Destination

Each cyclist in the defined 3 cyclist groups has an unique origin and a destination, which cyclists travel from and to whilst the simulation is running. Cyclists do not start their daily journeys at the same location, but start their journey on varying locations, based on their category. In this sub chapter, the possible origins and destination are discussed per cyclist category.

Work cyclist

A work cyclist can have two possible origins /destinations, which are a residential address and an employment address, located in the Centrum district, within Amsterdam or outside Amsterdam.

Residential address in Centrum
Residential addresses are defined according to population distribution of the Centrum district. The district has 10 neighborhoods, which each house a share of the total population. The number of work cyclists is divided between the neighborhoods according to the population share. To simulate the distribution within a neighborhood, a random location in a neighborhood is assigned to the defined number of work cyclists.

Employment address in Centrum
Employment addresses are simulated by distributing the arriving work cyclists across the 10 neighborhoods of the Centrum district. Employment locations are distributed according to the number of jobs available per neighborhood. The final location is defined by an equal randomized spatial distribution of the destinations across the neighborhoods.

Employment/residential address outside Centrum
The city districts of West, Oost and Zuid are not added to the network due to the added complexity. To simulate their arrival from other districts, or the arrival from Centrum in other districts, the locations where main bicycle arteries cross the Centrum district border are defined as the origin or destination of these cyclists. To simulate the real system, West has 2 locations, Zuid has 3 locations and Oost has 2 locations. The total number of cyclists per district is equally distributed between the origin and destination locations of a district.

Employment/residential address outside Amsterdam
Centraal Station, the main train station, has two main locations for the parking and storing of bicycles. In this case study, the travelers arriving at Centraal Station, or departing from Centraal Station, depart from or arrive at these two locations as their origin or destination.

Shopping cyclist

Origin
Shopping cyclists start their journey to a shopping location from a residential location in Amsterdam. The share of shopping cyclists in each neighborhood is defined by the share of residents per neighborhood. Origin location are equally distributed across within the neighborhood.

Destination
The destination of a shopping cyclist is a shopping location. The district Centrum has numerous shops, which are divided between the neighborhoods. The share of each neighborhood defines the number of shopping cyclist destinations, which are randomly distributed across the neighborhood.

Tourist cyclist

Origin
The tourist cyclist group starts at one of the rental locations. In this case study, 6 locations from various suppliers were selected, the flexible bike-sharing apps and other initiatives have not been included. Although market shares of these suppliers might vary, it is assumed that these 6 rental locations contribute equally to the 2.000 tourist cyclists on an average day in Amsterdam. Figure 3.2 shows the determined locations with pink dots.

Destination
The destination of a tourist cyclist is different to that of a work or shopping cyclist, and is randomly selected from a list of 12 main touristic attractions, as found in table 3.5 and in Figure 3.2 with green dots . After the arrival of the tourist at the touristic location, the tourist randomly selects another touristic attraction, to approach the unpredictable behavior of the tourist cyclist. If the tourist has reached the limit of his rental period, or if the tourist has visited 6 touristic locations, it returns to the original rental location.

No.	Tourist attraction
1	Wallen
2	Westertoren
3	Amsterdam Centraal
4	de Dam
5	Begijnhof
6	Artis
7	Anne Frank Huis
8	Dungeons
9	Rijksmuseum
10	Heineken Experience
11	Magere Brug
12	Rembrandtplein

Table 3.5: Selected touristic attractions for tourist cyclists in Amsterdam

Figure 3.2: Locations of bike-rental companies (Pink) and touristic attractions(Green) in Amsterdam

3.3.4 Start time & Return time

Work & shopping cyclist

The start time for a work or shopping cyclist is defined as the time when these cyclist starts to move from origin to destination. In the case study, the start time of the work cyclist and the shopping cyclist is defined by drawing a cyclist distribution shown in the "Meerjarenplan Fiets 2017 - 2022" 2017, shown in Figure 3.2. The third section from the bottom indicates the number of cyclists on the network during the time periods indicated on the X-axis. In this case study, it is assumed that all work cyclists start before 13:00, and return after 13:00. The start time is distributed according to the share per time period before 13:00, the return time is distributed according to the share per time period after 13:00. For each agent, the definitive start time is created by taking the start hour (i.e. 10:00), to which a random amount of minutes between 0 and 60 is added, in steps of 5 minutes. The same process is performed for the return time, with the same randomized added number of minutes. The result is a spread in the start and return times that approaches the distribution of the number of cyclists as close as possible.

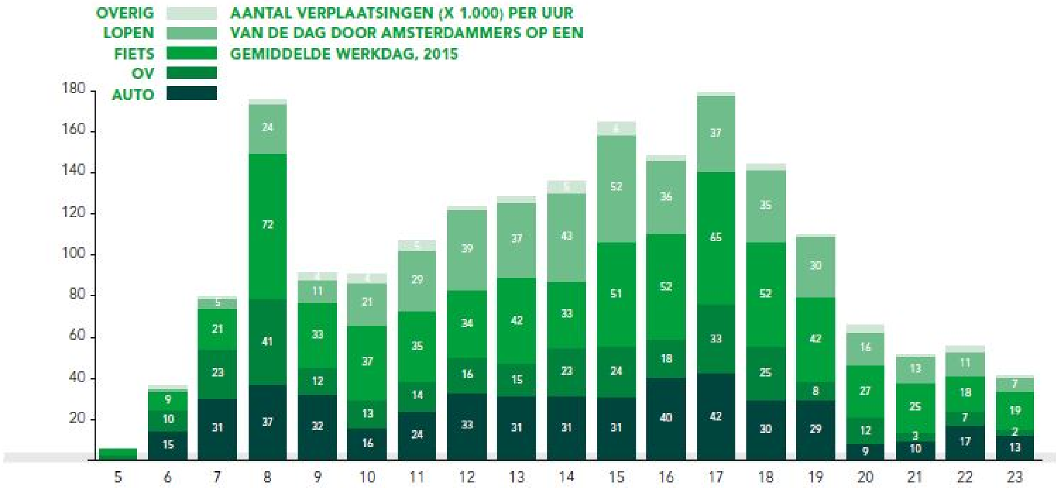

Figure 3.3: Distribution of the number of movements on the Amsterdam road network (Amsterdam, 2017a)

Tourist cyclist

The start time of the tourist cyclist is randomly selected between 09:00 and 13:00, in steps of 10 minutes. The same method is followed for the return time, which is defined as a random selected time between 13:00 and 18:00, also in steps of 10 minutes. As with the number of tourists, the precise distribution of tourists during the day could not be sufficiently deducted from available census data. It is therefor assumed that the tourist cyclist is active between 09:00 and 18:00, the common shop opening hours in Amsterdam.

3.4 Model simulation

The previous sections are a description of the case study in the Centrum district, which has created a number of partial products. A network representation, specifically for cyclists, with a road safety class has been created. Three categories of cyclists have been defined, including their respective quantities, origin, location, start time and return time. In the diagram by Barcelo (figure 3.1), the following phase is defined as the computer model. The conceptual model and case study are joined and translated to a create a simulation model, able to calculate outputs for the defined input variables.

To allow exploration of the case study within the context of the conceptual model, a simulation model is created. Multiple software packages are able to create Agent

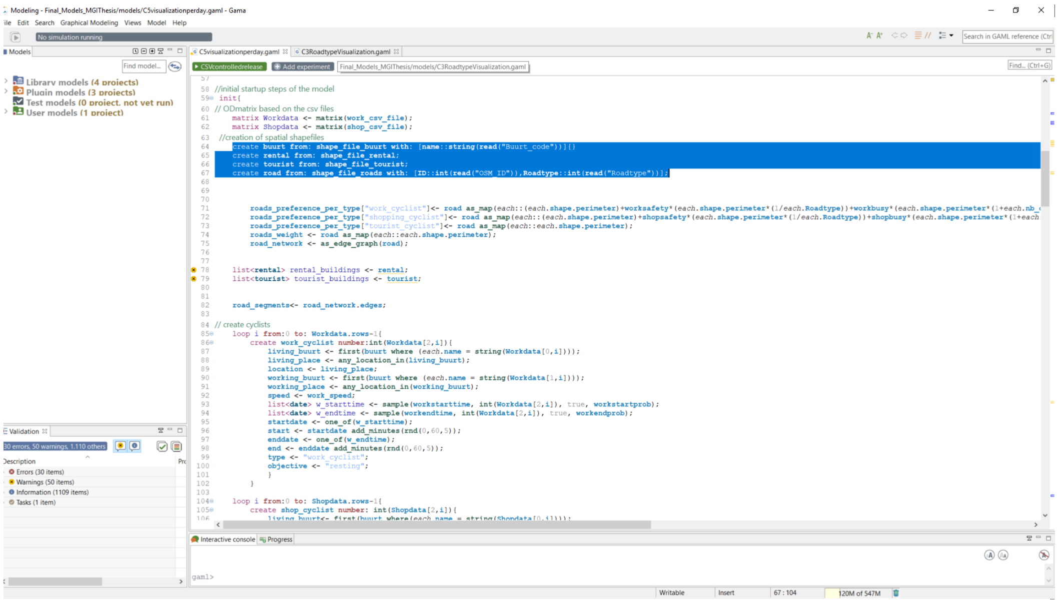

Figure 3.4: Overview of the GAMA platform GUI, showing the simulation script, model parameters and the console

Based Model (ABM) simulations, but only a few are able to handle spatially expressed ABM simulations. For this research, the open source platform GAMA is used to develop this simulation. The GAMA platform is based on the Eclipse software package, and is fully customizable for each desired application. Furthermore, GAMA is able to handle shape file input, create spatially referenced output files and numerous 2D and 3D visualization options. In the GAMA platform, a simulation of an average day in Amsterdam is created. Figure 3.2 showed a distribution of the number of cyclists on the network in Amsterdam, between 05:00 and 24:00/0:00. The timescale of this simulation is therefor set between 5:00 and 0:00, as the available data is only offered for this period. Due to the size of the simulation, the output update frequency is set at 5 minutes in 'model time', so 1 model cycle translates to 5 minutes in the simulated time period. In total, the simulation will run 228 model cycles.

Model Implementation

The precise workings and relations of the model are visualized in the Appendix XX. To improve readability and comprehension of this research phase, this subchapter continues with a summarized explanation of the model phases. In figure 3.3, the main phases of a GAMA simulation are visualized in a basic relational flowchart. These main phases are used to explain the inner workings of the GAMA model for this case study.
In chapter 3.3 the main input files have been created, which are a bicycle network

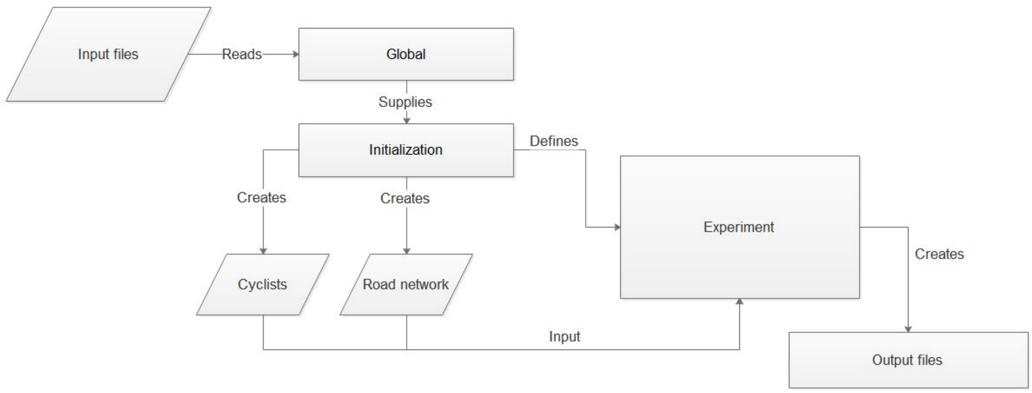

Figure 3.5: Rudimentary elements of the GAMA simulation model

shape file, a neighborhood shape file and two Comma Separated Value files for the distribution of the work and shopping cyclist according to the census data.

The global phase allows the model to read the input files and define the general variables of the simulation. Examples are the starting time, the time step per model cycle, the spatial extent and the end time of the simulation. The definition of the input files and variables is used in the initialization phase of the model.

Initialization
In the initialization phase, the main layout of the simulation is created. Within the GAMA model environment, the main elements are defined in so-called 'species', the proprietary term for agents in the GAMA environment. The shape file of the road network is used to create a road graph, the network that supports the route calculation and the movement of the cyclists. This road graph is stored as the specie "Road".
Separate cyclist categories are created as the separate species "Work cyclist", "Shopping cyclist" and "Tourist cyclist" The number, origin neighborhood and destination neighborhood of the work and shopping cyclists is defined, after which the definitive origin and destination location is randomly selected within the origin and destination neighborhood. Location is set to the origin location, and the cyclist specie is assigned a start time and return time based on the distribution described in figure 3.2. The tourist cyclist number, origin location and first destination location is randomly selected from the available locations. A start time and return time are defined according to the case study, after which the cyclist location is set to the origin location. The actions of the agents are defined within species, in an 'reflex'. The reflex describes conditional statements, which are re-checked each simulation step, defining the behavior of each agent during each simulation step.

After these two phases, the experiment is executed for the aforementioned 228 cycles. The execution of the model cycles, and therefor the increasing 'time of day', triggers the movement of cyclists species across the road graph specie, which is registered by the road network specie in the form of current positions and cumulative totals on each segment. In figure 3.3, 3.4 and 3.5 the process of a simulation step for a work/shopping cyclist, tourist cyclist and the road network is illustrated with a flowchart. Figure 3.3 displays the decision steps of a work or shopping cyclist during

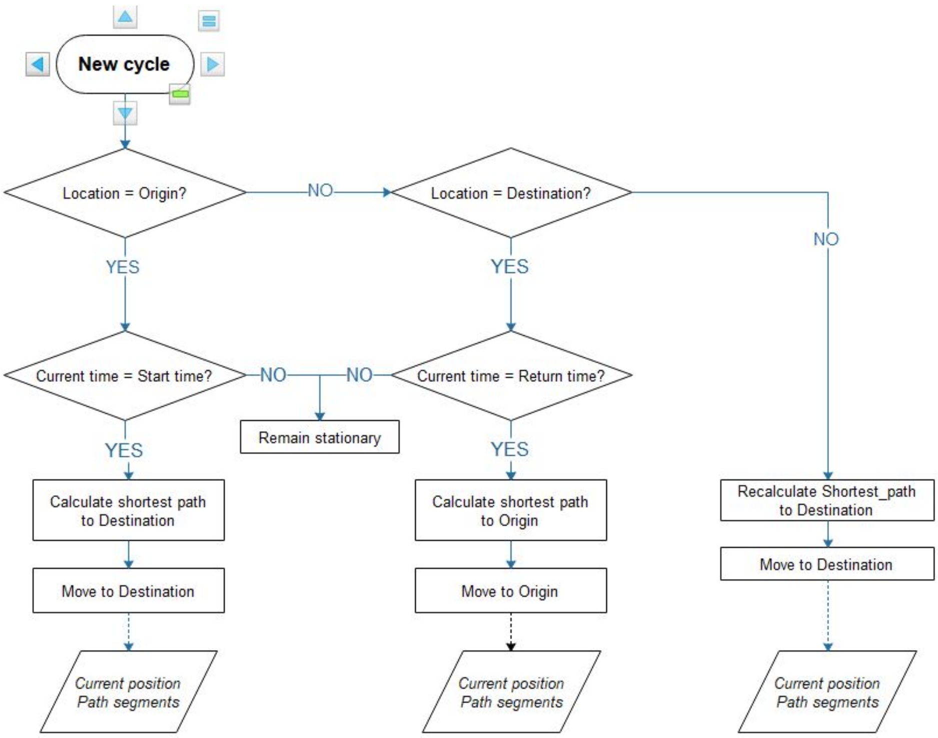

Figure 3.6: Decision process of a Work or Shopping cyclist during one model cycle

one model step. Important note: within the GAMA environment, 'location' is the precise position of an agent within the set environment. The 'current position' is the network segment an agent is on, when registered by the model.

If the location is origin or destination, and the current time is equal to the start or return time, the cyclist calculates the shortest path to the destination or origin, and starts moving.
If the location is origin or destination, but the current time is not equal to a start or return time, the cyclist remains stationary.
If the location is not origin or destination, the cyclist is considered to be moving in the network. In this case, the cyclist re-calculates the path, to account for the potentially changed network weights, and continues to the origin or destination.
After each model cycle, the current location of a cyclist, and the covered segments

between the current model step and the last model step are communicated to the road network. Figure 3.4 demonstrates the decision steps of a tourist cyclist during

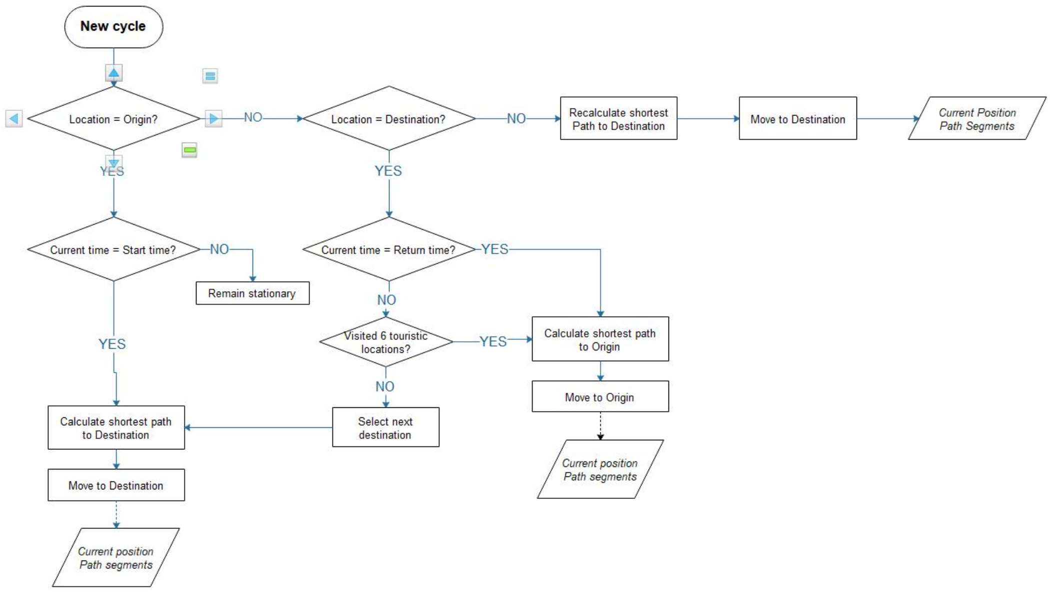

Figure 3.7: Decision process of a tourist cyclist during one model cycle

one model step.
If location is origin, and the current time is equal to start time, the cyclist calculates the shortest path and starts moving to a destination.
If location is destination, and the current time is not equal to return time, the tourist cyclist selects another destination, calculates the shortest path and starts moving to the next destination
If location is destination, and the current time is equal to return time, the tourist cyclist calculates the shortest path to origin, and starts moving to the origin location.
If location is neither origin or destination, and the current time is not equal to return time, the cyclist recalculates the shortest path to the chosen destination to account for the potentially changed network weights.
After each model step, the current location of a cyclist, and the covered segments since the last model cycle are communicated to the road network. Figure 3.5 visualizes the update process of the road network during one model cycle. At the beginning of each cycle, the road specie counts the number of agent species on each network segment. After this, the road network adds the used segments by each cyclist to a cumulative map, creating a total amount of cyclist that have crossed the segments. The updated road map is then used to influence the cyclist behavior.

Cyclist behavior

In section 3.2.4, the following assumption was made: A cyclist path algorithm is sensitive to three factors: Physical distance, safety class and the number of cyclists on

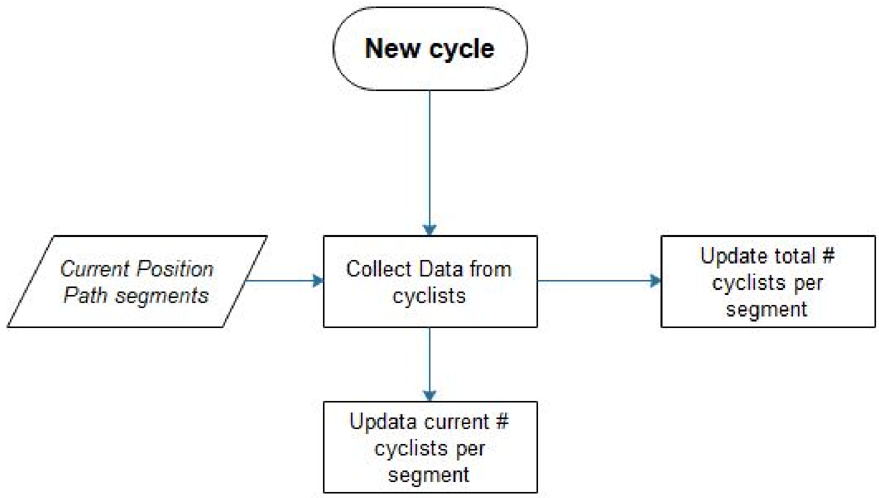

Figure 3.8: Update process of the road network during one model cycle

a segment. The cyclist response to these factors is defined in the GAMA simulation to simulate their influence.

If a cyclist is triggered to move, it calculates a shortest path across the road network to the destination, based on the segment length. To incorporate a road safety and occupation factor, a virtual road network is assigned to each cyclist category. On this virtual network, the length of each segment is increased according to the road safety class of each segment, and the current number of cyclists on each segment. This addition is performed with the following formula:

$$L_v = L_p + L_p * (1/R) + L_p * (1 + N_c) \tag{3.1}$$

Where L_v is the resulting segment length in the virtual network, and L_p is the perimeter or physical length value derived from the general road network. R is the road safety class integer, and N_c is the current number of users on the segment. This equation has been made on the assumption that, deduced from a number of test runs, the N_c rarely exceeds 10 cyclists. On specific segments, this creates a heavier influence, but as the road class value is static and omnipresent, the result is an almost equal influential factor to the static Road safety class factor.

The shortest path algorithm is now applied to the virtual weighted road network, producing a path. This resulting path is then applied to the actual road graph specie, and the cyclist starts moving according to this path, visualized in figure 3.7.

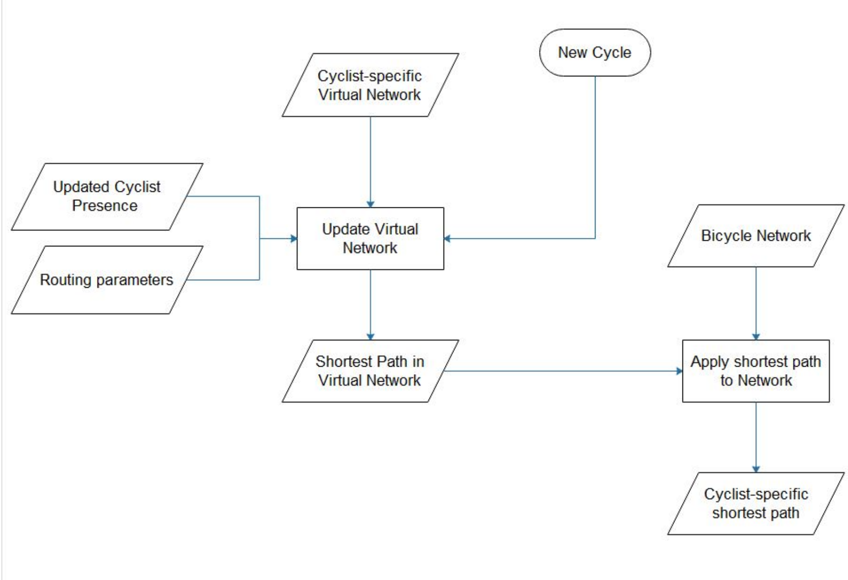

Figure 3.9: Diagram of the virtual network application, the update cycle and the application of the shortest path by the cyclist.

As defined in the road network update diagram, the number of cyclists on a network segment is updated each model cycle, which translates to an updated virtual map for each cyclist category. This mechanism simulates the influence of a changing network circumstance between two model cycles, and is a feedback loop towards the cyclists.

To facilitate the testing, activation and calibration of each variable, two parameters are introduced, named S (Safety) and B (Busy), which are placed in front of the main elements in the formula. These variables allow the model to be simulated with varying weights of road safety class and occupation of segments. In the simulation, the final expression is therefor stated as:

$$L_v = L_p + S * (L_p * (1/R)) + B * (L_p * (1 + N_c)) \tag{3.2}$$

Within the scope of this research, a tourist cyclist is not influenced by these factors. As the behavior of a tourist cyclist can not be rooted in related research, it is assumed to move from origin to destination via the shortest path. It moves at a lower speed to simulate a less-experienced cyclist in an unfamiliar environment, with a non-utilitarian movement motive.

Cyclist speed

It is assumed that the speed of a cyclist depends on the transportation motive.

Utilitarian cyclists like a work or shopping cyclist are expected to maintain a higher speed, which according to census data should be around 15 to 17 km/h, which is incorporated in the simulation. Tourist cyclists move with a lower speed of 10 km/h, to simulate the aforementioned non-experienced behavior. (Amsterdam, 2017a).

Simulation output

One of the attractive aspects of the GAMA platform is the flexibility in output files and formats. As an example, the aspects of species can be visualized for checking purposes, saved as text files or comma separated value files, but can be stored as shape files as well, including a projection and coordinate system.

The output of the simulation therefor depends on the nature of the experiment that is performed within the GAMA environment. In this research the spatial aspects is deemed important, which leads to a shape file output. The shape files that are created can be registrations for the full model execution, but can also be specified for a specific time slot. In all cases, the output is a shape file of the road network, containing the spatial extent of a segment, the OSM ID and the total number of cyclists that have been registered per segment, within the given period of time.

During the execution of the simulation, the model creates three main outputs to allow visual inspection. Figure 3.8 shows the current situation on the network, showing the network, the cyclists, their movement, the rental locations and the touristic locations. Figure 3.9 visualizes the current number of cyclists per road network segment, increasing the size of the segments with a growing number of cyclists on the segment. Figure 3.10 visualizes the total number of cyclists that has crossed the road segments, by increasing the size of the segments accordingly. These visual outputs are updated every model cycle, or every 5 minutes in model time. These outputs are merely displays, and are not stored unless the model is prompted to do so.

Figure 3.10: GAMA overview display. During simulation, cyclist agents are visible during their movements. Yellow dots represent bike rental locations, red dots represent touristic locations

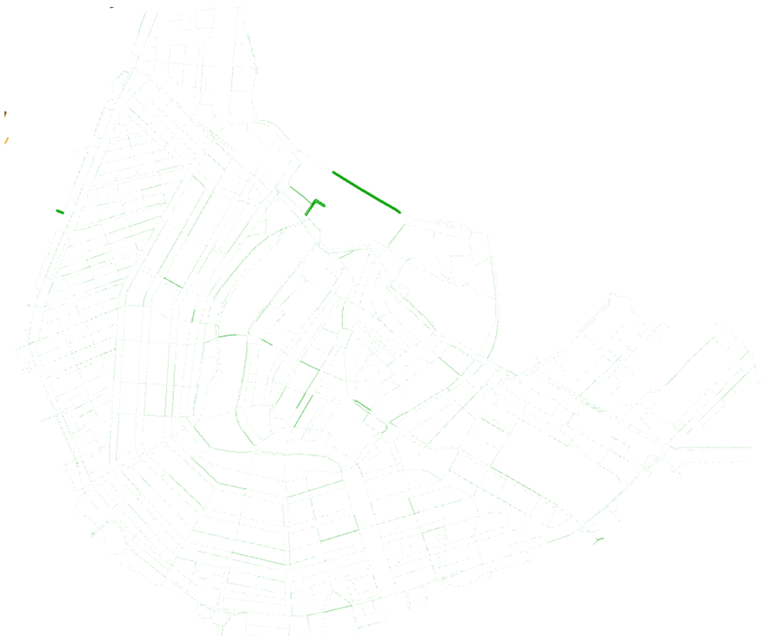

Figure 3.11: GAMA display, during simulation, of the current cyclist presence per segment. growing cyclist numbers increase width of segments.

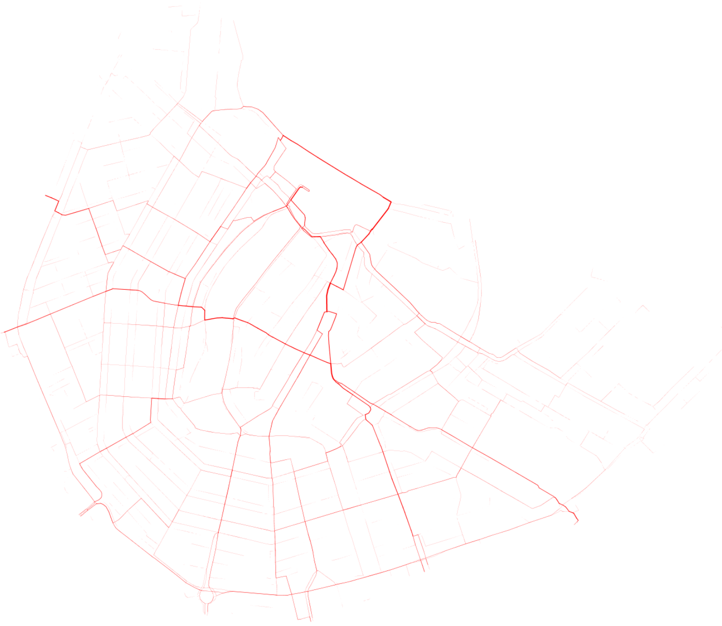

Figure 3.12: GAMA display, during simulation, total number of cyclists per segment. higher cyclist number increases segment width

For analysis purposes, the model is able to create Comma Separated Value (CSV) files, containing the OSM ID of each segment, and the total amount of cyclists per segment within a given time period. This time period can be adapted to the desired analysis requirements.

3.5 Experiments

To determine the influence of external variables on the routing behavior of cyclists in Amsterdam, an experiment is defined with the described GAMA simulation model.

3.5.1 Experiment time period

The distribution of cyclists on the network will be simulated during busy and calm moments on an average day in Amsterdam, to investigate the influence of road safety and occupation variables. According to the time distribution in figure 3.2 (page 32), the number of cyclists on the network reaches a peak between 08:00 and 09:00, when 72.000 cyclists are moving across the bicycle network in the entire city of Amsterdam. In this same distribution, the time between 14:00 and 15:00 stands out, as it is a time period where a very low amount of 33.000 cyclists move across the network.

During the experiment, the simulation will be executed for a full defined day (05:00 to 23:00, or 228 cycles), but the total number of cyclists is reset each whole hour. At 09:00 and 15:00, a shape file output is generated of the road network, containing the total number of cyclists per segment, between 08:00 and 09:00.

3.5.2 Locations

To evaluate the influence of the routing variables, 10 comparison locations have been defined to assess the possible difference in cyclist distribution under the varying network circumstances. Selecting these segments is done according to a first test run of the simulation. In this simulation, all variables were not active, creating a shape file output of a shortest path only distribution, at 09:00. 10 segments with a high presence of cyclists or a central position in Amsterdam were selected, as shown in Figure 3.7. Table 3.6 defines the locations with the OSM ID and street name.

OSM_ID	**Street name**
7370821	Plantage Middenlaan
7371095	Rokin
7371193	Damrak
7371206	Zeedijk
7371240	Oude Hoogstraat
7371585	Paleisstraat
7372003	Vijzelstraat
7373035	Raadhuisstraat
7376082	Singel
54630815	Jodenbreestraat

Table 3.6: 10 comparison locations in the Centrum district

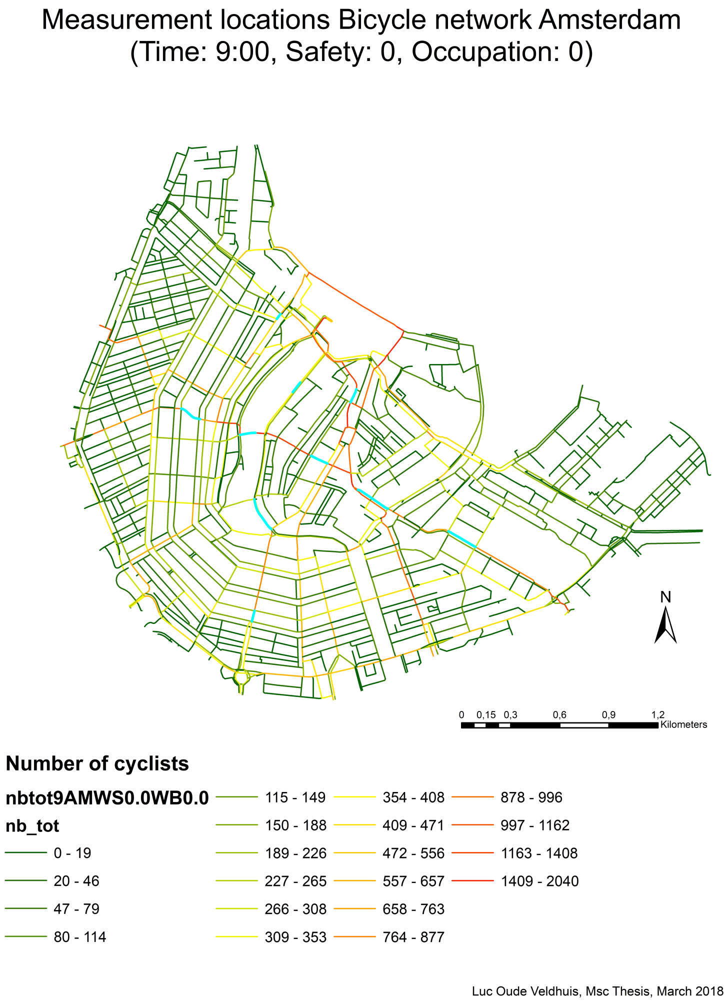

Figure 3.13: Location of measurement locations in Amsterdam, colored light-blue

3.5.3 Routing variables

To assess the influence of the routing variables on the distribution of cyclists across the network, the added values 'S' and 'B' are used to activate and amplify the routing variables. As a baseline scenario, the first simulation is performed with both values set at 0, translating to a situation where cyclists only select the shortest path to their destination. In the following simulations, the 'S' and 'B' values are set at 0, 1 or 2 to activate and amplify the influence of the road safety and occupation variables. Table XX summarizes the settings for these 4 simulations.

Simulation	'S' value	'B' value	Description
1	0	0	Baseline scenario, no variables activated
2	1	0	Road safety variable activated
3	0	1	Occupation variable activated
4	1	1	Both variables activated
5	2	2	Both variables amplified with factor 2.

Table 3.7: The specific settings of the 'B' and 'S' values in the 5 performed simulations

3.5.4 Output files

The result of these 5 simulations are 10 shapefiles, containing the number of cyclists on each segment at 09:00 and 14:00. Attributes of these shapefiles are the spatial extent of each segment, the OSM ID and the total number of cyclists on that segment. The spatial projection of this dataset during the model execution is set at EPSG:28992, or RD New, for compatibility purposes. GAMA can however create shape file outputs in any desired EPSG standard.

3.6 Summary

A conceptual model of the bicycle network in Amsterdam has been defined, based on the methodology proposed in the book "*Models, Traffic Models, Simulation and Traffic Simulation*", by Barcelo (2011). A system analysis identified the four main components of the bicycle network. Cyclist, network, origin and destination form the four main components, which influence each other according to the defined relationships. This conceptual model has been used as the basis for the case study.

The case study has been prepared for the bicycle network in Amsterdam, following the components and relationships identified in the conceptual model. The scope of the case study has been limited to the Centrum district of Amsterdam, allowing a better estimation on the in- and outgoing cyclist traffic. In the case study, the network has been created by combining two Open Street Maps datasets, resulting in a network which contains all infrastructure legally accessible to bicycles. In the case study simulation, it is assumed that cyclists make 1 round trip on a daily basis. Cyclist categories were defined as work cyclist, shopping cyclist and tourist cyclist. These categories define specific origin and destination locations for each cyclist type, based on the census data provided by the city of Amsterdam, as well as their specific routing behavior. Last, the departure and return times were specified, based on the network load distribution in the census data.

In the simulation model, the conceptual model and case study have been combined to create a simulation of the bicycle network. The GAMA platform has been introduced, as well as the main elements of the simulation model. Cyclists determine their path with a shortest path algorithm, whilst moving from origin to destination or vice-versa. Each cyclist uses a virtual network to calculate their type-specific shortest path. The features of this virtual network are equal to the normal network, but the segment lengths are influenced by the road safety class and the presence of other users, based on the cyclist category. The path resulting from this virtual network is then transferred to the real network, to simulate the influence of said parameters.
The simulation model is therefor able to simulate the behavior and interactions of cyclists on the bicycle network simultaneously, and register the total presence of all cyclists types within a predefined time period.
The influential routing parameters have been defined as 'S' (Road safety class) and 'B'(occupation). The resulting output has been defined as a shapefile, containing all network segments with the OSM ID and total number of cyclists within the given time slots, defined at 08:00-09:00 and 14:00-15:00.

Last, the experiments have been defined. The simulation model will be run in 5 different settings, each having a specific combination of the influential routing parameters. Resulting from these simulations are 10 shapefiles of the network, which are discussed in chapter 4.

Results

4

In this chapter a qualitative and quantitative analysis on the results of the defined experiments are presented. Furthermore, the relation between the model and the actual bicycle network in Amsterdam is discussed, to provide an insight in the applicability of this Agent Based Model simulation.

4.1 Qualitative analysis

First observations

Figure 4.1 and 4.2 show the distribution of cyclists on the bicycle network, illustrating the effect of adding and amplifying routing variables. In figure 4.1, the distribution of cyclists on the network between 08:00 and 09:00 is displayed, where cyclists calculate a path solely on a shortest path basis. Figure 4.2 shows the distribution of cyclists on the network between 08:00 and 09:00, including the routing parameters for both road safety and occupation per segment set at 2. The extrusion height increases with the number of cyclists, the color scheme varies between green and red, related to the number of cyclists. Positioning the images side by side allows a first

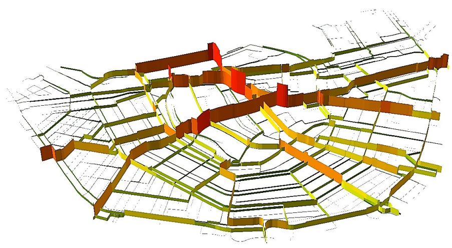

Figure 4.1: Cyclist distribution on the network from 08:00 to 09:00, no influencing variables, extruded on number of cyclists

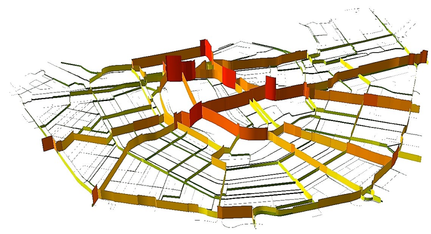

Figure 4.2: Cyclist distribution on the network from 08:00 to 09:00, Road safety parameter and occupation parameter set at 2, extruded to number of cyclists

comparison of the cyclist distribution on the network. First, a difference is visible in the outer ring of the Centrum district. In the first scenario, the smaller roads are used more by cyclists, whereas the second scenario shows a lower amount of cyclists on these segments. Furthermore, the images clearly show that the second scenario creates a concentration of cyclists on certain road segments, indicated by the larger extrusion and red colors. A logical consequence of this development is the visible lower number of cyclists on the less-favorable roads. Based on this visualization, it becomes clear that weight values on the road sections have an influence on the distribution of cyclist on the network

Qualitative analysis

During the experiment, 5 simulations have been executed under varying weigth value levels and combinations. The shape-file output from these simulations was stored and further analyzed. The first simulation was a baseline simulation, to determine the distribution of cyclists on the network without influence by weight variables. The total amount of cyclists per segment was stored, and joined on OSM ID to the weight maps of the 4 other simulations.
For each simulation, the baseline amount of cyclists per segment was subtracted from the value of that specific simulation, resulting in a difference value. This difference value indicates either increase or reduction of the number of cyclists on each segment. The increase or reduction was visualized with a green-yellow-red color gradient, where green indicates reduction of the number of cyclists (less crowded), and a red color indicates an increase of the number of cyclists. In the following sub chapter, the maps created for 09:00 are compared to the 09:00 baseline map, and the 15:00 maps are compared to the baseline 15:00 map.

Weight maps 09:00

Figure 4.3 is the baseline heat map at 09:00, clearly indicating a difference in cyclist numbers across the various segments of the map. The number of cyclists per segments ranges between 0 and 2040.

When the cyclist routing mechanism is influenced by the occupation parameter, as displayed in Figure 4.4, an increase and decrease on specific road sections is visible. The change in sections is focused on separate segments, and only shows distinctive changes on specific segments in the cyclist distribution across the network.

The road safety parameter is activated and set at 1 in Figure 4.5, resulting in a more noticeable variation in cyclist distribution. Clearly visible are the larger green and red trajectories, indicating an increase or reduction on larger sections within the network. The finer mazed streets show a decrease in the number of cyclists, and main corridors with higher numbers of cyclists become visible.

Activating both parameters results in what appears to be a combination of both effects. In figure 4.6, the clear increase and decrease as shown in figure 4.5 (Road safety parameter active) is less distinctive, as both parameters are activated. The map also shows the increase on the fragmented locations of figure 4.4, but also shows the larger trajectories of figure 4.5.

Figure 4.7 visualizes the effect of amplifying both parameters by doubling their weight (parameter is set at 2). In this visualization, it becomes quite clear that this level of weight values has an impact on larger combinations of segments on the network, indicating a large effect of the road safety variable.

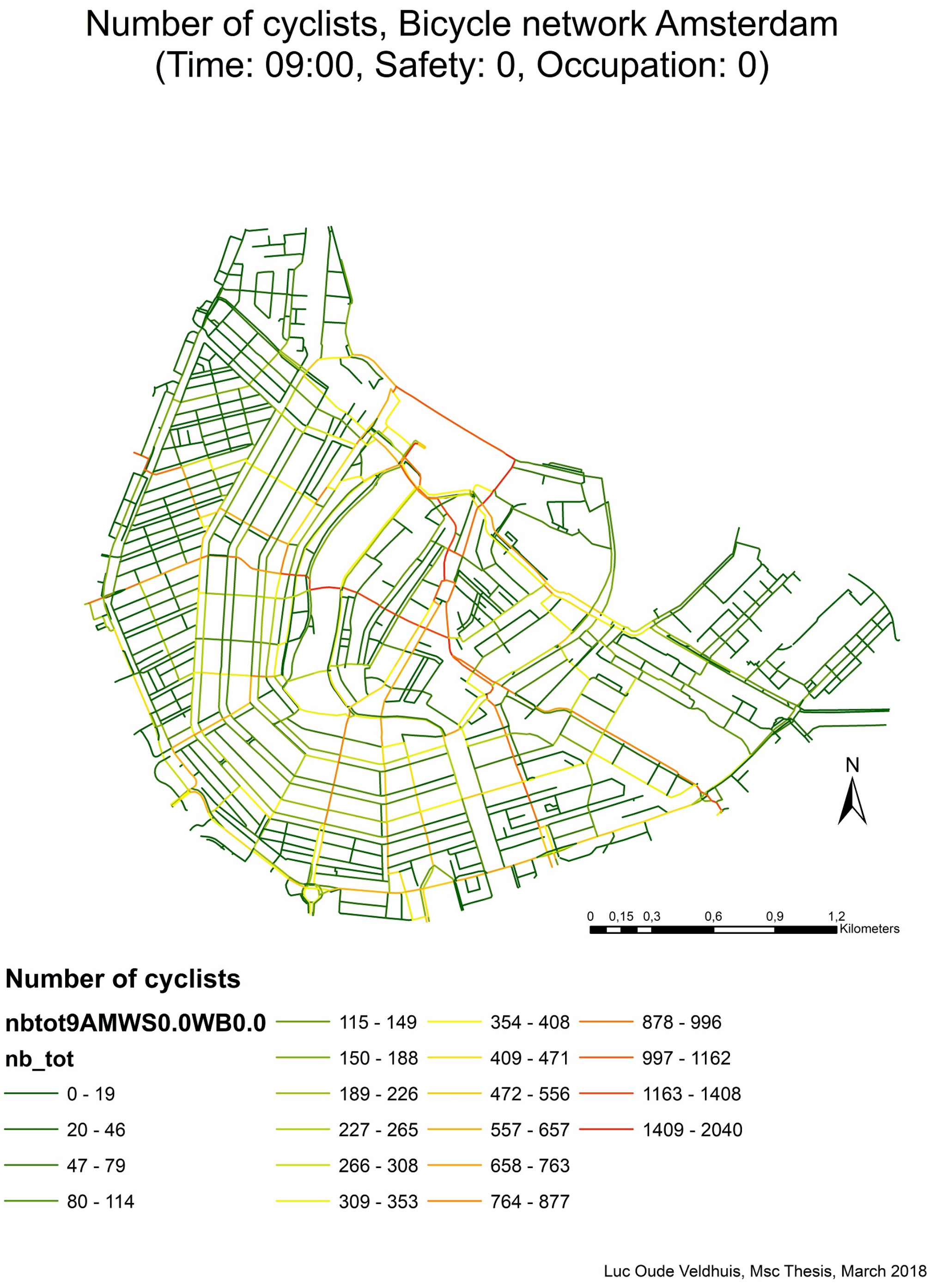

Figure 4.3: Baseline cyclist distribution between 08:00 - 09:00.
Green indicates a lower number of cyclists, red indicates a higher number of cyclists.

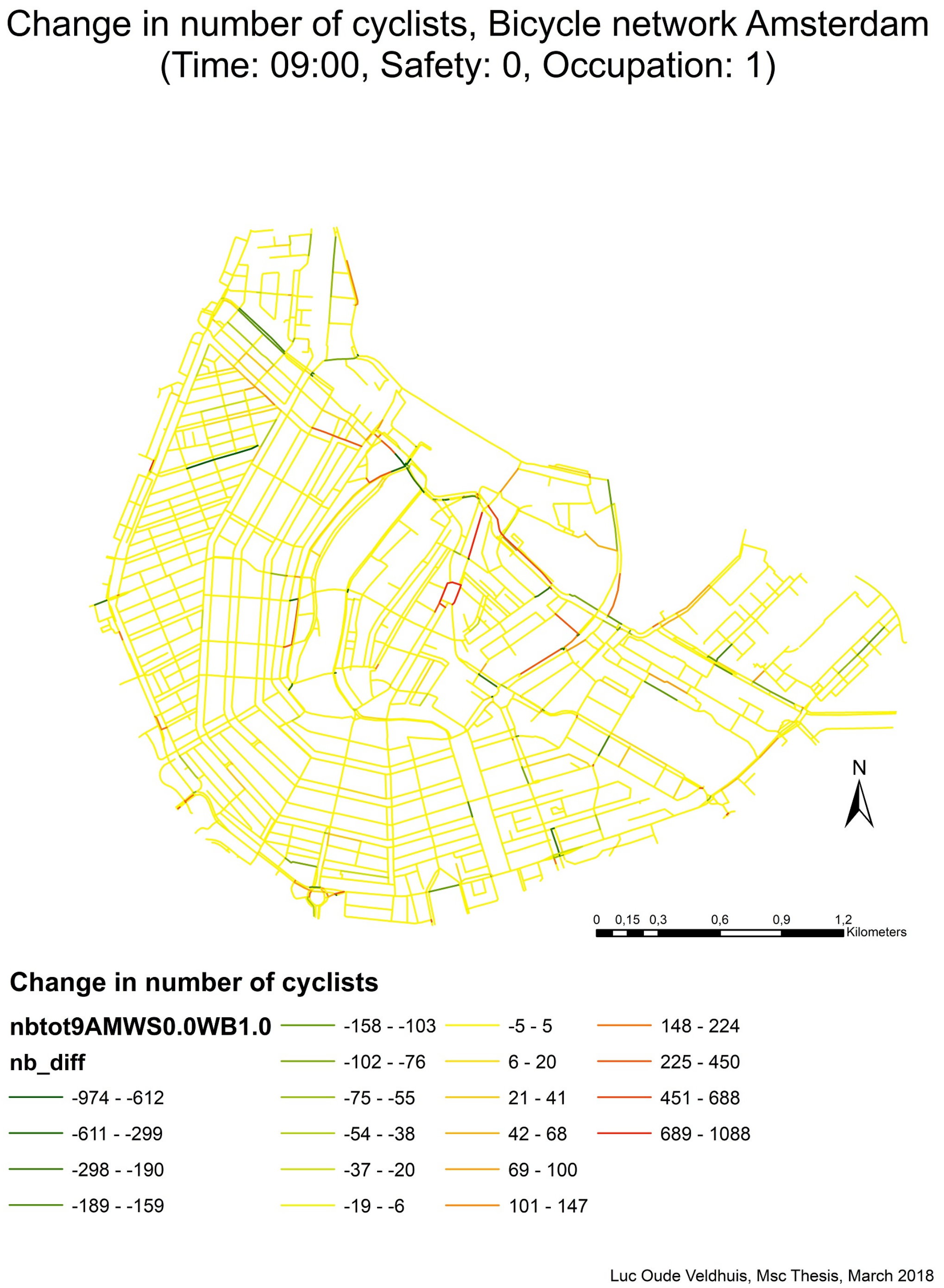

Figure 4.4: Difference map on cyclist distribution between 08:00 - 09:00. Road safety parameter: 0. Occupation Parameter: 1.
Green indicates a reduced number of cyclists, red indicates an increased number of cyclists.

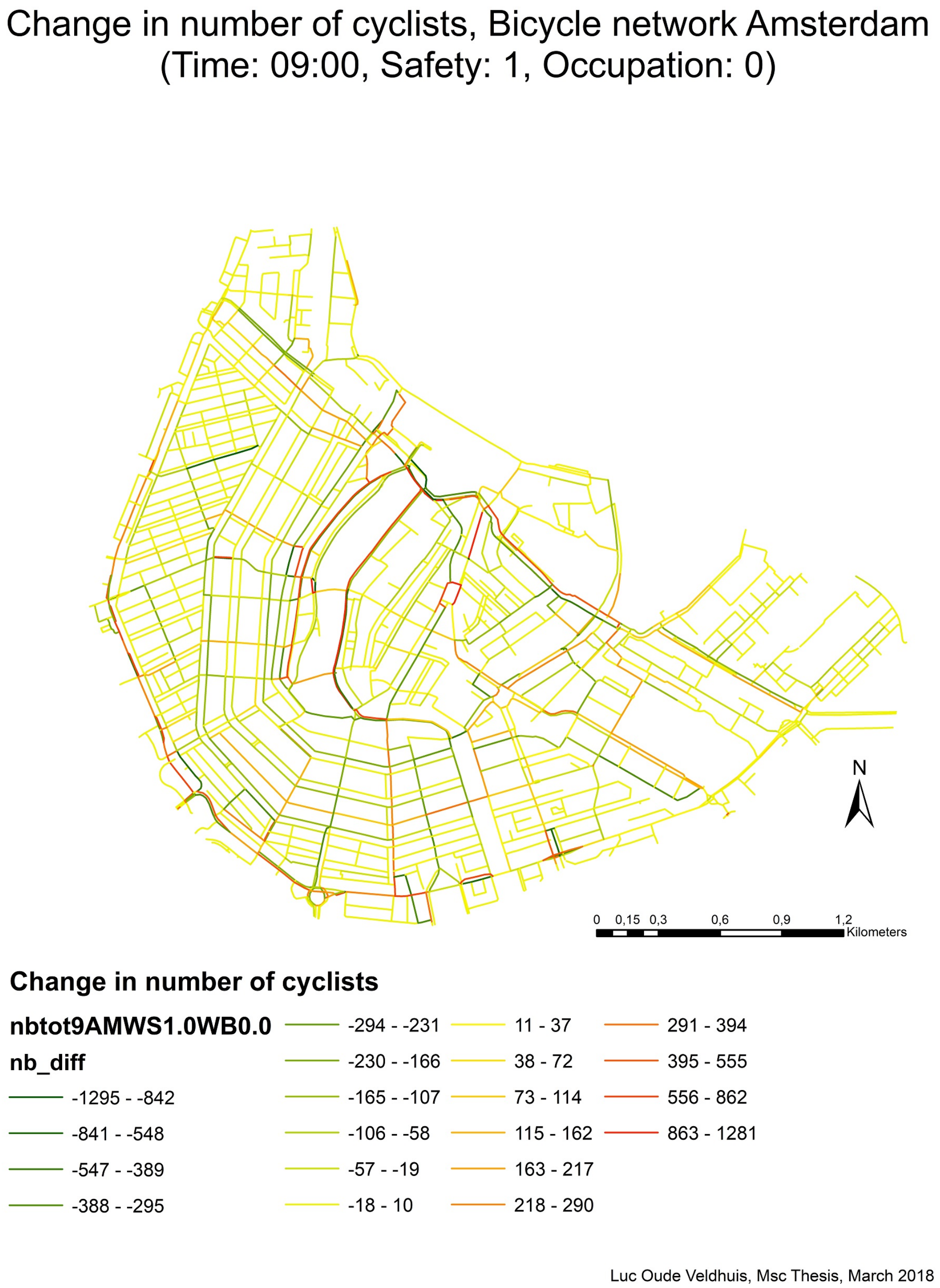

Figure 4.5: Difference map on cyclist distribution between 08:00 - 09:00. Road safety parameter: 1. Occupation Parameter: 0.
Green indicates a reduced number of cyclists, red indicates an increased number of cyclists.

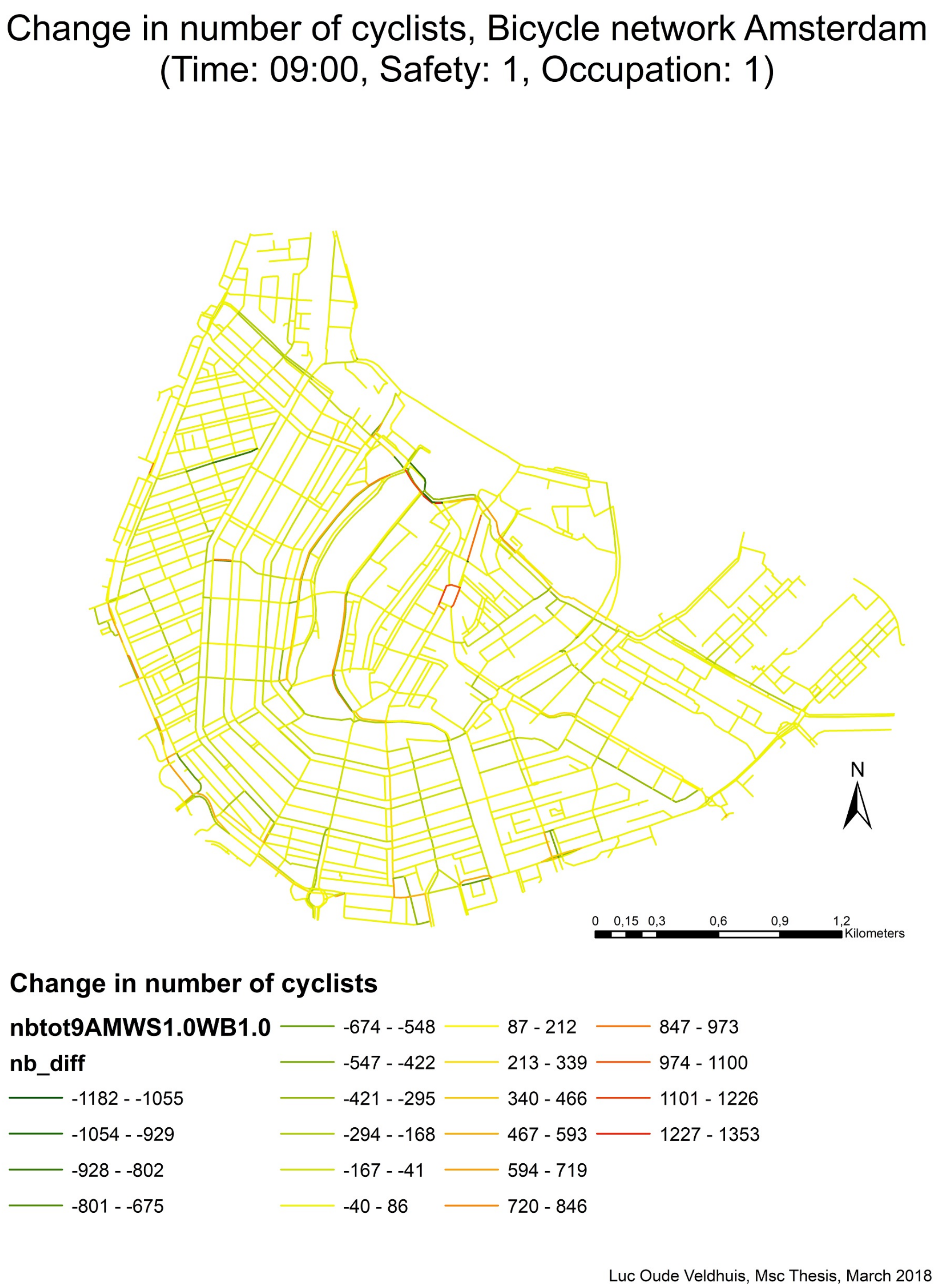

Figure 4.6: Difference map on cyclist distribution between 08:00 - 09:00. Road safety parameter: 1. Occupation Parameter: 1.
Green indicates a reduced number of cyclists, red indicates an increased number of cyclists.

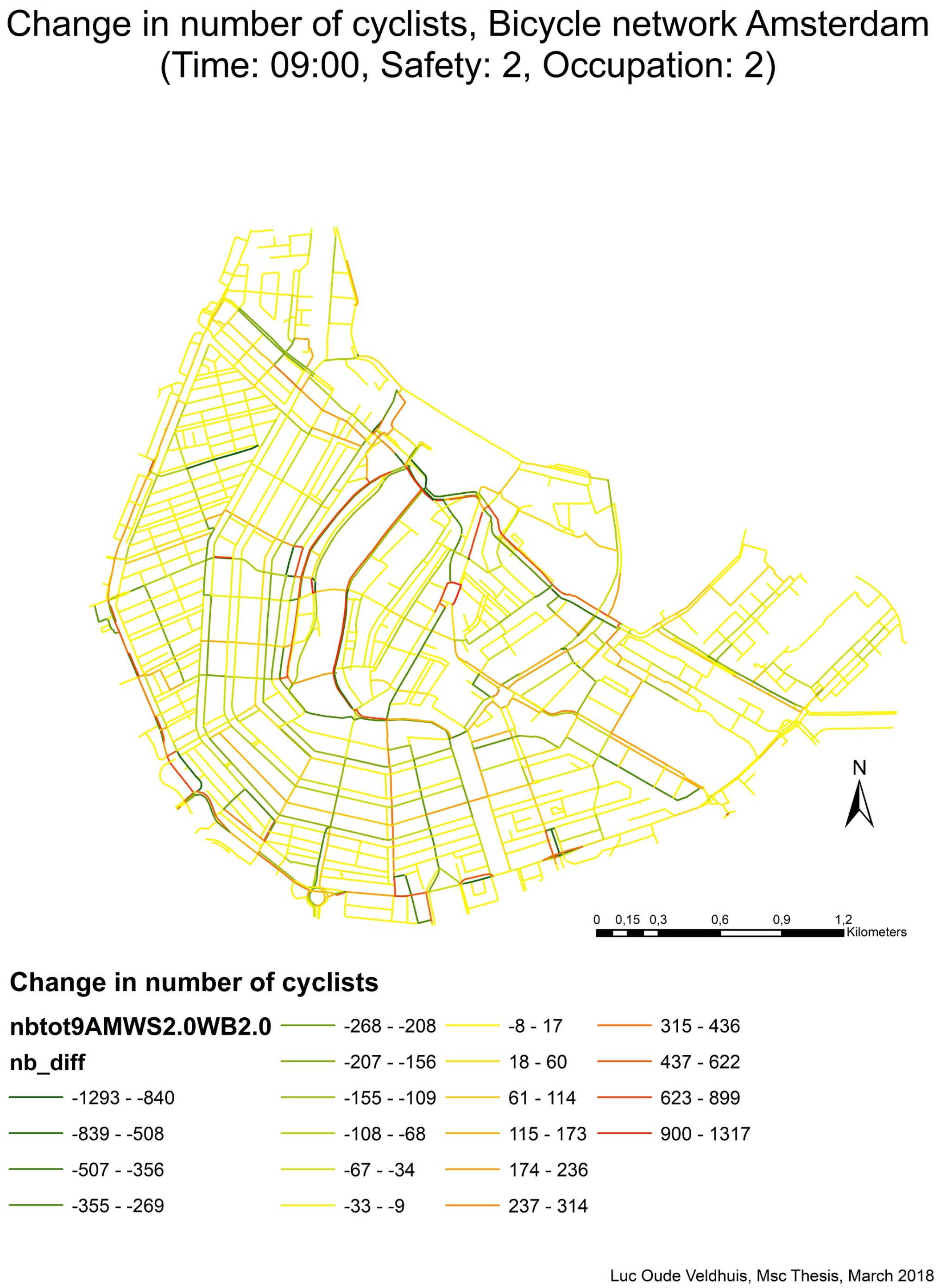

Figure 4.7: Difference map on cyclist distribution between 08:00 - 09:00. Road safety parameter: 2. Occupation Parameter: 2.
Green indicates a reduced number of cyclists, red indicates an increased number of cyclists.

Weight maps 15:00

Figure 4.8 displays a heat map of the number of cyclists on the network, at 14:00 in the simulation environment. The legend indicates a smaller range in the amount of cyclists present at the different network segments, ranging between 0 to 721. The main corridors are clearly visible, with a yellow, orange or red color, indicating a higher number of cyclists.

Activating the separate weight parameters creates a comparable image to that of 09:00, as shown in figure 4.9 and figure 4.10. Activation of the occupation parameter shows a scattered impact on separate segments of the network, whereas the road safety translates to larger sections with increased or reduced cyclist presence.

Continuing, when both parameters are activated, as shown in figure 4.11, differences between 09:00 and 15:00 can be found. The difference map in figure 4.11 shows more distinctive changes on larger sections of the road network, with less scattered changes on separate segments of the road network, when compared to the difference map at 09:00

Amplifying both parameters, as shown in figure 4.12, results in a difference map that is comparable to figure 4.11. Interesting is the stronger decrease on the side roads, and the clearer distinction of main corridors with increased number of cyclists.

Overall, the cyclist distribution maps at 15:00 in the simulation indicates a stronger impact of the routing variables.

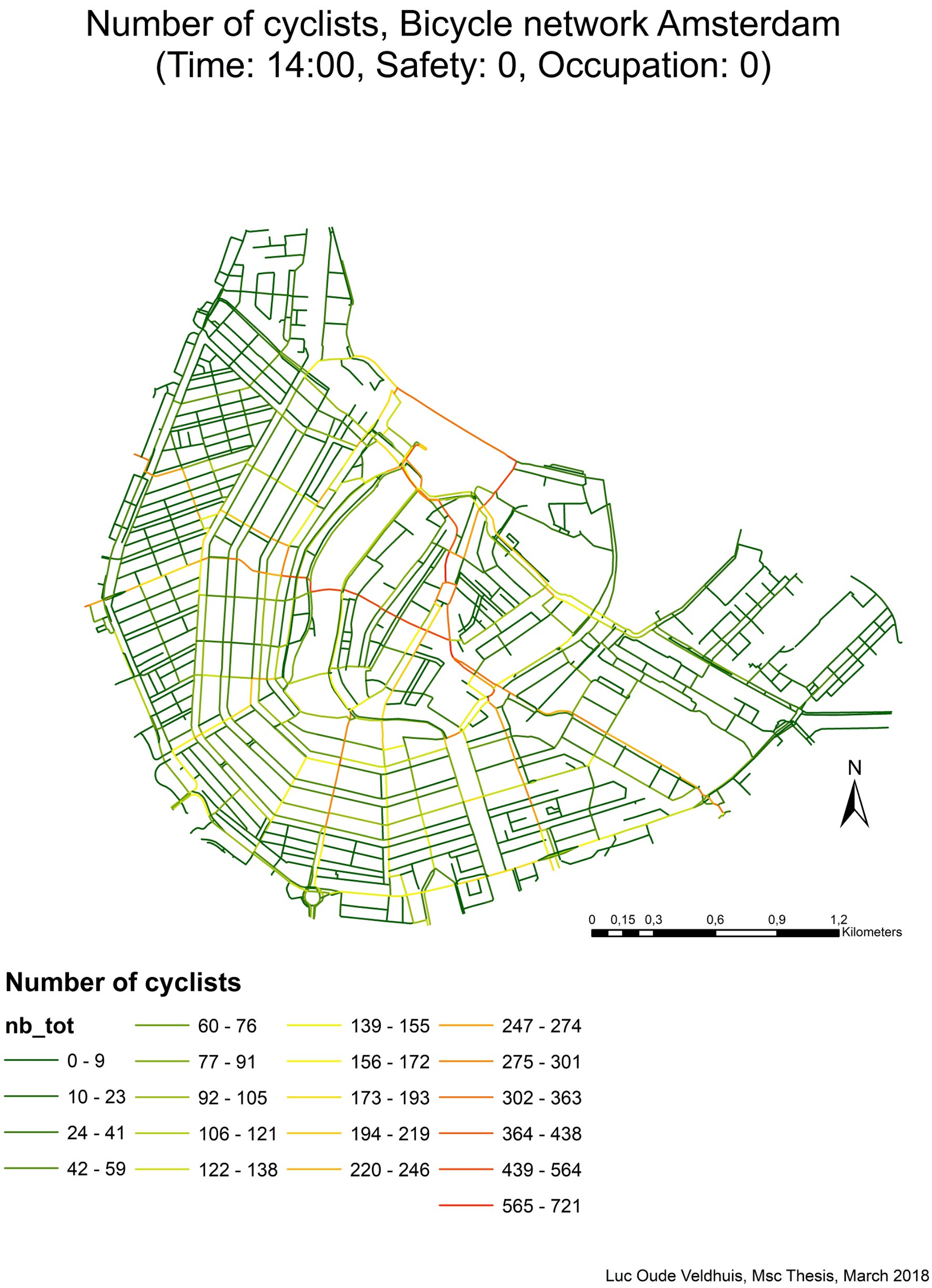

Figure 4.8: Baseline cyclist distribution between 14:00 - 15:00.
Green indicates a lower number of cyclists, red indicates a higher number of cyclists.

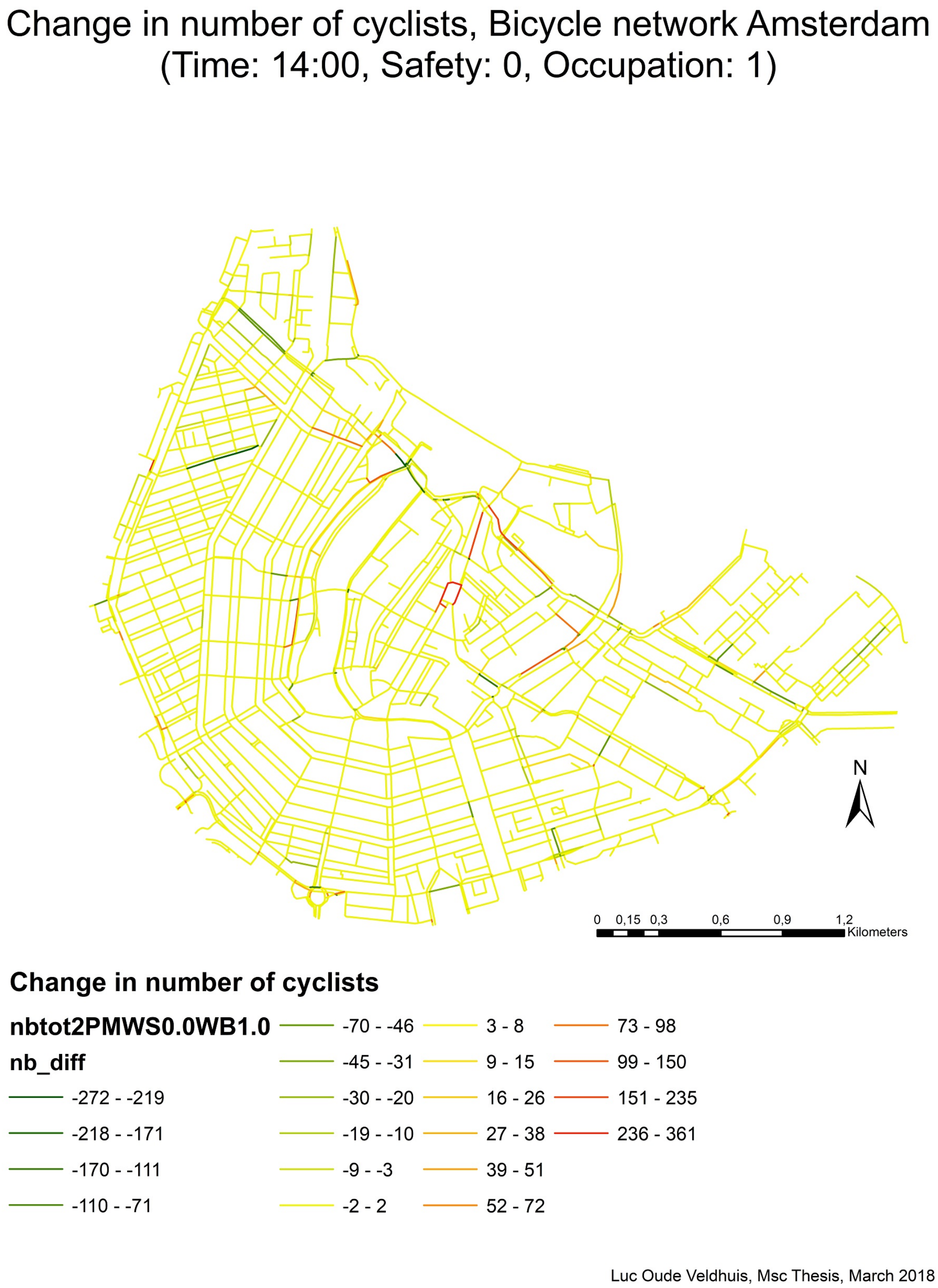

Figure 4.9: Difference map on cyclist distribution between 14:00 - 15:00. Road safety parameter: 0. Occupation Parameter: 1.
Green indicates a decreased number of cyclists, red indicates an increased number of cyclists.

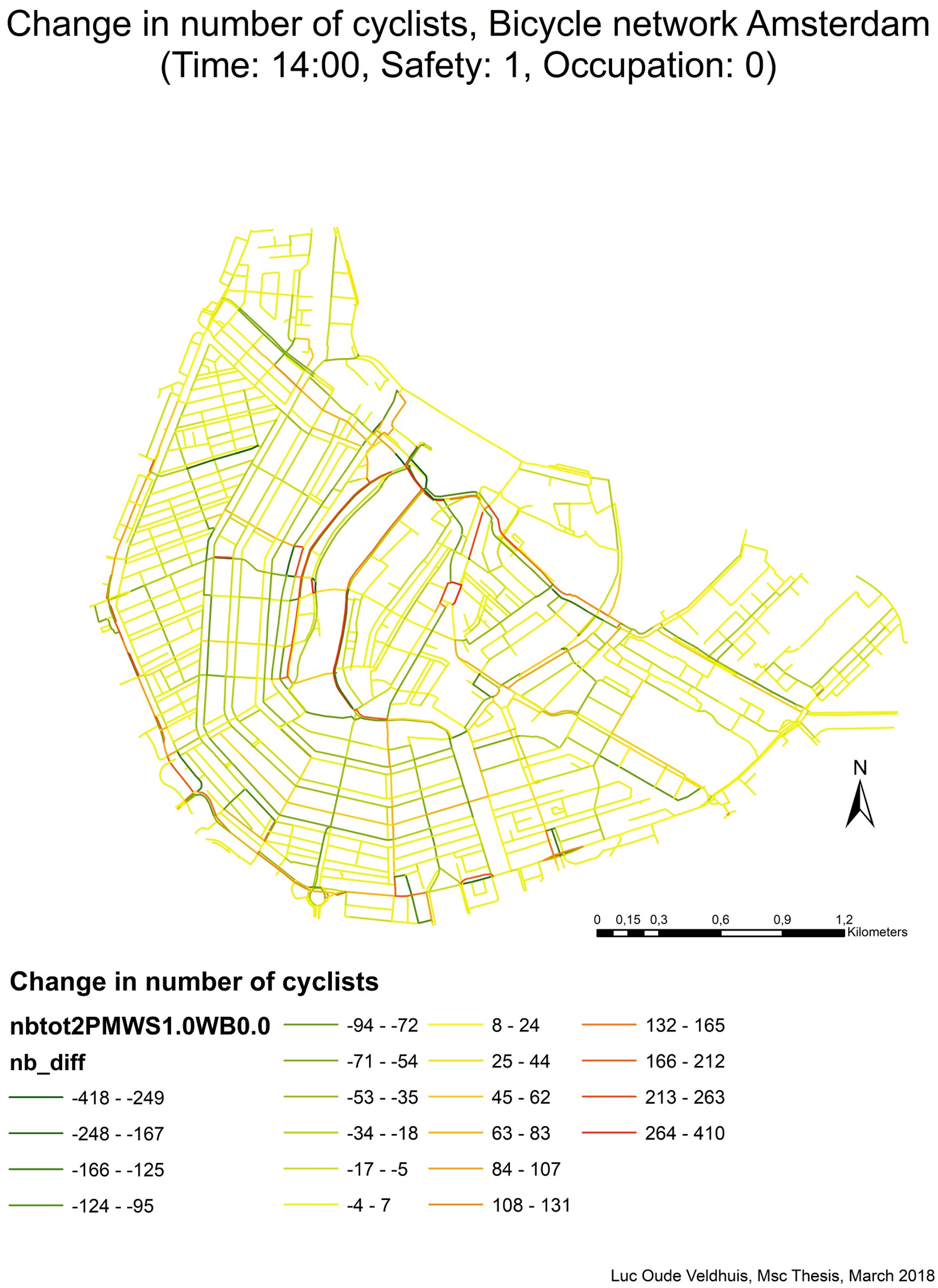

Figure 4.10: Difference map on cyclist distribution between 14:00 - 15:00. Road safety parameter: 1. Occupation Parameter: 0.
Green indicates a decreased number of cyclists, red indicates an increased number of cyclists.

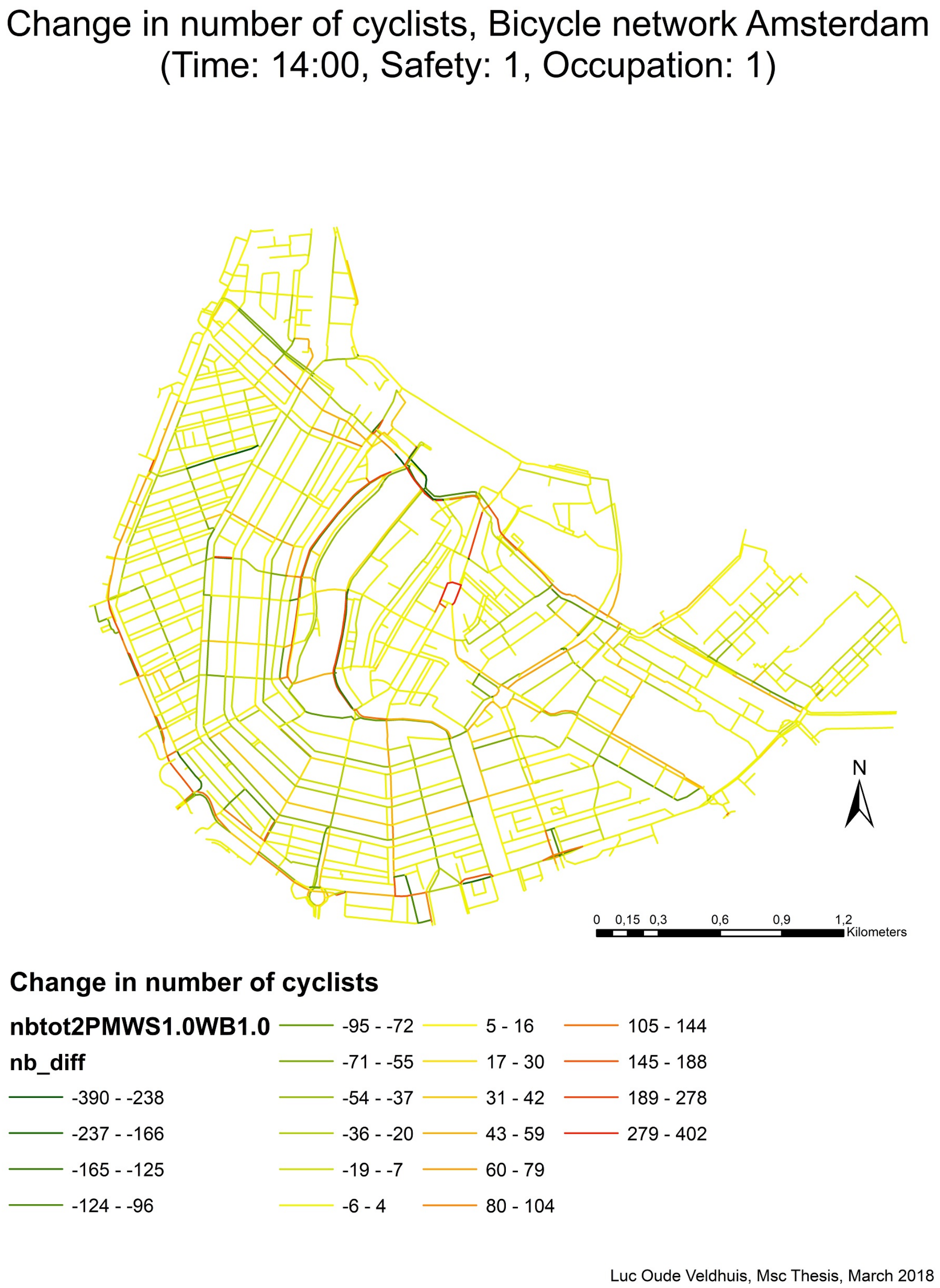

Figure 4.11: Difference map on cyclist distribution between 14:00 - 15:00. Road safety parameter: 1. Occupation Parameter: 1.
Green indicates a decreased number of cyclists, red indicates an increased number of cyclists.

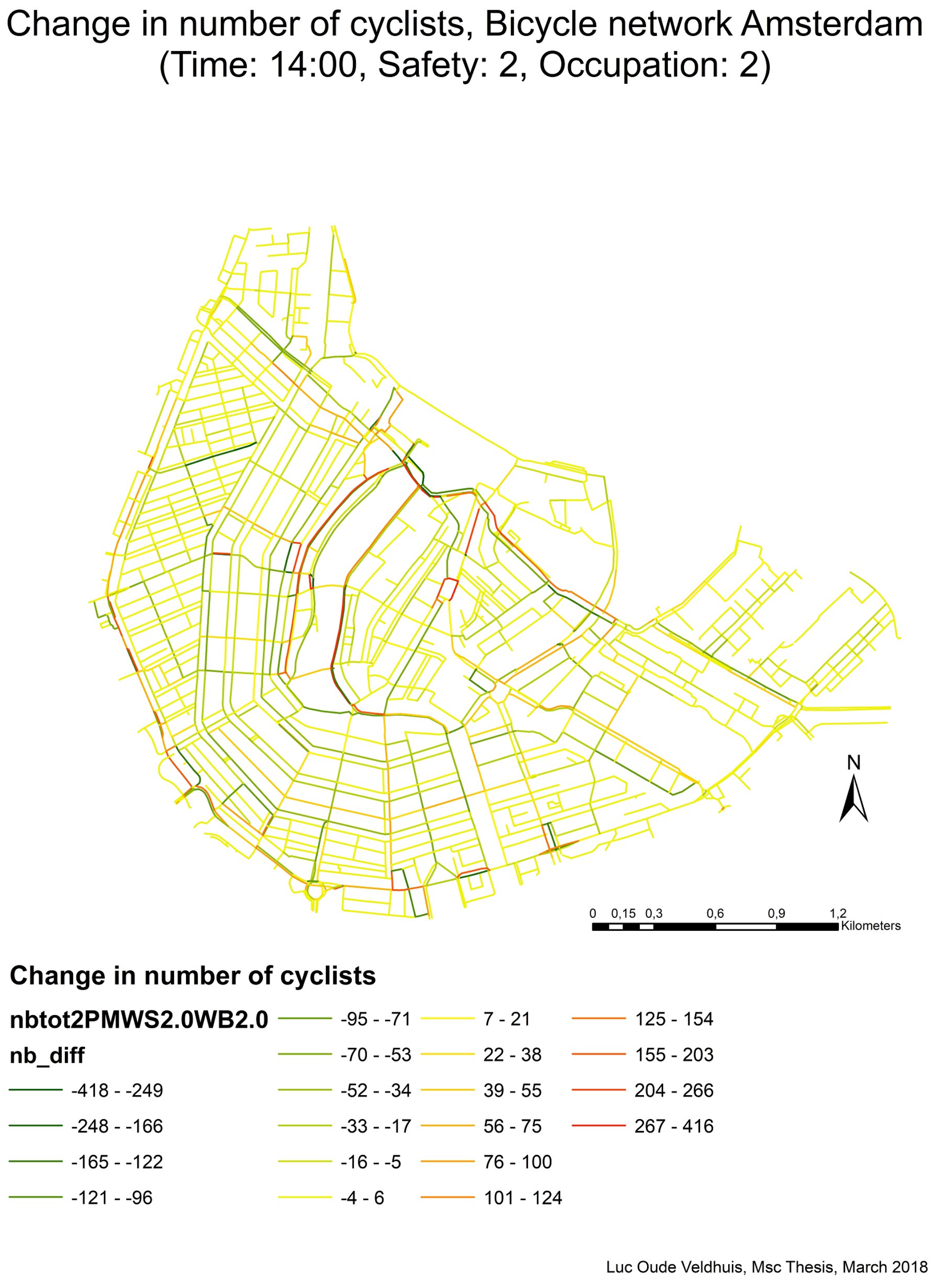

Figure 4.12: Difference map on cyclist distribution between 14:00 - 15:00. Road safety parameter: 2. Occupation Parameter: 2.
Green indicates a decreased number of cyclists, red indicates an increased number of cyclists.

4.2 Quantitative analysis

The observations made in the qualitative analysis create a first indication of the impact weight variables have on cyclist distribution in the model. As specified in chapter 3.5 (Experiments), 10 comparison locations were defined to examine the impact on specific sections of the network. After the execution of the 5 simulations in the GAMA environment, the number of cyclists on the 10 comparison locations were extracted from the shapefiles, created at 09:00 and 14:00. In Excel, this tabular date was translated to a bar graph for each of the 5 simulations, at both 09:00 and 14:00 in the simulation. In this section, both histograms are shortly discussed to examine the effect of the variables on the 10 comparison locations.

Histogram 09:00

Figure 4.13 contains the bar charts resulting from the shapefile output at 09:00, on 10 segments, within the 5 simulations. Having these graphs side by side reveals some interesting differences between the simulations.
The second (orange) bar in each graph represents the number of cyclists on the Rokin. When the road safety variable is switched off, the Rokin is selected by 35 cyclists. Activation of the road safety factor increases this number to 700, 1000 and 1100, as seen in bar graph 3, 4, and 5. A comparable development is observed for the Damrak, showing an increase on activation of the road safety factor.
Other segments show a decrease in the number of cyclists, as is visible in the case of the Zeedijk, or remain almost stable, in the case of the Paleisstraat. A distinctive result is the difference between scenario 3 and 5, where both variables are activated, with varying weight values. The ratio between the variables remains equal, but the resulting bar graphs show different cyclist presence per scenario.

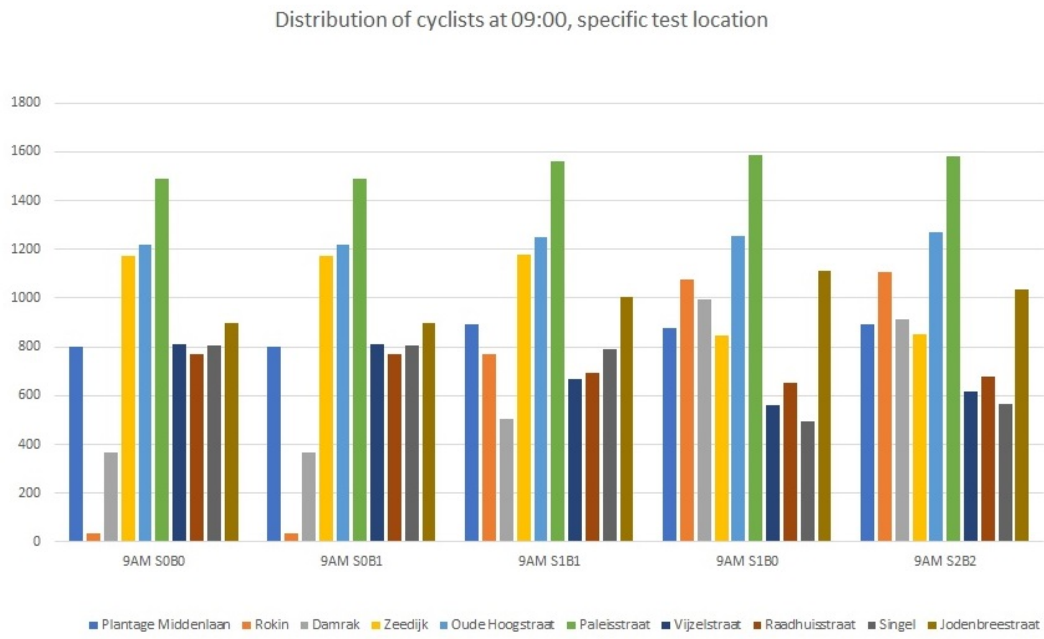

Figure 4.13: Histogram of the total number of cyclists between 08:00-09:00

Histogram 15:00

In figure 4.14, the bar charts are visualized, resulting from the shapefile output at 15:00, on 10 segments, within the 5 simulations. First, the Rokin and Damrak locations show comparable behavior at 09:00 and 15:00, with a large increase in cyclist presence under the activation of the road safety variable. An explanation could be found in the higher safety factor, 4, of the Rokin and Damrak segments, while surrounding segments have a road safety class of 2 and 3.

A switched off road safety variable but an activated occupation variable decreases cyclist presence on the Zeedijk and the Singel, and activating the road safety variable decreases the number of cyclists on the Vijzelstraat and Raadhuisstraat. At 09:00, simulation 3 and 5 produced varying results, although the ratio between the road safety variable and the occupation variable remained equal. In the output shape-files produced at 15:00, the bar graphs also show different amount between scenario 3 and 5.

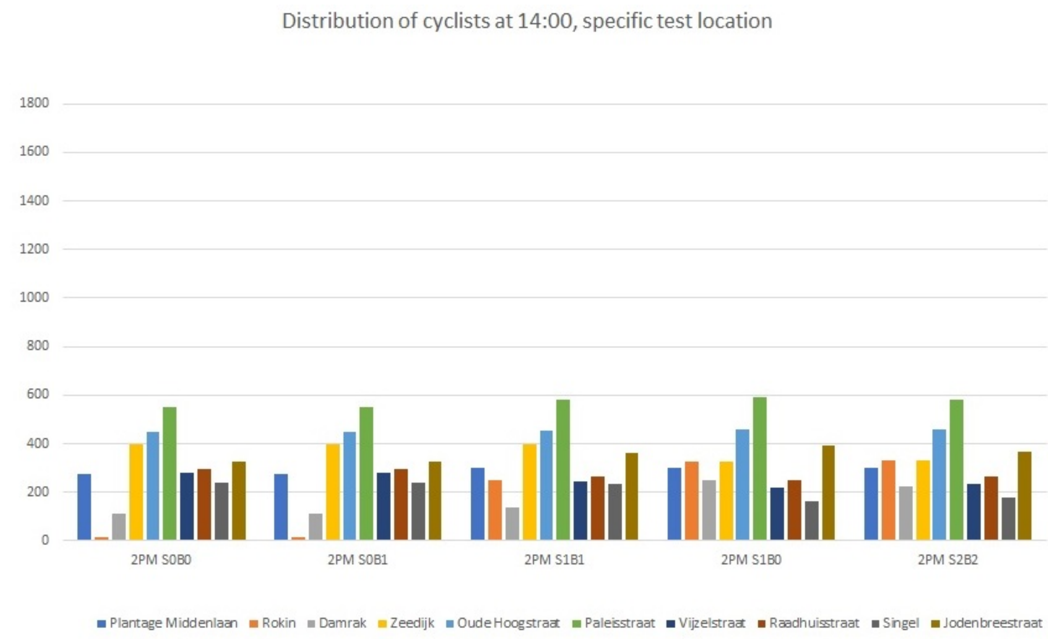

Figure 4.14: Histogram of the total number of cyclists between 14:00-15:00

Comparison to the bicycle network in Amsterdam

An Agent Based Model is expected to predict possible output variables, under varying input variables, without using the actual bicycle network. (Barcelo, 2011). To test the capability of this Agent Based Model, the output variables produced by this model in the simulations are compared to the variables of available research on the number of cyclists on the network of Amsterdam.

A number of provinces in the Netherlands organize the yearly "Fietstelweek" (*Bicycle counting week*), to gain more insights on the behavior of cyclists on their road networks. During this week, cyclists provide GNSS based position with a mobile phone application, which is bundled and processed. The final product is a database for this specific week, displaying the number of cyclists on road sections all over the Netherlands. An important aspect of this event is the voluntary provision of location data during this week. Although cyclists with the mobile application can provide their location data, they are still able to switch off the location tracking application when desired. The resulting data is therefor considered to be a mere indication of the actual number of cyclists, and not a determined amount or distribution of cyclists on a daily basis. It can however be used as a first guideline to examine the similarities and differences between the simulation and the 'real' system.

To compare the output variables of the Agent Based Model to the actual number of cyclists on the bicycle network in Amsterdam, the data collected during the

Fietstelweek 2017 is used. First, the number of cyclists on the network during the Fietstelweek 2017 was extracted, on the same 10 comparison locations described in the methodology. Second, this data was combined in a bar chart with three scenarios between 14:00-15:00, as the values fell within a comparable range, allowing a visual comparison of the data. Figure 4.15 shows a side-by-side comparison of the Fietstelweek data and the three 15:00 scenarios, displayed in one bar chart.

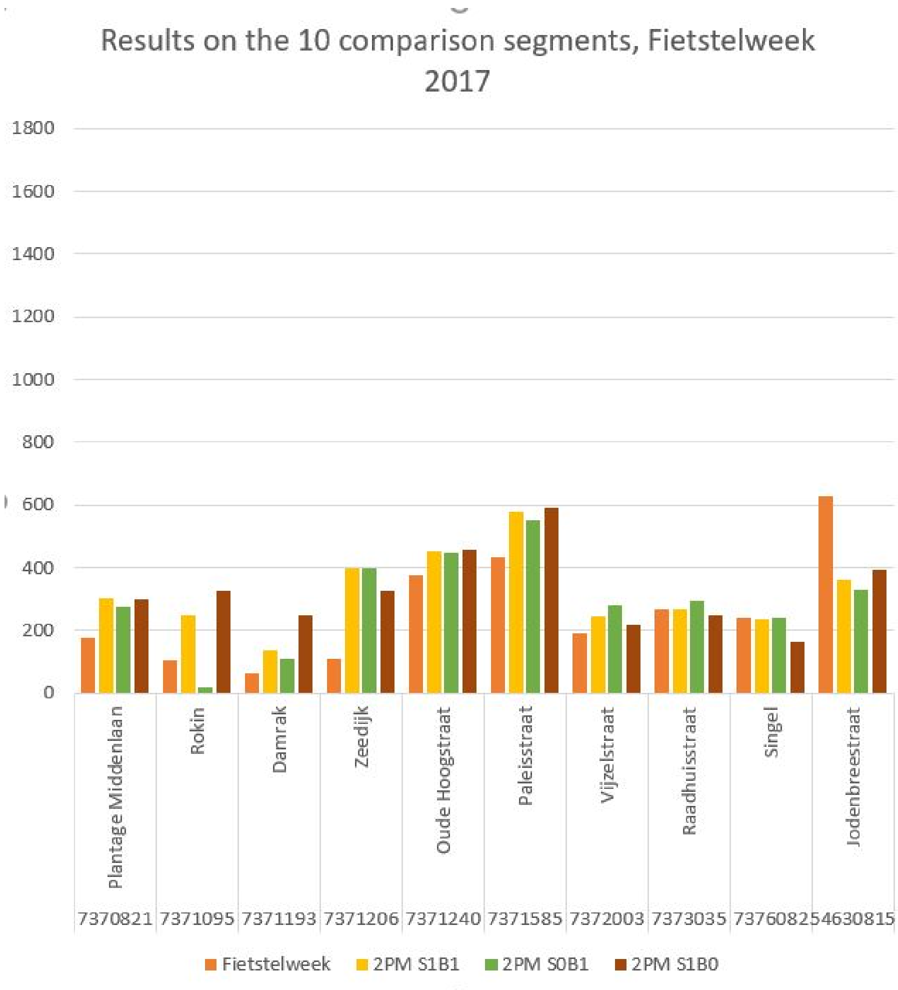

Figure 4.15: Bar chart, comparison between Fietstelweek data and simulation output

On the far left side, the orange bar visualizes the number on the comparison locations during the Fietstelweek. The following bars display the number of cyclists on the location between 14:00 and 15:00. Results from the simulation approach the ratio of the Fietstelweek, as is clearly visible in the bar chart, although still dependent on the scenario. Absolute numbers are not universally fitting, as seen at the Jodenbreestraat. Across the 10 comparison locations, the distribution of cyclists in the simulation scenarios appears to approach that of the measured numbers from the Fietstelweek.

4.3 Summary

A qualitative comparison of the difference maps with the baseline maps produced a number of observations. First, the effect of the separate parameters on the distribution of cyclists on the network. Activating the road safety parameter results in an increase or decrease of cyclists on longer distances of connected segments in the network. The occupation parameter however manifests itself with local increased or decreased number of cyclists, often limited to one network segment.

Combining the two parameters translates to a combination of their respective effects on the network. However, a difference can be observed between the morning and afternoon time period, as the morning maps display a smaller and more scattered pattern, when activating both parameters. Amplifying the parameters with a factor 2 produces comparable images in both time slots. It does appear that the mentioned impact of the road safety parameters, manifested as larger sections of increase or decrease, becomes more visible when amplified with this factor. The occupation parameter effects can not be clearly distinguished in this simulation.

In a quantitative analysis, 10 comparison locations are defined, to examine the effects of the 5 scenarios on cyclist distribution. As visible in the bar charts, the sensitivity of these 10 locations to the 5 scenarios shows variation. Some locations show a dramatic increase or decrease (Rokin, Damrak), while other locations remain practically stable (Paleisstraat). Overall, the bar-charts display of the morning and afternoon time period show similar responses to the scenarios on the 10 comparison locations.

To examine the capabilities of this simulation, the results of the Fietstelweek were added to the results of the simulations, allowing a side by side comparison. The overall cyclist distribution during the Fietstelweek, on the 10 comparison locations, displays similarities when visualized with the results of the simulations. This does not universally validate the simulation, but shows that the simulation model is able to approach the behavior of the ’real’ system.

5 Conclusion

To conclude this research, the four main research questions defined in chapter 1.3 are answered, followed by an in-depth elaboration:

- *What approach is suitable to define a bicycle transportation network in an Agent Based Model?*
  A multi-layered agent architecture for traffic-related choice is the suitable approach to define an bicycle transportation network in an Agent Based Model, within this research setting. Agents are able to maintain movement, whilst recalculating the defined path to determine the validity of the chosen path.

- *In what way can routing mechanisms for cyclists be influenced by external variables?*
  Routing mechanisms can be influenced by a variety of external variables, which can be related to culture, infrastructure and cyclist status on the road. The geographical location of a bicycle network and the accompanying status of a cyclist determine the cyclists' sensitivity to these external variables.

- *What is the influence of behavioral variables on the bicycle network in the case of Amsterdam?*
  In a simulation of the network of Amsterdam, influencing the routing behavior with additional parameters translates to increase and decrease of cyclist presence on (a part of) the network segments. Addition and activation of parameters within a simulation results in a change in cyclist presence, when compared to a non-influenced scenario.

- *Is the proposed Agent Based Model for Amsterdam suitable for predictive research on this and other bicycle networks?*
  The proposed Agent Based Model is, within the restrictions defined in the model, an additional method to perform predictive research on bicycle transportation networks. The Agent Based Model simulation can provide a first exploration on the effects of infrastructural or behavioral changes that approach the 'real-life' cyclist presence values on the bicycle network.

To answer research question 1, a literature study on related research was performed. This literature study brought forward that Agent Based Modeling and Simulation is the method of choice when studying complex systems, such as the bicycle transportation network of Amsterdam. The complex nature of the system can often not be grasped in the limitations of an equation-based model, which could result in oversimplification and loss of detail in the model or resulting simulation. Based on the inventory research by Klügl and Bazzan, a multi-layered agent architecture was deemed as most suitable for this application.

Answering research question 2 required a literature research on the (routing) behavior of cyclists, and external parameters that could influence this behavior. Literature presents a number of variables, which seem to contradict each other. However, a clear distinction was made, as the geographic location and the resulting status of the cyclist influences the behavior of the cyclist. Research performed in non-cyclist societies as the U.S.A. and Canada indicated a strong preference for paths between origin and destination that formed the optimal trade-off between cyclists infrastructure and the shortest possible distance. However, research in cyclist societies (Denmark, the Netherlands), indicated that the presence of other users or other traffic groups on mixed roads influenced the routing choices of cyclists. Overall, related research indicates behavior of cyclists can be influenced by multiple external parameters (necessary for question 3 & 4!), varying with the geographical location, the related status of the cyclist in traffic systems and the availability of cyclist infrastructure.

Research question 3 was answered with a simulation model of the bicycle network in Amsterdam. With a conceptual model of the bicycle network in Amsterdam and a case study definition, the simulation model can calculate output values based on input variables on cyclist numbers, network, origin and destination. Within the GAMA platform a simulation was created, which allowed the addition and activation of two influential routing parameters, based on the cyclist road safety class and the number of other cyclists on a network segment. 5 experiments were defined, with varying activated parameters, resulting in 10 shape files. Qualitative analysis of these shape files was performed with difference maps, which indicated that both parameters influenced the distribution of cyclists on the network, during two different time periods of an average day in Amsterdam. Activation of separate parameters shows separate effects on the cyclist distribution, during both time periods, when compared to the baseline scenario with inactive parameters. Quantitative analysis on 10 comparison locations revealed that activation of the parameters can have quite varying results on network segments. Some segments displayed dramatic increase or decrease, whilst other segments appear uninfluenced by the activation of these parameters.

The final research question, question 4, could only be answered after the first result analysis and a comparison to the scarce cyclist distribution data on the 'real' system. Comparison of the simulation results on the 10 comparison locations with data from the Fietstelweek shows the simulation approaches the real system in terms of cyclist distribution. In absolute numbers, the simulation does not always match the results of the Fietstelweek. However, the overall trend in cyclist distribution across the 10 comparison locations shows similarities, when comparing the simulation output to the Fietstelweek dataset. These similarities do not fully validate this simulation, but do indicate that the simulation is able to approach the effects of cyclist behavior on cyclist distribution in the 'real' system.

6 Discussion

Agent Based Modeling, or ABM, translates a complex system to a model of interdependent agents, in order to calculate the outputs of the complex system with a set of input variables, without utilizing the actual system. Agents are able to take a fixed number of decisions, but respond to the decision made by other agents, simulating the complexity of all interacting components of a complex system. (Bonabeau, 2002) In this research, these capacities have been applied to calculate the outputs of a bicycle transportation network, which consists of more than 60.000 agents, interacting in a time period of 18 hours.

As ABM relies on the combined workings and interactions of agents, these have to be individually defined to create a valid representation of the overall functioning of the system. Defining these interactions forms the largest challenge, as the main influential parameters have to be identified. Within this research, the definition of these individual parameters proved to be a challenge. To provide the necessary quantities, behavior parameters and other information, a number of assumptions was made. Although based on official census data, these assumptions do influence the accuracy of the outputs of the simulated complex systems.
This chapter reflects on the chosen methods and assumptions, and discusses the possible applications of the simulation output values.

6.1 Model components

The main components of the model are the cyclists, the network, the origin and the destination. Each sub chapter reflects on the source, necessary assumptions and noteworthy elements of these elements. Furthermore, the model output validity is discussed.

6.1.1 Cyclist behavior

In the conceptual model, the use case and the simulation, the routing behavior of cyclists is defined. Based on the related research, it is assumed cyclists desire a shortest path to their destination, which can be influenced by the safety level of the infrastructure and the number of other cyclists on the network segments, hereby combining findings from the research performed by Broach et al. (2011), Snizek et al. (2013), Dill and Gliebe (2008), and Schepers et al. (2017)

The defined cyclist behavior is therefor a simplified representation of the 'real' system, which results in generalizations based on cyclist categories. Precision of individual cyclist behavior is not incorporated, as it can not be deduced from census data or other provided datasets. Cyclist behavior could be influenced by a vast variety of parameters, ranging from a preference for scenic routes, to a path that allows a quick stop for groceries whilst returning from a working location. These parameters border on a different research area, namely that of the behavioral studies. Based on the related research, the assumed parameters have been selected, as these parameters could be quantified based on available data.

Further research on quantifiable influential parameters in cyclist behavior would improve the conceptual model, the use case and the simulation model. Research conducted by Dill and Gliebe (2008) would be a method to determine these factors specifically for the use case in Amsterdam. Resulting findings would improve the accuracy of the simulation,as the behavior of the simulated agents could more closely resemble the actual cyclist behavior on the network in Amsterdam.

In this research, the influential parameters have been selected based on related research. The selection of these parameters has generalized the overall behavior of a cyclist, but has provided a quantifiable basis to replicate the influence of external parameters on the routing behavior. Further research on potential parameters would therefor only increase the accuracy of this research, as the behavior can be more precisely resembled.

6.1.2 Network

The network created in the case study and the simulation model is a simplification of the model in Amsterdam. It consists of the for cyclists legally accessible streets and paths, but this is where a new problem arises in Amsterdam. Cyclists in Amsterdam tend to violate these rules, and show behavior where all possible road segments are used to continue their path. This behavior does change the use of road segments, as cyclists might use paths which would officially never be a part of the bicycle infrastructure. Although the city of Amsterdam is proposing the implementation of a code of conduct for cyclists, this behavior is difficult to quantify.(Amsterdam, 2011) As this can not be deducted from census data or other datasets, the network used in this case study and simulation does not incorporate 'illegal' pathways for cyclists.

The city of Amsterdam has proposed other developments on the network, such as the PlusNet. This network layer consists of optimized cyclist routes with separated bicycle lanes and other cyclist supporting infrastructure. This includes so called "green waves", allowing cyclists to maintain a right of way at traffic lights on long stretches of road, wider bicycle paths and safer crossings.(Amsterdam, 2015b) Although possibly influential, these developments could not be incorporated within the set time for this research. In future or continuing research, these mechanisms and developments should be included in a simulation model, to examine their influence on the cyclist distribution.

6.1.3 Cyclist quantities, origins & destinations

A number of assumptions have been made on the number, the origin and the destination of cyclists in both the case study and simulation. The quantities of cyclists, in all three categories, is a topic which is not (yet) researched by the city of Amsterdam. The number of arriving working cyclists could be deduced from census data, as the share of workers in Centrum that used a bicycle for their daily commute is a known figure, as well as the total amount of employed persons in the Centrum district. However, their origin remains unknown, and had to be deduced and assumed, based on the available census data. A comparable method has been used to determine the number of shopping cyclists. This category was calculated by considering all citizens residing in Centrum, without employment, as a shopping cyclist

Furthermore, the tourist cyclist category remains an assumed group. The precise quantity of cyclists with a recreational or touristic background can only be deduced from a phrase in the Mobility Vision 2017. Although not problematic, the recent developments in bicycle sharing technologies can increase or decrease the quantity of tourist cyclists on the network.

Origin, destination and quantity of agent categories are not explicitly named as necessary resources by Klügl and Bazzan; Barcelo, but are of the highest relevance in a fine mazed network that is the bicycle network of Amsterdam. The quantity, origin and destination of cyclists in Amsterdam has been calculated with valid assumptions based on the census data provided by the City of Amsterdam. (Amsterdam, 2017b; Amsterdam, 2015a) Overall, these generalizations do increase the uncertainty of the model output. To improve the accuracy of the quantities, origins and destinations of cyclists, further research on the travel patterns of cyclists and the the connected motives could be performed.

6.1.4 Simulation

The GAMA platform has proven itself as a useful tool within the scope of this research. It is able to handle shape file inputs, allows multiple methods of agent coordination and shows an overall flexibility towards specific aspects of specific models.

Within the simulation, the cyclists had to perform a shortest path calculation, while moving or being stationary, based on physical segment length, road safety class and occupation class. Cyclists calculated a full path between origin and destination, based on the specific routing variables. The formula determining the weights of those parameters has been created to create an (almost) equal weight for each parameter, but does not necessarily resemble the ratio which would be supporting the decision process in a 'real' cyclist. More precise estimations of the influence ratio between these parameters would improve the behavior of cyclists within the simulation.

Furthermore, the cyclist was able to calculate a full path between origin and destination, including potential weight factors, which could be interpreted as the cyclist having knowledge on all development of the network. To limit the extent of this pre-existing knowledge, the cyclist recalculated the path every model cycle, which translates to a recalculation of the path every 5 minutes.

A novel approach in the GAMA simulation was that of the multiple cyclist categories which influence another with their presence, and calculate their own specific shortest path based on the overall presence of agents. Each cyclist creates a specific virtual network, which segment lengths are altered according to the routing parameters defined by the cyclist category. The cyclist calculates a shortest path on this virtual network when prompted to do so, which is then transferred to the general network to form the cyclist path. This approach allows the simulation to recreate the effect of cyclist presence on the shortest path calculation, with three cyclist categories moving on the network simultaneously.

6.1.5 Model output

The results of the simulation can, based on these resources, never be presented as an absolute truth, or a prediction of the precise cyclist behavior under defined circumstances. However, within the limitations of the resource data, the simulation is able to provide a first indication of possible changes in the cyclist distribution on a given network, under varying routing parameters.
Furthermore, adapting the amount of cyclists or the network characteristics to development scenarios could provide an additional indication of the possible impact

on cyclist distribution, and network load distribution. With the GAMA environment, this impact can be studied at any desired (simulated) time of day, and allows full customization to the desired application.

6.2 Geo-spatial Applications of Agent Based Modeling

In the final phases of this research, a reflection on the applied methodology is a suitable exercise. Overall, Agent Based Modeling has shown to be a powerful tool in the analysis and simulation of complex systems, such as the bicycle network in Amsterdam. However, the reflection of the separate components also immediately identifies a challenge in the use of Agent Based Modeling, which is formed by those components.

As the elements of a complex system are reduced to a number of interdependent and interacting agents, these agents have to be very precisely defined, requiring extensive knowledge on the all aspects relevant to the complex system. However, the nature of a complex system proposes a challenge: definition of agents and interactions requires simplification of agent mechanisms. Agent Based Modeling is presented as an alternative to equation based modeling, as it is able to model complex systems without the danger of oversimplification. However, as the micro-interactions between agents are often equation based, simplification is still a necessary tool in Agent Based Modeling, as some interactions can not be fully specified.

In an ideal situation, where the researcher has all information on the complex system, this simplification can be justified. In a less ideal situation, where the researcher does not have precise information on all system components and interactions, simplification of components and interactions has to be performed on an assumption basis. If correctly executed, this does not necessarily result in problems or skewed output values, but does simplify the functioning of a unknown part of the system based on the available information. Within the scope of this research, it is difficult to identify a point or threshold where (over)simplification with assumptions disqualifies the output of an Agent Based Model, but forms a possibility when developing these models with limited knowledge on components.

The power and validity of an Agent Based Model is therefor not only found in its abilities to correctly reproduce the interactions within a complex system. The depth and precision of knowledge on the separate system components and interactions appears to be an equally important factor in validity determination of Agent Based Models.

In this research, the power and the validity of the Agent Based Model for the bicycle network of Amsterdam remains, to a degree, questionable. The components and interactions within the complex system are well defined, and are validated by the real system. However, the assumptions supporting the component definitions and interactions, although based on valid census data, form the Achilles heel of this research. A lack of research on behavioral aspects and quantities resulted in simplification with the use of assumptions, reducing the accuracy of the definition and interaction of each component.

Overall, this model could form a good addition to the toolkit of spatial planners, traffic flow engineers and GIS specialists to analyze and simulate the bicycle network of Amsterdam, but under two very strict conditions:

1. Additional research has to be performed to support the definition of influential parameters in cyclist behavior.

2. Further data collection has to be performed on the quantity, motive, origin and destination of cyclists.

If these two conditions are met, this model can produce valid results regarding the effects of cyclist behavior and infrastructural changes on network load distribution.

7 Recommendations

Based on the previous chapters, this research will be concluded with a number of final recommendations.

1. The City of Amsterdam would be very wise to re-evaluate the feedback mechanisms on the redevelopment of the bicycle network in the city. Overall, the tested variables result in network wide changes, which should not be taken lightly. A satisfaction survey and bicycle path width percentage do not provide sufficient insights in the actual effects of the proposed infrastructural changes.

2. The simulation model created in GAMA is only applicable to cyclists in Amsterdam, although it can be adapted to other cities. This challenge can be solved by collecting city-specific data on cyclist origin, destination and quantities, combined with a city-specific network on cyclist infrastructure, to adapt the model to other cities.

3. The accuracy of the Agent Based simulation in this research can be improved if further research is conducted in the spirit of Dill and Gliebe (2008) and Broach et al. (2011) and the Fietstelweek methodology, to benchmark and adjust the model. Accurate GNSS location data on cyclists, combined with the transportation motive increases the accuracy of the model by specifying departure time, preferred routes and return times.

4. Incorporation of other traffic groups is a logical development step for this model, as the movement of other road users influences traffic lights, cyclist speed and other influential parameters.

5. In the described Mobility Vision (Amsterdam, 2011), additional benchmark mechanisms should be incorporated, as the effects of cyclist behavior appear to have network wide effects. A satisfaction survey and a bicycle path width over 2.5m is not a sufficient feedback mechanism when assessing the quality of such a vast network.

8 Final remarks

“People love cycling but hate cyclists.” - *Peter Zanzottera, 2009*

Appendices

Appendix A

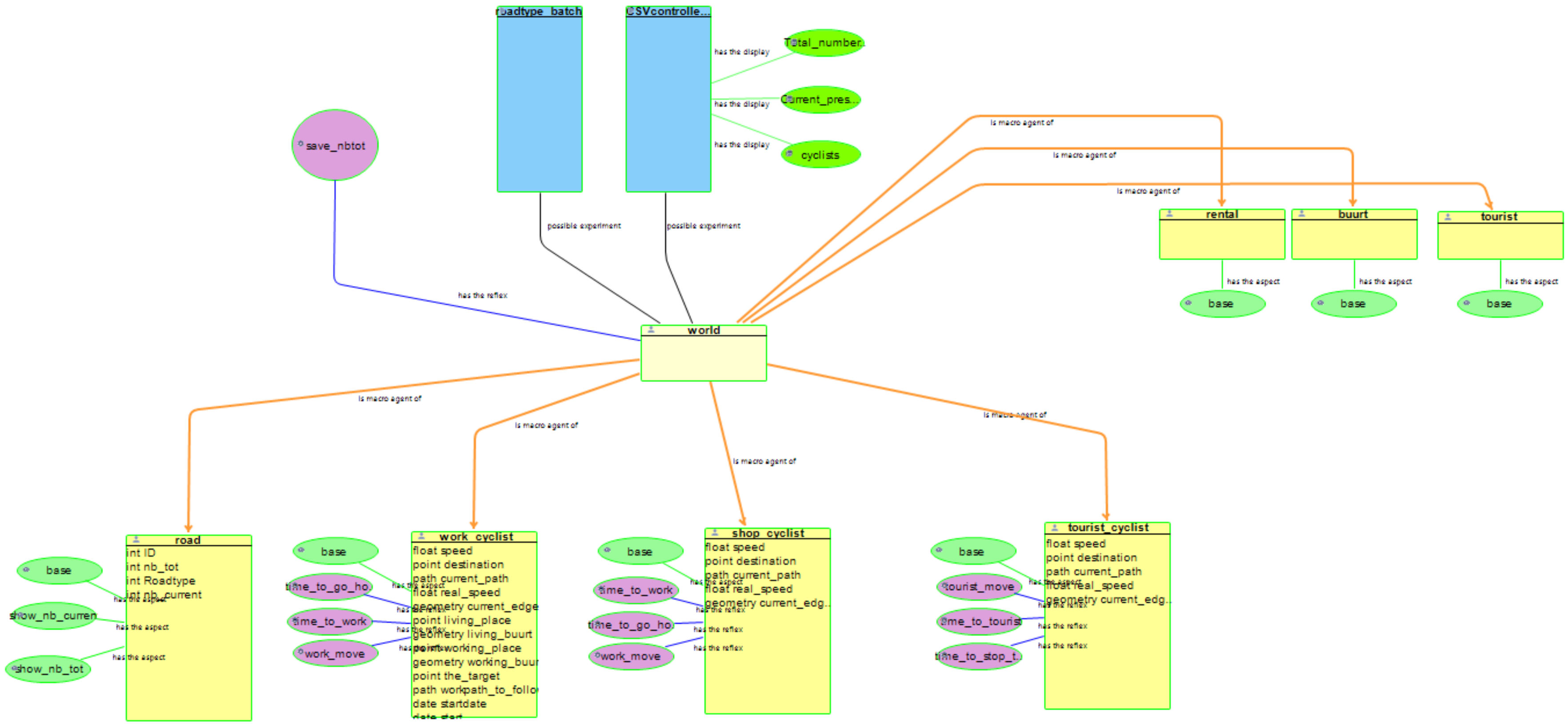

Figure .1: System Diagram of the GAMA simulation model, with 3 monitoring displays and one final shapefile output after 1 full model execution 05:00 - 23:00

Appendix B

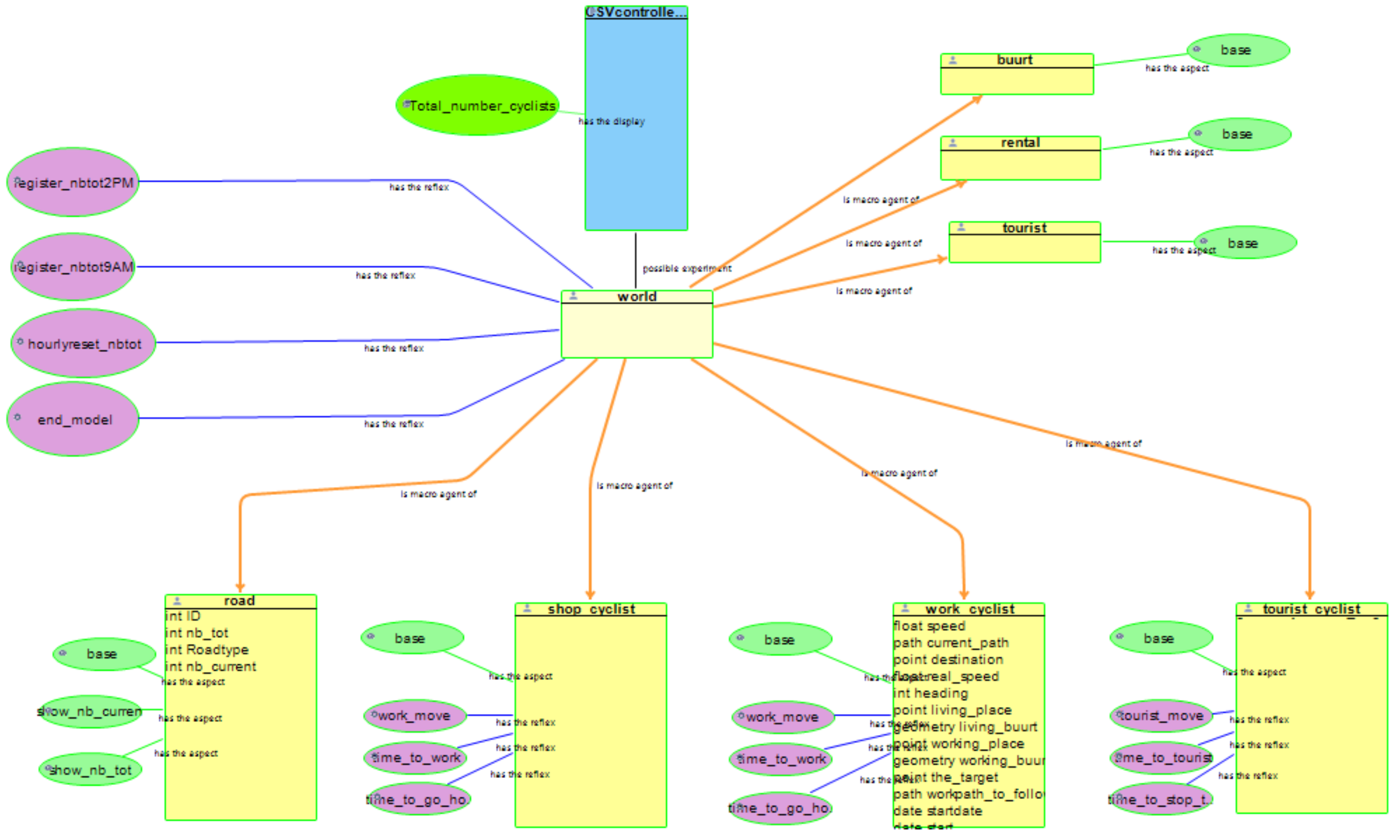

Figure .2: System Diagram of the GAMA simulation model used in the experiments of chapter 3.5.
1 monitoring display, 5 simultaneous simulations, shapefile output at 09:00 and 15:00, with an hourly reset total number of cyclists.

Bibliography

Amsterdam, Gemeente (2011). *Fietsmonitor Meerjarenplan Fiets 2012-2016* (cit. on pp. 4, 16, 17, 24, 75, 80).

– (2013a). *MobiliteitsAanpak Amsterdam 2030* (cit. on pp. 2, 4).

– (2013b). *Plusnetten Gemeente Amsterdam*.

– (2015a). *Hoofdstuk 6: Mobiliteit en Verkeer* (cit. on pp. 3, 23, 30, 76).

– (2015b). *Uitvoeringsagenda Mobiliteit* (cit. on p. 76).

– (2017a). *Meerjarenplan fiets 2017-2022* (cit. on pp. 2–4, 21, 36, 37, 44).

– (2018). *De Staat van de Stad Amsterdam IX* (cit. on pp. 30, 31).

Amsterdam, OIS Gemeente (2017b). *Stadsdelen in Cijfers* (cit. on pp. 22–24, 30, 76).

Bandini, Stefania, Sara Manzoni, and Giuseppe Vizzari (2009). „Agent Based Modeling and Simulation: An Informatics Perspective“. In: 12 (cit. on pp. 9, 10, 17).

Barcelo, Jaume (2011). „Models, Traffic Models, Simulation, and Traffic Simulation“. In: *Fundamentals of Traffic Simulation*. Springer, New York, NY, pp. 1–62 (cit. on pp. 19–21, 50, 68, 76).

Bonabeau, Eric (2002). „Agent-based modeling: Methods and techniques for simulating human systems“. In: *Proceedings of the National Academy of Sciences* 99.suppl 3, pp. 7280–7287 (cit. on pp. 9, 10, 17, 74).

Broach, Joseph, Jennifer Dill, and John Gliebe (2011). „Where do cyclists ride? A route choice model developed with revealed preference GPS data“. In: *Transportation Research Part A* A.46, pp. 1730–1740 (cit. on pp. 15, 17, 27, 28, 75, 80).

Broeke, Guus ten, George van Voorn, and Arend Ligtenberg (2016). „Which Sensitivity Analysis Method Should I Use for My Agent-Based Model?“ In: *Journal of Artificial Societies and Social Simulation* 19.1, p. 5.

Chen, B. and H. H. Cheng (2010). „A Review of the Applications of Agent Technology in Traffic and Transportation Systems“. In: *IEEE Transactions on Intelligent Transportation Systems* 11.2, pp. 485–497.

Crooks, Andrew, Christian Castle, and Michael Batty (2008b). „Key challenges in agent-based modelling for geo-spatial simulation“. In: *Computers, Environment and Urban Systems* 32.6. GeoComputation: Modeling with spatial agents, pp. 417 –430.

Crooks, Andrew, Christian Castle, and Michael Batty (2008a). „Key challenges in agent-based modelling for geo-spatial simulation“. In: *Computers, Environment and Urban Systems* 2008.32, pp. 417–430.

Daellenbach, H.G. (1995). *Systems and Decision making: a management science approach* (cit. on p. 20).

Dia, Hussein (2002). „An agent-based approach to modelling driver route choice behaviour under the influence of real-time information“. In: *Transportation Research* C.10, pp. 331 –349 (cit. on p. 25).

Dill, Jennifer and John Gliebe (2008). „Understanding and measuring bicycling behavior: a focus on travel time and route choice“. In: *Final report OTREC-RR-08-03 prepared for Oregon Transportation Research and Education Consortium (OTREC)* (cit. on pp. 15, 17, 25, 75, 80).

Dozza, M., J. Werneke, and M. Mackenzie (2013). *e-BikeSAFE: A Naturalistic Cycling Study to Understand how Electrical Bicycles Change Cycling Behaviour and Influence*.

Hager, Karsten, Jürgen Rauh, and Wolfgang Rid (2015). „Agent-based Modeling of Traffic Behavior in Growing Metropolitan Areas“. In: *Transportation Research Procedia* 10. 18th Euro Working Group on Transportation, EWGT 2015, 14-16 July 2015, Delft, The Netherlands, pp. 306 –315.

Heinen, Eva, Kees Maat, and Bert van Wee (2013). „The effect of work-related factors on the bicycle commute mode choice in the Netherlands“. In: *Transportation* 2013.40, pp. 23–43.

Helbing, Dirk and Stefano Balietti (2012). „Chapter 2, Agent Based Modelling“. In: pp. 25–70.

Hunt, John and J Abraham (2007). „Influences on Bicycle Use“. In: *Transportation: Planning, Policy, Research, Practice* 34 (4), pp. 453–470 (cit. on p. 14).

Joubert, Johan, Pieter Fouriea, and Kay Axhausen (2010). „Large-Scale Agent-Based Combined Traffic Simulation of Private Cars and Commercial Vehicles“. In: *Transportation Research Record Journal* 2168.1, pp. 24–32 (cit. on p. 6).

Karima, Benhamza, Hamid Seridi, and Herman Akdag (2012). „Agent-based modeling for traffic simulation“. In: *Courrier du Savoir* 14.9 (cit. on pp. 5, 6).

Klügl, F. and G. Rindsfuser (2011). „Agent-Based Route (and Mode) Choice Simulation in Real-World Networks“. In: 2, pp. 22–29 (cit. on p. 12).

Klügl, Franziska and Ana Bazzan (2013). „A review on agent-based technology for traffic and transportation“. In: *The Knowledge Engineering Review*, p. 29 (cit. on pp. 5, 6, 10–12, 17, 72, 76).

Klügl, Franziska and Ana L.C. Bazzan (2012). „Agent-Based Modeling and Simulation“. In: *AI Magazine* 33.3, pp. 11–29 (cit. on pp. 12, 13).

Mobiliteitsbeleid, Kennisinstituut voor (2017). „Mobiliteitsbeeld 2017“. In: (cit. on pp. 21, 22, 30, 31).

Paruchuri, Praveen, Alok Pullalarevu, and Kamalakar Karlapalem (2002). „Multi agent simulation of unorganized traffic“. In: *The First International Joint Conference on Autonomous Agents & Multiagent Systems* (cit. on pp. 6, 13).

Schepers, P., D. Twisk, E. Fishman, A. Fyhri, and A. Jensen (2017). „The Dutch road to a high level of cycling safety“. In: *Safety Science* 92, pp. 264 –273 (cit. on pp. 15, 17, 22, 25, 28, 29, 75).

Snizek, Bernhard, Thomas Alexander Sick Nielsen, and Hans Skov-Petersen (2013). „Mapping bicyclists' experiences in Copenhagen“. In: *Journal of Transport Geography* 30, pp. 227–233 (cit. on pp. 16, 17, 75).

Thomas, Tom, Rinus Jaarsma, and Bas Tutert (2008). „Temporal variations of bicycle demand in the Netherlands: The influence of weather on cycling“. In: *Centre for Transport Studies*.

Tilahun, Nebiyou, David Levinson, and Kevin Krizek (2007). „Trails, Lanes, or Traffic: The Value of Different Bicycle Facilities Using an Adaptive Stated Preference Survey“. In: *Transportation Research: A policy and practice* 41.4, pp. 287–301 (cit. on p. 14).