# Unraveling the Dynamics of MaaS

*An Exploratory Study on the use of System Dynamics for the analysis of Pricing Interventions in MaaS Systems*

TU Delft

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## *An Exploratory Study on the use of System Dynamics for the analysis of Pricing Interventions in MaaS Systems*

by

J. D. Godoy Landínez

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# Preface

Since I was a kid, I have never been a person of words, I love numbers and being among them is a big essence of myself. Writing this thesis was then a big challenge for me, where I had to face myself continuously and I am thankful for the learning experience that it was. This was a great opportunity to reflect upon myself and now I feel I have discovered new abilities I did not know I had. I hope this thesis is a small contribution to the research at TU Delft and that it adds some value to the future students who will be having the same learning experience I had.

Thanks to my supervisors Els and Jan who I consider to be people with excellent human qualities and that was one of the main reasons for my willingness to work with them. I appreciated their feedback and although I did not succeed every time, they were very supportive on my way towards the end of the project.

I want to thank MaaS global for their support with the project. I am very passionate about the topic and it was a great privilege to get to talk to Sampo Hietanen for the development of this thesis. Also thanks to Anne Durand and Lucas Harms from the Netherlands Institute for Transportation Research. They always showed genuine interest towards the project and supported me in everything I needed.

Thanks to family, friends and everyone who showed me their support in the development of this project. I hope the readers enjoy it and feel they are learning something new while reading among figures in these almost 90 pages.

*J. D. Godoy Landínez*
*Delft, August 2018*

# Executive Summary

Traffic congestion has proven to be a wicked problem that is affecting people's economy and health. Until now, traditional policies have not yet been able to solve the problem entirely. To tackle such a challenge, new innovative measures are needed. Mobility as a Service (MaaS), a new paradigm in mobility where all modes of transportation are offered to the user in packages through a digital platform, offers a new approach with a service that could compete with private car ownership, the main cause of traffic. However, there is no policy research on the implications of MaaS and whether an intervention from the government is necessary to boost the reduction in traffic congestion in this new paradigm. MaaS is a system full of uncertainty and it's adoption is a time changing complex process. System Dynamics is an interesting method to close the research gap identified, since it is commonly used in time changing systems with high uncertainty. However, this is a method not commonly use for the study of mobility, and there is a need to identify the challenges when using this method. The main objective of this thesis project is to **evaluate the use of System Dynamics as a research method to understand MaaS**.

The following research question is proposed:

***What are the advantages and disadvantages of using System Dynamics for the analysis of pricing policies in MaaS systems with the objective to reduce traffic congestion?***

The overarching method to follow to answer the main research question is the modelling process of System Dynamics. This process consists of five steps:

- Conceptualization: Using literature review and interviews to experts, the model is conceptualized. The experts consulted are Sampo Hietanen, CEO of MaaS Global and Lucas harms, head of the MaaS research team at the Netherlands institute for Transport policy Analysis.

- Formalization: With existing theories, the exact mathematical structure of the model is defined.

- Implementation: The model is tested with data from a specific case of study. Three main sources of data are used in this step. The department of statistics of the municipality of Amsterdam, the Dutch department of statistics and Amsterdam's Public Transport Operator GVB.

- Validation: The model is subjected to multiple tests to identify the limitations that surrounds its development. A face validation is used to support this tests. The face validation is carried out with Anne Durand, a researcher of MaaS in the Netherlands Institute for Transport Policy Analysis.

- Application: First, through literature review, the main relevant pricing policies are identified. Then, the model is run with each of the relevant policies to see their effects on the different KPIs proposed. The policies to be implemented are tested to evaluate their effectiveness in the base case. A second analysis to be done is an uncertainty analysis. The policies are evaluated under different types of uncertainties to check for their robustness.

After the modeling process is completed, the development is analyzed to identify the main advantages and disadvantages of using System Dynamics for analyzing pricing policies in a MaaS system to reduce traffic congestion.

The following table provides an overview of the advantages and disadvantages of using SD for analyzing pricing interventions in a MaaS system.

| **Advantages** | **Disadvantages** |
|---|---|
| It is simple to integrate the economic, IT and transportation concepts necessary to understand MaaS | Dynamic explanations of MaaS are not common in literature. |
| It offers a chance to create mechanisms out of perceptions and opinions to create a complete model | Lack of research about pricing mechanisms and effect of MaaS on private car ownership limits the model capacities |
| Offers a chance to implement choice modelling dynamically to see how travel times and prices change with time | Modeling taxi behavior is complex due to lack of exclusivity of users. Users may use both MaaS and non MaaS Services even if they do not buy a MaaS subscription |
| By using causal loop diagrams, it is possible to explain the behavior of the system and the main dynamics involved. | Choice modelling requires that the common practice of adoption models in SD is modified. |
| Policies may be compared quantitatively and specific policy advise is plausible | Not possible to model the impact of users choices on habitual preferences. There is an important dynamic missing |
| The methodology is able to provide recommendations under high uncertainty | The model need a large amount of data. |
| It is possible to have a robust model with low sensitivity and values within the theoretical ranges. | Without demand segmentation and area disaggregation, it is not possible to have accurate results. |

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# 1

# Research Definition

The objectives of this chapter are to introduce the research objective of this project and to explain the methodological framework followed to accomplish this objective. It starts with a motivation explaining the relevance for this thesis topic and introducing the objective for the development of the thesis project. Then, it presents the research question with the underlying research sub-questions. After that, it explains the methodological framework followed for the accomplishment of the objective proposed. And finally, it gives a summary of the composition of this report.

## 1.1. Motivation

This section states the relevance of this research project and introduces the research objectives.

Traffic congestion is a phenomenon that affects citizens of many countries around the globe. For instance, in the USA, Los Angeles commuters spent over 100 hours in traffic jams during 2017 (INRIX, 2017). Also, the city of New York is losing 864000 dollars every day due to the worked time consumed by congestion in the metro system (Walker, 2018). In the Netherlands, traffic jams cost Dutch road transportation industry 1.2 billion euros every year (TLN, 2017). These examples not only show that traffic congestion costs billions of euros to countries every year but also that the problem is not exclusive to private transportation. Moreover, traffic congestion has other negative externalities that are not related to the time lost in traffic jams. Research has proven the existence of negative impacts on public health as a cause of the emissions of pollutants from traffic (Levy, Buonocore, and Von Stackelberg, 2010). Other research has shown that the impacts on health are not only related to pollution but also to the stress generated in citizens dealing with traffic congestion (Hoehner et al., 2013). "Sustainable Cities and Commodities" and "Good Health and Well Being" were set as sustainable development goals from the United Nations in 2015 (UN, 2015). Reducing the effects of the impacts on health due to pollution and stress are steps in the right direction towards the achievement of these goals. For its relevance at the international level, urban mobility is an International Grand Challenge.

Reducing Traffic congestion is a difficult task. It can be classified as a wicked problem. A wicked problem is a challenge defined by two main characteristics (Head et al., 2008): disagreement on values and disagreement on knowledge. First, there is disagreement about the degree to which traffic congestion needs to be reduced. Some researches argue that there are situations where traffic congestion is not necessarily harmful. They state traffic congestion is also a natural phenomenon given by the economic growth and for which finding a solution might harm the economy because of the high expenses to do so (Sweet, 2014). Moreover, solutions for traffic congestion are given in the politics arena, which is characterized by multiplicity of actors with differences in perceptions and goals (Macharis and Bernardini, 2015). This add difficulties to the implementation of solutions. The second characteristic of wicked problems is that there is not enough knowledge to provide a solution. The range of policies applied to solve the problem of traffic congestion is very wide. At first, policies aimed at controlling urban traffic with the use of technologies such as traffic lights and innovative technological systems for urban control (Hamilton, Waterson, Cherrett, Robinson, and Snell, 2013). Nowadays, there are discussions in much more other areas ranging from the promotion of other transportation modes such as the bicycle (McClintock, 2002) to the use of pricing policies to motivate the use of public transport PT (Cats, Reimal, and Susilo, 2014). The complexity of the system and the relevance of the search for solutions is a call for new innovative ideas and policies towards the achievement of a sustainable mobility system.

A new innovative proposal to tackle traffic congestion is the implementation of a new mobility paradigm called Mobility as a Service (MaaS). According to Hietanen (2014), MaaS is a new service system for urban mobility being developed by upcoming start-up companies. The main characteristic of a MaaS system is that a high diversity of transportation services are offered to the user on a single platform. In other words, a user can access a service from a group of different transportation modes available, such as public transport, taxis, car rental, bike sharing, car sharing and others, by the use of a single interface, usually a mobile application. In this new system, the user can interchange dynamically between private and public modes of transportation by using a unified gateway. This system promotes the use of multiple modes for the flexibility and customization offered to the user by the platform. In this model, users either pay a monthly subscription to have access to the services or they pay only for the services they use (Hietanen, 2014).

It is argued that MaaS could be a solution for traffic congestion since it would promote efficient car sharing and the use of public transportation. Moreover, promoters of this new system state that having a flexible package with multiple transportation modes offered could compete against the use of private car. The main assumption is that users of private cars stick to having their own car because of the flexibility and the comfort that it offers. If a system gives them the same flexibility and comfort, it is possible that users sell their cars and shift to more sustainable modes of transportation (Hietanen, 2014). However, these effects are not clear in literature yet, especially because MaaS has not been broadly implemented yet (Lund, 2016). On the other hand, there are already many stakeholders committed to MaaS development at a large scale. Companies, universities and Non-Governmental Organisations (NGOs) are already defining common strategies to study, promote and implement MaaS at larger levels. In the Netherlands, Connekt, an independent network for smart mobility, created the MaaS Taskforce, a group of stakeholders responsible of promoting the implementation of MaaS in the country and beyond borders (Connekt, 2017). At the European level, the MaaS-alliance has the same role (The MaaS Alliance, 2015). With these organisations, the awareness about MaaS is growing and it is becoming a common topic in transportation research.

Currently, research around MaaS is focusing on the role of MaaS Service Providers (MSPs). MSPs are the companies or organizations responsible for providing the digital platform service. It is common to find studies about the digital infrastructure and the cyber security issues around MaaS (Callegati, Giallorenzo, Melis, and Prandini, 2017). Also, studies about the preferences of users towards these services are trending (Ratilainen, 2017). However, there are no or few policy research studies about the role of the government in the implementation of MaaS (Connekt, 2017). Since the effect of MaaS implementation on traffic congestion is unknown, it is unclear whether the government has an incentive to create interventions, such as tax schemes and subsidies that are favorable to MaaS adoption. Moreover, there is total uncertainty regarding what is the expected effect of these interventions on the traffic system. The current state of the art does not allow to fill this research gap completely. The lack of research generates large uncertainty in the data and on the mechanisms which surround the solution to this question.

However, under scenarios of large uncertainty in the behavior, data and mechanisms of a system, there is a modeling method that could raise conclusions on the performance of pricing governmental interventions in a MaaS system and whether these interventions are convenient to reduce traffic congestion. This method is called System Dynamics (SD). SD is used for the understanding of complex systems with feedback mechanisms (Sterman, 2000). A feedback mechanism occurs when the decisions and the behavior of the variables of today will influence the decisions and the behavior of these same variables in the future. In other words, SD helps to describe the causal relations within a system and how they affect its behavior in time. It is grounded in the theories of nonlinear dynamics and feedback control. In this method, a complex system, such as MaaS, is basically modeled in terms of entangled integral equations.

SD is a common tool in Policy Analysis for problems that change their nature with time. It is used for well-informed decision-making processes and it promotes an academic discussion to design solutions to societal problems (Bala, Arshad, and Noh, 2017). However, there are only a few studies that are using this tool to evaluate how policy interventions can affect traffic congestion and pollution in urban environments. Common transportation modeling approaches apply static models. This is, these models do not describe the evolution of the system but rather a picture in a specific point of time (Ortuzar and Willumsen, 2011). Hence, these models are unable to capture the changing dynamics of the adoption of a new system, such as the adoption of MaaS. It does not mean they are not useful. Some of these models have already been applied to MaaS to see what could be its implications in traffic when fully implemented (van Kuijk, 2017) but there is no research available about the use of System Dynamics to understand MaaS and whether it could describe the implications in traffic congestion of its evolution to a fully implemented system.

To conclude, traffic congestion is a wicked problem affecting people's economy and health. To tackle such a challenge, new innovative measures are needed. MaaS offers a new approach with a service that could compete with private car ownership. However, there is no policy research on the implications of MaaS and whether an intervention from the government is necessary to boost the reduction in traffic congestion. Since MaaS is a system full of uncertainty and it's adoption is a time changing complex process, SD is an interesting method to close the research gap identified. This conclusion leads to the identification of the research objective for this thesis. This objective is to **evaluate the use of SD as a research method to study the effect on traffic congestion of different pricing interventions in a MaaS system**. Three goals need to be achieved to fulfill this objective. First, it is expected to see the possible behavior of traffic congestion under a MaaS system. It is relevant to test the assumptions that MaaS can help to reduce this phenomenon. Secondly, it is intended to see possible scenarios under which pricing policies could reduce traffic congestion. Finally, it is important to reflect on the process of this research to identify the relevance and utility of SD as a method to study the possible implications on traffic congestion of pricing interventions in MaaS systems.

## 1.2. Research Questions

This section introduces the main research question raised for this project in accordance with the research objective written in the previous section. Then, it states the necessary research sub-questions to be answered towards the successful development of a solution for the main question.

### 1.2.1. Main Research Question

As mentioned in the motivation section, the objective of this research is to evaluate the use of SD to study the effect of pricing interventions on traffic congestion in MaaS systems. The following main research question is derived from the objective proposed:

***What are the advantages and disadvantages of using System Dynamics for the analysis of pricing interventions in MaaS systems with the objective to reduce traffic congestion?***

### 1.2.2. Research Sub-questions

In the motivation section, three important goals for the successful achievement of the objective are stated: identify the behavior of traffic congestion in a MaaS system, identify relevant pricing policies that could boost the reduction on traffic congestion in a MaaS system, and to identify the advantages and disadvantages of the use of SD to analyze the behavior of traffic congestion on MaaS systems under pricing interventions. The following research sub-questions are raised as a representation of these necessary goals towards the fulfillment of this thesis.

The first step is to use SD to build a model for MaaS systems. Hence, the following question is proposed as a start for the project:

***How can MaaS systems be conceptualized in terms of feedback relations between quantitative variables?***

As explained in the motivation, SD is a methodology that describes systems with feedback mechanisms. These mechanisms need to be identified as a first step of the process. The first question should lead to the description of the behavior of traffic congestion in a MaaS system. Once this objective is accomplished, the next step is to use the model built to evaluate possible pricing interventions and their effects on traffic congestion. The following two research sub-questions lead to that goal.

***Which are the relevant pricing interventions to the system that could affect traffic congestion?***

First, it is necessary to identify the relevant interventions that could boost the reduction of traffic congestion under MaaS. Then, the policies identified need to be implemented and tested in the model, leading to the next question:

***How different types of pricing interventions affect the performance of traffic congestion in the system modelled?***

The final step is to reflect on the process followed towards the accomplishment of the first objectives. From this reflection, the main advantages and disadvantages of the method used may be described.

***What are the main advantages and disadvantages when using System Dynamics to analyze Mobility as a Service and its effects on Traffic Congestion?***

To conclude, the first question relates to the process of understanding MaaS and modeling it with the use of SD. It has a direct relation with the goal of describing the behavior of traffic congestion in MaaS systems. The second and third sub-questions refer to the process of policy identification and policy testing with the use of the SD model built. This permits to identify the policies that could reduce traffic congestion in MaaS systems. Finally, the last sub-question closes the cycle of this research with a reflection to answer the third sub-question and the main research question. This leads to the identification of the main advantages and disadvantages of using SD to evaluate the impacts on traffic congestion of pricing interventions in MaaS systems.

## 1.3. Project Scope

This section uses the two-dimensional framework formulated by Florian, Gaudry, and Lardinois (1988) to map the scope of this project. The objective is to understand where this research stands in relation to common practices of transportation modeling and planning.

The framework from Florian, Gaudry, and Lardinois (1988) uses two dimensions to understand and classify transportation planning problems. The two dimensions proposed are named “level of analysis” and “perspective”. The first dimension refers to which variables of the transportation system are of relevance for the objective of the research. The second dimension refers to the type of decision process involved in the policy question asked. To understand better this framework, it can be represented in the following figure:

Figure 1.1 shows a table which rows represent the different levels of analysis of a transportation problem in relation with the first dimension and which columns represent the different types of decision process involved in reference to the second dimension. In the perspective dimension, the column "operational" refers to actions taken by transport suppliers and decision makers in the day to day operations of the system. This perspective is out of the scope of this project. The model objective is to analyze tax and subsidies schemes and not operational issues such as management of failures of the modes of transportation in the system. The "strategic" perspective refers to big investment interventions such as changes in the transport infrastructure. This level is, as the previous one, out of the scope of the project for the analysis is not meant to be about a long term infrastructure building policy but rather a middle term policy involving pricing interventions. The "tactical" category refers to actions of allocation of resources to impact the system. Taxes, fares and subsidies, which are the focus of this project, belong to this category. In this perspective, impacts are visible in a mid-term horizon. For this reason, the time frame in the model for this project must be a value in which the effects are visible but also not highly affected by possible changes in the strategic perspective.

In the dimension “levels of analysis”, the transportation system is classified to six components. From figure 1.1, it is visible what the endogenous and exogenous components of the model should be according to every perception option. Endogenous components, which are those that are calculated internally by the model, are represented with a gray square while exogenous components, which correspond to those variables that are inputs to the model or external variables that are out of relevance and do not affect the system, are represented by a white square. In the tactical perception, corresponding to the one used in this project, the endogenous components are demand, performance and transportation supply actions. These components should be taken into account for the objectives of this research. In specific, the performance of the system is the center of the problem of traffic congestion when performance is understood as time efficiency. The demand and transport supply actions correspond to the relations within the MaaS system between the service

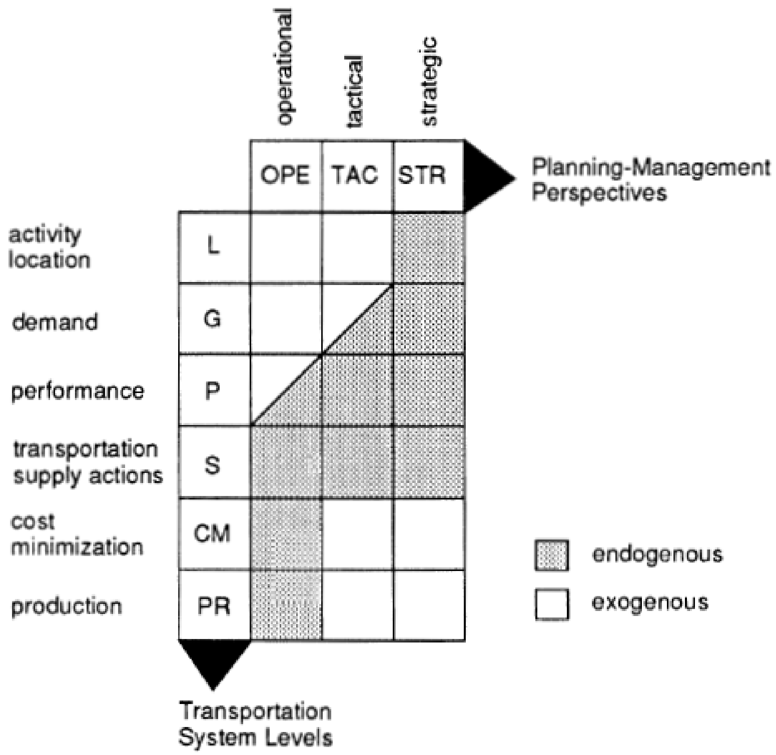



Figure 1.1: Two-dimensional framework for transportation planning problems (Florian, Gaudry, and Lardinois, 1988)

providers and the users. These interactions must be modeled endogenously for the purpose of understanding performance. According to the figure, demand might have a dual role as an exogenous or endogenous variable. This choice depends on the objectives of the model. For this thesis, it is relevant to intended o identify how MaaS affects traffic congestion. Hence, the demand of the use of private car needs to be modelled endogenously. However, the total travel demand is an exogenous value, since whether MaaS will attract new inhabitants from other cities is outside of the scope. The production and cost minimization components are exogenous variables that are more related to the microeconomics effects of service providers. These are outside of the scope of the research question, since the objective is to analyze traffic congestion. They will not be analyzed thoroughly in this project although they could be taken as exogenous inputs to the model. The activity location corresponds to the spatial scope for the model. It is not modelled endogenously but it is rather an input to the model.

To conclude, this project focuses on the tactical perspective of the two-dimensional framework. While performance is the main outcome of interest for the research question, other variables such as transportation supply actions must be modeled endogenously within this perspective. Cost minimization, production and activity location, although they are exogenous and might be outside of the scope of the main research question, might be used as inputs to the model. Demand has a dual role. For this research, the demand of the use of cars is modelled endogenously and the total travel demand is exogenous.

## 1.4. Methodology

This section explains more in detail what are the methods to be used to accomplish the objectives and to answer the research question. First, it explains the general research approach used for the development of the project. After, it describes the methods used to answer each of the research sub-questions. Finally, it summarizes these concepts with the use of a research flow diagram to understand the development of the project.

### 1.4.1. Research Approach

MaaS is a complex system. Not only does it involve a multiplicity of actors but it also deals with the complexity of the social interactions of the transportation market. It is necessary to explore new methodologies to overcome the lack of understanding of this sociotechnical system. According to Neuman (2013), research studies can be classified as either quantitative or qualitative. The identification of the type of research is relevant for the selection of a proper research approach. Even though the research question has a qualitative answer, SD, the main subject of study is an essentially quantitative method. Moreover, two of the three research objectives are only accomplished by a quantitative answer. The numerical description of the behavior of MaaS and the mathematical analysis of the influence of the pricing interventions in this system. Hence, this model is classified as quantitative research. Quantitative research can be broadly divided into two categories: exploratory and conclusive. While conclusive research can either establish the existence or nonexistence of causal relations, exploratory research lacks these characteristics (Neuman, 2013)

An exploratory research approach will be followed to answer the main research question and develop the role that SD should have when analyzing pricing policies under a MaaS system. This approach is useful when there is high uncertainty in the knowledge behind a topic, when the scope of the project is unclear or when the concepts and problems are not well defined. MaaS is a new concept that is recently being studied. Hence, there is not enough literature to support quantitative relations between the causal variables within the system. However, with an exploratory approach it is possible to establish the first step towards the use of System Dynamics in this topic. This approach is helpful when a single theory does not describe the system sufficiently. It is possible to understand what are the difficulties of this methodology and what are the relevant variables to understand MaaS from an SD perspective. These are the reasons why an exploratory approach is chosen for this study.

### 1.4.2. Methods

This section gives an overview of the different methods used to answer each of the sub-questions proposed for this exploratory research. The methods are described after restating each of the research sub-questions in the following paragraphs.

***How can MaaS systems be conceptualized in terms of feedback relations between quantitative variables?***

The specific overarching method to be used for this research sub-question is System Dynamics (SD). Sterman (2000) provides a definition of SD by stating that it is an approach to study complexity that is grounded on nonlinear dynamics and control theory. This approach tries to explain the behavior in time of complex dynamic systems. Sterman (2000) states that dynamic complexity arises when all or some of certain characteristics describe a system. These characteristics are: Dynamic, tightly coupled, governed by feedback, nonlinear, history-dependent, self-organizing, adaptive, counter-intuitive, policy-resistant and characterized by trade-offs.

Even though all of these features are present in the MaaS system, there are two main characteristics that provide justification for using this modeling approach compared to other modeling techniques. First, the time dimension is important to develop an answer for the research question. In other words, the problem is dynamic. When analyzing MaaS as a policy, there might be possibilities where certain tax schemes generate the same benefit but on different time frames. These types of policies need to be treated differently. A static model does not allow to check for these nuances. Usual regression models in transportation are static and when they are dynamic, they focus on small time frames such as 24h models (Ortuzar and Willumsen, 2011). Secondly, the system Is governed by feedback. In other words, when a variable changes in a certain moment of time, it will trigger dynamics that will affect the same variable in the future as well Sterman, 2000. For example, when adopting new technologies, the word of mouth plays an important role on the number of users of the system. Namely, the users of today can attract or repel users in the future.

The following paragraphs explain the modeling process of translating the system into feedback relations. This process has five steps as defined by (Sterman, 2000): Problem Articulation, Model Conceptualization, Model Formulation, Testing and Model Application.

The first step of the modeling process is the **Problem Articulation**. This is perhaps the most important step in the modeling process. In this step, the specific question to be solved is identified and scoped. When models are bigger than needed, they are less likable to provide insights to solve the problems that they were built for. This phenomenon is known as the Ockham's razor (Ariew, 1976). To avoid this problem, there are three things that must be defined in the problem articulation.

The first aspect to be considered is theme selection. It is important to identify what is the problem and why is it a problem. This process corresponds to the identification of the research gap for this thesis project. The methods to solve this question are usually desk research, including a literature review, and interviews with stakeholders.

The key variables in the model must be identified. In this thesis, the literature review provides all the theoretical background behind the topic to build a model. It helps to identify what are the definitions and main characteristics of MaaS. Besides, identifying the key variables helps to know what parts of the system must be left out for the proper lead to a solution for the research question. The key words to be used during the search in article databases are **"Mobility as a Service"**, **"Integrated Mobility"**, **"Transportation Pricing Policy"** and **"Transportation System Dynamics"**. Moreover, the Key Performance Indicators (KPIs) are identified. These are the variables under which policies will be tested. These variables need to be in direct contact with the research objective. in specific, they should represent traffic congestion.

Interviews with experts are also a useful method to gather knowledge for the problem articulation. There is no specific formal methodology to be followed during interviews in this research. However, interviews done in an informal setting to complement the literature gathered from the desk research are included.

There are interviews included from the following experts for the problem articulation:

- Sampo Hietanen: CEO and founder of MaaS global and the first one to introduce the concept of MaaS.
- Lucas Harms: Head of the MaaS Research Team at the Institute for Transport Policy Analysis in The Netherlands.

Finally, The time horizon is a critical factor for this step. it is important to define the time scope of the model. It is already being mentioned that for the purpose of this research, only the tactical level would be taken into account. The identification of a specific quantitative time horizon depends on the scenario in which the model is tested.

The second step in the SD modeling process is the **Model Conceptualization**. This step needs a deep literature review. It uses already formulated theories with quantitative relations to formulate a model that explains the behavior of the system. **Wegener's cycle**, a feedback relation used in transportation modeling is a special conceptual tool included in this step of the modeling process (Wegener, 2004).

In this step, the model is represented with diagrams. The specific common diagramming tool used in this thesis are causal loop diagrams. Specific numbers and equations are not necessary at this step, the objective is only to formulate an explain the system in terms of feedback and accumulation relations.

The **Model Formalization** step is where the specific structure of the model is finally proposed. Based on the literature and the purpose of the project, in this step, it is necessary to define the specific parameters, equations and initial values that are meant to be used in the model. The mathematical tools of **Akcelic Functions**, a function to calculate travel time in roads (Akcelik, 1991), and **Choice Modelling**, a method to model choices of actors (Hensher and Johnson, 2018), are included for specific mathematical relations within the model. Ortuzar and Willumsen (2011) is used as a guide for the process.

In this step, the base scenario for which the model is implemented need to be defined with the relevant data. This is called **Model Implementation**. In this thesis project, the model is to be tested for the area covering **Amsterdam Transport Region**. This region is made up by the municipalities of Aalsmeer, Amstelveen, Amsterdam, Beemster, Diemen, Edam-Volendam, Haarlemmermeer, Landsmeer, Oostzaan, Ouder-Amstel, Purmerend, Uithoorn, Waterland, Wormerland and Zaanstad. This area is the area interconnected by the

Public Transport Network and these municipalities act together in the implementation of transportation policies Vervoerregio Amsterdam, 2018.

There are mainly four data sources to be used for the development of the Amsterdam Region scenario in the model. The data is available on their platforms on the internet:

- Statistics Netherlands (CBS): A governmental institution from The Netherlands dedicated to organize and provide reliable data for social debate (CBS, 2018).
- Research, Information and Statistics from Amsterdam Municipality (OIS): Data from research from the Municiaplity of Amsterdam is available on the internet at their open data initiative (OIS, 2018).
- Taximonitor Amsterdam: This is a yearly report about the state of the taxi market in the city of Amsterdam (Gemeente Amsterdam, 2018).
- GVB: GVB is the company responsible of the management of the public transport in the city of Amsterdam (GVB, 2018).

The first analysis to be done is a base case analysis. Here, a specific base case is chosen to run the model. The analysis is meant to understand how the key performance indicators will behave and what are the dynamics that explain this behavior.

**Testing** or **Model Validation** is a process in which the model is evaluated to see if it useful for the purpose by which it was created. This process is continuously being done while the model is being developed. It leads to constant changes in the other steps of the modeling process because this step is the one that is specifically design to identify flaws on the progress of the research. Sterman (2000) is used as a guide of the tests to be done in the validation process.

Moreover, to support the validation process, an interview is held with the following expert:

- Anne Durand: full-time researcher in the topic of MaaS at the **Netherlands Institute for Transport and policy Analysis** known as KIM.

She has access to the model and there is a feedback session in an informal setting to check the model design, implications and results.

**Which are the relevant pricing interventions to the system that could affect traffic congestion?**

The relevant step of the modeling process to identify the most relevant policies for evaluation is the **Policy Design and Evaluation** step or **Model Application**.

In this step, it is necessary to establish a Policy Design. The policy design has two components. First, the relevant policies for the model need to be identified. For this, the same interviews to be done in the setting of the problem articulation are used for the identification of these policies with experts on the field. Then, this policies need to be implemented in the model. The implementation of the policies in the model might require new structures including more feedback loops in the system. This step, also requires the setting of the scenarios under which it will be tested. The scenarios correspond to foreseeable futures under which the system might be subjected that are relevant for the project. The identification of these scenarios is brought up from the literature review or from interviews to stakeholders.

**How different types of tax schemes and service packages affect the key performance indicators for traffic congestion in the system modelled?**

After setting up the policy design and the scenarios by which the policies will be tested, the model is run with each of the relevant policies to see their effects on the different KPIs proposed. The policies to be implemented are tested to evaluate their effectiveness in the base case. A second analysis to be done is an uncertainty analysis. The policies are evaluated under different types of uncertainties to check for their robustness.

***What are the main advantages and disadvantages when using system dynamics to analyze Mobility as a Service and its effects in Traffic Congestion?***

The method to solve this question is observational research. This question is related to the validation of the model since it is the process in which more flaws are found and where the challenges to overcome while modeling are clear. By doing observation on the practice of the modeling process itself and how it has changed the validation outcomes, it is possible to identify the main challenges encountered while using system dynamics to evaluate Mobility as a Service. The interview with Anne Durand includes questions related to the critique of the method itself to identify its advantages and disadvantages.

## 1.5. Report Structure

This report consists of seven chapters. The first and current chapter corresponds to the research definition.

Chapter two is Model conceptualization. In this chapter, the process towards the formulation of a dynamic model is presented. This chapter includes the literature review and how it shaped the model developed. Also, it presents the main insights obtained from the interviews held. Then, it presents and overview of the model components and sub-models designed for explanatory purposes. It breaks down the components of the model and its causal relations. This chapter ends with a summary of the structure of the model.

The third chapter is called model formalization. In this chapter, the specific mathematical tools for the implementation of the model are presented and related to the model built. The third chapter shows the detailed structure of the model in terms of causal-loop diagrams. This chapter is equivalent to the formulation of a simulation model step of the modelling process. It ends with a summary of the detailed mathematical structure presented.

Chapter four, model implementation, presents the base case chosen for the model and its data input. Formally, this chapter still corresponds to the formulation of a simulation model step. However, it is independent from chapter four to make a differentiation between the mathematical structure, which is endogenous and the base case scenario which relates to exogenous inputs. Besides, this chapter also presents the results of the base case scenario and its correspondent analysis. At the end of the chapter, a summary about the base case results, its data input and its data treatment with the corresponding limitations is presented.

Chapter five presents the model validation process of the model. It includes a summary of the main outcomes of each of the validation tests presented, including the face validation with the interview at KIM. At the end of the chapter, a summary with the main findings from this process is presented.

Chapter six introduces the policy design implemented to test the model under different scenarios and uncertainties present. It shows the results for each of the scenarios presented and gives at the end of the chapter a summary with the findings and possible policy recommendations. This chapter is known as model application.

In chapter seven, there is a critical reflection on the process followed that lead to identify the main advantages and disadvantages of using SD to study the effect on traffic congestion of pricing interventions in MaaS systems.

The last chapter is conclusions. It includes three sections: one conclusion section summarizing the main findings of the research project, one limitations section stating what are the limitations of the model and possible improvements and one recommendations section with possible ideas for future research.

Finally, to summarize, figure 1.2 offers an overview in a diagram of the methods used for this research and their relation with the chapters here introduced.

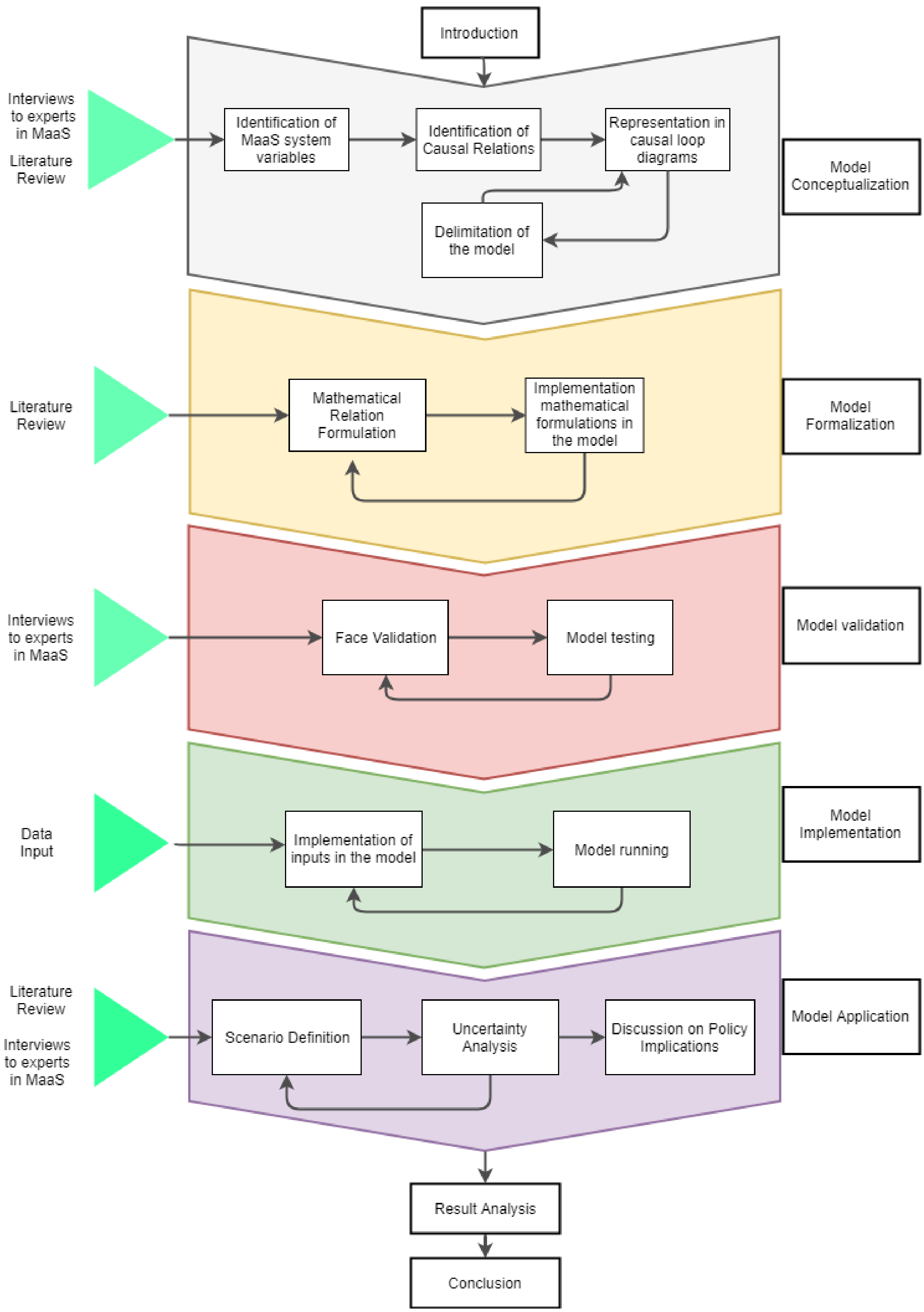



Figure 1.2: Research flow diagram

# 2
# Model Conceptualization

This chapter describes the process towards the construction of a dynamic hypothesis. In other words, the objective of this chapter is to understand the drivers of MaaS and its implementations to translate them into a model. This chapter has three main sections. First, it develops the literature review and interviews followed towards the understanding of MaaS and explains the implications of these findings towards the building process of a model. Then, the second section organizes the information found towards building a structure that can represent the behavior of the system. Finally, a summary is given with the main structure of the model and the endogenous and exogenous variables involved.

## 2.1. Literature Review

This section describes the important insights from the literature review around MaaS and how they relate to the interests of this project. The objective is to identify the main concepts around MaaS and what are the drivers that will influence the system on time. It is critical to identify the time nature of the system since SD is fundamentally used for dynamic problems.

### 2.1.1. Mobility as a Service Definition

To begin understanding the problem, the first step is to define it. This project lies on the concept of MaaS. Since this new business model has recently been developing, the concept itself has been dynamic, too. The first and basic definition was provided by Hietanen (2014). To him, MaaS is a mobility distribution model where all needs of the user are satisfied by a unified platform. In this distribution model, the service provider offers mobility packages to the user that can be paid monthly, like a mobile phone contract.

There are four core features from this definition that are relevant for the understanding of MaaS. First, it integrates specifically mobility services. Whenever a service is not oriented to offer a user the possibility to move between two places, it is not considered as a MaaS service. However, this is not enough to differentiate MaaS from a general transport service. A second important characteristic is that MaaS offers the opportunity to integrate services. This is, a single platform, for example a digital application, is able to offer the user different transport modes. Interconnectivity is then fundamental for a service to be considered as a MaaS system. A MaaS service also offers bundles. This is, the service is offered in packages that are generally paid monthly, like a mobile phone contract. Finally, a fundamental characteristic for a service to be considered MaaS is that it is user-oriented. In other words, the service accommodates to the user characteristics and needs, and it is not the case that the user accommodates to the service, such as a traditional transport service. As the base of the MaaS system, these characteristics should be included in the SD model.

The definition of Hietanen (2014) offers a good starting point to understand MaaS. However, it lacks in specificity. Other authors have delimited more thoroughly what the boundaries of the definition are and they have added specific characteristics to consider what a MaaS service is. Some of them have focused on the communication aspects of MaaS. Cox (2015) enhances the definition by stating that MaaS has strong similarities with the telecommunications sector. Finger, Bert, and Kupfer (2015) stated that internet is a natural platform for the service of MaaS to be implemented. Callegati, Giallorenzo, Melis, and Prandini (2017) makes a more thorough reflection on this aspect of MaaS. In this article, the concept of Mobility as a Service takes inspiration from the concept of Cloud Computing. In Cloud Computing, users access services without regards of where they are hosted. These services are accessed by mediation of a single interface. Hence, the users perceive they receive the service from a single agent. When, in reality there is a federation of mobility operators, each trading its resources in a digital market. In other words, even though all services are integrated in a single platform, the transport modes offered in the platform are still competitive between each other.

Other authors have focused their research on defining what the characteristics of MaaS are instead of providing a specific definition. They focus on defining a framework to understand mobility services. According to Kamargianni, Li, Matyas, and Schäfer (2016), a MaaS system can be understood according to its level of integration. This is a list of the different types of integration that can be found in these mobility services.

- Ticket and payment integration: All modes can be accessed by the use of a single smart card or ticket. Besides, they are all charged to a single account. This sort of integration let the user access services faster and the payment is easier, making public transportation more attractive.
- Mobility Package integration: Customers prepay for an amount (in time or distance) of a combination of mobility services.
- ICT integration: there is a single application or web interface that can be used to access information of all the modes offered.

MaaS systems can be classified to three integration levels according to the degree to which they achieve the integration features described before:

- Partial integration: Platforms that only achieve either payment integration or ticket integration, combined with ICT integration.
- Advanced Integration: It includes Payment integration, ticket integration and ICT integration.
- Advanced + Mobility Package: Extension of the previous one plus the feature of offering mobility packages to users.

The framework offered by Kamargianni, Li, Matyas, and Schäfer (2016) has contradictions with the one presented previously from Hietanen (2014). Hietanen (2014) states that systems without the full integration could also be considered MaaS systems. While for the former one, the presence of packages is necessary in the concept. Even though the added value of MaaS is in its alleged flexibility for the packages included, it is important to consider in the model that full integration might not be necessarily possible, because not all transportation service providers necessarily agree to be a part of MaaS. The possibility to run the model with different integration scenarios should be included.

There is an important conclusion from this study. It is that the literature studied has shown that all types of integration have positive impacts on the demand of transportation. This is, when studying MaaS, not only changes in the transport demand due to changes in behavior and car-ownership should be considered, but also other components of the MaaS system such as intermodal journey planner, payment methods, booking system, real time information and mobility packages. This implies that the quality of the digital platform has an impact on the behavior on the user. This causal relation should be included in the SD model.

Jittrapirom et al. (2017) identifies the core characteristics of MaaS systems. For this, 12 different digital platforms that fit the definition of MaaS by Hietanen (2014) were carefully analyzed. The core characteristics proposed by the authors are:

- Integration of transport modes: MaaS systems offer the user an opportunity to integrate all different modes of transportation into one single platform.
- Tariff option: MaaS providers are responsible of charging the user the tariff for the service. The tariff can be a regular monthly payment in form of packages or payment for the direct use of the system in a specific time, mode and/or distance.
- One platform: All necessary digital services for users' trips, such as trip planning, booking and payment, can be accessed by them in one single platform.

- Multiple actors: MaaS ecosystems are characterized by the interaction of multiplicity actors. The main ones are the users, the platform service providers and the transport providers. Other actors such as the government are facilitators of the system.

- Demand orientation: MaaS is a user-centric paradigm. It offers a solution that is best from customer's perspective.

- Personalization: The system offers the user services according to his/her profile, preferences and behavior.

- Customization: The user can also modify service options according to his/her preferences.

Comparing with the previous definitions exposed, Jittrapirom et al. (2017) three new concepts to the definition of MaaS. Two of these concepts, personalization and customization emphasizes that MaaS services have the possibility to offer specific services designed for the user. This is done by gathering the data of the user through the platform. The other fundamental concept added is that MaaS is a system that is characterized by a multiplicity of actors with platform service providers, also known as MaaS Service Providers (MSPs), transportation providers and users being the main ones.

To conclude, recalling the core characteristics of MaaS derived from Hietanen (2014), it is possible to summarize the added features of the authors that have studied the definition of MaaS. First, it is a system that offers mobility services. However, these services still compete between each other through a digital market. Secondly, interconnectivity is a key feature of the system. It is related to integration. This integration may be partial or full depending on whether there is ticket, payment, ICT and package integration in the digital platform. Third, the packages may be offered in bundles to be paid regularly as in the telecommunications sector. Finally, the system is user-centered, and it offers customization and personalization options to the user. This makes the development of the digital platform a critical characteristic for the implications of MaaS in the transport system, specifically, in traffic congestion. Moreover, another characteristic of the MaaS system is that it is a multi-actor system. This adds complexity to the policy process. It is an aspect of MaaS that needs to be studied more thoroughly for this research.

### 2.1.2. MaaS Definition for this Project

The previous paragraphs conclude about the characteristics of MaaS defined in literature. These characteristics are summarized in the following definition to be used in the research project.

*MaaS is a subscription based service that offers its users mobility solutions by means of different transportation modes (competitive mobility services). The service is supported by a single digital platform that integrates these transportation modes (interconnectivity) and gives the user support by mean of digital services (user-centered). The services are offered individually or by packages that are be paid at regular periods (bundles). Moreover, MaaS operates in a system with multiple actors.*

It is close to the definition from Hietanen (2014). However it adds specificity in that MaaS is not only about the mobility services offered but also about the complementary digital services which Kamargianni, Li, Matyas, and Schäfer (2016) has shown to be relevant to understand the development of MaaS. And also, it specifies the multi-actor nature of the MaaS system.

Figure 2.2 shows a simple illustration of the concept of MaaS. In the figure, it is visible that the idea of MaaS is to integrate all transportation providers, whether they are public or private, into a single digital platform. This platform is the media on which users rely to interact with the transportation providers' network and it is the access to the market of mobility for the transportation providers. Besides, it offers services such as bundling, routing, payments, etc.

The proposed definition is fundamental because the System Dynamics model to be built has to include all the proposed characteristics. The level of integration is not explicitly mentioned in the definition because different MaaS service providers differ in this characteristic. An approach to deal with this uncertainty is to include it as different scenarios to analyze within the model.

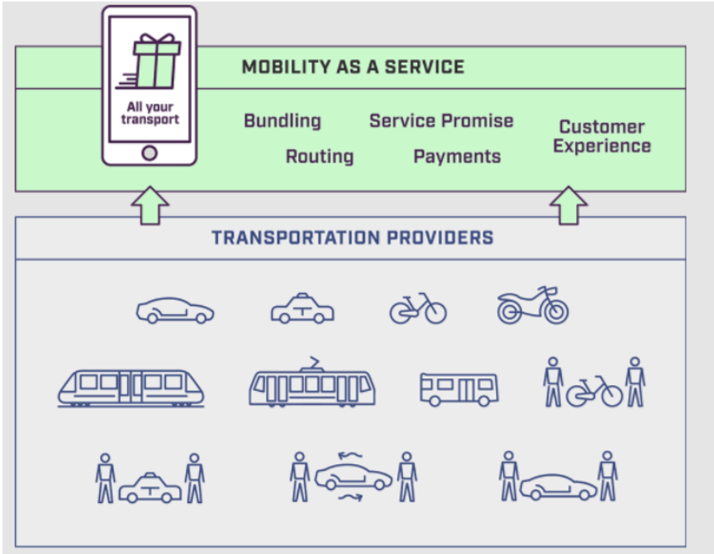



Figure 2.1: MaaS System Definition (MaaS Global, 2018)

### 2.1.3. MaaS Framework

This section explains the framework under which MaaS is studied, with the objective to define more thoroughly the characteristics of MaaS. In specific, there are two important aspects to analyze: the specific actors involved in the operation and development of MaaS and the modes of transportation included in the system.

The main framework for the different types of MaaS services is developed by Holmberg, Collado, Sarasini, and Williander (2016). This framework is useful to characterize where the definition of MaaS used in this project stands and what specific characteristics it has. Within the mentioned framework, MaaS can be analyzed by two different dimensions: level of system integration and ownership. The framework can be visually understood in the following figure.

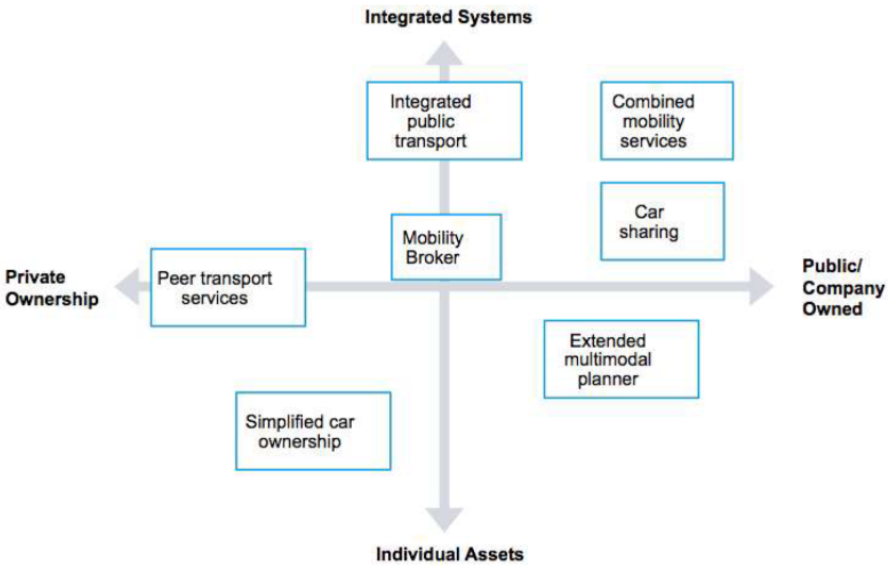



Figure 2.2: Integration Vs Ownership Model Holmberg, Collado, Sarasini, and Williander, 2016

The level of system integration accounts for the number of assets that are included in the service. This can range from a simple car sharing platform to a fully integrated system that includes car sharing, bike sharing, taxi companies and public transport. The second dimension is the level of ownership. There is a common believe that all MaaS platforms exclude the use of private car. However, this is not always the case. For instance, peer transport services such as car pooling can be included in the MaaS platform. In these platforms, the modes of transportation are privately owned. Most common MaaS platforms developed until now have public or company owned assets.

The definition provided for this project is in the category of Combined Mobility Services (CMS) because it does not make any distinction on the ownership nature of the assets offered. Hence, it implies that there are no exceptions. These includes taxi companies and public transport, which are integrated systems with publicly or company owned assets. Modeling levels of ownership on the left of the graph is not relevant for this study. There are mainly two reasons. Most of the capacity is installed in the company or publicly owned services and secondly, for the case of privately owned assets, whenever a user takes a car of other user, the number of cars being used is conserved because it is a transaction of two users that do not affect the number of trips in the other modes of transportation. Hence, it is sufficient to model privately owned transportation as a single component in the SD model. It is explicitly defined as simply "Private Car". Finally, as mentioned before, the level of integration can be considered a scenario of the SD model.

A critical characteristic to define MaaS within a framework is the specific types of services offered. van Kuijk (2017) sets out the main modes available in MaaS systems when they have CMS characteristics. By interviewing experts, he determines what the most probable services to be encountered in MaaS systems are. The study concludes that MaaS will most likely include five services within the packages.

- Public Transport: Lines that move significant amount of passengers such as metros, trams, buses and trains.
- Shared Car: The use of car stations were the user can pick up a car owned or managed by the MaaS provider. The same car might be used by other users in other stations.
- Shared Bike: The use of bike stations were the user can pick up a bike owned or managed by the MaaS provider. The same bike might be used by other users in other stations
- Taxi: A taxi corresponds to a drop on drop off service where the user is picked up at his or her convenience.
- Shared Taxi: It is when the taxi is shared by other users that do not necessarily have the same destination but may have similar routes.

It is important to highlight that besides the included services, users may still use their own private assets such as private bike or a private car. Moreover, as mentioned before, private car is a category that already account for the impact on traffic congestion of privately owned assets since these services do not affect other services in the system.

Figure 2.3 shows the configuration of MaaS services as described above. The users can decide to be a part of MaaS which offers integration services or choose their preferred service without a MaaS subscription.

The final aspect to describe of the MaaS framework is the multiactor nature of these systems. CMS systems have a specific set of actors that at involved in it. Jittrapirom et al. (2017) introduced the users, MSPs and transportation providers as the main ones. However, this set of actors is more deeply explained by Holmberg, Collado, Sarasini, and Williander, 2016:

- Transport Service Providers: These are private providers of mobility services. It includes car sharing companies, bike sharing companies, taxi companies, among others. Public transport has a different role, then it is not considered in this category.
- Public Transport Operators (PTOs): Public Transport is considered to have a different role because it is considered a merit good. A merit good is a good that is not sufficiently attractive enough for users individually but because of the negative externalities of not using it, it is necessary to subsidize it (Musgrave, 1956).
- CMS Service Operator: The operators provide the CMS offerings and manage them locally.
- CMS Service Provider: This actor is responsible of ensuring the growth of the CMS. For this, it is important to act coherently with the CMS operators and grow the service geographically.

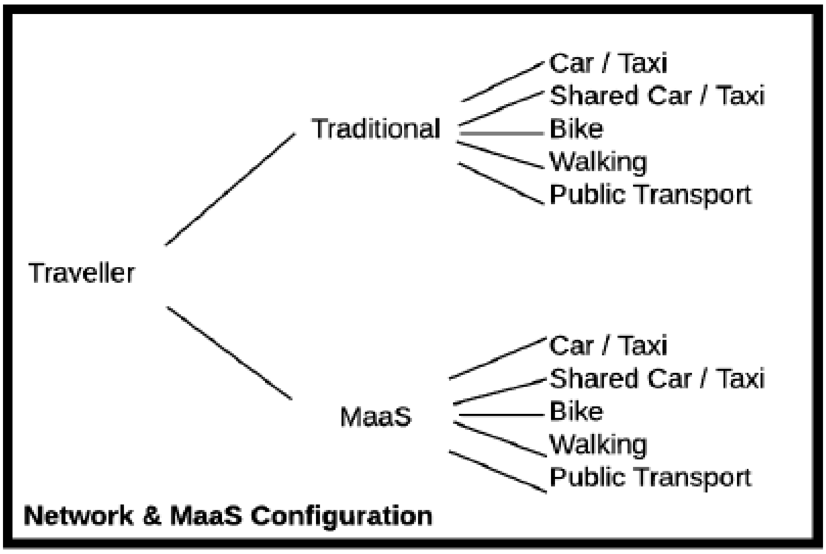



Figure 2.3: MaaS Service Configuration (van Kuijk, 2017)

- Mobility Manager: This is the role of the government, who is interested in ensuring mobility services for users while avoiding negative externalities (such as traffic congestion or pollution).
- Platform Service Providers: These actors, usually companies, provide the digital services to ensure the system keeps functioning.

Together with the users, these actors and their interactions make the MaaS system. Even though Musgrave (1956) makes a distinction between CMS Providers and CMS Operators. In practice, these actors and the platform service providers act together as a single actor as a MaaS company. For the simplicity of the SD model to be built, they will be joined in a single actor, the MaaS Service providers (MSPs).

To summarize, the application of the MaaS framework with the objectives of this thesis project brings up three conclusions. To understand the system of MaaS while keeping the model as simple as possible, only CMS type services will be included, taking into account that peer sharing keeps the number of private car users constant. The second conclusion is that there are seven modes likely to be implemented in the MaaS service. These modes, namely private car, car share, taxi, taxi share, bike, bike share, and PT, should be in a model for the understanding of MaaS. Lastly, MaaS is a multiactor system. The main actors to be included in the model are users, PTOs, transport service providers, MSPs and the government.

### 2.1.4. Implementation of MaaS

MaaS is a concept that is not fully implemented yet. However, there are studies already stating what seem to be the most important challenges MaaS will be facing and what will be the drivers of its development. Understanding these characteristics is relevant for the develop of the conceptual model because they can bring up clues about the possible behavior of the MaaS system in the future. These section presents the main findings of the literature on these aspects and relates them with the development of an SD model for the understanding of MaaS. At the end, a summary with important variables and relations to take into account for the development of an SD model is presented.

The first studies to be presented mainly show the possible implications of MaaS in user behavior and what are the drivers for users to adopt MaaS.

Karlsson, Sochor, and Strömberg (2016) is one of the most relevant studies on the implementation of MaaS to date. A pilot was designed with the platform UbiGo in Gothenburg, Sweden. The project was framed as a test to see the potential of implementing MaaS. The service was tested over a period of six months within the Go Smart project, where the users were continuously interviewed and their behavior when commuting was analyzed. The findings were:

- Service use: There was an overestimation of the use of transport services. Consumers bought more transport hours than what needed.
- Travel behavior: Consumers reported a decrease in the use of private car and an increase in alternative modes, specially public transport and car sharing.
- Satisfaction: At the end of the trial, 97% of the users wanted to continue with the service.
- Attitudes: Consumers reported an increase in the attitudes towards alternative modes and less positive to private cars.

As seen in the results of the study, most outcomes are positive for the implementations of MaaS. When asked about positive aspects of the experience, it was found out that the users appreciated the face to face customer service available, the flexibility of the service and the digital services offered by the platform. On the other hand, this study also identified important barriers when adopting MaaS. Accessibility and economy are critical factors. Customers which did not have any car sharing station close by did not take the subscription. And some users expected the price to be at least equally expensive as of what they use now, not more expensive.

Matyas and Kamargianni (2017) proposed a choice experiment to determine the preferences of MaaS for users. This study was followed by Ratilainen (2017) to show what are the main explanatory variables for users adopting MaaS. It is shown that the main explanatory variables for users adopting a MaaS package are price, pick up time and full accessibility to public transportation. Besides, car users are reluctant to the adoption of MaaS because they see it as a downgrade. Hence, MaaS prices need to be very low compared to car ownership to be attractive Ratilainen (2017). The following chart shows the results encountered for different target groups:

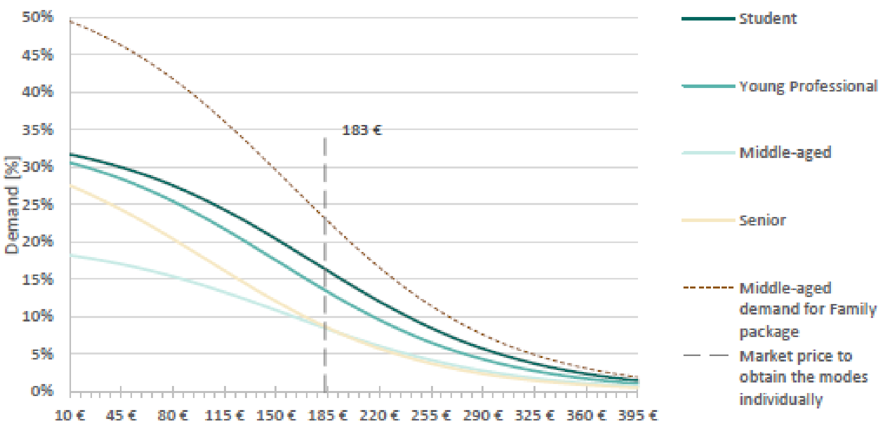



Figure 2.4: Demand of MaaS dependent on price of a large package (a large package includes unlimited public transport unlimited bike share and 6 taxi services per month within a 5km radius). (Ratilainen, 2017)

Figure 2.4 shows the behavior of the expected demand of MaaS as a percentage of total demand for users in Helsinki as a function of the price of a monthly package. A package includes unlimited public transport, bike share and six taxi services per month within a radio of 5km. As expected, the demand of MaaS decays with the increase in the price of the package. The dotted lines show the current value of the package in the market. The study shows that young professionals and students are keener than middle aged people to use MaaS.

Based on the same experiment described before, Sochor, Strömberg, and Karlsson (2014) state what the motivations of users to take MaaS before, during and after the experiment are. At the end, the users answered that the most relevant factor were flexibility, curiosity and economy. On the other hand, the main deterrents to use MaaS were mainly the price and a mismatch between the needs of the user and the offer of the provider. It is important to be able to balance the demand and the offer of the services provided. This is a challenge specially in areas far from urban centers.

Sochor, Strömberg, and Karlsson (2015) is based on the same experiment with Ubigo. During the implementation of the program, the different behaviors of the users of the try of MaaS were observed. Most users shifted to more sustainable modes of transportation, either car sharing or public transportation, with a degree of satisfaction higher than 90%.

The following studies focus on the offer side of the market. They try to find what drives service transport providers to be a part of MaaS and what should be their role in this new system for its implementation.

Callegati, Giallorenzo, Melis, and Prandini (2017) identified the main barriers for the development of MaaS are not in the users.They are rather structural and economic such as lack of investment, current regulatory issues where MaaS subscriptions cannot be subsidized by taxes as public transport, fear and lack of experience to the new business relations, loss of identity of transport companies because of the change in customer relationship, new pricing, etc. Project partners need to work together and this is not easy because there is a strong change in the paradigm.

Smith, Sochor, and Karlssona (2017) states that there are two possible roles for PTOs within the MaaS system. First, PTOs can be the coordinator of the system. PTOs would have total control of the offer of MaaS and they would be responsible of the integration of the system and adding new mobility providers. In MaaS terms, PTOs would have the role of MSPs at the same time. This option ensures the stability of MaaS in the long term. However, it does not allow for competition between different providers. Hence, the satisfaction of the user would not be the priority but rather maximizing the use of PT. This option may not lead to private car users to adopt MaaS. The other option is to have a commercial coordinator and PT as just a collaborator in the market. In this option, there is more competition between providers, optimizing the user's satisfaction.

Summarizing, it is possible to classify the findings until now about the drivers on the implementation of MaaS in two groups, those related to the demand (users) and those related to the offer (transport service providers). Ideally, these relations should be taken into account for the development of an SD model. There are mainly five causal relations that influence users on their decision to adopt MaaS. First, the first adopters of MaaS will probably do it for curiosity for it is the main cause in the experiment. Secondly, the main deterrent of MaaS is price. If the price of MaaS is too high, users will not adopt it. Moreover, for MaaS to be effective for traffic congestion, the price might have to be very low compared to private car ownership. Third, the higher the flexibility, in terms of more integration with multiple service providers, the higher the chance of users to keep MaaS. Fourth, service quality is a key for users to keep MaaS. Service quality is understood as the quality of the customer service and the digital services offered by MSPs. Finally, accessibility plays a key role in the perception of users toward MaaS. If PT, Car Share or Bike Share infrastructure is easily accessible, there is a higher chance to adopt and keep MaaS. The main key drivers of the development of MaaS at the offer side of the market are the role of PTOs in the MaaS system, as whether they will be or not the MSPs, regulatory issues as whether MaaS can take advantage of the subsidies of PT, and business related variables such as the financial investment and the business relations between MSPs and transport service providers.

### 2.1.5. Impacts of MaaS on Traffic Congestion

This section presents the main findings about the relation of MaaS with traffic congestion. First, it introduces main studies being developed until now and then it provides a summary of the findings to identify causal relations to be included in the model.

There is still much uncertainty on what will be the effects of MaaS on traffic congestion. Even though studies have shown that users tend to go towards more sustainable modes of transportation when MaaS is implemented, the option to get less efficient urban environments is still possible (Sochor, Strömberg, and Karlsson, 2015). The following figure provides insight on why.

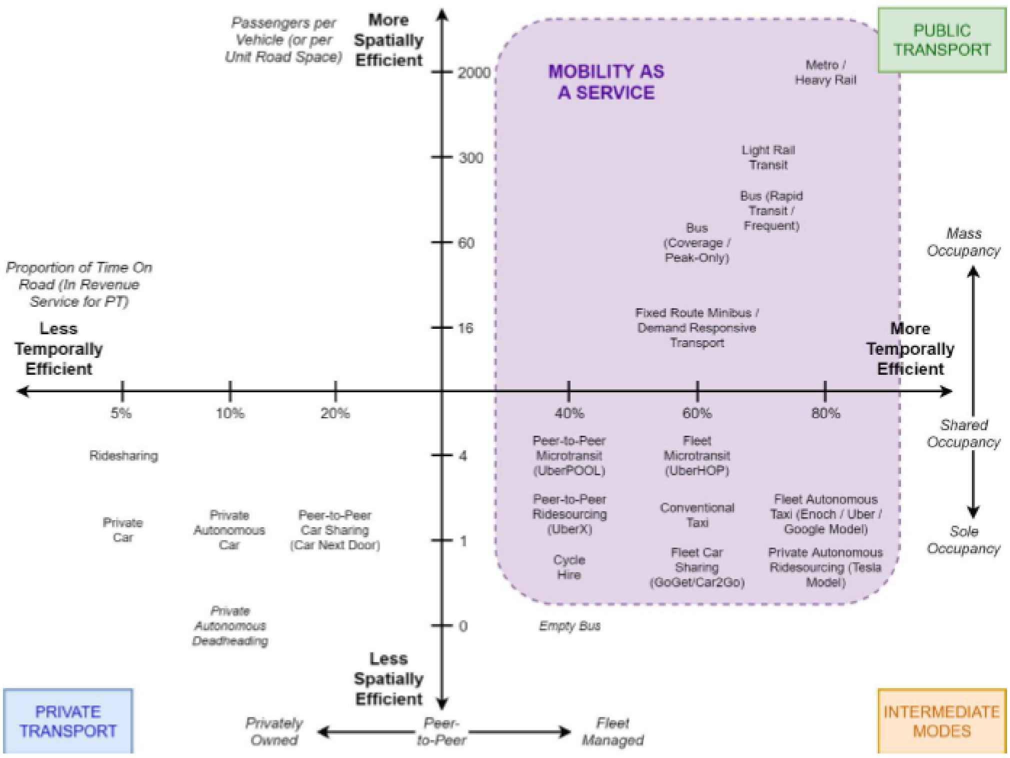



Figure 2.5: Modal Efficiency Framework Wong, Hensher, and Mulley, 2017

Figure 2.5 shows the modal efficiency framework proposed by Wong, Hensher, and Mulley (2017), This figure shows in the horizontal axis what is comparatively the time efficiency of different modes of transportation. The time efficiency corresponds to the travel time spent in these modes. On the vertical axis, it is possible to see the spatial efficiency of the same modes. The spatial efficiency refers to the capacity of the vehicles compared to their size. The graph shows the range of modes that are offered by MaaS. As it is observable, these modes tend to be more time efficient. This is why it is believed that traffic congestion could be reduced. However, Mobility as a Service also offer modes that are very spatially inefficient. If users who previously used more efficient modes feel attracted to less efficient spatial modes, traffic congestion would grow. Hence, even though MaaS is good for user flexibility, it is not conclusive that MaaS is good for traffic congestion. Wong, Hensher, and Mulley (2017) main conclusion is that it is necessary to change the view on the change proposed by MaaS. Instead of focusing on commercially-driven objectives, it is important to see what are the impacts on society and how to use the system to our advantage.

Fiedler, Čáp, and Čertick (2017) uses network modeling to analyze what could be the impact on traffic congestion on-demand services. On-demand services refer to the use of shared taxi with support of route optimization from digital platforms. It is found that even though the number of vehicles needed to satisfy the current transportation demand is reduced. It may happen that these vehicles do more stops in the system, increasing distance driven and travel time.

Narayan, Cats, Oort, and Hoogendoorn (2017) did a multi-agent simulation analyzing the behavior of traffic in a system where fixed and on-demand public transport coexist together with the support of digital applications. This is a situation a the one offered by MaaS. It is found that the system can become more efficient and reduces traffic congestion because the users optimize their decisions to reduce travel time.

The main conclusion of this section is that the literature regarding the effect of MaaS on traffic congestion is still not conclusive. There is no specific study about the impacts of MaaS on traffic congestion, and the research on on-demand services that are close to the scenario of MaaS contradict each other. New approaches are necessary to overcome the gap. SD offers the chance to include societal behavior and analyze uncertainties under different scenarios. Besides, it offers the chance to describe how MaaS adoption processes could behave in the future.

Even though there are not specific findings to be added to the SD model, the model should offer the chance for an ambiguous behavior Either the system increases congestion because of the adoption towards less spatially efficient modes or PT and more efficient modes become more attractive.

### 2.1.6. Summary

This section summarizes the most relevant findings of the literature review to facilitate their implementation in an SD model.

The literature reviewed was classified to four main topics: MaaS definition and characteristics, the MaaS framework, the drivers of MaaS and the relation between MaaS and traffic congestion.

From the MaaS definition, four key characteristics were identified: MaaS is a system that offers mobility services to users, these services are integrated in a digital platform, the platform at the same time offers digital services personalized for and customized by the users and the transport modes can be offered independently or in packages that are paid at regular periods in time.

The MaaS framework offered insight about three important features of MaaS as studied in this research. First, MaaS is equivalent to CMS in the MaaS framework, which means that the services offered have assets owned publicly or by organizations and these services are highly integrated in a platform. It is important to recall that different levels of integration can be modelled as scenarios in the model proposed and that the effects of privately owned share assets is out of the focus of the model because it is a transaction that does not have a net effect in traffic congestion. The second feature is the types of services offered by MaaS. Seven modes were identified as the most relevant ones: Private car, car share, taxi, taxi share, bike, bike share and PT. Finally, MaaS is a multiactor system with four main players: Users, MSPs, PTOs and transport service providers.

In the section drivers of MaaS, the main drivers of MaaS that affect the demand and the offer of the system were identified. Users are initially highly influenced by curiosity, afterwards they decide to keep using MaaS depending on its flexibility, its price, its service quality and the accessibility to the different transport modes. The offer of MaaS is highly driven by the role of PTOs in the system, the investment to MaaS systems, and business relations between key players.

Until now, the impact of MaaS on traffic congestion is unknown but it is clear that it can either increase congestion because of the incentive to use taxis or decrease it because of the use of more sustainable modes such as PT or the bike.

The previous findings lead the path to build and SD model that explains the system.

## 2.2. Interviews with Experts

This section presents the main findings from the interviews done to the experts in the field of MaaS and their implications to the building process of an SD model. To remember, two interviews are held in this process to support the assumptions of the model. The interviewed experts are Sampo Hietanen, the CEO of MaaS Global, the first MaaS Service Provider, and Lucas Harms, the head of the MaaS research team at the Institute for Transport Policy Analysis in the Netherlands. The questions asked to the experts may be seen in appendix A. The information asked is framed here in terms of the relation between MaaS and traffic congestion and what are the drivers of this relation.

According to Sampo, there is not enough evidence to support that MaaS will reduce traffic congestion. However, it is clear that MaaS offers an opportunity. Most of people's budget spent on mobility goes to the use of the car. MaaS offers the chance for other transport providers to compete against car ownership. The assumption is that MaaS can offer the user similar flexibility than a car offers them. To him, the mechanism by which congestion would be reduced goes through reduction of car ownership due to new solutions in the market that can compete against such a good system as cars.

MaaS is the chance for cities to rethink their view on mobility. It will change peoples' preferences towards modes of transportation but to which modes and what extent is unknown. Sampo mentioned that up to now, people selling their cars have already being reported but it is not enough to proof a large scale change. He mentions a statistic that sounds promising. 91% of the trips done in MaaS are done in PT. If the trend continues, it could have a positive effect on traffic. He expects to see changes in the system in a period between three to five years. Moreover, Sampo argues that MaaS has the added value that it is a market solution, where the users freely decide to give up their cars instead of being commanded by taxes and interventions.

An important input from Sampo is the perceptions of other stakeholders in the system. As told by him, city governments, taxis and users are in line with the view of a open MaaS market. However, PTOs are not keen to the idea of MaaS as an open competitive system. In the light of the main drivers of MaaS identified on the previous section, PTOs would prefer to be the MSPs themselves rather than letting commercial operators compete between each other.

One last comment is that MaaS is a service that requires large investment because of the size of the market and the big digital infrastructure needed to attend the demand. Financial management will be a challenge for the implementation of MaaS.

Lucas Harms states that up to now there is no evidence at all of the implications of MaaS towards traffic congestion. Research being done is full of uncertainties. However, the key driver of this behavior are the attitudes and perception of users towards cars. He argues that these attitudes change prominently between different groups of the demand. Young people are more open to services such as shared taxi and flexible systems, while older users have higher intrinsic preferences towards private car. He mentioned that according to studies, age and income are the main variables that explain traffic congestion. Travel times and traffic congestion does not seem to contribute to people's decision to own a car.

Other important driver to take into account is the increasing use of automated vehicles. Probably, they will change the perceptions of people towards taxi and the prices might decrease which would make a difference in the outcomes of MaaS.

Summarizing, according to the experts, the key to the relation between MaaS and traffic congestion is the level of preference of users towards private car. Users more keen to use private car might hardly shift to a different system. While other users, open to other possibilities would shift their service and even sell their car, reducing car ownership and traffic congestion. This relation between car ownership and MaaS must play a key role in the SD model presented. However, it is a challenge, since there is total uncertainty to the extent at which this mechanism functions.

There are other important aspects to take into account. First, there is a conflict on the role of PT at MaaS because while MSPs favour an open market, PTOs would prefer a single operator responsible of the whole system, and secondly, MaaS is a big financial challenge to overcome because it requires big investment.

## 2.3. Conceptual model

This section starts uses the findings of the literature review and the interviews to create a dynamic hypothesis about the mechanisms that drive the behavior of the system.

It starts with a brief introduction about causal-loop diagrams, which is a basic SD notation, for the reader to understand the figures to be presented while developing the model. It continues by delimiting the space-time structure of the model and defining the KPIs. Both aspects will be defined in accordance with the objectives of this research project. Then, Wegener's circle, a common feedback relation used in transportation modelling problems, and a SD model about the adoption of digital services proposed by Ruutu, Casey, and Kotovirta (2017) are introduced. This is the starting point of the development of the model. After that, the findings of the literature review and the interviews are added to the model. At the end of the chapter, a summary of the conceptual model is presented with a graphical representation of the system in terms of a causal-loop diagram.

### 2.3.1. Causal Loop Diagrams

Causal loop diagrams (CLDs) are a communication tool that represent the feedback structure of the system being modeled with SD. CLDs are useful for capturing the hypothesis of what causes the main dynamics in a system, to understand the mental models of the different stakeholders or to communicate the important feedbacks that are responsible for a problem (Sterman, 2000).

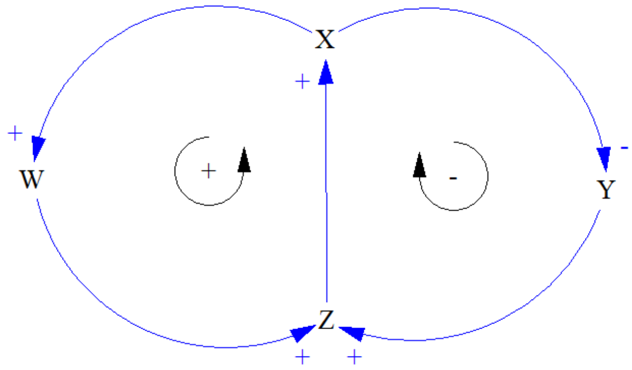



Figure 2.6: Causal Loop Diagram

Figure 2.6 shows a Causal Loop Diagram of four interconnected variables. There are two concepts to understand how to read a CLD: Causal Links and Feedback Loops.

First, an arrow in the diagram is called a Causal link and it represents a relation between two variables. The plus or minus symbol represents whether the causal relation has a positive or a negative impact respectively. This symbol is called the Link Polarity. For instance, in figure 2.6, the link connecting the variable $X$ and the variable $W$ indicates that if the variable $X$ grows, it has a positive effect on the quantity of the variable $W$.

$$W = f(X) \tag{2.1}$$

$$\frac{\partial W}{\partial X} > 0 \tag{2.2}$$

Mathematically, the line indicates that the variable $W$ is a function of the variable $X$, as shown in equation 2.1 and the plus symbol indicates that this relation has a positive first derivative, as seen in equation 2.2. Likewise, when the polarity of a causal link is negative, as the relation between variables $X$ and $Y$ in figure 2.6, the meaning is that an increase in variable $X$ would decrease the value of $Y$. This is seen mathematically in equations 2.3 and 2.4.

$$Y = f(X) \tag{2.3}$$

$$\frac{\partial Y}{\partial X} < 0 \tag{2.4}$$

It is important to clarify describe the relations only between the two variables between them. When a variable is affected by more than one Causal Link, such as $Z$ in figure 2.6, the actual behavior will be given by the mixed interaction between these Causal Links. Since an actual System Dynamics model has many Causal links, it becomes hard to understand what causes the behavior in the system by just interpreting causal relations. This is why the concept of feedback loops is necessary.

A Feedback Loop is a representation of a feedback structure in a System Dynamics model Sterman, 2000. In CLDs, feedback loops are identified whenever a group of causal links has a cyclical relation. For example, in figure 2.6, the variables $X$,$W$ and $Z$ form a feedback loop because the causal links are sequentially connected in a cyclical structure. Important feedback loops are usually identified with a loop identifier (Sterman, 2000). A loop identifier is the symbol in figure 2.6 that is in the middle of the loop. The arrow follows the path of the causal links that form the loop. It can be clockwise or counterclockwise. The sign inside the symbol indicates whether a loop is reinforcing (+), which means that each variable in the cycle has an overall positive impact on itself due to the interaction of all the variables in the cycle, or balancing (-), which means that each variable in the cycle has an overall negative impact on itself due to the interaction of all the variables in the cycle. The symbol of the link is easy to calculate by just counting the number of minuses in the causal links of the loop. If the number is odd, the loop is negative or balancing. If the number is even, the loop is positive or reinforcing.

### 2.3.2. Time-Space Structure

One of the key aspects of the formulation of a dynamic hypothesis step is to determine a time-space structure for the model. It is outlined by a time range, a time unit and a spatial structure.

The objective of this model is to evaluate transportation policies at a tactical level. In specific, the policies to be evaluated are those related to fares, subsidies and taxes. These policies are usually implemented a mid-term time frame. During the interview, Sampo Hietanen mentioned that the expected time frame to see changes in mobility due to the implementation of MaaS is from three to five years. The time chosen needs to be higher than this value to see if the behavior stabilizes. The exact time frame chosen depends on the case of study implemented at the moment the model is tested. The criterion is that it must be below a time range where traffic congestion is affected by infrastructure of the city of households moving to new locations.

The time unit for this model is set to months. The main reason is that the subscription packages of MaaS are usually paid every month, facilitating the control of the variables in the model.

The spatial structure used for this model is a single zone structure. The main reason to do so is to simplify the model. Since the objective is to analyze policies at a general level and not the specifics of every small region within the city, there is no differentiation between neighborhoods or roads within the area. All area related values are calculated by the average among users inside the area. Notice that not only households within the area must be included for these averages but also users living outside of the area of study because of the possibility of in, out and through traffic. It is transportation demand and not population what matters when analyzing traffic congestion.

### 2.3.3. Determination of Key Performance Indicators

The objective of this project is to explore, under the context of MaaS, how the use of SD can evaluate the impact of policies related to fares, prices and taxes on traffic congestion. For this, the following performance indicators are chosen as a measurement of success of the different policies in the model.

- Traffic congestion: This is the main variable to be identified in the context of this project. The chosen methodology and one of the main measurements of traffic congestion is the ratio of traffic load (number of vehicles at a certain time on the road) and traffic capacity (maximum number of vehicles that fit the road).

  Since traffic load is dependent on time, it is necessary to define the time at which this measurement will be considered to calculate the performance indicator. To capture the highest impact on traffic congestion, the chosen time is the peak period during a working day. In conclusion, this performance indicator does not capture the effect of MaaS on traffic congestion off the peak hours.

  Traffic Congestion can also be measured as the additional percentage of travel time spent commuting compared to free floe travel time. Free flow travel time is the time when there is no congestion. This measurement will be known as extra travel time index and it has the added value that it has a physical value easy to understand.

- Car ownership: Since the measurement of traffic congestion does not capture the general state of traffic but only on peak hours, another key performance indicator is used to evaluate the impact of MaaS on a general perspective. Given that one of the main arguments for the implementation of MaaS is that it would discourage the use of private vehicles reducing traffic congestion, car ownership is used as a proxy of the state of traffic in the city. It is calculated as the private car fleet (number of private vehicles) divided by the total number of users of transportation in a city.

The private car fleet and the demand of transportation users are not only calculated with data from the city but also in surrounding areas to consider in, out and through traffic on the city.

- Modal Split: Another way to measure traffic congestion that also allows to understand why congestion has a specific behavior is the modal split. The modal split is the percentage of trips being carried by each of the transportation modes available. If the percentage of private cars and taxis decrease while the percentage of more sustainable modes such as PT or bike increases, it means a policy is successful to reduce traffic congestion.

### 2.3.4. Wegener's cycle

This section introduces Wegener's cycle and its role in transportation modelling.

The main feedback relation in transportation systems, as the one to be analyzed by this project, is described by Wegener's cycle Wegener, 2004. This feedback relation is commonly used in urban modeling relating transportation to land use Ortuzar and Willumsen, 2011. It is a visual representation of the mechanism by which mobility is usually described in literature regarding transportation modeling. It is intended that the system dynamics model to be built include the relevant dynamics expressed by this loop. The following figure shows this feedback relation.

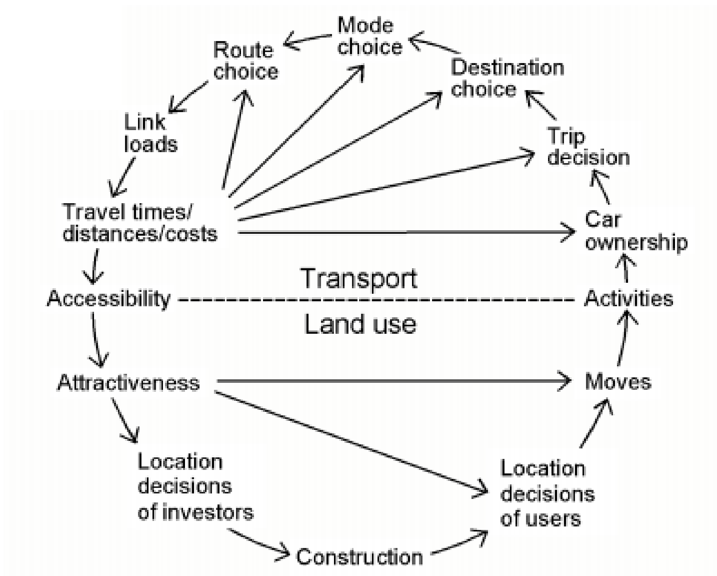



Figure 2.7: Wegener's cycle (Wegener, 2008)

Figure 2.7 shows that Wegener's circle can be divided in two. Half of the circle explains the modeling process for transport and the other half explain the effects on land use. These two parts are related because research has shown that the changes in transportation can lead to changes in the land use structure and vice versa. The following paragraphs explain each of the components in the circle and what they represent.

Trip decision is the decision of a user to make or not a trip to another destination. His/her decision is influenced by whether the user has a car or not. Trip decision determines the number of users of transportation services because it corresponds to the number of users who decided to make a trip. The next component is destination choice. It describes the start and end points set up by the users demanding transportation whenever they make a trip.

When the travel points are clear, the user decides on his or her mode of transportation. This is determined by the mode choice component. This component is critical for the development of this project since choosing a mode of transportation will be determined by whether the user owns or not a MaaS subscription. Once the mode of transportation is chosen, the user decides the route to reach the destination in the component route choice. By counting the number of users passing certain street, the route choice leads to the assignation of link loads. These link loads are related to traffic congestion since more cars produce more congestion and can hence be used to estimate travel times. Travel times determine the measure of accessibility of a place. The longer the time it takes to go somewhere, the least accessible that place is considered.

The land use side of the circle starts with accessibility. The accessibility of a place can determine how attractive it is for living and for business. This attractiveness determines whether firms and users decide to relocate in a new area. This is the mechanism by which transportation change land-use. The loop is closed under the assumption that the more people and firms in an area stimulate activities in this same area. Users feel motivated to buy new cars depending on the activities offered.

Wegener's cycles is used as one of the main structures to build the model. The next section describes another model structure considered for this research.

### 2.3.5. Digital Platforms Adoption Model

There is not sufficient research regarding the use of System Dynamics to evaluate MaaS as a tool to reduce traffic congestion. However, Ruutu, Casey, and Kotovirta (2017) propose a model for the development of digital platforms and specifically mention it can be used for the analysis regarding the adoption of MaaS. This model is a good starting point for the development of this research.

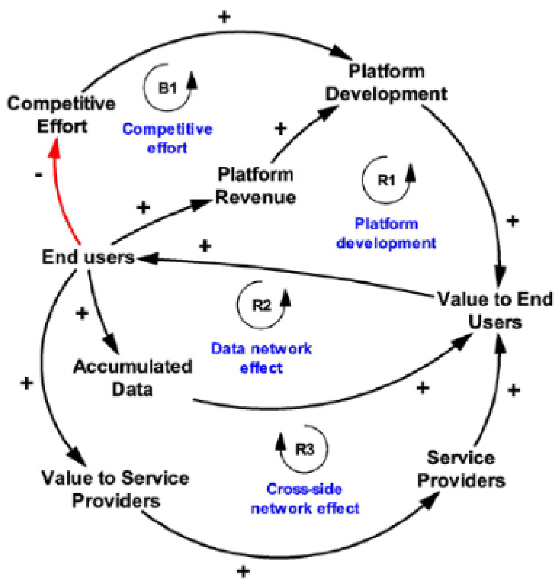



Figure 2.8: Congestion charging price causal loop

The model by Ruutu is based on four main dynamics represented in causal loops as seen in figure 2.8

Competitive effort, which states that if there is a gap in the market share of the platform, new resources will be invested in developing the platform. In other words, the least end users, the more effort to gain new users by developing the platform. A higher development adds a higher value to the platform, increasing its attractiveness to users. Hence, new users acquire the platform due to this mechanism.

Platform development states that the more revenue for the platform, the more reinvestment in platform development. This reinvestment increases the value to end users of the platform. This development represents all the options provided by the platform, such as trip planning, booking, or any other improvement in the service concept or the technology.

The data network effect states that the more users are in the platform, the more data is collected from these users. When new data is collected, this data can be used to improve the platform be developing service optimizations. Eventually, this increases the value of the platform for users.

Finally, the cross-side network effect corresponds to the second side of the market of the service platform. In this case, transport service providers are attracted to use the platform because they see more users are using it. The more service providers that accept the platform, the more attractive it is for new users. In the case of MaaS, service providers that are attracted by the service are taxis, PTOs, bike sharing companies, among others.

### 2.3.6. Model Main Structure

This section explains the development of the main structure of the model to be built using the two structures introduced in the previous sections.

As explained before, most transportation modeling projects are guided by different implementations of Wegener's circle. The circle is a representation in form of a loop of the dynamics that are present in transportation systems.

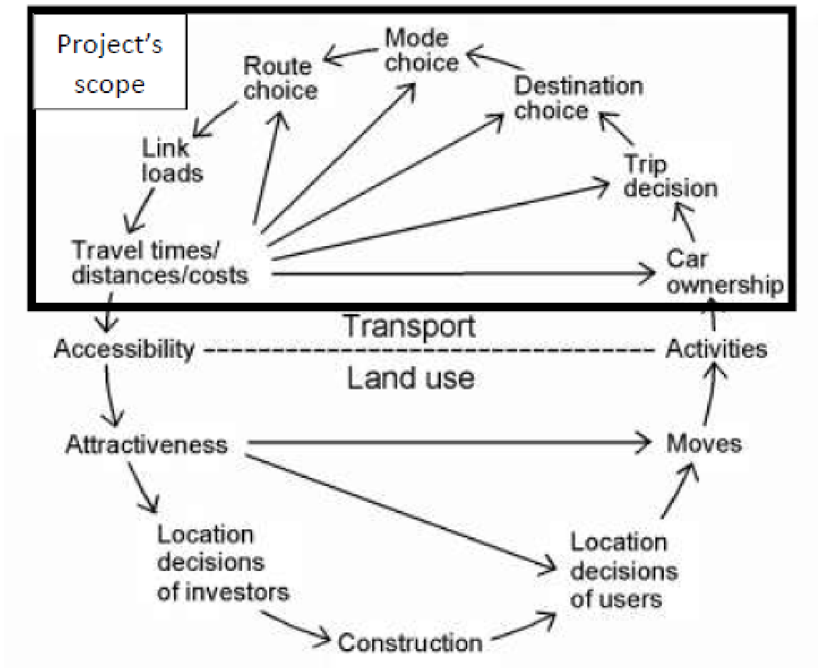



Figure 2.9: Scope of the project in Wegener's circle

Since the scope of this project is to analyze policies at a tactical level, this is, policies related to prices, fares and taxes, only part of the circle is relevant for this model. The relevant part is selected in figure 2.9. The rest of the circle is important in the long term when the infrastructure of the city changes causing changes in the housing location of the residents. This is called the strategic level.

Since the spatial scope of this model treats a city as a single zone, which values are averaged for analysis, the choices of Wegener's cycle related to location are irrelevant. In other words, since only average values are considered, it is out of scope to understand the specific traffic to each of the zones of the city. Hence, trip decision, destination choice and route choice are not considered in the model.

According to Lucas Harms, head of MaaS Research at KIM, studies have shown that the impact of travel times, distances and costs on car ownership is low compared to the impact of other variables such as income and family structure. This also implies that car ownership might be more related to nonmonetary values such as flexibility and comfortability, rather than simple traffic related variables. These findings change the model structure and car ownership is not directly related to Wegener's cycle.

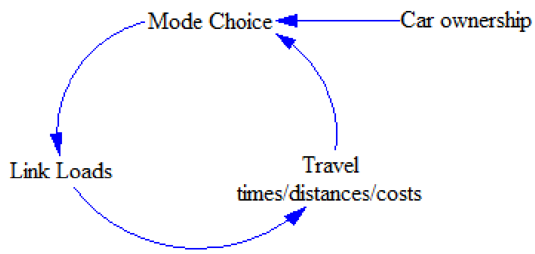



Figure 2.10: Reduced Wegener's cycle

Figure 2.10 shows the reduced version of Wegener's cycle which is coherent with the scope of study of this project and the findings about travel times/distances/costs with car ownership. Even though the model is reduced, each of these components will add complexity to the model. It is important to specify that the figure showed is not yet a causal-loop diagram. It does not show a relation between variables but between components of a transportation system.

Now, it is necessary to add to the model the different findings from the literature review and the interviews to see where would they impact Wegener's cycle. In other words, the findings will show how MaaS could alter the transportation system. First, an implementation of Wegener's circle for the case of MaaS is applied. In figure 2.10, the mode choice component corresponds to the choice users make when deciding what mode of transportation to use to go to their destinations. In the case of MaaS, and as proposed by van Kuijk (2017), there are two choices involved in this process. First, the choice of whether to use or not a MaaS subscription and then what specific mode of transportation will be used to commute. By implementing this modification, the first two characteristics of the definition of MaaS are included to the model (mobility offer and interconnectivity).

To determine now which of these modes is more popular, it is necessary to establish their attractiveness to the users. As seen in Wegener's cycle, the variables that are relevant to determine the attractiveness of a mode of transportation and utterly define the choice model are travel times, distances and costs. This relation lead to figure 2.11, which is a representation in causal loop diagram of Wegener's circle for the case of MaaS.

Figure 2.11 shows more complexity than the one presented in Figure 2.10. The added complexity corresponds to a second loop due to the two choices involved in the MaaS system. In the figure, Mode Choice Loop corresponds to the simple version presented in figure 2.10. When MaaS is added to the system, a new choice is made where the MaaS utility is determined by the utility of the modes offered by MaaS. This utility determines the number of users inside and outside MaaS. Users within MaaS are expected to have different behavior, which changes the number of users of each mode. This new loop is called MaaS Choice Loop. Moreover, the travel times of the system are a representation of the accessibility of a mode. The impact of them in the MaaS choice account for the finding that accessibility is a key feature for users when deciding to adopt MaaS.

The second structure, the digital service platform model, is also implemented for the case of MaaS. The same four loops in the model from Ruutu, Casey, and Kotovirta (2017) are kept in the MaaS model with some modifications. Figure 2.12 shows the result after this implementation. The loops Competitive Effort, Platform Development and Data Network Effect keep the same logic as presented in figure 2.8. On the other hand, the loop Cross Network Effect has a modification. In figure 2.8, the adoption of MaaS from service providers led directly to a higher value or utility of MaaS. However, since the value of MaaS is used in the context of a mode choice model, the relation is not expressed directly. The realistic mechanism is that the new service providers affect the variables that change the user behavior. These variables are, namely, travel times and costs. The mechanism by which these variables are modified is simple. The more taxis in the system, the more traffic congestion, which ultimately leads to more travel time. A second mechanism is that the more taxis, the least waiting time for users reducing travel times in the system. It is relevant to add that these causal-loops represent the effects of the digital services to the user. As mentioned in the literature review, good quality service is a key feature in the adoption of MaaS.

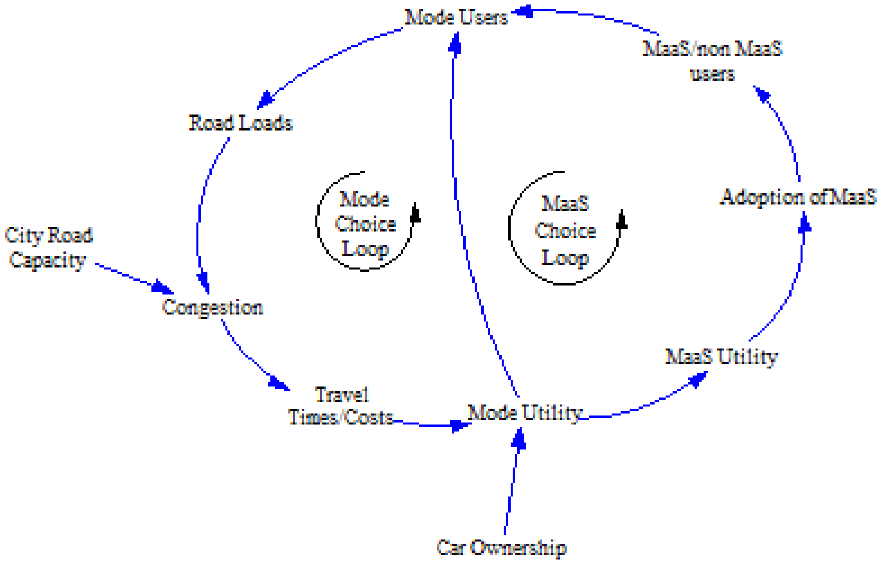



Figure 2.11: MaaS Wegener's Causal Loop

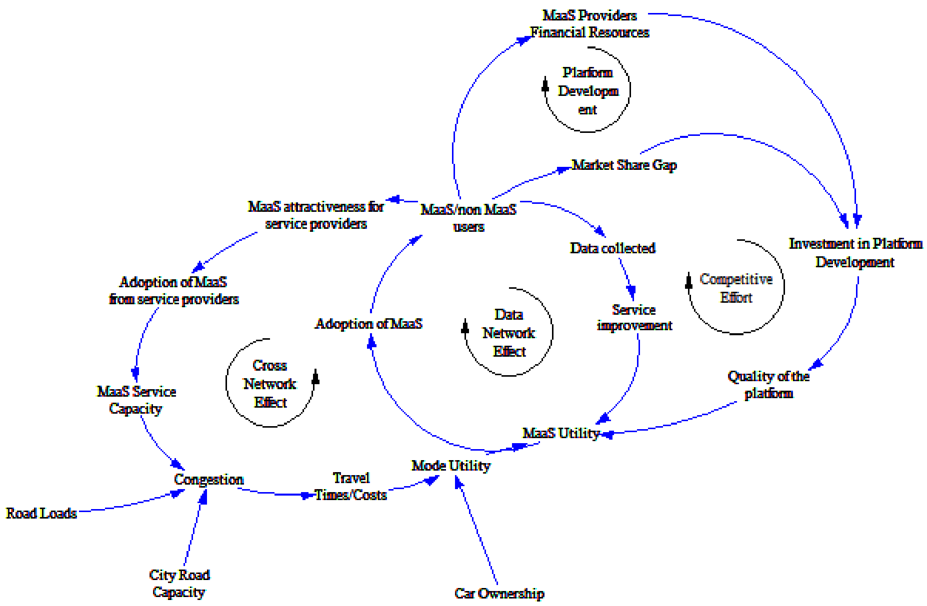



Figure 2.12: Digital service platform model applied to MaaS

### 2.3.7. Summary

This section presents the final model structure defined for the SD model of this project. It is checked in the light of the findings of the literature review and the interviews to see if it includes the characteristics of the system that were identified.

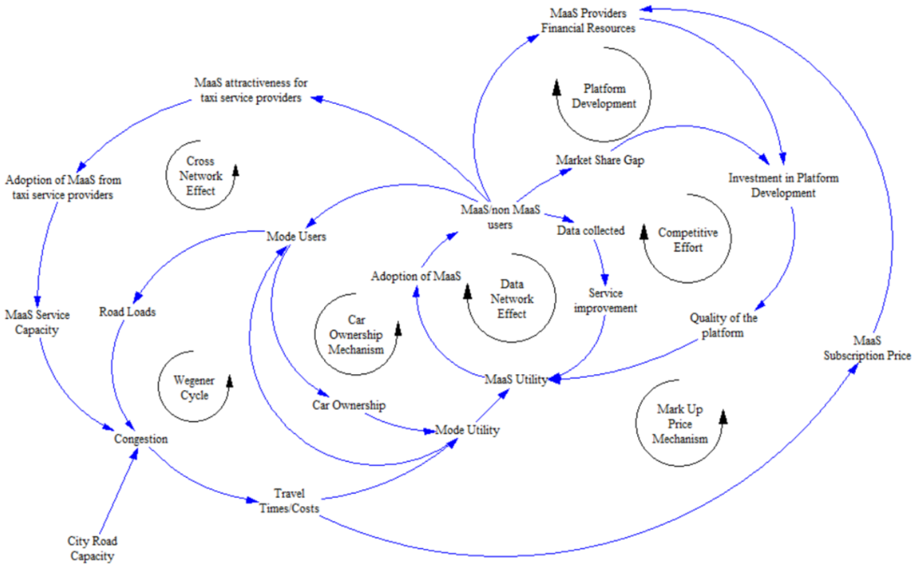



Figure 2.13: MaaS model main structure

Figure 2.13 shows the final model when the two structures are joined. The price of the MaaS subscription is added as a variable given that Ratilainen (2017) found that the price of MaaS packages is a key variable to understand the adoption of MaaS. This causal relation is presented in red color. The other drivers of MaaS users are also included. Flexibility is given by the different modes that MaaS offer to the user, service quality is given by the platform investment and the data effect and the accessibility is interpreted as the access and egress time to each of the modes of transportation which are implicitly included in the travel times and costs of each mode.

Also, the model has mechanisms for both increasing or reducing traffic. If the user chooses car or taxi, traffic increases but if the user choose a sustainable mode, such as bike or PT, it may reduce. Hence, the model is in line with the ambiguous knowledge about the effect of MaaS in traffic congestion. A causal relation for change in car ownership is present, shown in red, where the number of private car users drive the demand for cars. The more cars being unused, the more cars being sold. This mechanism is based on the interview with Sampo Hietanen.

Finally, The multi-actor nature is also represented by the system, where MSPs' resources are included in the system, transportation providers are responsible for offering the different modes of transportation and adopting MaaS and users are the ones making choices on whether to use MaaS or a specific mode of transport. There are still two key actors not explicitly included in the system, PTOs and the government. The role of these actors is more thoroughly developed in the following chapters, where the detailed model is explained.

# 3

# Model Formalization

This chapter shows the details of the SD model built and the most important mathematical formulations needed to understand the behavior of the system. It starts by introducing the structure of the model and the concept of stock-flow diagrams. These diagrams are used to represent the differential equations of the system graphically. With this knowledge, it is possible to understand the detailed formulations of the model. After that, the detailed structure of the model is introduced and each of its sub-models are explained with detail. At the end of the chapter, the model is summarized and analyzed in relation with the main findings of the literature review and the interviews in the model conceptualization.

## 3.1. Detailed Model introduction

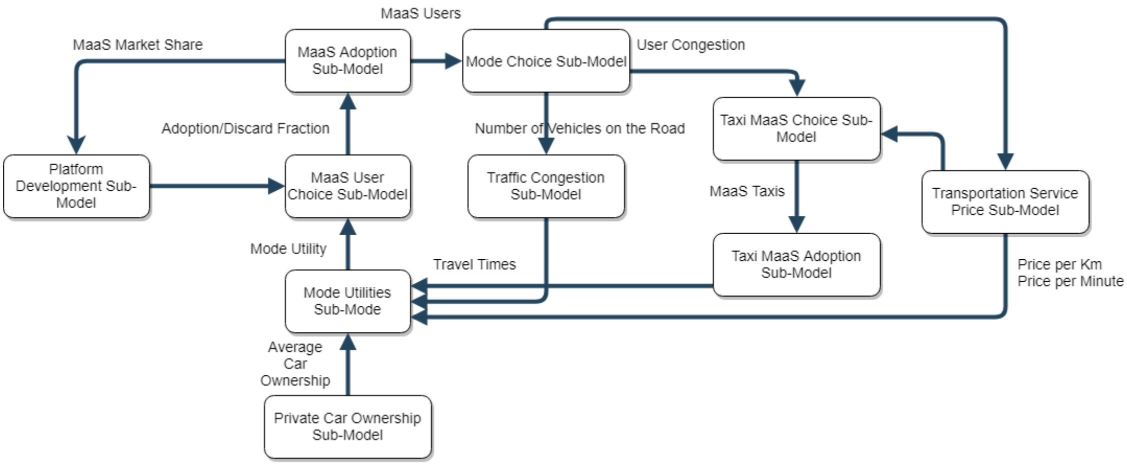



Figure 3.1: Sub-Models Relation to Wegener's Cycle

Figure 3.1 shows a general view of the full structure of the SD model created. These sub-models follow the structure shown the previous chapter in figure 2.13. The labels between the sub-models identifying the arrows between them are the names of the variables that connect the sub-models. Ten sub-models are used to include the seven causal loops described before. The following section offers an introduction of stock-flow diagrams, a notation necessary to understand the specifics of the sub-models built.

## 3.2. Stock-Flow Diagram

One of the main disadvantages of CLDs is that they do not capture whether a relation between two variables is caused by an accumulation effect (Sterman, 2000). An accumulation effect occurs when a variable is the result of the accumulation of other variables. All SD systems have accumulation effects. Otherwise, they would not be translated into integral equations (Bala, Arshad, and Noh, 2017). Essentially, a Stock-Flow diagram is a representation of a system in terms of first order differential equations. The SD representation that is able to account for this effect is the Stock-Flow diagram. This representation is shown in figure 3.2.

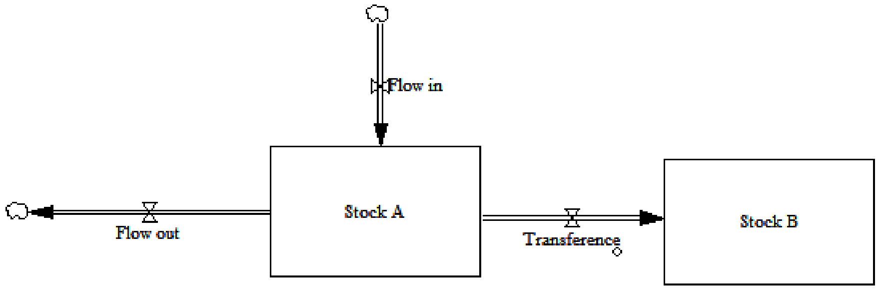



Figure 3.2: Stock Flow Diagram

Figure 3.2 shows a Stock-flow diagram. A stock is a representation of a variable that tends to accumulate with time. In the figure, stocks are represented by a white rectangle. These variables are the ones that represent the state of the system. A flow is the variable that indicate the speed at which a stock accumulates or decumulates. They would be the ones that define the derivative of the Stock in a first differential order equation. The flows are represented in the diagram as a valve, as seen in figure 3.2. The valve has an arrow that indicates whether it is an inflow, which means that if the flow grows, the stock accumulates faster or an outflow, which indicates that if the flow increases, the stock decumulates faster. The outflow of a stock can be the inflow of another stock. In the figure, this is called a transference because the quantity is being transferred from Stock A to Stock B. The cloud at the end or beginning of an arrow indicate that the flow is going or coming from outside the boundaries of the model.

Mathematically, a stock is the integral of the flows affecting that Stock. As mentioned before, the diagram is a representation of a matheatical differential (integral) equation. For instance, equation 3.1 would describe the behavior of Stock A.

$$Stock_A = \int_{t_0}^{t_f} (Flow_{in} - Flow_{out} - Transference)dt + Stock_A(t_0) \tag{3.1}$$

The limits of the integral are the time where the system is going to be analyzed. They correspond to the time scope of the model. The last term of the equation corresponds to the initial state of the stock.

After understanding SD notation, it is possible to understand the following detailed description of the SD models built for this project.

## 3.3. Sub-model Description

The complete model is made up by 10 sub-models. The structure of each of these sub-models is explained here.

### 3.3.1. Sub-model of MaaS adoption by users

This sub-model expresses the mechanism by which users adopt MaaS.

Figure 3.3 shows the graphical representation of this sub-model. External variables are shown in yellow and unit conversions are shown in red. Inputs related to traffic data are shown in blue. In this sub-model, the total travel demand is given by an *initial travel demand* and a *total travel demand growth* which are external variables. This means that the total travel demand is exogenous to the model. The total demand of users can move between two variables which represent MaaS Users and Potential MaaS Users. When *Potential MaaS Users* adopt MaaS, they become *MaaS Users*. When *MaaS Users* discard MaaS, they become *Potential MaaS*

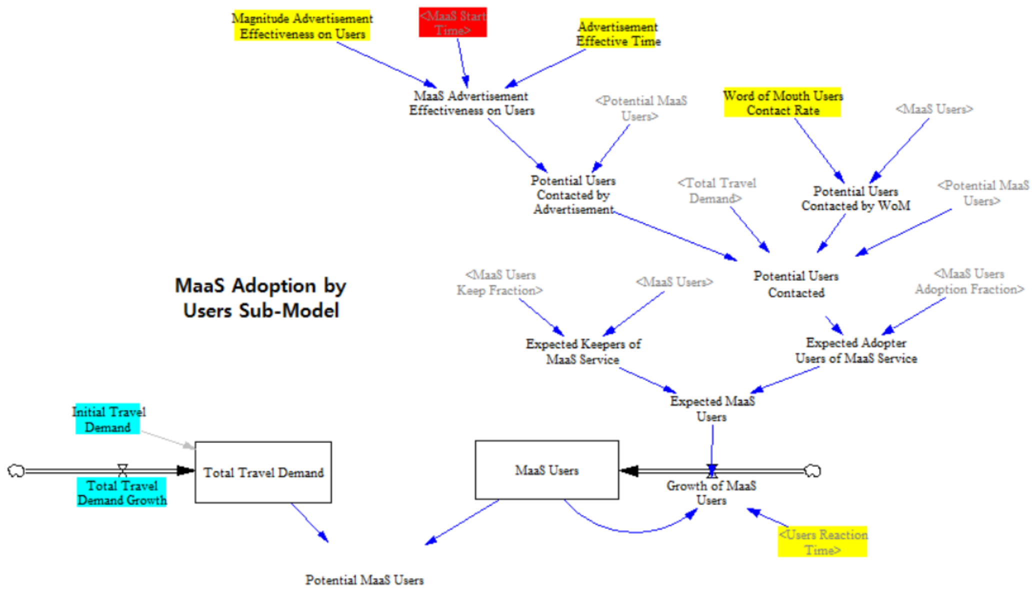



Figure 3.3: MaaS Adoption by Users

*Users.*

The adoption dynamic is composed by two mechanisms. First, there are users that adopt MaaS due to advertisement. In this mechanism, *Potential MaaS Users* have contact with *advertisement* and depending on the *effectiveness* of this advertisement, more users become contacted potential users. The effectiveness of the advertisement is a percentage of users that is continuously being contacted. This mechanism is meant to represent the first driver of MaaS, curiosity. The second mechanism is word of mouth. In this mechanism, *MaaS Users* may have contact with the remaining *Potential MaaS Users*. This contact is determined by a *contact rate* which is the number of potential users that are in continuous contact with a MaaS user. The contacted users decide whether to be part of MaaS depending on an *adoption fraction*. This adoption fraction determines what is the percentage of contacted potential MaaS Users that is expected to be a part of MaaS. The real number of MaaS users is a time delay of the expected MaaS users. The extent of the delay corresponds to the *User Reaction Time*. This means that the expected number of users takes on average one month to react and become a part of MaaS. The discard mechanism is very similar. From the current MaaS Users, there is a percentage indicated by the *discard fraction* that is expected to keep using MaaS.

The variable in red *MaaS Start Time* indicates the advertisement effect when to start acting. The *advertisement effective time* is the length of action of the advertisement effect.

One aspect to highlight of this sub-model is that it differs to common adoption models used in literature. Normally, in these common models, the adopt and discard fractions are expressed as time rates (Sterman, 2000). They represent the growth of a stock in time. If these common models were used in this sub-model, they would represent percentage of users becoming MaaS Users **every month**. However, this approach does not work well in this model because the common formulation used in transportation to calculate the number of users of a service is choice modeling and this approach is used in static scenarios. This formulation is used to calculate the **percentage of the total number of users** that will use a service, which is a different measure than the percentage growth per month. Hence, the adoption model is adapted to fit with the choice model formulation. This is the reason why the fractions in these sub-model represent the expected percentage of the total number of users using MaaS instead of percentage growth per month. The following subsection introduces choice modelling deeply and how it is formulated. Understanding choice modelling is also fundamental to grasp the formulation of the MaaS choice and Mode Choice sub-models.

### 3.3.2. Choice Model

A choice model is a mathematical formulation that tries to describe the choice behavior of agents when they must decide to select one from a set of different options. The outcome of a choice modelling is a fraction which represents the probability of certain choice being selected (Ortuzar and Willumsen, 2011). This representation is fundamental for this project, since decisions such as adopting a MaaS subscription and using a specific mode of transportation are modeled using this formulation.

To calculate the probability of a specific choice, discrete choice modeling uses a decision rule. The most common decision rule is that users choose the alternative with the highest utility for them. Utility is a measure that determines all positive implications for the user to choose a specific option. Formally, for every choice $i$, there is a utility $U_i$. The utility is defined as a function of certain attributes $X_{ij}$ Hensher and Johnson (2018).

$$U_i = \sum_j \theta_{ij} X_{ij} + \epsilon_i \tag{3.2}$$

Equation 3.2 shows the classical formulation of utilities in choice modelling problems. Utility is a linear function of a set of attributes $X$. Each attribute has a contribution to $U_i$ given by the coefficients $\theta_{ij}$. Research has shown that common important attributes in mode choice are travel times and travel costs for the user. The term $\epsilon_i$ is a random variable that accounts for the limitations of the analyst to consider all possible variables. This term is known as the error term and is treated as a random variable. For this reason, it is said that the utility has a deterministic part $V_i$ and a random part $\epsilon_i$. This random part is the responsible that the choices by the user are not deterministic. This is, not every user chooses always the same option. Therefore, it is necessary to discuss probabilities.

$$P(i|C) = P(U_i > U_j \forall j \in C) \tag{3.3}$$

Equation 3.3 shows the formal description of how probabilities are calculated. For a given set of options $C$, the probability of choosing option $i$ is equal to the probability of $U_i$ being higher to all other utilities on the same set.

When the error terms of utilities are independent and identically distributed and they follow a logistic distribution with parameters 0 and $\beta$, equation 3.3 turns to an extreme value distribution due to Gumbel's theorem. This assumption implies that $\epsilon_i$ is the maximum of random variables capturing unobservable attributes. In other words, it assumed that there exists a highest unobservable attribute that is the only one that changes the value of the utility. The logistic distribution obtained is described by the following formula.

$$P(i|C) = \frac{e^{\beta V_i}}{\sum_j e^{\beta V_j}} \tag{3.4}$$

Equation 3.4 shows the formula for the calculation of probabilities from the values of the utility of each option. This formula represents what is called a logit model. The scale parameter $\beta$ indicates the sensitivity of the choice model. This is, if the value of this parameter is high, there is a higher probability that the user chooses the option with the higher utility. If on the other side, it has a low value, the user is indifferent of the utilities and all possibilities have the same probability to be selected.

The parameters of the choice model ($\theta_{ij}, \beta$) are estimated by adjusting the results to stated or revealed preferences. Stated preferences are usually answers to surveys and revealed preferences are the actual behavior for users. When adjusting the parameters, it is mathematically impossible to have unique values for all of them because there are more unknowns than equations. Usually, one of the parameters $\theta_{ij}$ is set as 1, which means that the attribute $X_{ij}$ has the same units as the utility $U_i$. With this modification, the physical meaning of utility is easier to understand.

The model previously explained describes a choice process when there is only one decision to be made. However, it is relevant for this project to understand how to handle choice modeling process when there are sequential decisions to be made. In this case, the previous decisions affect what are the possibilities to choose in the next decision. A technique based on the logit model for the purpose for sequential decisions is called a nested logit model.

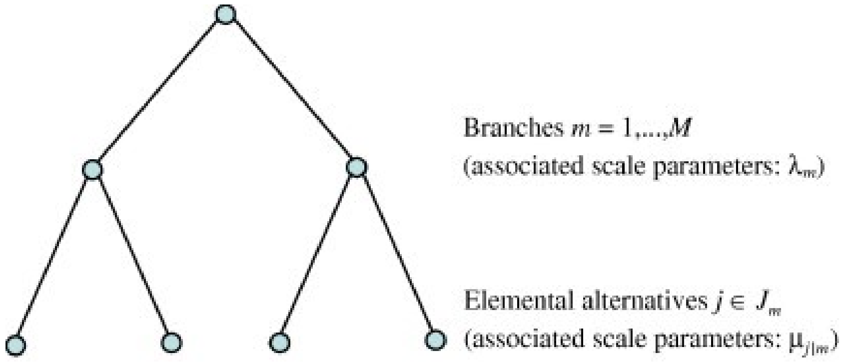



Figure 3.4: Nested Choice Model

A nested logit model is used when there are sequential options to be considered. As shown in figure 3.4, branches correspond to the first choice and each branch leads to a second-choice with what is called elemental alternatives. These models apply the same probability formulas in equation 3.4 but they are expanded using Bayes theorem.

$$P(m, j) = P(j|m)P(m) \tag{3.5}$$

Equation 3.5 shows the formulation of Bayes theorem for the tree in figure 3.4. The probability of choosing alternative $j$ in branch $m$ is the probability of $m$ times the probability of j given that m is chosen. Letting the deterministic part of the utility be noted as $V$ and by replacing equation 3.4 in Bayes theorem the following equations is derived.

$$P(m, j) = \frac{e^{\mu_{j|m} V_{j|m}}}{\sum_{k \in J_m} e^{\mu_{k|m} V_{k|m}}} \frac{e^{\lambda_m V_m}}{\sum_{i \in M} e^{\lambda_i V_i}} \tag{3.6}$$

Equation 3.6 defines the calculation of the probability of an actor choosing the combination of chooses $j$ and $m$ in the decision process.

Now that the choice modelling concept is explained, the subsections using this concept are described.

### 3.3.3. MaaS use choice model by users

This sub-model is the one that calculates *MaaS Utility* from the *quality of the platform*, the *data collected* from users by the platform and the *utility of the modes* of transportation offered by MaaS. This model is also responsible of relating the MaaS utility calculated to the *Adoption of MaaS*. All these relations can be seen in figure 3.5.

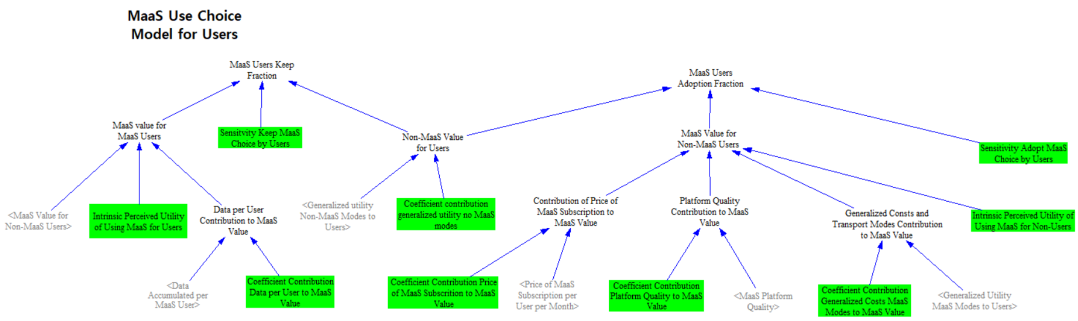



Figure 3.5: MaaS Choice sub-model

In figure 3.5, it is possible to see, at the two top variables, that this sub-model is responsible to calculate the discard and adoption fraction mentioned in the previous sub-model. These values are calculated by using a nested logit choice model with the utilities of using and not using MaaS. Since adopting and discarding

MaaS are two different decisions, each of them corresponds to a different logit model.

The adoption fraction compares the *value of MaaS for Non-Users* with the *value of no MaaS for Non-Users*. Non-users do not have access to a MaaS platform that adds value to their modes of transportation. Hence, the only contribution to the value of not using MaaS is given by the modes of transportation of a Non-MaaS user. On the other hand, non-MaaS users perceive an added value due to the services offered by the platform. This value is represented by the platform quality contribution. However, there are also added cost of using MaaS. First, the user must pay a MaaS subscription fee and secondly there is an attitudinal resistance to change. This resistance is expressed by the *Intrinsic Perceived Utility of Using MaaS*.

For the keep fraction, the same comparison is made. However, the utility of having a MaaS subscription perceived by a MaaS user is different than the one perceived by a non-MaaS user. Hence, a new utility is defined. The new value adds, to the non-user value, the improvement in the service due of the user preferences gathered by the platform. This data can be used to offer discounts and optimize the service experience. Besides, once a user is using MaaS, there might be a change resistance to leave the system. This resistance is represented as the intrinsic perceived utility of using MaaS. The effects of data and the platform quality represent one of the drivers of MaaS, quality digital service.

The green color in the variables indicates that these are the coefficients that are part of a choice model implementation.

### 3.3.4. Sub-model of MaaS adoption by taxi drivers

This sub-model corresponds to the behavior of the taxi service providers.This model has the same structure as the one about the adoption of MaaS by users. Instead of users, taxis decide whether to be part of MaaS or not by a mechanism of advertisement adoption and discard. The adoption and discard fractions are determined by the taxi MaaS Choice sub-model.

It is important to notice that public transport operators are not included in the model as adopters. There are strong reasons to do this. PTOs cannot continuously adopt MaaS since they correspond to companies that have a big capacity. Once one of them enter the model, it changes completely. It does not make sense to model these transitions with a continuous model because of these discrete changes. Each taxi on the other hand only slightly changes the model, making them more suitable for a continuous methodology such as an adoption model. Moreover, the role of PTOs is an important uncertainty of the system because it is a driver of MaaS. By assuming these providers enter the service by a market mechanism, it is already assumed that PTOs would take the role of an additional mobility service instead of being in control of the system. This role is rather modelled as an uncertainty.

### 3.3.5. MaaS use choice model by taxi drivers

This model explains the mechanism by which the adoption and discard fraction of taxi drivers is calculated.

Figure 3.6 shows the structure of the sub-model. Again, there are two different fractions that determine the decision by taxi drivers of adopting or leaving MaaS. This decision is dependent on the value of using or not using MaaS. There are intrinsic preferences that account for the resistance of change by MaaS users to leave MaaS and by non-MaaS users to acquire MaaS. Besides these intrinsic preferences, the value of MaaS is higher if there is a gap on the demand of taxis, if there are more MaaS or non-MaaS taxis demanded than those that are available, the value of having or not having MaaS rises respectively because there is a demand that is not being satisfied. Likewise, if there are more taxis offered than needed, the value decreases. Naturally, taxi drivers are also attracted to the service that pays a better commission for their job. This model assumes that the system with the higher price pays a higher commission to the taxi drivers.

The number of taxis demanded is calculated in the mode choice sub-model.

### 3.3.6. Private car ownership sub-model

Modeling private car ownership is a difficult task because there is not enough research about the impact of attitudinal variables towards MaaS. Furthermore, research has shown that the impact of variables such as travel time and travel costs is not relevant for the decision of owning or not owning a car. For these reasons,

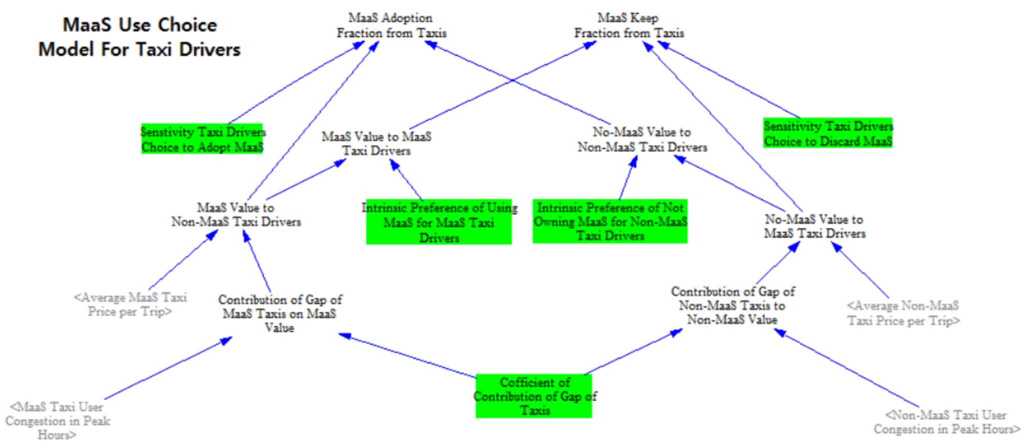



Figure 3.6: MaaS Choice for taxi drivers.

this model assumes that the utility of owning a car is an external variable for which MaaS does not have any influence. However, the fact that the utility is external does not mean the private car fleet is not reduced by the influence of MaaS.

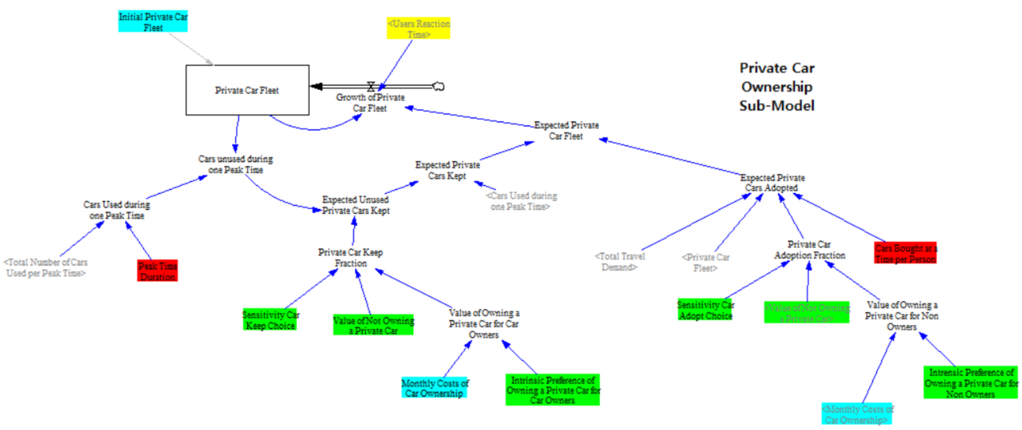



Figure 3.7: Car Ownership Submodel.

Figure 3.7 shows the mechanism by which private car ownership changes under the influence of MaaS. This model assumes that since allegedly less cars will be be used due to MaaS, people who stop using their cars will consider selling them. The fraction of people selling their car will be given by a logit model of the external utilities of having or not having a car. This relation was proposed by Sampo Hietanen as a motivation for the implementation of MaaS. However, he recognizes, there is not enough literature and experience yet to confirm it.

The variable peak time duration is necessary to relate the private car fleet with the number of cars available to be used in every peak. The assumption is that all private cars can potentially be used during peak hours. The cars bought per person is a unit conversion indicating how many cars a person buys when they decide to buy one. The assumed value is one.

### 3.3.7. MaaS platform development sub-model

This sub-model explains the influence of data collected and quality of the platform on the utility of MaaS. This corresponds to the loops of "Data Network Effect" and "Platform Development" shown in the model from Ruutu, Casey, and Kotovirta (2017). The sub-model is shown in figure 3.8.

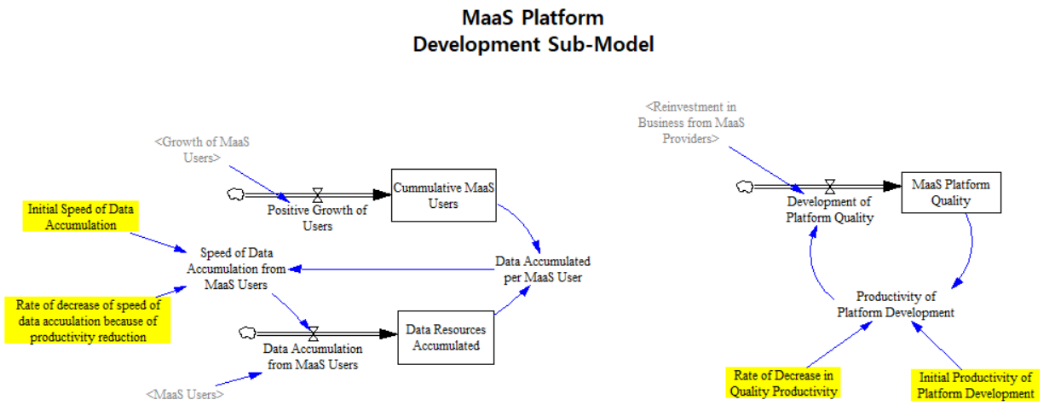



Figure 3.8: Platform development submodel.

Figure 3.8 shows that the sub-model is composed by two parts. First, the calculation of the data accumulated per user which is the variable that directly affects the value of MaaS. This variable is calculated by the ratio of the data resources accumulated with the cumulative number of MaaS Users. Data resources accumulated is the integral in time of the number of MaaS users multiplied by the speed of data accumulation. In other words, it is assumed that the platform accumulates data depending on the time that each user has been using the MaaS platform. The more time, the more data accumulated. Since it is unrealistic that the platform keeps accumulating infinite data, it is expected that the speed of data accumulation decreases on time because it is harder to gather non-redundant data.

The second calculation corresponds to the platform quality. It is the integral of the resources reinvested on the platform. The speed of improvement is given by the productivity. Again, it is expected that the productivity decreases on time because of productivity decay.

### 3.3.8. MaaS providers financial sub-model

This model is responsible for determining the finances of the MaaS providers. This mode is in the relation between the variables *MaaS subscription Price* with *MaaS Providers Financial Resources*. Besides, it calculates the *Market Share Gap* and the size of the *Investment in platform development*.

Figure 3.9 shows that the model consists of a stock that tracks the financial resources of MaaS providers. The stock increases due to the monthly payments of the subscription fee done by the MaaS users. These resources are used to pay the operational costs of MaaS providers and the reinvestment in business from MaaS providers. As commented before, this reinvestment increases platform quality.

The reinvestment in business is a percentage of the financial resources of the providers. This percentage is motivated by a competitive effort (see figure 2.8), if MaaS has incomplete control of the expected mobility market share, it is assumed that companies reinvest to get new clients. This model has a limitation. It assumes that MaaS providers do not reinvest if they compete between each other. However, this only happens if the full market is dominated by MaaS. To overcome this limitation, it is assumed that this reinvestment is part of the fixed costs.

The costs in the system have three origins. First, the payments to taxis for the trips included in the MaaS package. These payments depend on the market price for taxi services. Secondly, the payment to public transport operators for the use of their services by MaaS users. This model assumes that in the negotiation with the operators to be part of MaaS, these offer a discount to MaaS companies for the possibility of an increase in the demand of public transport. Finally, there are fixed operational costs for the maintenance of servers and the payment of debts for the initial investment.

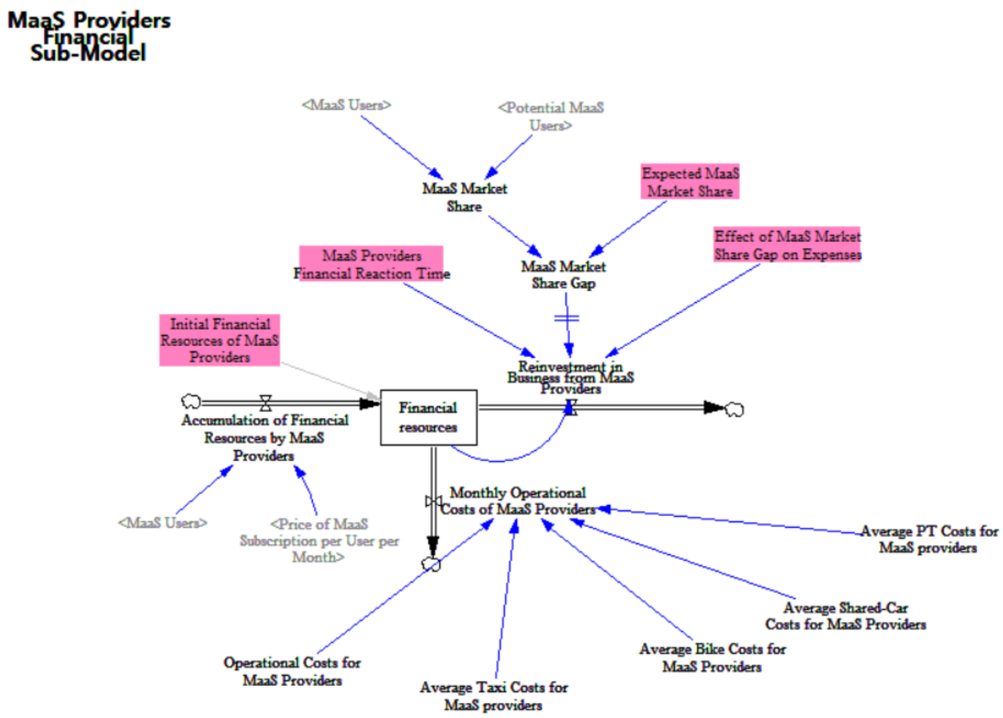



Figure 3.9: Financial Sub-Model.

The pink color in the variables related to this model is an indicator that these variables correspond to actions implemented by MSPs. These variables permit to add the multiactor nature of MaaS to the model.

### 3.3.9. Mode Choice Sub-model

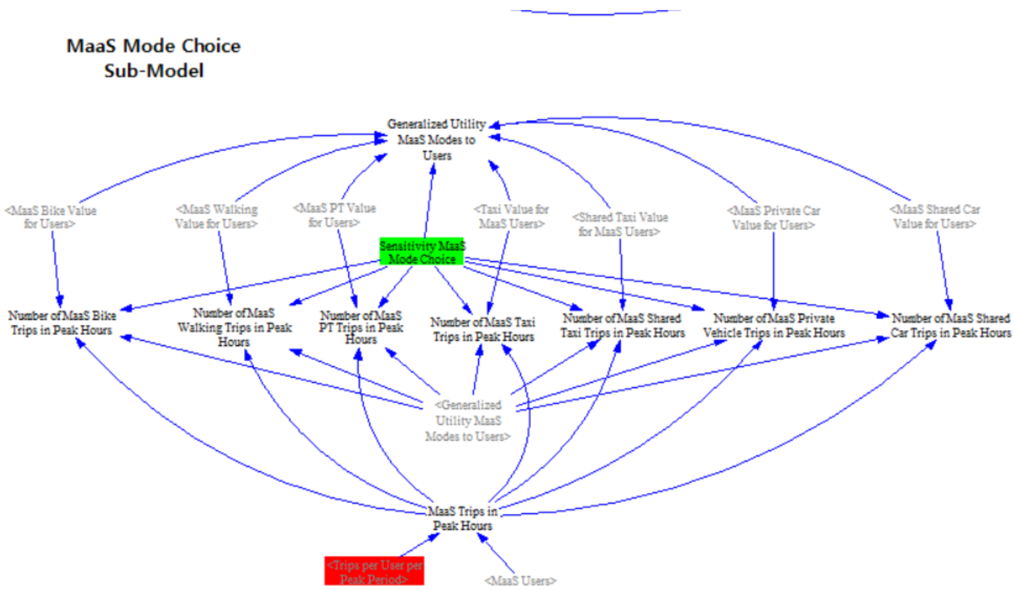



Figure 3.10: MaaS mode choice sub-model.

Figure 3.10 shows the choice model implemented to calculate the distribution among modes of the MaaS users. It is a logit model that uses the utility for users of each of the modes of transportation to determine the number of users of each mode of transportation. The generalized utility of this system is used in the nested logit model to determine the choice of MaaS by users. The same logit model is implemented to calculate the number of user in each mode of transportation outside of the MaaS system.

### 3.3.10. Mode Utility Sub-model

This sub-model consists of many different sub-models. It is used to calculate the mode value for MaaS and Non-MaaS users to determine the number of users taking each mode with the previously explained mode choice model. As seen before with Wegener's circle, each mode utility depends on the travel times and travel costs of each mode of transportation.

Some of the utilities require the understanding of the concept of Akcelic's curves. These are a method to calculate the travel time of agents in a system in presence of congestion (Akcelik, 1991).

$$t = t_0 + 0.25T(\frac{q}{C} - 1 + \sqrt{(\frac{q}{C} - 1)^2 + \frac{Jq}{TC}}) \tag{3.7}$$

Equation 3.7 shows the equation that describes Akcelik's curve (Akcelik, 1991). In the equation, $t$ is the travel time spent in a specific link, $t_0$ is the free flow travel time, this is the travel time in the absence of congestion, $T$ and $J$ are model parameters usually reported in literature, $q$ is the traffic load on the link, and $C$ is the max traffic load allowed in the link.

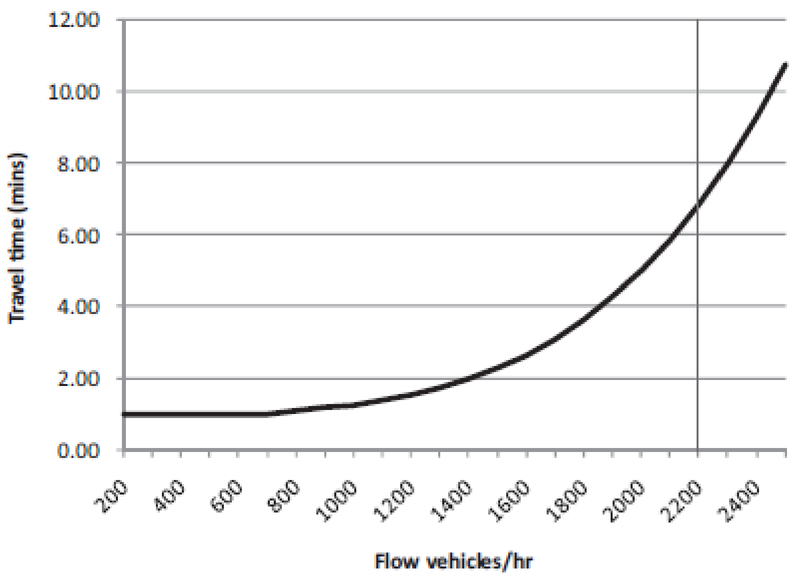



Figure 3.11: Example of an Akcelic's curve. (Ortuzar and Willumsen, 2011)

Figure 3.11 shows an example of an Akcelik's curve. Whenever the load on the link (number of vehicles) increases, the travel time increases, too. The vertical line indicates the point where the load reaches the capacity value. This function has the advantage that it permits to calculate travel times on a system when the capacity is surpassed. In other words, it is able to include the effects of queuing.

Now that this concept is understood, the utilities of each of the transportation modes are explained.

Figure 3.12 shows the utility of biking by MaaS users. Since bike times and costs are not influenced by MaaS, these values are external. The value of time is used to compare times and costs with a single unit, Euros. The same model used in figure 3.12 was applied to walking mode because all values are external as they are not influenced by the system.

There is no explicit bike share utility implemented in the model. The assumption is that bike and bike share can be implemented together with an average acces/egress time given that the values that affect bike

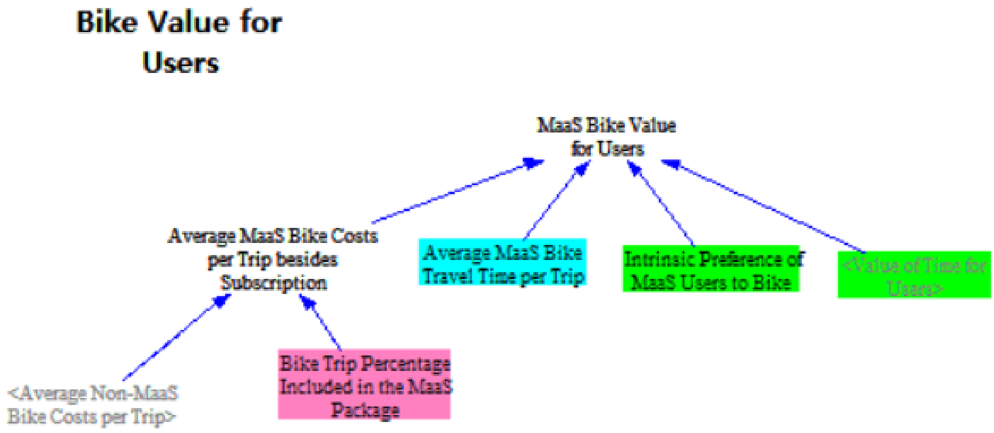



Figure 3.12: Utility of bike for MaaS users

value are not affected by traffic congestion.

The value in pink color in the system is the percentage to which the bike service will be covered by MaaS. This variable is used as a scenario of different integration levels of the system with the bike mode. Physically, it represents the percentage of the capacity of bike share systems that are included in the package. It can also represent whether the package offers the user a rented bike.

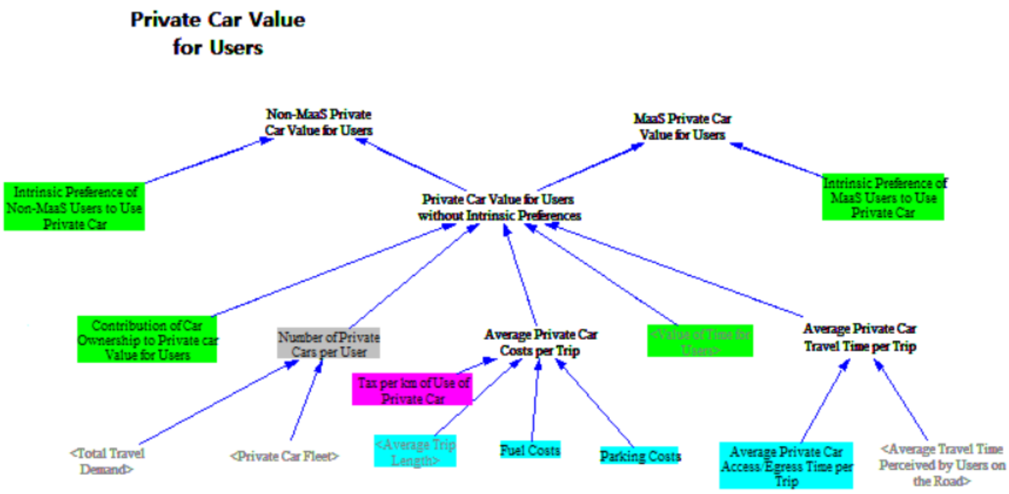



Figure 3.13: Private Car Utility

The value of private car has a similar structure to the one with the bike, the difference is that a new variable influences the value of private car. The number of private cars per user affects the value of private car since users with a car are more prone to use it. This variable is in gray because it corresponds to a key performance indicator. Moreover, the time spent in the road is a function of traffic congestion. The car share mode has a similar model to the one of private car but it is not influenced by car ownership.

Public transport value has a more complex structure. The complexity lies in the calculation of the time in the system. First, the user perceives the travel time as an average of the travel time in the recent past days. Therefore, the variable average perceived travel time has a delay mark. The total time consists of travel time and access and egress time. Besides the delay in the perception of the travel time, the system is complex because of the structure of public transport. Since public transport consists of buses which are affected by congestion and other systems like tram that are not, it is necessary to calculate the total travel time in the

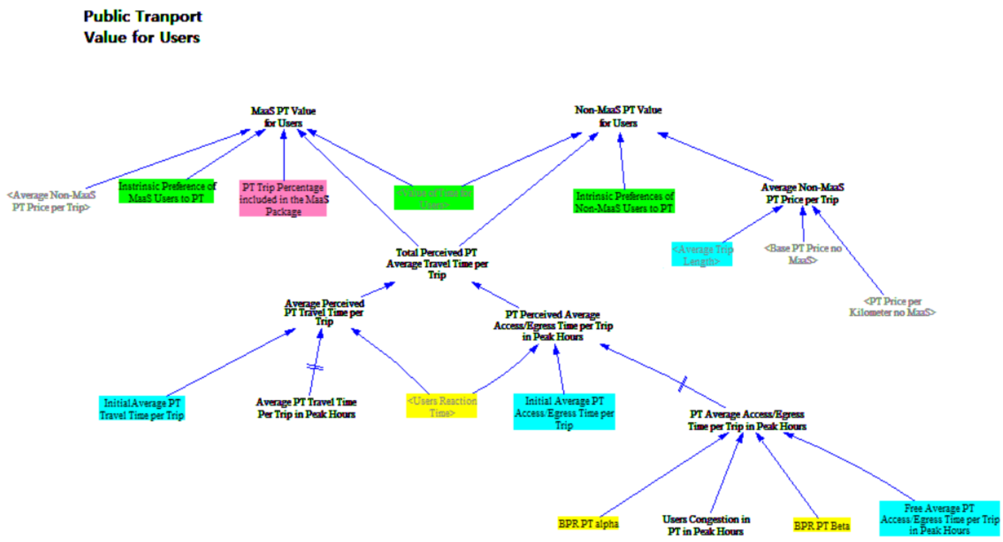



Figure 3.14: Utility of Public Transport

system as a weighted average with the capacity of each of these types.

The PT utility sub-model has a variable called "PT trip percentage included in the MaaS package". This variable has a default value of one which means users do not have to pay anything for using public transport within MaaS. This variable can be varied to assume that not all PTOs agree to be a part of MaaS and create different scenarios.

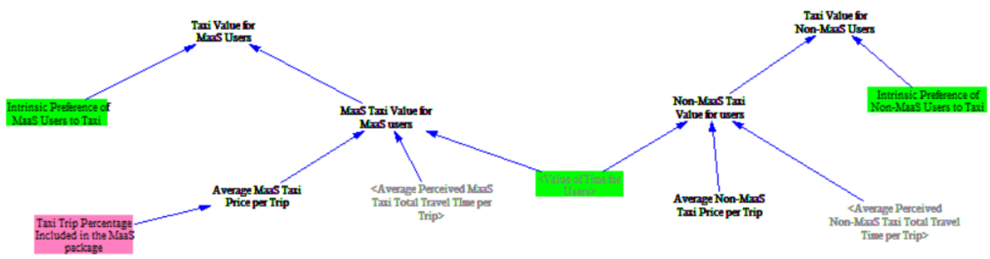



Figure 3.15: Taxi Value

The value of taxi for users also has a high complexity. The times are calculated including travel time and access and egress time to the taxi. The travel time is dependent on the congestion on the system and the access time is an Akcelik's function of the user congestion. MaaS and Non-MaaS taxis are treated independently. In other words, both MaaS and non-MaaS taxis have their own capacity and access time.

For the calculation of costs of taxis, it is assumed that a specific number of taxis is included in the package every month.

The value of shared taxi is calculated by assuming that the costs of a non-shared taxi are divided by the number of occupants of the taxi. This number is assumed to be constant. Besides, there is a delay in the total travel time of this mode due to the movements the taxi should make to take each passenger close to their destination. This delay also affects the taxi cost.

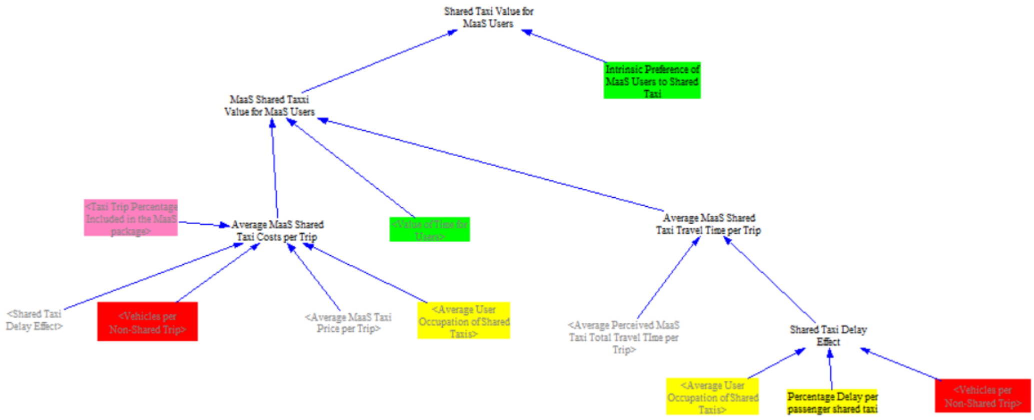



Figure 3.16: Shared Taxi utility

### 3.3.11. Traffic congestion sub-model

The traffic congestion sub-model just adds up the total number of vehicles on the road depending on the services demanded from the mode choice results. Then, it calculates the traffic congestion and average travel time on the road with the use of an Akcelick's function considering the road capacity of the area of study.

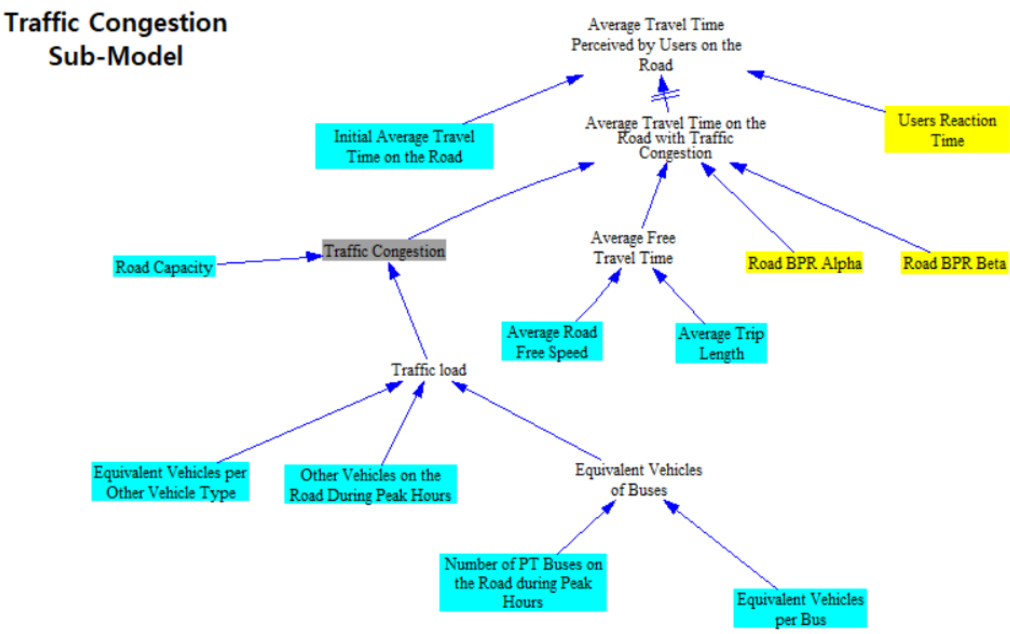



Figure 3.17: Traffic Congestion Sub-model

### 3.3.12. Transportation services price sub-model

The price sub-model calculates the price of transportation services by assuming that the price increases whenever the demand is higher than the offer and it decreases whenever the offer is higher than the demand. This model was inspired by the MIT thesis Economic Supply and Demand by Whelan, Msefer, and Chung (2001). Figure 3.18 shows the structure of the model. The same model was used for public transportation, Non-MaaS taxi and MaaS taxi price.

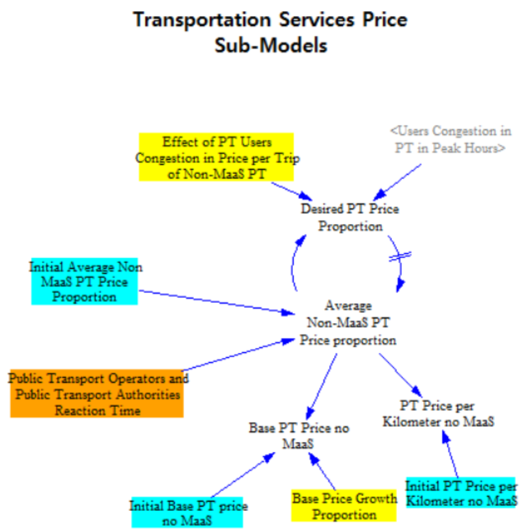



Figure 3.18: Transportation Service Pricing Sub-Model

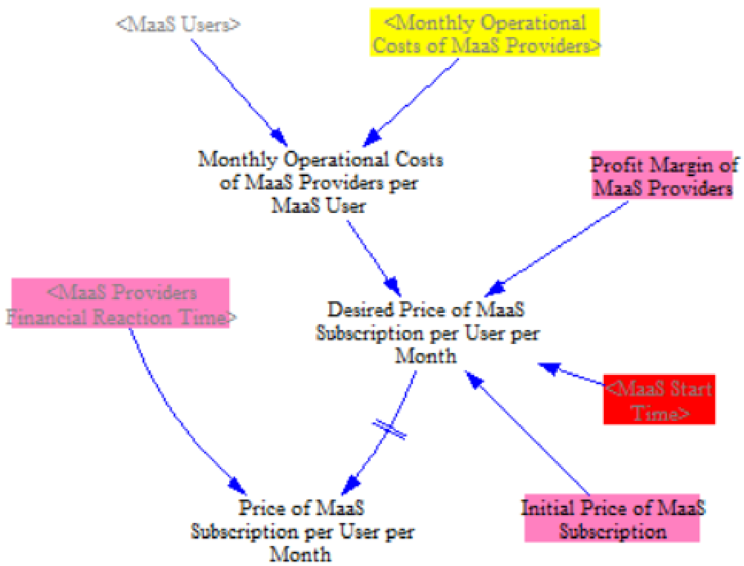



Figure 3.19: MaaS Subscription Price Sub-Model

In figure 3.18, the user congestion corresponds to the balance between offer and demand in the system. Whenever there is an imbalance, the price changes. There is a delay because the actors in the market cannot react immediately to the changes in the demand. Hence, there is a reaction time that need to be considered. This mechanism has a limitation. It assumes that the price of public transport follows a free market mechanism. This is not always true because the price of PT is usually defined by policy processes. However, if the parameters of the model are fitted using the prices of PT in the past, it might be a good approximate of the future behavior. However, there is a need for further research on how to model the mechanism by which PT price changes.

Finally, figure 3.19 shows the pricing model for the price of the MaaS subscription package. It is assumed that the price of the MaaS subscription equals the total costs of MaaS providers divided by total number of

MaaS users plus a margin of profit. Again, a delay is needed to account for the reaction of MaaS providers to the market changes.

## 3.4. Summary

This sections analyses the SD model built in the light of the main characteristics, drivers, its framework components and the relation between MaaS and traffic congestion.

The model needs to implement the four core features of MaaS. First, MaaS offers a variety mobility services. This is clear in the model in the mode utility sub-model where each of the transport modes that could be available in MaaS according to van Kuijk (2017) are included in the system. Secondly, MaaS integrates is system in a digital platform that offers digital services to the users. This characteristic corresponds to the submodel of platform development where both quality of the platform and personalization due to data gathering from the user are included. The model integrates the modes it offer by the use of a nested logit choice model where the value of the different modes of MaaS influence the total value of MaaS. Finally, the model offers the possibility to include the modes in bundles by variables that indicate the percentage of the service that is included in the package and the MaaS package price.

The second aspect to check with the model is if it fits with the findings of the framework of MaaS. First, MaaS in in his thesis is considered equivalent to a CMS. In other words, the assets belong to the service provider and not to the users. This is clear in the model because the service providers have total control over the price and their financial strategies. Hence, there is no possibility for user involvement in these aspects. Peer Share services are excluded of the model because they keep traffic congestion constant. If a user decides to give its car to another user, the amount of cars on the road is the same. Hence, the effect of these services is already included in the private car value. Bike share services are assumed similarly to be part of the common bike value. This is possible because the values of time and the price of the bike are independent from MaaS developments in the model. Hence,these services may be averaged into one. Finally, in relation with the MaaS framework, all actors have levers they can control in the system. The only actor missing in the model until now is the government that will be included later in the policy analysis chapter.

The key drivers of MaaS are also implemented in the model. The curiosity driver of MaaS is given by the User adoption sub-model with the advertisement effect. The main deterrent of MaaS, price, is included in the MaaS choice model with a negative contribution for MaaS value. Since the MaaS choice model is a nested logit model, the added value of multiple modes account for the flexibility of MaaS as an positive driver. The service quality is included as an explicit variable in the platform development sub-model and the value of customization that MaaS has is present in the contribution of data collected at the platform development sub-model. Finally, the role of accessibility is given by the access and egress times to each of the possible modes available. If the times increase, the system becomes less attractive. Hence, MaaS become less attractive as well.

The drivers of the offer are also present in the system. The financial challenges are explicitly added as a sub-model. Issues like the role of PTOs can be analyzed by targeting different variables during the analysis. For instance, if it is believed that PTO is the main MSP, probably the value PTOs will try to maximize is the sum between revenue of MaaS and revenue of PT instead of just the revenue of PT, both are easy to calculate in the model by multiplying number of users with price.

The sub-model of private car was built with the perceptions from the experts, that were expressed during the interviews. The model allows to take the value of private car as an uncertainty. Hence, it is possible to emulate the uncertain behavior of this critical aspect of the system.

To conclude, the sub-model offers a complete hypothesis of the behavior of MaaS that takes into account the relevant literature findings up to now.

# 4

# Model Implementation

This chapter describes the process of the model implementation. It is discussed what is the case of study chosen to explore the utilities of the model and what are the scope and the data inputs for this base case. After, the base case results are presented with an analysis of the behavior of the system and its most influential dynamics.

## 4.1. Case of Study Description

The city chosen as a case of study to apply in this exploratory research is the city of Amsterdam. There are three reasons for this. First, logistically, it is easier for this research project to get data and information resources from a city in The Netherlands. Moreover, Amsterdam is the city with the highest travel demand in the country. Finally, some MaaS providers are already starting their business in Amsterdam which gives this research more relevance.

### 4.1.1. Background

This section describes the background about traffic congestion and MaaS development in the city of Amsterdam to understand the context of the case of study chosen.

Amsterdam is a city that has good transportation infrastructure. It has a road network with a total of 4808 km (Tomtom, 2018). The infrastructure of public transport includes fourteen tram lines, four metro lines with a total length of 42 km and a total of 218 buses (GVB, 2018). Due to its good infrastructure and urban planning, Amsterdam has managed to keep stable traffic congestion levels in the last ten years.

On the other hand, the levels of traffic congestion in peak hours go up to 52%, which means that users take 52% more time to commute in the evening peaks (Tomtom, 2018). Moreover, Amsterdam is a city that is expected to have challenges related to mobility and spatial development in the future. The city grows at a rate of 10000 inhabitants per year and tourism is growing at a rate of 450000 visitors per year. The speed of these changes makes the necessity to create more efficient mobility standards. Also, the city is suffering from a parking problem. Car users are spending usually more than 15 minutes finding a place to park. Besides, these autos also occupy public space, difficulting the transit of pedestrians, too (Gemeente, 2013).

Amsterdam is a city that has historically shown to be very innovative in mobility management. The city has a long term vision on mobility and it's already thinking in the challenges of the future. In the last years, Amsterdam is not only being improving its infrastructure and spatial development but also has put focus on Smart Mobility. The use of technologies is expected to be fundamental for the development of the city. In 2016, a two year mobility plan was developed that included digital monitoring of parking, promotion of self-driving cars and even the creation of a pilot program for Mobility as a Service Amsterdam, 2018. This pilot program was done in the district of Zuidas.

After the pilot, the users stated that the experience was positive. Most of them tried new combinations such as public transport with bike or even taxi with bike. Users said that Uber was an excelent replacement for car leasing and that public transport was a good one. More importantly, the users stated they would be willing to try different services if the use of car become worse. The most important factors for the users to choose a service where comfortability, travel time and availability of the service. The leased car was missed the most in the evening peak, when public transport is more crowded, in the weekends, for complex trips and for spontaneous needs (Amsterdam Zuidas, 2018).

The city of Amsterdam is getting close to have a full operational MaaS service. Whim gloal, the first MaaS provider, which is already implemented in Helsinki plans to start business in Amsterdam during 2018 MaaS Global, 2018.

## 4.2. Model Scope

This section describes the specific model scope for the case chosen for analysis. It describes what specific region of Amsterdam is being analyzed and what simplifications are done in this area. Moreover, the time frame for which the model is to be run is also presented here.

### 4.2.1. Spatial Scope

There are two critical things to consider when defining the spatial treatment of the area of study. First, it is important to define where are the spatial boundaries of the area for which the traffic congestion and the demand of transport will be considered. This model considers all seven districts of Amsterdam.

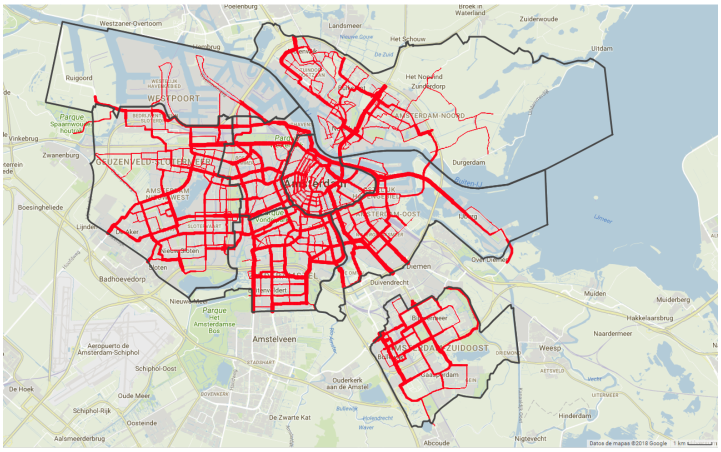



Figure 4.1: Districts of Amsterdam and traffic prognoses by 2015 (Amsterdam Gemeente, 2018)

Figure 4.1 shows the study area to be considered. It includes all seven districts of the city of Amsterdam. The red lines in the figure are the data of traffic in the city by 2015. The wider the line, the more traffic load in the road. This is the starting point of the study and this is the traffic congestion that will be considered.

The second critical aspect to define the spatial scope is the level of aggregation. Usually, transportation models consider the division of the area of study by zones so that specific local behavior can be grasped. The objective of this study is not to understand how congestion will behave in every specific road but rather how the system of MaaS behaves as a whole. Hence, no division of the area of study will be considered. All values regarding traffic congestion will correspond to average values among the users of transportation systems in the city.

Even though only traffic congestion in the area shown by figure 4.1 will be considered, it is important to take into account that many users of transportation systems in the city come from areas outside of the city. This means that the specific data regarding average number of cars per user need to consider users living outside of the area of study. It is assumed that these users can also access MaaS services. Hence, the effect of MaaS can also be felt outside of the boundaries of the area of study. However, it will not be quantified by the model.


Figure 4.2: Amsterdam Transport Region (Vervoerregio Amsterdam, 2018)

As a simplification, it will be assumed that only users living in Amsterdam Transport Area commute to Amsterdam during peak hours. Thus, the extended area where car ownership will be considered is now given by figure 4.2.

### 4.2.2. Time Frame

This projects aim at understanding MaaS through SD at the tactical level. This is, the level in which there are no big changes in infrastructure and housing due to the impact of MaaS.

Table 4.1: Investment in Urban development in Amsterdam until 2040 in millions of Euros (Amsterdam Gemeente, 2014)

| Item | 2010-2020 | 2020-2030 | 2030+ | Total |
|---|---|---|---|---|
| Infrastructure | 10.080 | 4.805–6.715 | 10.200–10.860 | 25.085–27.655 |
| Area Development | 780 | 765 | 933 | 2.478 |
| Green Spaces | 129 | 47 | 2 | 178 |

Table 4.1 shows the expected investment in Urban Development for the city of Amsterdam until 2040 as stated by the city municipality in its vision of the city. It is expected that the years 2020 to 2030 have lower investment required than the previous ten year period. No big changes in the current trends of the housing and infrastructure market are expected in this period. However, after year 2030, due to the growth of the region of Zuidas, big investments will be needed. To avoid dealing with the strategical decisions by user during this period, a time frame of 12 years is proposed for the developed SD model.

## 4.3. Model Input

This section makes a description of the data used as an input in the model and describes special treatments to adapt the input data to the model created. It provides an overview of the sources used and specific procedures to adapt the data for the SD model. For a detailed formulation of the model, see Appendix B. The data input will be classified in six categories:

### 4.3.1. Transportation Related Data

Transportation related data includes all variables that have a relation to the transportation system. It includes transportation costs, travel times, car ownership, travel demand and the capacity of the different modes of transportation. Four main sources were used to fill this variables. OIS, GVB, Taximonitor and CBS provide free access to data about the city, including data related to transportation and infrastructure. The research project from van Kuijk (2017) at Connekt was used as a guide for the access and egress times of the different services. The datasets found provide the data about travel demand, car ownership and travel times required for the model.

### 4.3.2. Choice Modeling Coefficients

This category includes all the coefficients used for the choice model implemented in the SD model. It includes both sensitivity and contribution coefficients.

The coefficients were found by fitting the them to the historical modal split of the city from 2011 to 2015. Unfortunately, the modal split does not make a difference between private cars and taxis. To determine the taxi split and the shared car split, it was assumed that these systems by year 2011 are operating at full capacity.

Table 4.2: Coefficients Mode Choice

| Mode | Intrinsic Preference | Value of Time | Price Contribution | Car Ownership Contribution |
|---|---|---|---|---|
| **Private Car** | 0.412041 | -0.016457 | -0.052989 | 0.151306 |
| **Public Transport** | -0.262446 | -0.002412 | -0.177813 | 0 |
| **Bike** | 0.796892 | -0.025921 | -0.000441 | 0 |
| **Walk** | 0 | -0.006896 | 0 | 0 |
| **Taxi** | -2.75284 | -0.035294 | -7.46 $10^{-05}$ | 0 |
| **Shared Taxi** | -0.0420258 | -0.9957 | -0.3409 | 0 |
| **Shared Car** | -5.53747 | -0.0001 | -0.000001 | 0 |

Table 4.2 shows the coefficients obtained for the modal split. The utility of each mode is given by the following equation:

$$V_i = IP_i + VoT_i * t_i + PC_i * p_i + CCO_i * ACO \tag{4.1}$$

Equation 4.1 shows the form of the utilities for the mode choice implemented in the model. The sensitivity is set as one. Each mode has their own value of time ($VoT$), price contribution ($PC$) and intrinsic preferences ($IP$). Only the value of private car is affected with the average car ownership ($ACO$) due to the contribution of car ownership ($CCO$). Some models assume that the value of time is the same in all modes of transport. However, the results obtained did not fit accurately with the modal split. An explanation is that the travel demand has no level of aggregation in the model. This means, it is assumed that the behavior of all users can be summarized as a single user with an average behavior. By using different coefficients in each mode, it accounts for the differences in perception when a user takes certain mode. For instance, bike users may value time different than private car users because there are differences in comfort between these modes. It is recommended for future research to do a proper market segmentation, permitting to apply a single value of time for all transport modes.

The parameters of the mode choice of MaaS users are assumed to be the same as for Non-MaaS Users. The assumption is that there is no change in the intrinsic preferences and perceptions of users using MaaS and users without a subscription.

### 4.3.3. MaaS providers variables

This category includes all variables in which MaaS providers have direct control as part of their business strategies. Since this input correspond to unknown future behavior, the following main assumptions were made to define it for the base case scenario.

- MaaS Providers goal is that MaaS has the total market share of mobility services so that everyone has a MaaS subscription.
- There is a one billion Euros initial investment in MaaS services. This assumption is taken because it is the order of Magnitude of the total investment in shared mobility services since 2010 until now (McKinsey, 2017).

- MaaS providers will keep reinvesting as long as they are in a competitive market where many providers offer the services to the users.
- The profit margin of MaaS packages is 10%. This value might be optimized to see what is the best scenario for the providers.
- MaaS providers check their business strategy every six months.
- The initial price of a MaaS package was taken from the current market price in Finland Ratilainen, 2017.

### 4.3.4. Transport Operators Variables

Public Transport Operators variables includes all variable for which the Transport Operators have direct control. This category is also related to one of the main policy discussion topics addressed in the case description. There is a debarte on what should be the role of public transport in MaaS. The role can be defined by the four variables in this category.

- PTOs and PTAs reaction time sets the time at which PTOs define their pricing strategy. It is assumed to be every six months.
- PT Percentage Price Discount for MaaS providers is a variable that will be used as a policy to determine if traffic congestion could be diminished by discounting the price of the ticket to them.
- PT Trip Percentage included in the MaaS Package is a variable that tells how well integrated is Public Transport with MaaS. If it is one, it means that the users will not be charged because PT and MaaS are fully integrated. If there is partial integration, some PTOs will agree to MaaS while others will not. Hence, users would have to pay money outside of their package to fulfill their transport needs. This input is used for Policy Analysis. It is set as one as default.
- Bike Trip Percentage Included in the MaaS Package is a variable that says whether the MaaS package include access to bike rental and bike share. The value is set as one which means full integration.

### 4.3.5. SD model parameters

This category includes the parameters of the model that determine its behavior. It does not include choice modeling parameters since they are already classified in a different category.

Most of these parameters are mainly based on educated guesses because of lack of data. There is high uncertainty regarding them. There are seven categories to classify these parameters, each of them with specific characteristics and methods of estimation.

- Adoption models: The users and taxi drivers' adoption models are determined by two important parameters. First, the advertisment effectiveness. This parameter is totally unknown. It can have a value between zero and one and it determines the percentage of people that is contacted by advertisement to try a MaaS subscription. Usually, it is modelled as a step value that has a specific duration in time and then the effect disappears. In the SD model created, it has a small value of 0.001% as default. The effective time is one year.
- Platform Development: The platform development sub-model is highly affected by the parameters that determine the value of platform quality and data accumulated per MaaS user. The educated guess is that the platform gets 10 Mbytes of data per user per month and that this speed reduces because the data becomes redundant with time. This is the order of magnitude of the data spent by a user in a GPS system (Tractive, 2018). The platform quality has an abstract unit. It is assumed that the productivity is one quality unit per Euro.
- Users Reaction Time: This variable corresponds to the time that a user takes to rethink the modes of transportation the her or she is using. It is assumed to be one month since this reflection process may happen every time the subscription is paid.
- Shared Taxi Parameters: There are two parameters in the shared Taxi utility model that are unknown. First, the average user occupation of shared taxis is not known. Moreover, this value should be actually modeled endogenously. However, it is taken as a constant with a standard value of four because the

contribution of shared taxis to traffic congestion is very low. A model boundary analysis could be used to see if this assumption is plausible. The second parameter is the percentage of the delay due to the stops for new passengers.It is assumed to be around 10% per passenger.

- Akcelik's Functions: The coefficients for these functions are usually reported in literature. However, they are not commonly used to analyze aggregated zones such as a city but rather a disagregated link analysis. Hence, the coefficients might change. The method to determine the coefficients was fitting by assuring that the the initial calculated perceived travel or access/egress time is the same as the data gotten from the Amsterdam Municipality. Moreover, there is a restriction where the travel time when the city is congested during the evening peak is 52% higher than the free flow travel time (Tomtom, 2018).

- Price Effects: The price effects correspond to the coefficients that determine how fast is the change of price of a service when the offer does not match the demand. There is no research for this coefficient regarding transportation services in Amsterdam. However, the coefficient was fitted to match the historical data of price of PT and taxis. The pricing mechanism of public transport is not necessarily managed by free market because it is a policy process with governmental intervention. However, the free market model is assumed for simplicity in the base case, given that the fit provide an approximation to the real behavior of the system.

- Operational Costs for MaaS Providers per User: The value of the costs to maintain the digital infrastructure and operate MaaS beyond the transportation services is unknown. It is assumed to be 10 Euros per User per Month.

## 4.4. Base Case Analysis

This section shows the results of the model after the implementation of the base case. It shows the results of the different KPIs defined, then it offers an explanation for the behavior of the KPIs in terms of the causal-loop diagrams that explain this behavior. At the end of the section, a summary with the main findings of this analysis is presented.

### 4.4.1. KPI Results

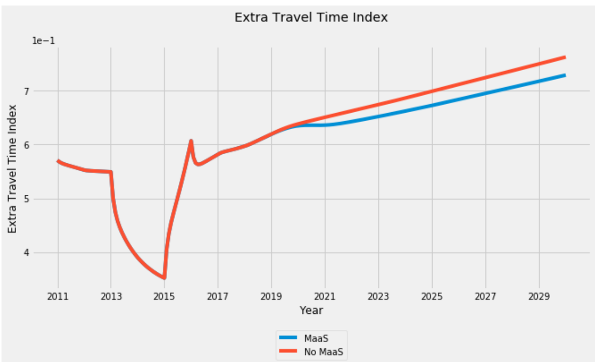
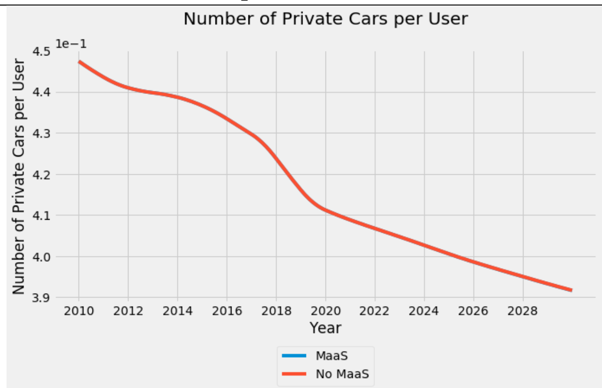
| Extra Travel Time Index | Private Car Ownership |
|---|---|
|  |  |



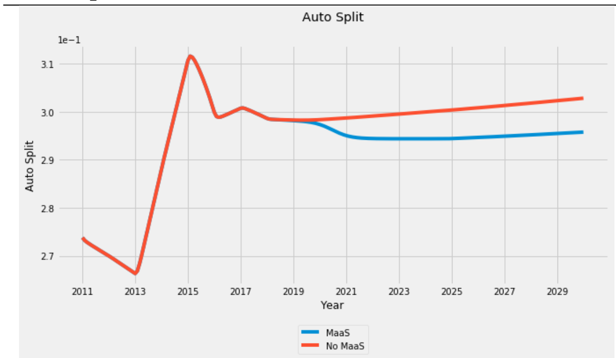


Figure 4.3: Extra Travel Time Index and private Car Ownership

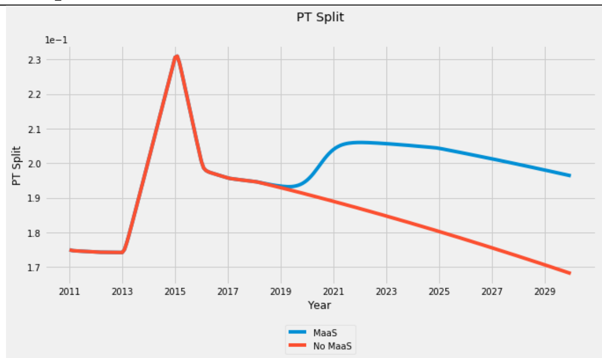
Figure 4.3 shows the results of the main KPIs chosen when running the model in the base case. The figure at the left shows the results for the travel time index. The line in orange indicates the result if MaaS is not implemented. It shows a steady growth of the index in time. On the other hand, if MaaS is implemented, as shown by the blue line, the index grows below the line of the no MaaS case. This could indicate that MaaS decreases traffic congestion. However, the growth of the index in the MaaS case is not very significant and the index keeps growing with a positive slope similar to the one in the case without MaaS.

The plot on the right shows the results of the number of private cars owned per user. When there is no MaaS, the behavior decreases steadily. If MaaS is implemented, the results show that with the parameters of the base case, there is no reduction of car ownership compared to the case without MaaS. In the base case, there is a high resistance of car owners to get rid of their cars.

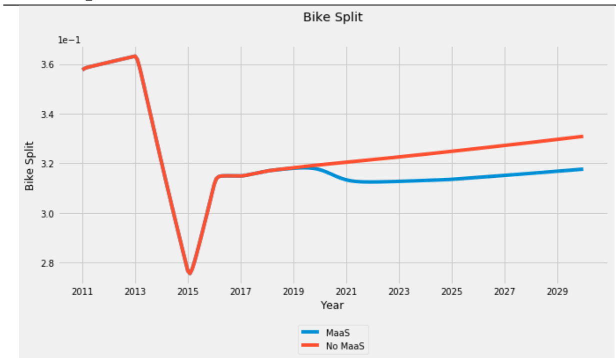
Auto Split




PT Split




Bike Split




Walking Split

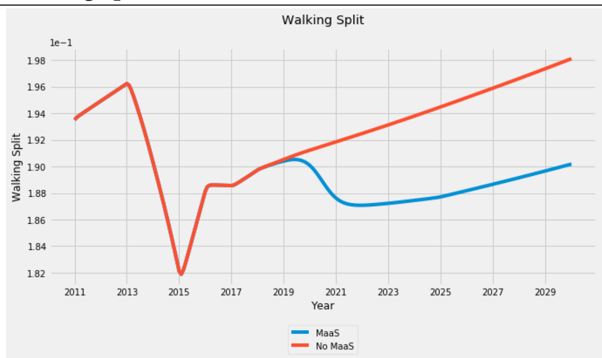



Figure 4.4: Modal Split Behavior

Figure 4.4 shows the behavior of the modal split in the development of MaaS. The orange lines represent the behavior when there is no MaaS implementation. The blue ones show the case when MaaS is implemented.

The no MaaS scenario results show that in general, the use percentage of PT decrease with time while the percentage of users of car, walking and biking tend to grow. Probably in the base case, the growth of congestion and price in PT is playing in favour of the bike, car and walk modes. Moreover, PT has a lower intrinsic preference than the other modes. When MaaS is implemented, the trend has a change. On one side, the use of PT grows until a certain point where the curve gets a similar slope than the no MaaS case. This dynamic is compensated by a decrease in the use of auto, bike and walking modes. MaaS is, as Sampo Hietanen mentioned during the interview, reaching more attention of the users in the short time. However, for the base case analyzed in the model, in the long term the reduction is temporal and the trend of an increasing auto split continues although at a lower rank.

Since the auto split is the main responsible of the traffic congestion on the road, its behavior explains the results found for the extra travel time index.

Figure 4.5 shows a deeper look into the behavior of the modal split of the different modes that are based on the use of cars. The model shows that the values of the modal split of taxis, shared taxis and shared cars are very small compared to the value of the modal split of private cars. Hence, almost all the behavior of the auto split can be explained from the use of private car. When MaaS is implemented, there is a significant growth in the use of Taxis and Shared Cars. The implementation of MaaS also attracts users to use these modes. The resistance to shared taxi is too high, then its modal split is zero. It is a mode that does not attract any user in the model.

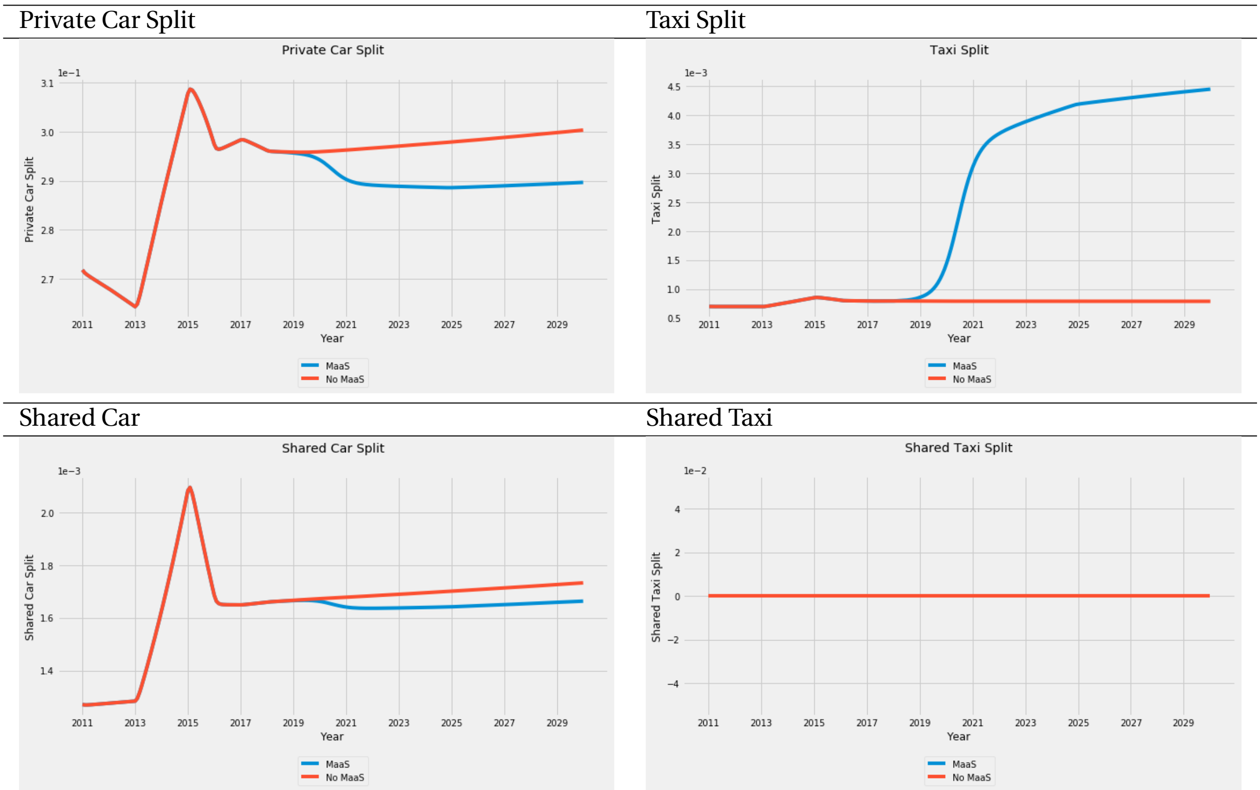



Figure 4.5: Modal Split Behavior

From the previously shown results of the KPI behavior. It is possible to conclude that, for the base case implemented, traffic congestion under a MaaS system decreases in the short term but the trend goes back to the initial state of a growing traffic congestion. MaaS provokes a substitution effect where PT increases its value while the use of Auto, walking and bike decrease its use. However, this behavior only stays for a short term period of time. The change in the auto split is mostly manifested in the modal split of private car. Shared taxi, taxi and share car have a significantly low modal split compared to private car. However, taxis and shared cars perceive an increase in their uses due to MaaS.

### 4.4.2. Results Analysis

This section explains the behavior observed for the KPIs in the run of the base case. Since the visualization of the results lead to understand that the main driver of this behavior was a temporary substitution between PT with auto, walking and bike, this section focuses on explaining this effect.

To begin with, the base case assumes that the travel times, prices and intrinsic preferences of biking and walking are constant. Since choice modeling calculate the modal split from the differences in the values between modes, the variation of walking and biking can be explained in terms of the variation of the other modes relative to theirs. Hence, the temporary substitution effect found in the results necessarily comes from the variation in the values of PT and private car. This is where the core of the behavior of the model is been given.

Figure 4.6 shows an explanation of the behavior of the KPIs in the system. The causal loops with the black labels correspond to the active causal loops when there is no MaaS system implemented. In this situation, the private car congestion loop is a deterrent loop that reduces the trend on the use of private car. When more people choose private car, congestion become worse, increasing travel times. This reduces the value of private car, reducing the number of users. On the other hand, traffic congestion shows a growing behavior. This

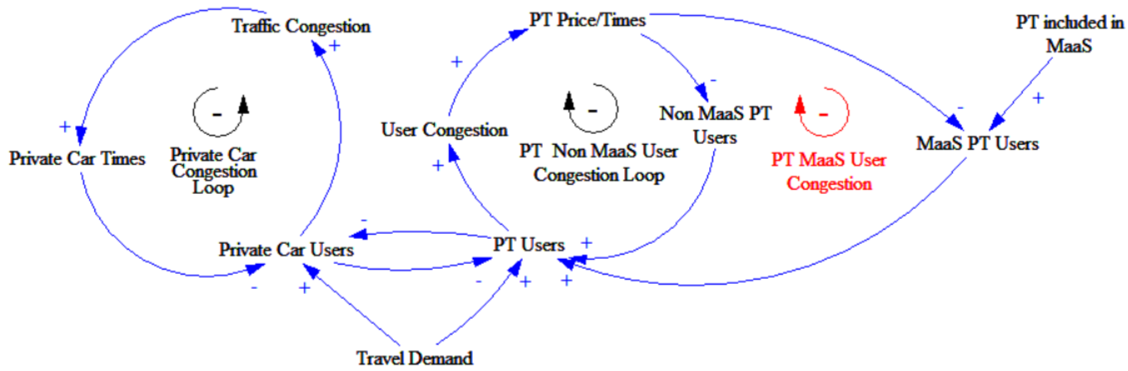



Figure 4.6: Causal Loop Substitution Effect

happens because the negative causal loop does not compensate the growth of the demand of users which is an external input.

In the side of PT, whenever the number of users grow, this increases user congestion. Then the price and times of PT increase, reducing the value and the number of users. This explains why PT split is decreasing. The line between the variable PT users and Private car users intends to show that there is a substitution effect. If the number of PT users grows, the number of private car decrease. This happens taking into account that the value of the other modes of transportation is constant.

When MaaS is activated, the causal loop in red is activated. This causal loop has an identical structure as the PT user congestion loop. However, it includes an external variable that accounts for the inclusion of MaaS in the MaaS package. This increases the value of PT for MaaS users. Ultimately, this leads to more PT users. And because of the substitution effect, the number of private car users decrease. This explains why in the graphs at the previous section, the activation of MaaS had a positive effect for PT and a negative effect for the private car. However, since the PT MaaS User Congestion loop is also a negative loop, the effect of the increase in PT users lead to an increase in the user congestion on the system. The user congestion increases the price and the travel times of PT, ultimately decreasing the value of PT. Hence, the slope of the traffic congestion goes back to its state previous to the implementation of MaaS. Actually, when the model is run for a longer period, traffic congestion in the MaaS case has no difference with the no MaaS case in the long run. It reaches the same previous state because if traffic congestion in the MaaS case grows more than in the non-MaaS case, the cycle of private car traffic congestion would reduce the number of private cars, increasing again the number of PT users. Since the external parameters of the value of PT and private car remain constant, the long term values of traffic congestion are the same. The increase in PT price and total travel time compensates the increase in value due to the use of MaaS.

An evidence that this mechanism explains the behavior of the KPIs is that the value of PT when MaaS is implemented has a lower value than when it is not. This is easy to observe in figure 4.7.

This explanation leaves the doubt whether there is a form to avoid arriving to the same initial state. If not, this would mean that under the conditions of the base case, it is not possible to reduce traffic congestion. The answer lies in the behavior of the number of cars owned per user. If this value changes, the value of private car itself decreases outside of the substitution mechanism shown before. For the base case, there is no reduction in private cars per user.

The loop of private car ownership in figure 4.8 shows the mechanism by which a new trend in traffic congestion could be reached. The reinforcing loop at the right, shown in red, can reduce the number of private cars in the system when the number of private car users decreases. This means that when MaaS is implemented, since the number of PT users substitute private car users, the unused cars could be sold.

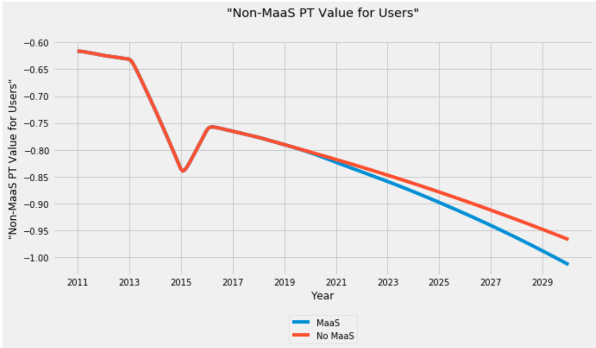



Figure 4.7: PT Value for Users

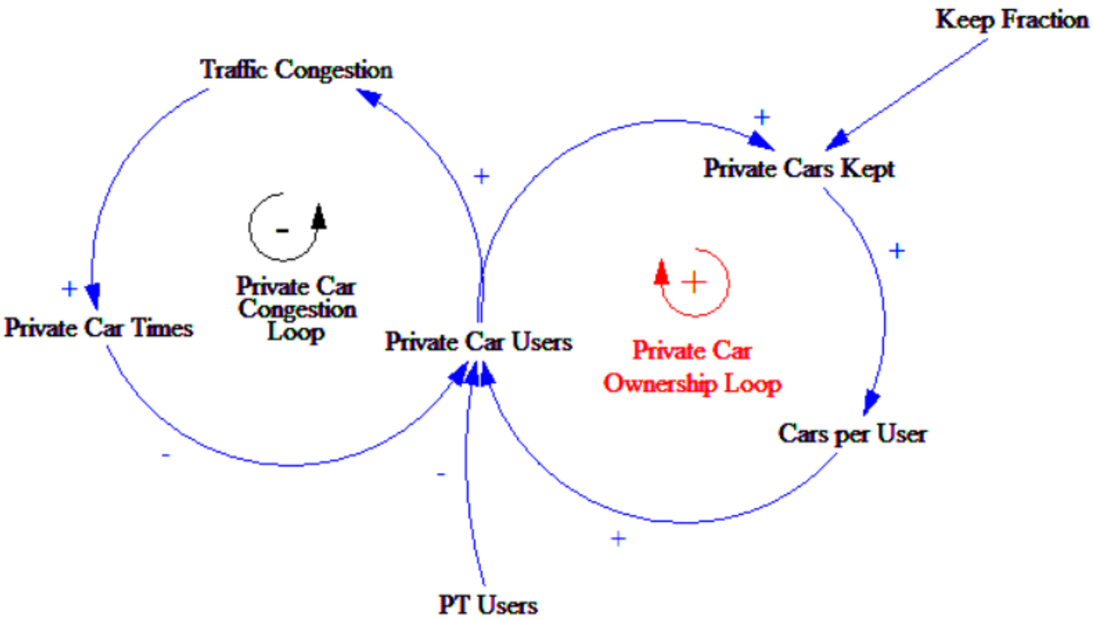



Figure 4.8: Private Car Ownership Mechanism

Hence, when the system reaches equilibrium again, the value of private car would have also been reduced by car ownership and not only by traffic congestion. This means that the equilibrium between PT and car would be reached at a different point of traffic congestion, leading to a stable reduction in time. This mechanism is sensitive to the keep fraction of those unused cars. In the base case, the parameters lead to a high keep fraction. Then, not many cars are sold and traffic congestion goes back to the same behavior as when there is no MaaS.

## 4.5. Summary

To summarize, after running the base case, it is found that when MaaS is activated, the growth of traffic congestion is temporarily lower than in the case there is no MaaS. However, the system goes back to its previous state. In the model, applying MaaS does not lead to a reduction in traffic congestion in the long term.

The main mode responsible of traffic congestion is private car. The modal split of shared car, shared taxis and taxis does not act significantly. They are one magnitude order below the modal split of private car, even though, according to the model, taxis and shared car attract more users in a MaaS system.

The reason why the robust behavior in traffic congestion is presented is that the value gained by the inclusion of MaaS in a bundle is lost with the increase of price and travel times on Public Transport due to user congestion. Since the price and the times increase, users go back to using a private car. This mechanism is opposed by the sales of cars being unused by the users who change their mode of transportation. However, in the base case, the fraction of cars that are being sold is too low, probably because the intrinsic value of having a car is too big. If this selling mechanism is intensified, there is a probability traffic congestion reach an equilibrium at a lower traffic congestion than expected.

It is important to state that these conclusions are given under the important assumption that the price of public transportation grows with a free market mechanism. However, after checking what happens if the price of PT is assumed to be constant, it is found that the travel times would still increase, causing the same dynamic where traffic congestion is not reduced in the long term.

On the other hand, even though it is expected that the traffic congestion is reduced in the long term, this does not happen inside the time frame chosen for this model. So, this behavior could be affected by strategical changes such as people moving to new places and changes in infrastructure. There is an incentive to study how these strategical changes can be used to keep the reduction in traffic congestion in the long term.

# 5 Model Validation

This section presents the validation step of the SD model implemented. The main findings of the nine validation tests carried out are stated. Some of these tests are supported by a face validation interview with Anne Durand, a MaaS researcher from KIM. Whenever an input of her is used in a test, it is explicitly mentioned. This step brings important insights to answer the main research question of this thesis project, since it is here where the main advantages and disadvantages of the model are identified. At the end of the chapter, a summary gathers the main conclusion from this chapter.

## 5.1. Boundary Adequacy

The first test done to validate the model is the boundary adequacy. This test is done to check whether the model is useful to solve the questions for which it was created. The test has two parts: Structure inspection and Face validation.

In the structure inspection, the objective is to analyze whether the KPIs used to answer the research question are modelled endogenously in the model. It is found that all the defined KPIs, namely traffic congestion, private car fleet and the modal split are not linearly defined by any input. All of them are included in a feedback loop within the model. Hence, the outputs are within the scope of the model.

After checking that the KPIs are modelled endogenously, it is important to verify that all the important dynamics were included in the model. In other words, none of the KPIs should strongly affect the inputs of the model. Otherwise, it loses some reliability. After asking Anne Durand to do an overview of the boundaries of the model, two issues are identified. First, the model does not offer a mechanism by which the attitudinal variables, which refer to the intrinsic preferences of the users towards the modes, are influenced by the KPIs or the accessibility related variables (time and distances). This relation is missing because research has shown that these variables have a strong relation with habit. Hence, the preferences of a user towards a mode increase when they use the mode for longer periods of time. Even though this issue is mentioned, the limitation is that the research about the magnitude of this causal relation is unknown. Hence, it increases the uncertainty in the model. To try to offer a solution to this issue, the choice model coefficients of users under MaaS must be treated as uncertainties in an uncertainty analysis.

The second issue identified by Anne Durand in the boundary adequacy test is that modelling the use of taxis, shared car and shared taxis might not be necessary to answer the research question since traffic congestion is usually too low to make any effect on the system. Hence, new uncertainty in the model is created without need. This is specially true for the use of shared taxi where the modal split is zero. On the other hand, in literature, van Kuijk (2017) states that there are expected scenarios in the future where the use of taxi and shared car can have a modal split of more than 10%. Hence, even though now the modal split is too low, it does not mean that it will keep being this way once MaaS is implemented. Moreover, Wong, Hensher, and Mulley (2017) states that a mechanism by which traffic congestion could increase in MaaS is if it increases the value of taxis. Hence, if this mode is left out, an important feedback loop in the system is eliminated. For these reasons, the model keep the modes implemented but special care needs to be taken whenever the results show a significant growth in the use of any of these modes. If this happens, the causes and assumptions of this behavior must be clear.

## 5.2. Structure Assessment

The objective of the structure test is to check that the structure and equations used in the model comply with the existent theory on MaaS and transportation modeling. It requires structure and formulae inspection combined with face validation methods. Three main modeling techniques adopted from transportation modeling were adopted in this SD model: Wegener's cycle, Akcelik functions and choice modeling. It is important to check that all of them are well implemented and are being used appropriately.

Wegener's cycle is represented by a causal loop in the model. The only important change is that the line connecting travel times and private car ownership was not taken into account since according to Lucas Harms, this relation is not supported by literature. The Akcelik formulae are well implemented in the model. However, there are two issues to take into account regarding the validity of this functions. First, there is an error being committed when it is assumed that all the city of Amsterdam can be treated with a single function. Some places of the city might have very high congestion, while most of them will have low congestion. This effect produces that the result shows a behavior that might not be a realistic value of the absolute traffic congestion in the city. Hence, due to this formulation, the value of congestion derived by this might not be accurate and it is recommended to use it comparatively to a reference base case so that the analysis become relative. In this case, it makes sense to say certain scenario is better than the base case instead of rate the result as good or bad when the measurement could be inaccurate. The second aspect is that there is no information about estimated coefficients for the use of Akcelik functions to calculate access/egress times. These functions are usually used for traffic in links instead. Hence, these parameters need to be validated using parameter assessment.

The other structure to be taken into account is the choice model. The formulation of the mode choice allows to calculate the modal split at a specific point in time. Hence, the calculation of the model split at peak hours is straightforward. However, the decision of using or not using MaaS does not happen at the same time context that the mode choice. The MaaS choice happens monthly, while the user chooses a mode of transportation daily. This questions the validity of the model because the user is taking the decision of using MaaS which affects at least one month of his or her commuting habits based on only one point in time. One solution could be to take the average of the logarithmic sum of the utility modes in the last month. However, this goes against Bayes theorem since it changes the formulation. The solution applied was that the travel times and the prices considered for the mode choice are based on the average of the last month. Hence, the utility of the modes is affected to reflect the monthly perception of the user. Moreover, the user does not decide daily its mode of transportation based on the current travel time and prices but rather on the perceptions seen before. This assumption permits to use a static model in a dynamic environment. The second challenge encountered while validating the MaaS choice formulation was that the discard and adoption fraction do not affect the same population. While the discard decision could be taken by any user of MaaS, the adopt decision can only be taken by those who have a contact with the service, either via advertisement or word of mouth. This issue breaks with the symmetry of the model. This is why both decisions have different coefficients, so that the value of the fraction obtained is coherent with the population targeted. One more detail to recall is that the adoption model of the system is adapted to avoid that the percentages of adoption and keep are rates per time but rather they represent an expected number of users. Otherwise, the static model of choice modeling cannot be coupled to an SD dynamic adoption model.

## 5.3. Dimensional Consistency

This test is made up by two parts. First, it checks that all variables in the system have consistent units such that variables that the units of every variable are consistent with the operations of the units that lead to that variable. Then, it is evaluated whether all variables in the system have physical meaning.

There are two main challenges found when implementing the model regarding dimensional consistency. First, the choice model implementation is a static model. This means, that its results can only be interpreted for a specific point in time. On the other hand, when it is required to calculate the revenue of MSPs and PTOs, the rates of increase or decrease of this processes are rates that indicate the flow of the income and outcome of revenue per month. An assumption must be made to calculate this rate. In this model, it is assumed that during a working day there are two peak periods. This assumption underestimates the total revenue of the system because it does not account for off peak hours, but on the other hand, most of the revenue of these companies come from peak times. Hence, the KPI is still useful to evaluate the financial state of these actors. The second challenge found is more complex. Choice modelling assumes that all users that travel during peak hours are on the transportation system at the same time. However, this is not necessarily true. PT and taxis travel at frequencies and the same asset can be used to transport more passengers than the capacity they have and not all users take their modes of transport at the same time. This issue calls for a correction in the model that accounts for the frequency of the service. Ideally, this correction would be dynamical because the frequency also depends on the travel times. But then, there are two problems. First, user congestion could be underestimated because of the virtual increase of the capacity and this would lead to lower travel times than the reality. Then, the duration of the peak would have to be used as a KPI of the system but this is a value with limited literature. Even if this solution is plausible, there is another problem. The pricing model of the system would have to change since the demand would never be higher than the offer as the offer just need more trips to cover the full demand. Then, the model would need a mechanism such that the peak duration controls the price of the system and there is no literature that could help to build this model. It is recommended for future research to understand this mechanism better by studying how PTOs and taxis set their prices. This would help to lead to a system with better dimensional consistency. For now, in this model, it is assumed that all users move at the same time in peak hours. The user congestion and traffic congestion become then values that might overestimate congestion. It is recommended to use them to study different scenarios relative to each other.

The second part of the dimensional analysis is to check whether every variable has a real life meaning. This validation test is particularly hard for the model implemented because many of the functions of MaaS choice modeling have powers and logarithms which can only calculate values in dimensionless variables. The conversion from utilities to probabilities is an abstract step for which system dynamics loose track of the dimensions taken into account. Choice modeling solves this problem by using a sensitivity coefficient. It does conserve the units but there is no physical but rather an abstract meaning of the coefficient. To tackle this difficulty, all utilities are understood as the value in terms of Euros per trip that the user pays or looses to get the transportation service in a specific MaaS setting and mode. By using this, every variable but the sensitivity is understood in physical terms. The sensitivity then can be better understood if it is considered as a parameter of a formula. In that sense, it has only mathematical but not physical purposes. This parameter states how sensitive are the users to the utilities of the different options faced. If they are more sensitive, it is more probable that the user go to the utility with the higher value. If they are less sensitive, all modes tend to have the same number of users even though the values differ.

## 5.4. Parameter Assessment

This test checks that the parameters in the model are consistent. Two methods are used. First, all model parameters are checked so that the value is consistent and has a realistic value. There are two groups of parameters that require extra attention for their values do not have an evident physical representation. First, parameters of Akcelik's functions and secondly choice modeling parameters. These parameters that require extra attention were estimated by fitting the result to known initial data. To verify that the found parameters after the fitting process are realistic, the choice modeling parameters are compared to the values proposed by van Kuijk, 2017 for the city center of Amsterdam while the parameters of the Akcelik's functions are compared to common values in literature according to Ortuzar and Willumsen, 2011.

Table 5.1 shows the value of the parameters of the developed SD model in comparison to the parameters estimated by van Kuijk (2017). Both models take walking as the reference point of the value of the different modes. Hence, both consider the value of walking to be 0. The highest differences are present in the modes of bike and private car. The explanation to these differences is that van Kuijk (2017) uses a unique value of time for all users and he assumes the price coefficient as one. In the mode choice at this project, these assumptions are not considered. However, it is observable that the value of the coefficients is within similar orders of magnitude. The only extreme case is private car. Besides the differences in the assumptions about the coefficients, van Kuijk (2017) does a market segmentation where some users just do not use car. Hence, the value of 45 in the table above is just a representation of certain group of users and not an average users.

Since this research considers a unique value, it is expected that it is much lower because it also accounts for those users that never use a car because the do not have one.

Table 5.1: Comparison Parameters Intrinsic Preference per Mode of Transport

| Mode | Intrinsic Preference SD model | Intrinsic Preference (van Kuijk, 2017) for hybrid users |
|---|---|---|
| **Private Car** | 0.47 | -45 |
| **PT** | -0.262446 | -3 |
| **Bike** | 0.796892 | -3 |
| **Walk** | 0 | 0 |
| **Taxi** | -2.75284 | -2 |
| **Shared Car** | -5.53747 | -3 |
| **Shared Taxi** | -0.0420258 | -3 |

Other relevant assumptions that explain the difference of the parameters is that the SD model built considers the whole transport area of Amsterdam, while the model for van Kuijk (2017) focuses on the city center of Amsterdam. The preferences of the users in different areas are influenced by other values independent of travel times and price, such as availability of parking spots, availability of infrastructure, among others. The SD model assumes that all this values are uniformly distributed which creates a source for error in the model. However, the model can still capture overall behavior if the values used are a good representation of the average user. An issue mentioned by Anne Durand from KIM is that the intrinsic preferences of the users correspond to habits, which is an uncertainty in the model. moreover, she stated that for the results to be more reliable, the model should consider a market segmentation of the demand. The reason is that different societal groups have very different intrinsic preferences. For instance, older uses are much more prone to use a car. Doing this market segmentation would give more reliability to the coefficients used. For now, even though they are calculated using the actual modal split of the city, there is uncertainty in the values used and specially on how they will change in the future. It is then important to keep record of the scenarios evaluated when using SD for policy analysis purposes.

The Akcelik coefficients are calculated by fitting the initial value of traffic congestion to the known average travel time and congestion values. It is known that Amsterdam has a traffic congestion of 53% during the evening peak, measured as the percentage of increase in travel time compared to free flow. Hence, by knowing the average travel time, it is possible to derive the free flow travel time. Once the free frow travel time is derived, the values of the parameters are calculated by iteration until they fit within the theoretical restrictions of the Akcelik functions.

Table 5.2: Akcelik Parameter Assessment

| Coefficient | Value in the SD Model | Restriction | Common Value |
|---|---|---|---|
| **Analysis Time (T)** | 30 | | |
| **Analysis Time PT** | 15 | 0 | 60 |
| **Analysis Time Taxi** | 10 | | |

Table 5.2 shows the values obtained for the Akcelik parameters in the system. The parameters fit within the theoretical restrictions of the Akcelik function. However, they are far from common used values found in literature (Ortuzar and Willumsen, 2011). The main reason that could explain this differences is that Akcelik functions are commonly used for analysis of links in a system. The parameters in the model are trying to analyze a full city network. Further research is necessary to evaluate the use of Akcelik functions for the full network. Moreover, the parameters for PT and taxi are not analyzing flow of cars over a road but flow of users within the service. Even though both problems are analyzing flows over a limited space (which are the assumptions of the Akcelik function), the common parameters used may not apply under different applications.

## 5.5. Time Step

The Time Step of the model used for the numerical calculation of the integral equations is 0.25. If this value is reduced by half, no significant changes are perceived in the results of the model. However, if a time step with 0.5 is chosen, the model does not reach convergence and the results are not reliable.

## 5.6. Extreme Conditions

The behavior of certain variables of the system are usually known when subjected to extreme conditions. Extreme value testing verifies that the mode is valid under these extreme conditions.

The chosen variables to analyze are private car ownership, MaaS Market Share, MaaS Taxis Market Share and the Auto Split. For all these variables, the lower limit is zero while the upper limit is one. Hence, it is possible to identify if any extreme variation in a parameter makes the system go off the valid ranges.

The model was run for each of the relevant variables and each of the 81 parameters for extremely high and extremely low values at these parameters. After this, the maximum and minimum value of each of the time series obtained as a result is calculated. These values are compared to the limits of the variables and the parameters for which the model gets off ranges are reported in the following table.

Table 5.3: Inconsistent Parameters according to Extreme Value Testing

| Variable | Value | Limit | Parameter | Parameter Value |
|---|---|---|---|---|
| **Number of Private Cars per User** | 1.3 | 1 | Users Reaction Time | 0.1 |
| **MaaS Market Share** | -1.5 | 0 | Users Reaction Time | 0.1 |
| **MaaS Taxis Market Share** | -609736.9 | 0 | Public Transport Operators and Public Transport Authorities Reaction Time | 0.1 |

Table 5.3 shows the variables for which inconsistent results were found and the parameters that caused these results. Only two parameters were found to lead to invalid results. User Reaction Time and PTOs Reaction Time cause off limits results for Number of Private Cars per User, MaaS Market Share and MaaS Taxis Market Share. Although at first, the explanation could be that the model is badly implemented, the real reason for this mismatch s because these variables are mainly used in delay structures. When these structures have very low values, they require a smaller time step to keep the accuracy in the integration. In this case, the problems caused are because of integration errors while running the model at these extreme parameters. Since these values are not reached under real experiments with the model. The time step does not required to be reduced.

The previous analysis leads to conclude that the model does not go to the invalid range when subjected to extreme parameters. However, it is important to see if the variables are reaching the right value under extremes conditions. To do this test, it is necessary to check the behavior of each of the variables under the different extreme parameters tested where the behavior is known. When this test is implemented in the MaaS SD model created for this thesis, no invalid behaviors are found.

## 5.7. Sensitivity Analysis

The sensitivity analysis helps to see how the system behaves under uncertain parameters. For this test,the values of the parameters are varied to evaluate how much do this variation affect the KPIs. In this project, the 88 parameters of the model are varied a 10% of their original value. Those parameters where the original value is zero are varied between 0 and 0.1 if they correspond to percentages and between -0.1 and 0.1 if they correspond to other type of parameter.

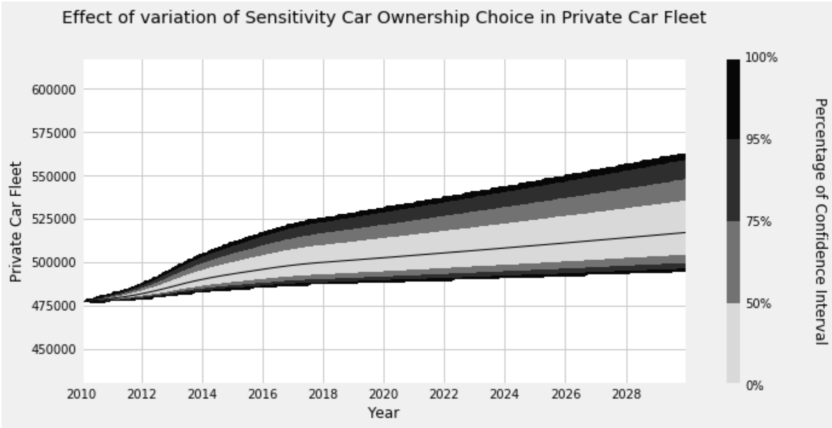



Figure 5.1: Private Car Fleet Sensitivity of Sensitivity of Car Ownership Choice

Figure 5.1 shows an example of the results of the sensitivity analysis of the Private Car Fleet when the value of sensitivity of car ownership choice is changed. This example is chosen because it has high relevance in the base case. In the implementation section, it is concluded that the sales of car can reduce traffic congestion while avoiding that the raise in prices of PT cancel the added value of PT because of MaaS. The percentages in the figure show the probability that a result is within the marked areas.

| Private Car Fleet | Extra Travel Time Index |
|---|---|

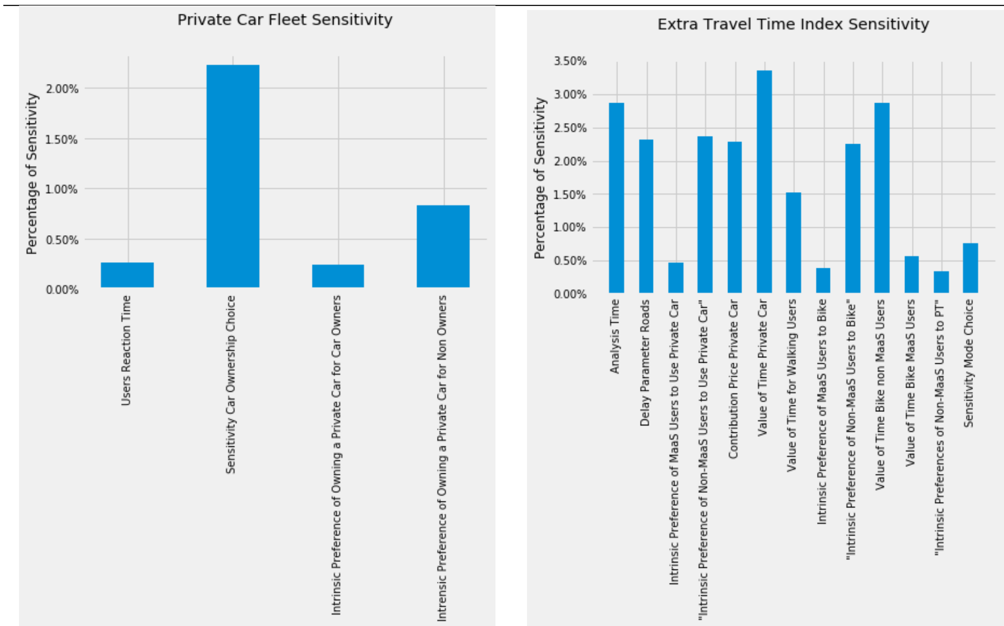



Figure 5.2: Most Sensitive Variables per KPI

Figure 5.2 shows the variables that have a higher impact on the KPIs. For each of the KPIs, the more relevant parameters are shown (those with more than a 0.25% of variation). To measure this influence, the average standard deviation of each of the variables when the parameters are changed is compared to the mean value of each of the parameters. In other words, the percentage in the graphs show the percentage of variation of the variables when a there is a 10% of variation in the input parameters. The results of the Extra Travel Time Index are sensitive to those parameters related to the mode choice. A 10% variation in these parameters can lead to variation of more than 3% in the KPIs. Even though the value of the KPIs does not vary more than a 5%, it might be possible that uncertainties interact with each other. It is important to run a uncertainty analysis to evaluate the policies that are recommended taking into account this issue. .

Another result is that the variation of the Private Car Fleet seems to be only influenced by car ownership choice variables. This means the mechanism by which private cars are sold is strongly dependent on external inputs to the model. Even though the private car selling mechanism is unknown and only base on perceptions, it is not strongly influenced by other inputs of the model, which makes it easier to observe the dynamics of this mechanism.

## 5.8. Behavior Reproduction

Unfortunately, data about past behavior of the traffic system in Amsterdam is limited. However, the municipality of Amsterdam has some reports about the modal split on the city in the latest years OIS, 2018.

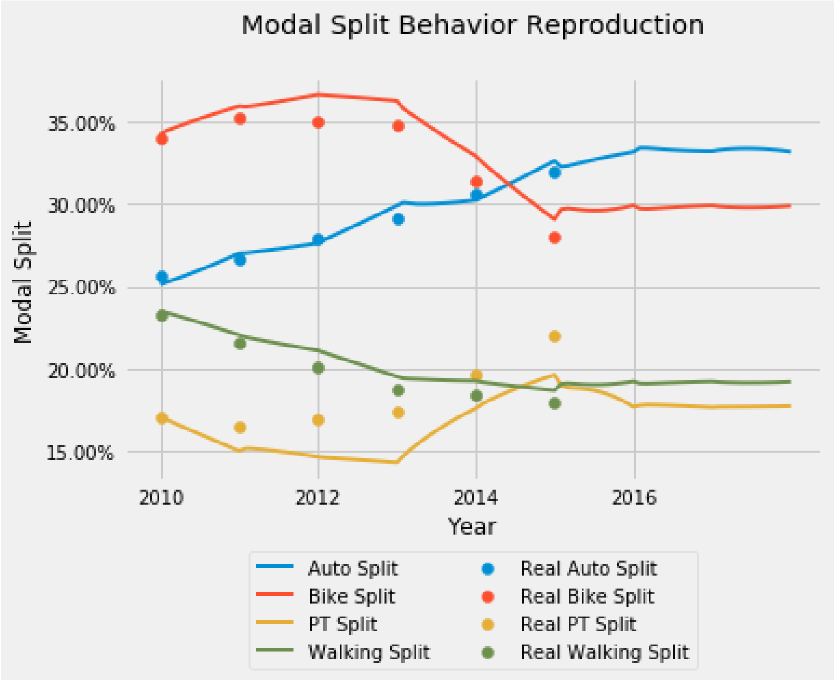



Figure 5.3: Modal Split Behavior Reproduction

Figure 5.3 shows the reproduction of results when the model is run from year 2011 to 2018. The dots indicate the real values of the modal split as reported by the municipality of Amsterdam. The model is able to partly explain the behavior of the system. However, it lacks accuracy. This reinforces the idea that it is better to use the model in a comparative analysis rather than looking for absolute values of the behavior of the system. Another issue to comment is that to reach a good level of fitting between the real and the modelled modal split, it is necessary to implement intrinsic preferences that vary with time. By using just constant values, the behavior does not explain the system. When consulting this phenomenon with Anne Durand in the face interview, she mentioned that the there is a habit component in the value of the system that should be taken into account in the model and it might explain the modal split in the system. Moreover, she states that the differences in preferences between different regions and societal groups should be considered in the model to gain accuracy in the system.

Figure 5.4 shows the results of the behavior reproduction of the average travel time in minutes between 2011 and 2018. From the period between 2011 to 2015, the model shows good explanatory value to understand the change in travel time in the system. However, after 2015, the model looses great accuracy. One of the reasons might be that the value of congestion which is responsible of the change in the travel time is not realistic because of the error in the model while explaining the capacity of the system since it is affected by the frequency. However, the model offers a good approximation and since the objective is to compare different scenarios to see what is more favorable for traffic congestion, it does not need to have exact values but rather to show how the dynamics of the system change according to different policies implemented.

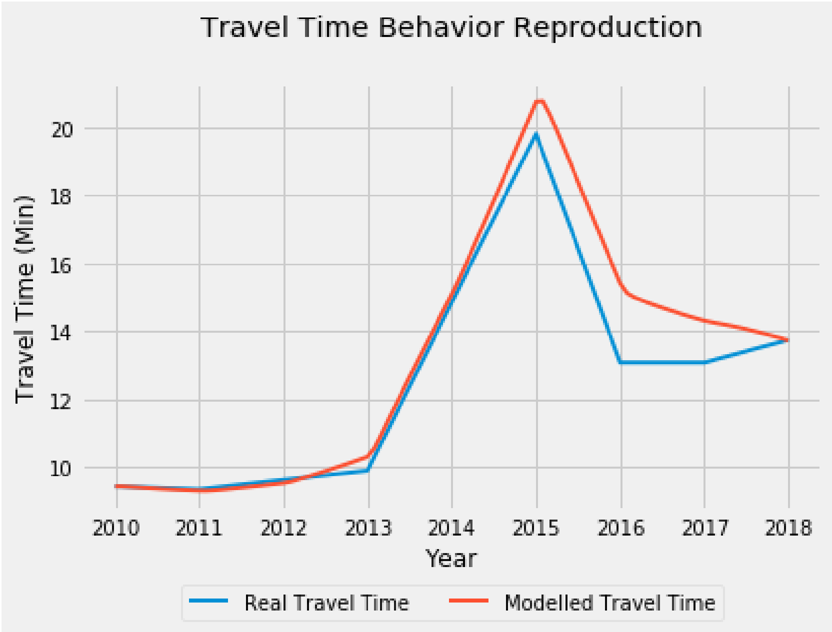



Figure 5.4: Travel Time Behavior Reproduction

## 5.9. Summary

This section presents a summary of the main findings found in the validation process of the model.

First, the KPIs of the model are modeled endogenously. Hence, they are within the scope of the model. However, there are two issues that might prove wrong boundaries. First, shared taxis, shared cars and taxis have a very low modal split that could be ignored to answer the question about traffic congestion. However, they are kept for the high uncertainty in the future that may rise the use of these modes. The second issue is that the use of the modes may change the preferences of the users. There should be additional feedback loops. However, their mechanism is unknown. Therefore, they are modeled as uncertainties.

Another issue regarding the intrinsic preferences of users is that they vary considerably between different societal groups. Assuming only an average user is present in the system leads to accuracy errors in the KPIs. An analysis with a segmented market is useful to solve this issue. However, for the objective of comparing policies, the model still has value since there is no need to know absolute but relative results.

The spatial level of aggregation in the system is another point that could improve the accuracy of the model. All parameters are not identically distributed among the city. These leads to problems in accuracy. In specific, the Akcelik parameters are usually used in literature to model link flows and not whole network systems.

The way the model deals with time proves to challenge the validation of the model. First, choice modeling is used to find values in a specific point of time. So, there is a need to assume that there are a number of peak points during a month to find monthly values of costs. Also, by assuming that all the users are in the system at a specific point in time, an error is made with the capacity of the modes of transport, because they have more capacity due to the fact that they can do more than one trip within a peak period. However, the definition of a peak period is an arbitrary value that may change considerably the traffic congestion in the system. This problem could be solved by assuming that the capacity is a hard constraint that is never reached but this leads to problems in the pricing sub-model. It is necessary to do further research on how pricing of the modes of transportation is decided to improve the models and overcome the time frame limitations.

One last finding is that the coupling in choice modeling with SD leads to include variables in the model that do not have physical values such as the sensitivity. Hence, it is hard to validate whether these variables are realistic.

# 6
# Model Application

This chapter presents how the model is used for policy analysis purposes and what types of policy recommendations can be brought from this process. It starts with a section identifying the most relevant policies from the literature and from the interviews held with KIM and Sampo Hietanen. Then, it presents the experimental design to analyze the implementation of the different policies in the model. After that, the results are presented. Finally, a summary is given with the main findings from this chapter.

## 6.1. Policy Identification

This section identifies the relevant policies to be applied in the MaaS system by two different methods. First, a literature review on MaaS and transportation policy leads to identify the main policy discussions about the implementation of MaaS. Then, the specific situation of Amsterdam is analyzed to see what discussions are more relevant for the case of study. After that, the inputs of the interviews with Sampo Hietanen and KIM are presented. Finally, a summary of the section identifies the main findings and the main policies to be included in the SD model.

### 6.1.1. Literature Review

This section explores the current literature review regarding transportation policy in relation to MaaS. It is the objective to identify the most relevant policy discussions surrounding the implementation of MaaS systems.

As an introduction to the future of policy due to innovations in mobility, Docherty, Marsden, and Anable (2017) gives arguments to intervene in the system and also sets out modes and methods of governance to ensure a transition with public value. Essentially, Docherty, Marsden, and Anable (2017) calls for the debate on the balance that must exist between the role for the private companies and for the state in the regulations of smart mobility and specifically in MaaS. It is of high relevance to study whether the government should strongly regulate MSPs (or maybe becoming one itself) to keep control of the policy around transportation, especially because there is an incentive to MSPs to create more mobility needs, worsening traffic congestion. A core discussion in this debate is how to tax MSPs since they might profit from public assets.

Mulley, Nelson, and Wright (2017) is an important study as an example of the previous considerations. It shows that Community Transport (CT) providers in Australia are willing to change to a MaaS type of service. The subsidy regime of these types of organizations is changing. Before, they would receive the subsidy directly to give their services to the users, these brought a problem of cross subsidization where customers with lower needs were subsidizing customers with higher needs. But now, since mid 2018, the customers will receive their subsidy, which they can spend in other priorities and not only transport. CTs fear that with the lack of subsidy, the costs of transportation will seem too high and customers will not use the service. Then, the door is open to become MaaS service providers for the clients and be more efficient by also offering packages to non users of CT.

The previous study shows that one of the main discussions in the policy field on the adoption of MaaS is what should be the role of subsidies. Specifically, what should be done with the subsidies of public transport.

The previous article shows how subsidizing the demand may promote the implementation of MaaS. However, it might make PT less attractive. One of the main problem of this approach is that it is common to find that, by law, commercial entities cannot be allowed to profit from subsidized public transport.

Another topic specifically analyzed in the literature is the subsidization of private vehicles. As argued by Koglin (2017), current tax legislation subsidize private car in Sweden when offered by employers. This legislation does not help for the implementation of MaaS since the users have an incentive to keep using their own private cars. The solution offered by Holmberg, Collado, Sarasini, and Williander (2016) is that this current tax system should offer equal conditions for private car and MaaS to compete. This wold allow for the MaaS market to expand.

König, Eckhardt, Aapaoja, Sochor, and Karlsson (2016) states that public transportation should have a major role enabling pilots for integrated mobility systems. One of the major barriers for MaaS to develop is the lack of financing. Public transport or the government could help to create these programs as a policy matter. However, there are institutional barriers for this outcome to happen.

To conclude, the relevant discussions for the relation of MaaS with traffic congestion in the literature are what should be the role of the government, how to finance the creation of MSPs, and whether the subsidies of transportation should keep promoting the use of car or PT or whether they should be given to the user to decide form herself/himself.

### 6.1.2. Relevant Policies in Amsterdam

Connekt (2017), a network of stakeholders in the transport network is promoting the development of MaaS in The Netherlands. By creating the MaaS Task-force, a group of companies, governmental and research institutions are promoting the implementation of MaaS on a larger scale. The task-force has already identified some of the policies that could help to ease the spread of MaaS. This discussion and a group of actions is proposed in a document called the MaaSifiest (Connekt, 2017). Currently, tax regulations give tax discounts to employers that offer their employees a car in leasing. This promotes the use of car and does not let other options to be considered. For the sake of MaaS, it is important to change this incentive to a demand driven subsidy so that the user can decide how to spend the subsidy and he or she might take a MaaS subscription. Another issue described is that for users who are taxed for owning a car, not using the car is more expensive because other modes of transportation bring an additional liability. This would be different if the use of car rather than the possession was taxed (Connekt, 2017).

### 6.1.3. Interviews

According to Sampo Hietanen, until now, the implementation of MaaS has been focusing on developing pilots. But this needs to change. MaaS is a business model that to make changes requires big investment. Political will is needed to incentivize the market. There are two key questions that will shape the future. How will MaaS packages be taxed? and will the city governments implement the infrastructure changes needed for the cities to facilitate multi-modal transport?.Regarding taxation, according to Hietanen, MaaS packages are taxed more heavily than the use of private car. With subsidies for the leasing of autos, it is hard for MaaS to compete against car ownership. He calls for governments to let the different modes of transportation to compete in equal conditions. Moreover, he states that before thinking of raising taxes for car ownership, it is of importance to have a good alternative for the users otherwise the tax will not make them change their mode of transportation. The objective is to have a fully developed MaaS system and high availability of good PT.

One of the barriers that need to be solved according to Hietanen is that PTOs do not want MaaS to be a fully competitive market. This highlightens the importance of studying the role of PTOs in the MaaS ecosystem to see whether they should be the MSPs themselves or just one more mode of transportation competing in the digital market offered by MSPs.

To Lucas Harms, head of the MaaS research team at KIM, besides the common discussions about the role of PTO and the subsidies on MaaS, PT or private car, there is one specific policy for the case of Amsterdam that could be interesting to study. There are parking subsidies for the use of Shared Cars. Users of this service can park for free in the city. He believes, with MaaS, the use of this service could grow and reduce the availability of public space.

### 6.1.4. Relevant Policies Summary

Summarizing the findings of the methods to identify the relevant policies to be applied to the development o MaaS, it is possible to classify them in three groups.

First, one of the main discussions is which actor will have the role of the MSP. Whether the government, PTOs or a commercial actor play this role will have strong societal impacts in the system. It is believed that if it is commercial, the government might lose control of transport policy and traffic congestion could increase. If the role is taken by the government or PTOs, the lack of competition would not lead to the satisfaction of the users and they might not leave the ownership of their cars.

The second discussion is that the implementation of MaaS will require high investments. Until now, the implementation has been focusing on pilots. However, these pilots might not show an approximate of the actual potential of MaaS. Investing in the creation of MaaS developments could be a policy to help the system. It is unsure whether this would lead to less traffic congestion.

The final discussion is where to allocate the subsidies and taxes in the MaaS system. Currently PT and leasing of autos are subsidized. Sampo Hietanen suggests to implement a subsidy that is controlled by the demand so that all the modes of transportation compete under equal circumstances. Moreover, Connekt (2017) states that instead of taxing car ownership, it would be useful to tax the car use since users would not feel compelled to use their cars.

## 6.2. Experimental Design

The experimental design is the map that helps to understand how the experiments were set for the result generation of this project.

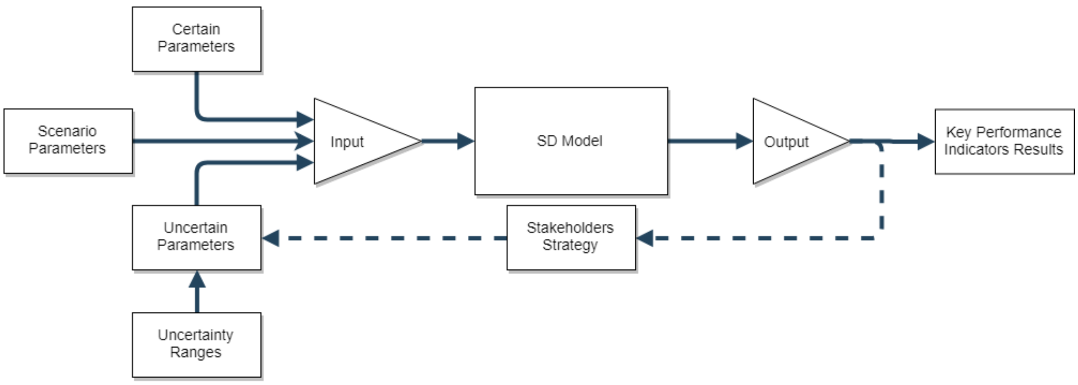



Figure 6.1: Uncertainty Analysis Experimental Design

Figure 6.1 shows a graphical representation of the experimental design used for the development of the policy and uncertainty analysis in this project. The center of the graph shows the core of the experiments, the SD model. The objective is to analyze how the input of this model affects the output, represented in terms of the key performance indicators. The input of the model is given by three different types of parameters. The certain parameters which are parameters with a fixed value, the uncertain parameters whose value is unknown and the scenario parameters, which are parameters whose value is known under specific circumstances that are of special interest to study. For this analysis, the set of scenarios is used to define different levels of MaaS integration. The treatment of the uncertain parameters in this design is by statistical sampling. The model is run continuously under random values uniformly distributed of the uncertain parameters in specific ranges and the results are obtained in the form of a frequency distribution.

Since one of the characteristics of MaaS is that it is a multi-actor system, the actions and interventions of other actors than the government to the system need to be analyzed, too. This helps to understand what are their interest and opportunities and how they could affect the KPIs.

The following subsections describes what are the specific added key performance indicators, scenarios, uncertainties and policies considered for this model and how are they implemented and measured quantitatively.

### 6.2.1. Additional Key Performance Indicators

Besides the previously defined key performance indicators, it is necessary to add three performance indicators to account for the objectives of other actors that have influence in the system and to include the cost of the policies applied by the government as an important variable for analysis.

- Financial Resources of MaaS Service Providers: It is expected that the MSPs operate to maximize their financial resources with the profit from the services offered to the users. Those variables that are controlled by the MSPs may probably have a value such that their profits are maximized.
- Revenue of Public Transport Operators: Public transport operators actions are assumed to be those that maximize their revenues.
- Policy Costs: Whenever a policy is applied to the system, it is critical to know what are the total costs of the policies implemented to analyze what is the cost effectiveness of these policies. The objective of reducing traffic congestion must be done with the least financial resources possible.

### 6.2.2. Scenario Definition

In the model conceptualization, it is argued that one of the key drivers of MaaS is the role of PTOs in the system. They could take control of MaaS by being the MSP themselves or they could just be one more competitor in the digital market enabled by MSPs. The literature review about relevant policies has also shown that the government could take control of MSPs to ensure that the system leads to a lower traffic congestion. Hence, it is important to analyze the implications of who is in control of the MaaS system. To account for this, three different scenarios are considered. Either MSPs are a commercial actor, the government or PTOs. This scenarios will not affect the input of the model. However, they do modify the analysis of the output. If the PTOs become in control of MSPs, PTOs will not try to maximize only PT revenue but the sum of the revenue of PT and MSPs. If the government is in control, the policy costs might be compensated by MSPs revenues. hence, the KPI is policy costs plus the revenue of MSPs. If MSPs are an independent commercial actor, they only focus on maximizing MSPs revenues.

The other important difference in the scenario to analyze is the level of integration. The level of integration, as described in the model conceptualization, states whether the different transport modes are included in the MaaS platform and whether they are covered by MaaS packages. The model will assume that relations between commercial actors such as integration with taxis and car share companies can easily be decided by MSPs. Hence, MSPs decide how much of this packages will be covered in the system. Bike share and PT are usually in control of PTOs. Hence, the integration of these systems are an uncertainty dependent on the negotiations between these actors. Four scenarios will be considered. These scenarios are a combination of the options of including or not including PT and of including or not including bike share.

### 6.2.3. Uncertainties

All the inputs of the model but those related to known data provided by CBS, OIS or GVB are considered uncertainties in the model. The parameters can vary up to a 50% of the original value in the base case. The uncertainty analysis requires wider ranges than the sensitivity analysis because the objective is not to understand how sensitive the system is but to see how it varies when the full uncertainty space is considered. Even though the full spectrum of the parameters could be used as when extreme conditions are evaluated, the reality is those values are very unlikely to be considered, given that the parameters are already fitted to the current situation.

### 6.2.4. Policy Levers

The policy levers are the variables implemented in the SD model that represent the different actor's influence on the system depending on the different choices they make. Here, the different policy levers implemented for each of the actors in the system are presented.

The PTOs have control of the following levers:

- PT Percentage Price Discount for MaaS providers: This variable reduces the costs that are charged to MaaS providers for every ticket of PT. It could help to stimulate the users to use MSPs to access the PT system. Hence, it could grow the number of PT users, increasing PT revenue. No other lever is in control of PT. The reason is that the level of integration for which also PTOs must agree is modelled as an scenario in the model.

The MSPs have control of the following levers:

- Taxi Trip Percentage Included in the MaaS Package: As mentioned before, it is assumed that MSPs can decide how much of the taxi trips to cover in their packages.
- Shared Car Trip percentage Included in the MaaS Package: This variable tells the percentage of coverage of Shared Car services by the maaS package.
- Profit margin of MaaS Providers: This variable is used by MSPs to set the price of their packages. It is the percentage of profit that they gain in relation to the costs of providing the service.
- Expected MaaS Market Share: This variable sets the goal market share of MSPs. If they reach the goal, they stop reinvesting in the system.
- Effect of MaaS Market Share Gap on Expenses: This variable states how aggressive are MSPs when reinvesting in business. It says the percentage of profits reinvested in relation to the gap to the goal market share.

The Government is in control of the following levers:

- Raise Tax on Car Ownership: This leaver increase the costs of owning a car in Euros/Month. It represent reducing subsidies for leasing or increasing taxes for car ownership.
- Transportation Subsidy to Users: This lever gives every user a subsidy in Euros/Trip. It increases the value of MaaS and No-MaaS for user since they can choose any of the two options.
- Percentage subsidy on MaaS Subscription: This level gives the user a percentage of the price of their MaaS subscription if they adopt MaaS.
- Tax per Km of Use of Private Car: This lever is used to tax the distance driven of private cars.
- Percentage subsidy on PT: This lever subsidizes a percentage of the cost of PT to the users.
- Subsidies to MaaS Companies: This lever gives subsidies to MaaS users to create their business.

## 6.3. Results

This section presents the results obtained from applying the experimental design to the SD model. First, it shows the results when the policies are applied to the base case without uncertainties, then it presents the results of the uncertainty analysis. Finally, at the end of the chapter a summary with the main findings of the experiments done is offered.

### 6.3.1. Base Case Results

This subsection presents the impacts of the different policy levers of the government to the behavior of the KPIs in the base case. The objective is to analyze these policies in relation to the findings of the model implementation regarding the base case.

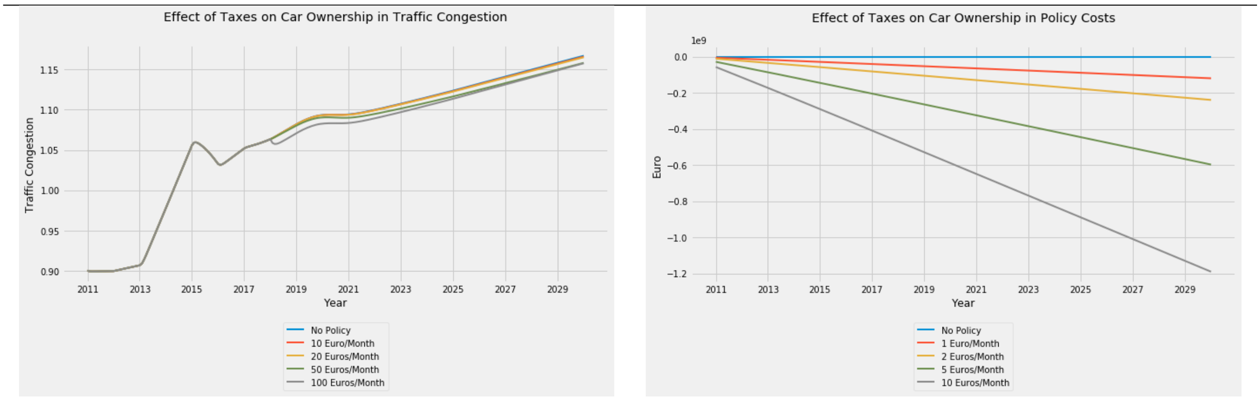



Figure 6.2: Effects of Taxing Car Ownership in the Base Case

Figure 6.2 shows the results of applying, with different magnitudes, a raise in taxes on car ownership. This policy is equivalent to reducing benefits for leasing a car. The figure on the left shows that traffic congestion decreases when the tax is risen. This is supported by the mechanism explained in the model implementation. When the value of owning a car decreases, the probability that the car is sold grows. This result has a big limitation. There is no knowledge on the impact of MaaS on the attitudinal values that make people sell their cars. Hence, even though it works in the base case,this result is surrounded by big uncertainty. The figure also shows that there is a tipping point where the effect has a long term effect. This happens when the taxes pass the value of owning a car. The graph on the right shows that the policy costs are negative because the government actually earns money from this policy. This is not necessarily good, because this money is a transference from the users, which are losing money with this policy.

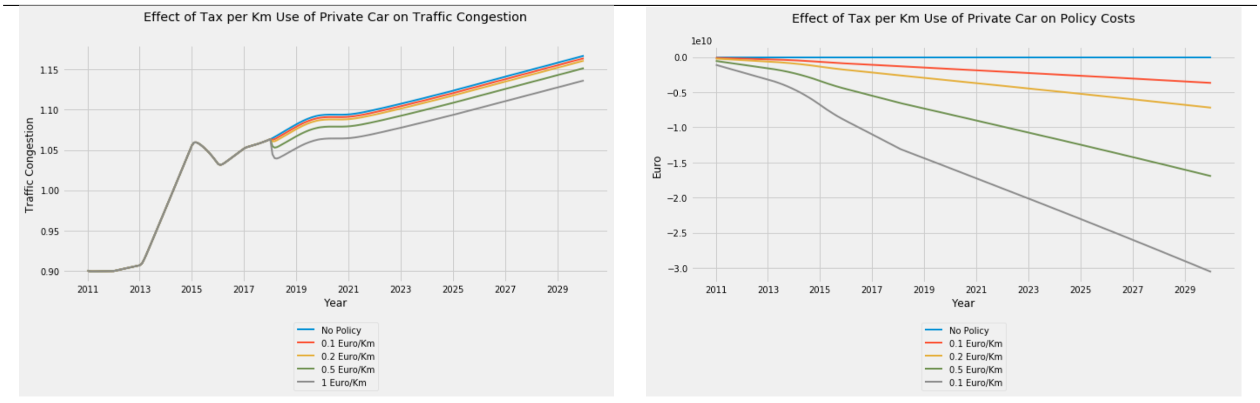



Figure 6.3: Effects of taxing car use in the base case

In figure 6.3, the effects of taxing the distance driven by cars instead of ownership is shown. The model shows a drastic instant change in the system because of this tax. The reason is that the tax affect directly the mode choice instead of the MaaS choice. This tax seems to be able to drastically reduce traffic congestion and keep the reduction in the long term. The users leaving auto might not be only going to PT but also bike and walking modal split, which are modes that are not affected by increase of prices due to user congestion. Hence, the model stabilizes at lower traffic congestion values. Again, this policy leads to negative policy costs because the government is earning money from the users.

When the policy of giving subsidies directly to the users is implemented, traffic congestion does not change. This is seen in figure 6.4 This happens because the relative values of all the alternatives is kept the same since all gain the same value when the policy is applied. However, the effects of this policy might change if it is applied at the same time with other policy such as taxing car ownership. This combination makes sense because as Sampo Hietanen mentioned, it would put all transport modes in the same conditions to compete. Even though the policy keeps traffic congestion constant, the policy costs naturally grow when the subsidy is higher.

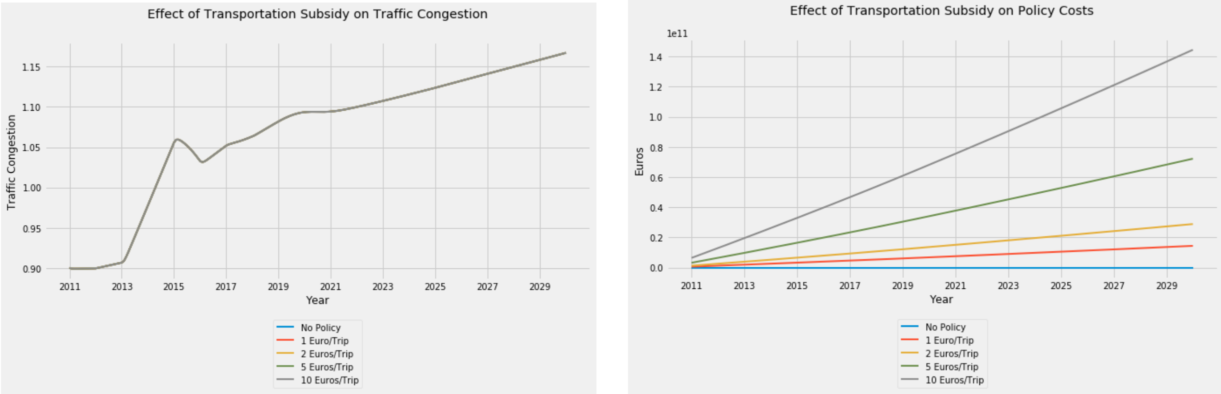



Figure 6.4: Effects of subsidizing the demand of transport in the base case

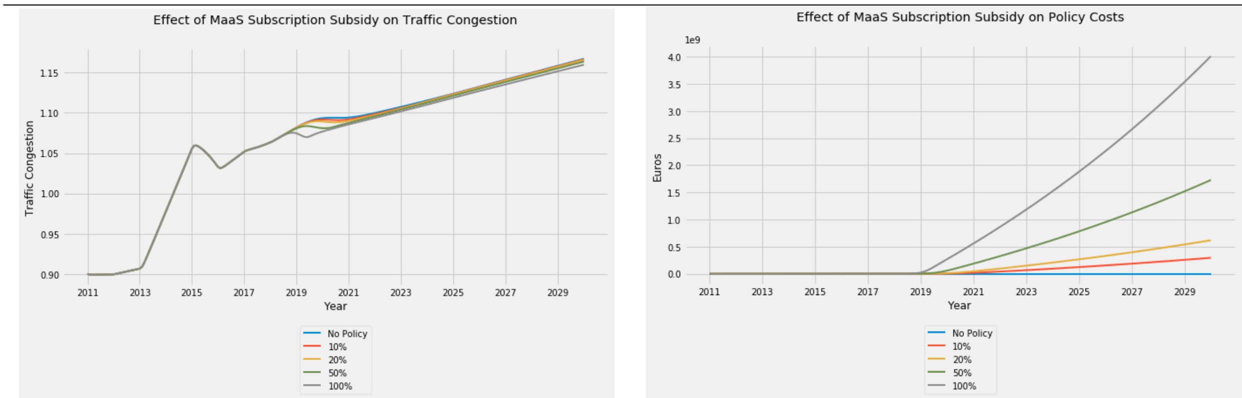



Figure 6.5: Effects of subsidizing MaaS subscriptions in the base case

When MaaS subscription is subsidized, there is an effective reduction in traffic congestion. However, the effect seems to be only temporary. Probably, the users are being attracted to PT, but after the price increases, they start using their private cars again. This policy has positive costs that grow when the percentage of the MaaS subscription covered grows. Probably if the full subscription is covered, the traffic congestion stabilizes at a lower point. However, the policy growth would be exponential because PTOs would have the opportunity to charge very high prices without affecting their number of users.

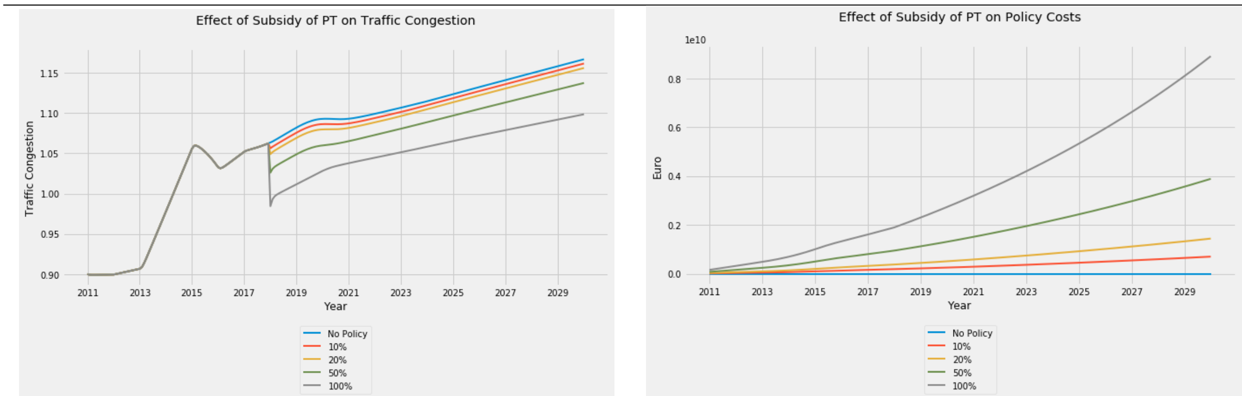



Figure 6.6: Effects of subsidizing PT in the base case

The effects of subsidizing PT also tend to stabilize to the initial state with time unless the full price is covered. If the full fare is covered, the policy costs growth exponentially. Also, the behavior has a anomaly at the start time. This is given because the subsidy affects the mode choice directly and there is a sudden growth in the price of PT that turns the behavior back to its initial state.

Finally, the subsidization of MaaS companies has a low effect on traffic congestion. besides, this effect only works temporarily. The reason this policy works temporarily is because with high initial investments it is possible to invest more in the quality of the platform and customization. hence, the users feel rapidly attracted to MaaS. but then, the increase in PT price will eventually stabilize the system. Moreover, the increase in quality of MaaS happens at a decreasing rate in the model. hence, the investment effect is steadily less effective. Since this policy only affects the initial investment, the policy costs are constant.

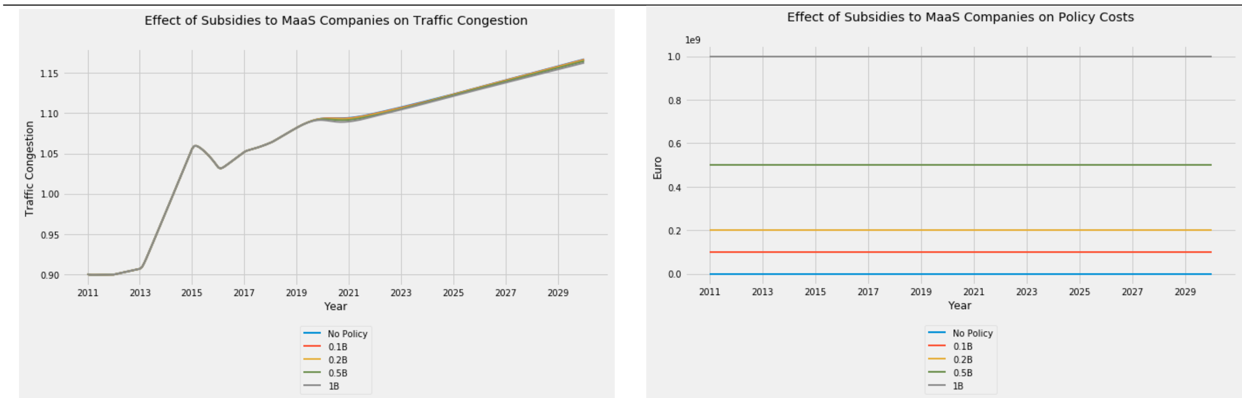



Figure 6.7: Effects of subsidizing MaaS companies in the base case

The following figures show the behavior of traffic congestion under the actions controlled by other actors rather than the government.

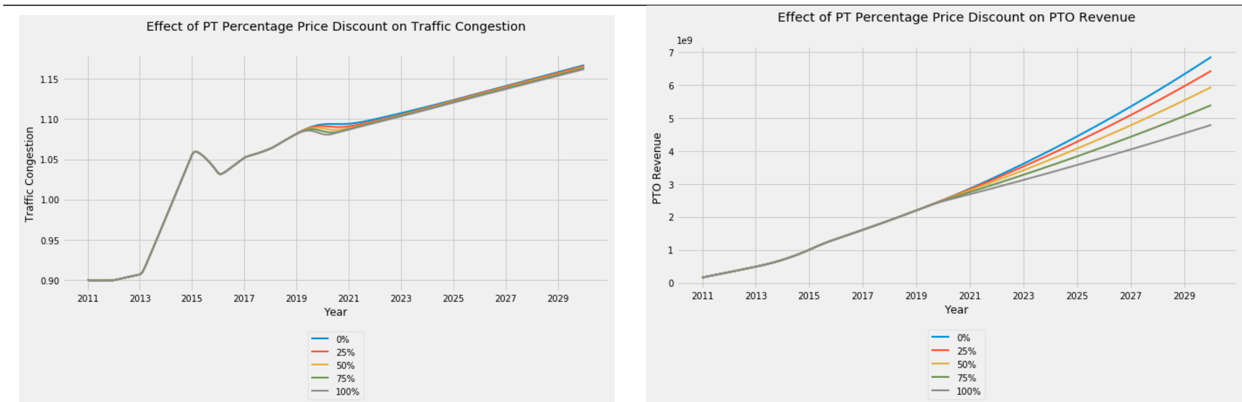



Figure 6.8: Effects of different PT discount percentages to MSPs

Figure 6.8 show traffic congestion when PTOs give discount prices to MSPs. The results show a slight decrease on traffic congestion that is only temporary. On the other hand, there seems to be no incentive to apply the discount because the revenue of PTOs fall when this is done, which means that the newly attracted users are not covering the money lost in the discount.

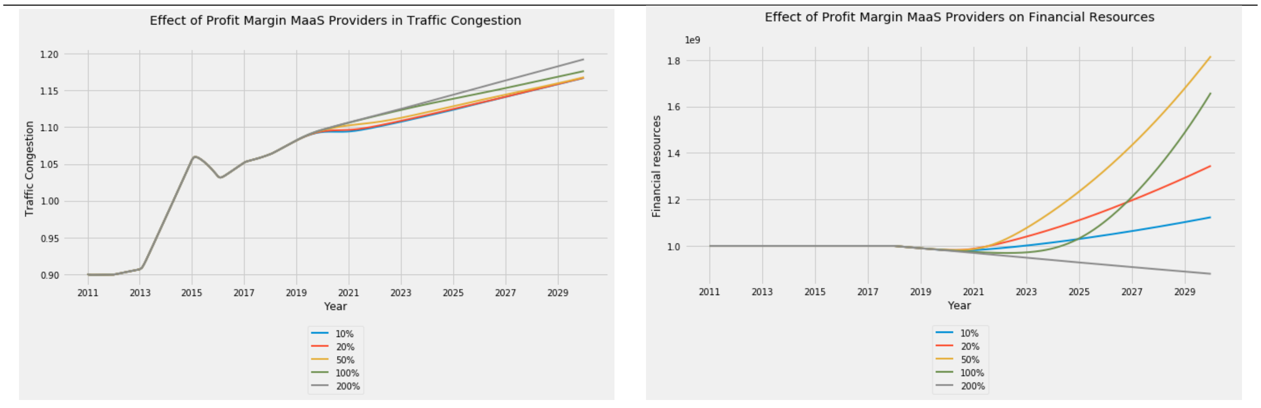



Figure 6.9: Effects of different MSPs Profit Margins

When the perspective of MSPs is observed, as in figure 6.9, it is noticeable that low profit margins favour the reduction of traffic congestion. However, for MSPs it is better to have higher profit margins because this increases their revenue. This shows that there is a conflict between the interests of the MSPs and the government. However, if the profit margin is too high, the revenue starts to fall because the price of MaaS does not attract users anymore.

To summarize the base case results, subsidizing the demand has no effect on traffic congestion although it could be used in combination with other policies, subsidizing PT or MaaS subscription has a temporary reduction on traffic congestion that then returns to the initial value for the increase of price in PT. If the full fares are covered, the reduction in traffic congestion can be stable but then the policy costs grow exponentially. Likewise, investing in the implementation of MaaS companies only reduces traffic congestion slightly in a temporary time interval. Finally, the policies that seem to be effective are taxing car ownership and taxing car use because they can reduce the private car fleet in the system. Hence, traffic congestion has a long term reduction.

### 6.3.2. Uncertainty Analysis Results

This subsection shows the results of the uncertainty analysis applied to the SD model. For each of the actors with levers on the system, it is shown what are the most effective policy in each of the scenarios designed. It is also shown how these actions affect traffic congestion and car ownership.

Figure 6.10 shows the results of the uncertainty analysis for different policies that may be applied by PTOs. The legend shows the colors to identify each of the policies applied. The envelope figure at the center of the picture shows the range of uncertainty in the results for each of the policies applied. The envelopes mean that the actual behavior is limited by the colored area. The bar figure on the right shows the distribution of the results at the end of the run. The dots indicate the location of the upper and lower quintiles of the results. The dotted line indicates the mean of the results. Figure 6.10 shows that the results of this model have a high uncertainty. However, it is possible to drive conclusions from some of the results. in this case, it is shown that for a full integration scenario, where both bike and PT are included in the package, if PTOs apply discounts to MSPs, the mean of the revenue does not increase. Hence, there are no incentives for PT to apply discounts for MaaS providers. However, since the uncertainty is big, even though it is possible to state a preferred policy, the robustness of this policy is very low. In other words, there is a high probability for the policy to have a result different that the mean.

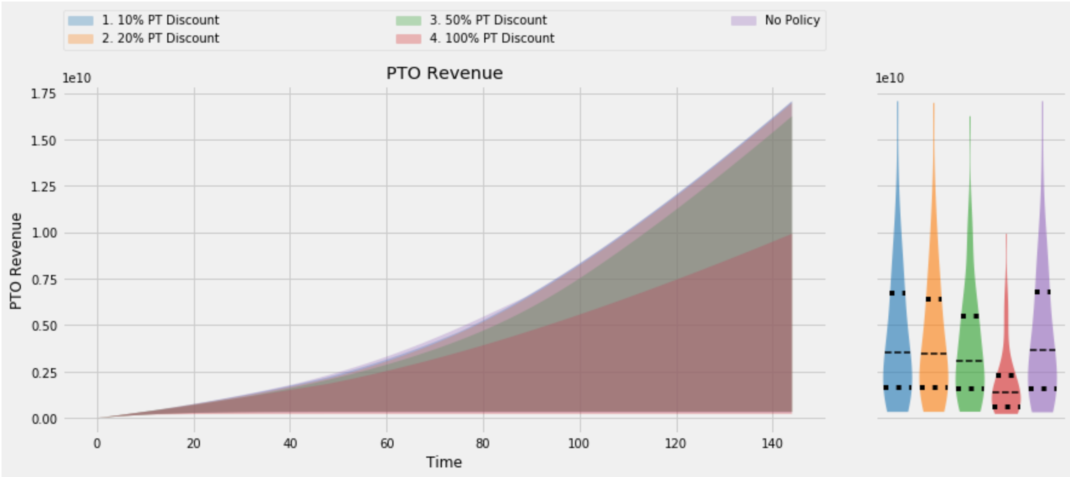



Figure 6.10: Uncertainty Analysis PTO Revenue for a full integration scenario. Both Bike and PT are included in the MaaS package

Table 6.1: Results Best policy per Scenario under PTO perspective

| | | PTO Revenue | PTO and MSP Revenue | Traffic Congestion | Cars per User |
|---|---|---|---|---|---|
| **No Integration** | **Best Policy** | No Policy | No Policy | Indifferent | Indifferent |
| | **Mean** | 0.3 | 0.38 | 1.95 | 0.7 |
| | **Lower Quintile** | 0.13 | 0.24 | 0.95 | 0.4 |
| | **Upper Quintile** | 0.56 | 0.65 | 3.05 | 0.98 |
| **Bike Included** | **Best Policy** | No Policy | No Policy | Indifferent | Indifferent |
| | **Mean** | 0.3 | 0.4 | 1.7 | 0.79 |
| | **Lower Quintile** | 0.12 | 0.2 | 0.5 | 0.39 |
| | **Upper Quintile** | 0.55 | 0.6 | 3.5 | 1 |
| **PT Included** | **Best Policy** | No Policy | ***No Policy*** | ***100% PT Discount*** | ***100% PT Discount*** |
| | **Mean** | 0.38 | ***0.5*** | ***1.25*** | ***0.61*** |
| | **Lower Quintile** | 0.1 | ***0.25*** | ***0.49*** | ***0.39*** |
| | **Upper Quintile** | 0.7 | ***0.75*** | ***3.2*** | ***0.98*** |
| **Full Integration** | **Best Policy** | ***No Policy*** | ***10% PT Discount*** | 100% PT Discount | 100% PT Discount |
| | **Mean** | ***0.38*** | ***0.5*** | 1.5 | 0.72 |
| | **Lower Quintile** | ***0.18*** | ***0.25*** | 0.25 | 0.38 |
| | **Upper Quintile** | ***0.7*** | ***0.75*** | 3.25 | 0.98 |

Table 6.1 shows, depending on different levels of integration, what the best policy applied by PTOs is for the optimization of different KPIs. The table also shows the mean and the lower and upper quintiles of these KPIs to evaluate performance. The policies that are in bold indicate that they correspond to the best option among the different levels of integration to maximize the KPI. The results show that the best scenario for PTOs is to have full integration of the system because it maximizes their revenue either if they are just a player of MaaS or if they control the system. Moreover, the highest utility for PTOs is reached when they are responsible of the role of MSPs. Hence, there is indeed an incentive for PTOs to oppose an open digital market. The best scenario for the government to reduce traffic congestion is given when PTOs apply discounts to MaaS providers. However, the best policy to PTOs is to not apply any discount. Summarizing, PTOs want to have control of the MSPs while avoiding any price discount, while for the government, the best scenario is when the price is discounted.

If the objective is to choose a policy that does not have a high uncertainty so that unexpected negative results are avoided, the best scenario would be to have full integration with high discount. The lower quintile shows a traffic congestion of just 0.25 and it is the minimum value compared to all the other policies. This means that among all the uncertainties, there is a high probability, they reduce traffic congestion considerably. Specially, because the upper quintile of 3.25 has a value comparable to the other policies. To explain better, this scenario even though is not the one which reduces traffic congestion the most on average, it is a scenario for which if there is deviation in the intended behavior of the policy, there is a high chance that the unexpected behavior is positive and reduces traffic congestion.

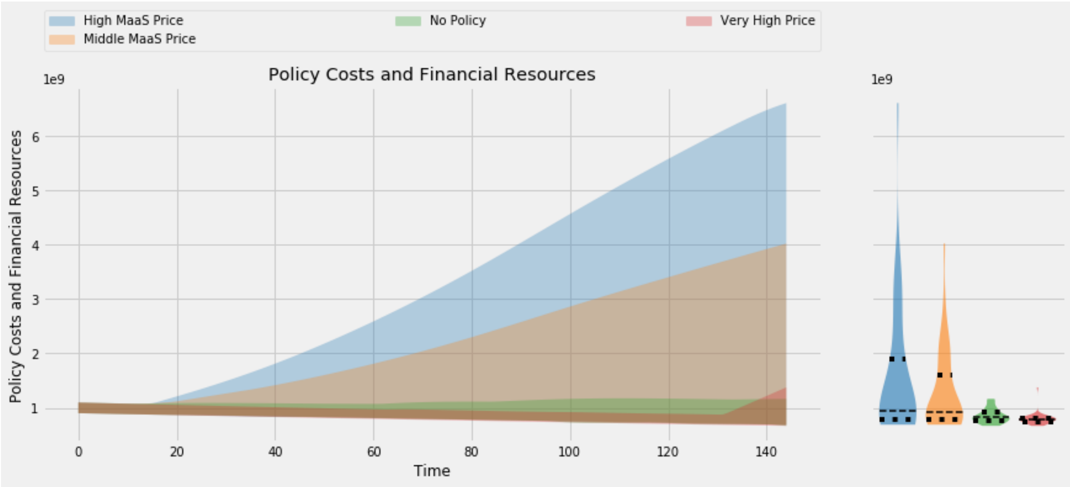



Figure 6.11: Uncertainty Pricing Policy Analysis MSP Revenue for a full integration scenario. Both Bike and PT are included in the MaaS package

Figure 6.11 shows the uncertainty analysis of applying different pricing policies in the perspective of MSPs. The base case scenario has a profit margin og 10%, the medium price corresponds to 50%, high price 100% and very high price 1000%. The results show that there is an optimal price for MSPs where if the price is increased, the profit will not compensate for the fall in the number of users. For the case of MSPs, when the uncertainty analysis is carried out to evaluate the effects in traffic congestion, it is found that there is total indifference for the government on what policies MSP applies. However, there is no indifference in the desired integration scenario. It is found that the best scenario to reduce traffic congestion and have a better chance to increase MSPs financial resources is a full integration scenario. On the other hand, the results are full of uncertainty. There is no guarantee a full integration scenario will lead to less congestion and more revenue, and there is no clarity on what best policy or most robust policy to apply for MSPs.

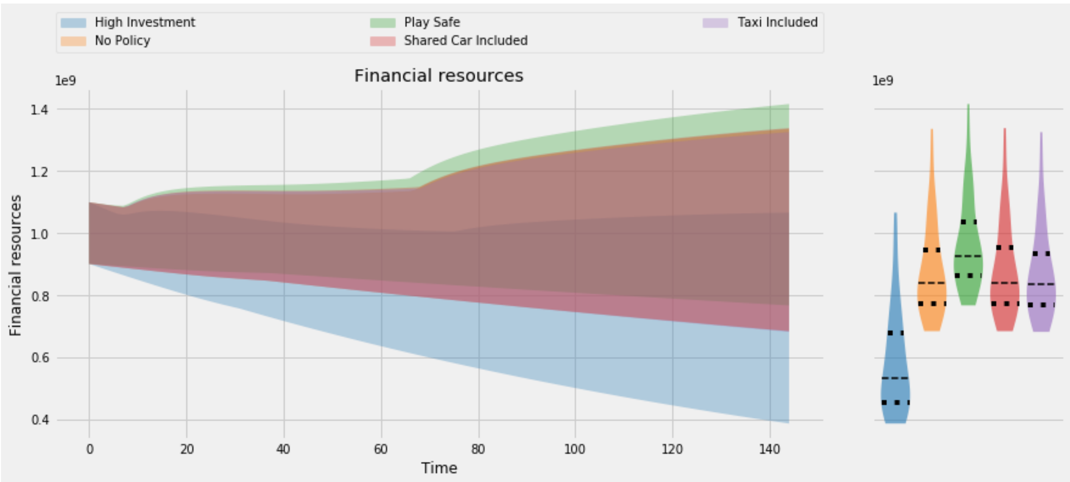



Figure 6.12: Uncertainty Financial Policy Analysis MSP Revenue for a full integration scenario. Both Bike and PT are included in the MaaS package

Figure 6.12 shows other policies available for MSPs and their impact in revenue at the most favorable scenario for MSPs. The results show that compared to the base case with no policy, there is no difference in revenue when shared car and taxis are fully included in the system. However, there is an important conclusion regarding the reinvestment strategy. If the MSPs choose an aggressive investment strategy, the users gained will not compensate for the reinvestment in the system. On the other hand, playing safe, which means with low expectations on the market share and avoiding big reinvestments will bring a better outcome in the revenue of MSPs. Since the investment is being used to increase the platform quality, these results are showing that in the model, the cost of platform quality is not compensated by the new users in the system.

For the case of the government, five policies were formulated: the reduction of subsidies on leasing and the increase of subsidies on transport demand, the reduction of subsidies on leasing and the increase of subsidies on PT use, the reduction of subsidies on leasing and the increase of subsidies on MaaS Subscription packages, the reduction of taxes on car ownership and the increase of taxes on distance driven and finally, an initial investment to MaaS companies. For those policies for which there is a reduction in leasing and an increase in subsidies in other component of the system, it is assumed that the reduction in leasing subsidies is 5 Euros per month and the subsidy has the same value.

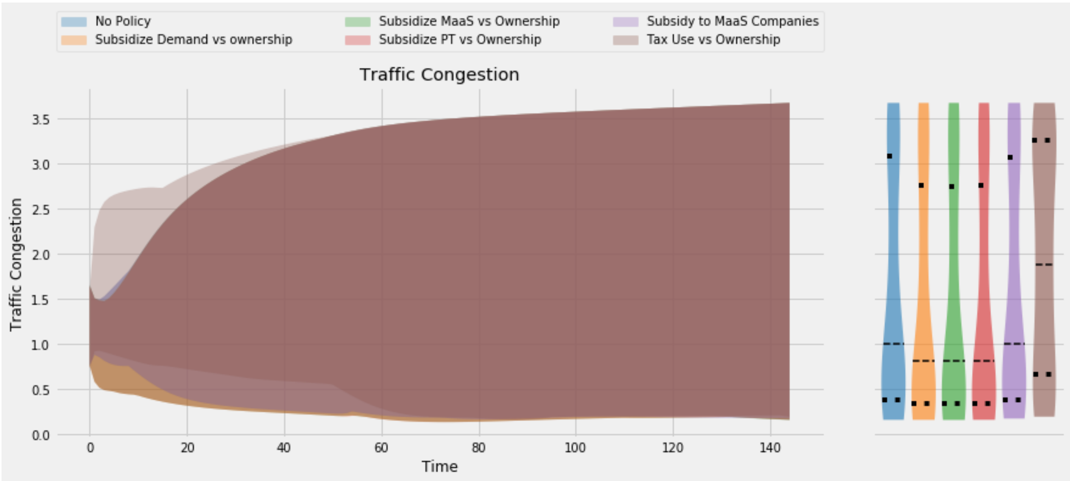



Figure 6.13: Uncertainty Financial Policy Analysis traffic congestion for a full integration scenario. Both Bike and PT are included in the MaaS package

Figure 6.13 shows the results of the different policies to be appplied by the government. The results show that the span of uncertainty cover almost the full spectrum of the possible results of traffic congestion. However, there are clear differences in the average values of traffic congestion at the final period. First, the policy to tax car distance does not work to decrease traffic congestion. Probably, by reducing taxes in car ownership to increase them in taxing car use, new users are feeling attracted to buy a car. Hence, the more availability of private cars appeal the users to use them more than what the tax in the distance driven makes users decide for a different mode. Probably, even though the argument is that taxes on ownership force people to use the car, it is the fact of having a car that has the most impact. Also, the result distribution of this policy shows that traffic congestion either is very high or very low at the end of the study period. The reason for this is that the value of the tax is on the edge of the value of not owning a car. Then, this is the tipping point where users make a choice depending on small differences of values.

The policy to subsidize MaaS companies does not improve traffic congestion. in fact, it seems to have exactly the same performance as no policy at all. Probably, the mechanism by which quality productivity and data productivity go down makes the system stabilize too fast for the investment to be efficient.

All the other three policies have similar performance. Probably, since PT is the backbone of MaaS packages, and the scenario tested corresponds to full integration, subsidizing MaaS, PT or directly the user has the same impact because in all those options the user feel attracted to PT because MaaS offers flexibility and the subsidy on leasing is not effective anymore.

Table 6.2: Results Best policy per Scenario under government perspective

| | | **Policy Costs** | **Policy Costs and MSP Revenue** | **Traffic Congestion** | **Cars per User** |
|---|---|---|---|---|---|
| **No Integration** | **Best Policy** | Subsidize MaaS vs Ownership | **Subsidize MaaS vs Ownership** | Any Subsidy vs Ownership | Any Subsidy vs Ownership |
| | **Mean** | 0.34 | **1.18** | 1.05 | 0.42 |
| | **Lower Quintile** | 0.12 | **0.83** | 0.25 | 0.12 |
| | **Upper Quintile** | 0.56 | **1.33** | 3.1 | 0.95 |
| **Bike Included** | **Best Policy** | Subsidize MaaS vs Ownership | **Subsidize MaaS vs Ownership** | Any Subsidy vs Ownership | Any Subsidy vs Ownership |
| | **Mean** | 0.32 | **1.2** | 1.1 | 0.39 |
| | **Lower Quintile** | 0.06 | **0.95** | 0.35 | 0.15 |
| | **Upper Quintile** | 0.58 | **1.38** | 3 | 0.97 |
| **PT Included** | **Best Policy** | **Subsidize MaaS vs Ownership** | *Subsidize MaaS vs Ownership* | *Any Subsidy vs Ownership* | *Any Subsidy vs Ownership* |
| | **Mean** | **0.27** | *1.1* | *1* | *0.4* |
| | **Lower Quintile** | **-0.01** | *0.83* | *0.25* | *0.18* |
| | **Upper Quintile** | **0.55** | *1.25* | *2.95* | *0.78* |
| **Full Integration** | **Best Policy** | ***Subsidize MaaS vs Ownership*** | *Subsidize MaaS vs Ownership* | **Any Subsidy vs Ownership** | **Any Subsidy vs Ownership** |
| | **Mean** | ***0.27*** | *1.1* | **0.8** | **0.37** |
| | **Lower Quintile** | ***-0.01*** | *0.83* | **0.3** | **0.2** |
| | **Upper Quintile** | ***0.55*** | *1.38* | **2.75** | **0.92** |

Table 6.2 shows the results for the analysis of the policies from the government's perspective for all scenarios tested. The model shows that the most effective policies for reducing traffic congestion and private car ownership are those that subsidize either PT, MaaS packages or directly the demand while reducing the leasing benefit. The most favorable scenario for reducing traffic congestion and car ownership is a full integration system. However, if the government wants to control MaaS as an MSP, the most favorable scenarios are No integration and only including bike. The reason is that in scenarios that include PT with high subsidies lead to a decrease in the price of MaaS subscriptions. Hence, the government creates a conflict of interest between keeping MaaS financially sustainable and reducing traffic congestion.

The model suggests that the government should not be the provider of MaaS. However, the model does suggest there is an incentive for the government to intervene by reducing leasing subsidies are increasing taxes in car ownership while subsidizing MaaS subscriptions. This policy keeps the costs low and helps to reduce traffic congestion. This has a limitation. First, the model assumes that MSPs use a constant profit margin. If they increase the price to earn more profit because of the subsidies given by the government, it might be harder for the government to keep the subsidies for the user. In this scenario, it is probably better to subsidize the demand directly.

It is important to insist that the results of the model are subjected to great uncertainty. Hence, the possibility of the outcome being not as predicted is very high.

## 6.4. Summary

Summarizing the outcomes of the uncertainty analysis for each of the actors it is possible to understand how the actors may interact. First, there is no incentive for PTOs to create any discount for MSPs to be more attractive to users. Moreover, the best scenario for PTOs to increase its revenue is when they are in charge of the role of the MSPs. The best scenario for PTOs is when only PT is included in the system of MaaS. This makes sense because PTOs would be intentionally make PT more attractive in the system. hence, full integration with a bike is not the best scenario for them. If this scenario is implemented, it goes in accordance with the objectives to reduce traffic congestion and private car ownership.

MSPs have a preference towards a full integrated scenario, since this increase the value of MaaS for the users. However, it is uncertain within the scenario what is the best policy to be applied by MSPs to reduce traffic congestion. however, if they want to increase their performance, the results show that they should keep a low reinvestment strategy and low expectations from the market, because fast reinvestment with a decreasing rate in quality productivity does not attract users to the system fast enough to cover the reinvestment.

For the government, there is no incentive to take the role of the MSPs because it creates a conflict on keeping the revenue of the MSP high while trying to reduce traffic congestion. The best scenario for the government is to have a full integrated system where users have more options to compete against car ownership. Moreover, the government preferred policy is to reduce subsidies on leasing while subsidizing MaaS, under the assumption that MSPs will not see as a chance to increase prices. If they do, the approach of the government should be to subsidize the demand directly while increasing taxes in car ownership or to subsidize PT.

The previous outcomes show us that the level of integration will be determined strongly by the strength of PTOs in the negotiations to create MaaS packages. PTOs want to have a partially integrated scenario with just PT and they want to have the role of MSPs, while for the government and MSPs, it is preferred to integrate completely. For the user, an according to the results shown until now without considering interactions within the actors, the fully integrated scenario where the government applies subsidies to MaaS packages produces an outcome with less traffic congestion than if PTOs have the role of MSPs and there is a partially integrated scenario.

# 7 Analysis

This chapter identifies what are the main advantages and disadvantages of the use of System Dynamics for the analysis of pricing policies on MaaS to reduce traffic congestion. For every step of the modelling process, the main advantages and disadvantages identified are discussed.

The model conceptualization step of this process lead to the successful integration of the common transportation modeling concept of Wegener's cycle with the adoption model for digital platforms of Ruutu, Casey, and Kotovirta (2017). Moreover, the relations exposed during the interviews by Sampo Hietanen were also easily included in the system. This simplicity offered by SD to integrate different theories turns out to be very useful to conceptualize MaaS. It is a complex that joins theories from transportation modelling, economics and Information Technology. SD is a powerful tool to integrate these theories easily and coherently.

Moreover, even in the lack of literature, as in the case of MaaS, SD can be used to create models out of perceptions and opinions as in the case of the private car ownership mechanism. This is useful to be able to complete the model with missing theoretical background.

A disadvantage in the modelling conceptualization is that it is not common to find research about MaaS that explain its behavior dynamically. Most research is descriptive and focus on the behavior of MaaS at a specific point in time but not on its characteristics in time. Hence, it is necessary to base the dynamic conceptualization on static representations of the system.

In the model formalization, MaaS proved to be useful again to integrate different theories to explain the MaaS system. In specific, MaaS offers a unique opportunity to implement a dynamic choice model where the travel times and prices are a response of the user's decisions, relating them to external factors such as service quality that are not usually included in choice modelling.

On the other hand, there are extensive disadvantages in the model formalization process. First, there is not enough research to model accurately the mechanisms by which public transport is priced and how private car ownership is reduced due to MaaS. Moreover, modelling taxis seems to be important since taxis could increase traffic congestion in the future of MaaS. However, this mode is hard to model because MaaS Taxis and non MaaS Taxis are not necessarily exclusive to each other. A user can ask for a taxi that belongs to MaaS even if he is not paying subscription. Finally, while in static methods, it is assumed that the user can decide daily whether he is a part of MaaS or not, because there is only interest in one point in time, this assumption is not valid dynamically because while the decision of taking a mode of transport is made daily, the decision of taking a MaaS subscription is done every month. This means that the choice modelling implementation requires special care in a SD model. For this thesis, the common adoption model by Sterman (2000) is modified so that the adoption fraction means an expected percentage of users rather than a number of users adopting the system per month.

The main advantage of the model implementation is that SD is capable of comparing different pricing policies with these methodologies and define clear policy recommendations and conclusions. More importantly, by the use of causal loop diagrams, it is possible to define the main mechanisms that govern the behavior of the system. In the base case in this project, the most important mechanism is the substitution of private car by PT and its only temporary effect. With these methodology, new loops are identified that create a better informed policy discussion towards making effective policy solutions.

The main disadvantage of the model implementation is that the model needs a high quantity of data. Hence, if data is missing, it is necessary to make rough assumptions that reduce the accuracy of the model. In this model, there is no spatial disaggregation. If space is disaggregated, it is necessary to calculate every parameter for every zone defined in space.

Several issues are identified in the model validation step:

The intrinsic preferences of users vary considerably between different societal groups. Assuming only an average user is present in the system leads to accuracy errors in the KPIs. An analysis with a segmented market is useful to solve this issue. However, it requires to use advanced techniques such as sub-scripting the SD model. This increases considerably the amount of data needed.

The spacial level of aggregation in the system is another point that is disadvantageous for SD. The system has very low accuracy because the attitudinal and behavioral variables have strong variations between different areas of the city. Disaggregating the space in the model can lead not only to more data needs as described before, but it may reduce the running speed of the model considerably.

Scoping the time has also proven to be very challenging when dealing with MaaS and SD Choice modeling is used to find values in a specific point of time. So, there is a need to assume that there are a number of peak points during a month to find monthly values of costs. Also, by assuming that all the users are in the system at a specific point in time, an error is made with the capacity of the modes of transport, because they have more capacity due to the fact that they can do more than one trip within a peak period. However, the definition of a peak period is an arbitrary value that may change considerably the traffic congestion in the system. This problem could be solved by assuming that the capacity is a hard constraint that is never reached but this leads to problems in the pricing and traffic congestion sub-models. It is necessary to do further research on how pricing of the modes of transportation is decided and how travel time should be accurately modelled to improve the models and overcome the time frame limitations.

One last disadvantage identified in the model validation is that the coupling in choice modeling with SD leads to include variables in the model that do not have physical values such as the sensitivity. Hence, it is hard to validate whether these variables are realistic.

On the other hand, the model validation also showed that with SD and by fitting some parameters to real past data, it is possible to have a model with values under realistic ranges and a low sensitivity where there is less than a 5% variation for a 10% variation in the parameters.

Finally, regarding the model application, the clear advantage is that SD is able to provide specific policy advice and behavior explanations for the MaaS system, even under the presence of high uncertainty. The main disadvantage is that the model may only be used for comparative purposes, since the flaws in the model formalization and implementation lead to inaccurate results.

To summarize, the following table offers a list of the advantages and disadvantages identified.

Table 7.1: Main advantages and disadvantages of SD for the purpose of analyzing pricing policies in a MaaS system to reduce traffic congestion

| **Advantages** | **Disadvantages** |
|---|---|
| It is simple to integrate the economic, IT and transportation concepts necessary to understand MaaS | Dynamic explanations of MaaS are not common in literature. |
| It offers a chance to create mechanisms out of perceptions and opinions to create a complete model | Lack of research about pricing mechanisms and effect of MaaS on private car ownership limits the model capacities |
| Offers a chance to implement choice modelling dynamically to see how travel times and prices change with time | Modeling taxi behavior is complex due to lack of exclusivity of users. Users may use both MaaS and non MaaS Services even if they do not buy a MaaS subscription |
| By using causal loop diagrams, it is possible to explain the behavior of the system and the main dynamics involved. | Choice modelling requires that the adoption fraction of MaaS does not represent a growth of users per month but rather an absolute value which goes against the common practice of SD. |
| Policies may be compared quantitatively and specific policy advise is plausible | Not possible to model the impact of users choices on habitual preferences. There is an important dynamic missing |
| The methodology is able to provide recommendations under high uncertainty | The model need a high amount of data. |
| It is possible to have a robust model with low sensitivity and values within the theoretical ranges. | Without demand segmentation and area disaggreagation, it is not possible to have accurate results. |

# 8
# Conclusions

This chapter gives a solution to the research questions formulated in this research with the findings of the different steps of the modeling process.

**How can MaaS systems be conceptualized in terms of feedback relations between quantitative variables?**

From the literature review, it is identified that there are five characteristics that define MaaS: MaaS is a system that offers mobility services to users, these services are integrated in a digital platform, the platform at the same time offers digital services personalized for and customized by the users, the transport modes can be offered independently or in packages that are paid at regular periods in time and MaaS operates in a multi-actor arena.

By using the MaaS framework from Holmberg, Collado, Sarasini, and Williander (2016), it is identified that the services offered have assets owned publicly or by organizations and these services are highly integrated in a platform. Seven modes are identified as the most relevant services: Private car, car share, taxi, taxi share, bike, bike share and Public Transport. Finally, MaaS is a multiactor system with four main players: Users, Mobility Service Providers, Public Transport Operators and transport service providers.

The main drivers of MaaS that affect the demand of the system are that users are initially highly influenced by curiosity, flexibility, price, service quality and the accessibility to the different transport modes. The offer of MaaS is highly driven by the investment to MaaS systems, and business relations between key players.

From interviews held with experts, it is found that the key to the relation between MaaS and traffic congestion is the level of preference of users towards private car. Users more keen to use private car might hardly shift to a different system. While other users, open to other possibilities would shift their service and even sell their car, reducing car ownership and traffic congestion. This relation between car ownership and MaaS plays a key role in the System Dynamics model presented.

The previous findings lead the path to build and SD model that explain the system.

Figure 8.1 shows the final model conceptualized. The model has seven causal loops. The data network effect, that explains how data accumulation of users increase MaaS value; cross network effect, which explains how taxis decide to become a part of MaaS; platform development, which explains how investment of MaaS providers become an increase in the quality of MaaS platforms; the competitive effort, which determines the rate at which MaaS companies reinvest in themselves; Wegener cycle, which describes the relation between travel times, the number of users and traffic congestion; car ownership mechanism which explains the mechanism by which car ownership changes in a MaaS system; and the markup price mechanism which assumes that MaaS providers expect a fix percentage profit margin.

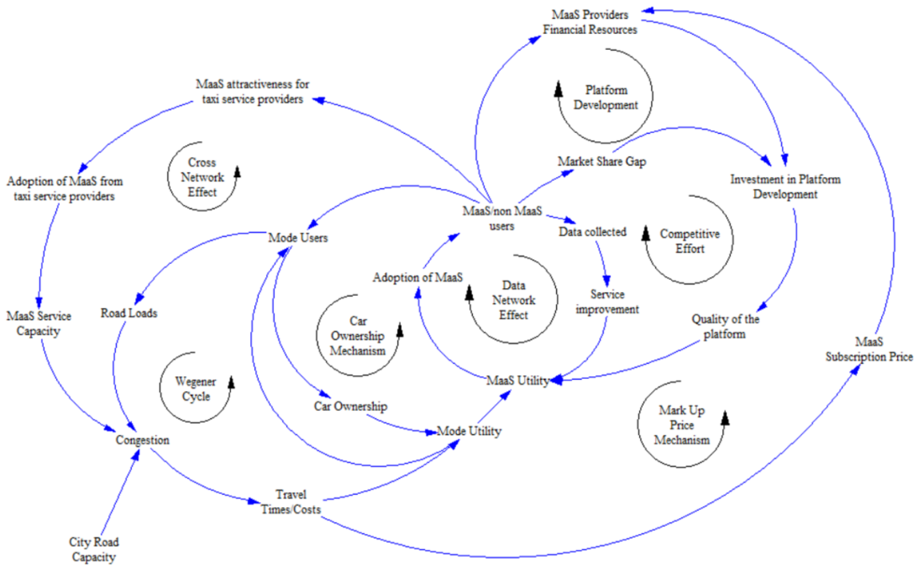



Figure 8.1: MaaS model main structure

**Which are the relevant pricing interventions to the system that could affect traffic congestion?**

One of the main discussions is which actor will have the role of the MaaS Service Provider. Whether the government, Public Transport Operators or a commercial actor play this role will have strong societal impacts in the system. It is believed by Wong, Hensher, and Mulley (2017) that if it is commercial, the government might lose control of transport policy and traffic congestion could increase. If the role is taken by the government or Public Transport Operators, the lack of competition would not lead to the satisfaction of the users and they might not leave the ownership of their cars.

The second discussion is that the implementation of MaaS will require high investments. Until now, the implementation has been focusing on pilots. However, these pilots might not show an approximate of the actual potential of MaaS. Investing in the creation of MaaS developments could be a policy to help the system. It is unsure whether this would lead to less traffic congestion.

The final discussion is where to allocate the subsidies and taxes in the MaaS system. Currently PT and leasing of autos are subsidized. MSPs are calling for a subsidy that is controlled by the demand so that all the modes of transportation compete under equal circumstances. This also applies in the case of Amsterdam to car share which does not have to pay for the use of parking. Moreover, Connekt (2017) states that instead of taxing car ownership, it would be useful to tax the car use since users would not feel compelled to use their cars. Other common allocations for subsidies mentioned in literature are PT and MaaS subscription packages

***How different types of tax schemes and service packages affect the performance of traffic congestion in the system modelled?***

After running the SD model built, the following results are found under the assumptions of the model:

First, there is no incentive for Public Transport operators to create any discount for MaaS Service providers to be more attractive to users. Moreover, the best scenario for Public Transport Operators to increase its revenue is when they are in charge of the role of the MaaS Service Provider. Moreover, these operators do not have an incentive to include bike sharing and bike rental services in the MaaS packages. This makes sense because Public Transport Operators would be intentionally trying to increase the number of Public Transport Users. Hence, full integration with a bike is not the best scenario for them. However, if the preferred scenario is implemented, it is possible to obtain an effective reduction in traffic congestion.

MaaS Service Providers have a preference towards a full integrated scenario, since this increase the value of MaaS for the users. However, it is uncertain within the scenario what is the best policy to be applied by

MaaS Service Providers to reduce traffic congestion. On the other hand, if they want to increase their performance, the results show that they should keep a low reinvestment strategy and low expectations from the market, because fast reinvestment with a decreasing rate in quality productivity does not attract users to the system fast enough to cover the reinvestment.

For the government, there is no incentive to offer the MaaS service publicly because it creates a conflict on keeping the revenue of the MaaS Service high while trying to reduce traffic congestion. The best scenario for the government is to have a full integrated system where users have more options to compete against car ownership. Moreover, the government preferred policy is to reduce subsidies on leasing while subsidizing MaaS, under the assumption that MaaS Service Providers will not see that as a chance to increase prices. If they do, the approach of the government should be to subsidize the demand directly while increasing taxes in car ownership.

The previous outcomes show us that the level of integration will be determined strongly by the strength of Public Transport operators in the negotiations to create MaaS packages. Public Transport Operators want to have a partially integrated scenario with just Public Transport and they want to have the role of Mobility Service Providers, while for the government and Mobility Service Providers, it is preferred to integrate completely. For the user, an according to the results shown until now without considering interactions within the actors, the fully integrated scenario where the government applies subsidies to MaaS packages produces an outcome with less traffic congestion than if Public Transport Operators have the role of Mobility Service Providers and there is a partially integrated scenario.

***What are the main advantages and disadvantages when using system dynamics to analyze Mobility as a Service and its effects in Traffic Congestion?***

The following table provides an overview of the advantages and disadvantages of using SD for analyzing pricing interventions in a MaaS system.

Table 8.1: Main advantages and disadvantages of SD for the purpose of analyzing pricing policies in a MaaS system to reduce traffic congestion

| **Advantages** | **Disadvantages** |
|---|---|
| It is simple to integrate the economic, IT and transportation concepts necessary to understand MaaS | Dynamic explanations of MaaS are not common in literature. |
| It offers a chance to create mechanisms out of perceptions and opinions to create a complete model | Lack of research about pricing mechanisms and effect of MaaS on private car ownership limits the model capacities |
| Offers a chance to implement choice modelling dynamically to see how travel times and prices change with time | Modeling taxi behavior is complex due to lack of exclusivity of users. Users may use both MaaS and non MaaS Services even if they do not buy a MaaS subscription |
| By using causal loop diagrams, it is possible to explain the behavior of the system and the main dynamics involved. | Choice modelling requires that the adoption fraction of MaaS does not represent a growth of users per month but rather an absolute value which goes against the common practice of SD. |
| Policies may be compared quantitatively and specific policy advise is plausible | Not possible to model the impact of users choices on habitual preferences. There is an important dynamic missing |
| The methodology is able to provide recommendations under high uncertainty | The model need a high amount of data. |
| It is possible to have a robust model with low sensitivity and values within the theoretical ranges. | Without demand segmentation and area disaggreagation, it is not possible to have accurate results. |

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# Appendices

# A

# Interview Questions

This appendix show the questions asked during the interviews with experts for the conceptualization of the model built.

- What do you think could be the impacts of MaaS on traffic congestion patterns?
- Are there cities that already had changes in congestion patterns due to MaaS? to what extent?
- Are the users of MaaS giving out their cars?
- What are the attitudes of governments towards MaaS?
- What are the attitudes of transport providers towards maaS.
- What are the incentives for governments to support the growth of MaaS?
- What are the main barriers to overcome to implement a successful MaaS roaming ecosystem?
- Under your perception, what are the actions governments should take for MaaS to be sustainable in the long term?
- In specific, which are the policies, in terms of taxes and subsidies, that should be implemented now for a successful growth of MaaS?

# B

# Model Input

```
Coefficient Contribution Price of MaaS Subscrition to MaaS Value=
	1/50
	~	(Euros/Trip)/(Euros/(persons*Month))
	~		|

Contribution Price Private Car=
	0.052989
	~
	~		|

MaaS PT Value for Users=
	-(Total Perceived PT Average Travel Time per Trip*Value of Time PT MaaS Users+DELAY1\
		("Average Non-MaaS PT Price per Trip"*Contribution Price PT MaaS Users,Users Reaction Time
	)*(1-Percentage Subsidy on Public Transport)*(1-PT Trip Percentage included in the MaaS Package\
		)
	)+Instrinsic Preference of MaaS Users to PT
	~	Euros/Trip
	~		|

Number of Private Cars per User=
	(Private Car Fleet)/Total Travel Demand
	~	vehicles/persons
	~		|

MaaS Shared Taxxi Value for MaaS Users=
	-Value of Time Shared Taxi MaaS Users*Average MaaS Shared Taxi Travel Time per Trip-\
		Average MaaS Shared Taxi Costs per Trip*Contribution Shared Taxi Price MaaS Users
	~	Euros/Trip
	~		|

Private Car Value for Users without Intrinsic Preferences=
	-Value of Time Private Car*Average Private Car Travel Time per Trip-Contribution Price Private Car\
		*Average Private Car Costs per Trip+Number of Private Cars per User
	*(Contribution of Car Ownership to Private car Value for Users)
	~	Euros/Trip
	~		|

"Non-MaaS Bike Value for Users"=
	DELAY1(-(Value of Time Bike non MaaS Users*"Average Non-MaaS Bike Travel Time per Trip"\
		+Contribution Bike Price non MaaS Users*"Average Non-MaaS Bike Costs per Trip"),
	Users Reaction Time
	)+"Intrinsic Preference of Non-MaaS Users to Bike"
	~	Euros/Trip
	~		|

Extra Travel Time Index=
	Average Travel Time Perceived by Users on the Road/Average Free Travel Time-1
	~
	~		|

"Non-MaaS PT Value for Users"=
	-Total Perceived PT Average Travel Time per Trip*Value of Time PT non MaaS Users-Contribution Price PT non Maa
		*DELAY1("Average Non-MaaS PT Price per Trip",Users Reaction Time
	)*(1-STEP(Percentage Subsidy on Public Transport, MaaS Start Time
	))+"Intrinsic Preferences of Non-MaaS Users to PT"
	~	Euros/Trip
	~		|
```

```
MaaS Taxi Value for MaaS users=
	-Value of Time Taxi MaaS Users*Average Perceived MaaS Taxi Total Travel TIme per Trip\
		-
	DELAY1(Average MaaS Taxi Price per Trip*Contribution Taxi Price MaaS Users,Users Reaction Time\
		)
	~	Euros/Trip
	~		|

"Non-MaaS Shared Taxi Value for Users"=
	-("Average Non-MaaS Shared Taxi Travel Time per Trip"*Value of Time Shared Taxi non MaaS Users\
		+"Average Non-MaaS Shared Taxi Costs per Trip"*Contribution Shared Taxi Price non MaaS Users
	)
	~	Euros/Trip
	~		|

Value of Time Private Car=
	0.0164567
	~
	~		|

"Shared Car Value for Non-MaaS Users without Intrinsic preferences"=
	-Shared Car Travel Time per Trip*Value of Time Shared Car non MaaS Users-"Shared-Car Price per Trip for Users"\
		*Contribution price Shared Car Value non MaaS Users
	~	Euros/Trip
	~		|

Contribution Price PT MaaS Users=
	0.177813
	~
	~		|

"Non-MaaS Taxi Value for users"=
	DELAY1(-"Average Non-MaaS Taxi Price per Trip"*Contribution Taxi Price non MaaS Users\
		,Users Reaction Time)-"Average Perceived Non-MaaS Taxi Total Travel Time per Trip"
	*Value of Time Taxi non MaaS Users
	~	Euros/Trip
	~		|

Contribution price Shared Car Value non MaaS Users=
	1e-06
	~
	~		|

Contribution Shared Taxi Price MaaS Users=
	0.340877
	~
	~		|

Contribution Shared Taxi Price non MaaS Users=
	0.340877
	~
	~		|

Contribution Taxi Price MaaS Users=
	7.45909e-05
	~
	~		|
```

```
"Shared-Car Price per Trip for Users"=
	DELAY1("Cost Shared-Car per Minute"*Average Travel Time Perceived by Users on the Road\
		,Users Reaction Time)
	~	Euros/Trip
	~	Car2Go
	|

"Shared-Car Value for maaS users without Intrinsic Preferences"=
	-Value of Time Shared Car MaaS Users*Shared Car Travel Time per Trip-"Shared-Car price per Trip for MaaS Users
	*Contribution price Shared Car Value MaaS Users
	~	Euros/Trip
	~		|

Contribution Bike Price MaaS Users=
	0.000441342
	~
	~		|

Value of Time PT MaaS Users=
	0.00241185
	~
	~		|

Value of Time Bike MaaS Users=
	0.025921
	~
	~		|

Contribution Price PT non MaaS Users=
	0.177813
	~
	~		|

Contribution price Shared Car Value MaaS Users=
	1e-06
	~
	~		|

Value of Time Shared Taxi MaaS Users=
	0.995741
	~
	~		|

Contribution Bike Price non MaaS Users=
	0.000441342
	~
	~		|

Value of Time Taxi MaaS Users=
	0.0352938
	~
	~		|

Value of Time Bike non MaaS Users=
	0.025921
	~
	~		|
```

Contribution Taxi Price non MaaS Users=
7.45909e-05
~
~ |

Value of Time Shared Car non MaaS Users=
0.0001
~
~ |

MaaS Bike Value for Users=
DELAY1(-Average MaaS Bike Costs per Trip besides Subscription*Contribution Bike Price MaaS Users\
-Average MaaS Bike Travel Time per Trip*Value of Time Bike MaaS Users
,Users Reaction Time)+Intrinsic Preference of MaaS Users to Bike
~ Euros/Trip
~ |

Value of Owning a Private Car for Non Owners=
Intrensic Preference of Owning a Private Car for Non Owners-Monthly Costs of Car Ownership\
-STEP(Raise Tax on Car Ownership, MaaS Start Time)
~ Euros/Month
~ |

Value of Time PT non MaaS Users=
0.00241185
~
~ |

Value of Time Shared Car MaaS Users=
0.0001
~
~ |

Value of Time Shared Taxi non MaaS Users=
0.995741
~
~ |

Value of Owning a Private Car for Car Owners=
Intrinsic Preference of Owning a Private Car for Car Owners-Monthly Costs of Car Ownership\
-STEP(Raise Tax on Car Ownership, MaaS Start Time)
~ Euros/Month
~ |

Value of Time Taxi non MaaS Users=
0.0352938
~
~ |

Analysis Time Taxi=
10
~ Minutes
~ |

Analysis Time PT=
15
~ Minutes
~ |

```
"Average Non-MaaS Taxi Access/Egress Time per Trip"=
	"Free Average Taxi Acces/Egres Time per Trip"+(1/4)*Analysis Time Taxi*(("Non-MaaS Taxi User Congestion in Peak
	-1)+SQRT(("Non-MaaS Taxi User Congestion in Peak Hours"-1)^2+8*Delay Parameter Taxi
	*"Non-MaaS Taxi User Congestion in Peak Hours"
	/(Analysis Time Taxi*"Non-MaaS Taxis in Peak Hours")))
	~	Minutes/Trip
	~		|

"Average MaaS Taxi Access/Egress Time per Trip"=
	"Free Average Taxi Acces/Egres Time per Trip"+(1/4)*Analysis Time Taxi*((MaaS Taxi User Congestion in Peak Hour
	-1)+SQRT((MaaS Taxi User Congestion in Peak Hours
	-1)^2+8*Delay Parameter Taxi
	*MaaS Taxi User Congestion in Peak Hours
	/(Analysis Time Taxi*MaaS Taxis in Peak Hours)))
	~	Minutes/Trip
	~		|

"PT Average Access/Egress Time per Trip in Peak Hours"=
	"Free Average PT Access/Egress Time per Trip in Peak Hours"+(1/4)*Analysis Time PT*(\
		(Users Congestion in PT in Peak Hours
	-1)+SQRT((Users Congestion in PT in Peak Hours-1)^2+8*Delay Parameter PT
	*Users Congestion in PT in Peak Hours
	/(Analysis Time PT*PT Capacity)))
	~	Minutes/Trip
	~		|

Average Travel Time on the Road with Traffic Congestion=
	Average Free Travel Time+(1/4)*Analysis Time*((Traffic Congestion-1)+SQRT((Traffic Congestion
	-1)^2+8*Delay Parameter Roads
	*Traffic Congestion
	/(Analysis Time*Road Capacity)))
	~	Minutes/Trip
	~		|

Analysis Time=
	30
	~	Minutes/Trip
	~		|

Walking Value=
	DELAY1(-Value of Time for Walking Users*Average Walking Travel Time per Trip,Users Reaction Time\
		)
	~	Euros/Trip
	~		|

Average Private Car Costs per Trip=
	DELAY1(Average Trip Length*Fuel Costs+Parking Costs+Average Trip Length*STEP(Tax per km of Use of Private Ca
		,MaaS Start Time),Users Reaction Time)
	~	Euros/Trip
	~	van Kuijk

		CBS gasoline price
	|

Average Private Car Travel Time per Trip=
	DELAY1("Average Private Car Access/Egress Time per Trip",Users Reaction Time)+Average Travel Time Perceived b
	~	Minutes/Trip
```

```
	~		|

Shared Car Travel Time per Trip=
	Average Travel Time Perceived by Users on the Road+DELAY1("Shared-Car Access/Egress Time"\
		,Users Reaction Time)
	~	Minutes/Trip
	~		|

Potential MaaS Taxis Contacted by WoM from WoM=
	MaaS Taxis*Word of Mouth Contact Rate
	~	vehicles
	~		|

"Number of Non-MaaS Shared Taxi Trips in Peak Hours"=
	IF THEN ELSE(Sensitivity Mode Choice*("Shared Taxi Value for Non-MaaS Users"-"Generalized utility Non-MaaS Mo
	)<-15,0,
	"Non-MaaS Trips in Peak Hours"*exp(Sensitivity Mode Choice*("Shared Taxi Value for Non-MaaS Users"\
		-"Generalized utility Non-MaaS Modes to Users"
	)))
	~	Trip/peak
	~		|

"Number of Non-MaaS Taxi Trips in Peak Hours"=
	IF THEN ELSE(Sensitivity Mode Choice*("Taxi Value for Non-MaaS Users"-"Generalized utility Non-MaaS Modes to U
	)<-15,0,
	exp(Sensitivity Mode Choice*("Taxi Value for Non-MaaS Users"-"Generalized utility Non-MaaS Modes to Users"
	))*"Non-MaaS Trips in Peak Hours")
	~	Trip/peak
	~		|

Private Car Adoption Fraction=
	IF THEN ELSE(Sensitivity Car Ownership Choice*(-Value of Owning a Private Car for Non Owners
	)>15,0,
	IF THEN ELSE(Sensitivity Car Ownership Choice*(-Value of Owning a Private Car for Non Owners
	)<-15,1,1/(1+exp(Sensitivity Car Ownership Choice*(-Value of Owning a Private Car for Non Owners
	)))))
	~	1
	~		|

MaaS Taxi User Congestion in Peak Hours=
	(Number of MaaS Taxi Trips in Peak Hours*"Vehicles per Non-Shared Trip"+Number of MaaS Shared Taxi Trips in Pe
		/
	Average User Occupation of Shared Taxis)/(MaaS Taxis in Peak Hours
	)
	~	1
	~		|

Private Car Keep Fraction=
	IF THEN ELSE(Sensitivity Car Ownership Choice*(-Value of Owning a Private Car for Car Owners
	)>15,0,
	IF THEN ELSE(Sensitivity Car Ownership Choice*(-Value of Owning a Private Car for Car Owners
	)<-15,1,
	1/(1+exp(Sensitivity Car Ownership Choice*(-Value of Owning a Private Car for Car Owners\
		))
	)))
	~	1
	~		|
```

```
"Number of Non-MaaS PT Trips in Peak Hours"=
	IF THEN ELSE(Sensitivity Mode Choice*("Non-MaaS PT Value for Users"-"Generalized utility Non-MaaS Modes to Us
	)<-15,0,
	"Non-MaaS Trips in Peak Hours"*exp(Sensitivity Mode Choice*("Non-MaaS PT Value for Users"\
		-"Generalized utility Non-MaaS Modes to Users"
	)))
	~	Trip/peak
	~		|

"Non-MaaS Shared Car Value for Users"=
	"Intrinsic preference of Non-MaaS Users to Shared Car"+"Shared Car Value for Non-MaaS Users without Intrinsic pref
	~	Euros/Trip
	~		|

MaaS Adoption Fraction from Taxis=
	IF THEN ELSE(Sensitivity Taxi Drivers MaaS Choice*("No-MaaS Value to Non-MaaS Taxi Drivers"\
		-"MaaS Value to Non-MaaS Taxi Drivers"
	) <-15, 1,IF THEN ELSE(Sensitivity Taxi Drivers MaaS Choice*("No-MaaS Value to Non-MaaS Taxi Drivers"\
		-"MaaS Value to Non-MaaS Taxi Drivers"
	) > 15, 0 , 1/(1+exp(Sensitivity Taxi Drivers MaaS Choice*("No-MaaS Value to Non-MaaS Taxi Drivers"\
		-"MaaS Value to Non-MaaS Taxi Drivers"
	)))
	))
	~	vehicles/vehicles
	~		|

PT Buses User Capacity=
	Bus User Capacity*Number of PT Buses on the Road during Peak Hours
	~	Trip/peak
	~		|

MaaS Users Keep Fraction=
	IF THEN ELSE(Sensitivity MaaS Choice by Users*("Non-MaaS Value for Users"-MaaS value for MaaS Users\
		) < -15,1,IF THEN ELSE
	(Sensitivity MaaS Choice by Users*("Non-MaaS Value for Users"-MaaS value for MaaS Users\
		) > 15 , 0 , 1/(exp(Sensitivity MaaS Choice by Users
	*("Non-MaaS Value for Users"-MaaS value for MaaS Users))+1)))
	~	persons/persons
	~		|

MaaS value for MaaS Users=
	Data per User Contribution to MaaS Value+"MaaS Value for Non-MaaS Users"+Intrinsic Perceived Utility of Using Maa
	~	Euros/Trip
	~		|

"MaaS Value for Non-MaaS Users"=
	Contribution of Price of MaaS Subscription to MaaS Value+Generalized Utility MaaS Modes to Users
	+"Intrinsic Perceived Utility of Using MaaS for Non-Users"+Platform Quality Contribution to MaaS Value\
		+Transportation Subsidy to Users
	~	Euros/Trip
	~		|

MaaS Value to MaaS Taxi Drivers=
	Intrinsic Preference of Using MaaS for MaaS Taxi Drivers+"MaaS Value to Non-MaaS Taxi Drivers"
	~	Euros/Trip
	~		|

Average PT Travel Time Per Trip in Peak Hours=
```

```
	(PT Buses User Capacity*Average Travel Time Buses+PT User Capacity with Modes off the Road
	*Average Trip PT Travel Time with Modes off the Road)/(PT Buses User Capacity+PT User Capacity with Modes off th
	)
	~	Minutes/Trip
	~		|

"Number of Non-MaaS Private Car Trips in Peak Hours"=
	"Non-MaaS Trips in Peak Hours"*exp(Sensitivity Mode Choice*("Non-MaaS Private Car Value for Users"\
		-
	"Generalized utility Non-MaaS Modes to Users"
	))
	~	Trip/peak
	~		|

Generalized Utility MaaS Modes to Users=
	(1/Sensitivity Mode Choice)*LN(exp(Sensitivity Mode Choice*MaaS Bike Value for Users\
		)+exp(Sensitivity Mode Choice
	*MaaS Private Car Value for Users)+exp(MaaS PT Value for Users*Sensitivity Mode Choice\
		)+exp(Shared Taxi Value for MaaS Users
	*Sensitivity Mode Choice)+exp(Taxi Value for MaaS Users*Sensitivity Mode Choice)+exp\
		(Walking Value
	*Sensitivity Mode Choice)+exp(MaaS Shared Car Value for Users
	*Sensitivity Mode Choice))
	~	Euros/Trip
	~		|

Reinvestment in Business from MaaS Providers=
	MAX(0,Financial resources)*STEP(1,MaaS Start Time)*
	(SMOOTH(MAX(0,MaaS Market Share Gap*Effect of MaaS Market Share Gap on Expenses),MaaS Providers Financi
	))
	~	Euros/Month
	~		|

MaaS Advertisment Effectiveness on Taxi Drivers=
	Magnitude Advertisement Effectiveness*PULSE(MaaS Start Time, Advertisement Effective Time\
		)
	~	vehicles/(vehicles)
	~		|

"Non-MaaS Taxi User Congestion in Peak Hours"=
	("Number of Non-MaaS Taxi Trips in Peak Hours"*"Vehicles per Non-Shared Trip"+"Number of Non-MaaS Shared Ta
	/Average User Occupation of Shared Taxis)/("Non-MaaS Taxis in Peak Hours"
	)
	~	vehicles/vehicles
	~		|

"No-MaaS Value to Non-MaaS Taxi Drivers"=
	"Intrinsic Preference of Not Owning MaaS for Non-MaaS Taxi Drivers"+"No-MaaS Value to MaaS Taxi Drivers"
	~	Euros/Trip
	~		|

"Average Perceived MaaS Taxi Agress/Egress Time per Trip"=
	IF THEN ELSE( Time <= MaaS Start Time,"Free Average Taxi Acces/Egres Time per Trip",\
		SMOOTHI("Average MaaS Taxi Access/Egress Time per Trip"
	,Users Reaction Time,"Free Average Taxi Acces/Egres Time per Trip"))
	~	Minutes/Trip
	~		|
```

```
"Taxi Value for Non-MaaS Users"=
	"Intrinsic Preference of Non-MaaS Users to Taxi"+"Non-MaaS Taxi Value for users"
	~	Euros/Trip
	~		|

"Non-MaaS Private Car Value for Users"=
	"Intrinsic Preference of Non-MaaS Users to Use Private Car"+Private Car Value for Users without Intrinsic Preferences
	~	Euros/Trip
	~		|

"Number of Non-MaaS Shared Car Trips in Peak Hours"=
	IF THEN ELSE(Sensitivity Mode Choice*("Non-MaaS Shared Car Value for Users"-"Generalized utility Non-MaaS Moc
	)< -15,0,
	"Non-MaaS Trips in Peak Hours"*exp(Sensitivity Mode Choice*("Non-MaaS Shared Car Value for Users"\
		-"Generalized utility Non-MaaS Modes to Users"
	)))
	~	Trip/peak
	~		|

"Generalized utility Non-MaaS Modes to Users"=
	(1/Sensitivity Mode Choice)*LN(exp(Sensitivity Mode Choice*"Non-MaaS Bike Value for Users"\
		)+exp(Sensitivity Mode Choice
	*"Non-MaaS Private Car Value for Users")+exp(Sensitivity Mode Choice*"Non-MaaS PT Value for Users"\
		)+exp(Sensitivity Mode Choice
	*"Shared Taxi Value for Non-MaaS Users")+exp(Sensitivity Mode Choice*"Taxi Value for Non-MaaS Users"
	)+exp(Sensitivity Mode Choice*Walking Value)+exp(Sensitivity Mode Choice
	*"Non-MaaS Shared Car Value for Users"))
	~	Euros/Trip
	~		|

"Non-MaaS Value for Users"=
	"Generalized utility Non-MaaS Modes to Users"+Transportation Subsidy to Users
	~	Euros/Trip
	~		|

PT Capacity=
	PT Buses User Capacity+PT User Capacity with Modes off the Road
	~	Trip/peak
	~		|

Number of MaaS Walking Trips in Peak Hours=
	IF THEN ELSE(Sensitivity Mode Choice*(Walking Value-Generalized Utility MaaS Modes to Users
	)<-15,0,
	MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(Walking Value-Generalized Utility MaaS Modes to Users
	)))
	~	Trip/peak
	~		|

"Number of Non-MaaS Walking Trips in Peak Hours"=
	IF THEN ELSE(Sensitivity Mode Choice*(Walking Value-"Generalized utility Non-MaaS Modes to Users"
	)<-15,0,
	"Non-MaaS Trips in Peak Hours"*exp(Sensitivity Mode Choice*(Walking Value-"Generalized utility Non-MaaS Modes t
	)))
	~	Trip/peak
	~		|

"Number of Non-MaaS Bike Trips in Peak Hours"=
	IF THEN ELSE(Sensitivity Mode Choice*("Non-MaaS Bike Value for Users"-"Generalized utility Non-MaaS Modes to U
```

```
	)<-15,0,
	"Non-MaaS Trips in Peak Hours"*exp(Sensitivity Mode Choice*("Non-MaaS Bike Value for Users"\
		-"Generalized utility Non-MaaS Modes to Users"
	)))
	~	Trip/peak
	~		|

Traffic Congestion=
	Traffic load/Road Capacity
	~	1
	~		|

Policy Costs and Financial Resources=
	Financial resources-Policy Costs
	~	Euros
	~		|

"Average Non-MaaS PT Price proportion"=
	DELAY1I(Desired PT Price Proportion,Public Transport Operators and Public Transport Authorities Reaction Time\
		,Initial Average Non MaaS PT Price Proportion)
	~	1
	~		|

"Average Non-MaaS Taxi Price Proportion"=
	DELAY1I("Average Desired Non-MaaS Taxi Price Proportion",Public Transport Operators and Public Transport Author
	,Initial Average Non maaS Taxi Price Proportion)
	~	1
	~		|

Initial Average Non MaaS PT Price Proportion= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(241,10)],(0,1),(96,1.749),(241,1.749) ))
	~	1
	~		|

Initial Average Non maaS Taxi Price Proportion= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(241,10)],(0,1),(96,0.7859),(241,0.7869) ))
	~	1
	~		|

"Shared Taxi Value for Non-MaaS Users"=
	"Non-MaaS Shared Taxi Value for Users"+"Intrinsic Preference of Non-MaaS Users to Shared Taxi"
	~	Euros/Trip
	~		|

Financial resources= INTEG (
	Accumulation of Financial Resources by MaaS Providers-Monthly Operational Costs of MaaS Providers\
		-Reinvestment in Business from MaaS Providers,
		Initial Financial Resources of MaaS Providers+Subsidies to new MaaS Companies)
	~	Euros
	~		|

Subsidies to new MaaS Companies=
	0
	~	Euros
	~		|
```

```
MaaS Taxis Market Share=
	MaaS Taxis/Total Taxi Capacity
	~	1
	~		|

Tax per km of Use of Private Car=
	0
	~	Euros/km
	~		|

Policy Costs per Month=
	Total Travel Demand*Peak Periods per Month*Transportation Subsidy to Users*Trips per User per Peak Period\
		-Average Trip Length
	*Tax per km of Use of Private Car*Number of Private Car Trips in Peak Hours*Peak Periods per Month
	-Private Car Fleet*Raise Tax on Car Ownership*Fraction of taxes paid per vehicle+Percentage Subsidy on MaaS Subs
		*MaaS Users*Price of MaaS Subscription per User per Month
	+Percentage Subsidy on Public Transport*Number of PT Trips in Peak Hours*"Average Non-MaaS PT Price per Trip"\
		*Peak Periods per Month
	~	Euros/Month
	~		|

Contribution of Price of MaaS Subscription to MaaS Value=
	-Coefficient Contribution Price of MaaS Subscrition to MaaS Value*Price of MaaS Subscription per User per Month\
		*(1-Percentage Subsidy on MaaS Subscription)
	~	Euros/Trip
	~		|

Percentage Subsidy on Public Transport=
	0
	~	1
	~		|

Raise Tax on Car Ownership=
	0
	~	Euros/Month
	~		|

Average PT Price per Trip for MaaS providers=
	"Average Non-MaaS PT Price per Trip"*(1-PT Percentage Price Discount for MaaS providers\
		)*PT Trip Percentage included in the MaaS Package*(1-Percentage Subsidy on Public Transport\
		)
	~	Euros/Trip
	~		|

Fraction of taxes paid per vehicle=
	1
	~	1/vehicles
	~		|

Change of Preference of non MaaS Users to Shared Taxi=
	0
	~	Euros/Trip/Month
	~		|

Percentage Subsidy on MaaS Subscription=
	0
	~	1
	~		|
```

```
Policy Costs= INTEG (
	Policy Costs per Month,
		Subsidies to new MaaS Companies)
	~	Euros
	~		|

Transportation Subsidy to Users=
	0
	~	Euros/Trip
	~		|

Total PT and MaaS Revenue=
	PTO Revenue+Financial resources
	~	Euros
	~		|

"Average Non-MaaS PT Price per Trip"=
	Base PT Price no MaaS+PT Price per Kilometer no MaaS*Average Trip Length
	~	Euros/Trip
	~		|

PTO Revenue Growth=
	Peak Periods per Month*(Number of PT Trips in Peak Hours-PT Percentage Price Discount for MaaS providers\
		*Number of MaaS PT Trips in Peak Hours)*"Average Non-MaaS PT Price per Trip"
	~	Euros/Month
	~		|

PTO Revenue= INTEG (
	PTO Revenue Growth,
		0)
	~	Euros
	~		|

Average MaaS Taxi Price per Trip=
	(Base MaaS Taxi Price per Trip+Average Trip Length*MaaS Taxi Price per Km+Average Travel Time Perceived by Us
	*MaaS Taxi Price per Minute)*(1-Taxi Trip Percentage Included in the MaaS package)
	~	Euros/Trip
	~		|

Average MaaS Shared Taxi Costs per Trip=
	Average MaaS Taxi Price per Trip*Shared Taxi Delay Effect/(Average User Occupation of Shared Taxis
	*"Vehicles per Non-Shared Trip"
	)*(1-Taxi Trip Percentage Included in the MaaS package)
	~	Euros/Trip
	~		|

Shared Taxi Value for MaaS Users=
	MaaS Shared Taxxi Value for MaaS Users+Intrinsic Preference of MaaS Users to Shared Taxi
	~	Euros/Trip
	~		|

Taxi Value for MaaS Users=
	MaaS Taxi Value for MaaS users+Intrinsic Preference of MaaS Users to Taxi
	~	Euros/Trip
	~		|

Average Shared Taxi Costs per Peak for MaaS Providers=
```

Number of MaaS Shared Taxi Trips in Peak Hours*Average MaaS Shared Taxi Costs per Trip
*Taxi Trip Percentage Included in the MaaS package
~ Euros/peak
~ |

"Average non-Shared Taxi Costs per Peakfor MaaS Providers"=
Average MaaS Taxi Price per Trip*Number of MaaS Taxi Trips in Peak Hours*Taxi Trip Percentage Included in the Ma
~ Euros/peak
~ |

Desired Price of MaaS Subscription per User per Month=
IF THEN ELSE(Time <=MaaS Start Time,Initial Price of MaaS Subscription,Monthly Operational Costs of MaaS Provid
*(1+Profit Margin of MaaS Providers))
~ Euros/(persons*Month)
~ |

Initial Price of MaaS Subscription=
100
~ Euros/(persons*Month)
~ |

Average Desired MaaSTaxi Price Proportion=
IF THEN ELSE(Time <= MaaS Start Time,"Average Non-MaaS Taxi Price Proportion",(1+(MaaS Taxi User Congestion
-1)*"Effect of Taxi User Congestion in Price per Trip of Non-MaaS Taxi"
)*Average MaaS Taxi Price Proportion)
~ 1
~ |

Contribution of Gap of MaaS Taxis on MaaS Value=
MaaS Taxi User Congestion in Peak Hours*Cofficient of Contribution of Gap of Taxis
~ Euros/Trip
~ |

Average MaaS Taxi Price Proportion=
DELAY1I(Average Desired MaaSTaxi Price Proportion
,MaaS Providers Financial Reaction Time,"Average Non-MaaS Taxi Price Proportion"
)
~ 1
~ |

"MaaS Value to Non-MaaS Taxi Drivers"=
Average MaaS Taxi Price per Trip+Contribution of Gap of MaaS Taxis on MaaS Value
~ Euros/Trip
~ |

MaaS Shared Car Value for Users=
Intrinsic Preference of MaaS Users to Shared Car+"Shared-Car Value for maaS users without Intrinsic Preferences"
~ Euros/Trip
~ |

MaaS Private Car Value for Users=
Intrinsic Preference of MaaS Users to Use Private Car+Private Car Value for Users without Intrinsic Preferences
~ Euros/Trip
~ |

"Contribution of Gap of Non-MaaS Taxis to Non-MaaS Value"=
Cofficient of Contribution of Gap of Taxis*"Non-MaaS Taxi User Congestion in Peak Hours"
~ Euros/Trip

~ |

Contribution of Car Ownership to Private car Value for Users=
0.151306
~ (Euros/Trip)/(vehicles/persons)
~ fit MS relation Roy van Kuijk
|

Intrinsic Preference of Owning a Private Car for Car Owners=
150
~ Euros/Month
~ |

"Average Perceived non-MaaS Taxi Access/Egress Time per Trip"=
DELAY1I("Average Non-MaaS Taxi Access/Egress Time per Trip",Users Reaction Time,"Initial Average Access/Egres
)
~ Minutes/Trip
~ |

Growth of MaaS Taxis=
(Expected MaaS Taxis-MaaS Taxis)/Public Transport Operators and Public Transport Authorities Reaction Time
~ vehicles/Month
~ |

"Intrinsic Preference of Non-MaaS Users to Taxi"=
-5.51019
~ Euros/Trip
~ fit MS
|

Average Taxi Costs for MaaS providers=
("Average non-Shared Taxi Costs per Peakfor MaaS Providers"+Average Shared Taxi Costs per Peak for MaaS Provi
)*Peak Periods per Month
~ Euros/Month
~ |

Average MaaS Bike Costs per Trip besides Subscription=
(1-Bike Trip Percentage Included in the MaaS Package)*"Average Non-MaaS Bike Costs per Trip"
~ Euros/Trip
~ |

Average MaaS Shared Taxi Travel Time per Trip=
Average Perceived MaaS Taxi Total Travel TIme per Trip*Shared Taxi Delay Effect
~ Minutes/Trip
~ |

"Intrinsic Preference of Non-MaaS Users to Shared Taxi"=
-0.0420258
~ Euros/Trip
~ van Kuijk ms fit
|

Number of MaaS Shared Taxi Trips in Peak Hours=
IF THEN ELSE(Sensitivity Mode Choice*(Shared Taxi Value for MaaS Users-Generalized Utility MaaS Modes to Users
)<-15,0,
MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(Shared Taxi Value for MaaS Users\
-Generalized Utility MaaS Modes to Users
)))

```
	~	Trip/peak
	~		|

"Average Non-MaaS Shared Taxi Costs per Trip"=
	"Average Non-MaaS Taxi Price per Trip"*(Shared Taxi Delay Effect)/(Average User Occupation of Shared Taxis\
		*"Vehicles per Non-Shared Trip"
	)
	~	Euros/Trip
	~		|

"Average Non-MaaS Shared Taxi Travel Time per Trip"=
	Shared Taxi Delay Effect*"Average Perceived Non-MaaS Taxi Total Travel Time per Trip"
	~	Minutes/Trip
	~		|

"Average Non-MaaS Taxi Price per Trip"=
	"Base Non-MaaS Taxi Price per Trip"+Average Trip Length*"Non-MaaS Taxi Price per Km"\
		+Average Travel Time Perceived by Users on the Road
	*"Non-MaaS Taxi Price per Minute"
	~	Euros/Trip
	~		|

Average Perceived MaaS Taxi Total Travel TIme per Trip=
	"Average Perceived MaaS Taxi Agress/Egress Time per Trip"+Average Travel Time Perceived by Users on the Road
	~	Minutes/Trip
	~		|

"Average Perceived Non-MaaS Taxi Total Travel Time per Trip"=
	"Average Perceived non-MaaS Taxi Access/Egress Time per Trip"+Average Travel Time Perceived by Users on the R
	~	Minutes/Trip
	~		|

Number of MaaS Taxi Trips in Peak Hours=
	IF THEN ELSE(Sensitivity Mode Choice*(Taxi Value for MaaS Users-Generalized Utility MaaS Modes to Users
	)<-15,0,
	MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(Taxi Value for MaaS Users-Generalized Utility MaaS Modes
	)))
	~	Trip/peak
	~		|

Total Number of Cars Used per Peak Time=
	Auto Split*Total Travel Demand*Trips per User per Peak Period*"Vehicles per Non-Shared Trip"
	~	vehicles/peak
	~		|

Taxi Trip Percentage Included in the MaaS package=
	0.1
	~	1
	~		|

"Shared-Car price per Trip for MaaS Users besides Subscription"=
	"Shared-Car Price per Trip for Users"*(1-Shared Car Trip percentage Included in the MaaS package
	)
	~	Euros/Trip
	~		|

Shared Car Trip percentage Included in the MaaS package=
	0.1
```

```
	~	1
	~		|

Price of MaaS Subscription per User per Month=
	DELAY1(Desired Price of MaaS Subscription per User per Month,MaaS Providers Financial Reaction Time\
		)
	~	Euros/(persons*Month)
	~		|

Average Bike Costs for MaaS Providers=
	Number of MaaS Bike Trips in Peak Hours*("Average Non-MaaS Bike Costs per Trip"-Average MaaS Bike Costs per T
	)*Peak Periods per Month
	~	Euros/Month
	~		|

Monthly Operational Costs of MaaS Providers=
	Operational Costs for MaaS Providers+Average PT Costs for MaaS providers+Average Taxi Costs for MaaS providers
		+Average Bike Costs for MaaS Providers+"Average Shared-Car Costs for MaaS Providers"
	~	Euros/Month
	~		|

MaaS Providers Financial Reaction Time=
	6
	~	Month
	~		|

"Average Shared-Car Costs for MaaS Providers"=
	Number of MaaS Shared Car Trips in Peak Hours*("Shared-Car Price per Trip for Users"\
		-"Shared-Car price per Trip for MaaS Users besides Subscription"
	)*Peak Periods per Month
	~	Euros/Month
	~		|

Number of MaaS Bike Trips in Peak Hours=
	IF THEN ELSE(Sensitivity Mode Choice*(MaaS Bike Value for Users-Generalized Utility MaaS Modes to Users
	)<-15,0,

	MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(MaaS Bike Value for Users-Generalized Utility MaaS Modes
	)))
	~	Trip/peak
	~		|

"Fraction ASC-CarOwn"=
	0.5
	~	1
	~		|

"Intrinsic Preference of Non-MaaS Users to Use Private Car"=
	0.412041
	~	Euros/Trip
	~	Fit MS
	|

"Intrinsic Preferences of Non-MaaS Users to PT"=
	-0.262446
	~	Euros/Trip
	~	fit MS
	|
```

```
"Intrinsic preference of Non-MaaS Users to Shared Car"=
	-5.53747
	~	Euros/Trip
	~	fit MS
	|

"Base Non-MaaS Taxi Price per Trip"=
	(1+("Average Non-MaaS Taxi Price Proportion"-1)*Taxi Basic Price Growth Proportion)*\
		"Initial Non-MaaS Base Taxi Price per Trip"
	~	Euros/Trip
	~		|

"Intrinsic Preference of Non-MaaS Users to Bike"=
	0.796892
	~	Euros/Trip
	~	fit MS
	|

Taxi Price per Minute Growth Proportion=
	1.1
	~	1
	~		|

"Non-MaaS Taxi Price per Minute"=
	(1+("Average Non-MaaS Taxi Price Proportion"-1)*Taxi Price per Minute Growth Proportion\
		)*"Initial Non-MaaS Taxi Price per Minute"
	~	Euros/Minutes
	~		|

Taxi Basic Price Growth Proportion=
	1.1
	~	1
	~		|

"Initial Non-MaaS Taxi Price per Minute"= WITH LOOKUP (
	INITIAL TIME/Unit of Time*0,
		([(0,0)-(10,10)],(0,0.31),(12,0.31),(24,0.33),(36,0.34),(48,0.35),(60,0.36),(72,0.36\
		),(84,0.36),(96,0.37) ))
	~	Euros/Minutes
	~		|

Base Price Growth Proportion=
	0.3
	~	1
	~		|

MaaS Taxi Price per Km=
	Average MaaS Taxi Price Proportion*"Initial Non-MaaS Taxi Price per Km"
	~	Euros/km
	~		|

MaaS Taxi Price per Minute=
	Average MaaS Taxi Price Proportion*"Initial Non-MaaS Taxi Price per Minute"
	~	Euros/Minutes
	~		|

PT Price per Kilometer no MaaS=
```

```
	Initial PT Price per Kilometer no MaaS*"Average Non-MaaS PT Price proportion"
	~	Euros/km
	~		|

"Average Non-MaaS Bike Costs per Trip"=
	Average Trip Length*"Average Non-MaaS Bike Costs per Km"
	~	Euros/Trip
	~		|

Base MaaS Taxi Price per Trip=
	Average MaaS Taxi Price Proportion*"Initial Non-MaaS Base Taxi Price per Trip"
	~	Euros/Trip
	~		|

Base PT Price no MaaS=
	Initial Base PT price no MaaS*(1+("Average Non-MaaS PT Price proportion"-1)*Base Price Growth Proportion\
		)
	~	Euros/Trip
	~		|

"Initial Non-MaaS Taxi Price per Km"= WITH LOOKUP (
	INITIAL TIME/Unit of Time*0,
		([(0,0)-(10,10)],(0,1.91),(12,1.92),(24,2.02),(36,2.08),(48,2.12),(60,2.17),(72,2.18\
		),(84,2.19),(96,2.22) ))
	~	Euros/km
	~		|

"No-MaaS Value to MaaS Taxi Drivers"=
	"Contribution of Gap of Non-MaaS Taxis to Non-MaaS Value"+"Average Non-MaaS Taxi Price per Trip"
	~	Euros/Trip
	~		|

Fuel Costs= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(10,10)],(0,0.455753),(12,0.505906),(24,0.552019),(36,0.592074),(48,0.584333\
		),(60,0.570532),(72,0.524418),(84,0.497154),(96,0.522399),(251,0.522399) ))
	~	Euros/km
	~		|

Trips in a Peak=
	1
	~	Trip
	~		|

"Non-MaaS Taxi Price per Km"=
	"Average Non-MaaS Taxi Price Proportion"*"Initial Non-MaaS Taxi Price per Km"
	~	Euros/km
	~		|

Initial PT Price per Kilometer no MaaS= WITH LOOKUP (
	INITIAL TIME/Unit of Time*0,
		([(0,0)-(10,10)],(0,0.103),(12,0.105),(24,0.142),(36,0.145),(48,0.148),(60,0.151),(\
		72,0.154),(84,0.154),(96,0.155) ))
	~	Euros/km
	~		|

Parking Costs= WITH LOOKUP (
	Time/Unit of Time,
```

```
        ([(0,0)-(10,10)],(0,1.30945),(12,1.35278),(24,1.37344),(36,1.43012),(48,1.4434),(60\
        ,1.63426),(72,1.64681),(84,1.64681),(96,1.64681),(251,1.64681) ))
	~	Euros/Trip
	~		|

"Cost Shared-Car per Minute"=
	0.31
	~	Euros/Minutes
	~		|

Expected Unused Private Cars Kept=
	Cars unused during one Peak Time*Private Car Keep Fraction
	~	vehicles
	~		|

Expected Private Cars Kept=
	Cars Used during one Peak Time+Expected Unused Private Cars Kept
	~	vehicles
	~		|

Expected Private Cars Adopted=
	(Total Travel Demand*Cars Bought at a Time per Person-Private Car Fleet)*Private Car Adoption Fraction
	~	vehicles
	~		|

Average User Occupation of Shared Taxis=
	3
	~	Trip/vehicles
	~		|

"Non-MaaS Taxis in Peak Hours"=
	Availability Ratio of Taxis during Peak Hours*Potential MaaS Taxis+0.01
	~	vehicles/peak
	~		|

Expected Private Car Fleet=
	Expected Private Cars Adopted+Expected Private Cars Kept
	~	vehicles
	~		|

Intrensic Preference of Owning a Private Car for Non Owners=
	-30
	~	Euros/Month
	~		|

Potential Users Contacted=
	MIN(Potential MaaS Users,(Potential Users Contacted by Advertisement+Potential Users Contacted by WoM\
		)*(Potential MaaS Users)/(Total Travel Demand))
	~	persons
	~		|

Growth of Private Car Fleet=
	(Expected Private Car Fleet-Private Car Fleet)/Users Reaction Time
	~	vehicles/Month
	~		|

Private Car Fleet= INTEG (
	Growth of Private Car Fleet,
```

Initial Private Car Fleet)
~ vehicles
~ |

Monthly Costs of Car Ownership= WITH LOOKUP (
Time/Unit of Time,
([(0,0)-(241,60)],(0,52.5291),(12,50.7316),(24,46.3324),(36,43.3005),(48,46.2585),(\
60,49.099),(72,49.4842),(84,51.9944),(96,56.5133),(108,56.5133),(120,56.5133),(132,\
56.5133),(144,56.5133),(156,56.5133),(168,56.5133),(180,56.5133),(192,56.5133),(204\
,56.5133),(216,56.5133),(228,56.5133),(240,56.5133),(252,56.5133) ))
~ Euros/Month
~ CBS
|

Cars unused during one Peak Time=
MAX(0,Private Car Fleet-Cars Used during one Peak Time
)
~ vehicles
~ |

Cars Used during one Peak Time=
Total Number of Cars Used per Peak Time*Peak Time Duration
~ vehicles
~ |

Sensitivity Car Ownership Choice=
0.1
~ 1/(Euros/Month)
~ |

Cars Bought at a Time per Person=
1
~ vehicles/persons
~ |

Expected Adopter Taxis of MaaS=
MaaS Adoption Fraction from Taxis*Potential MaaS Taxis Contacted
~ vehicles
~ |

Total Taxi Capacity= INTEG (
Total Taxi Capacity Growth,
Initial Total Taxi Capacity)
~ vehicles
~ |

Positive Growth of Users=
MAX(0, Growth of MaaS Users)
~ persons/Month
~ |

Potential MaaS Taxis=
Total Taxi Capacity-MaaS Taxis
~ vehicles
~ |

MaaS Taxis= INTEG (
Growth of MaaS Taxis,

```
		0)
	~	vehicles
	~		|

Potential MaaS Taxis Contacted by Advertisement=
	Potential MaaS Taxis*MaaS Advertisment Effectiveness on Taxi Drivers
	~	vehicles
	~		|

MaaS Users= INTEG (
	Growth of MaaS Users,
		0)
	~	persons
	~		|

Expected Keeper Taxis of MaaS=
	MaaS Taxis*MaaS Keep Fraction from Taxis
	~	vehicles
	~		|

"PT Perceived Average Access/Egress Time per Trip in Peak Hours"=
	SMOOTHI("PT Average Access/Egress Time per Trip in Peak Hours",Users Reaction Time,"Initial Average PT Access
)
	~	Minutes/Trip
	~		|

Cummulative MaaS Users= INTEG (
	Positive Growth of Users,
		0)
	~	persons
	~		|

Expected MaaS Taxis=
	Expected Adopter Taxis of MaaS+Expected Keeper Taxis of MaaS
	~	vehicles
	~		|

Average Travel Time Perceived by Users on the Road=
	SMOOTHI(Average Travel Time on the Road with Traffic Congestion, Users Reaction Time\
		, Initial Average Travel Time on the Road
 )
	~	Minutes/Trip
	~		|

Potential MaaS Users=
	Total Travel Demand-MaaS Users
	~	persons
	~		|

Growth of MaaS Users=
	(Expected MaaS Users-MaaS Users)/Users Reaction Time
	~	persons/Month
	~		|

Average Perceived PT Travel Time per Trip=
	SMOOTHI(Average PT Travel Time Per Trip in Peak Hours,Users Reaction Time,InitialAverage PT Travel Time per T
		)
	~	Minutes/Trip
```

```
	~		|

Potential MaaS Taxis Contacted=
	MIN(Potential MaaS Taxis,(Potential MaaS Taxis Contacted by Advertisement+Potential MaaS Taxis Contacted by Wo
		)*(Potential MaaS Taxis)/(MaaS Taxis+Potential MaaS Taxis))
	~	vehicles
	~		|

Data Accumulated per MaaS User=
	Data Resources Accumulated/MAX(1,Cummulative MaaS Users)
	~	Mbytes/persons
	~		|

Expected MaaS Users=
	Expected Adopter Users of MaaS Service+Expected Keepers of MaaS Service
	~	persons
	~		|

MaaS Advertisement Effectiveness on Users=
	Magnitude Advertisement Effectiveness*PULSE(MaaS Start Time, Advertisement Effective Time\
		)
	~	persons/(persons)
	~		|

"Intrinsic Perceived Utility of Using MaaS for Non-Users"=
	-2
	~	Euros/Trip
	~		|

Potential Users Contacted by Advertisement=
	MaaS Advertisement Effectiveness on Users*Potential MaaS Users
	~	persons
	~		|

Potential Users Contacted by WoM=
	MaaS Users*Word of Mouth Contact Rate
	~	persons
	~		|

Number of Shared Taxi Trips in Peak Hours=
	Number of MaaS Shared Taxi Trips in Peak Hours+"Number of Non-MaaS Shared Taxi Trips in Peak Hours"
	~	Trip/peak
	~		|

Expected Adopter Users of MaaS Service=
	MaaS Users Adoption Fraction*Potential Users Contacted
	~	persons
	~		|

Expected Keepers of MaaS Service=
	MaaS Users*MaaS Users Keep Fraction
	~	persons
	~		|

Total Travel Demand Growth= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(264,1000)],(0,1156),(12,1105.13),(24,993.333),(36,1055.75),(48,995.5),(60,\
		1083.38),(72,1337.75),(84,1254.54),(96,2109.42),(108,2008.58),(120,918.75),(132,823.75\
```

```
		),(144,795),(156,814.583),(168,851.25),(180,854.167),(192,808.333),(204,793.75),(216\
		,802.083),(228,794.583),(241,778.333) ))
	~	persons/Month
	~	CBS PBL
	|

Total Travel Demand= INTEG (
	Total Travel Demand Growth,
		Initial Travel Demand)
	~	persons
	~		|

Number of Shared Car Trips in Peak Hours=
	Number of MaaS Shared Car Trips in Peak Hours+"Number of Non-MaaS Shared Car Trips in Peak Hours"
	~	Trip/peak
	~		|

Magnitude Advertisement Effectiveness=
	0.001
	~	1
	~		|

Number of MaaS Shared Car Trips in Peak Hours=
	IF THEN ELSE(Sensitivity Mode Choice*(MaaS Shared Car Value for Users-Generalized Utility MaaS Modes to Users
	)<-15,0,MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(MaaS Shared Car Value for Users\
		-Generalized Utility MaaS Modes to Users
	)))
	~	Trip/peak
	~		|

Shared Car Split=
	Number of Shared Car Trips in Peak Hours/Total Number of Trips in Peak Hours
	~	1
	~		|

Advertisement Effective Time=
	12
	~	Month
	~		|

Auto Split=
	Private Car Split+Taxi Split+Shared Taxi Split+Shared Car Split
	~	1
	~		|

Traffic load=
	Total Number of Cars Used per Peak Time
	+Other Vehicles on the Road During Peak Hours*Equivalent Vehicles per Other Vehicle Type\
		+Equivalent Vehicles of Buses
	~	vehicles/peak
	~		|

Equivalent Vehicles per Other Vehicle Type=
	1.13
	~	1
	~	Calculated \
		https://www.evofenedex.nl/kennis/vervoer/maten-en-gewichten-vrachtwagens/af\
		metingen-vrachtautos-en-combinaties-eu
```

|

PT User Capacity with Modes off the Road= WITH LOOKUP (
Time/Unit of Time,
([(0,0)-(10,10)],(0,53906.7),(12,53906.7),(24,53309.3),(36,53309.3),(48,53299),(60,\
52701.7),(72,47480),(84,47480),(96,47480),(108,47480),(120,47480),(132,47480),(144,\
47480),(156,47480),(168,47480),(180,47480),(192,47480),(204,47480),(216,47480),(228\
,47480),(240,47480),(252,47480) ))
~ (Trip/peak)
~ GVB Calculated
|

MaaS Start Time=
300
~ Month
~ |

Average Travel Time Buses=
Average Travel Time Perceived by Users on the Road*Stops Correction
~ Minutes/Trip
~ |

Stops Correction=
2
~ 1
~ fit vanBron: afd. Verkeer en Openbare Ruimte
Publicatie: Amsterdam in cijfers 2017
Download: 2017_jaarboek_416.xlsxTom Tom
|

Shared Taxi Split=
Number of Shared Taxi Trips in Peak Hours/Total Number of Trips in Peak Hours
~ 1
~ |

Taxi Split=
Number of Taxi Trips in Peak Hours/Total Number of Trips in Peak Hours
~ 1
~ |

Bike Split=
Number of Bike Trips in Peak Hours/Total Number of Trips in Peak Hours
~ 1
~ |

Private Car Split=
Number of Private Car Trips in Peak Hours/Total Number of Trips in Peak Hours
~ 1
~ |

Number of Walking Trips in Peak Hours=
Number of MaaS Walking Trips in Peak Hours+"Number of Non-MaaS Walking Trips in Peak Hours"
~ Trip/peak
~ |

Intrinsic Preference of MaaS Users to Shared Car=
-5.53747
~ Euros/Trip

~ van Kuijk Proportion
|

"Non-MaaS Trips in Peak Hours"=
Potential MaaS Users*Trips per User per Peak Period
~ Trip/peak
~ |

Number of Taxi Trips in Peak Hours=
Number of MaaS Taxi Trips in Peak Hours+"Number of Non-MaaS Taxi Trips in Peak Hours"
~ Trip/peak
~ |

PT Split=
Number of PT Trips in Peak Hours/Total Number of Trips in Peak Hours
~ 1
~ |

Number of Bike Trips in Peak Hours=
Number of MaaS Bike Trips in Peak Hours+"Number of Non-MaaS Bike Trips in Peak Hours"
~ Trip/peak
~ |

Number of Private Car Trips in Peak Hours=
Number of MaaS Private Vehicle Trips in Peak Hours+"Number of Non-MaaS Private Car Trips in Peak Hours"
~ Trip/peak
~ |

Number of PT Trips in Peak Hours=
Number of MaaS PT Trips in Peak Hours+"Number of Non-MaaS PT Trips in Peak Hours"
~ Trip/peak
~ |

MaaS Market Share=
MaaS Users/(MaaS Users+Potential MaaS Users)
~ persons/persons
~ |

"Shared-Car Access/Egress Time"=
30
~ Minutes/Trip
~ van Kuijk
|

Walking Split=
Number of Walking Trips in Peak Hours/Total Number of Trips in Peak Hours
~ 1
~ |

Total Number of Trips in Peak Hours=
"Non-MaaS Trips in Peak Hours"+MaaS Trips in Peak Hours
~ Trip/peak
~ |

Unit of Time=
1
~ Month
~ |

Bus User Capacity=
118
~ (Trip/vehicles)
~ Calculated GVB
|

Equivalent Vehicles of Buses=
Equivalent Vehicles per Bus*Number of PT Buses on the Road during Peak Hours
~ vehicles/peak
~ |

Equivalent Vehicles per Bus=
3
~ vehicles/vehicles
~ GVB Calculated
|

Number of PT Buses on the Road during Peak Hours= WITH LOOKUP (
Time/Unit of Time,
([(0,0)-(10,10)],(0,267),(12,258),(24,211),(36,199),(48,198),(60,198),(72,194),(84,\
203),(96,218),(108,218),(120,218),(132,218),(144,218),(156,218),(168,218),(180,218)\
,(192,218),(204,218),(216,218),(228,218),(240,218),(252,218) ))
~ vehicles/peak
~ GVB
|

Productivity of Platform Development=
Initial Productivity of Platform Development*exp(-Rate of Decrease in Quality Productivity\
*MaaS Platform Quality)
~ Quality Unit/Euros
~ |

Initial Speed of Data Accumulation=
0.1
~ Mbytes/(persons*Month)
~ |

Rate of Decrease in Quality Productivity=
1/1.7e+09
~ 1/Quality Unit
~ |

Speed of Data Accumulation from MaaS Users=
Initial Speed of Data Accumulation*exp(-Rate of decrease of speed of data accuulation because of productivity reducti
*Data Accumulated per MaaS User)
~ Mbytes/(persons*Month)
~ |

Initial Productivity of Platform Development=
1
~ Quality Unit/Euros
~ |

Rate of decrease of speed of data accuulation because of productivity reduction=
1/50
~ persons/Mbytes
~ |

```
Cofficient of Contribution of Gap of Taxis=
	10
	~	Euros/Trip
	~		|

MaaS Keep Fraction from Taxis=
	IF THEN ELSE( Sensitivity Taxi Drivers MaaS Choice
	*(-MaaS Value to MaaS Taxi Drivers+"No-MaaS Value to MaaS Taxi Drivers")<-15 ,1,IF THEN ELSE\
		( Sensitivity Taxi Drivers MaaS Choice
	*(-MaaS Value to MaaS Taxi Drivers+"No-MaaS Value to MaaS Taxi Drivers")>15 , 0 , 1/\
		(exp(Sensitivity Taxi Drivers MaaS Choice
	*(-MaaS Value to MaaS Taxi Drivers+"No-MaaS Value to MaaS Taxi Drivers"))+1)))
	~	vehicles/vehicles
	~		|

Intrinsic Perceived Utility of Using MaaS for Users=
	0
	~	Euros/Trip
	~		|

Availability Ratio of Taxis during Peak Hours=
	1
	~	1/peak
	~		|

MaaS Taxis in Peak Hours=
	Availability Ratio of Taxis during Peak Hours* MaaS Taxis+1
	~	vehicles/peak
	~		|

Operational Costs for MaaS Providers=
	MaaS Users*Operational Costs for MaaS Providers per User
	~	Euros/Month
	~		|

Operational Costs for MaaS Providers per User=
	5
	~	Euros/(Month*persons)
	~		|

"Average Desired Non-MaaS Taxi Price Proportion"=
	"Average Non-MaaS Taxi Price Proportion"*(1+"Effect of Taxi User Congestion in Price per Trip of Non-MaaS Taxi"
	*("Non-MaaS Taxi User Congestion in Peak Hours"-1))
	~	1
	~		|

Total Taxi Capacity Growth=
	22.396
	~	vehicles/Month
	~	file:///C:/Users/JuanDavid/Downloads/taximonitor_2016_en_eerste_helft_2017.pdf

		Linear Regression
	|

Initial Travel Demand= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(10,10)],(-12,1.05238e+06),(0,1.06617e+06),(12,1.08013e+06),(24,1.0927e+06)\
```

```
        ,(36,1.10397e+06),(48,1.11803e+06),(60,1.12786e+06),(72,1.14404e+06),(84,1.15996e+06\
        ),(96,1.17414e+06),(108,1.21059e+06),(120,1.22235e+06),(132,1.23264e+06),(144,1.24212e+06\
        ),(156,1.25172e+06),(168,1.26167e+06),(180,1.27215e+06),(192,1.28217e+06),(204,1.29155e+06\
        ),(216,1.30122e+06),(228,1.3108e+06),(240,1.32029e+06),(252,1.32948e+06) ))
    ~   persons
    ~   CBS PBL
    |

Monthly Operational Costs of MaaS Providers per MaaS User=
    Monthly Operational Costs of MaaS Providers/(MaaS Users+1e-10)
    ~   Euros/(Month*persons)
    ~       |

Accumulation of Financial Resources by MaaS Providers=
    MaaS Users*(Price of MaaS Subscription per User per Month)
    ~   Euros/Month
    ~       |

Number of MaaS Private Vehicle Trips in Peak Hours=
    IF THEN ELSE(Sensitivity Mode Choice*(MaaS Private Car Value for Users-Generalized Utility MaaS Modes to Users
    )<-15,0,
    MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(MaaS Private Car Value for Users\
        -Generalized Utility MaaS Modes to Users
    )))
    ~   Trip/peak
    ~       |

Number of MaaS PT Trips in Peak Hours=
    IF THEN ELSE(Sensitivity Mode Choice*(MaaS PT Value for Users-Generalized Utility MaaS Modes to Users
    )<-15,0,
    MaaS Trips in Peak Hours*exp(Sensitivity Mode Choice*(MaaS PT Value for Users-Generalized Utility MaaS Modes to
    )))
    ~   Trip/peak
    ~       |

Intrinsic Preference of Using MaaS for MaaS Taxi Drivers=
    5
    ~   Euros/Trip
    ~       |

"Intrinsic Preference of Not Owning MaaS for Non-MaaS Taxi Drivers"=
    5
    ~   Euros/Trip
    ~       |

Trips per User per Peak Period=
    1
    ~   Trip/(persons*peak)
    ~       |

Other Vehicles on the Road During Peak Hours= WITH LOOKUP (
    Time/Unit of Time,
        ([(0,0)-(10,10)],(0,35058),(12,34966),(24,34766),(36,33957),(48,33493),(60,33906),(\
        72,33856),(84,34379),(96,34551),(108,34551),(120,34551),(132,34551),(144,34551),(156\
        ,34551),(168,34551),(180,34551),(192,34551),(204,34551),(216,34551),(228,34551),(240\
        ,34551),(252,34551) ))
    ~   vehicles/peak
    ~   CBS RDW
```

|

Shared Taxi Delay Effect=
1+"Vehicles per Non-Shared Trip"*Percentage Delay per passenger shared taxi*Average User Occupation of Shared T
~ 1
~ |

Peak Time Duration=
1
~ peak
~ |

Development of Platform Quality=
Reinvestment in Business from MaaS Providers*Productivity of Platform Development
~ Quality Unit/Month
~ |

Profit Margin of MaaS Providers=
0.1
~ Euros/Euros
~ |

MaaS Trips in Peak Hours=
Trips per User per Peak Period*MaaS Users
~ Trip/peak
~ |

Average PT Costs for MaaS providers=
Number of MaaS PT Trips in Peak Hours*Average PT Price per Trip for MaaS providers*Peak Periods per Month
~ Euros/Month
~ |

"Vehicles per Non-Shared Trip"=
1
~ vehicles/Trip
~ |

Sensitivity Taxi Drivers MaaS Choice=
0.1
~ 1/(Euros/Trip)
~ |

MaaS Market Share Gap=
Expected MaaS Market Share-MaaS Market Share
~ persons/persons
~ |

MaaS Users Adoption Fraction=
IF THEN ELSE( Sensitivity MaaS Choice by Users*("Non-MaaS Value for Users"-"MaaS Value for Non-MaaS Users"\
) < -15,1,IF THEN ELSE( Sensitivity MaaS Choice by Users*("Non-MaaS Value for Users"\
-"MaaS Value for Non-MaaS Users") > 15, 0 , 1/(1+exp(Sensitivity MaaS Choice by Users\
*("Non-MaaS Value for Users"-"MaaS Value for Non-MaaS Users")))))
~ persons/persons
~ |

Instrinsic Preference of MaaS Users to PT=
-0.262446
~ Euros/Trip

~ van Kuijk proportion
|

Intrinsic Preference of MaaS Users to Use Private Car=
0.412041
~ Euros/Trip
~ van Kuijk proportion
|

Intrinsic Preference of MaaS Users to Shared Taxi=
-0.0420258
~ Euros/Trip
~ van Kuijk Proportion
|

Intrinsic Preference of MaaS Users to Taxi=
-2.75284
~ Euros/Trip
~ van Kuijk Proportion
|

"Effect of Taxi User Congestion in Price per Trip of Non-MaaS Taxi"=
0.004
~ 1
~ |

"Effect of PT Users Congestion in Price per Trip of Non-MaaS PT"=
0.01
~ 1
~ |

Expected MaaS Market Share=
0.9
~ persons/persons
~ |

"Initial Non-MaaS Base Taxi Price per Trip"= WITH LOOKUP (
INITIAL TIME/Unit of Time*0,
([(0,0)-(10,10)],(0,2.58),(12,2.59),(24,2.74),(36,2.83),(48,2.89),(60,2.95),(72,2.97\
),(84,2.98),(96,3.02) ))
~ Euros/Trip
~ van Kuijk
|

Percentage Delay per passenger shared taxi=
0.05
~ 1
~ |

Initial Financial Resources of MaaS Providers=
1e+09
~ Euros
~ |

Public Transport Operators and Public Transport Authorities Reaction Time=
6
~ Month
~ |

```
PT Percentage Price Discount for MaaS providers=
	0
	~	1
	~		|

PT Trips in Peak Hours=
	Number of MaaS PT Trips in Peak Hours+"Number of Non-MaaS PT Trips in Peak Hours"
	~	Trip/peak
	~		|

Peak Periods per Month=
	50
	~	peak/Month
	~		|

Desired PT Price Proportion=
	(1+(Users Congestion in PT in Peak Hours-1)*"Effect of PT Users Congestion in Price per Trip of Non-MaaS PT"\
		)*"Average Non-MaaS PT Price proportion"
	~	1
	~		|

Initial Base PT price no MaaS= WITH LOOKUP (
	INITIAL TIME/Unit of Time*0,
		([(0,0)-(241,10)],(0,0.78),(12,0.79),(24,0.83),(36,0.86),(48,0.87),(60,0.88),(72,0.89\
		),(84,0.89),(96,0.9) ))
	~	Euros/Trip
	~	GVB

		Prijsindex CBS
	|

Sensitivity Mode Choice=
	1
	~	1/(Euros/Trip)
	~		|

Sensitivity MaaS Choice by Users=
	0.3
	~	1/(Euros/Trip)
	~		|

Users Congestion in PT in Peak Hours=
	PT Trips in Peak Hours/PT Capacity
	~	Trip/Trip
	~		|

Users Reaction Time=
	1
	~	Month
	~		|

Intrinsic Preference of MaaS Users to Bike=
	0.796892
	~	Euros/Trip
	~	van Kuijk Proportion
	|
```

```
Average Road Free Speed= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(241,10)],(0,1.04949),(12,0.951997),(24,0.924908),(36,0.897818),(48,0.921552\
		),(60,0.945285),(72,1.08188),(241,1.08188) ))
	~	km/Minutes
	~	Tom Tom and Congestion Level
	|

Average Free Travel Time=
	Average Trip Length/(Average Road Free Speed)
	~	Minutes/Trip
	~		|

"Free Average Taxi Acces/Egres Time per Trip"=
	8
	~	Minutes/Trip
	~	Tom Tom and van Kuijk
	|

Average PT Speed with Modes off the Road= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(10,10)],(0,0.395136),(12,0.392048),(24,0.381942),(36,0.375784),(48,0.392431\
		),(60,0.401153),(72,0.468908),(84,0.468908),(96,0.468908),(108,0.468908),(120,0.468908\
		),(132,0.468908),(144,0.468908),(156,0.468908),(168,0.468908),(180,0.468908),(192,0.468908\
		),(204,0.468908),(216,0.468908),(228,0.468908),(240,0.468908),(252,0.468908) ))
	~	km/Minutes
	~	Calculated Travel Time Correction Factor Travel time off road
	|

Average Trip Length= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(241,10)],(0,6.40468),(12,5.95318),(24,5.9491),(36,5.94502),(48,9.32782),(60\
		,12.7106),(72,9.31452),(84,9.31452),(96,9.31452),(108,9.31452),(120,9.31452),(132,9.31452\
		),(144,9.31452),(156,9.31452),(168,9.31452),(180,9.31452),(192,9.31452),(204,9.31452\
		),(216,9.31452),(228,9.31452),(240,9.31452),(252,9.31452) ))
	~	km/Trip
	~	Bron: afd. Verkeer en Openbare Ruimte
		Publicatie: Amsterdam in cijfers 2017
		Download: 2017_jaarboek_416.xlsx
	|

Initial Total Taxi Capacity= WITH LOOKUP (
	Time/ Unit of Time,
		([(0,0)-(10,10)],(0,2222.9),(12,2491.65),(24,2760.4),(36,3029.16),(48,3297.91),(60,\
		3566.66),(72,3835.41),(84,4104.16),(96,4372.92),(108,4641.67),(120,4910.42),(132,5179.17\
		),(144,5447.92),(156,5716.68),(168,5985.43),(180,6254.18),(192,6522.93),(204,6791.68\
		),(216,7060.44),(228,7329.19),(240,7597.94),(252,7866.69),(264,8135.44),(276,8404.2\
		),(288,8672.95),(300,8941.7) ))
	~	vehicles
	~	file:///C:/Users/JuanDavid/Downloads/taximonitor_2016_en_eerste_helft_2017.\
		pdf
	|

InitialAverage PT Travel Time per Trip= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(241,30)],(0,17.1976),(12,16.4588),(24,16.7506),(36,17.0424),(48,25.5802),(\
		60,34.118),(72,21.9165),(84,21.9165),(96,21.92),(108,21.9165),(120,21.9165),(132,21.9165\
		),(144,21.9165),(156,21.9165),(168,21.9165),(180,21.9165),(192,21.9165),(204,21.9165\
```

```
		),(216,21.9165),(228,21.9165),(240,21.9165),(252,21.9165) ))
	~	Minutes/Trip
	~	Bron: afd. Verkeer en Openbare Ruimte
		Publicatie: Amsterdam in cijfers 2017
		Download: 2017_jaarboek_416.xlsx
	|

Initial Private Car Fleet= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(10,10)],(0,476986),(12,476492),(24,476669),(36,481219),(48,486559),(60,484887\
		),(72,498483),(84,505766),(96,511539),(108,514080),(120,519669),(132,525257),(144,530846\
		),(156,536435),(168,542024),(180,547612),(192,553201),(204,558790),(216,564379),(228\
		,569967),(240,575556),(252,581145) ))
	~	vehicles
	~	RDW CBS
	|

Delay Parameter Roads=
	500000
	~	Minutes*vehicles/(Trip*peak)
	~	Fit initial travel time
	|

Delay Parameter PT=
	500000
	~	Minutes/peak
	~		|

Delay Parameter Taxi=
	10
	~	vehicles*Minutes/(Trip*peak)
	~	Fit  Tom Tom van Kuijk
	|

"Average Private Car Access/Egress Time per Trip"=
	16
	~	Minutes/Trip
	~	van Kuijk
	|

"Free Average PT Access/Egress Time per Trip in Peak Hours"=
	10
	~	Minutes/Trip
	~	Tom Tom anVan Kuijk
	|

"Initial Average PT Access/Egress Time per Trip"=
	25
	~	Minutes/Trip
	~	Bron: afd. Verkeer en Openbare Ruimte
		Publicatie: Amsterdam in cijfers 2017
		Download: 2017_jaarboek_416.xlsx
	|

Effect of MaaS Market Share Gap on Expenses=
	0.001
	~	(Euros/Euros)/(Month*(persons/persons))
	~		|
```

```
"Initial Average Access/Egress Time per Trip non-MaaS Taxi"=
	8
	~	Minutes/Trip
	~	van Kuijk
	|

Platform Quality Contribution to MaaS Value=
	Coefficient Contribution Platform Quality to MaaS Value*MaaS Platform Quality
	~	Euros/Trip
	~		|

Initial Average Travel Time on the Road= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(252,20)],(0,9.44469),(12,9.3573),(24,9.63283),(36,9.90836),(48,14.8556),(60\
		,19.8028),(72,13.0865),(84,13.0865),(96,13.75),(252,13.75) ))
	~	Minutes/Trip
	~	Bron: afd. Verkeer en Openbare Ruimte
		Publicatie: Amsterdam in cijfers 2017
		Download: 2017_jaarboek_416.xlsx
	|

Average Trip PT Travel Time with Modes off the Road=
	Average Trip Length/Average PT Speed with Modes off the Road
	~	Minutes/Trip
	~		|

MaaS Platform Quality= INTEG (
	Development of Platform Quality,
		1)
	~	Quality Unit
	~		|

Total Perceived PT Average Travel Time per Trip=
	"PT Perceived Average Access/Egress Time per Trip in Peak Hours"+Average Perceived PT Travel Time per Trip
	~	Minutes/Trip
	~		|

Bike Trip Percentage Included in the MaaS Package=
	1
	~	1
	~		|

"Average Non-MaaS Bike Costs per Km"=
	0.08
	~	Euros/km
	~		|

Average MaaS Bike Travel Time per Trip=
	41.9153
	~	Minutes/Trip
	~	van Kuijk
	|

"Average Non-MaaS Bike Travel Time per Trip"= WITH LOOKUP (
	Time/Unit of Time,
		([(0,0)-(241,10)],(0,28.8211),(12,26.7893),(24,26.7709),(36,26.7526),(48,41.9752),(\
		60,57.1978),(72,41.9153),(84,41.9153),(96,41.9153),(251,41.9153) ))
```

~ Minutes/Trip
~ Zorn, Walter (2015-03-27). "Speed&Power Calculator". Retrieved 2015-03-27.

Bron: afd. Verkeer en Openbare Ruimte
Publicatie: Amsterdam in cijfers 2017
Download: 2017_jaarboek_416.xlsx
|

Road Capacity= WITH LOOKUP (
(Time/Unit of Time),
([(0,0)-(300,380000)],(0,372600),(12,373200),(24,372200),(36,367400),(48,368600),(60\
,369200),(72,369800),(84,369000),(96,368600),(108,368600),(120,368600),(132,368600)\
,(144,368600),(156,368600),(168,368600),(180,368600),(192,368600),(204,368600),(216\
,368600),(228,368600),(240,368600),(252,368600) ))
~ vehicles/peak
~ CBS
|

PT Trip Percentage included in the MaaS Package=
1
~ 1
~ |

Value of Time for Walking Users=
0.0068955
~ Euros/Minutes
~ van Kuijk
|

Average Walking Travel Time per Trip= WITH LOOKUP (
Time/Unit of Time,
([(0,0)-(10,10)],(0,80.0585),(12,74.4147),(24,74.3637),(36,74.3127),(48,116.598),(60\
,158.883),(72,116.431),(84,116.431),(96,116.431),(108,116.431),(120,116.431),(132,116.431\
),(144,116.431),(156,116.431),(168,116.431),(180,116.431),(192,116.431),(204,116.431\
),(216,116.431),(228,116.431),(240,116.431),(252,116.431) ))
~ Minutes/Trip
~ DIVV
|

Coefficient Contribution Data per User to MaaS Value=
0.1
~ (Euros/Trip)/(Mbytes/persons)
~ |

Coefficient Contribution Platform Quality to MaaS Value=
1e-08
~ (Euros/Trip)/Quality Unit
~ |

Data Accumulation from MaaS Users=
MaaS Users*Speed of Data Accumulation from MaaS Users
~ Mbytes/Month
~ |

Data per User Contribution to MaaS Value=
Coefficient Contribution Data per User to MaaS Value*Data Accumulated per MaaS User
~ Euros/Trip
~ |

```
Data Resources Accumulated= INTEG (
	Data Accumulation from MaaS Users,
		0)
	~	Mbytes
	~		|

Word of Mouth Contact Rate=
	3
	~	persons/(persons)
	~		|

********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|

FINAL TIME  = 240
	~	Month
	~	The final time for the simulation.
	|

INITIAL TIME  = 0
	~	Month
	~	The initial time for the simulation.
	|

SAVEPER  = 1
	~	Month [0,?]
	~	The frequency with which output is stored.
	|

TIME STEP  = 0.25
	~	Month [0,?]
	~	The time step for the simulation.
	|

\\\---/// Sketch information - do not modify anything except names
V300  Do not put anything below this section - it will be ignored
*View 1
$192-192-192,0,Times New Roman|12||0-0-0|0-0-0|0-0-255|-1--1--1|-1--1--1|96,96,50,0
10,1,MaaS Users,762,61,87,36,3,131,0,0,0,0,0,0
10,2,Potential MaaS Users,544,193,71,47,8,131,0,0,0,0,0,0
11,3,4780,805,-108,6,8,38,3,0,0,1,0,0,0
10,4,Expected Keepers of MaaS Service,805,-81,68,19,40,3,0,0,-1,0,0,0
10,5,Word of Mouth Contact Rate,1045,-379,51,19,8,3,0,4,0,0,0,0,-1--1--1,255-255-0,|12||0-0-0
10,6,MaaS Users Adoption Fraction,1268,-166,64,19,8,2,0,3,-1,0,0,0,128-128-128,0-0-0,|12||128-128-128
10,7,MaaS Users Keep Fraction,706,-164,58,19,8,2,0,3,-1,0,0,0,128-128-128,0-0-0,|12||128-128-128
10,8,MaaS Advertisement Effectiveness on Users,671,-379,72,19,8,3,0,0,0,0,0,0
10,9,Data Resources Accumulated,2280,694,57,32,3,131,0,0,0,0,0,0
12,10,48,2047,689,10,8,0,3,0,0,-1,0,0,0
1,11,13,9,4,0,0,22,0,0,0,-1--1--1,,1|(2176,689)|
1,12,13,10,100,0,0,22,0,0,0,-1--1--1,,1|(2087,689)|
11,13,48,2124,689,6,8,34,3,0,0,1,0,0,0
10,14,Data Accumulation from MaaS Users,2124,716,61,19,40,3,0,0,-1,0,0,0
10,15,Speed of Data Accumulation from MaaS Users,2035,613,60,28,8,3,0,0,0,0,0,0
1,16,15,13,1,0,0,0,0,128,0,-1--1--1,,1|(2090,652)|
```