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Analysis of Traffic in Mexico City:

Mapping of the System's Dynamic Structure and Policy Recommendation

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DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

ABSTRACT

This thesis documents a System Dynamics study in which the problem of vehicle traffic in Mexico's City is analysed. The document explored the System Dynamic methodology that was used, the results of the dynamic model and some recommended policies to solve the observed problem.

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Introduction

According to data from the Mexican National Institute of Statistics and Geography (INEGI, 2015), Mexico City has grown to the point that it has a population of nearly 9 million people without considering all its urban surroundings. That growth has also created a city with almost a twenty kilometre radius therefore pushing its population to acquire more than two million automotive vehicles (FIMEVIC, 2016). The sheer size of the city has created a massive saturation of the transportation services and therefore caused a massive loss on productivity and quality of life.

Mexico City experienced an incredible growth from 1950 to 1970 moving from only 3.1 million inhabitants to 6.9 million. Even though the growth of the population has diminished each year since then, the amount of people in the city still reached 8.9 million in the latest poll. And even of the growth rate has dwindled, it still has a value a little over 3% annual growth (INEGI, 2015). However is important to notice that these numbers only explain what has happened within the political limits of the city; when considering all the urban area, the actual population includes more than 20 million people (FIMEVIC, 2016).

Hand in hand with the population growth, the amount of vehicles in the city has increased massively since 1950. Nowadays the city has an enormous transportation network that includes more than 32 public busses, 100 thousand taxis, 12 subway lines with more than 180 stations, and more than 2 million private vehicles (FIMEVIC, 2016). However, the growth of the transportation network is reaching its limits as the density of population continues to increase.

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Based on the described situation of the transportation network in Mexico City, this master thesis will focus on mapping the structure and behaviour of this complex system and on analysing different policies that may be helpful. This will be accomplished through the design, and development of a System Dynamics (SD) Model. Said model will aim to explain the current situation of the system and to provide a simulation based analysis of some policies that have been considered by Mexico City's decision makers.

Observed Problem

The government of Mexico City has made a huge effort in developing the transportation network to try to accommodate the needs of everybody. It can be

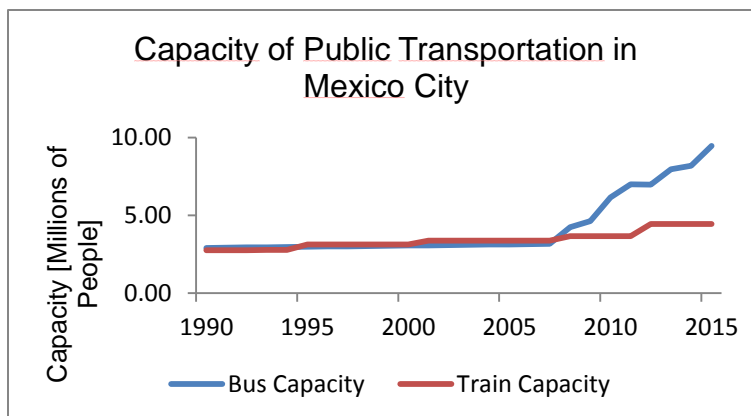


Figure 1. Capacity of Public Transportation in Millions of People per day. (FIMEVIC, 2016. and Metro, 2017).

observed in Figure 1 that the maximum capacity of the main two public transportation systems has been increased to provide service to up to 14 million people at a time. In turn this has allowed the population to travel 28.3 million trips per day (FIMEVIC, 2016). However, it is important to note that the expansion of transportation capacity is not simple or free. The cost of the expansion has been gigantic as just the latest line of the Metro system added to over 9 billion MXN (435 Million USD).

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However, in spite of huge efforts and investments, the transportation services have continued to saturate. Said saturation has driven the average transportation speed from an average of 40 kilometres per hour (km/hr) to under 10 km/hr as it can be observed in Figure 2.

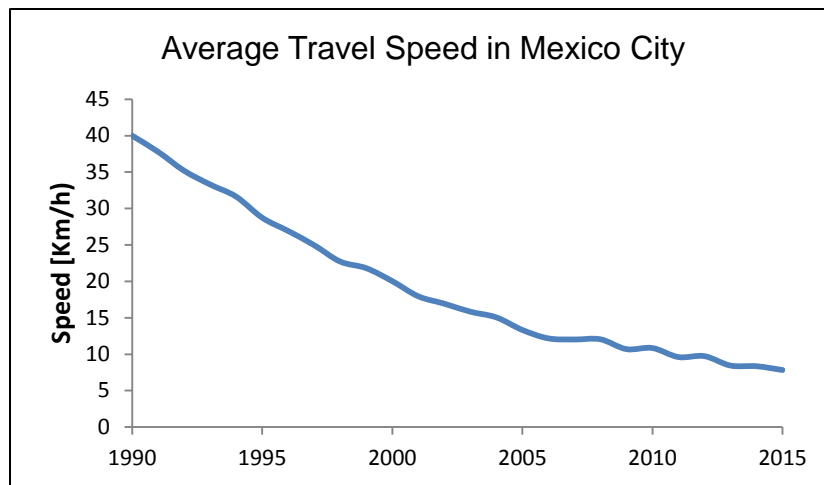


Figure 2. Average Travel Speed in Mexico City from 1990 to 2015. (FIMEVIC, 2016).

It is also important to notice, from Figure 2, that the speed of travelling in Mexico City has not decreased in a linear way. In his book “Business Dynamics” John Sterman (2000, pp.111) indicates that behaviours with decreasing rates such as the one observed (It decreases more slowly each year) indicate goal-seeking structures. This implies that there is a complex set of variables affecting the travel speed by setting a goal or objective. This is important because the efforts in expanding the infrastructure have not managed to increase said goal.

The failure to stop the decrease of the average speed has created a variety of problems that include loss of productivity, noise and air pollution, less quality of life, and extra fuel consumption (Anas & Lindsey, 2011).

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Purely from an economic standpoint, this situation creates a loss in productivity due to the amount of time spent while travelling to different activities. The loss of those man hours is equivalent to 80,000 Mexican pesos (MXN) a year per worker (Animal Político, 2013) which amounts to 320 billion MXN (15.5 billion USD) in total loss of productivity per year. The economic impact of this problem is by itself enough to justify this study.

Additionally to the loss of productivity, the consumption of fossil fuels because of traffic in the city amounts to 301,000 gasoline barrels per day (14% of the national consumption of fossil fuels) according to the Trust for the Betterment of Communication Lines in Mexico City, FIMEVIC (2017). Aside from the obvious economic impact of fuel requirements, the use of fossil fuels in vehicles generates over two million tons of air pollutants each year. The amount of pollution liberated into the air puts Mexico City outside the recommended limit of suspended particles in the air at least 50% of the days of the year.

Thesis Hypothesis

The behaviour of the travel speed in Mexico City is being caused by the interrelationship between the change in the size of the population, the growth of the city area, and the balance achieved between the three major transportation methods: busses, trains and private vehicles.

In other words, unless the combined capacity of the whole transportation network grows faster than the change in the size of the population, the travel speed

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will remain at levels under 10 km/hr. This will be explored in detail in the Method section.

Part of the World to be Studied

As mentioned previously, the objective of this thesis is to analyse the behaviour of the transportation system in Mexico City. This city and its population have specific geographic and social characteristics that have been taken into account during the development of this project.

Geographic characteristics.

Mexico City is the capital of Mexico and it is located in its central region. The city was founded in the year 1325 by the Aztecs (The New York Times, 2006). This



Figure 3. *Mexico's City Location and Position of Texcoco's Lake.* Lesniewski, R. (2018)

is important to consider as the Aztec prophecies indicated that they would recognize the spot their city should be founded when they saw an eagle eating a serpent on top of a cactus (The image is depicted in Mexico's national flag). Said place happened to be on a small island in the Lake of Texcoco. Therefore, Mexico City is located in Mexico's Valley at 2,204 meters over sea level and in the middle of two different mountain ranges and a volcanic range.

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As the city grew, Texcoco's lake dried out which in turned caused new settlements to be built in the newly dried land. Nowadays (as it can be observed in figure 3) a great part of the city lies on layers of mud and clay that can be as deep as 91 meters (The New York Times, 2017).

Additionally, according to the OCDE, Mexico City's growth has caused its urban area to expand beyond its geopolitical limits. The name Metropolitan Area of Mexico's Valley is used to refer to the whole urban settlement which occupies an area of over 7,800 square kilometres. This area includes all of Mexico City, and 59 local municipalities from two other States.

In this paper the geographic characteristics were considered when analysing different policies to solve the observed problem. One of the main observations is that the construction of subway systems and other type of transportation infrastructure can be hindered by the softness of the ground in the lake area or the complexity of the land in the mountainous areas.

Socioeconomic characteristics.

On the other hand, there are important societal and economic characteristics of Mexico's Valley Metropolitan Area (MVMA). The main aspects considered for this thesis are the city transportation landscape and the socioeconomic situation of the population. These two aspects had a major influence on the way the observed problem was mapped and analysed.

In her report, "Mexico City: Mobility and Transport" (2006). Ortega-Alcazar, I. indicates one of the main aspects of the city's transportation system: the disparity

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between the way it has been designed and the way it is used. “One would describe Mexico City as a cityscape oriented to privately-owned cars. Statistics show, however, that the metropolitan area actually depends heavily on public transport and that 81% of all daily journeys are completed by this mode.” (Ortega-Alcazar, I., 2006). This observation is supported by statistics from FIMEVIC which indicate that 71% of the vehicles used on the streets for daily transportation are private cars. This method of transportation however, provides for less than 20% of the daily trips taken in the city.

On the socioeconomic side, the MVMA population has very discernible economic levels. The Mexican Association of Market Intelligence (AMAI in Spanish) establishes levels A/B and C+ as the families in position to afford private vehicles; in MVMA only 21% of the population is in said situation. The other 79% of the population does not have enough resources to afford private methods of transportation and must therefore use the available public options.

Related Literature

There are several articles and studies in the topic of transportation in both macro and local levels. This section therefore goes through some of the main ideas that have been discussed in the field of transportation systems and mentions how they have been considered for this thesis. This review is divided in two sections: observations about the transportation system in Mexico City and existing research regarding transportation.

Transportation in Mexico City

As mentioned before, this city has grown with specific characteristics regarding traffic. In her study, Ortega-Alcazar says that “since the 1970s, the period during which the city experienced its most rapid demographic and territorial expansion, Mexico City exploded in size and a road-dominated landscape was consolidated” (2006). Ortega-Alcazar makes that comment based on the fact that the construction of car lanes was prioritized over the construction of public infrastructure such as trams or subway rails.

The comments from Ortega-Alcazar are specially justified when considering the major efforts of the city, according to data from the Mobility Department (SEMOVI, 2018), were the construction of different high-speed avenues, bridges and high level streets. However, FIMEVIC (2017) stated that one of the main concerns of these types of works is the “induced traffic”; this means that even if the new infrastructure diminishes traffic in certain areas of the street network, the traffic is just moved to the points of arrival. Based on first-hand experience and the

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increasing travel time in the city, the efforts in street infrastructure have not been able to solve the problem.

FIMEVIC's report establishes that the city's government has conducted internal analyses about the situation and established the following as priority actions in order to attempt solving the problem:

- Construction of new high speed corridors
- Modernization of infrastructure in saturated crossings
- Expansion of bicycle roads
- Augmentation of the size of the busses used for public transportation
- Regulation of heavy duty vehicles

It is important to notice that even though the local government has conducted some analyses in order to try to come up with solutions, those were internal projects. There is an unnerving lack of available papers, studies or articles around the saturation of the transportation system in Mexico.

Existing Research Regarding Transportation

The research about transportation methods focuses mainly around the change in people's behaviour. Brandsar Torgeir (2013) indicates that when a person decides to change transportation methods he or she is breaking a habit. He also establishes that changing said habits is a conscious decision deriving from a change in the person's environment. Finally Torgeir affirms, citing Gärling & Axhausen (2003), that there are three main delays in any kind of change in transportation method:

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- Perceiving the attractiveness of a different transportation method
- Changing the behaviour
- Adapting and internalizing the specifics of the new transportation

Shifting a little bit more into systems-based research, Ennio Cascetta (2009) indicates that travel-demand models try to map the way infrastructure affects the way people travel. This is important because the way a model assigns the number of users using different transportation methods can have a big impact over the results. Cascetta (2009) therefore explains in detail the different variables that may come into play when mapping this kind of decisions. His first main observation is that the model can use socioeconomic data to assign decision making priorities (people with more money will prioritize time). The second main observation is that the most important considerations for transport selection are time and usefulness of the alternative.

Method

As established in the introduction, this thesis will use a System Dynamics (SD) focus in order to analyse the problem of transportation in Mexico's Valle Metropolitan Area (MVMA). In order to effectively implement a SD perspective this thesis follows the P'HAPI methodology.

P'HAPI Approach to Dynamic Modelling

This methodology is recommended during the University of Bergen's Master in System Dynamics Programme. It is based on an iterative process designed to understand, map and simulate problems in complicated systems. Its name refers to the five steps in the methodology:

- P – Problem Identification.
- H – Dynamic Hypothesis
- A – Analysis of Structure and Behaviour
- P – Policy Design and Analysis
- I – Implementation Analysis

It is important to note that, as SD is focused on simulation models, the steps from the methodology are not necessarily sequential. These steps are iterative, in other words, there is a cyclical procedure between the mapping and analysis phases.

Finally, the SD analysis was developed with the help of Stella Architect® Software from iseesystems. This software allowed me to build the system structure and execute repeated simulations and analysis.

Review of Observed Problem

As specified in the introduction, the observed problem is the diminishing speed of the average travel speed in Mexico City in spite of the increases in both the train and busses networks. This problem is considered optimal for a dynamic assessment because of the non-linear behaviour of the average travel speed which indicates a confluence of several different variables.

Dynamic Hypothesis

As mentioned in the “Thesis Hypothesis” section, this project was developed by focusing on the interrelationships of the three main transportation methods in Mexico City: private cars, busses and subway trains (According to SEMOVI these account for over 90% of daily travels). The only way to solve the transportation problem in the city is to consider these three methods together as one complex system.

This dynamic hypothesis is better explained in Figure 4 which presents a high level Causal Loop (CL) structure. In the CL we can observe that there are three Reinforcing Loops that work in a similar manner between each of the three transportation methods (R-A1, R-A2, R-A3). These loops indicate that if more people choose to use one of the alternatives, less people are going to be using the others.

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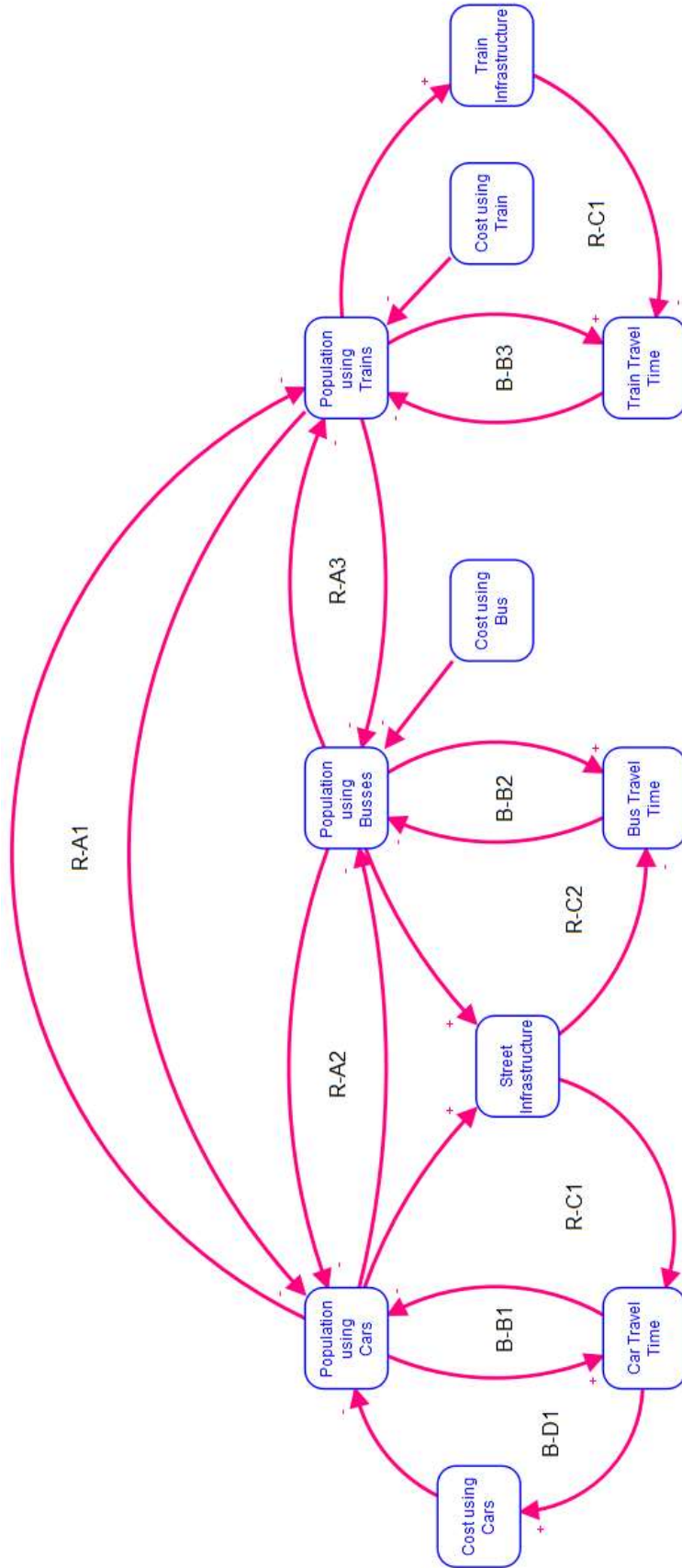


Figure 4. High Level Causal Loop Diagram of Dynamic Hypothesis

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As it can be observed in the diagram, the system is more complex than just an interchange of people between transportation methods. As Cascetta (2009) indicated, the way people make decisions are usually influenced by cost and time which add complexity to the system as evidenced in the Balancing Loops (B-B1, B-B2, B-B3) between the amount of population using a transportation method and the travel time of that kind of transportation. These loops indicate that the faster a transport is the more people will choose to use it which in turn will saturate that option and make it slower.

The third set of loops consists of three reinforcing loops linking the amount of available infrastructure, the travel time of a transportation method, and the amount of people using the transport. In this case the loops (R-C1, R-C2, R-C3) show how an increase in people using a type of transport incentivize the further development of infrastructure which in turn de-saturates the transport and makes it faster, and therefore more attractive to people.

Finally, it is important to observe one last loop that adds an important characteristic to the system. The balancing loop B-D1 shows the relationship between the travel time and the cost of using a car. Longer trips increase the cost of using a car therefore making cars less attractive which lead people towards other transportation methods. On the other hand, the bus and train systems do not count with this loop as the government subsidizes the cost of these transports and therefore it stays relatively constant.

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In order to better understand the system's behaviour, the high level CLD is not sufficient and therefore it was necessary to create a whole Stock and Flow Model (SFM). This model details each one of the sections showed in the CLD.

High level view of the stock and flow diagram.

Figure 5 shows the high level structure that was used to build the SFM. It can be observed that it is really similar to the CLD as it groups the whole structure into five sections:

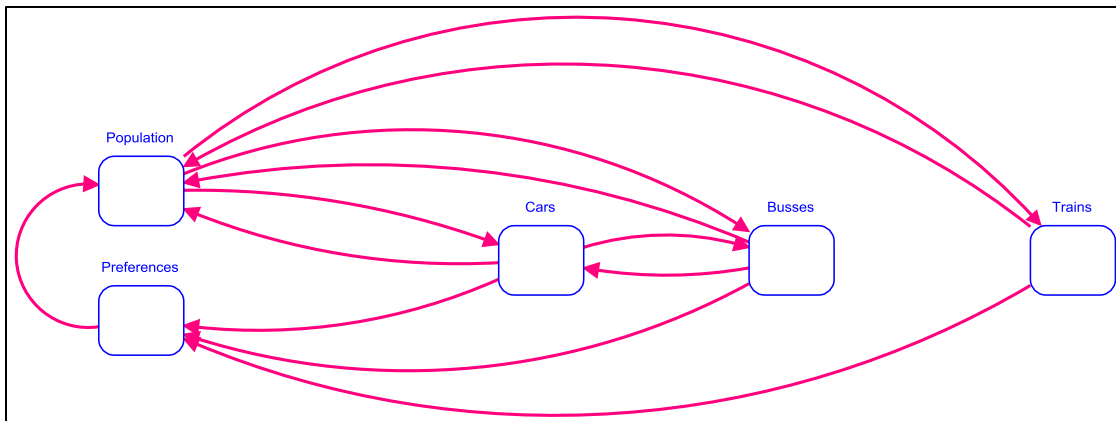


Figure 5. High Level View of Stock and Flow Diagram

- Population: This section contains the stocks and flows pertinent to the amount of people with access to each kind of transportation, and the growth of the population.
- Preferences: This presents a decision making structure in which the cost and travel time of each alternative is compared.
- Cars: Maps the way infrastructure is created according to the growth of the population using private vehicles and how this affects both travel time and travel cost.

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- Busses: Shows the increase of the capacity of this service and its impact over the rest of the system.
- Trains: Explores the way the increase in train capacity affects the travel time for its users and how that affects their decision making.

Population module.

As mentioned previously, this module maps the way the population grows and how this affects the amount of population that can choose each type of available transportation. As there are several stocks, flows and variables working in the model, they will be presented in small sections throughout this thesis (To see the entire module go to Appendix 1).

Mexico City's population.

The first building block is the general behaviour of the population. To model this, the population was conceptualized as a stock in which more people can exist

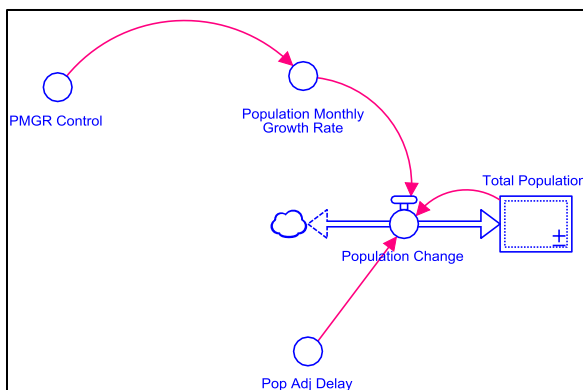


Figure 6. *Total Population Growth SFD*

if there is a positive “Population Change” flow. The change in population is then determined by the current population multiplied by the “Population Monthly Growth Rate” and divided by the “Pop. Adj. Delay” which indicates the change is month by month. According

to data from the National Institute of Geography and Statistics (INEGI, 2017), the population growth rate is of 0.13% per month and the current active population adds up to sixteen million people.

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Mexico's City private vehicles.

In a parallel way to the population SFD, the model considers the way the amount of cars in the city changes a simple Stock and Flow structure (Figure 7). In this case, the initial amount of cars in the stock "People with Cars in the City" was

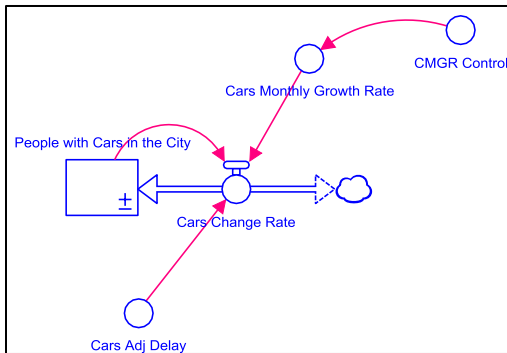


Figure 7. *Private Vehicles SFD*

taken from FIMEVIC (2017) and it has a value of 1.8 million vehicles. Data from the same source suggests that the vehicular growth rate is of 0.37% per month. Almost double the growth rate of the population.

Transportation options.

The final piece of the puzzle regarding this part of the Population Module is the segmentation by available transportation. In Figure 8, it can be observed that

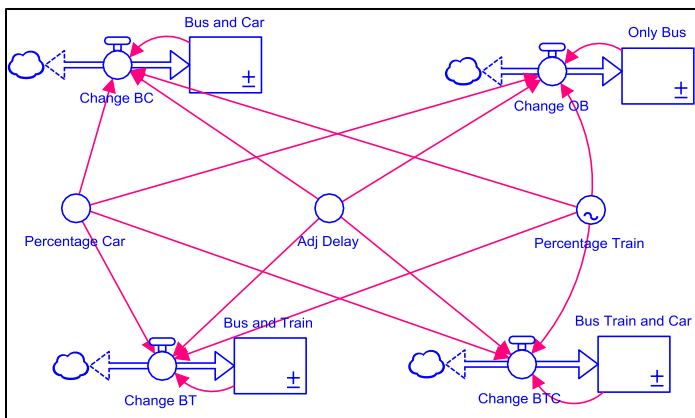


Figure 8. *Population segmented by access to transportation SFD*

not every person has access to every transportation method.

First of all, we can notice that although everyone has access to the bus network, only a certain percentage of people

have access to the train network

and/or to a car. Additionally, it can be noticed that there is a delay factor affecting the change of the population in each one of the stocks. Finally, it should be noticed that as the total population of the city and the amount of private vehicles change,

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the percentage of people with access to cars is going to increase therefore changing the distribution of the segments.

This part of the model is dependent on the change in the percentage of people with cars but also on the assumption that even as the capacity of the trains increases, its coverage is going to remain around 50%. The assumption was made based on current coverage and the expectation that even with a focus on train development, the expansion of the train network would not match the growth of the population.

Preferences module.

This module presents a decision map which considers the cost and time of travelling of each one of the available transportation methods. This decision process has three steps and tries to emulate the way people choose the way they will travel. This module gets information from all the other modules (Cars, Busses and Trains modules) and provides input to the population module.



Figure 9. Example of cost comparison formula for Preferences Module

The first step of the decision process is to register and compare the costs and travel times of each transportation option. To do this the model compares each value against the minimum available as can be seen in Figure 9. With this process the model can determine which

alternative of transportation has the lowest cost and the fastest travel time. After this, on the second step, each transportation method gets assigned a grade based

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on the result of the first step and how travel time is weighted (In this model travel time was determined to be slightly more important than cost 60/40). The third and final step is to determine the order of preference or model scenario for each transportation alternative. Figure 10 shows how the decision process was mapped:

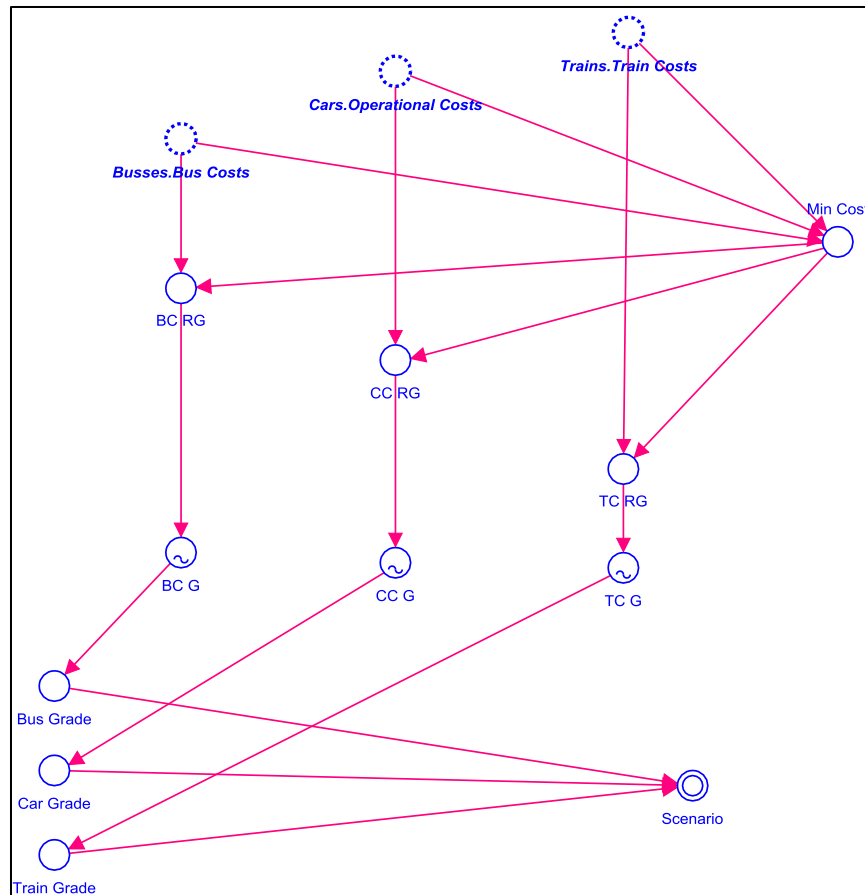


Figure 10. Preferences Module decision process

It can be observed that this structure receives the calculated cost of each one of the transportation methods from their respective modules. A “convertor variable” (Min Cost) then chooses the minimal cost available which is used to calculate a relative grade for each transport (BC RG stands for Bus Cost Relative Grade). The relative grades are then transformed into a standard grade on a scale that goes from zero to a hundred through a graphic function (Figure 11). Said

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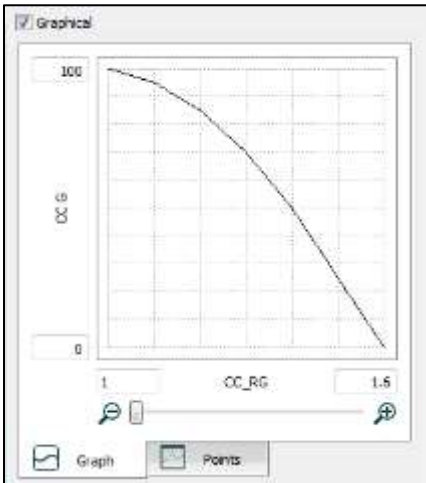


Figure 11. Graphical function used to calculate grades on a 0-100 scale

function was designed to quickly penalize big deviations from the minimum cost; it can be noticed that the function diminishes the grade faster and faster as the deviation from the minimum cost grows and that anything bigger than a 1.6 deviation is graded with a zero.

Finally, the calculated grades are averaged with the calculated grades from travel time (which follow the same structure and can be observed in Appendix 2) and the results are used to define under which scenario is the model working at each time step. The model works with six different scenarios:

1. Bus Grade > Car Grade > Train Grade
2. Bus Grade > Train Grade > Car Grade
3. Car Grade > Bus Grade > Train Grade
4. Car Grade > Train Grade > Bus Grade
5. Train Grade > Car Grade > Bus Grade
6. Train Grade > Bus Grade > Car Grade

The used scenario tells the model the priority order for each transportation method. As discussed in previous sections, this will in turn influence how many people choose to use each method of transportation.

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Cars module.

In this module, which can be observed as a whole in Appendix 3, there are three main sections that are analysed. The first section looks at the amount of people using cars as a method of transportation and calculates, based on that, the amount of vehicles on the street. The second section analyses how the saturation of the street network leads to the construction of new infrastructure. And the third section calculates the changes in travel cost and time derived from the saturation of the streets.

Amount of private vehicles on the streets.

As mentioned before, this section of the module calculates the amount of vehicles on the street at each time step. The structure showed in Figure 12 shows that this section utilizes data from the “Busses Module”. This is important because both, the Cars and Busses networks, are considered to share the same streets;

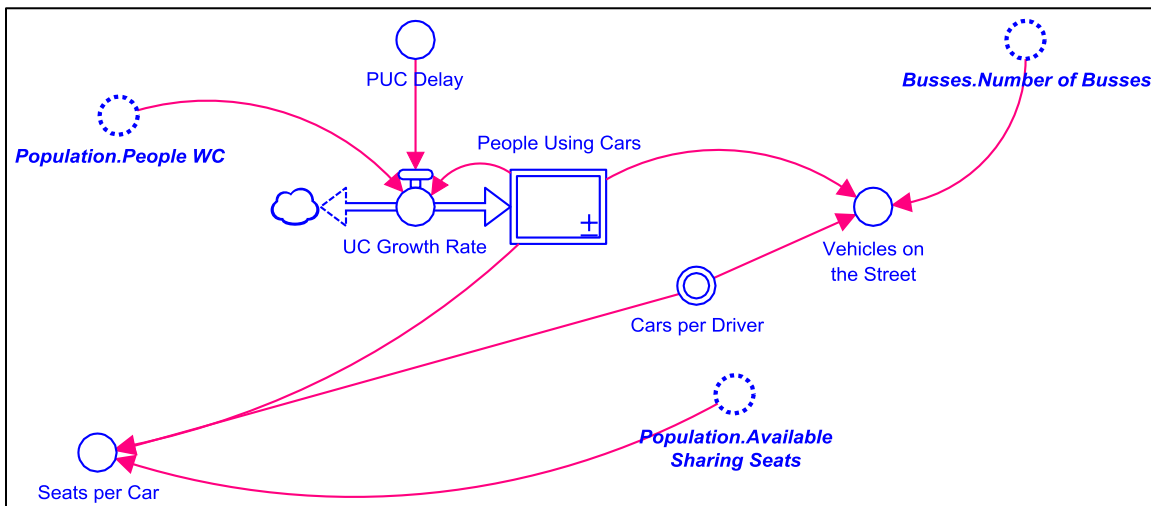


Figure 12. Amount of private vehicles on the streets SFD

although MVMA does have bus-only lanes in the city, these are not considered in the model as they provide service for only a small fraction of the population.

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The main structure of this section is the stock and flow of “People using Cars” and “UC (Using Cars) Growth Rate”. The initial value of the amount of people using cars was calculated with data from the FIMEVIC (2017). The flow of people that go into or out of the stock is determined by contrasting the amount of people that are currently in the stock against the amount of people who chose cars as their method of transportation (as determined in the Preferences Module). Finally, the flow has a delay variable which means that change is not instantaneous.

The secondary structure of this section calculates different values. Firstly, it calculates the amount of vehicles on the streets using, as mentioned previously, data from the busses Module and calculating the amount of cars used by each driver (assumed to be 1). Secondly, the model calculates the amount of used seats in each car for the purposes of policy analysis (This is explained in the Policy chapter of this thesis).

Street capacity development.

This section focuses on the process of expanding the Street network in the Metropolitan Area. It considers several delays as certain time is required to notice the saturation of the streets, order the construction of new capacity and actually finishing the expansion works. The expanded capacity also plays a role diminishing the saturation of the streets.

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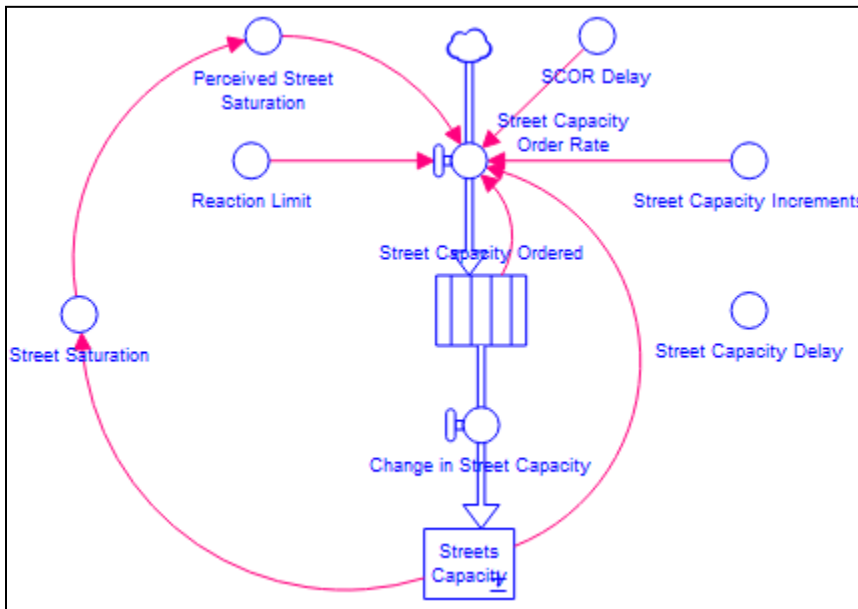


Figure 13. *Street Capacity Development SFD*

As the order of extra capacity depends on the saturation levels of the street, it can be assumed that no “forward-looking” strategy was used by the government.

Instead, street capacity has been built as needed. It is important to take a mental note of this fact as it was an important element considered during policy analysis.

As street saturation level is vital for this section of the model, it is important to explain that this is calculated as the existing ratio of Street Capacity divided by the amount of vehicles on the street (explained in the previous section). However, a phenomenon such as street saturation is not noticed from one day to the next, therefore the model considers a delayed variable for such perception. In his book “Business Dynamics”, John Sterman (2000) explains that information is usually perceived with a delay as not all people find about it at the same time; a third degree delay is therefore considered in this structure to model the way street saturation is perceived. Finally, the model was built with a “Reaction Limit” variable to simulate that the government does not order new infrastructure just because a small increase in street saturation was noticed; this variable was assigned a 1.5 value which means new street capacity is only ordered after saturation is at 150%.

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Once the perception of street saturation was modelled, the next step was to show the way infrastructure is ordered and delivered, this is used as a key relationship based on Kutz, M (Handbook of Transportation Engineering, 2004) studies where he states that “high volumes justify the need for extra infrastructure”. For this, a “two stocks - two flows” structure was utilized. The first flow represents how the new capacity is ordered. It is dependent on whether there is already an infrastructure project in the pipeline, the percentage increase that is ordered (Street Capacity Increments variable) and the delay to order. The assumption is that the government does not order new street capacity constantly nor expands more than 10% of the network at a time as any of those would paralyze the city’s streets. After that, the stock “Street Capacity Ordered” represents the work in process; this work cannot be delivered partially and therefore must stay inside the conveyor stock for the entirety of the construction time (18 months as estimated from previous projects as published in SEMOVI). Once the works are finished, they go through the second flow as the new streets are opened to the public and get “stored” into the streets capacity. Finally, the new street capacity value is used to recalculate the street saturation levels.

For purposes of this thesis, it is important to notice that the repair of current street capacity was not taken into consideration and therefore it is assumed that a 100% of the available capacity is in use. On the other hand, it is assumed that street capacity can continue to increase without limitations for the foreseeable future but this is an important issue that should be considered if the timeframe of the model is altered; street capacity cannot be expanded infinitely.

Calculation of travel time and cost.

The third section is conceptually easier to explain as it only calculates the way cost and time are affected due to the saturation of the street network. This section assumes that an increase in street density is going to have an impact in both the travel time and the cost of travel. Therefore, to calculate the changes in those variables an initial reference value is used. A structure to calculate the inflation impact over the costs was added as inflation can be very disruptive for individuals.

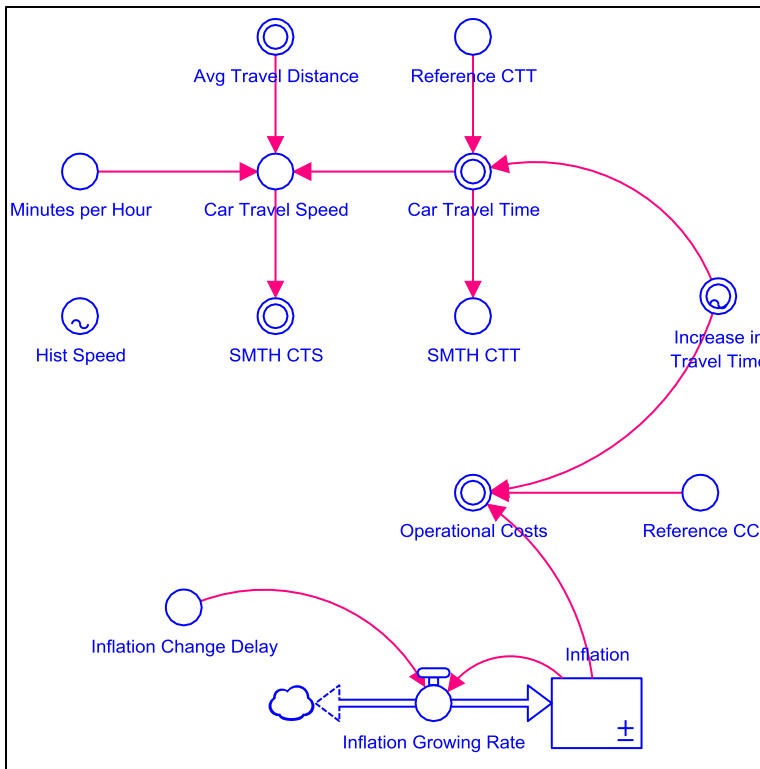


Figure 14. Car travel time and cost SFD

In Figure 14 it can be observed that the variable “Increase in Travel Time” is determined by a graph function. This function follows an exponential curve. This behaviour was selected because as the number of cars on the streets increases, they not only share the limited space,

but they also increase the amount of interactions between vehicles. The graphic function used for this variable can be observed in Figure 15.

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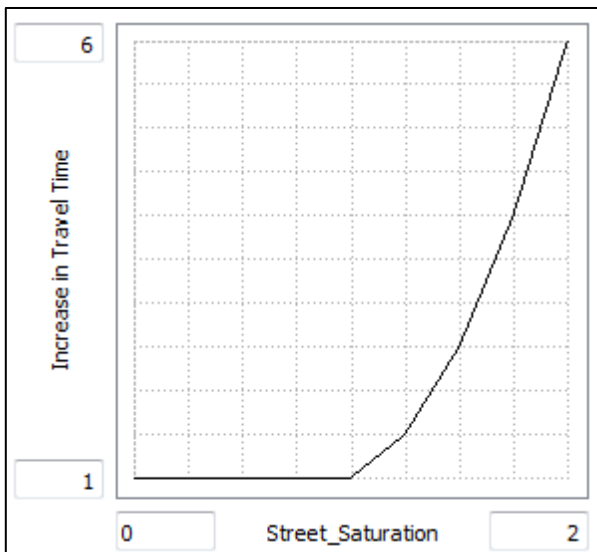


Figure 15. Graphical Function of the relationship between street saturation and travel time

Once the impact of street saturation has been estimated, the model factors said impact into the reference cost and travel time to get the values at each time step. The reference values were estimated using data from FIMEVIC (2017) and stand as follows:

- Reference Car Travel Time: 18 minutes. Estimated from the average distance of each trip (12 km) and the speed the streets were designed for (60 km/hour).
- Reference Car Travel Cost: \$120 pesos (\$6 USD) per trip. This was calculated from the average gasoline consumption per kilometre (7 litres per 100 km), the cost of gasoline (\$14 pesos per litre), and the cost of parking (\$100 pesos per day).

After calculating both the travel time and the travel cost, the values are sent to the Preferences Module in order to be compared with the other transportation methods. The travel speed of the cars is then calculated by dividing the average travel distance by the calculated travel time. It is important to notice that the model has two variables which smooth the results of the travel time and speed; this is used for graphical purposes only and has no effect over the operation of the model.

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Finally, the inflation structure simulates the way prices increase over time. In this case, the value of the inflation is accumulated following the same behaviour as a compound interest formula:

$$\text{New Value} = \text{Previous Value} * (\text{Interest Rate})^{\# \text{ of time Periods}}$$

Busses module.

This module, as well as the train module, is built in a very similar way to the Cars Module. It also has three sections (which can be observed as a whole in Appendix 4) which calculate the amount of people using the network, the growth of its infrastructure, and the cost and time estimation. The following description of the model will therefore not be as deep as the previous section; the logical aspects of the structure have already been explained and justified.

Amount of bus users.

This small structure is used to calculate the amount of people using the bus network. As established before, the flow of bus users is calculated based on the

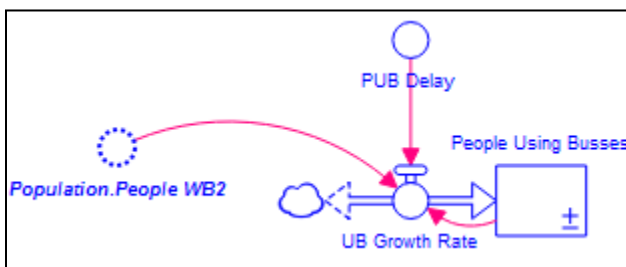


Figure 16. *Amount of Bus Users SFD*

analysis which was executed in the Preferences and Population Modules. Figure 16 shows how in this case the structure is simpler than

for the cars module as it does not

need an extra calculation to consider the relationship between drivers and cars.

The stock of bus users therefore increases and decreases as it is determined by the flow and the change delay.

Bus service capacity development.

In a similar manner to the Street Capacity Development section, the capacity of the bus network will be increased based on its saturation levels. However, in this case it is important to notice that the model does not consider a possible decrease in capacity as it is assumed that any malfunctioning vehicles would be replaced immediately. The ordered capacity will then be delayed and eventually added to the existing capacity.

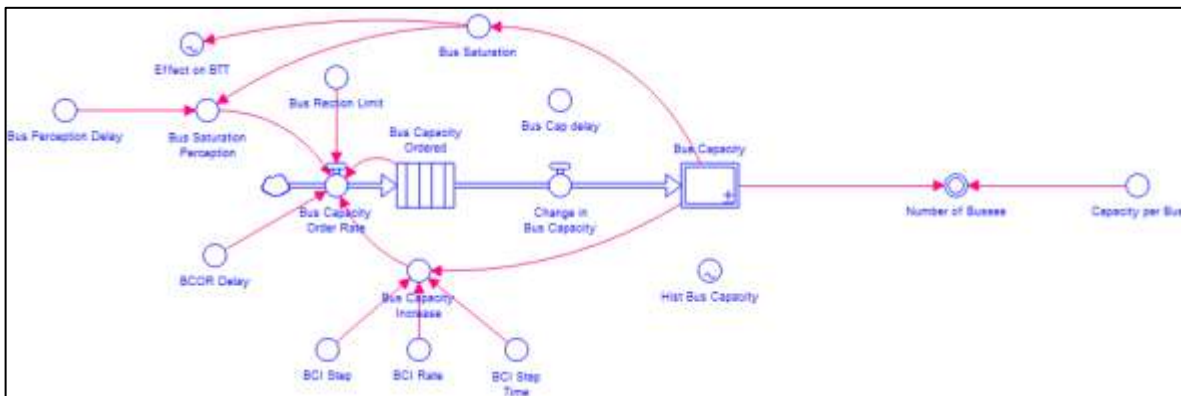


Figure 16. *Busses Network capacity development SFD*

It can be observed in Figure 16 that the structure of this section is almost identical to the one for Street Capacity. The saturation of the system takes a while to be perceived (third order delay as explained previously) and eventually triggers an order for new capacity when the saturation goes above 150%. The new capacity then is processed and delivered at the same time after an average delay of only 12 months (Based on historical data retrieved from SEMOVI as well as first-hand knowledge of this process). The new capacity, which is calculated in amount of people, is then added to the existing capacity and the number of required busses is then calculated based on the average capacity per bus (30 individuals

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per bus). The number of busses then adds to the number of vehicles on the street as explained in the Cars Module Chapter.

One main difference in this part of the module is the three added variables BCI Step, BCI Rate and BCI Step Time. These variables were introduced to capture an important change in policy executed in MVMA in which the focus on the expansion of the bus network was prioritized. Said change occurred in 2007 and the rate at which the bus network was developed increased massively. Therefore the model introduces the three aforementioned variables to simulate said change in policy.

Calculation of bus travel time and cost.

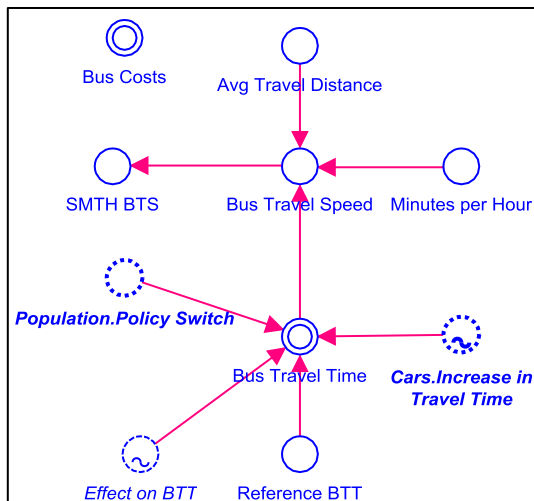


Figure 17. *Bus travel cost and time estimation*

As explored in the Cars Module, the calculation of the travel time and cost is straightforward. The increase of the size of the bus network contributes to the saturation on the streets. Said saturation then affects the Bus Travel Time. The main difference in this section is that the cost of travel stands alone and is not affected by

changes in other variables.

In this case, the reference travel time of a bus trip considers similar parameters to those in the Cars Module but the expected average speed of the busses is slower. This puts the reference travel time at 20 minutes per trip. This

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value is modified by the “Increase in Travel Time” that was calculated in the Cars Module.

It is noticeable that the cost is not affected by any of the variables. This is due to the fact that the local government subsidizes the cost of transportation and therefore holds the cost per trip at the same value. Considering this, the model does not change the original cost of this service.

Trains module.

This module follows the same logic as the two previously explained. The model considers that a certain amount of users are going to choose this transportation method, the system will increase its saturation and therefore the travel time and cost leading to an order to increase capacity, and finally the new capacity will reduce the saturation levels. The full view of this module is located in Appendix 5.

Amount of train users.

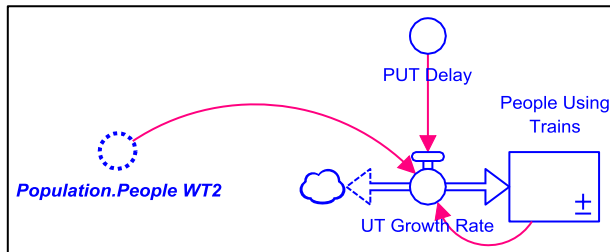


Figure 18. *Estimation of train users SFD*

In the same way as with the previous modules, this section shows how the amount of users of this service fluctuates from time step to time step. This section gets input from

the Population Module which creates the inflow or outflow of users in the system.

The amount of train users is represented by the stock “People Using Trains”.

Train service capacity development.

In this case, the expansion of the train network also follows the saturation of the system. It can be seen in Figure 19 that the structure is really similar to the structures of the other two modules.

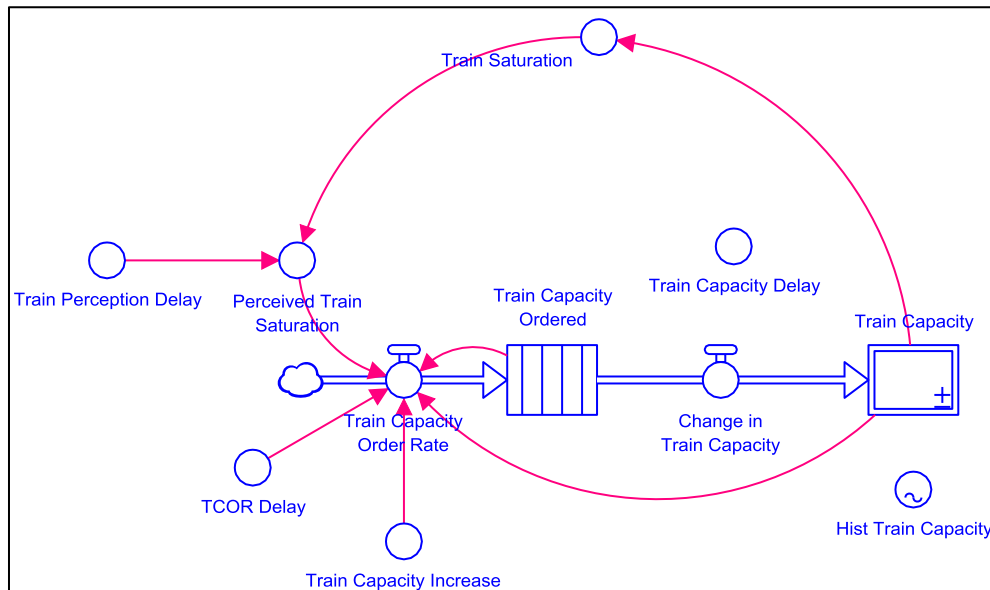


Figure 19. *Train capacity development SFD*

The saturation of the system takes certain time to be noticed which, as explained previously, was modelled with a third order delay. Once the saturation surpasses a 120%, the system orders new capacity in set increments (This was calculated from the historical data of the official subway webpage). The ordered capacity takes 48 months (again, estimated from historical data) to be delivered and then gets added to the available train capacity.

This section, as the previous, is not accounting for malfunctions or repairs. It is assumed that the network is operational most of the time. Additionally, the capacity is estimated in number of people able to use the system, not in number of wagons or stations.

Model Analysis

It is important to indicate that this section only describes the analyses that were executed. The results are shown in the Results and Discussion section of the thesis. Therefore the objective of this section is to describe and justify the analyses that were made.

Initial testing.

In a SD project, there are three initial analyses that must be taken into consideration before declaring a model finished. The first test is logical; all the variables, flows and stocks must have a logical and causal relationship. The second test backs the first one by analysing the units of each variable; a stock cannot store money if its inflow is people. Finally, the behaviour captured by the model must show a close resemblance to real life data.

These tests are based on John Sterman's steps for modelling a Dynamic System (2000).

Part of testing, of course, is comparing the simulated behavior of the model to the actual behavior of the system. But testing involves far more than the replication of historical behavior. Every variable must correspond to a meaningful concept in the real world. Every equation must be checked for dimensional consistency. (p.103)

Extreme conditions testing.

Following SD recommended practices (Sterman can be quoted but the practices can be found in many SD publications), it is important to test the model

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under extreme conditions of the variables. This type of testing allows the user to see what the possible limitations of the model are. Additionally, this kind of test can show if the model is robust enough, in other words, if the logical structure that was used keeps working under unforeseen situations.

Sensitivity testing.

“To judge the utility of a model requires the modeler to decide whether the structure and decision rules of the model correspond to the actual structure and decision rules used by the real people” (Sterman, J. 2000. P. 331). Sterman then affirms that one proper way of determining if the model is behaving as it should to be useful, the modeller should execute sensitivity analyses over several variables.

Sensitivity analyses show the importance a certain variable has over the performance of the system. If a small change in a variable creates big changes in the behaviour of the model, it can be said that the model is extremely sensitive to said variable. It is therefore important to test all the variables that could be expected to change in real life and conclude whether the model is behaving as it should.

For this thesis several variables were ran through a sensitivity analysis in order to determine their importance to the system. The analysed variables are:

- Reference travel time for cars, busses and trains
- Reference travel cost for cars, busses and trains
- Delay for capacity expansion for streets, busses and trains

Policy Exploration

Finally, as the objective of this model is to provide a solution for the observed problem, different policies will be tested. There are two different kinds of policies; the first one explores changes in parameters that are already part of the model while the second type adds a new structure to the model hoping to alter the observed problematic behaviour.

Internal policies.

For these analyses, different policies will be considered. As mentioned during the literature review section, the city is already considering accelerating the expansion of roads, busses and trains. Additionally, the city is considering the development of alternative methods such as bicycles. On the other hand, some other cities have experimented with additional tolls to encourage people to use public transportation. All these policies were analysed with the model.

New structure policy.

One policy that has been suggested several times but has never taken off is a “car-sharing” policy. The most common observable effort to implement this policy are the “High Occupancy Vehicle” (HOV) facilities which according to the United States Department of Transportation has been evolving since the 1970’s. This model therefore analyses a car-sharing policy in which car drivers are payed to share their car therefore diminishing the amount of people using public transportation and de-saturating the system. This policy also assumes that the city would then focus on expanding the street network to also de-saturate the streets. The structure of the policy can be observed in Figure 20.

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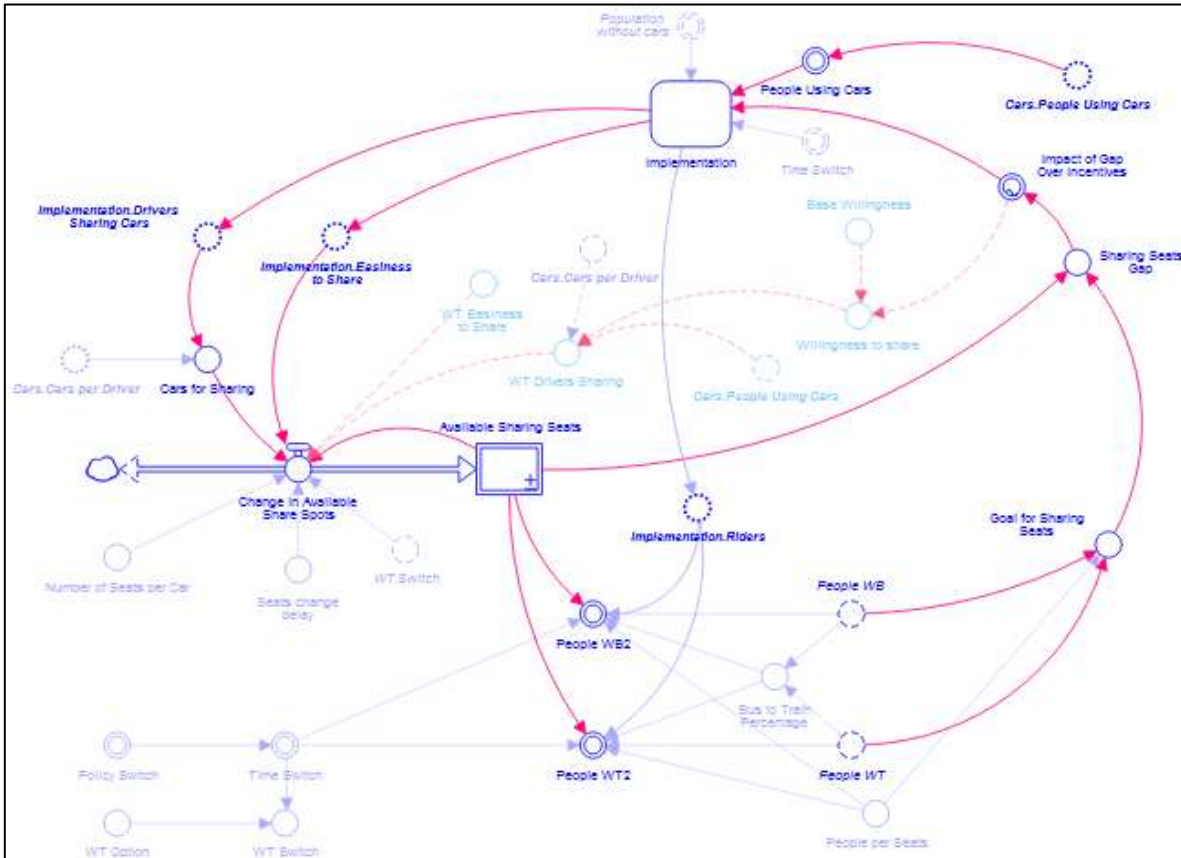


Figure 20. *New Structure Policy Testing SFD*

The SFD presented in Figure 20 has variables of three different colours. The grey variables indicate ghost variables (mirrors of variables in other sections of the model) or switch variables (variables that activate the use of the policy). The variables in light-blue and dotted lines represent the “wishful thinking” implementation of the policy. Finally the dark blue variables show the real structure of the policy and include an implementation module which will be explored in the next section of the thesis.

This policy will be analysed in two different ways. The first one will be through “wishful thinking”; in other words, assuming the implementation of the policy has no problems and happens with optimal conditions (this can be observed in the I. The second test will be executed through a real implementation structure

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which considers implementation delays and costs as well as variation in different feasibility variables.

New policy high level description.

The objective of the new structure policy, as mentioned before, is to improve the problem of traffic in MVMA. Figure 21 shows a high level causal loop of the SFD of the policy (Figure 20) in order to simplify its explanation. The main difference between the two diagrams is the lack of the flow and stock structure which “stores” the amount of available seats ready for sharing.

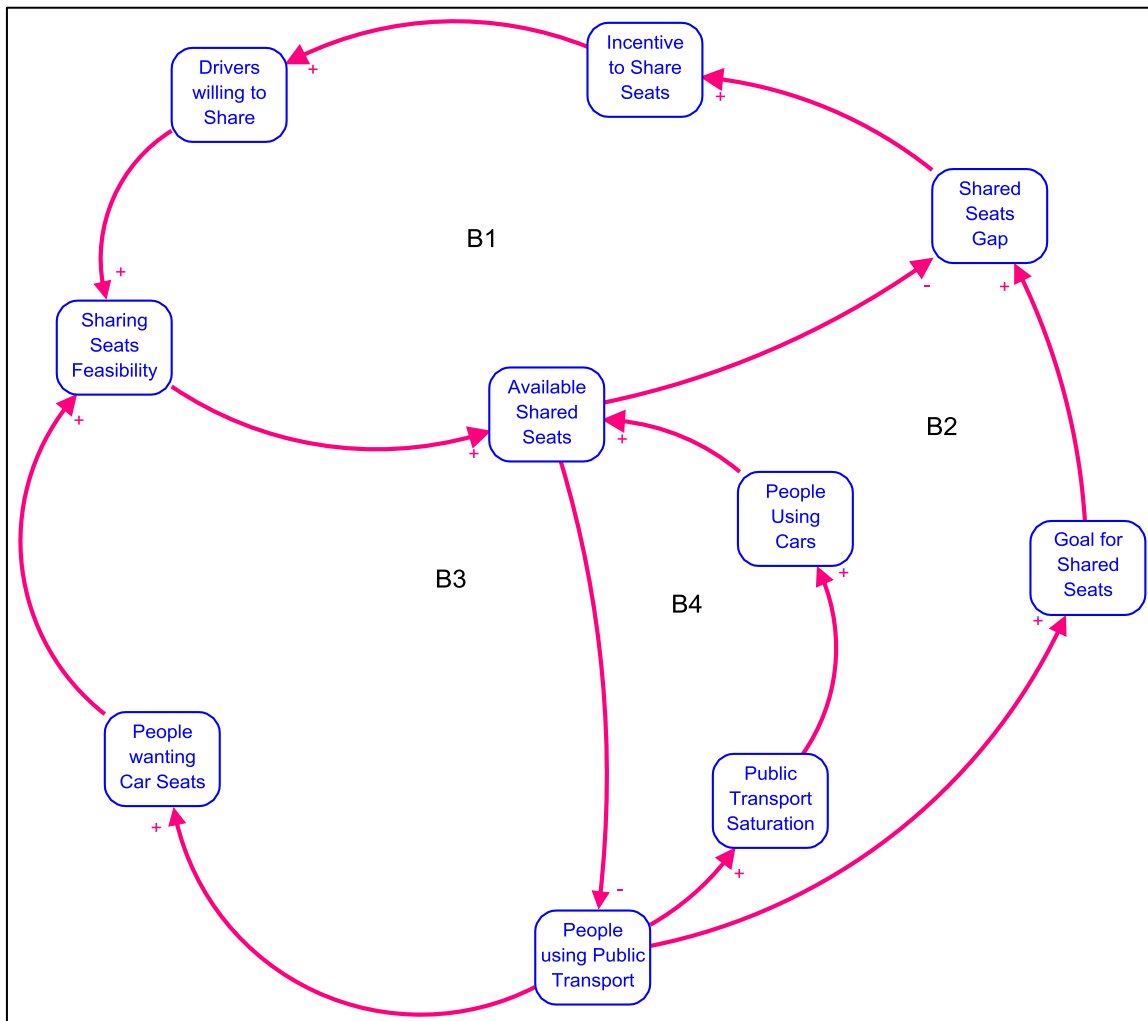


Figure 21. *New Structure Policy CLD*

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The CLD shows four balancing. In terms of the planned objective, the balancing loop number four is the most vital one as it will restrict the growth of the amount of people using cars. Balancing loop 4 describes how the increase in available shared seats will decrease the amount of people using public transportation services which will de-saturate those services therefore enticing some car drivers to utilize public transportation.

On the other hand, although not so directly influential, the balancing loops one, two, and three also have important effects. The first balancing loop describes how a decrease in available shared seats will increase the incentives to share car seats therefore increasing the willingness of drivers to share and finally causing an increase in shared seats; this balancing loop will assure that the number of shared seats stabilizes at a number that is sustainable by the system. The second balancing loop adds up to the first one by showing how the increasing numbers of people using public transportation will also eventually cause an increase of shared seats therefore causing a stabilizing effect. Finally the third loop shows the how the system might stabilize due to its feasibility; as more people use public transportation; more people are willing to travel by shared car and therefore the easier it is to coordinate the car sharing system.

As mentioned before, the SFD follows the same logic that is presented in the Causal Loop Diagram with the only difference being that the amount of available seats to share gets added up in a stock which varies each time period depending on the flow of people who are willing to share their car.

Implementation structure.

As mentioned before the analysis of the policy requires an implementation structure which can be optimistic or realistic. The optimistic scenario or “wishful thinking” assumes a policy gets implemented without problems. On the other hand, the realistic scenario shows a structure that considers possible delays, costs and restrictions of the policy.

Figure 22 shows the “wishful thinking” implementation section of the policy structure. It can be observed that the incentives have a direct impact over the willingness to share, and therefore over the amount of drivers sharing their car. It also assumes that there will always be people wanting to use a seat in a shared car. In this structure there are no delays accounting for the time it takes to liquidize the incentives, for people to be convinced, or for potential passengers to get coordinated with the drivers.

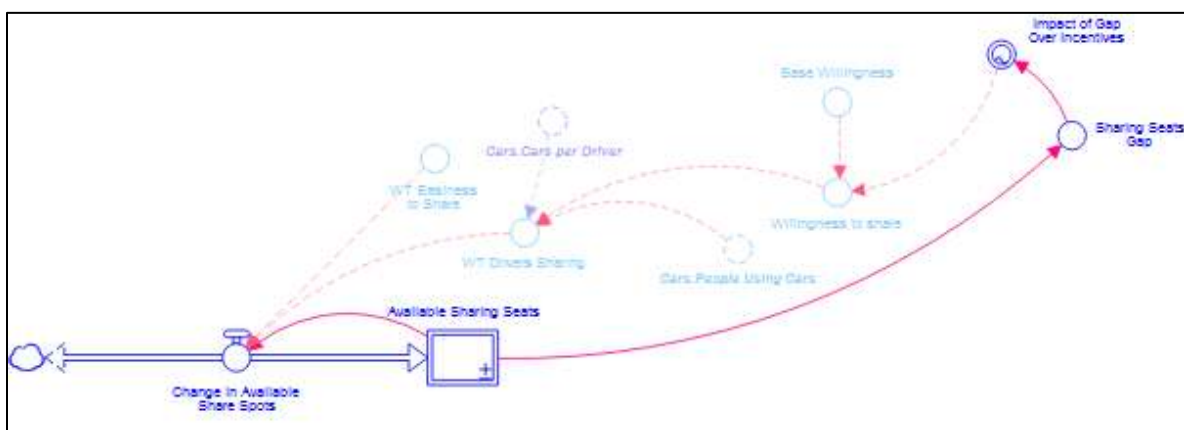


Figure 22. New Structure Policy Wishful Thinking SFD

The only limitations to this structure (which are analysed in the results chapter) come from the variables “Base Willingness” and “WT Easiness to share”.

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On the other hand, a realistic implementation requires a much more complex structure which can be observed in Figure 23. The realistic implementation structure considers three main limitations to the policy. The first one analyses the availability of a budget for incentives. The second limitation shows the time it takes to entice and screen potential drivers who will want to share their cars and their reaction to the change in incentives. Finally, the third implementation limitation analyses the time it takes for people without cars to be persuaded to use shared cars and for these people to be screened.

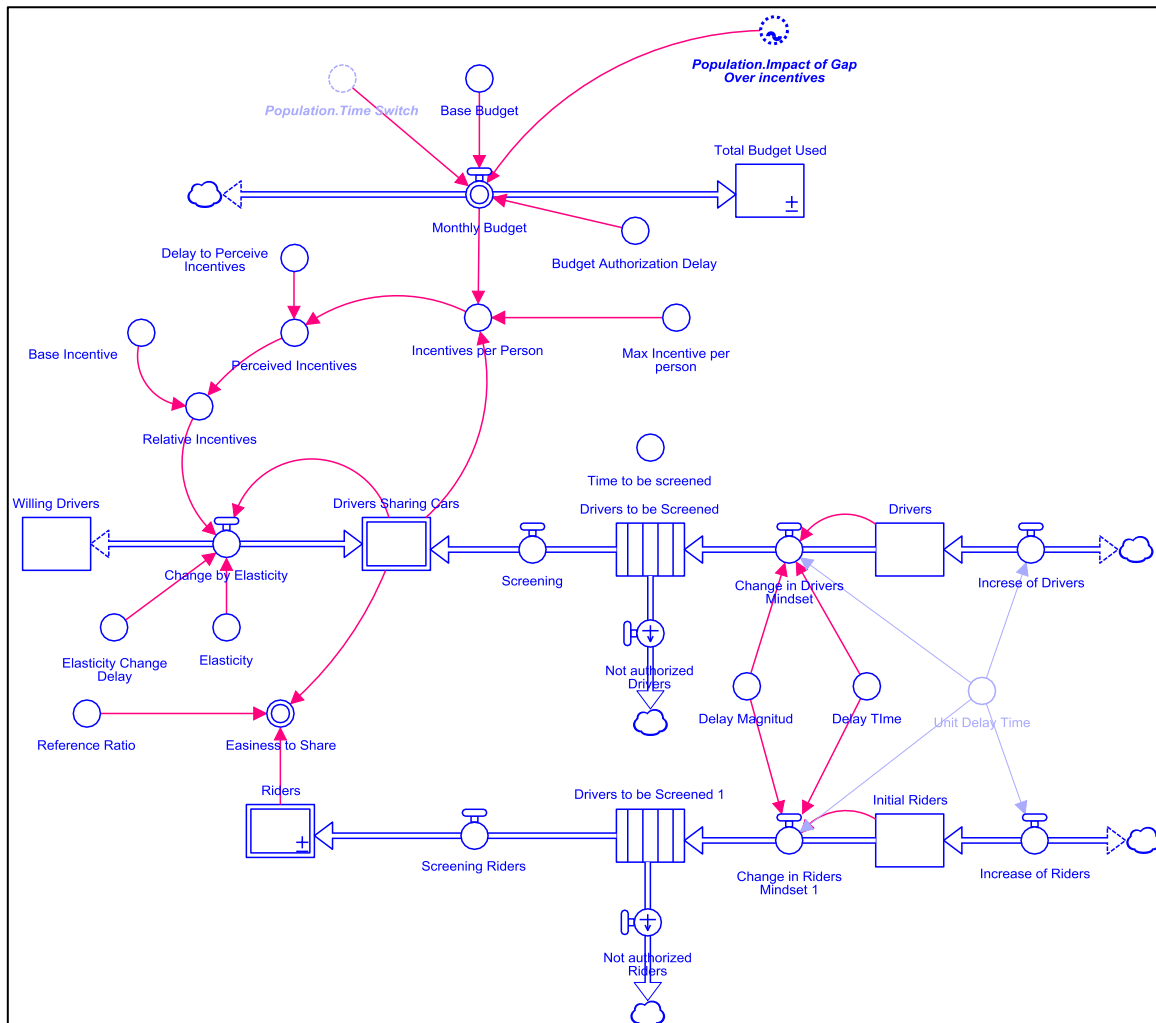


Figure 23. New Structure Policy Realistic Implementation SFD

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The budget section consists of a basic flow and stock structure in which a monthly budget is used and accumulated into the “Total Budget Used” (Used only for policy analysis purposes). The monthly budget flow is then affected by the required time to authorize the budget and the impact of the size between the desired and available shared seats quantity. Depending on the size of the gap, the base incentives can be doubled or eliminated.

The section about drivers willing to share their car is a little bit more complicated as it involves a three step process. The first step in the process is the “reception” of new drivers, in other words, drivers that have not yet been considered by the system. The second step represents a screening delay in which all drivers must be certified to be able to drive other passengers. Once drivers are certified and sharing their cars, the third step begins; the drivers react to the amount of incentives they are receiving and therefore stop sharing their car or continue sharing it. This section does not consider altruistic behaviour meaning that people will only be enticed by financial gain.

The third section is similar to the previous one with only one difference. Once the people asking for “rides” get enticed (step 1) and screened (step 2) they remain as potential “riders” as their participation does not depend on the incentives. The model assumes that as long as they can find a car that will take them to their destination they will use this service.

Research Results and Discussions

This section of the thesis will present the analyses, results and conclusions that were mentioned during the Method Chapter. As in said chapter, the presentation of results will follow the same order as indicated during the methodology explanation. Finally, it is important that the conclusions in this section will be partial and will be more deeply explored during the conclusions Chapter.

The P'HAPI methodology indicates analysis as the third step. However, the methodology is iterative and therefore there were several analysis executed before arriving at the final version of the model. This paper only presents the final analysis, in other words, the analysis that was made after reaching the final version of the model.

Initial Testing

The first set of analyses corresponds to the functionality of the developed model. As mentioned, this set includes logical and dimensional testing. Every variable must represent a meaningful real-world concept. Additionally, every variable must have been represented with an appropriate dimensional unit. Finally, the model must produce a behaviour that is close to the real life behaviour which was observed.

The first part of the model testing is complicated to document as it refers to the real-world meaning and use of each variable. Appendix 6 shows the documentation of all variables and equations which, after review seem to appropriately represent real-world variables. The secondary test of this

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corresponds to the reader as all the variables and structures were explained during the description of the dynamic hypothesis of this thesis.

The dimensional testing of all variables is also difficult to document as it would imply going through every variable and the corresponding formula. This test

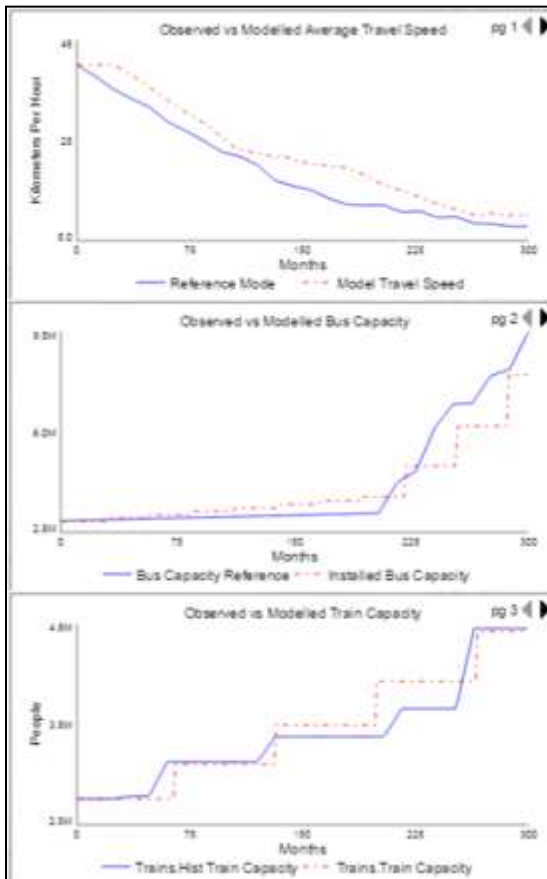


Figure 24. Observed vs Modelled Behaviours

was however effectively executed by the modelling software Stella Architect® (iseesystems) which automatically executes a unit check and reports any mismatching units. The result of this test was positive as there were no mismatches and all the units were congruent with their formulas.

Finally, the behaviour of the model was compared with the observed historical behaviour in order to analyse the validity of the model. Although the result was not a perfect match, there is a strong similarity

between the behaviour shown by the model and the real-life data (presented in Figure 24). The average travel time is showing a similar non-linear behaviour as the one observed by the historical data. In a similar manner, the bus capacity is following a similar behaviour to the real one even with the change of policy in 2007. Finally, although the train capacity is not following the exact same dates in which

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new lines were inaugurated, the resulting train capacity is nearly identical in both cases.

Taking into consideration this first set of analyses, it can be concluded that the model represents the structure and behaviour of the transportation system in a suitable manner.

Extreme Condition Testing

Once that the validity of the model was confirmed, the next step is to test the model under extreme conditions. For this, several variables were modified and a wide array of results was obtained. This thesis will not present the results of all the tests as some of them were fairly logical but it will present some of the most interesting results.

The first analysis that was made explored what would be the behaviour of the model if the population growth went to extreme levels. The selected levels were a growth of zero and a growth of 10% per month. The results under these conditions were more or less predictable as it can be observed in figure 25. For extreme growth, it can be observed that the number of users is limited by the

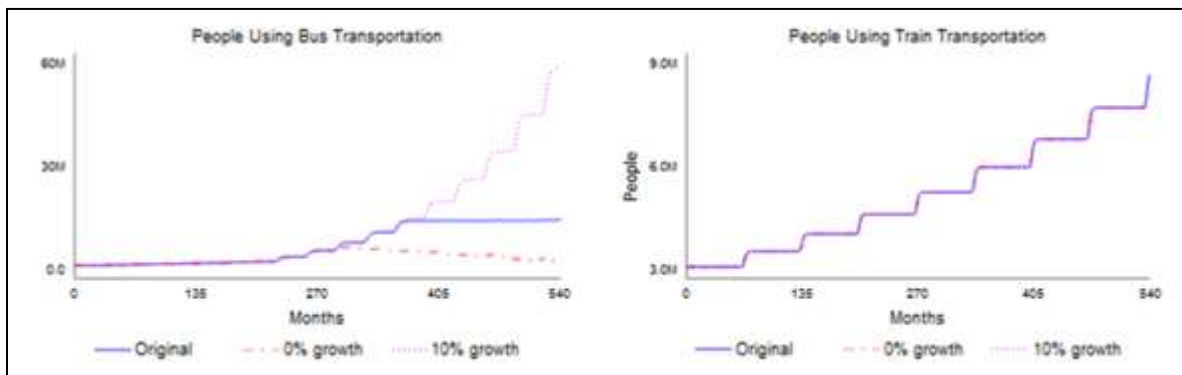


Figure 25. Extreme condition testing 1; Train and Bus Capacity Growth

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speed at which the system capacity can grow. The curious result is observed when the population growth is zero as the amount of people using train services is as much as the capacity will allow while the bus occupancy does not even reach the value of the original run. Although the result is unexpected, it is logical as the reason people choose to travel by train is that the average travel speed of a bus is

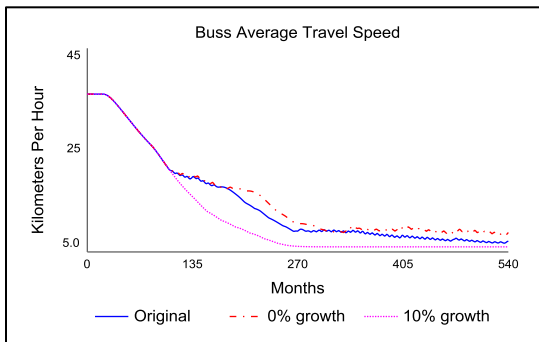


Figure 26. *Extreme condition testing 1; Bus Travel Speed*

really low in all three scenarios.

Although the behaviour is not exactly what would be expected, this test shows that the model is still acting in a logical way in spite of the extreme conditions. Perhaps the major caveat

would be that there is no limit to the capacity expansion a transportation method can have and therefore they keep growing as fast as the model allows.

The second scenario for extreme testing was modifying the rate at which the population acquires cars. For this test the analysis used values of 0% and 0.8% monthly growth. The results showed in figure 27 indicate that the model once again behaved logically. When the amount of people with cars remains constant, the majority of the population decide to use the bus transportation (the streets do not get saturated in that case) therefore not requiring a huge development of the train network. On the other hand, when the available cars increase at an accelerated pace, the streets get saturated forcing the train system to grow as fast as possible. In any case, the model follows a logical procedure and holds under these conditions.

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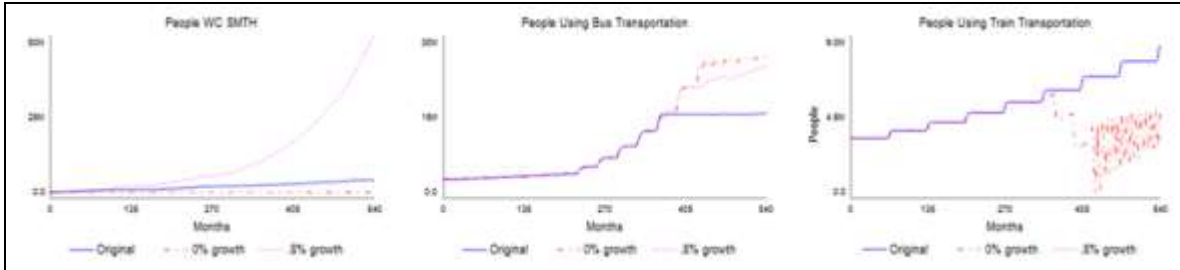


Figure 27. Extreme condition testing 2; Car, Bus and Train systems usage

Model Sensitivity Analysis

As the model was proven to be functional, the next step is to test the sensitivity of variables that could feasibly be modified. As established before, the variables that were tested for sensitivity are: travel cost, travel time and capacity development delay.

Capacity development delay.

This analysis shows the behavior of the variables that have been under observation (Car travel time, Bus Capacity and Train Capacity) when the delays on the development of the transportation system vary. The sensitivity analysis was run under six different scenarios in which the capacity building of the different systems had the following values:

	Street Cap. Delay	Bus Cap. Delay	Train Cap. Delay
SA 1	0	1	1
SA 2	9.6	10.4	10.4
SA 3	19.2	19.8	19.8
SA 4	28.8	29.2	29.2
SA 5	38.4	38.6	38.6
SA 6	48	48	48

Figure 28. Delay Sensitivity Parameters in Months

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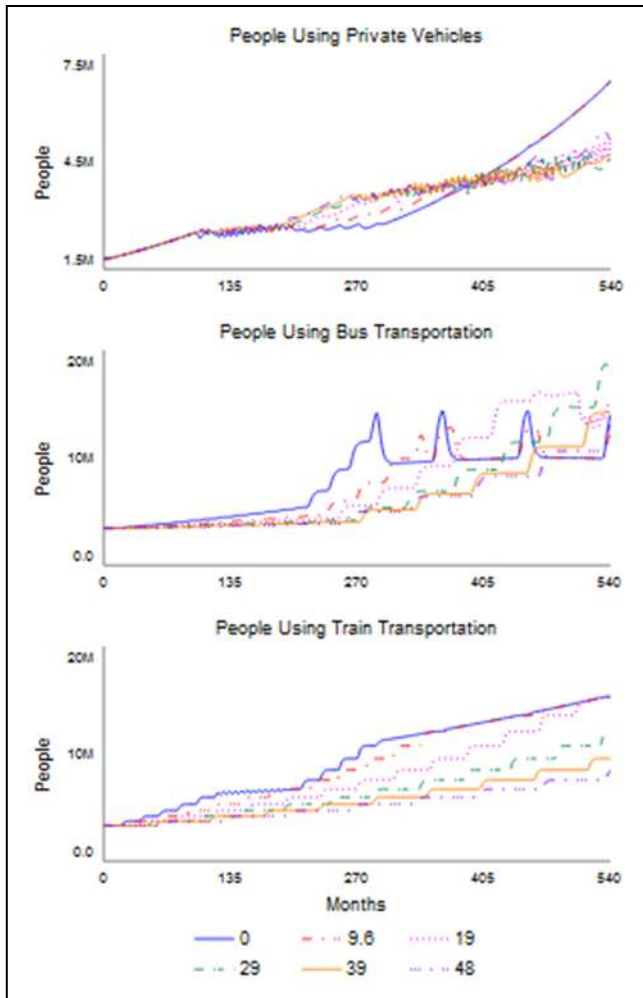


Figure 29. *Transportation Expansion; Delay Sensitivity*

The result of this analysis is significant as the variations in the capacity delay variables have a huge effect over the performance of the model. For starters, the value of the average speed of travel for cars has a 100% value change from the best performing scenario (Delay 0) to the worst (Delay 48). Similarly, it can be observed in Figure 28 that the changes in capacity delay create heavy variations when calculating the amount of people using each type of transportation. The amount

of people using the train system varies as much as 78% while the amount of people using busses varies as much as 72%.

It can be concluded from this sensitivity analysis that the impact of the capacity development delays is significant to the model. It is therefore important to proceed with care when simulating changes to this variable. Although the model is not considering the implementation problems of reducing or incrementing the delay time of this variable, anyone making use of the model must keep those limitations in mind.

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Reference travel time.

The second variable to be tested was the reference travel time of the different transportation methods. In a similar way, different values were tested to see how that affected the behavior of the model. In this case, the results are presented when individual changes were made to the reference travel times of the transportation systems.

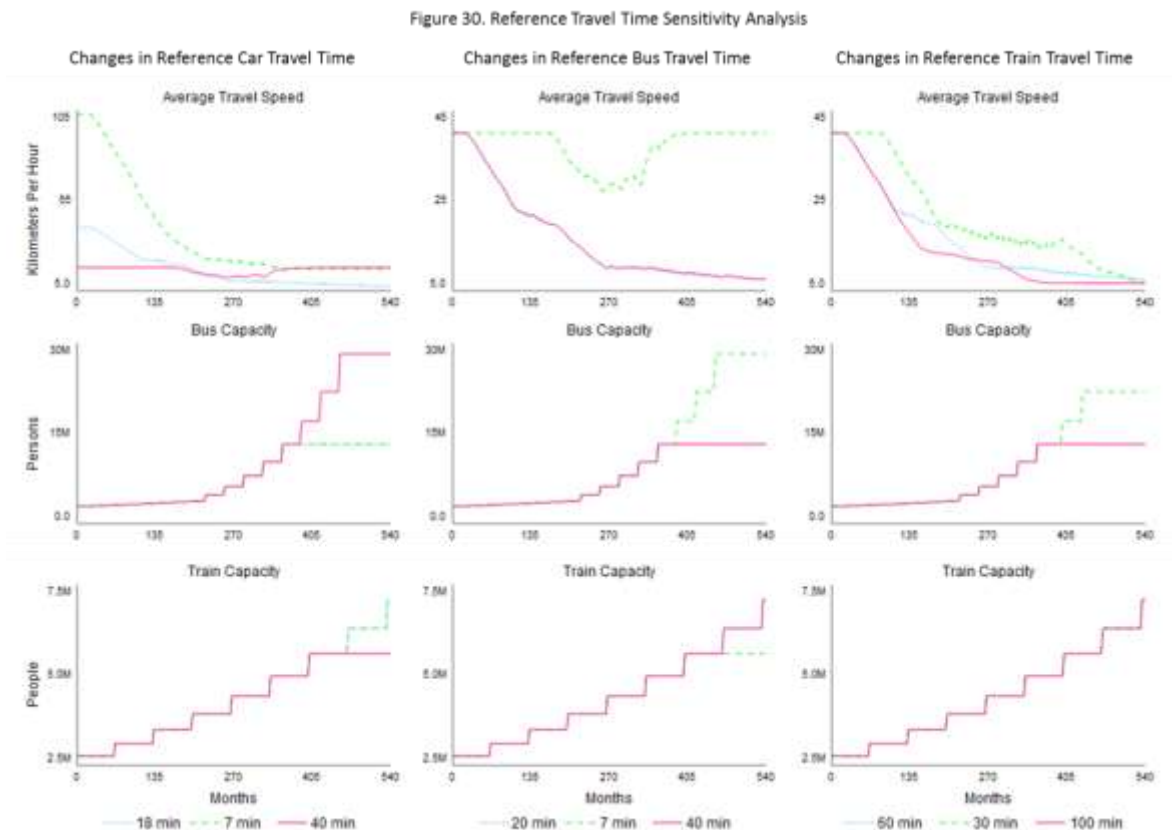
- Reference Car Travel Time: 6, 18, and 40 minutes.
- Reference Bus Travel Time: 7, 20, and 40 minutes.
- Reference Train Travel Time: 30, 60, and 100 minutes.

Figure 30 shows an array with the graphics of the different results. It can be observed that these variables have a significance sway over the behavior of the model. Changing the initial values of the reference travel time for the different transportation methods has an obvious influence over the Car Travel Speed, however it also has strong effects over the development of capacity for public services.

Altering the reference travel time for cars has an immediate and logical effect over the behaviour of the Average Travel Speed of cars. This variable is, after all, setting the initial value of the travel speed. In this case it is interesting to observe that initiating the simulation with a high car travel time has the secondary effect of pushing the development of the bus system therefore ending up with a better speed average than in the other simulations.

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The middle column of Figure 30 shows how altering the value of the Bus Reference travel time affects the model. This variable has a huge effect on the Average Travel Speed of cars. It can be seen, when the reference travel time is set to a minimum, that having a faster service incentivized people to use the bus instead of cars and therefore accelerated the development of the bus infrastructure. This is also noticeable because under that scenario the development of the train system is not required to be as high as projected in other situations.



Finally, it is interesting to see the impact of the reference train travel time over the behaviour of the car travel speed. When the reference train travel time is reduced, the fall of the car travel speed is delayed while the opposite happens when the train reference travel speed is increased. This happens most probably because a faster train system discourages people from using cars. On the other

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hand, it is also interesting to observe that the capacity of the train system is not able to grow fast enough to satisfy the demand when the initial reference travel time is smaller; therefore the model compensates by accelerating the development of the bus network.

In conclusion, it is important to notice that changing the reference speeds can have a big impact on the performance of the model. Said impact is not limited to the Car Travel Speed as it also has a substantial effect on infrastructure development. One interesting behaviour that will be later explored in policy analysis is the effect fast bus travel speeds have over the overall performance of the system.

Reference travel cost.

The third and final sensitivity analysis focuses on the different costs of using a service. Altering the reference travel cost may make one of the transportation methods more accessible than the others therefore incentivising a faster infrastructure development and therefore diminishing the pressure over the other systems. As with the previous analysis, this section will observe the changes individually instead of simultaneously.

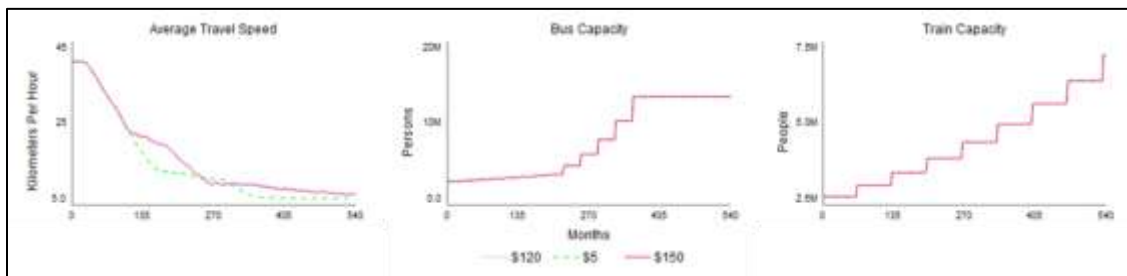


Figure 31. Average Travel Speed, and Bus and Train Capacity; Car Reference Travel Cost Sensitivity

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The first observation of this analysis is that the reference cost of car travel does not have a big impact over the performance of the model. This is caused by the fact that when the reference cost is low, the public systems cannot satisfy the whole demand by themselves and the cars still remain available only for a fraction of the population. When the car reference cost is high, it does not make a big difference because it is already the most expensive method of transportation anyways.

Contrary to that, the reference travel cost of busses does have a big impact over the model. This effect is particularly noticeable when the reference cost is diminished. Under said situation, most people try to use busses instead of trains therefore incentivising the government to increase the available bus capacity. This in turn helps clear the streets and allows for the car travel speed to reach its intended goal. On the other hand, if the reference cost is increased, the pressure stays over the train transportation system.

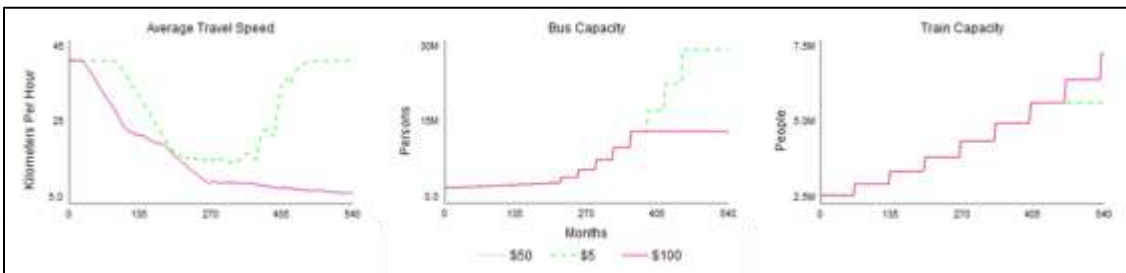


Figure 32. Average Travel Speed, and Bus and Train Capacity; Bus Reference Travel Cost Sensitivity

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Finally, the reference cost of the train network cannot be diminished much as it is already the cheapest service. It is interesting to notice that increasing the reference cost of this service creates a similar effect than diminishing the reference

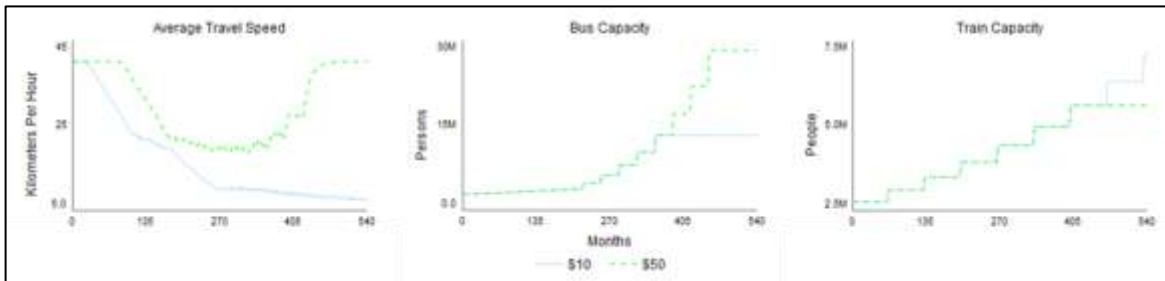


Figure 33. *Average Travel Speed, and Bus and Train Capacity; Train Reference Travel Cost Sensitivity* cost of busses; this happens because in both cases the preference shifts from the train transportation to the bus transportation. It can be observed that when said shift happens, the development of bus infrastructure gets prioritized. This is also an interesting phenomenon which will be considered during the policy analysis.

Policy Exploration Results

After analysing the effect of several variables over the model and understanding the main alterations the model can suffer, the focus shifted towards providing a potential solution for the observed problem (the diminishing travel speed). As mentioned in the methodology section, potential solution policies can be either internal to the model, through the change of certain parameters, or additional to the model, through the aggregation of an additional structure.

Internal policies.

There are many different policies that can be analysed by changing parameters inside the model. However, it is important to consider that altering the values of certain variables might have implications outside of the scope of this

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model. In this case, the internal policies to be analysed come from the objectives the MVMA government set (mentioned in the introduction section) mainly increasing the capacity of the streets and the subway system, and adding bicycle lanes. Additionally, this thesis will explore the option of reducing the travel speed of the bus system; this could be achieved by generating bus-only lanes in the available street network.

The first analysed policy was the increment of the rate at which the street and train capacity is being developed. As this analysis is a policy one, the effect of this policy will start at the time step 300. In figure 33 we can observe that the policy

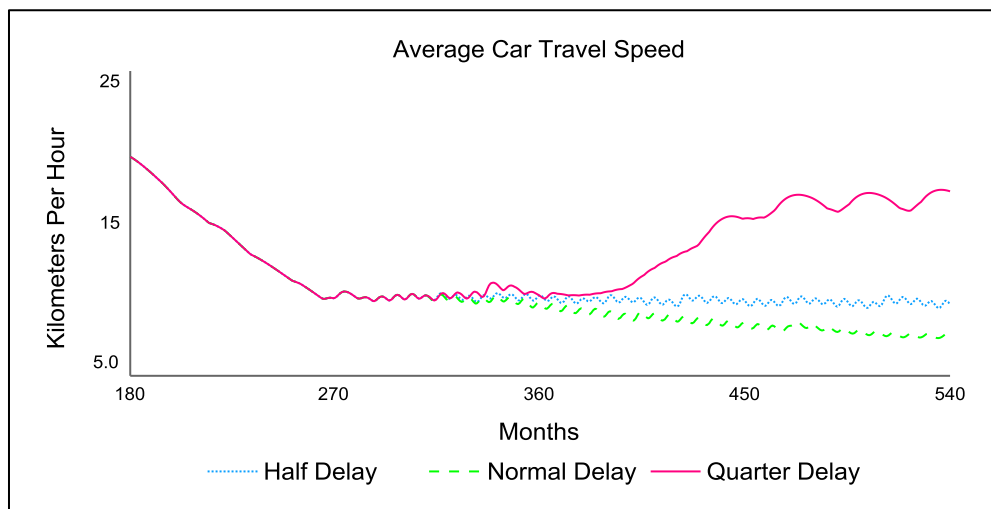


Figure 34. Policy Analysis; Increase in capacity development rate

indeed has a positive effect over the car average travel speed. At Half-Delay or, basically, double the rate at which capacity is developed, the travel speed remains more or less constant. If the delay is cut in four, the average travel speed improves significantly. However, as mentioned before a quick analysis of this policy is not recommended as the costs of accelerating the construction of new infrastructure might be unfeasible. In this case, in order to reach the half-delay benefits, the city

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would have to increase the street capacity by 95% and the train capacity by 81% in the next 20 years. Those numbers imply almost doubling current capacity and therefore, in a super saturated city, it could be an impossible achievement.

The second policy that was analysed was the creation of more bicycle lanes. For this, the model just assumed that the number of people using the three main methods of transportation would instead use the bicycle lanes. This means that the

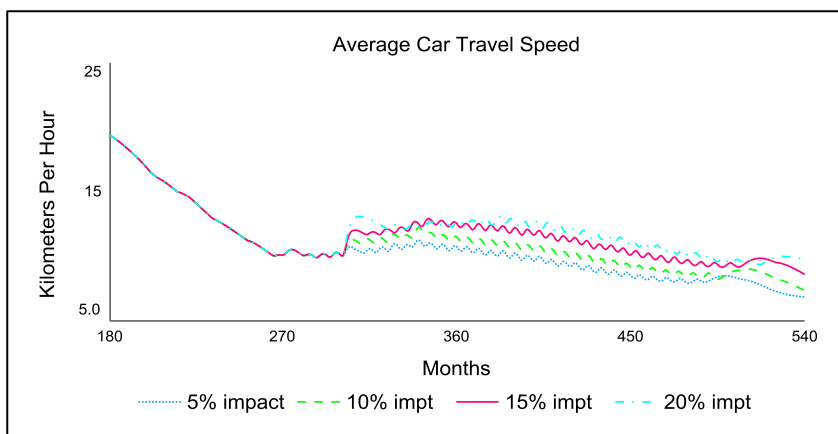


Figure 34. Policy Analysis; Addition of Bicycle lanes

amount of people using the main systems would be less and therefore the current capacity would be more sufficient.

Finally, the third explored policy analyses the possibility of improving the travel speed of the bus system by adding designated lanes only for busses. In the model, the only change will be on the parameter bus travel time. The results of this analysis were very positive and present a relatively feasible policy. Diminishing the travel time of the busses and therefore augmenting their perceived speed has a very positive impact over the average car travel time. Figure 35 shows the different scenarios for this policy analysis (10% less travel time, 30% less, 50% less and 70% less). It can be noticed that every scenario from 30% reduction in time and more eventually balances out the car travel speed at a healthy 40 km/hr.

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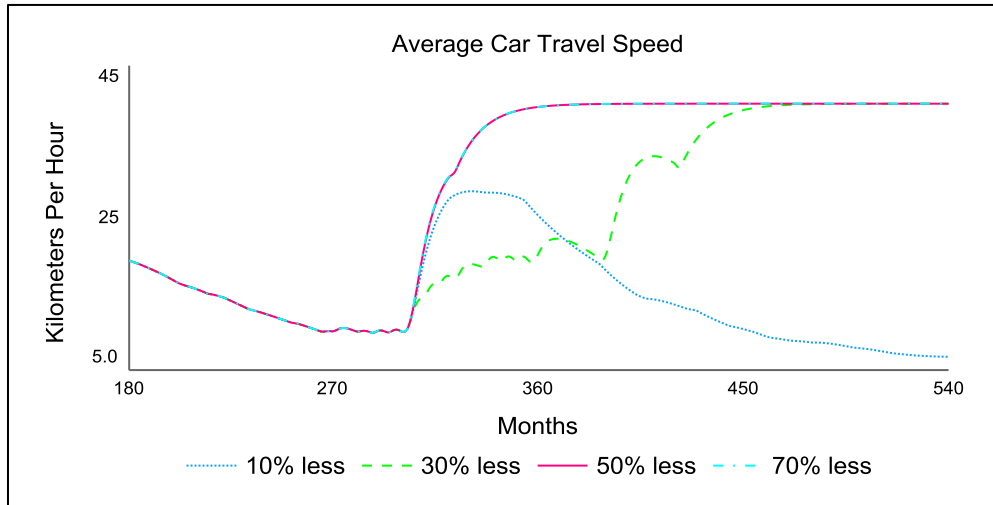


Figure 35. Policy Analysis; Bus Only Lanes

However, it is important to consider that increasing the busses speed by one third will require effort and probably more time than just changing a parameter in a model.

New structure policy analysis.

Finally, we arrive at the analysis of the new structure policy to evaluate the policy of sharing car seats. This policy was suggested because it takes advantage of an infrastructure that is already there only by increasing its efficiency. Therefore, the potential costs of implementing the policy could be less than developing a whole new infrastructure. As explained in the methodology section, this policy was analysed in two ways: wishful thinking and realistic thinking.

Figure 36 shows the difference between the two policies and the “as-is” performance. It clearly shows the wishful thinking scenario to be more effective than the realistic one. However, both policy scenarios present improvements over the current operation of the system.

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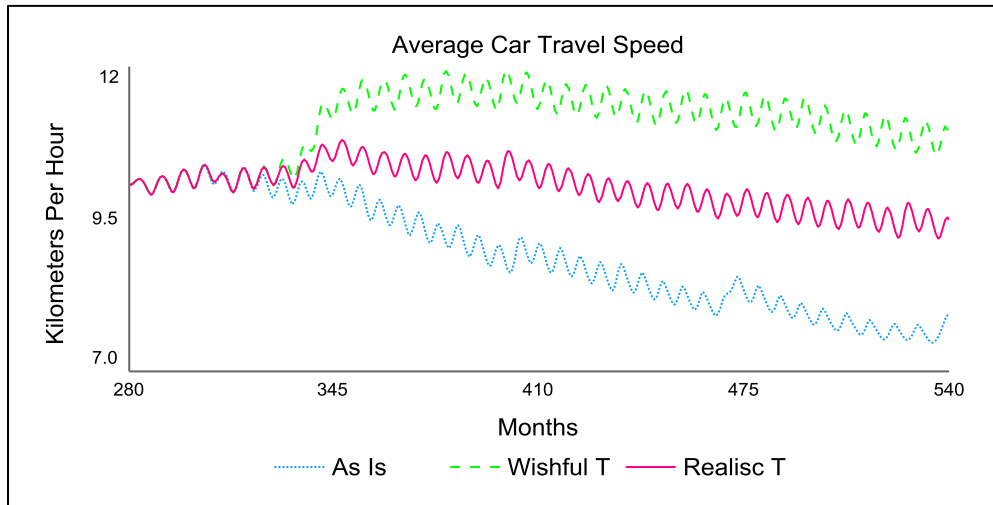


Figure 36. Policy Analysis; Car Sharing Policy Wishful and Realistic Thinking

It can be observed that the current way of operating will just continue to drive down the average car speed while implementing the policy will have an immediate impact. Even in the realistic thinking simulation, which considers policy adoption delays, the impact can be perceived almost immediately.

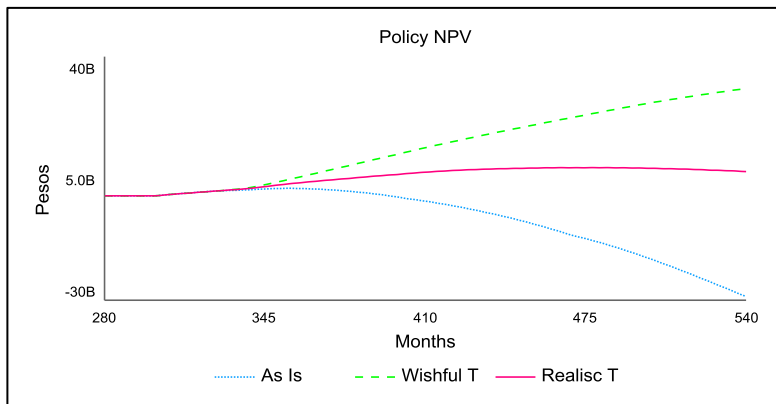


Figure 36. Policy Analysis; Net Present Value Analysis

In addition to the observed improvement over the travel speed, an estimated Net Present Value analysis shows that both the Wishful thinking policy and the realistic

policy show positive net monetary flows. This is clearly a positive result as the current way of operation would incur in massive costs.

Finally, it is worth mentioning that both the Wishful thinking and the realistic policies can have varying results if the parameters of their structures are modified.

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Describing all the possible scenarios would be impossible and therefore it is recommended to utilize the model interactive feature to explore all possible variants.

Conclusions

Executing a System Dynamics analysis proved to be extremely useful. It allowed the understanding of the interactions that exist within a very complex system. By designing the model structure it was necessary to reason how each element of the system could affect the next one and therefore just by constructing the model, the understanding of the system was elevated. Additionally, this type of analysis is great to visualize the kind of delays that exist in a model just as Cascetta (2009) affirmed in his book.

On the other hand, building a model based on dynamics provides a very distinct advantage which is simulation. Being able to simulate different values within the variables, alternative policies and potential new structures gives a strong advantage over other analysis methodologies.

Regarding the observed problem, the results demonstrate that it cannot be solved by just attacking the lack of infrastructure. The problem is systemic and therefore the solutions must consider the state of the whole system.

Policy

Considering the observed results, it is easy to recommend the car sharing policy as it presents positive results over the current operating model even when considering a realistic implementation. However, it is important to mention that this

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policy could be augmented with the Bus-Only lane policy mentioned in the Internal Policies section. The combination of both policies could prove excellent to solve the observed problem.

Why the proposed policy is realistic

The recommended policy is realistic mainly because of two things. Firstly, it only looks to optimize the use of an infrastructure which is already there. Secondly, it plays into the whole system not only by taking advantage of the private cars but also by liberating the public services.

Potential Additional Research

As additional research SD modellers could dig deeper into the specific structure and behaviour of the bus and subway systems. Additionally a model of the street network could be built to analyse this problem in a more specific way; focusing on trouble points rather than on the system as a whole.

On the other hand, the internal policies that were mentioned could be explored further by building a whole structure for its implementation. It could be very interesting to see the potential impact and cost-benefit analysis for said policies.

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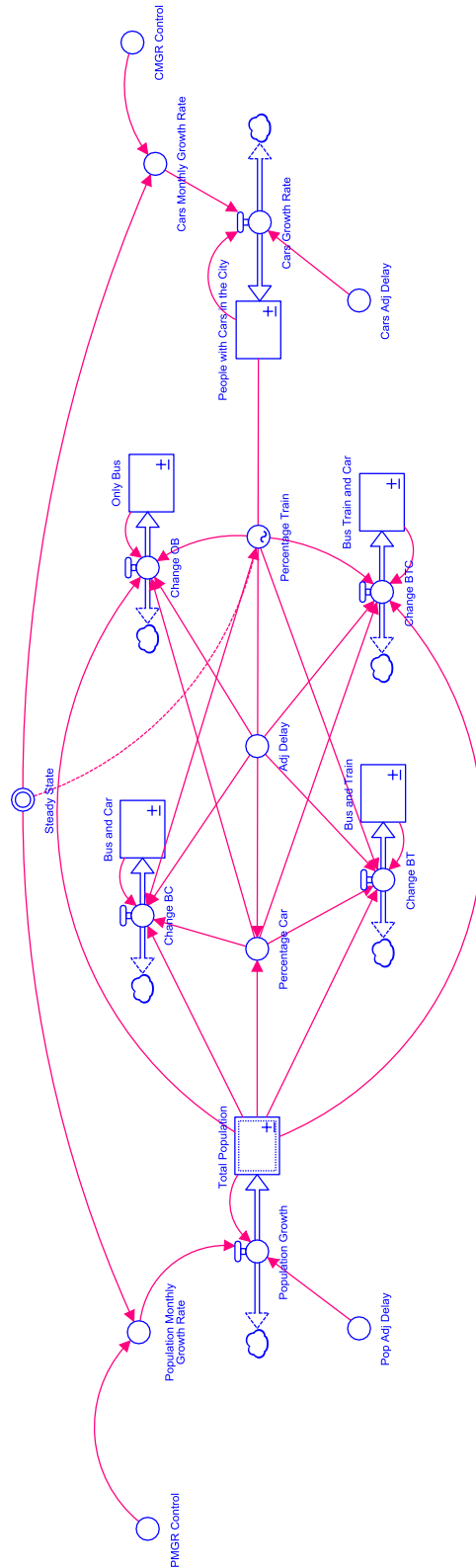
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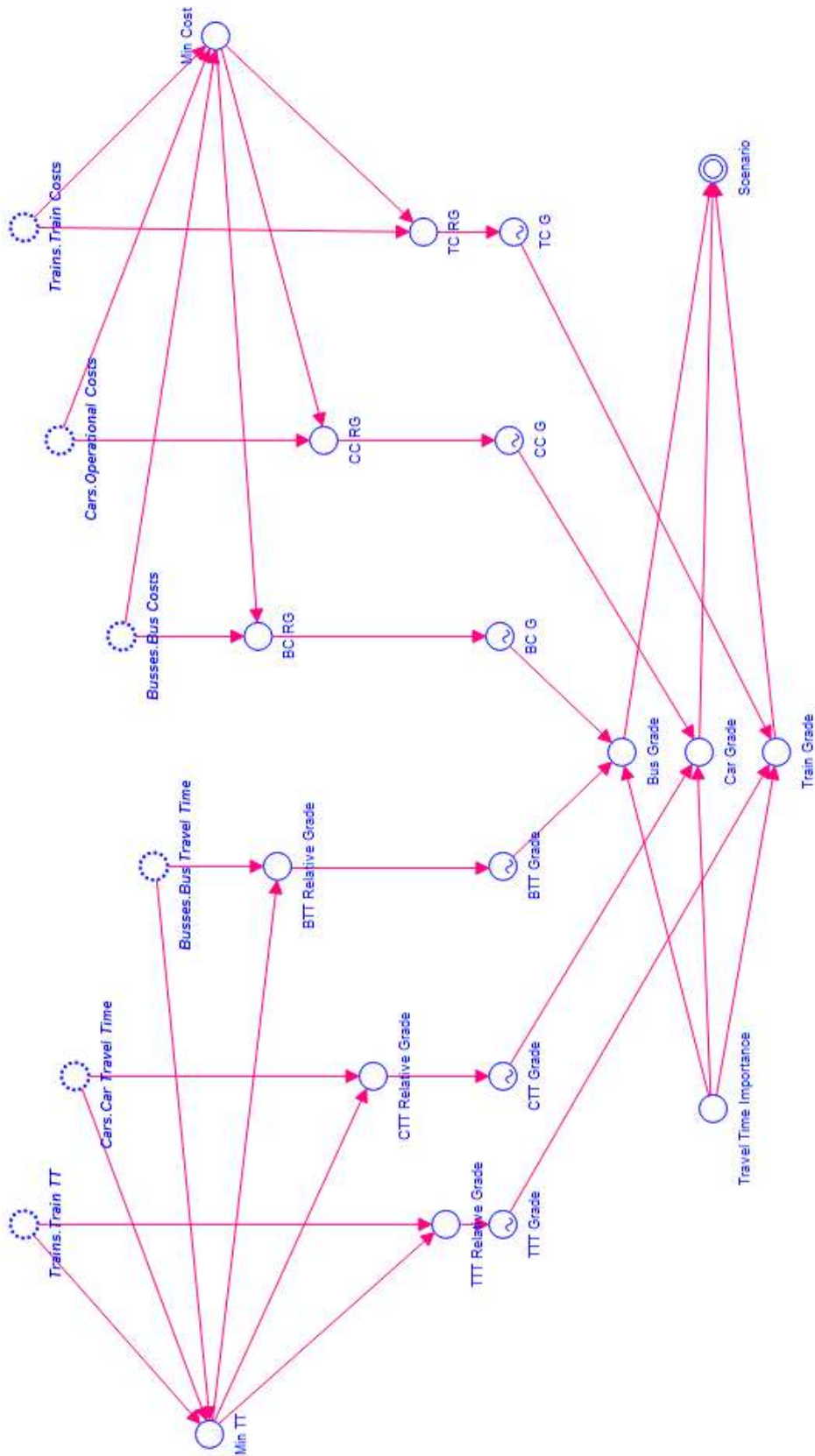
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Appendix 1. SFD. Population Distribution According to Possibilities



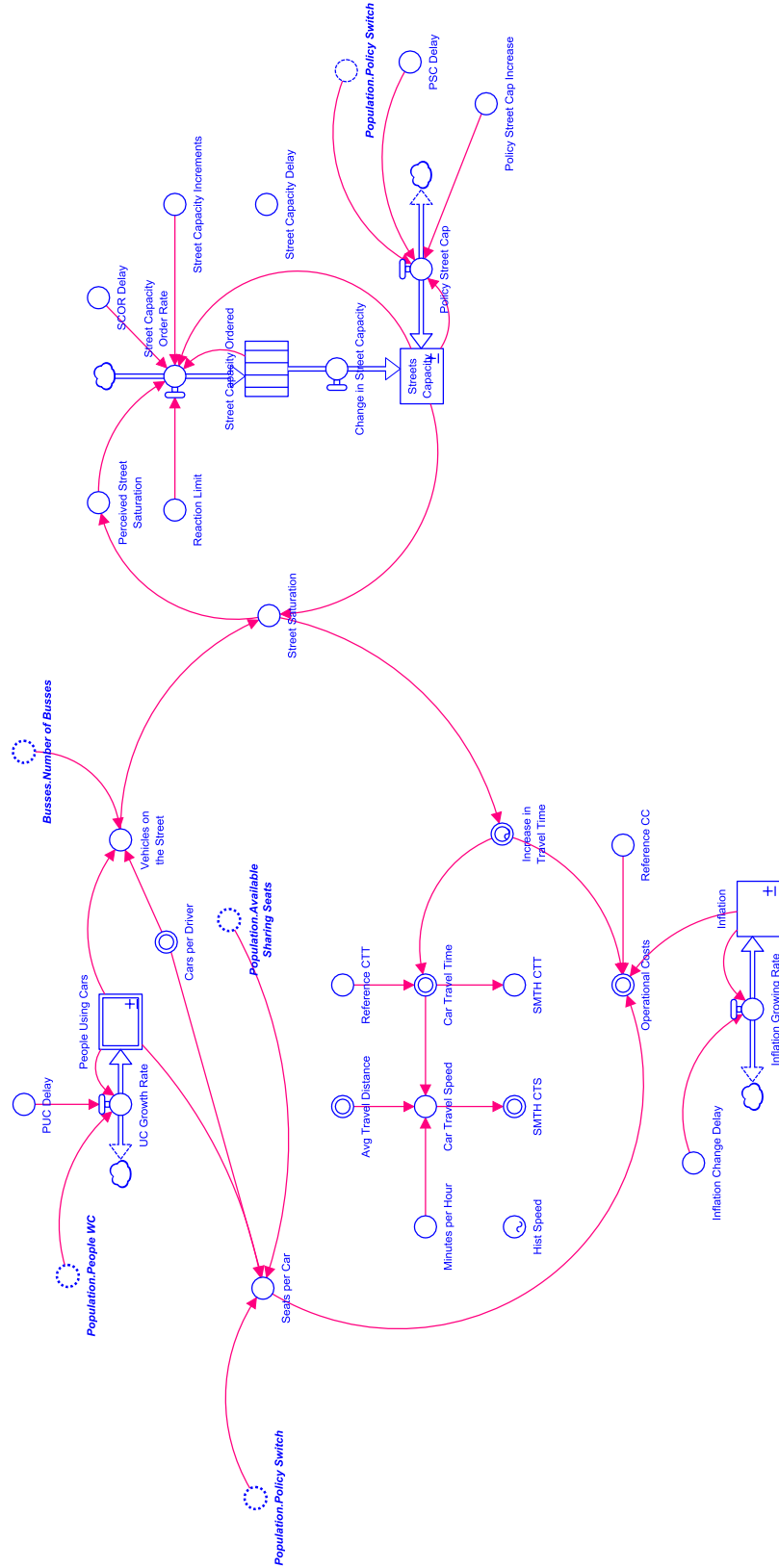
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Appendix 2. SFD for Scenario Definition.



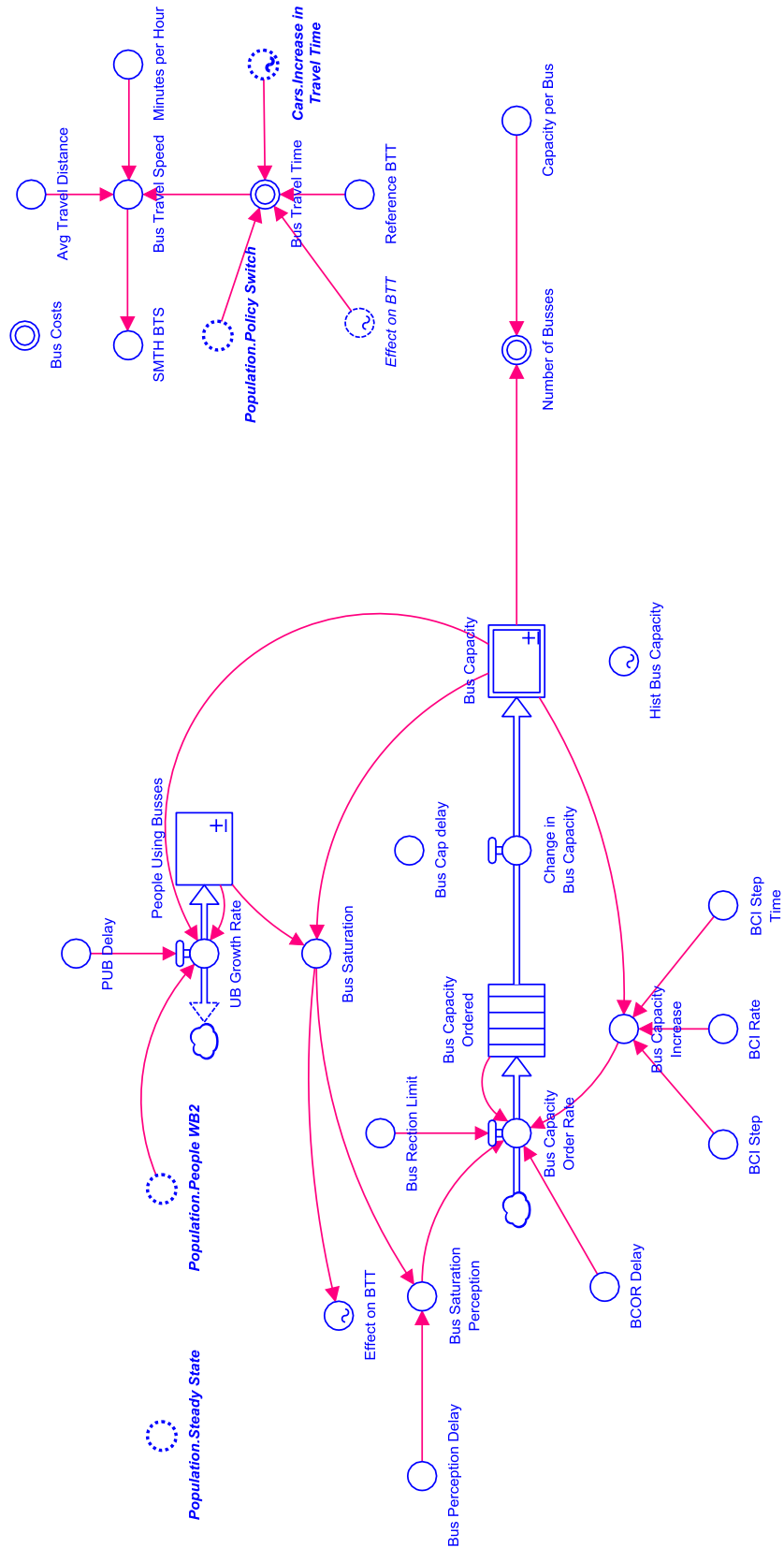
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Appendix 3. SFD Complete Cars Module

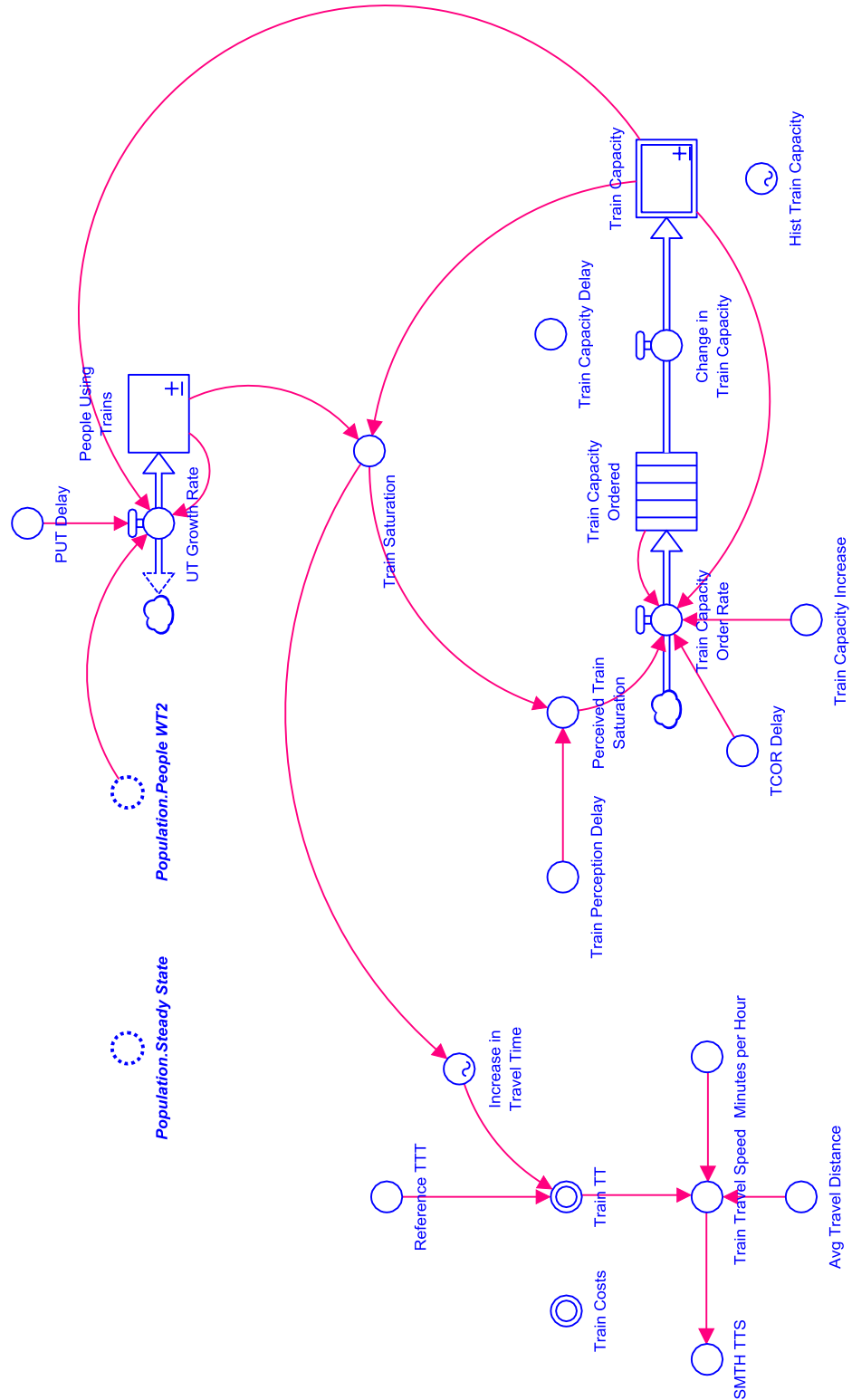


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Appendix 4. SFD Busses Module



Appendix 5. SFD Trains Module.



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Appendix 6. Model Formulas

Top-Level Model:

Busses:

$$\text{Bus_Capacity}(t) = \text{Bus_Capacity}(t - dt) + (\text{Change_in_Bus_Capacity}) * dt$$

INIT Bus_Capacity = IF(Population.Steady_State=1) THEN 12000000
ELSE 2890250

INFLOWS:

$$\text{Change_in_Bus_Capacity} = \text{CONVEYOR OUTFLOW}$$

$$\text{Bus_Capacity_Ordered}(t) = \text{Bus_Capacity_Ordered}(t - dt) + (\text{Bus_Capacity_Order_Rate} - \text{Change_in_Bus_Capacity}) * dt$$

$$\text{INIT Bus_Capacity_Ordered} = 0$$

$$\text{TRANSIT TIME} = \text{Bus_Cap_delay}$$

$$\text{CAPACITY} = \text{INF}$$

$$\text{INFLOW LIMIT} = \text{INF}$$

INFLOWS:

Bus_Capacity_Order_Rate = (IF(Bus_Capacity_Ordered>0.001) THEN
0 ELSE(IF(Bus_Saturation_Perception>=Bus_Rection_Limit-.001) THEN
Bus_Capacity_Increase ELSE 0))/BCOR_Delay

OUTFLOWS:

$$\text{Change_in_Bus_Capacity} = \text{CONVEYOR OUTFLOW}$$

$$\text{People_Using_Busses}(t) = \text{People_Using_Busses}(t - dt) + (\text{UB_Growth_Rate}) * dt$$

$$\text{INIT People_Using_Busses} = 2890250$$

INFLOWS:

UB_Growth_Rate = IF(Population.People_WB2>Bus_Capacity*1.2)
THEN (Bus_Capacity*1.2-People_Using_Busses)/PUB_Delay ELSE
(Population.People_WB2-People_Using_Busses)/PUB_Delay

$$\text{Avg_Travel_Distance} = 12$$

$$\text{BCI_Rate} = .15$$

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BCI_Step = 1

BCI_Step_Time = 204

BCOR_Delay = 1

Bus_Cap_delay = 12

Bus_Capacity_Increase = (STEP(BCI_Step, BCI_Step_Time)+BCI_Rate)*Bus_Capacity

Bus_Costs = 50

Bus_Perception_Delay = 3

Bus_Rection_Limit = 1.2

Bus_Saturation = People_Using_Busses/Bus_Capacity

Bus_Saturation_Perception = SMTH1(Bus_Saturation, Bus_Perception_Delay)

Bus_Travel_Speed =
Avg_Travel_Distance/(Bus_Travel_Time/Minutes_per_Hour)

Bus_Travel_Time =
(Cars.Increase_in_Travel_Time*Reference_BTT*(IF(Population.Policy_Switch=1)
THEN Effect_on_BTT ELSE 1))

Capacity_per_Bus = 30

Effect_on_BTT = GRAPH(Bus_Saturation)

(0.000, 0.7000), (0.100, 0.7890), (0.200, 0.8397), (0.300, 0.8740), (0.400, 0.9041), (0.500, 0.9356), (0.600, 0.9521), (0.700, 0.9671), (0.800, 0.9849), (0.900, 0.9918), (1.000, 0.9973)

Hist_Bus_Capacity = GRAPH(TIME)

(0.0, 2890245), (12.0, 2920025), (24.0, 2935030), (36.0, 2950112), (48.0, 2965272), (60.0, 2980509), (72.0, 2995825), (84.0, 3011219), (96.0, 3026693), (108.0, 3042246), (120.0, 3057879), (132.0, 3073592), (144.0, 3089386), (156.0, 3105261), (168.0, 3121218), (180.0, 3137257), (192.0, 3153378), (204.0, 3169583), (216.0, 4243625), (228.0, 4636383), (240.0, 6143788), (252.0, 6969469), (264.0, 6997634), (276.0, 7954651), (288.0, 8174816), (300.0, 9457455)

Minutes_per_Hour = 60

Number_of_Busses = Bus_Capacity/Capacity_per_Bus

PUB_Delay = 1

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Reference_BTT = 20

SMTH_BTS = SMTH1(Bus_Travel_Speed, 12)

Cars:

Inflation(t) = Inflation(t - dt) + (Inflation_Change_Rate) * dt

INIT Inflation = 1.0003

INFLOWS:

Inflation_Change_Rate = ((Inflation*1)-
Inflation)/Inflation_Change_Delay

People_Using_Cars(t) = People_Using_Cars(t - dt) + (UC_Growth_Rate) *
dt

INIT People_Using_Cars = 1800000

INFLOWS:

UC_Growth_Rate = (Population.People_WC-
People_Using_Cars)/PUC_Delay

Street_Capacity_Ordered(t) = Street_Capacity_Ordered(t - dt) +
(Street_Capacity_Order_Rate - Change_in_Street_Capacity) * dt

INIT Street_Capacity_Ordered = 0

TRANSIT TIME = Street_Capacity_Delay

CAPACITY = INF

INFLOW LIMIT = INF

INFLOWS:

Street_Capacity_Order_Rate =
(IF(Perceived_Street_Saturation>=Reaction_Limit) THEN
(IF(Street_Capacity_Ordered>.0001) THEN 0 ELSE
Streets_Capacity*(Street_Capacity_Increments)) ELSE 0)/SCOR_Delay

OUTFLOWS:

Change_in_Street_Capacity = CONVEYOR OUTFLOW

Streets_Capacity(t) = Streets_Capacity(t - dt) +
(Change_in_Street_Capacity + Policy_Street_Cap) * dt

INIT Streets_Capacity = 2000000

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INFLOWS:

Change_in_Street_Capacity = CONVEYOR OUTFLOW

Policy_Street_Cap = (IF(Population.Policy_Switch=1
AND(TIME>=301)) THEN Streets_Capacity*Policy_Street_Cap_Increase ELSE
0)/PSC_Delay

Avg_Travel_Distance = 12

Car_Travel_Speed =
Avg_Travel_Distance/(Car_Travel_Time/Minutes_per_Hour)

Car_Travel_Time = Reference_CTT*Increase_in_Travel_Time

Cars_per_Driver = 1

Hist_Speed = GRAPH(TIME)

(0.0, 40.0), (12.0, 37.78), (24.0, 35.18), (36.0, 33.29), (48.0, 31.62), (60.0,
28.73), (72.0, 26.91), (84.0, 24.96), (96.0, 22.71), (108.0, 21.81), (120.0, 20.03),
(132.0, 16.93), (144.0, 15.83), (156.0, 15.05), (168.0, 13.33), (180.0, 12.17),
(192.0, 12.02), (204.0, 12.04), (216.0, 10.69), (228.0, 10.84), (240.0, 9.6), (252.0,
9.73), (264.0, 8.44), (276.0, 8.35), (288.0, 7.83), (300.0, 7.83)

Increase_in_Travel_Time = GRAPH(Street_Saturation)

(0.000, 1.000), (0.250, 1.000), (0.500, 1.000), (0.750, 1.000), (1.000, 1.000),
(1.250, 1.500), (1.500, 2.500), (1.750, 4.000), (2.000, 6.000)

Inflation_Change_Delay = 1

Minutes_per_Hour = 60

Operational_Costs =
Reference_CC*(Increase_in_Travel_Time*0.5)*Inflation/Seats_per_Car

Perceived_Street_Saturation = SMTH1(Street_Saturation, 3)

Policy_Street_Cap_Increase = .0017

PSC_Delay = 1

PUC_Delay = 1

Reaction_Limit = 1.5

Reference_CC = 120

Reference_CTT = 18

SCOR_Delay = 1

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Seats_per_Car = IF(Population.Policy_Switch=1) THEN
1+Population.Available_Sharing_Seats/SMTHN(People_Using_Cars*Cars_per_Driver, 3, 3) ELSE 1

SMTH_CTS = SMTH1(Car_Travel_Speed, 12)

SMTH_CTT = SMTH1(Car_Travel_Time, 12)

Street_Capacity_Delay = 18

Street_Capacity_Increments = .1

Street_Saturation = Vehicles_on_the_Street/Streets_Capacity

Vehicles_on_the_Street =
Cars_per_Driver*People_Using_Cars+Busses.Number_of_Busses

Population:

Available_Sharing_Seats(t) = Available_Sharing_Seats(t - dt) +
(Change_in_Available_Share_Spots) * dt

INIT Available_Sharing_Seats = 0

INFLOWS:

Change_in_Available_Share_Spots = IF(WT_Switch=1) THEN
((WT_Drivers_Sharing*WT_Easiness_to_Share*Number_of_Seats_per_Car)-
Available_Sharing_Seats)/Seats_change_delay ELSE
((Cars_for_Sharing*Implementation.Easiness_to_Share*Number_of_Seats_per_Car)-
Available_Sharing_Seats)/Seats_change_delay

Bus_and_Car(t) = Bus_and_Car(t - dt) + (Change_BC) * dt

INIT Bus_and_Car = Total_Population*Percentage_Car*(1-
Percentage_Train)

INFLOWS:

Change_BC = (Total_Population*Percentage_Car*(1-
Percentage_Train)-Bus_and_Car)/Adj_Delay

Bus_and_Train(t) = Bus_and_Train(t - dt) + (Change_BT) * dt

INIT Bus_and_Train = Total_Population*(1-
Percentage_Car)*Percentage_Train

INFLOWS:

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$$\text{Change_BT} = (\text{Total_Population} * (1 - \text{Percentage_Car}) * \text{Percentage_Train-Bus_and_Train}) / \text{Adj_Delay}$$

$$\text{Bus_Train_and_Car}(t) = \text{Bus_Train_and_Car}(t - dt) + (\text{Change_BTC}) * dt$$

$$\text{INIT Bus_Train_and_Car} = \text{Total_Population} * \text{Percentage_Car} * \text{Percentage_Train}$$

INFLOWS:

$$\text{Change_BTC} = (\text{Total_Population} * \text{Percentage_Car} * \text{Percentage_Train-Bus_Train_and_Car}) / \text{Adj_Delay}$$

$$\text{Only_Bus}(t) = \text{Only_Bus}(t - dt) + (\text{Change_OB}) * dt$$

$$\text{INIT Only_Bus} = \text{Total_Population} * (1 - \text{Percentage_Car}) * (1 - \text{Percentage_Train})$$

INFLOWS:

$$\text{Change_OB} = (\text{Total_Population} * (1 - \text{Percentage_Car}) * (1 - \text{Percentage_Train}) - \text{Only_Bus}) / \text{Adj_Delay}$$

$$\text{People_with_Cars_in_the_City}(t) = \text{People_with_Cars_in_the_City}(t - dt) + (\text{Cars_Change_Rate}) * dt$$

$$\text{INIT People_with_Cars_in_the_City} = 1800000$$

INFLOWS:

$$\text{Cars_Change_Rate} = \text{People_with_Cars_in_the_City} * \text{Cars_Monthly_Growth_Rate} / \text{Cars_Adj_Delay}$$

$$\text{Policy_NPV}(t) = \text{Policy_NPV}(t - dt) + (\text{Change_in_NPV}) * dt$$

$$\text{INIT Policy_NPV} = 0$$

INFLOWS:

$$\text{Change_in_NPV} = \text{IF}(\text{TIME} < \text{Policy_Start_Time}) \text{ THEN } 0 \text{ ELSE } \text{Annual_Net_Benefits} / \text{Discount_Factor}$$

$$\text{Total_Population}(t) = \text{Total_Population}(t - dt) + (\text{Population_Growth}) * dt$$

$$\text{INIT Total_Population} = 16000000$$

INFLOWS:

$$\text{Population_Growth} = \text{Population_Monthly_Growth_Rate} * \text{Total_Population} / \text{Pop_Adj_Delay}$$

$$\text{Adj_Delay} = 1$$

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

Annual_Cost_of_Iddle_Time = 1020000000

Annual_Net_Benefits = Monthly_Savings-Implementation.Monthly_Budget

Base_Willingness = .2

Bus_to_Train_Percentage = People_WB/(People_WT+People_WB)

Cars_Adj_Delay = 1

Cars_for_Sharing =
(Implementation.Drivers_Sharing_Cars*Cars.Cars_per_Driver)

Cars_Monthly_Growth_Rate = IF(Steady_State=1) THEN 0 ELSE
CMGR_Control

CMGR_Control = .0037

Discount_Factor = (1+Discount_Rate)^Time_Periods

Discount_Rate = .0003

Estimated_Total_Investment_on_Infrastructure = 24000000000

Goal_for_Sharing_Seats = (People_WB+People_WT)*.2/People_per_Seats

Impact_of_Gap_Over_incentives = GRAPH(Sharing_Seats_Gap)
(0.000, 2.000), (0.125, 1.995), (0.250, 1.990), (0.375, 1.980), (0.500, 1.950),
(0.625, 1.850), (0.750, 1.650), (0.875, 1.400), (1.000, 1.000), (1.125, 0.600),
(1.250, 0.350), (1.375, 0.150), (1.500, 0.000)

Impact_of_Infrastructure_Change_on_Investment =
GRAPH(Infrastructure_Reduction_or_Increase)
(0.500, 0.000), (0.600, 0.000), (0.700, 0.000), (0.800, 0.000), (0.900, 0.000),
(1.000, 0.550), (1.100, 0.610), (1.200, 0.666), (1.300, 0.720), (1.400, 0.770),
(1.500, 0.830), (1.600, 0.880), (1.700, 0.950), (1.800, 1.000), (1.900, 1.050),
(2.000, 1.200)

Infrastructure_Reduction_or_Increase = IF(TIME<301)THEN 1 ELSE
((Busses.Bus_Capacity/Initial_Bus_Capacity)+(Trains.Train_Capacity/Initial_Train_
Capacity))/2

Initial_Bus_Capacity = HISTORY(Busses.Bus_Capacity, 300)

Initial_Train_Capacity = HISTORY(Trains.Train_Capacity, 300)

Initial_Travel_Speed = HISTORY(Cars.SMTH_CTS, 300)

Initial_Travel_Time = IF(TIME>300) THEN
Cars.Avg_Travel_Distance/Initial_Travel_Speed ELSE 1

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

Monthly_Idle_Time_Savings = (1-Reduction)*Annual_Cost_of_Iddle_Time

Monthly_Investment_Savings =
Estimated_Total_Investment_on_Infrastructure*(1-
Impact_of_Infrastructure_Change_on_Investment)/Months_under_Policy

Monthly_Savings =
Monthly_Investment_Savings+Monthly_Idle_Time_Savings

Months_under_Policy = 240

Number_of_Seats_per_Car = 2

People_per_Seats = 1

People_Using_Cars = Cars.People_Using_Cars

People_WB = SMTH3(IF(Preferences.Scenario=1 OR
Preferences.Scenario=2) THEN T1 ELSE IF(Preferences.Scenario=3 OR
Preferences.Scenario=6) THEN T2 ELSE T3, 3)

People_WB2 = IF(Time_Switch=1) THEN MAX(People_WB-
(MIN(Available_Sharing_Seats,
Implementation.Riders)*Bus_to_Train_Percentage*People_per_Seats), 0) ELSE
People_WB

People_WC = SMTH3(IF(Preferences.Scenario=3 OR
Preferences.Scenario=4) THEN T1 ELSE IF(Preferences.Scenario=1 OR
Preferences.Scenario=5) THEN T2 ELSE T3, 3)

People_WT = SMTH3(IF(Preferences.Scenario=5 OR
Preferences.Scenario=6) THEN T1 ELSE IF(Preferences.Scenario=2 OR
Preferences.Scenario=4) THEN T2 ELSE T3, 3)

People_WT2 = IF(Time_Switch=1) THEN MAX(People_WT-
(MIN(Available_Sharing_Seats, Implementation.Riders)*People_per_Seats*(1-
Bus_to_Train_Percentage)), 0) ELSE People_WT

Percentage_Car = People_with_Cars_in_the_City/Total_Population

Percentage_Train = GRAPH(IF(Steady_State=1) THEN .52 ELSE TIME)

(0.0, 0.520), (75.0, 0.510), (150.0, 0.500), (225.0, 0.490), (300.0, 0.480)

PMGR_Control = .0013

Policy_Start_Time = 300

Policy_Switch = 0

Policy_Travel_Time = Cars.Avg_Travel_Distance/Cars.SMTH_CTS

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

Pop_Adj_Delay = 1

Population_Monthly_Growth_Rate = IF(Steady_State=1) THEN 0 ELSE
PMGR_Control

Population_without_cars = Only_Bus+Bus_and_Train

Reduction = Policy_Travel_Time/Initial_Travel_Time

Seats_change_delay = 1

Sharing_Seats_Gap = Available_Sharing_Seats/Goal_for_Sharing_Seats

Steady_State = 0

T1 = IF(Preferences.Scenario=1 OR Preferences.Scenario=2) THEN
MIN(Bus_and_Car+Only_Bus+Bus_and_Train+Bus_Train_and_Car,
Busses.Bus_Capacity*1.2) ELSE (IF(Preferences.Scenario=3 OR
Preferences.Scenario=4) THEN Bus_Train_and_Car+Bus_and_Car ELSE
(MIN(Bus_and_Train+Bus_Train_and_Car, Trains.Train_Capacity*1.2)))

T2 = IF(Preferences.Scenario=1) THEN
(IF(Total_Population>Busses.Bus_Capacity*1.2) THEN Bus_and_Car*(1-
T1/(Total_Population)) ELSE 0) + (IF(Total_Population>Busses.Bus_Capacity*1.2)
THEN Bus_Train_and_Car*(1-T1/(Total_Population)) ELSE 0) ELSE
(IF(Preferences.Scenario=2) THEN
MIN((IF(Total_Population>Busses.Bus_Capacity*1.2) THEN Bus_and_Train*(1-
T1/(Total_Population)) ELSE 0) + (IF(Total_Population>Busses.Bus_Capacity*1.2)
THEN Bus_Train_and_Car*(1-T1/(Total_Population)) ELSE 0),
Trains.Train_Capacity*1.2) ELSE (IF(Preferences.Scenario=3) THEN
MIN(Only_Bus+Bus_and_Train, Busses.Bus_Capacity*1.2) ELSE
(IF(Preferences.Scenario=4) THEN MIN(Bus_and_Train,
Trains.Train_Capacity*1.2) ELSE (IF(Preferences.Scenario=5) THEN
Bus_and_Car +
(IF(Bus_and_Train+Bus_Train_and_Car>Trains.Train_Capacity*1.2) THEN
Bus_Train_and_Car*(1-T1/(Bus_and_Train+Bus_Train_and_Car)) ELSE 0)
ELSE MIN(Only_Bus+Bus_and_Car+
(IF(Bus_and_Train+Bus_Train_and_Car>Trains.Train_Capacity*1.2) THEN
Bus_and_Train*(1-T1/(Bus_Train_and_Car+Bus_and_Train)) ELSE 0) +
(IF(Bus_and_Train+Bus_Train_and_Car>Trains.Train_Capacity*1.2) THEN
Bus_Train_and_Car*(1-T1/(Bus_Train_and_Car+Bus_and_Train)) ELSE 0),
Busses.Bus_Capacity*1.2)))))

T3 = IF(Preferences.Scenario=1 OR Preferences.Scenario=3) THEN
MIN((IF(Only_Bus+Bus_and_Train>Busses.Bus_Capacity*1.2) THEN
Bus_and_Train*(1-T2/(Total_Population)) ELSE 0), Trains.Train_Capacity*1.2)
ELSE (IF(Preferences.Scenario=2 OR Preferences.Scenario=6) THEN
(IF(Total_Population>Busses.Bus_Capacity*1.2) THEN Bus_and_Car*(1-
T1/(Total_Population)) ELSE 0) + (IF(T2>0) THEN MAX(Bus_Train_and_Car*(1-

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

$(T1/Total_Population)-(T2/(Bus_and_Train+Bus_Train_and_Car))), 0) ELSE 0)$
ELSE MIN(Only_Bus +
(IF(Bus_and_Train+Bus_Train_and_Car>Trains.Train_Capacity*1.2) THEN
Bus_and_Train*(1-T2/(Bus_Train_and_Car+Bus_and_Train)) ELSE 0),
Busses.Bus_Capacity*1.2))

Time_Periods = (TIME-Policy_Start_Time)/Time_Units

Time_Switch = IF(TIME<=300 OR(Policy_Switch=0)) THEN 0 ELSE 1

Time_Units = 1

Willingness_to_share =
MIN(Base_Willingness*(Impact_of_Gap_Over_incentives), 1)

WT_Drivers_Sharing =
Willingness_to_share*Cars.People_Using_Cars*Cars.Cars_per_Driver

WT_Easiness_to_Share = .8

WT_Option = 0

WT_Switch = IF(Time_Switch=1 AND(WT_Option=1)) THEN 1 ELSE 0

Preferences:

BC_G = GRAPH(BC_RG)

(1.0000, 100.0), (1.1000, 95.0), (1.2000, 85.0), (1.3000, 70.0), (1.4000,
50.0), (1.5000, 25.0), (1.6000, 0.0)

BC_RG = Busses.Bus_Costs/Min_Cost

BTT_Grade = GRAPH(BTT_Relative_Grade)

(1.0000, 100.0), (1.1000, 95.0), (1.2000, 85.0), (1.3000, 70.0), (1.4000,
50.0), (1.5000, 25.0), (1.6000, 0.0)

BTT_Relative_Grade = Busses.Bus_Travel_Time/Min_TT

Bus_Grade = BTT_Grade*Travel_Time_Importance+BC_G*(1-
Travel_Time_Importance)

Car_Grade = CTT_Grade*Travel_Time_Importance+CC_G*(1-
Travel_Time_Importance)

CC_G = GRAPH(CC_RG)

(1.0000, 100.0), (1.1000, 95.0), (1.2000, 85.0), (1.3000, 70.0), (1.4000,
50.0), (1.5000, 25.0), (1.6000, 0.0)

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

CC_RG = Cars.Operational_Costs/Min_Cost

CTT_Grade = GRAPH(CTT_Relative_Grade)

(1.0000, 100.0), (1.1000, 95.0), (1.2000, 85.0), (1.3000, 70.0), (1.4000, 50.0), (1.5000, 25.0), (1.6000, 0.0)

CTT_Relative_Grade = Cars.Car_Travel_Time/Min_TT

Min_Cost = MIN(MIN(Trains.Train_Costs, Cars.Operational_Costs), Busses.Bus_Costs)

Min_TT = MIN(MIN(Trains.Train_TT, Cars.Car_Travel_Time), Busses.Bus_Travel_Time)

Scenario = IF(Bus_Grade>Car_Grade AND Car_Grade>Train_Grade) THEN 1 ELSE (IF(Bus_Grade>Train_Grade AND Train_Grade>Car_Grade) THEN 2 ELSE (IF(Car_Grade>Bus_Grade AND Bus_Grade>Train_Grade) THEN 3 ELSE (IF(Car_Grade>Train_Grade AND Train_Grade>Bus_Grade) THEN 4 ELSE (IF(Train_Grade>Car_Grade AND Car_Grade>Bus_Grade) THEN 5 ELSE 6))))

TC_G = GRAPH(TC_RG)

(1.0000, 100.0), (1.1000, 95.0), (1.2000, 85.0), (1.3000, 70.0), (1.4000, 50.0), (1.5000, 25.0), (1.6000, 0.0)

TC_RG = Trains.Train_Costs/Min_Cost

Train_Grade = TTT_Grade*Travel_Time_Importance+TC_G*(1-Travel_Time_Importance)

Travel_Time_Importance = .6

TTT_Grade = GRAPH(TTT_Relative_Grade)

(1.0000, 100.0), (1.1000, 95.0), (1.2000, 85.0), (1.3000, 70.0), (1.4000, 50.0), (1.5000, 25.0), (1.6000, 0.0)

TTT_Relative_Grade = Trains.Train_TT/Min_TT

Trains:

People_Using_Trains(t) = People_Using_Trains(t - dt) + (UT_Growth_Rate) * dt

INIT People_Using_Trains = 2757389

INFLOWS:

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

UT_Growth_Rate = IF(Population.People_WT2>Train_Capacity*1.2)
THEN (Train_Capacity*1.2-People_Using_Trains)/PUT_Delay ELSE
(Population.People_WT2-People_Using_Trains)/PUT_Delay

Train_Capacity(t) = Train_Capacity(t - dt) + (Change_in_Train_Capacity) *
dt

INIT Train_Capacity = IF(Population.Steady_State=1) THEN 12000000
ELSE 2757389

INFLOWS:

Change_in_Train_Capacity = CONVEYOR OUTFLOW

Train_Capacity_Ordered(t) = Train_Capacity_Ordered(t - dt) +
(Train_Capacity_Order_Rate - Change_in_Train_Capacity) * dt

INIT Train_Capacity_Ordered = 0

TRANSIT TIME = Train_Capacity_Delay

CAPACITY = INF

INFLOW LIMIT = INF

INFLOWS:

Train_Capacity_Order_Rate = (IF(Perceived_Train_Saturation<1.199)
THEN 0 ELSE (IF(Train_Capacity_Ordered> 0.001) THEN 0 ELSE
Train_Capacity_Increase*Train_Capacity))/TCOR_Delay

OUTFLOWS:

Change_in_Train_Capacity = CONVEYOR OUTFLOW

Avg_Travel_Distance = 12

Hist_Train_Capacity = GRAPH(TIME)

(0.0, 2757389), (12.0, 2757389), (24.0, 2757389), (36.0, 2784146), (48.0,
2784146), (60.0, 3124995), (72.0, 3124995), (84.0, 3124995), (96.0, 3124995),
(108.0, 3124995), (120.0, 3124995), (132.0, 3375124), (144.0, 3375124), (156.0,
3375124), (168.0, 3375124), (180.0, 3375124), (192.0, 3375124), (204.0,
3375124), (216.0, 3653198), (228.0, 3653198), (240.0, 3653198), (252.0,
3653198), (264.0, 4448846), (276.0, 4448846), (288.0, 4448846), (300.0,
4448846)

Increase_in_Travel_Time = GRAPH(Train_Saturation-1)

(0.000, 0.680), (0.100, 0.767), (0.200, 0.840), (0.300, 0.877), (0.400, 0.904),
(0.500, 0.895), (0.600, 0.913), (0.700, 0.932), (0.800, 0.959), (0.900, 1.000),
(1.000, 1.200), (1.100, 1.700), (1.200, 2.000)

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

Minutes_per_Hour = 60

Perceived_Train_Saturation = SMTH1(Train_Saturation,
Train_Perception_Delay)

PUT_Delay = 1

Reference_TTT = 60

SMTH_TTS = SMTH1(Train_Travel_Speed, 12)

TCOR_Delay = 1

Train_Capacity_Delay = 48

Train_Capacity_Increase = .5

Train_Costs = 10

Train_Perception_Delay = 3

Train_Saturation = People_Using_Trains/Train_Capacity

Train_Travel_Speed = Avg_Travel_Distance/(Train_TT/Minutes_per_Hour)

Train_TT = Reference_TTT*Increase_in_Travel_Time

Implementation:

Calc_Drivers(t) = Calc_Drivers(t - dt) + (Calc_Flow_Driver) * dt

INIT Calc_Drivers = 0

INFLOWS:

Calc_Flow_Driver = (IF(Population.Time_Switch=1) THEN
(Driver_Flow_Calc) ELSE 0)/Unit_Delay_Time

Calc_Riders(t) = Calc_Riders(t - dt) + (Calc_Flow_Riders) * dt

INIT Calc_Riders = 0

INFLOWS:

Calc_Flow_Riders = (IF(Population.Time_Switch=1) THEN
MAX(Rider_Flow_Calc, 0) ELSE 0)/Unit_Delay_Time

Drivers(t) = Drivers(t - dt) + (Increase_of_Drivers -
Change_in_Drivers_Mindset) * dt

INIT Drivers = 0

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

INFLOWS:

$$\text{Increase_of_Drivers} = \text{Driver_Flow_Calc}/\text{Unit_Delay_Time}$$

OUTFLOWS:

$$\text{Change_in_Drivers_Mindset} = \text{DELAYN}(\text{Drivers}, \text{Delay_Time}, \text{Delay_Magnitud})/\text{Unit_Delay_Time}$$

$$\text{Drivers_Sharing_Cars}(t) = \text{Drivers_Sharing_Cars}(t - dt) + (\text{Change_by_Elasticity} + \text{Screening}) * dt$$

$$\text{INIT Drivers_Sharing_Cars} = \text{IF}(\text{Population.Time_Switch}=1) \text{ THEN STEP}(.05*\text{Population.People_Using_Cars}, 300) \text{ ELSE } 1$$

INFLOWS:

$$\text{Change_by_Elasticity} = (\text{Drivers_Sharing_Cars}*(-1 + \text{Relative_Incentives}^{\text{Elasticity}}))/\text{Elasticity_Change_Delay}$$

$$\text{Screening} = \text{CONVEYOR OUTFLOW}$$

$$\text{Drivers_to_be_Screened}(t) = \text{Drivers_to_be_Screened}(t - dt) + (\text{Change_in_Drivers_Mindset} - \text{Screening} - \text{Not_authorized_Drivers}) * dt$$

$$\text{INIT Drivers_to_be_Screened} = 0$$

$$\text{TRANSIT TIME} = \text{Time_to_be_screened}$$

$$\text{CAPACITY} = \text{INF}$$

$$\text{INFLOW LIMIT} = \text{INF}$$

INFLOWS:

$$\text{Change_in_Drivers_Mindset} = \text{DELAYN}(\text{Drivers}, \text{Delay_Time}, \text{Delay_Magnitud})/\text{Unit_Delay_Time}$$

OUTFLOWS:

$$\text{Screening} = \text{CONVEYOR OUTFLOW}$$

$$\text{Not_authorized_Drivers} = \text{LEAKAGE OUTFLOW}$$

$$\text{LEAKAGE FRACTION} = .2$$

$$\text{Drivers_to_be_Screened_1}(t) = \text{Drivers_to_be_Screened_1}(t - dt) + (\text{Change_in_Riders_Mindset_1} - \text{Screening_Riders} - \text{Not_authorized_Riders}) * dt$$

$$\text{INIT Drivers_to_be_Screened_1} = 0$$

$$\text{TRANSIT TIME} = 1$$

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

CAPACITY = INF

INFLOW LIMIT = INF

INFLOWS:

Change_in_Riders_Mindset_1 = DELAYN(Initial_Riders, Delay_Tlme, Delay_Magnitud)/Unit_Delay_Time

OUTFLOWS:

Screening_Riders = CONVEYOR OUTFLOW

Not_authorized_Riders = LEAKAGE OUTFLOW

LEAKAGE FRACTION = .76

Initial_Riders(t) = Initial_Riders(t - dt) + (Increase_of_Riders - Change_in_Riders_Mindset_1) * dt

INIT Initial_Riders = 0

INFLOWS:

Increase_of_Riders = Rider_Flow_Calc/Unit_Delay_Time

OUTFLOWS:

Change_in_Riders_Mindset_1 = DELAYN(Initial_Riders, Delay_Tlme, Delay_Magnitud)/Unit_Delay_Time

Riders(t) = Riders(t - dt) + (Screening_Riders) * dt

INIT Riders = IF(Population.Time_Switch=1) THEN STEP(.05*Population.Population_without_cars, 300) ELSE 1

INFLOWS:

Screening_Riders = CONVEYOR OUTFLOW

Total_Budget_Used(t) = Total_Budget_Used(t - dt) + (Monthly_Budget) * dt

INIT Total_Budget_Used = 0

INFLOWS:

Monthly_Budget = IF(Population.Time_Switch=1) THEN SMTH3((Base_Budget*Population.Impact_of_Gap_Over_incentives), Budget_Authorization_Delay) ELSE 1

Willing_Drivers(t) = Willing_Drivers(t - dt) + (- Change_by_Elasticity) * dt

INIT Willing_Drivers = 0

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

OUTFLOWS:

$\text{Change_by_Elasticity} = (\text{Drivers_Sharing_Cars} * (-1 + \text{Relative_Incentives}^{\text{Elasticity}})) / \text{Elasticity_Change_Delay}$

Base_Budget = 1000000

Base_Incentive = 500

Budget_Authorization_Delay = 2

Delay_Magnitud = 3

Delay_Time = 120

Delay_to_Perceive_Incentives = 3

Driver_Flow_Calc = IF(TIME>300) THEN
MAX(Population.People_Using_Cars-Calc_Drivers, 0) ELSE 0

Easiness_to_Share = MIN(((Riders/Drivers_Sharing_Cars)/Reference_Ratio,
1)

Elasticity = .844

Elasticity_Change_Delay = 2

Incentives_per_Person = IF(TIME>303) THEN
MIN(SMTH1(Monthly_Budget, 3)/SMTH1(Drivers_Sharing_Cars, 3),
Max_Incentive_per_person) ELSE 0

Max_Incentive_per_person = 1000

Perceived_Incentives = SMTH3(Incentives_per_Person,
Delay_to_Perceive_Incentives)

Reference_Ratio = 3

Relative_Incentives = Perceived_Incentives/Base_Incentive

Rider_Flow_Calc = IF(TIME>300) THEN
MAX(Population.Population_without_cars-Calc_Riders, 0) ELSE 0

Time_to_be_screened = 1

Unit_Delay_Time = 1

{ The model has 245 (245) variables (array expansion in parens).

In 7 Modules with 16 Sectors.

Stocks: 28 (28) Flows: 31 (31) Converters: 186 (186)

DYNAMIC ANALYSIS OF TRAFFIC IN MEXICO CITY

Constants: 74 (74) Equations: 143 (143) Graphicals: 17 (17)

There are also 105 expanded macro variables.

}