Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia COPPE UFRJ

# USING SYSTEM DYNAMICS TO ASSESS THE IMPACT OF THE BRAZILIAN URBAN MOBILITY POLICY

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Tese de Doutorado apresentado ao Programa de Pós-graduação em Engenharia de Transportes, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia de Transportes.

Orientador: Glaydston Mattos Ribeiro

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TESE SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA (COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS EM ENGENHARIA DE TRANSPORTES.

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*A mim por não ter desistido, não só*
*do doutorado, mas de mim mesmo.*

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Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

USANDO A DINÂMICA DO SISTEMA PARA AVALIAR O IMPACTO DA POLÍTICA DE MOBILIDADE URBANA BRASILEIRA

Wlisses Bonelá Fontoura

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Orientador: Glaydston Mattos Ribeiro

Programa: Engenharia de Transportes

A Política Nacional de Mobilidade Urbana (PNMU) visa apoiar as cidades brasileiras na melhoria da acessibilidade e da mobilidade urbana. Desse modo, esta política estabelece os princípios e as diretrizes para dar suporte as cidades no desenvolvimento sustentável. Trata-se de um marco no planejamento urbano brasileiro e, por isso, existem diversos estudos que aplicam métodos e abordagens para analisar os efeitos da PNMU. Utilizando a Dinâmica de Sistemas (DS), os pesquisadores geralmente analisam os impactos da PNMU considerando apenas fatores econômicos, ambientais e de tráfego, focando no congestionamento e na poluição atmosférica. Porém, a PNMU aborda outras questões como segurança no trânsito, bem-estar da população, uso do solo, novas tecnologias, entre outros. Além disso, o padrão de viagens mudou após a pandemia de COVID-19 e essas mudanças devem ser consideradas no planejamento de transporte. Neste contexto, este trabalho tem como objetivo desenvolver modelos de apoio à decisão, utilizando a DS como ferramenta de modelagem e simulação, para verificar os efeitos da implantação da PNMU nas cidades brasileiras, abordando variáveis econômicas, ambientais, sociais, de tráfego e de uso do solo. Os resultados destacam a importância da implementação da PNMU para reduzir as externalidades negativas dos sistemas de transporte. Observa-se que tais medidas podem reduzir a poluição e o nível de congestionamento em 60%. Além disso, a redução de poluentes evita aproximadamente 1.000 internações por doenças respiratórias e cardiovasculares e 8.000 mortes em 32 anos.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

USING SYSTEM DYNAMICS TO ASSESS THE IMPACT OF THE BRAZILIAN URBAN MOBILITY POLICY

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The Brazilian Urban Mobility Policy (BUMP) seeks to support Brazilian cities in improving accessibility and urban mobility. Thus, this policy establishes the principles and guidelines to support the cities in the sustainable development. Because this policy is a milestone in Brazilian urban planning, there are several studies that apply methods and approaches to analyze the effects of the BUMP. Using System Dynamics (SD), the researchers usually analyze BUMP impacts considering only economic, environmental and traffic factors, focusing on congestion and air pollution. However, the BUMP addresses other factors such as traffic safety, life quality, land use, new technologies, among others. In addition, the travel pattern has changed after the COVID-19 pandemic and these changes must be considered in transportation planning. In this context, this work aims to develop decision support models, using SD as a modeling and simulation tool, to verify the effects of the BUMP implementation on Brazilian cities, addressing the traffic safety, health, environmental, economic, land use and traffic variables. The results show the importance of BUMP implementation to reduce the negative externalities of transportation systems. These measures can reduce air pollution and congestion by 60%. In addition, this reduction in air pollution prevents approximately 1,000 hospitalizations due to respiratory and cardiovascular diseases and 8,000 deaths in 32 years.

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## LIST OF ABBREVIATIONS

ANFAVEA – Brazilian Association of Automotive Vehicle Manufacturers

ANTP – Brazilian Association of Public Transports

BAU – Business-as-usual

BCG – Boston Consulting Group

BUMP – Brazilian Urban Mobility Policy

CD – Cardiovascular Diseases

CLD – Causal Loop Diagram

CNT – Brazilian Transport Confederation

$CO_2$ – Carbon Dioxide

DOAJ – Directory of Open Access Journals

FEHs – Full Electric Vehicles

dB – Decibel

DETRAN-RJ – Department of Transport of the State of Rio de Janeiro

DNIT – Brazilian Department of Transportation Infrastructure

EMTU-SP – The Metropolitan Company of Urban Transport of São Paulo

GDP – Gross Domestic Product

HEVs – Hybrid and Electric Vehicles

IBGE – The Brazilian Institute of Geography and Statistics

INEA – The State Environmental Institute

ITDP – The Institute for Transportation and Development Policy

LRT – Light Rail Transit

LUTI – Land-Use and Transport Interaction

MARS – Metropolitan Activity Relocation Simulator (MARS)

MRT – Mass Rapid Transit

$MtCO_2$ – Millions of Tons of Carbon Dioxide

NTU – Brazilian Association of Urban Transport Companies

PLE – Personal Learning Edition

PM – Particulate Matter

$PM_{2.5}$ – Particles with a diameter of 2.5 micrometers or less

RD – Respiratory Diseases

RTR – Rapid Transit to Resident

SD – System Dynamics

SFD – Stock and Flow Diagram

SINDIPEÇAS – The National Association of Brazilian Auto Parts Manufacturers

SLR – Systematic Literature Review

SuM4All$^{TM}$ – Sustainable Mobility for All

TDM – Transportation Demand Management

UNECE – The United Nations Economic Commission for Europe

VKT – Vehicle-Kilometers Traveled

WHO – World Health Organization

# 1 INTRODUCTION

Following the trend of developing countries, Brazil has presented a huge urban expansion in the last decades (The United Nations, 2018). However, this growth occurred in a disorderly way, resulting in several economic, social and environmental issues (Polidoro *et al.*, 2011; Wey *et al.*, 2016).

As a result of this chaotic process, several challenges have arisen for public managers, such as job creation, housing, infrastructure and basic urban services (Wei and Ewing, 2018). Facing this new reality, sustainable urban development has become one of the greatest challenges of this century not only in Brazil, but around the world (Seabra *et al.*, 2013).

Transportation systems are fundamental to human and economic development. Therefore, it is necessary to control them to achieve sustainable development (Sayyadi and Awasthi, 2016). The challenges to plan, develop and manage sustainable cities are higher when urban transport systems cannot meet minimum urban mobility requirements (Ahmad and Oliveira, 2016).

Nowadays, it is necessary reverse the ongoing negative course of urban transport systems to obtain inclusive, safe, resilient and sustainable cities (Rubim and Leitão, 2013). So, public managers should prioritize public transport and control car use. In addition, it is necessary to reduce motorized trips, promoting safe walking and cycling (Giles-Corti *et al.*, 2016).

Due to the socio-economic benefits and the costs of urban transport systems, transportation planning has become one of the main topics of discussion for public managers and researchers to guarantee the efficiency of these systems, reducing their externalities (Zhao *et al.*, 2010).

According to Sayyadi and Awasthi (2016), public policies are an effective way to amplify or limit the effects of urban transport systems, as the design and implementation of these measures encourage ways to live more sustainably. However, despite the importance of policies to stimulate sustainable urban mobility, their development is still a challenge for urban planners (Portugal *et al.*, 2019).

In Brazil, Law 12.587/2012 is a milestone for management of urban mobility, as this law establishes the guidelines of the Brazilian Urban Mobility Policy (BUMP) (Machado and Piccinini, 2018). The BUMP establishes mitigation measures, seeking the sustainable development of cities through the improvement and integration of different modes of transport (Brazil, 2012).

Although this law establishes measures to promote sustainable urban mobility in Brazilian cities, there are several obstacles to implement them (Tsay and Herrmann, 2013). Inefficient transport infrastructure and services, social inequality, urban sprawl and the massive car use make it difficult to introduce the concept of sustainable cities in Brazil (Martine and McGandanahan, 2013).

In this context, tools and methodologies are essential to assist managers in solving the sector's challenges, providing a global view of the system and, consequently, helping to find solutions to achieve sustainable urban mobility (Portugal *et al.*, 2019). According to Sayyadi and Awasthi (2016), qualitative, quantitative and hybrid approaches are commonly used to measure and analyze urban mobility. Among them, simulation has been widely used in transport planning (Kagho *et al.*, 2020).

Urban area and transportation systems should not be analyzed by linear approaches due to their complexities (Wang *et al.*, 2008). Despite this restriction, there are several tools to help transport planning, such as multi-criteria analysis, cost-benefit analysis and System Dynamics (SD). System Dynamics is a multidisciplinary method that uses models from a system perspective. This approach helps to develop a strategic view of a system, allowing to reproduce its dynamic behavior over a long period (Ford and Lyneis, 2020). The ability to predict the system' changes over the years is fundamental to develop and implement policies, as they "[…] may appear to be good in the short term but in the long term may have disastrous consequences and only a proper system dynamics model can capture this result" (Mallick *et al.*, 2014, p.2).

System dynamics approach is commonly applied in the transport sector, mainly in the analysis of public policies (Shepherd, 2014). This tool is well adapted to the current problems of the transport sector, standing out due to its intuitive interface and software availability, which allows the comprehensive and dynamic study of urban transport systems in the long term (Suryani *et al.*, 2020).

Studies that use SD to analyze sustainable transport policies generally address environmental, economic and traffic factors, focusing on air pollution and/or congestion. However, the BUMP has other goals besides reducing congestion and air pollution. The SD models found in the literature do not address all the important topics of this policy, such as: traffic congestion, traffic safety, health, air pollution, noise pollution, land use and the effects of new technologies (Fontoura and Ribeiro, 2021). This raises the following questions: BUMP measures reduce air pollution and congestion, but can they ensure travel safety? What are the effects of the BUMP incentives for the development and use of new technologies? How does the change in the travel pattern proposed by this policy impact human health? Does the BUMP implementation improve land use? Therefore, it is necessary to develop a new SD model that addresses all of them. In addition, urban transport systems are still adapting to the post-COVID-19 world and the new urban mobility pattern must be addressed in policies. Thus, this work aims to propose frameworks, using SD, to assess the impact of mitigation measures proposed by the BUMP, filling gaps identified in the literature.

## 1.1 Motivation

According to The United Nations (2018), approximately 92% of Brazilians will be living in urban areas in 2050. This projection indicates that urban areas will continue to grow quickly, making urban space planning more complex.

Due to the urban growth in the last few decades, Brazilian cities have become increasingly car-dominated and less sustainable (Hidalgo and Huizenga, 2013). Consequently, Brazilian cities present several problems related to transport, such as noise and air pollution, congestion, traffic accidents, bad public transit systems, environmental degradation, energy resources waste, reduced accessibility for people with disabilities, iniquity, among others (Pojani and Stead, 2015).

The impact of this unsustainable growth can be seen by numbers and indicators. The Brazilian automotive industry produced a total of 2.94 million light vehicles in 2019, reaching the 8$^{th}$ place in the ranking of the largest producers in the world (OICA, 2020). Due to the economic and health crisis during the COVID-19 pandemic, vehicle production fell by 31.6% in 2020 (ANFAVEA, 2021). However, Brazil remained in 9$^{th}$ place in the world ranking (OICA, 2021).

Excessive car use, population growth, inadequate infrastructure and bad public transport services result in high congestion levels in Brazilian cities (Bontempo *et al.*, 2014). Due to the COVID-19 pandemic, in 2020, traffic congestion dropped 10% in the biggest Brazilian cities. However, despite this reduction, Brazil still stood out in the world ranking with six state capitals among the 75 most congested cities in the world (TomTom, 2021). The country showed a slight improvement in 2021 with only three state capitals making the top 75 on that list (TomTom, 2022). However, five state capitals were still listed as one of the 100 most congested cities in the world in 2021 (TomTom, 2022).

In addition to traffic congestion, excessive car use results in a high number of traffic accidents. Traffic accidents are the eighth most common cause of death worldwide (WHO, 2018). In 2019, Brazil recorded 30,000 deaths caused by traffic accidents (Brazil, 2020a). According to data provided by the Ministry of Health, this number is 26% lower than the number of deaths in 2011, which indicates a reduction in recent years. The implementation of blood alcohol concentration laws caused this reduction (WHO, 2018). However, despite this effort, Brazil has not reached the goal of reducing the number of deaths by 50%. This goal was set in the Decade of Action for Road Safety 2011-2020, which was proclaimed by the United Nations General Assembly in 2011 (WHO, 2011). Thus, traffic accidents are still a problem in the country.

Another negative externality of urban transport systems is air pollution. In the Brazilian energy sector, transport was responsible for most $CO_2$ emissions in 2018, being 52.1% generated by freight transport (104.4 $MtCO_2$) and 47.9% by passenger transport (95.8 $MtCO_2$) (Angelo and Rittl, 2019). In addition to cause greenhouse effect, air pollution is a threat to human health, being one of the main causes of premature deaths and diseases worldwide (UNECE, 2021). In Brazil, 50,000 people died in 2016 due to diseases caused by air pollution (WHO, 2020).

Accessibility is another issue in the transport sector. The urban transport systems in many Brazilian cities are not appropriate for some groups of people, such as people with disabilities, pregnant women, obese people, low-income people, seniors, among others. Therefore, it is necessary to develop measures to solve the current problems and improve the accessibility of these groups (Machado and Lima, 2015).

In addition to the facts mentioned above, the post-COVID-19 pandemic scenario is still uncertain. Specialists point out that the pandemic can have structural and enduring effects on the urban mobility pattern (Sharifi and Khavarian-Garmsir, 2020). It is noted that there has been a drop in travel demand due to a combination of a long-lasting economic crisis and changing work habits (Koehl, 2021). In addition, during the pandemic, public transport usage reduced due to the risk of COVID-19 infection, reinforcing the use of car instead public transport. Therefore, these effects must be considered in urban planning and policy development.

Despite urban mobility influences our quality of life, Brazil faces several urban mobility problems, especially in big cities, where they manifest themselves more clearly (Rodrigues, 2016). Therefore, it is important to develop studies to understand the urban expansion and its effects. In addition to understanding this process, it is necessary to develop methods that help transport planning to eliminate or mitigate the externalities.

## 1.2 Objectives and Contributions

In this context, the following question arises: are the implementation of the Brazilian Urban Mobility Policy measures capable of solving the current problems of urban mobility in Brazilian cities, ensuring universal accessibility and sustainable development?

Given this research problem, this thesis aims to develop decision support models, using the System Dynamics method as a modeling and simulation tool, to verify the effects of the Brazilian Urban Mobility Policy, focusing on land use and economic, environmental, social and traffic variables.

To achieve this, this study has the following specific objectives:

1. Identify variables related to urban mobility and sustainable development;
2. Check the effects of BUMP measures on traffic congestion and traffic accidents;
3. Check how BUMP measures can improve human health;
4. Identify the effects of new mobility services;
5. Compare the effects of the BUMP measures in a pre- and post-COVID-19 pandemic scenario; and
6. Check the effects of the BUMP in Rio de Janeiro.

The contributions of this thesis are divided into two main areas:

(i) Academic field: proposition of new SD models to evaluate an urban mobility policy, addressing combined factors not previously explored in models available in the literature; and

(ii) Governmental sphere: this study can provide tools to support urban planning in Brazilian cities.

## 1.3 Thesis Structure

This thesis is a set of papers (published or under review) related to the subject presented in this chapter. Therefore, all chapters (except introduction and final considerations) present one or more papers related to the use of SD to assess the effects of BUMP.

As can be seen in Figure 1.1, this thesis is divided into six chapters. This chapter presented a brief overview of the study, presenting a description of the subject. For that, the research problem, motivation, objectives and contributions of this study are presented.

Chapter 2 presents a literature review to support the development of the proposed models. Therefore, a discussion about the Brazilian Urban Mobility Policy (BUMP) is presented, highlighting the main principles and guidelines of this policy. It also presented the main concepts, diagrams and tests applied to System Dynamics (SD) models. Finally, this chapter presents different applications of SD in urban mobility policy analysis, including BUMP.

Based on the gaps identified in the literature review of Chapter 2, Chapter 3 presents the first SD model proposed in this thesis. Based on Fontoura *et al.* (2019), the proposed model analyzes the effects of BUMP measures, focusing on congestion and pollution. In addition to prioritizing public transport over private transport, this model also addresses non-motorized transport and different types of public transport services. Then, this chapter also presents a case study in Rio de Janeiro and a comparative analysis between Brazilian megacities (Rio de Janeiro and São Paulo).

Chapter 4 presents another SD model to assess the effects of BUMP. In addition to the points evaluated in the model proposed in Chapter 3, this new model addresses the effects of the BUMP measures on human health and noise pollution. Other points mentioned by BUMP are also added to the model, such as land use, traffic speed, traffic accidents and new technologies. At the end of this chapter, a case study in Rio de Janeiro is presented.

In addition to assess the effects of BUMP on congestion and air pollution like the previous models, the model presented in Chapter 5 addresses two unexplored factors: new mobility services (hide-hailing) and the COVID-19 pandemic. This model combines SD with the discrete choice utility approach, following the Nobel Laureate Daniel McFadden works, to predict the modal share in different policy spaces. Therefore, the model allows identifying the impact of new mobility services and BUMP measures on modal share. After presenting the proposed model, this chapter shows the results of its application in Rio de Janeiro.

Finally, Chapter 6 presents the final considerations and suggestions for future studies. In addition, this chapter highlights the scientific publications resulting, directly or indirectly, from this thesis.

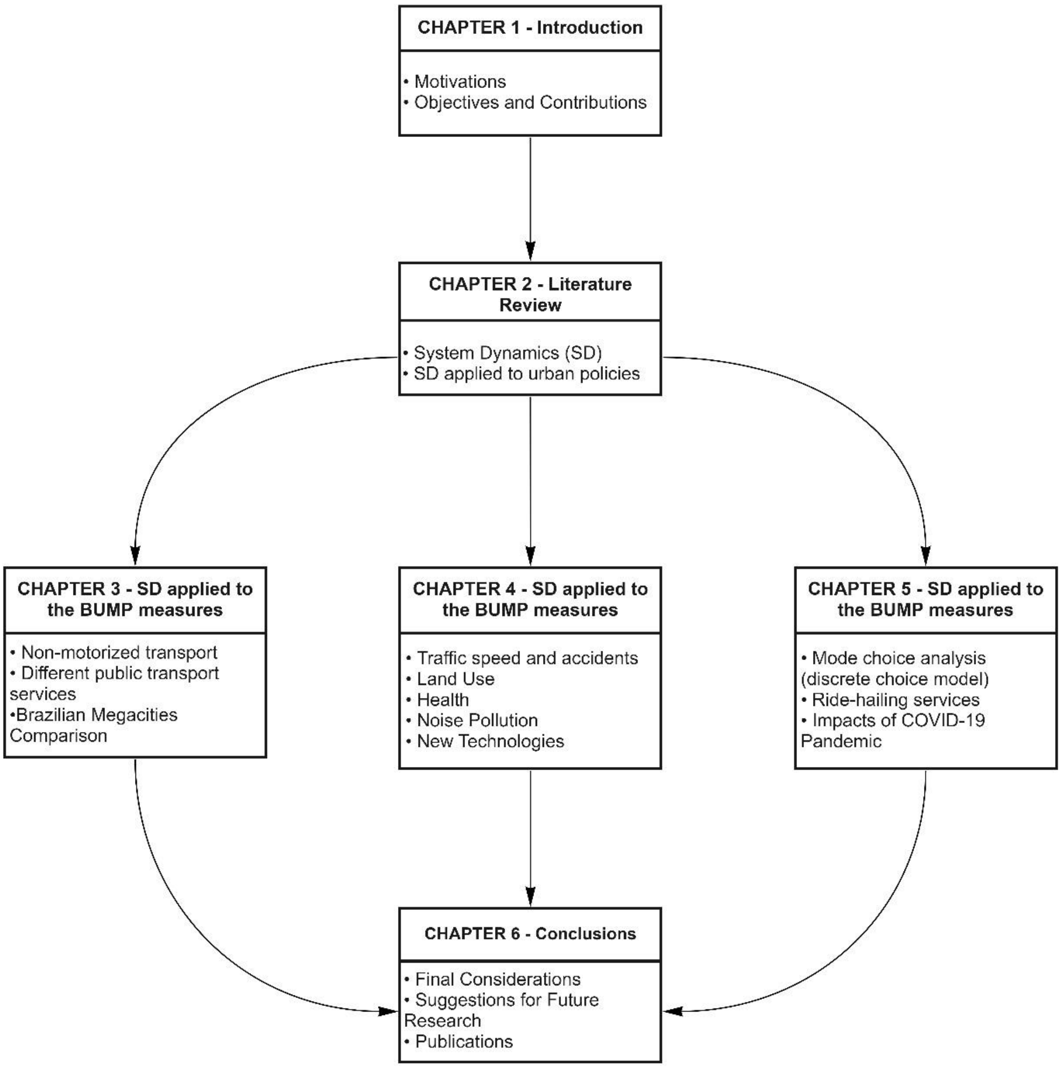


Figure 1.1 – Thesis structure

# 2 BRAZILIAN URBAN MOBILITY POLICY, SYSTEM DYNAMICS AND A SYSTEMATIC LITERATURE REVIEW

Urban mobility is a crucial element to build sustainable cities and has a significant impact on the quality of life (Nuvolati, 2009; Aguiar and Macário, 2017; Gaglione *et al.*, 2019). Therefore, urban mobility is a basic right, as well as health, education, safety, work and culture (Oliveira Júnior, 2011). In Brazil, Law 12,587/2012 is a milestone in the consolidation of the Brazilian Urban Mobility Policy as a mechanism for accessing basic rights and an instrument for the sustainable development of Brazilian cities (Paraná, 2019). Thus, this chapter presents the main objectives and principles of the Brazilian Urban Mobility Policy (BUMP).

As discussed in the first chapter, System Dynamics is a useful tool to assist the development, implementation and evaluation of public policies, being widely used in the transport sector (Sayyadi and Awasthi, 2020). Therefore, the main concepts and approaches of this method are presented in this chapter. In addition, this chapter also presents a systematic literature review (SLR) on the application of SD to analyze urban mobility policies. This review is an updated version of the SLR published in Fontoura and Ribeiro (2021). This study has been updated because it was conducted in 2019. In addition to the studies published after this year, new factors have been impacted urban mobility, such as the COVID-19 pandemic.

## 2.1 The Brazilian Urban Mobility Policy

Seventeen years after the first discussion in the Brazilian Congress, the Brazilian Urban Mobility Policy was sanctioned on January 3, 2012 (Gomide *et al.*, 2012). The Law nº 12,587 aims to provide tools to improve urban mobility in Brazilian cities (Almeida and Oliveira, 2014).

The BUMP is based on nine principles: universal accessibility; sustainable development; equity in public transportation; efficiency and effectiveness in the urban transport services; democratic management and social control of BUMP planning and evaluation; travel safety; fair distribution of benefits and burdens arising from the use of different modes and services; equity in the use of public spaces for circulation, roads and public areas; and efficiency, efficacy and effectiveness in urban circulation (Brazil, 2012).

In view of these principles, it is noted that the BUMP seeks to improve land use through sustainable urban mobility (Brazil, 2015). For that, one of the main guidelines of this policy prioritizes non-motorized transport over motorized transport and public transport services over private transport (Alves, 2014). Therefore, the BUMP emphasizes the importance to invest in infrastructure for these priority transports, such as exclusive bus lanes, cycle lanes and pedestrian paths (Brazil, 2012). It is worth mentioning that, regarding public transport, BUMP also highlights the need to promote equity of access and improve the services.

The use of non-motorized and public transports reduces air pollution, traffic congestion and trip costs. Therefore, this guideline is directly connected with the mitigation of environmental, social and economic costs associated to urban trips (Brazil, 2015). In addition to promoting urban mobility, the BUMP also encourages scientific-technological development and renewable energy use to reduce transport externalities (Brazil, 2012).

The BUMP not only encourages investments in sustainable transport, but it also suggests interventions to ensure minimum travel safety requirements (Valença and Santos, 2020). In addition to a safe environment, this policy also ensures an accessible environment, highlighting the need of people with reduced mobility (Brazil, 2012).

According to the BUMP, the population must participate in the planning, inspection and evaluation of the local urban mobility plans. Therefore, the population must be consulted to expose their needs, establishing, together with public managers, actions and strategies for the sustainable development of cities (Machado and Piccinini, 2018).

The Article 24 of this law addresses the urban mobility plan, which is a public management instrument for the BUMP implementation. In addition to contemplate all BUMP principles and guidelines, the urban mobility plan must present a short, medium and long-term planning with strategic actions and necessary resources to achieve the objectives of this law (Rubim and Leitão, 2013).

The urban mobility plan is mandatory for all cities with more than 20,000 people. Cities belonging to metropolitan areas or urban agglomerations with more than one million inhabitants must also carry out their mobility plans. According to the BUMP, the urban mobility plan is also mandatory in tourist cities because their urban mobility dynamics changes on weekends and holidays due to visitors (Brazil, 2012).

The BUMP establishes a period of three years (expired in 2015) for the preparation and approval of the urban mobility plans. This deadline has already been extended by some provisional measures, as some cities were not able to comply with this law due to limitations of financial, human and technological resources (Machado, 2019). The Law 14,000 presented in 2020 updates this deadline, which is April 2023 for cities with up to 250,000 inhabitants and April 2022 for cities with more than 250,000 people (Brazil, 2020b). These plans must be reviewed and updated at least once every 10 years. Cities that do not comply with this rule will be prevented from receiving federal funds for urban mobility until they meet the BUMP requirements (Brazil, 2015).

In a fiscal year, the federal government provides hundreds of millions of investments for the cities to carry out their mobility plans. However, this budget needs to be better controlled. According to Cavalcanti (2017), the institutions responsible for analyzing and monitoring these projects consider only the cost, environmental licensing, compatibility and functionality as evaluation criteria. Thus, sustainable urban mobility, which is the purpose of this policy, is not considered.

In addition to the need to improve the BUMP in terms of its monitoring and control, there are several challenges to implementing this policy. According to Bezerra *et al.* (2020), the main challenges are: resources availability, practical and technological, city characteristics, budget constraints, social and cultural factors, organizational aspects and lack of infrastructure for sustainable vehicles.

Machado and Piccinini (2018) suggest the systematization/compilation of norms, criteria and standards for the actions required by the BUMP, making easier its implementation and control. On the other hand, Cavalcanti *et al.* (2017) point out to the need to develop sustainability indicators to evaluate projects financed by this policy.

Despite requiring many public resources, the successful implementation of a policy does not depend only on the state apparatus, making it necessary to intersect interests and projects with population (Tonella, 2013). Thus, there are several factors for successful implementation of this policy.

### 2.2 System Dynamics

This section presents the main concepts of System Dynamics (SD) to facilitate the understanding of the models proposed in this study. More details about this method can be seen in Forrester (1961), Radzicki and Sterman (1994), Radzicki and Taylor (1997), Sterman (2000), Chaim (2009) and Bala *et al.* (2017).

System Dynamics (SD) was developed in the 1950s by Jay Forrester at the Massachusetts Institute of Technology (MIT) as an extension of cybernetics and system theory (Schwaninger, 2016). Based on fundamental concepts such as system, dynamics and structures, SD is an approach used to understand how systems change over time (Senaras, 2017). Therefore, SD seeks to understand how and why system's agents interacts, improving learning and decision making in complex systems (Ford and Lyneis, 2020).

SD aims to explore the complexity of real systems. Therefore, using mental models, this approach allows to reproduce problematic reactions and evaluate the effects of new policies in the system (Wen and Bai, 2017). However, SD is not a tool to predict the future, but an approach to analyze the current structure of a system and the reasons for its behavior (Featherston and Doolan, 2013).

Derived from feedback concepts of control theory, SD address the non-linearity, delay, feedback loops and uncertainties of the systems (Bala et. al., 2017). Consequently, this method is a useful mechanism for framing, understanding and discussing complex systems, being used more and more in different fields of study (Azar, 2012; Currie *et al.*, 2018).

The SD modeling process is not a linear sequence of steps, but a feedback process. To represent real systems, the SD models undergo constant interactions, continual questioning, testing and refinements. As can be seen in Figure 2.1, Sterman (2000) proposes an iterative modeling process, composed of five steps, to create SD models.

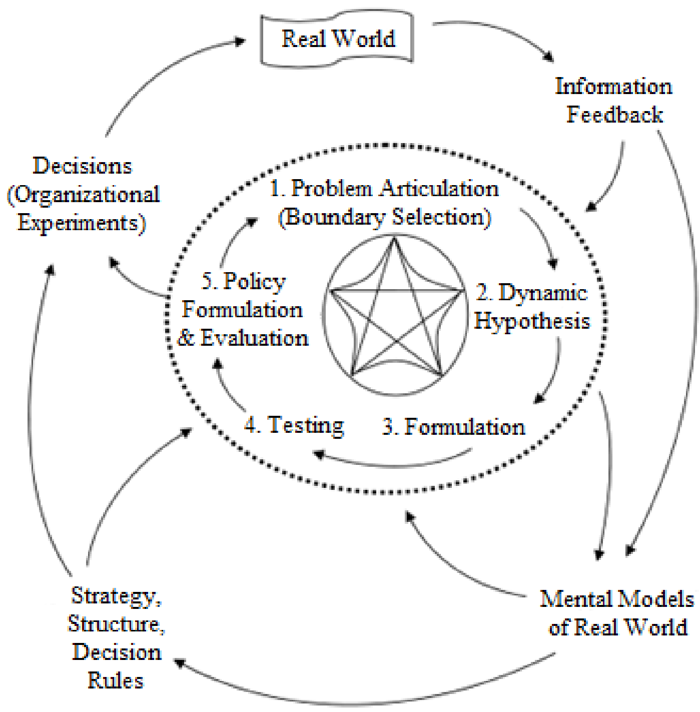


Figure 2.1 – Modelling process in System Dynamics

Source: Sterman (2000, p. 88).

The first step is to identify the problem and its causes. In addition, the variables and concepts that are important for understanding this problem are defined, as well as the time horizon needed to describe its symptoms and capture the effects of potential policies. In the second step, a dynamic hypothesis is developed to explain the problematic behavior through the interactions between the variables of the system. For this, a Causal Loop Diagram (CLD) must be developed to explain the causal relationships between the variables. Then, this diagram must be converted into a Stock and Flow Diagram (SFD), formalizing the system's stock and flow relationships.

In the third step, parameters, initial conditions and equations are established. Model testing is performed in the fourth step in which the simulated behavior is compared with the real behavior of the system. Finally, in Step 5, new policies are formulated and evaluated. For this, scenarios are created to verify the performance and robustness of these policies. The interconnections between the steps in Figure 2.1 represent the iterative cycle, showing that modeling is a feedback process.

In this context, SD involves the construction of mental models, formalizing the relationships of feedbacks and delays in the system. In addition, this method includes the simulation of these models to test the hypotheses about the behavior of the system.

### *2.2.1 Causal Loop Diagram*

SD uses causal loop diagrams to provide a better understanding of a problem, identifying the relationships between components in a system (Delgado-Maciel *et al.*, 2018). This diagram is the most important step in the development of a SD model, as the system structure is presented by feedback loops (Haghshenas *et al.*, 2015). The variables are related by causal links represented by arrows in a CLD with a negative or positive polarity.

The polarity of each causal link indicates the relationship between the variables. A positive link represents a proportional relationship between the variables, i.e., the variables change in the same direction. Therefore, "[…] if the independent (cause) increase (or decreases), the dependent (effect) variable also increases (decreases)" (Pagoni and Patroklos, 2019, p. 6). On the other hand, a negative polarity means that the linked variables change in opposite directions. It is worth mentioning that the links do not describe the variables, but the structure of the system. So, these links show what would happen if something changed in the system (Guimarães, 2007).

The set of links between variables forms casual loops, which are another outstanding feature of CLDs. These loops are circular chains of linked variables affecting one in turn (Bridgeland and Zahavi, 2009). For example, in a loop formed by four variables, one variable affects a second variable, which in turn affects a third variable. Finally, the third variable affects the fourth variable, which in turn affects the first.

Like links, causal loops have polarity. According to Sterman (2000), the main loops of a CLD must be highlighted by an identifier, like those in Figure 2.2, to represent its polarity. Positive feedback loops, also known as reinforcing loops, are identified when an increase of any variable affects the entire loop, resulting in an increase of the same variable (Pagoni and Patroklos, 2019). On the other hand, in negative loops (balancing loops), an increase in any variable results in a decrease of the same variable. It is worth noting that the polarity of the loop will be the same regardless of which variable initially changes (Sterman, 2000).

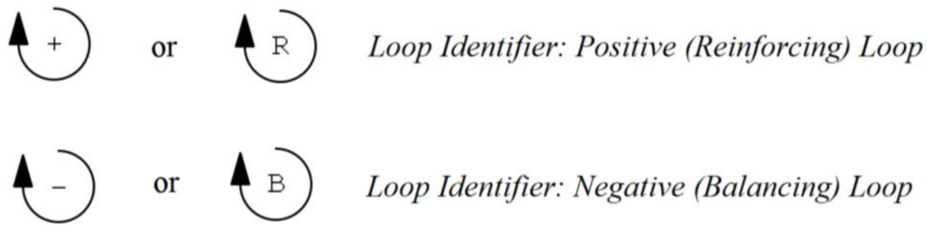


Figure 2.2 − Loop polarity indicators
Source: Sterman (2000, p. 138).

To verify the type of mechanism produced by a feedback loop, it is necessary to analyze the effects of an action. In the example shown in Figure 2.3, there are two feedbacks: one positive and one negative. In the reinforcing loop, the causal relationship between birth rate and population is positive, i.e., when the birth rate increases, the population increases, which leads to an increase in the birth rate. On the other hand, in the balancing loop, an increase in the population increases the death rate, which in turn decreases the population. In addition, the birth rate and the death rate are also impacted by the fractional birth rate and longevity, respectively. Therefore, an increase in fractional birth rate and/or an increase in average lifetime will increase the population.

In this context, it is observed that while a positive loop stimulates an unstable exponential growth or a collapse in system behavior, a negative loop stimulates asymptotically stabilized growth and stabilizes system behavior (Georgiadis and Vlachos, 2004). In addition to these two behaviors, there is the oscillatory behavior. Oscillation arises from negative feedback loop with long-time delays (Tian *et al.*, 2009). Time delays add phase delay elements to feedback loops, creating instability and increasing the probability of the system oscillation (Sterman, 2002). On CLDs, the delay is represented by an arrow with two dashes.

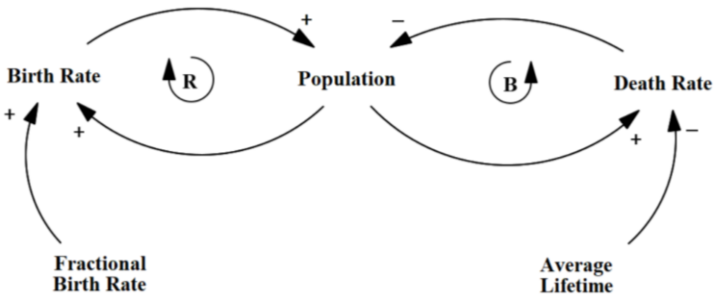


Figure 2.3 – Causal Loop Diagram for population model
Source: Sterman (2000, p. 138).

CLD is the qualitative approach to SD and is useful for understanding the problem and the structure of the system. To perform a more detailed quantitative analysis, a CLD is converted in a Stock and Flow Diagram (Niloofar *et al.*, 2021). This diagram distinguishes between variables that are stocks and those that are flows, i.e., distinguishes between accumulations and rates of change of resources in a system. Furthermore, the SFD allows the mathematical representation of the causal relationships, making it possible to simulate the framework. This diagram is presented below.

### *2.2.2 Stock and Flow Diagram*

Stock and Flow Diagrams (SFDs) uses mathematical formulas to show the inter-relationships between the variables of a system (Nasirzadeh and Nojedhi, 2013). To develop this diagram, four components are used: stocks, flows, auxiliary variables and connectors.

Stocks (also known as levels, accumulations or state variables) represent the accumulation of flows, i.e., these variables accumulate or integrate the system's rates of flow, determining its state at any point in time (Radzicki and Sterman, 1994). Therefore, stocks represent the state of resources, which can be anything that can be accumulated.

Flows are the variables that change stocks, increasing or decreasing their levels. These variables can be associated with the movement of resources and information in a system (Radzicki, 2020). Flows are represented by double-line arrows with valves and clouds, indicating the quantity (per unit of time) between stocks, see Figure 2.4. The valves regulate the system's rates of flows and the clouds represent the sources and sinks for the flows (Sterman, 2000).

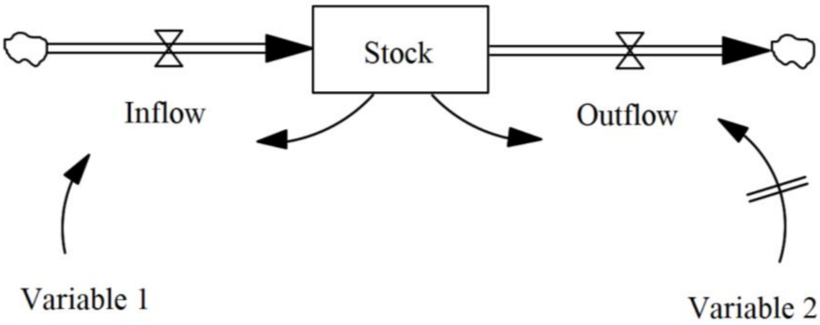


Figure 2.4 – Example of Stock and Flow Diagram

The auxiliary variables formulate the data and define the flow equations (Ghisolfi *et al.*, 2017). These variables do not accumulate but stores an equation or constant (Shiflet and Shiflet, 2014). Auxiliary variable equations convert inputs, provided by other variables in the model, into outputs (Tulinayo and van Bommel, 2013). Finally, connectors (arrows) are links that connect stocks, flows and auxiliary variables. To represent the connections that have a delay in the transmission of information, the connector is marked by two dashes.

For the example in Figure 2.4, the stock equation is:

$$Stock\ (t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock\ (t_0) \tag{2.1}$$

"[…] where Inflow(s) represents the value of the inflow at any time $s$ between the initial time $t_0$ and the current time $t$. Equivalently, the net rate of change of any stock, its derivative, is the inflow less the outflow" (Sterman, 2000, p. 194), defining the differential Equation (2.2).

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \tag{2.2}$$

In this context, it is noted that the SFD is used to classify the CLD variables and describe the feedback mechanisms through differential equations (Lane, 2008).

Therefore, SFD allows computer simulation and quantitative analysis. In general, simulation models are used to investigate and understand the behavior of systems over time, allowing to test alternative policies. For this, simulation software such as iThink, Powersim, Stella and Vensim are usually used in System Dynamics.

System Dynamics programs generally offer two methods of integration: Euler and Runge-Kutta (Fisher, 1994; Widmark, 2012). The Euler method is widely used due to its simplicity and suitability for many applications, being the most popular approach in dynamic modelling and simulation (Duggan, 2016; Marques *et al.*, 2021). Furthermore, according to Sterman (2000), the errors of this method are irrelevant in models that represent social and human systems. On the other hand, the Runge-Kutta method provides high accuracy to the model results, but it should be avoided in models with random perturbations (Sterman, 2000).

Before simulating a SD model, it is necessary to verify if it represents the system well, generating results close to reality. In other words, SD modellers must analyze whether the model reproduces the behavior of the problem adequately. For that, there are several tests for SD models, which will be discussed in the next section.

### *2.2.3 Model Testing*

System Dynamics models are simplified representations of real systems (Ford, 1999). Therefore, the purpose of model testing is to compare the simulated behavior with the real behavior of the system (Bala, 2017). To do so, this process starts from the beginning of the model development and only ends when the model is suitable for its purpose (Barlas, 1996).

Model testing is the process that verifies that the model is reliable, robust and applicable to reality (Ding *et al.*, 2016). For that, these tests check whether the model results are realistic, verifying that it responds plausibly when subjected to external influences (Sterman, 2000). It is worth mentioning that the Systems Dynamics approach does not aim at the exact simulation of a system, but the identification of its behavior patterns, providing a better understanding of the problem and helping the decision-making process (Senge and Forrester, 1980).

In addition to ensuring that the model reproduces the behaviors of the real system, model testing helps identifying flaws during the modeling process, improving SD models. For this, model testing

> "[…] involves identification and quantification of the error and uncertainty in the conceptual/simulation models, quantification of the numerical error in the computational solution, estimation of the simulation uncertainty, and finally, comparison between the computational results and the actual data" (Martis, 2006, p.40).

There are several tests and tools to evaluate SD models in the literature. Forrester and Senge (1980) were pioneers by proposing 17 tests, which are organized into three categories: Tests of Model Structure; Tests of Model Behavior; and Tests of Policy Implications. Grouping some of these tests and proposing new ones, Sterman (2000) presents a list of 12 tests to verify the reliability of a SD model, as can be seen in Table 2.1.

Table 2.1 – Clustering tests into five components of modeling

| **Test** | **Category** | **Components of modeling** |
|---|---|---|
| Boundary Adequacy | Advanced | Quantitative modeling |
| Structure Assessment | Intermediate | System's mapping and Quantitative modeling |
| Dimensional Consistency | Basic | Quantitative modeling |
| Parameter Assessment | Intermediate | Quantitative modeling |
| Extreme Conditions | Intermediate | Quantitative modeling |
| Integration Error | Basic | Quantitative modeling |
| Behavior Reproduction | Intermediate | Quantitative modeling |
| Behavior Anomaly | Advanced | Hypothesis testing |
| Family Member | Advanced | Hypothesis testing |
| Surprise Behavior | Intermediate | Hypothesis testing |
| Sensitivity Analysis | Intermediate | Hypothesis testing and Uncertainty analysis |
| System Improvement | Advanced | Forecasting & optimization |

Fonte: Adaptaded from Zagonel and Cobert (2006).

As discussed before, tests are applied throughout the entire model development process. To help the application of these tests, Zagonel and Cobert (2006) grouped the tests into five components of practice: System's Mapping; Quantitative Modeling; Hypothesis Testing; Uncertainty Analysis; and Forecasting/Optimization. Thus, for each component of modeling there is a set of tests that are more suitable. In addition, the tests are classified into three categories (Basic, Intermediate and Advanced) according to their complexity. Table 2.2 presents the category of each test and the stage of the modeling process in which they should be applied.

Table 2.2 – Tests for assessment of dynamic models

| Test | Purpose of Test | Tools and Procedures |
|---|---|---|
| **1. Boundary Adequacy** | To verify that the behavior of the model changes significantly when boundary assumptions are relaxed. | Model boundary charts, subsystem diagrams, causal diagrams, sock and flow maps and direct inspection of model equations. |
| **2. Structure Assessment** | To verify that the model conforms to the basic physics laws and decision rules capture the behavior of the actors in the system. | Policy structure diagrams, causal diagrams, stock and flow maps and direct inspection of model equations. Conduct partial model tests of the intended rationality of decision rules. |
| **3. Dimensional Consistency** | To verify that all equations are dimensionally consistent. | Dimensional analysis software. Inspect model equations for suspect parameters. |
| **4. Parameter Assessment** | To verify that the parameters values are consistent and have real world counterparts. | Statistical methods to estimate parameters. Partial model tests to calibrate subsystems. |
| **5. Extreme Conditions** | To verify that the model responds plausibly when subjected to extreme policies, shocks and parameters. | Test response to extreme values of each input, alone or in combination. Subject model to large shocks and extreme conditions. Implement tests that examine conformance to basic physical laws. |
| **6. Integration Error** | To verify that the results are sensitive to the choice of time step or numerical integration method. | Cut the time step in half and test for changes in behavior. Use different integration methods and test for changes in behavior. |
| **7. Behavior Reproduction** | To verify that the model reproduces the system behavior of interest in the system (qualitatively and quantitatively). | Compare model output and data qualitatively including modes of behavior, shape of variables, asymmetries, relative amplitudes and phasing and unusual events. |
| **8. Behavior Anomaly** | To check for anomalous behaviors when assumptions of the model are changed or deleted. | Zero out key effects (loop knockout analysis). Replace equilibrium assumptions with disequilibrium structures. |
| **9. Family Member** | To verify that the model successfully anticipates the response of the system to novel conditions. | Calibrate the model to the widest possible range of related systems. |
| **10. Surprise Behavior** | To verify that the model generates previously unobserved or unrecognized behavior and successfully anticipates the response of the system to novel conditions. | Resolve all discrepancies between model behavior and your understanding of the real system. |
| **11. Sensitivity Analysis** | To do numerical sensitivity, behavioral sensitivity and policy sensitivity | Perform univariate and multivariate sensitivity analysis. Use analytic methods (linearization, local and global stability analysis, etc.). |
| **12. System improvement** | To check that the modeling process helps to change the system for the better. | Design instruments in advance to assess the impact of the modeling process on mental models, behavior and outcomes. |

Source: Adapted from Sterman (2000).

## 2.3 System Dynamics for Sustainable Transportation Policies: A Systematic Literature Review

To verify the current state of scientific research on the application of SD in the analysis of sustainable transportation policies, it was carried out a Systematic Literature Review (SLR). According to Bramer *et al.* (2017), it is advisable to use multiple databases to obtain relevant references. Therefore, for the SLR, the search was conducted in five databases: Web of Science, Compendex, Scopus, Directory of Open Access Journals (DOAJ) and EBSCO.

Using the following combination of keywords: (urban policy AND sustainable transportation AND system dynamics) OR (urban policy AND urban mobility AND system dynamics) OR (system dynamics AND mitigation policies AND $CO_2$ emissions) OR (system dynamics AND mitigation policies AND congestion), it was identified 1145 papers. Then, the duplicate ones were eliminated. Also, those ones not aligned with the research topic were also eliminated. This analysis was based on the title and on the abstract of each paper. This process resulted in a portfolio with 46 papers which are discussed below. It is worth mentioning that the search for papers was carried out in the last week of July 2022.

Appendix A presents the synthesis of SLR with all the sustainable transportation policies that were analyzed through the SD and the main results. In addition, Appendix A also present the modes of transport (non-motorized and motorized), the sectors (Economy, Environmental, Land Use, New Technologies, Social, Traffic Accidents, Traffic Congestion and Traffic Safety) and the simulation time of each model. A summary of the main findings is presented below.

The problems of urban mobility become more evident in large urban areas and, therefore, the policy makers in these regions have been striving to meet urban sustainability standards (Pojani and Stead, 2015). Thus, the number of studies to solve such problems in those areas is increasing. All selected papers analyzed urban areas with more than two million inhabitants, except Bernardino *et al.* (2013), Asasuppakit and Thiengburanathum (2020) and Tonini *et al.* (2021) who carried out a case study in cities with less than 1 million inhabitants.

Among the selected articles, some studies did not assess the impact of policies in a city, but in a specific region. Liu *et al.* (2010b) and Sabounchi *et al.* (2014) carried out a case study in the Metropolitan Region of London, while Fontoura *et al.* (2019) and Procter *et al.* (2017) analyzed the Metropolitan Region of São Paulo and the Research

Triangle (North Carolina, USA), respectively. In addition, some studies consider the entire territory of a country. Ercan *et al.* (2016) and Keith *et al.* (2020) analyzed the United States, while the models of Barisa and Rosa (2018) and Benvenutti *et al.* (2019) were applied to Latvia and Brazil, respectively.

All papers assess the implementation of at least one policy. However, in almost all of them, it is analyzed the effects of proposed policies or measures. Considering the 46 papers, only seven consider some policy or goal set by the government. Fontoura *et al.* (2019), Fontoura *et al.* (2020), Tonini *et al.* (2021) and Fontoura *et al.* (2022) analyze the effects of the Brazilian Urban Mobility Policy (BUMP). Procter *et al.* (2017) proposed sustainable transportation policies and compared them with the goals set by the government. Finally, Liu *et al.* (2010a) and Ercan *et al.* (2016) adjusted existing public policies, simulating ambitious scenarios.

Motorized transport is addressed in 95% of the studies. Increasing the public transportation ridership and limiting private vehicles are the two most analyzed measures, being addressed in 42% and 38% of the studies, respectively. When these measures are not adopted, studies generally assess policies related to alternative fuels (mainly for private vehicles). On other hand, the non-motorized transport is addressed in only 28% of the papers. Therefore, it is observed that the major focus in these studies is to reduce the impact of private vehicles, while the incentive for non-motorized transport is not commonly explored in the literature.

When it comes to sustainable transportation, two of the main concerns are the air pollution and the energy consumption. Therefore, these two factors are widely used to calculate sustainable transportation indicators (Cheng *et al.* 2015; Litman, 2019). In this context, approximately 76% of the models have the environment sub-model. In addition, among the 46 papers, seventeen studies (37%) aim to analyze policies focused on reducing emissions and/or energy consumption in transport systems. Among the measures analyzed, priority public transportation, alternative fuel options, fuel tax and promotion of electric vehicles are highlighted.

Traffic congestion is also one of the main negative externalities of the transportation system, becoming a big challenge for urban planners and policymakers (Albalate and Fageda, 2019). Traffic congestion is addressed in 57% of the studies from the bibliographic studies. Three studies of them (Liu *et al.* (2010b), Sabounchi *et al.* (2014) and Zhang (2022)) are focused on evaluating the effects of a specific traffic congestion policy.

After the environmental issues, economic aspects are the factors most addressed in the papers (72%). This is justified since the economy directly affects travel demand, transportation infrastructure, impacting the entire system (Fontoura *et al.*, 2020).

Land use and social aspects are not usually explored in the SD models that analyze urban mobility. Therefore, both factors are addressed in only 28% of the papers. Although the social factors are not widely explored, three studies present a model that exclusively evaluate social issues. Macmillan *et al.* (2016) analyze how news about bicycle accidents affect the population and, consequently, the demand for this mode. After understanding the society, the culture and the human behavior, the authors propose procycling policies. Papageorgiou and Demetriou (2019) analyze the effects of public awareness of the sustainable habits. Similarly, Papageorgiou (2019) investigates strategies capable to change the mindsets of people towards active mobility. In addition to investigated awareness strategies, the author analyzes the introduction of Information and Communication Technology (ICT) in a computer simulated environment.

In addition to ensuring the displacement of people and cargo in urban areas with minimal impact on the environment, sustainable urban mobility policies must also guarantee the safety of these trips. Traffic speed is one of the main causes of traffic accidents (Mohanty and Gupta, 2015). However, in the bibliographic portfolio, only seven studies (Yang and Chen, 2000, Bernardino *et al.*, 2013, Bisen *et al.*, 2014, Haghshenas *et al.* 2015, Liu *et al.*, 2015b, Alonso et. al., 2017 and Khosravi *et al.*, 2020) address traffic speed. Likewise, the traffic accident is barely addressed, being incorporated only in Hu *et al.* (2020) and Hu *et al.* (2022) models.

About half of the studies address system infrastructure. In all of them, the infrastructure is associated with the road network. However, these studies only mention the size of the road network, disregarding the quality and maintenance of these roads. It is known that rougher roads reduce the quality of driving, reducing traffic safety and traffic speed (Bock *et al.*, 2021). However, this factor is not usually considered in SD models.

Due to the constant development of new technologies, transport systems are constantly changing. Therefore, new vehicles, services and alternative fuels are recurrently emerging. Among the selected papers, 15% of the models assess the effects of new technologies, being electric vehicles and carsharing the most addressed.

According to Zolfagharian *et al.* (2018), SD scholars are increasingly drawing to multi-method approaches to overcome the limitations of this approach. Therefore, they combine SD with one or more research methods to analyze complex problems and develop deeper solutions than a single method study can do.

Liu *et al.* (2010a) developed an integrated optimization model for urban transportation-environmental system, using a system dynamic model and a linear optimization model. To examine the urbanization process of Daqing City, Li *et al.* (2014) developed two models: an integrated system dynamic (SD) and CLUE-S model (SD-CLUES) and an integrated SD and stochastic cellular automata model (SD-CA). The first model clusters new urban developments in the downtown area or close to the main transportation networks. On the other hand, the second model allocates new urban cells in a scattered way across the study area. The authors compare the results of the two multi-level models and conclude that the SD-CA is closer to reality, presenting better results.

Tonini *et al.* (2021) combined system dynamics and analytic hierarchy process (AHP) to analyze the dynamics of individual behavior, in terms of mode choice, affected by BUMP instruments. It is worth mentioning that some authors used existing models in the literature. Guzman *et al.* (2014) and Alonso *et al.* (2017) used the Metropolitan Activity Relocation Simulator (MARS), a strategic and dynamic Land-Use and Transport Interaction (LUTI) model created by Pfaffenbichler (2003).

System dynamics can be applied to understand short and long-term impact of sustainable policies. Therefore, systems dynamics experts should consider the system attributes and policy goals to determine the period to analyze its effects. Regarding the simulation time, it is noted that there is not a standard to analyze the impacts of sustainable transportation policies. Most of the papers (65%) analyzed the long-term effects of the policy (more than 15 years). In addition, all studies evaluated policies or measures for one year or more, except for Yang and Chen (2000) and Wang *et al.* (2021), which simulated their models for only one day. Among the studies that simulated the model for years, the simulation time range is between 1 and 70 years, presenting an average of 25 years.

Despite the analysis of several policies, it was not found in the literature a study that analyze all modes of transport (motorized and non-motorized) and the eight aspects considered in this review (Economy, Environmental, Land Use, New Technologies, Social, Traffic Accidents, Traffic Congestion and Traffic Safety) at the same time. Also, despite the huge impact, none of the studies in this bibliographic portfolio analyzes the effects of the COVID-19 pandemic on transportation systems. Considering the time usually required to develop and publish research, this absence can be justified by the date on which the search for papers was carried out. Therefore, there is an opportunity for future research to develop a model that assesses the impact of sustainable transport policies considering all these factors.

## 2.4 Final remarks of the chapter

This chapter presented the main points addressed by the Brazilian Urban Mobility Policy. In addition to highlighting the objectives and principles of the BUMP, the review presented in this chapter allows to identify relevant factors that should be considered in the models proposed in this study.

Building a simulation model can be a tough task. There are many factors that influence a system. Thus, it is necessary identify the factors that most impact a system. Therefore, this chapter also presented a literature review on the application of SD in the analysis of urban mobility policies. As a result, the main factors and the gaps in the literature were found and will be explored in this study, as presented in the following chapters.

# 3 A FRAMEWORK FOR EVALUATING THE DYNAMIC IMPACTS OF THE BRAZILIAN URBAN MOBILITY POLICY FOR TRANSPORTATION SOCIOECONOMIC SYSTEMS

As mentioned in the previous chapter, the BUMP incentives the use of non-motorized and public transports. Therefore, this chapter presents a SD model to assess the effects of the BUMP, highlighting the strategies to change the current travel pattern, i.e., focusing on measures to replace motorized trips with non-motorized trips and private transport with public transport. The proposed model is based on Fontoura *et al.* (2019), which is the first SD model to evaluate the effects of the BUMP.

To test the proposed model and evaluate the effects of the BUMP, it was carried out a case study in the city of Rio Janeiro. Therefore, in addition to presenting the proposed model, this chapter shows the data collection for the case study. For the dynamic simulation, a period of 32 years was chosen, with 2018 as the base year (Year = 0) and 2050 as the last one (Year = 32). Based on the simulation results, a discussion about the BUMP effects is presented. Finally, at the end of this chapter, a comparison of the BUMP effects in Brazilian megacities (Rio de Janeiro and São Paulo) is also presented. It is noteworthy that the modeling and simulation was performed using software Vensim® PLE (Personal Learning Edition).

The proposed model presented in this chapter was published in Fontoura *et al.* (2020) and the comparison between Brazilian megacities was published in Fontoura *et al.* (2022).

## 3.1 Proposed Model

Like many SD models, in Fontoura *et al.* (2019), the public transport is represented by only one mode (bus) and non-motorized modes are not addressed. Seeking to better represent the Brazilian reality, more variables and relations were considered in this study. In the proposed model, public transport is represented by bus, train, subway and light rail transit (LRT). Also, the proposed model presents the BUMP's incentive to non-motorized trips. The simplified representation of the system, as well as the details of its components and their interactions are presented in the Causal Loop Diagram and Stock and Flow Diagram, which are discussed below.

### *3.1.1 Causal Loop Diagram*

Due to the complexity of the transport system and, consequently, the high number of variables involved, the proposed CLD is composed of sectors, where these variables are grouped. Thus, Figure 3.1 shows the CLD, which presents the relations between nine sectors (Population, Economy, Air Pollution, Travel Demand, Transport Supply, Non-Motorized Transport, Public Transport, Private Transport and Traffic Congestion) and the BUMP.

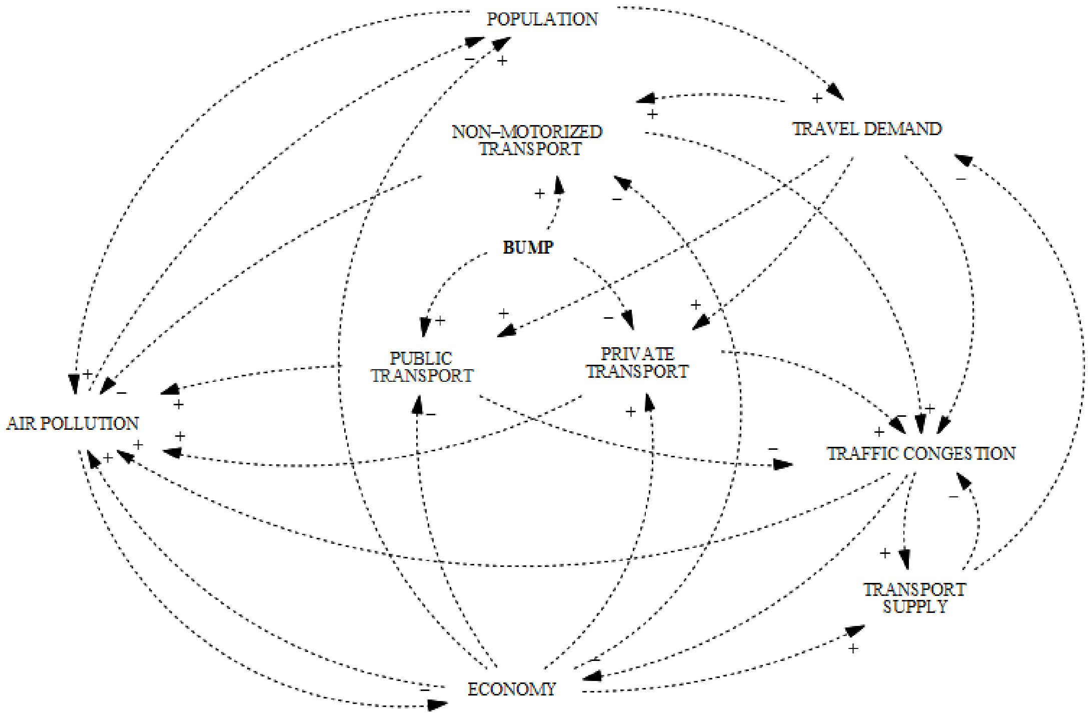


Figure 3.1 – Causal Loop Diagram for the first model

Source: Based on Fontoura *et al.* (2019).

The connections between these sectors form eighteen feedback loops, which are described below.

Feedback loops i - iii:

i. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Traffic Congestion $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Economy $\xrightarrow{+}$ Population **(R1)**

ii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Traffic Congestion $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Economy $\xrightarrow{+}$ Population **(R2)**

iii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Traffic Congestion $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Economy $\xrightarrow{+}$ Population **(B1).**

An increase in population raises the transportation demand (York *et al.*, 2017). Due to increased demand, the number of trips by all modes of transport also increases (Pfaffenbichler *et al.*, 2010). An increase in the number of trips with non-motorized transport reduces congestion level and, consequently, air pollution (Liu *et al.*, 2015a; Wen and Bai, 2017). Reducing air pollution has a positive impact on the economy, making the city more attractive to new residents (Yang *et al.*, 2014; Jia *et al.*, 2017). Therefore, the first loop (R1) describes a positive behavior among the variables, i.e., an increase in the first variable causes a growth on it, generating exponential growth over time. The difference between the first three loops is the type of transport. As BUMP encourages the use of public transportation over individual mode, it has been shown that the increase in the number of trips with public transport reduces the number of trips with individual transportation, reducing traffic congestion. Public transport and non-motorized transport have a proportionately inverse relationship with traffic congestion, since the increase in the number of trips with these modes reduce traffic congestion (Bedadala and Mallikarjuna, 2016). Thus, the second loop (R2) is also positive. However, an increase in the number of trips with individual vehicles increases the level of traffic congestion (Jia *et al.*, 2017), forming the balancing loop B1.

Feedback loops iv - vi:

iv. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Air Pollution $\xrightarrow{-}$ Economy $\xrightarrow{+}$ Population **(R3)**

v. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Air Pollution $\xrightarrow{-}$ Economy $\xrightarrow{+}$ Population **(R4)**

vi. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Economy $\xrightarrow{+}$ Population **(B2)**.

Loops R3, R4 and B2 are like loops R1, R2 and B1, but they do not have the Traffic Congestion sector. These loops present the direct relationship between the three types of transport (non-motorized, private and public) with the Air Pollutant Emissions. Despite this change, loops R3, R4 and B2 show the same behavior of loops R3, R4 and B2, respectively. It is noteworthy that, as in loop R1, the relationship between Public Transport and the Air Pollutant Emissions, presented in loop (v), considers that the increase of public transportation is carried out to the detriment of individual transportation and, therefore, the increase of the number of trips by this mode of transport reduces the Air Pollution.

Feedback loops vii - ix:

vii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Air Pollution $\xrightarrow{-}$ Population **(R5)**

viii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Air Pollution $\xrightarrow{-}$ Population **(R6)**

ix. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Population **(B3)**.

Loops R5, R6 and B3 are like the loops R3, R4 and B2, respectively, but they do not have the Economy sector. These loops show the direct relationship between two sectors: Air Pollution and Population. Despite this change, the loops compared previously present the same behaviors.

Feedback loop x:

x. Economy $\xrightarrow{+}$ Transport Supply $\xrightarrow{+}$ Traffic Congestion $\xrightarrow{+}$ Economy **(R7)**.

Economic growth results in more investment in transport infrastructure, increasing transport supply and, consequently, reducing traffic congestion. This reduction in the congestion level positively affects the local economy (Wang *et al.*, 2008), forming the self-reinforcing loop R7.

Feedback loop xi:

xi. Travel Demand $\xrightarrow{+}$ Traffic Congestion $\xrightarrow{+}$ Transport Supply $\xrightarrow{-}$ Travel Demand **(B4)**.

An increase in travel demand has a direct impact on the transportation system, increasing the traffic congestion level (Bernardino and Hoofd, 2013). To correct this situation, investments are made to increase the transport supply (Jia *et al.*, 2017), leading in a reduction of travel demand (the balancing loop B4).

Feedback loop xii:

xii. Traffic Congestion $\xrightarrow{+}$ Transport Supply $\xrightarrow{-}$ Traffic Congestion **(B5)**.

The increase in transport supply reduces traffic congestion (Jin and Rafferty, 2017). Conversely, according to Fontoura *et al.* (2019), an increase in the traffic congestion level demands available roads, affecting the transport supply (the negative loop B5).

Feedback loops xiii - xv:

xiii. Economy $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Economy **(B6)**

xiv. Economia $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Air Pollution $\xrightarrow{-}$ Economy **(R8)**

xv. Economia $\xrightarrow{+}$ Non-motorized Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Economy **(R9)**.

As the economy grows, the number of individual travels increases (Sayyadi and Awasthi, 2017). Thus, there is an increase in the air pollution (Rees *et al.*, 2017). As already discussed, this result has a negative effect on the economy (the negative loop B6). Economic growth increases the purchasing power, enhancing car ownership and, consequently, reducing the attractiveness of public transport and non-motorized transport. Therefore, the opposite happens with public and non-motorized transport, forming the positive loops R8 and R9.

Feedback loops xvi - xviii:

xvi. Economy $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Traffic Congestion $\xrightarrow{-}$ Economy **(B7)**

xvii. Economy $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Traffic Congestion $\xrightarrow{-}$ Economy **(R10)**

xviii. Economy $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Traffic Congestion $\xrightarrow{-}$ Economy **(R11)**.

The balancing loop B7 and the self-reinforcing loops R10 and R11 consider the Traffic Congestion sector. As already discussed, private transport and traffic congestion have a directly proportional relation. Conversely, an increase in the number of trips by public and non-motorized transport reduces the traffic congestion.

Besides presenting the relations between the nine sectors and the BUMP, the CLD does not present all variables nor classify them according to their type. Thus, all variables were classified and related in the Stock and Flow Diagram (SFD) which is presented below.

### *3.1.2 Stock Flow Diagram*

The Figure 3.2 shows the Stock and Flow Diagram proposed in this study. The next sections present the equations that connect all variables in the SFD, as well as the parameters and the considerations to carry out the case study.

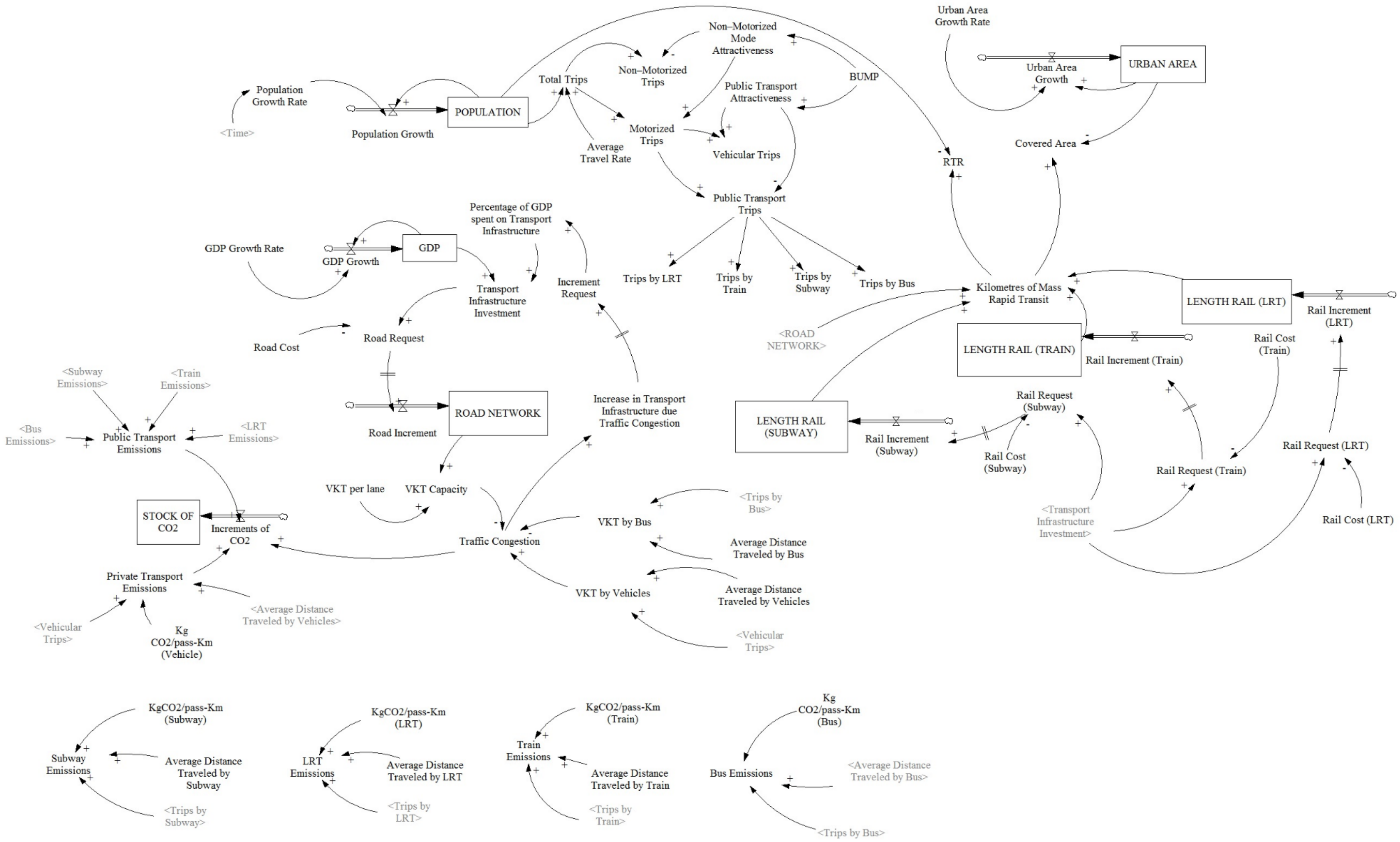


Figure 3.2 – Stock and Flow Diagram

*3.1.2.1 Population sector*

As can be seen in Figure 3.3, the Population sector depicts the developmental stage of a given region (Wang *et al.*, 2008). As a stock variable, the population is obtained from the population in a previous period plus the population growth (Table 3.1).

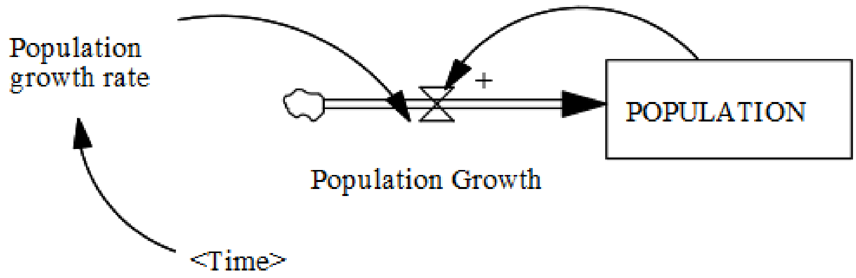


Figure 3.3 – Population sector

Table 3.1 – Population sector equations

| **Variable** | **Equation** | **Unit** |
|---|---|---|
| Population | $\int_{t_0}^{t} (\text{Population Growth})\, dt + \text{Population}\ (t_0)$ | Inhabitant |
| Population Growth | $\text{Population} \times \text{Population Growth Rate}$ | Inhabitant |

According to IBGE (2018), Rio de Janeiro has an estimated population of 6,520,266 inhabitants. To determine the population growth rate, it was used the AiBi method to project the population up to 2050. This method is a tool commonly used in population projections for Brazilian cities (IBGE, 2008). Therefore, based on the Census 2000, Census 2010 and an exogenous population projection for Rio de Janeiro State, the AiBi method calculates proportion factors for the city of Rio de Janeiro and projects its population. After performing this projection, a linear regression (Equation (3.1)) was performed to represents the population growth rate.

$$Population\ Growth\ Rate = -0.0002 \times Time + 0.0047 \qquad (3.1)$$

*3.1.2.2 Economy sector*

The Gross Domestic Product (GDP) growth has a direct impact on the investments made in the transportation sector, as can be seen in Figure 3.4. The variable "Investment in Transport Infrastructure in relation to GDP" corresponds to the percentage of GDP that is allocated to the maintenance and expansion of transport infrastructure. However, in the proposed model, the variable "Percentage of GDP spent in Transport Infrastructure" is influenced by traffic congestion. Therefore, if the system presents a high congestion level, there is an increase in transport investment to solve this negative externality.

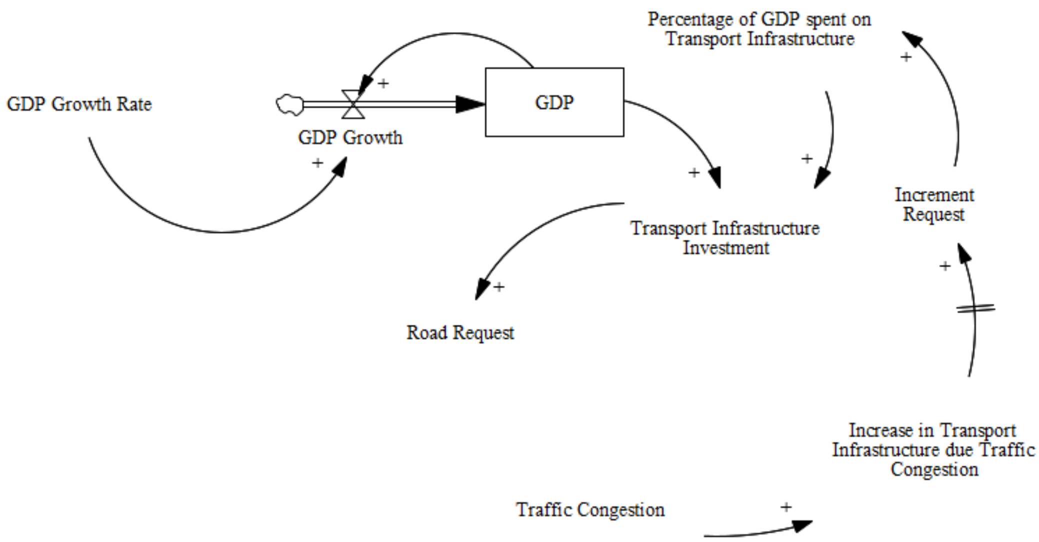


Figure 3.4 – Economy sector

The Vensim® PLE version does not allow calling the return of a function within another function. Therefore, two variables were created to represent this relationship (Table 3.2). The variable "Transport Infrastructure Investment due to Traffic Congestion" verifies if the system has traffic congestion. If the system is congested, the increase in investment will correspond to a percentage of the rate (represented by parameter A) normally intended for transport. If not, there is no increase in the normal transport infrastructure investment. The increase in investment does not happen instantaneously. Therefore, the variable "Increment Request" represents the delay between the period that the congestion was identified until the moment when the increase in transportation investment occurs. This delay is represented by parameter B. It is worth mentioning that the condition “Traffic Congestion > 1” seeks to identify if the system is congested. On this parameter, further explanations are presented in Section 3.1.2.6.

Table 3.2 – Economy sector equations

| Variable | Equation | Unit |
|---|---|---|
| GDP | $\int_{t_0}^{t} (\text{GDP Growth})\, dt + \text{GDP}\ (t_0)$ | US$ |
| GDP Growth | $\text{GDP} \times \text{GDP Growth Rate}$ | US$ |
| Transport Infrastructure Investment | $\text{GDP} \times \text{Percentage of GDP spent on Transport Infrastructure}$ | US$ |
| Percentage of GDP spent on Transport Infrastructure | $\text{Percentage of GDP} + \text{Increase Request}$ | Percentage |
| Increment Request | DELAY FIXED (Increase in Transport Infrastructure Investment due Traffic Congestion, B, 0) | Percentage |
| Increase in Transport Infrastructure Investment due Traffic Congestion | IF THEN ELSE (Traffic Congestion $> 1$, Percentage of GDP $\times$ A, 0) | Percentage |

The Rio de Janeiro's GDP is US$ 80.25 billion and historical data analysis shows that the GDP average annual growth rate in this city is 10% (IBGE, 2019). According to Rio de Janeiro City Hall (2016a, 2016b), the historical amount invested in the Rio de Janeiro city's urban infrastructure has been only 0.002% of the Rio de Janeiro's GDP. It was not found in the literature the increase in transport investment due to the traffic congestion nor a delay for this increase. Therefore, we adopted a 10% increase and a delay of 10 years. These estimates were based on specialists and staff from Rio de Janeiro's Department of Transportation.

#### *3.1.2.3 Travel Demand sector*

The travel demand is defined by the size of the population and the average travel rate per person, as shown in Figure 3.5. After calculating the total number of trips, it is possible to determine the number of trips performed with motorized and non-motorized modes. For this, the non-motorized mode attractiveness is used. After setting the number of motorized, it is possible to determine the number of trips that are carried out with public transport and private transport. Thus, the public transport attractiveness is used.

According to the proposed model, the non-motorized mode attractiveness and the public transport attractiveness are influenced by the BUMP, which is modelled by the ramp function. This function smoothly changes the variable value as a curve and its use is common in situations where it is necessary to simulate a linearly increasing or decreasing flow that is not constant over time (Abidin *et al.*, 2014). The ramp function assigns zero to the variable until the beginning of its behavior change. After this period, the curve changes the variable value until it reaches a certain value and then remains constant. Thus, this function allows simulating the period of adaptation to new policies (Coyle, 1996). The Travel Demand sector equations are listed in Table 3.3.

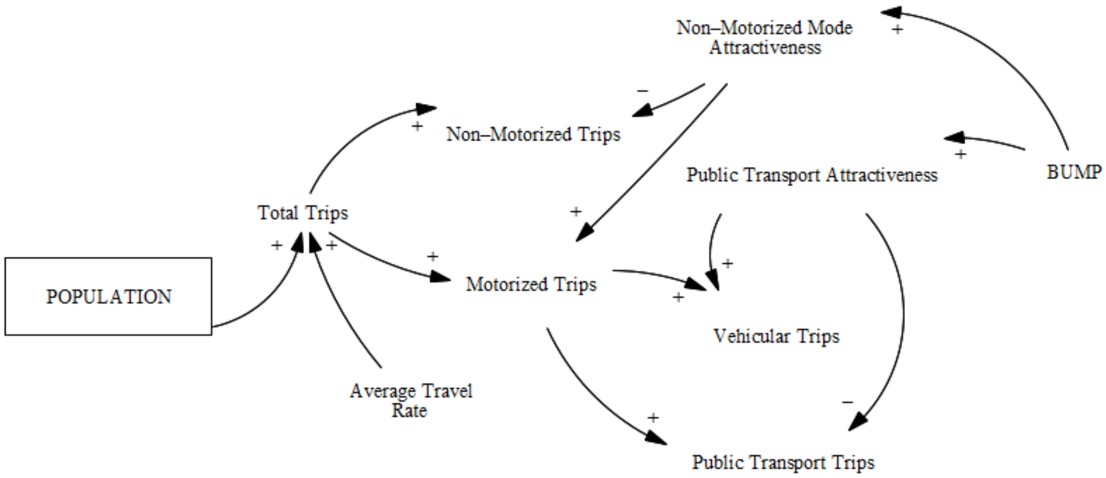


Figure 3.5– Travel Demand sector

Table 3.3 – Travel Demand sector equations

| Variable | Equation | Unit |
|---|---|---|
| Total Trips | Population × Average Travel Rate | Trip |
| Non-Motorized Trips | Total Trips × Non-Motorized mode Attractiveness | Trip |
| Motorized Trips | Total Trips × (1 − Non-Motorized mode Attractiveness) | Trip |
| Public Transport Trips | Motorized Trips × Public Transport Attractiveness | Trip |
| Vehicular Trips | Motorized Trips × (1 − Public Transport Attractiveness) | Trip |
| BUMP | RAMP (Slope, Start Time, End Time) | Percentage |

According to the Government of Rio de Janeiro (2015), the average travel rate in the city of Rio Janeiro is 2.17 trips per day, i.e., 729.05 trips per year. To determine the non-motorized mode attractiveness, it was established a relationship between the percentage of trips with this mode and the level of BUMP implementation. Similarly, the percentage of trips with public transport and the BUMP was used to determine the attractiveness of public transport. These assessments were carried out based on scenarios for urban mobility policies implementation, which were adapted to the Rio de Janeiro's reality.

Based on the Perkins and Will (2018) projections for 2050, a S-shaped curve was constructed (Figure 3.6) to represent the relationship between the percentage of trips with non-motorized modes in Rio de Janeiro and the level of BUMP implementation. In the absence of implantation, the percentage of travel with non-motorized transport is 28% in 2018 and, according to the projections, reaches 35% in 2050 if the BUMP is completely fulfilled. This change will initially be slow. Once the initial challenges of policy implementation are overcome, the growth becomes exponential until a reversal in the implementation rate, stabilizing at the end of the BUMP implementation. Therefore, the non-motorized mode attractiveness is defined by Equation (3.2).

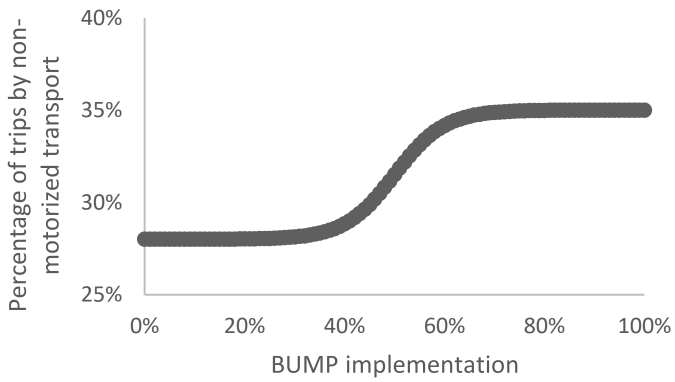


Figure 3.6 – Relationship between the BUMP and the use of non-motorized transport

$$\text{Non-Motorized Mode Attractiveness} = 0.035 \times \tanh[(10 \times \text{BUMP - 5})] + 0.315 \qquad (3.2)$$

Based on SuM4All$^{TM}$ (2017) projections, another S-Shaped curve was developed (Figure 3.7), to represent the relationship between the percentage of trips with public transportation in Rio de Janeiro and the level of BUMP implementation. Therefore, the attractiveness of public transport is defined by this function (Equation (3.3)), starting at 66% when there is no BUMP implementation and reaching 77.17% with the total implementation.

It is noteworthy that the choice of the sigmoid function to represent the attractiveness is justified by the fact that this function presents a behavior commonly observed in SD (Sterman, 2000). Therefore, this function is used to represent the behavior of policies implementation whose growth is exponential at first, but gradually decreases until the system reaches its equilibrium level.

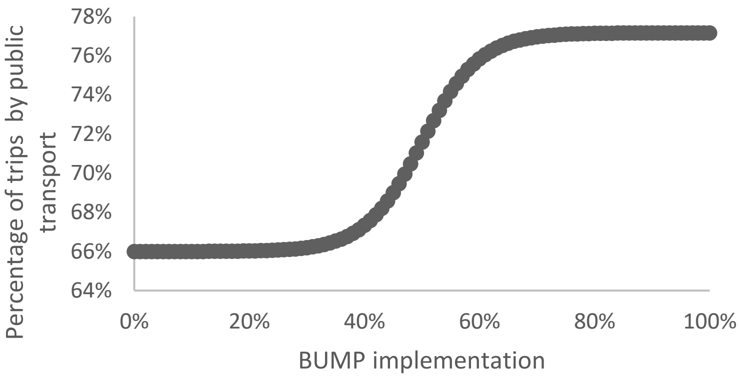


Figure 3.7 – Relationship between the BUMP and the use of public transport

$$\text{Public Transport Attractiveness} = 0.05585 \times \tanh[(10 \text{ x BUMP - } 5)] + 0.7185 \quad (3.3)$$

During the simulation period, the level of BUMP implementation will increase linearly to reach 100% by 2050. In addition, due to the Law nº 13,683/2018, which extended the deadline for preparing the Urban Mobility Plans to seven years (Brazil, 2018), we considered that BUMP implementation begins in 2019, i.e., year 1 in the simulation. Therefore, the BUMP is defined as Equation (3.4). It is worth mentioning that the model proposed in this chapter was developed before the publication of Law 14,000/2020 (Brazil, 2020b). Therefore, 2019 was used as the deadline for BUMP implementation.

$$BUMP = RAMP(0.0322582, 1, 32) \quad (3.4)$$

*3.1.2.4 Transport Supply sector*

The Transport Supply sector calculates the total extent of transport infrastructure to meet the travel demand, as can be seen in Figure 3.8. The transport supply equations are listed in Table 3.4. The total of request of road kilometers determines the growth of the road network. However, due to the planning, the time between bidding process and the road construction is not well-defined, there is an interval between the road request and the road network increment and this delay is represented by parameter C.

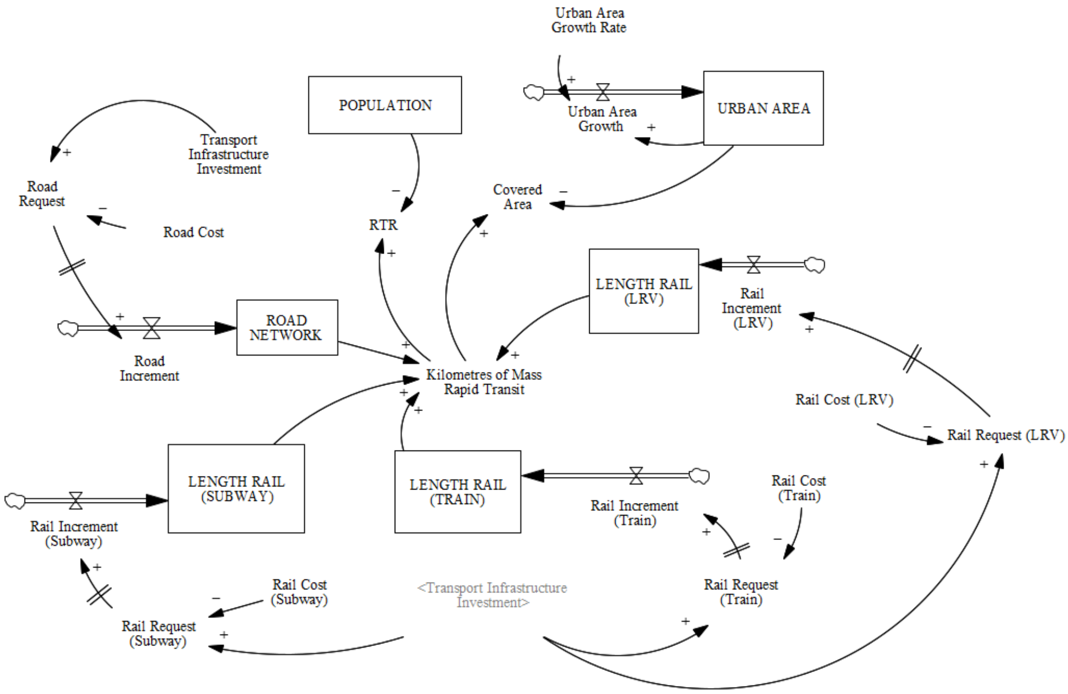


Figure 3.8 – Transport Supply sector

The total of requested road kilometers is determined by the ratio between the investments destined for transport and the road kilometer average price. Parameter D represents the percentage of transport infrastructure investment that will be destined for the expansion of the road network. Like the road network, there are equations to represent the transport supply. The delays for the implementation of train, subway and LRT rails are represented by the parameters E, G and I, respectively.

In addition to the system capacity, two urban mobility indicators are calculated: the Rapid Transit to Resident (RTR) and Covered Area. The RTR is expressed in kilometers of medium and high-capacity transport per million inhabitants. For this, it is necessary to determine the total extent of medium and high-capacity transport infrastructure. It is worth mentioning that, in addition to the rail transport, the percentage of road network destined to medium and high-capacity transport is used in the calculation, which is represented by parameter K.

The Rio de Janeiro’s Road network extension is 11,000 km, of which 1.57% (172.8 Km) is the length of rapid transit lines (ITDP and EMTU-SP, 2017). As for the total mileage of rails, Rio de Janeiro has 58 km, 170 km and 12 km of subway, train and LRT, respectively (Invepar, 2019; SuperVia, 2016 and VLT Carioca, 2018).

Table 3.4 − Transport Supply sector equations

| Variable | Equation | Unit |
|---|---|---|
| Road Network | $\int_{t_0}^{t}(\text{Road Increment})dt + \text{Road Network }(t_0)$ | Km |
| Road Increment | $\text{DELAY FIXED (Road Request, C, 0)}$ | Km |
| Road Request | $\frac{D \times \text{ Transport Infrastructure Investment}}{\text{Road Cost}}$ | Km |
| Length Rail (Train) | $\int_{t_0}^{t}(\text{Rail Increment (Train)})dt + \text{Length Rail (Train) }(t_0)$ | Km |
| Rail Increment (Train) | $\text{DELAY FIXED (Rail Request (Train), E, 0)}$ | Km |
| Rail Request (Train) | $\frac{F \times \text{ Transport Infrastructure Investment}}{\text{Rail Cost (Train)}}$ | Km |
| Length Rail (Subway) | $\int_{t_0}^{t}(\text{Rail Increment (Subway)})dt + \text{Length Rail (Subway) }(t_0)$ | Km |
| Rail Increment (Subway) | $\text{DELAY FIXED (Rail Request (Subway), G, 0)}$ | Km |
| Rail Request (Subway) | $\frac{H \times \text{ Transport Infrastructure Investment}}{\text{Rail Cost (Subway)}}$ | Km |
| Length Rail (LRT) | $\int_{t_0}^{t}(\text{Rail Increment (LRT)})dt + \text{Length Rail (LRT) }(t_0)$ | Km |
| Rail Increment (LRT) | $\text{DELAY FIXED (Rail Request (LRT), I, 0)}$ | Km |
| Rail Request (LRT) | $\frac{J \times \text{ Transport Infrastructure Investment}}{\text{Rail Cost (LRT)}}$ | Km |
| RTR | $\frac{\text{Kilometers of Mass Rapid Transit}}{\text{Millions of Urban Residents}}$ | $\frac{\text{Km of MRT}}{10^6\text{Residents}}$ |
| Kilometers of Mass Rapid Transit | Length Rail (Train) + Length Rail (Subway) + Length Rail (LRT) + K × Road Network | Km of M.R.T. |
| Covered Area | $\frac{\text{Kilometers of Mass Rapid Transit}}{\text{Urban Area}}$ | $\frac{\text{Km of MRT}}{\text{Km}^2}$ |
| Urban Area | $\int_{t_0}^{t}(\text{Urban Area Growth})dt + \text{Urban Area}(t_0)$ | $Km^2$ |
| Urban Area Growth | Urban Area × Urban Area Growth Rate | $Km^2$ |

Each construction has its specifications (planning, bidding and budget) and, therefore, each project has a schedule. Thus, there is a delay between the transportation investments and the effective road network expansion. After conducting interviews with experts in urban roads construction, it was considered a delay of three years. According to Mercedes-Benz (2018), for LRT and subway, the average time for planning and construction is six and 12 years, respectively. For train, it was adopted an intermediate value, nine years.

There are no projects to expand the rail system (subway, train and LRT) in the city of Rio de Janeiro. The expansion of these modes is slow and depends on political decisions. In the case of the train, for example, since the beginning of operations in 1998, SuperVia opened only eight new stations, six of which were inaugurated in 2016 due to the Olympic Games (SuperVia, 2016). Therefore, the expansion of these modes was not considered. Thus, parameters B, C and D are equal to zero.

According to DNIT (2018), the average cost for implantation/paving a road is US$ 789,750.00 per kilometer. Based on the investments made in completed projects in the city of Rio de Janeiro, it was possible to calculate the cost per kilometer for each mode, which is US$ 75,000,000.00, US$ 7,500,000.00 and US$ 9,625,000.00 for subway, train and LRT, respectively (Government of Rio de Janeiro, 2015, Rio de Janeiro City Hall, 2014).

According to IBGE (2017), the city of Rio de Janeiro has an area of 1,200.177 km². It was verified that Rio de Janeiro presented an average urban growth rate of 0.1% in the last years (IBGE, 2017).

*3.1.2.5 Public Transport sector*

The Public Transport sector (Figure 3.9) performs the modal split after determining the number of trips performed by this type of transport. Thus, the number of trips with bus, subway, train and LRT is equal to the share of each mode (L, M, N and O, respectively) times the number of public transport trips. The public transports are listed in Table 3.5.

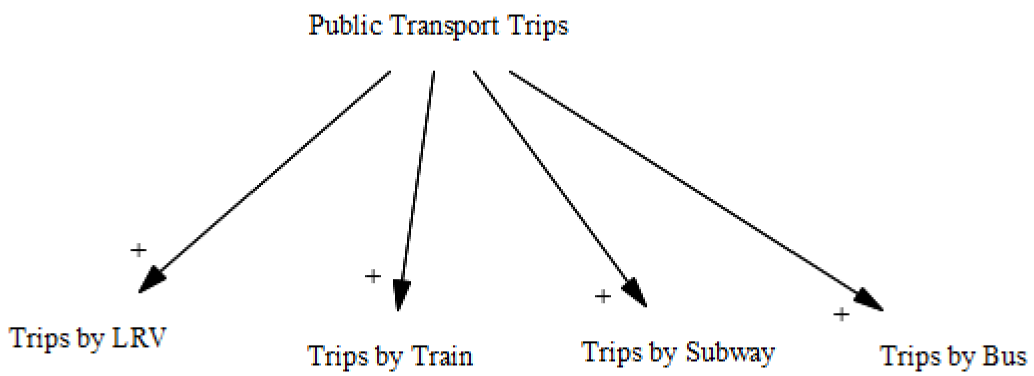


Figure 3.9 – Public Transport sector

Table 3.5 – Public Transport sector equations

| Variable | Equation | Unit |
|---|---|---|
| Trips by Bus | L × Public Transport Trips | Trips |
| Trips by Train | M × Public Transport Trips | Trips |
| Trips by Subway | N × Public Transport Trips | Trips |
| Trips by LRT | O × Public Transport Trips | Trips |

The trips by bus, train, subway and LRT represent, respectively, 73.26%, 10.01%, 15.25% and 1.48% of public transport trips in Rio de Janeiro (Rio de Janeiro City Hall, 2018; VLT Carioca, 2018).

*3.1.2.6 Traffic Congestion sector*

Based on Wang *et al.* (2008) and Sayyadi and Awasthi (2017), traffic congestion is determined by road capacity and the distance travelled by vehicles, as shown in Figure 3.10. This variable is dimensionless and represents how much the system is being used. In other words, if this variable assumes values above 1.00 means that the total distance travelled is greater than the capacity of the system, i.e., the system is congested.

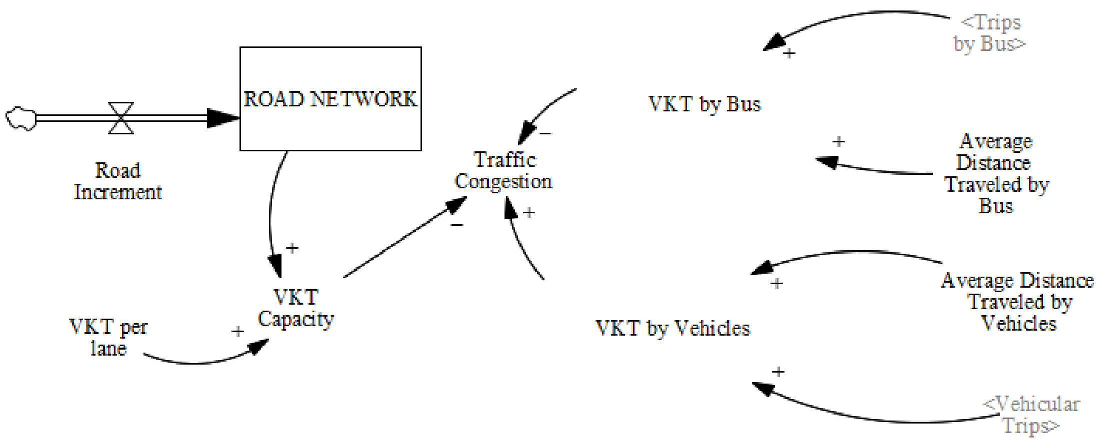


Figure 3.10 – Traffic Congestion sector

The total distances travelled, the sum of public and individual transports, is determined by the number of total trips times the average distance per trip. However, the average occupancy rates for buses and vehicles must be considered. As can be seen in Table 3.6, these rates are represented by the parameters P and Q, respectively.

It is worth mentioning that the time step of the simulation influences this sector. If simulation period is yearly, the values of the total distances travelled by collective and individual vehicles will represent the annual sum. In this case, the capacity of the roads must be multiplied by 365.

Table 3.6 – Traffic Congestion sector equations

| Variable | Equation | Unit |
|---|---|---|
| Traffic Congestion | $\frac{\text{VKT by Bus} + \text{VKT by vehicles}}{\text{VKT Capacity}}$ | - |
| VKT by Bus | $\frac{\text{Trips by Bus}}{\text{P}} \times \text{Average Distance Traveled by bus}$ | Km |
| VKT by Vehicles | $\frac{\text{Vehicular Trips}}{\text{Q}} \times \text{Average Distance Travelled by Vehicles}$ | Km |
| VKT Capacity | $\text{R} \times \text{Road Network} \times \text{VKT per lane}$ | Km |

According to CNT and NTU (2017), the average occupancy of cars and buses are 1.3 passengers/vehicle and 45 passengers/vehicle, respectively. Meanwhile, the average trip distances by individual vehicles and buses in large urban areas are 7.4 Km and 10.2 Km, respectively (ANTP, 2016; Government of Rio de Janeiro, 2015). For the Vehicle-Kilometers Traveled (VKT) per lane, it was used the value provided by the United States Department of Transportation, 1317 (Bureau of Transportation Statistics, 2022) because it was not found Brazilian data for it.

### *3.1.2.7 Air Pollution sector*

The use of motorized transport in urban areas always generates some type of pollution (atmospheric, sonorous, or visual). In this study, the level of $CO_2$ emission is used as a pollutant indicator. Public transport emissions represent the sum of emissions from all public transport modes, while individual transport emissions correspond to emissions generated by private vehicles. The Traffic Congestion sector influences the Air Pollution sector because traffic congestion increases by 20% the Air Pollution (Resende and Sousa, 2009). The equations of the Air Pollution sector (Figure 3.11) are listed in Table 3.7.

The average trip distance by train, subway and LRT in Rio de Janeiro is 20.5 km, 11.6 km and 3.25 km, respectively (Government of Rio de Janeiro, 2015, VLT Carioca, 2018). Therefore, the $CO_2$ emission in Kg $CO_2$/pass.Km, is 0.1268, 0.0160, 0.0055, 0.0035 and 0.00465 for each mode (Carvalho, 2011; Andrade *et al.*, 2017; Brazil, 2014).

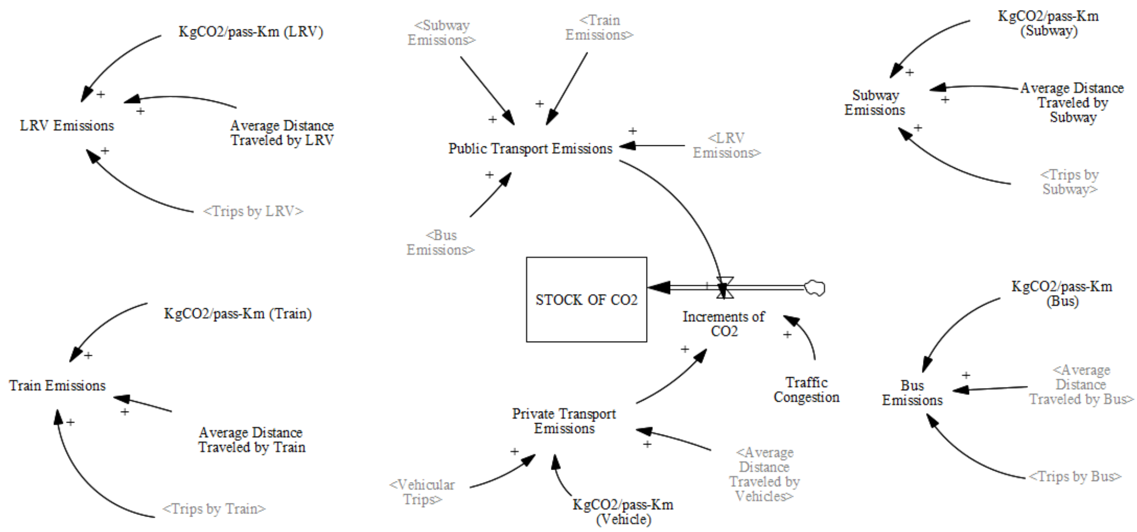


Figure 3.11 – Air Pollution sector

Table 3.7 – Air Pollution sector equations

| Variable | Equation | Unit |
|---|---|---|
| Stock of $CO_2$ | $\int_{t_0}^{t} (\text{Increments of } CO_2)\, dt + \text{Stock of } CO_2\ (t_0)$ | Kg $CO_2$ |
| Increments of $CO_2$ | IF THEN ELSE (Traffic Congestion > 1, 1,2 × (Private Transport Emissions + Public Transport Emissions), Private Transport Emissions + Public Transport Emissions | Kg $CO_2$ |
| Public Transport Emissions | Bus Emissions + Train Emissions + Subway Emissions +LRT Emissions | Kg $CO_2$ |
| Private Transport Emissions | Vehicular Trips × $KgCO_2$/pass-Km (Vehicle) × Average Distance Travelled by Vehicles | Kg $CO_2$ |
| Bus Emissions | Vehicular Trips × $KgCO_2$/pass-Km (Bus) × Average Distance Travelled by Bus | Kg $CO_2$ |
| Train Emissions | Vehicular Trips × $KgCO_2$/pass-Km (Train) × Average Distance Travelled by Train | Kg $CO_2$ |
| Subway Emissions | Vehicular Trips × $KgCO_2$/pass-Km (Subway) × Average Distance Travelled by Subway | Kg $CO_2$ |
| LRT Emissions | Vehicular Trips × $KgCO_2$/pass-Km (LRT) × Average Distance Travelled by LRT | Kg $CO_2$ |

#### *3.1.2.8 Initial Stocks*

This section presents the proposed model. In addition, we present the data collection process and the considerations made for the dynamic simulation. To summarize the information presented in this section, Table 3.8 presents the initial values for the stock variables.

Table 3.8 – Initial values for stock variables

| Variable | Initial value |
|---|---|
| Population | 6,520,266 inhabitants |
| GDP | US$ 80.25 billion |
| Road Network | 11000 Km |
| Length Rail (Train) | 170 Km |
| Length Rail (Subway) | 58 Km |
| Length Rail (LRT) | 12 Km |
| Urban Area | 1,200.177 $Km^2$ |
| Stock of CO2 | 0 Kg of $CO_2$ |

## 3.2 Dynamic simulation results

Before performing the simulation, it is necessary to check the reliability of the proposed model. As discussed before, there are several tests for SD models. In this study, the boundary adequacy, structure assessment, dimensional consistency, integration error and extreme condition were conducted.

It has been verified if the model respects the basic physics laws and captures the proper system components behavior. Moreover, the units of all variables and the dimensional constancy of all equations were checked. From the integration error test, it was observed that the model presents a realistic behavior for different integration times. Therefore, it was chosen one year time step. Finally, the extreme condition test was performed to verify if the model behaves realistically under extreme policies and situations. After verifying the model and performing the necessary corrections, the simulation of the proposed scenarios was performed. It is noteworthy that, due to the lack of historical data, it was not possible to simulate the past years and compare the results. However, our tests ensure that the results are realistic.

The first scenario is the base scenario, which was used to perform the tests. This scenario is the simulation of the proposed model using the parameters presented in the last section. In addition to the base scenario, four scenarios were developed. These scenarios evaluate aspects related to elements of a specific sector. The Base Scenario presents the impact of BUMP implementation in Rio de Janeiro. To highlight this impact, Scenario 1 presents the effects of non-implementation of the BUMP. Scenario 2 checks the impact of the individual vehicle occupancy rate on traffic congestion. Scenario 3 analyses the delay in requesting the increase in transport investment due to congestion. Finally, Scenario 4 analyses how the behavior of the curves developed to represent the attractiveness of non-motorized mode and the attractiveness of public transport can affect the system.

### *3.2.1 Base Scenario*

The results show that 5.43 billion trips are carried out in 2050, an increase of 5% when compared to 2018. As can be seen in Table 3.9, the number of non-motorized trips in 2018 is 1.44 billion, reaching 1.90 billion in 2050 (an increase of 32%). In addition, the number of motorized trips decreases from 3.71 billion in 2018 to 3.53 billion in 2050, i.e., a reduction of 5%.

Table 3.9 – Number of trips (in billions) and modal split

| Mode of transport | | Number of trips | | Modal split | |
|---|---|---|---|---|---|
| | | 2018 | 2050 | 2018 | 2050 |
| Total trips | Non-motorized trips | 1.44 | 1.90 | 28% | 35% |
| | Motorized trips | 3.72 | 3.53 | 72% | 65% |
| | Total | 5.16 | 5.43 | 100% | 100% |
| Motorized trips | Public transport | 2.46 | 2.724 | 66% | 77.17% |
| | Private transport | 1.26 | 0.806 | 34% | 22.83% |
| | Total | 3.72 | 3.53 | 100% | 100% |

In 2018, 66% of motorized trips are carried out by public transport, resulting in 2.45 billion of trips. In 2043 they reach a peak with 2.74 billion of trips by public transport and drops to 2.72 billion in 2050. Despite the increase in the level of BUMP implementation, the reduction in the number of trips by public transport occurs due to the reduction in the number of trips with motorized modes. However, when analyzing the modal split, it is observed that the number of trips with public transport represents 77.08% and 77.17% of the trips with motorized modes in 2043 and 2050, respectively. The private transport, which accounts for 34% of motorized trips in 2018, represents only 22.83% in 2050, resulting in a reduction of 457 million trips per year.

As shown in Figure 3.12, in year 0 the congestion level is 1,438, i.e., the total travel demand is 43.8% higher than the system capacity, generating traffic congestion.

The congestion level shows a growth until the ninth year, reaching a level of 1.483. After year 10, the congestion level begins to decrease, becoming less than 1.00 from year 20. Therefore, the BUMP implementation contributes to solve the problem of traffic congestion in Rio de Janeiro. It is worth noting that in year 20 the level of BUMP implementation is 61.3%.

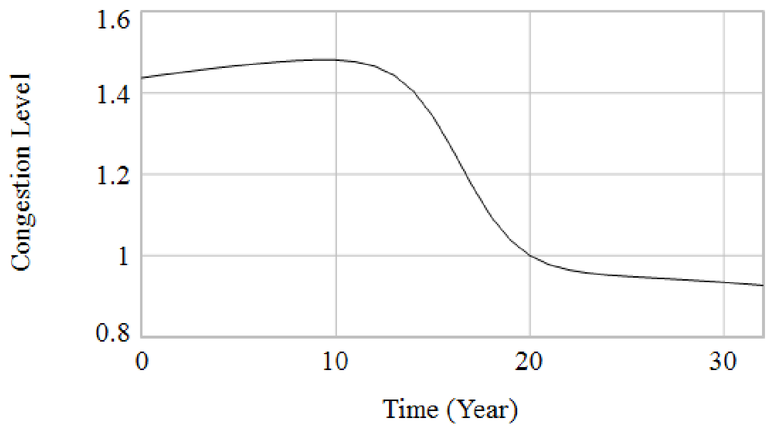


Figure 3.12 – Congestion level

The congestion level is greater than 1 in the first 19 years, so in this period occurs the increment request in transport infrastructure investment. Due to the 10 years delay, these increases in investment occur between years 10 and 29. After the BUMP full implementation, the congestion level reaches 0.92 in year 32. Therefore, the travel demand is very close to the system capacity.

Despite the annual average of congestion level below 1.00, there may still be demand peaks during the day, making the system congested. These possible temporary demand peaks are dissolved due to the one-year time step and does not impact on the results. The objective of this work is not to evaluate the daily variations, but to verify if the system is able to meet the average demand.

As for $CO_2$ emissions, there is a reduction in emissions over the years. Since there is no output from the variable "Stock of $CO_2$", this variable grows over the years, resulting in an accumulation of 49.66 million tons of $CO_2$ in 32 years. Despite this accumulation, the annual increase of $CO_2$, shown in Figure 3.13, evidences a change in the slope of the curve.

There is an increase in the first years of BUMP implementation, but this value reduces from the $11^{th}$ year. In the first 10 years, $CO_2$ emissions grow at an average rate of 0.33% per year. However, between year 11 and year 32, the $CO_2$ emissions decrease in an average rate of 2.2% per year, resulting in an emission of only 1.13 million tons $CO_2$ in year 32. Thus, it can be observed that even the total trips increasing by 5.24% in 32 years, the $CO_2$ emissions in year 32 represent, approximately, 60% of the emissions in year 0. The behavior of the annual $CO_2$ emission curve from year 20 is justified by the reduction of congestion level.

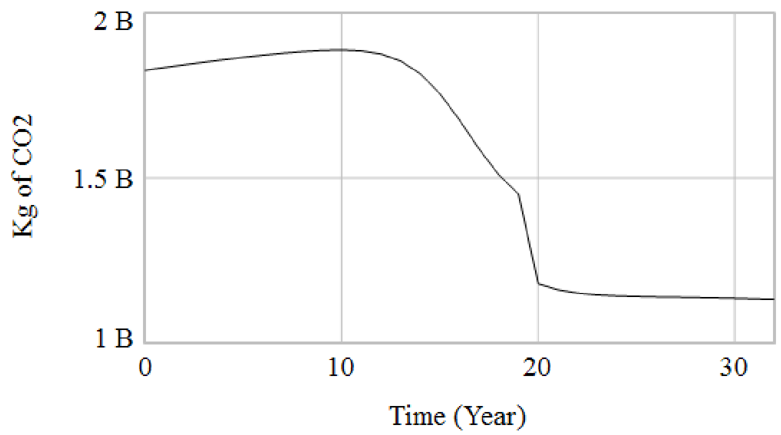


Figure 3.13 – Annual $CO_2$ emissions

Finally, it was verified the impact of BUMP implementation on urban mobility indicators. As evidenced in Figure 3.14, the RTR is 63.29 Km of mass rapid transit (MRT) per million inhabitants in year 0 and reduces an average rate of 0.24% per year, reaching 60.03 in year 22. This drop is justified by the population growth added to the lack of investments for the infrastructure expansion of train, subway and LRT. The growth on this indicator from year 23 is justified by the reduction of population growth rate. Despite this, the city of Rio de Janeiro shows values above the national average. According to Replogle and Fulton (2014) and ITDP (2016), the Brazil's RTR is 10.8 km of MRT per million inhabitants and the national projection for 2050 in a high-shift scenario is 32.4 km of MRT per million inhabitants.

It is observed in Figure 3.15 that in year 0 there is 0.3448 Km MRT for each $Km^2$ of the city of Rio de Janeiro. Like the RTR, the Covered Area reduces over the years due to the lack of investments in mass rapid transit and, therefore, it reaches the value of 0.3371 km of MRT per $km^2$ in year 32.

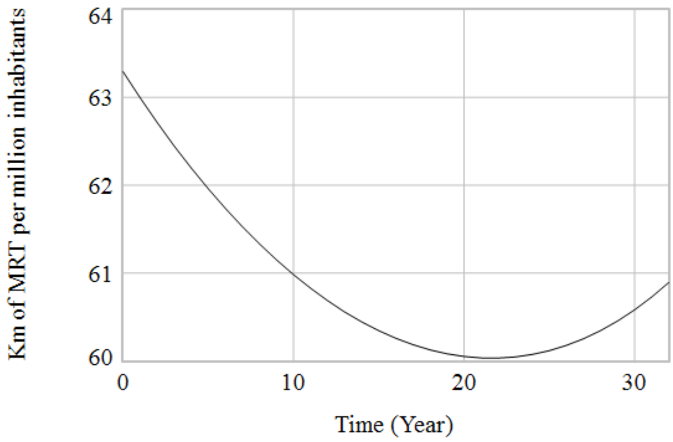

Figure 3.14 − RTR

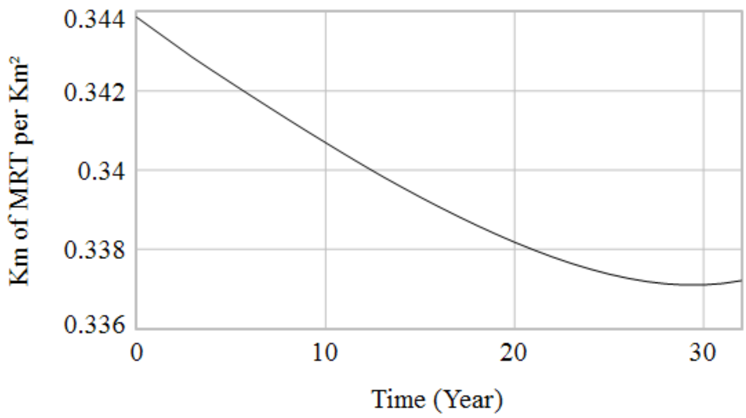

Figure 3.15 − Covered Area

### *3.2.2 Scenario 1*

Scenario 1 sought to identify the impact of BUMP non-implementation. Thus, this scenario assumes the growth rate of motorized transport and private transport in the last years. Between 2003 and 2012, the percentage of motorized trips in Rio de Janeiro grew at a rate of 0.90% per year and the share of individual trips grew at a rate of 1.11% per year (Government of Rio de Janeiro, 2015). Analyzing the current modal split of the city of Rio de Janeiro, where 72% of the trips are made by motorized modes and of this total 34% are carried out by individual transportation, it is noted that these average rates of growth remained between the years of 2012 and 2018.

As demonstrated in Figure 3.16, variables BUMP, Non-Motorized Transport Attractiveness and Public Transport Attractiveness were replaced by Percentage of trips by Motorized Transport and Private Transport, whose are defined by the Equations (3.5) and (3.6).

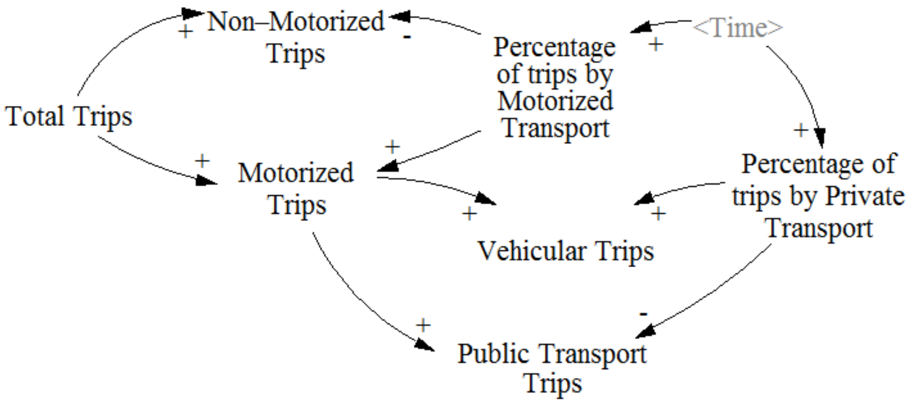


Figure 3.16 – Travel Demand sector without BUMP implementation

$$\text{Percentage of trips by Motorized Transport} = 0.72 \times (1.009^{\text{time}}) \quad (3.5)$$

$$\text{Percentage of trips by Private Transport} = 0.34 \times (1.0111^{\text{time}}) \quad (3.6)$$

The results show that the congestion level almost doubles, reaching 1.44 and 2.72 in 2018 and 2050, respectively. In the Air Pollution sector, it is noted a major environmental damage caused by the non-implementation of BUMP. The $CO_2$ emissions increase at an annual average rate of 1.85%, resulting in 3.28 million tons of $CO_2$ emitted in 2050. At the end of the 32 years, the stock of $CO_2$ is 1.6 times greater than the accumulated stock during the same period in the Base Scenario. Thus, without the BUMP implementation, the current Rio de Janeiro's transport system does not have capacity to meet the future demand and compromise the environment.

### *3.2.3 Scenario 2*

The BUMP does not only encourage public transportation but also the carpooling. Scenario 2 analyses the impact produced by the increasing the average occupancy rate of private vehicles for 2 and 3 people. Figure 3.17 shows a significant difference in traffic congestion when considering an average of two people per vehicle. In year 0, when there is no BUMP implementation, the traffic congestion level is below 1.00. Although this value increases in the first years, the congestion level remains below 1.00 during the whole period, reaching 0.63 in year 32. For an average of 3 people per vehicle, there is also a reduction in the traffic congestion (0.45 in year 32), but in smaller proportions than the reduction between the simulations with 1.3 and 2 people. Due to this positive impact, it is evident the importance the implementation of Transportation Demand Management strategies, such as rideshare.

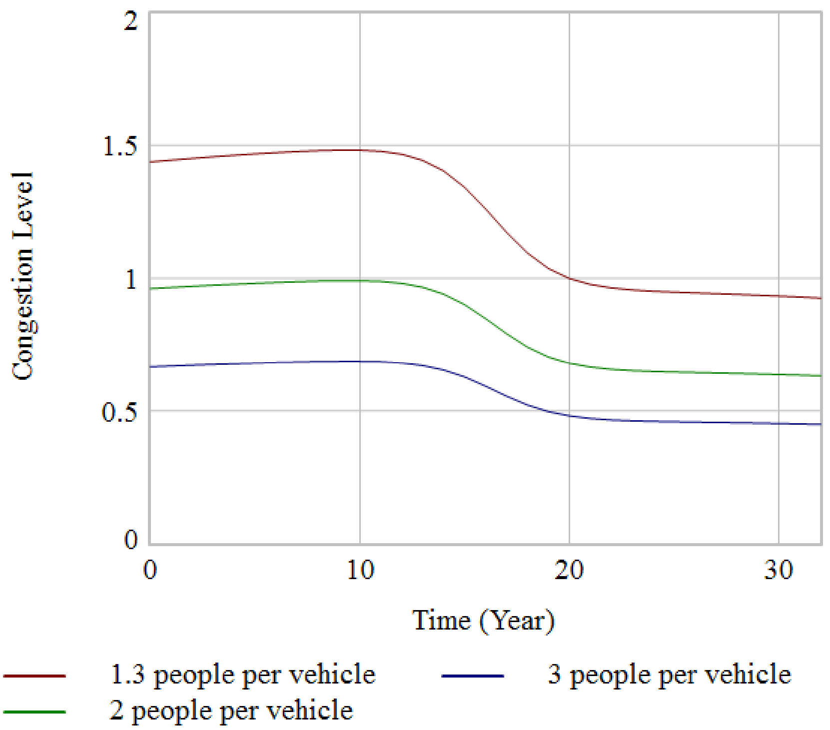


Figure 3.17 – Congestion level for different averages occupancy rate of private vehicles

### *3.2.4 Scenario 3*

Scenario 3 analyses the delay to increase transport investment due to traffic congestion. The 10-year delay considered in the Base Scenario does not have a significant impact on the congestion level. As can be seen in Table 3.10, the delay variation is less than $10^{-3}$.

Table 3.10 – Congestion level for different delays

| Year / *Delay* | 2028 | 2033 | 2038 | 2050 |
|---|---|---|---|---|
| No delay | 1.48198 | 134246 | 0.99969 | 0.927399 |
| 1 year | 1.48198 | 1.34246 | 0.99969 | 0.927399 |
| 2 years | 1.48201 | 1.34248 | 0.99971 | 0.927294 |
| 3 years | 1.48204 | 1.34251 | 0.999732 | 0.927179 |
| 4 years | 1.48208 | 1.34255 | 0.999757 | 0.927052 |
| 5 years | 1.48212 | 1.34258 | 0.999784 | 0.926912 |
| 7 years | 1.48221 | 1.34267 | 0.999846 | 0.92659 |
| 10 years | 1.48221 | 1.34283 | 0.999964 | 0.92624 |
| 15 years | 1.48221 | 1.34296 | 1.00025 | 0.926503 |
| 20 years | 1.48221 | 1.34296 | 1.00041 | 0.926927 |

This behavior is justified due to the low investment in transport infrastructure. Only 0.002% of Rio de Janeiro's GDP is destined to construction of new roads. Therefore, a 10% increase in this value does not generate a significant impact on road network increment. Then, an increase of 50% and 100% in investments were simulated. The results show that even if the value of transport investments were doubled, the congestion level would remain the same. Thus, there is a need to increase the investments in infrastructure to address the high levels of traffic congestion.

### *3.2.5 Scenario 4*

In previous scenarios, the travel behavior begins to change after approximately 50% of BUMP implementation (Figures 3.6 and 3.7). Scenario 4 analyses the impact of the curves developed to represent the attractiveness of non-motorized mode and the attractiveness of public transport. For this, it was considered that the trips behavior would begin to change significantly after 75% of BUMP implementation (Figures 3.18 and 3.19).

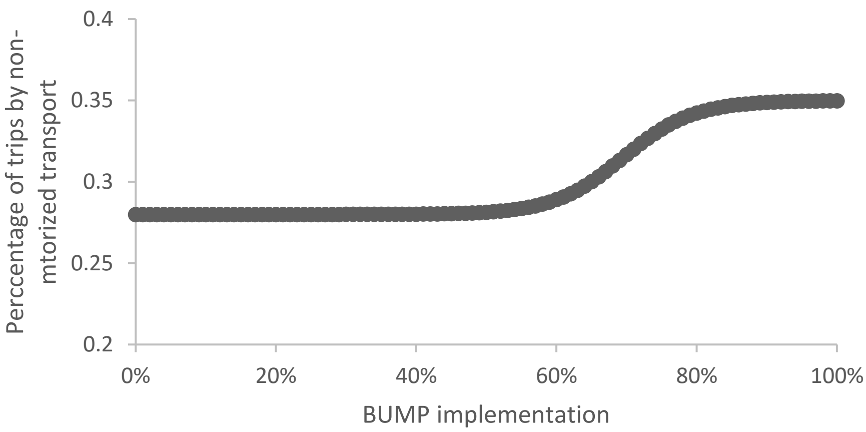


Figure 3.18 – New non-motorized attractiveness

In this scenario, the non-motorized mode attractiveness and the public transport attractiveness are defined by Equations (3.7) and (3.8).

$$\text{Non-Motorized Mode Attractiveness} = 0.035 \times \tanh[(10 \times \text{BUMP} - 6.95069)] + 0.315 \quad (3.7)$$

$$\text{Public Transport Attractiveness} = 0.05585 \times \tanh[(10 \times \text{BUMP} - 6.95069)] + 0.71585 \quad (3.8)$$

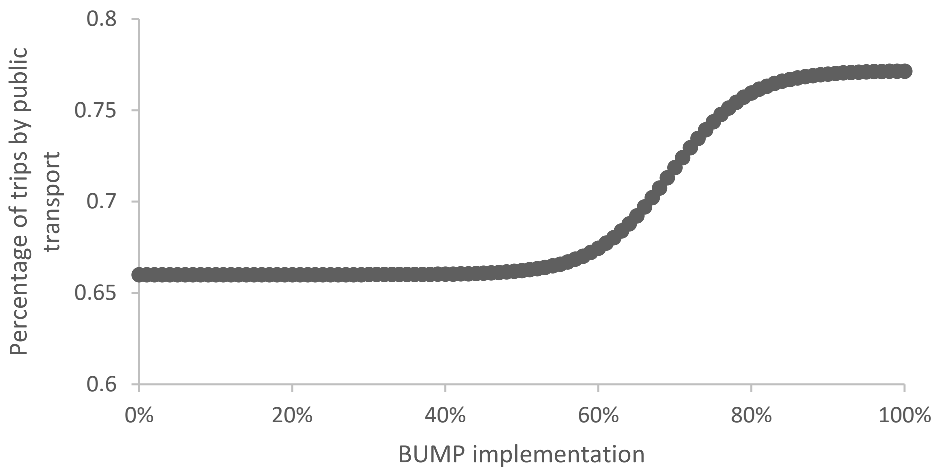


Figure 3.19 – New public transport attractiveness

This new S-Shaped curves did not change the amount of travel and the modal split obtained in Year 32. However, the congestion level becomes less than 1.00 only in Year 26, different from the Base Scenario where this occurs in Year 20. In addition, in the Base Scenario, the congestion level increases in the first nine years, reaching a maximum value of 1.483. In this scenario, the congestion level increases until the Year 14, reaching a maximum level of 1.5.

The accumulation of $CO_2$ in 32 years is 54.45 million tons, while it reached 49.66 million tons in Base scenario. The results of the first ten years are like the ones of the Base Scenario, but after Year 11, the annual emission begins to reach higher values with the great gap in year 20. This occurs because in the Base Scenario the congestion level is below 1.00 in Year 20. Thus, the variable is no longer multiplied by 1.2, increasing the difference of the annual emission between these scenarios. In the proposed model the BUMP does not influence the investments in transport infrastructure and, therefore, there are no changes in the urban mobility indicators.

In view of the results, it is observed that the model is efficient in capturing the effects of the BUMP measures, showing how the measures of this policy can reduce transportation externalities. In addition, it is noted that the implementation of this policy is fundamental for the sustainable development of Brazilian cities. To confirm that the proposed model is applicable to all cities, a comparison between Brazilian megacities is presented in the next section.

### 3.3 Brazilian megacities: quantifying the impacts of the Brazilian Urban Mobility Policy

Brazilian cities face several socioenvironmental problems associated with the urban growth, experiencing an urban mobility crisis (Maciel and Freitas, 2015). Due to the complexity of the transportation systems, these problems are bigger in megacities. According to the United Nations (2018), Brazil has two megacities: Rio de Janeiro and São Paulo. To compare the effects of BUMP in these two cities, the model presented in this chapter was applied for them and the results are presented here. It is worth mentioning that more information about the data used for the simulation of São Paulo can be seen in Fontoura *et al.* (2022).

Following the population growth, the number of daily trips increases in both megacities by 2050. However, after the fully BUMP implementation, the number of trips with non-motorized mode in the two megacities goes from 28% and 31% in Rio de Janeiro and São Paulo, respectively, to 35%. According to Figure 3.20, the increase of non-motorized trips has similar behavior in both megacities.

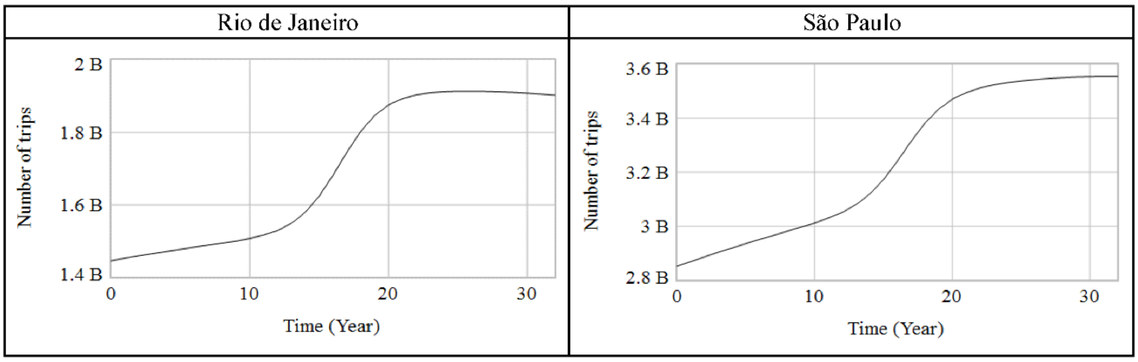


Figure 3.20 – Non-motorized trips in Brazilian megacities

Figure 3.21 shows that the number of motorized trips reduces in Rio de Janeiro and increases in São Paulo. Despite the increase in the number of motorized trips in São Paulo, the share of motorized trips has reduced over the years in this city. These different behaviors in the two megacities are caused by the greater proportion of non-motorized trips in São Paulo in the first year. The population growth and, consequently, the travel demand increase, added to the small growth of non-motorized trips, results in the motorized trips behavior in São Paulo.

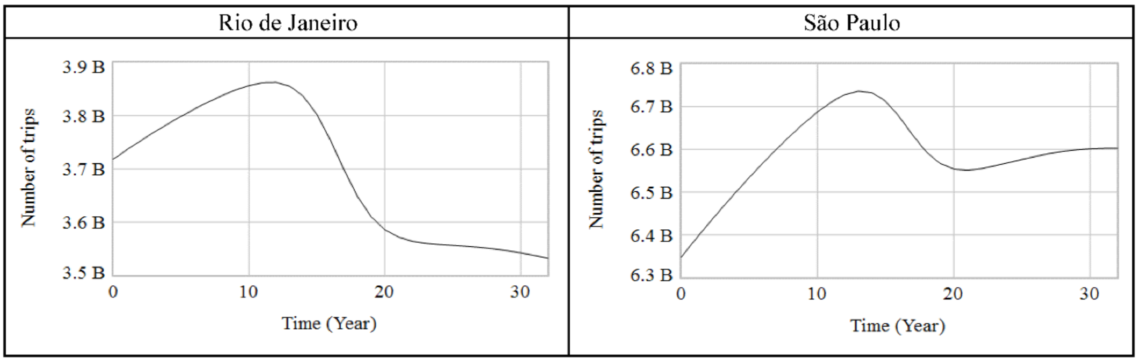


Figure 3.21 – Motorized trips in Brazilian megacities

In São Paulo, the number of trips by public transport increases by approximately 29%, from 3.68 billion in 2018 to 4.74 billion in 2050. However, unlike Rio de Janeiro, there has been no reduction in the number of trips by public transport in the last years, as can be seen in Figure 3.22.

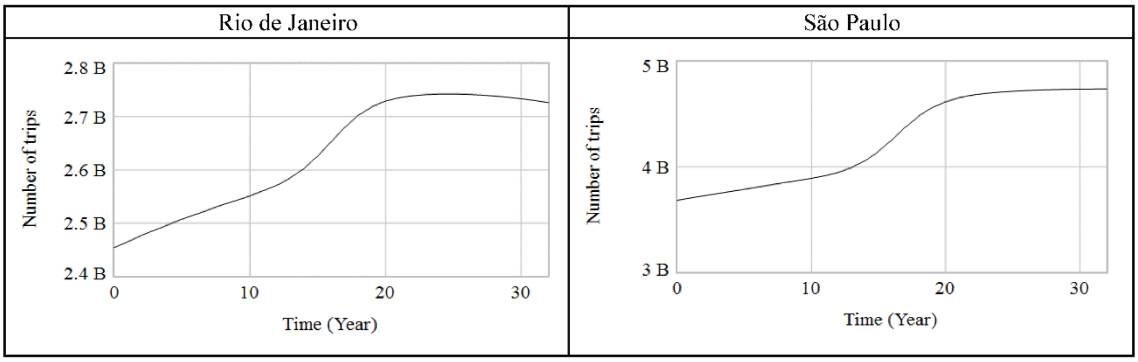


Figure 3.22 – Trips by public transport in Brazilian megacities

Figure 3.23 shows that, initially, the traffic congestion level is 1.4 in both cities, i.e., the total distance traveled is 40% higher than the system capacity. It increases until Year 9, reaching a level of 1.483 in Rio de Janeiro and 1.489 in São Paulo. After this year, the traffic congestion decreases. However, only in Year 19 the traffic congestion begins to be solved in Rio de Janeiro. For São Paulo, it happens in Year 21.

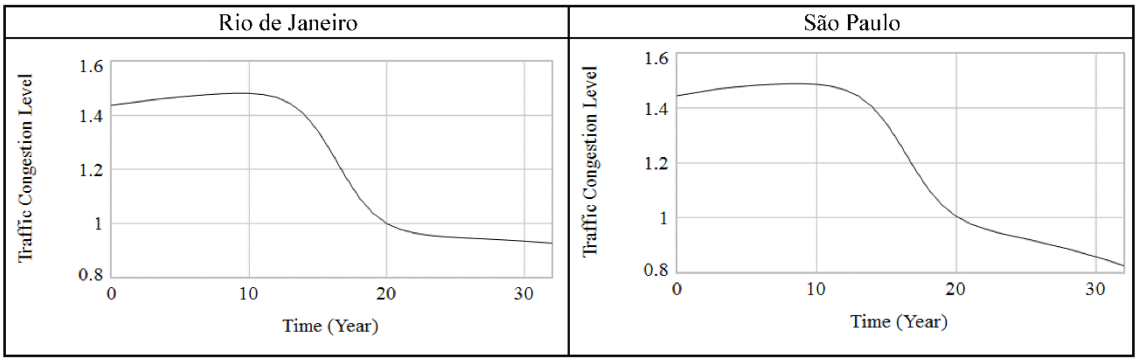


Figure 3.23 – Traffic congestion in Brazilian megacities

After fully BUMP implementation, the traffic congestion level in Rio de Janeiro is 0.92. In São Paulo, this reduction is higher, reaching 0.82. The results about traffic congestion show the need to implement other measures in both systems. In addition to replace private transport by public transport, it is necessary to implement policies that encourage trips by other modes of public transport. In Rio de Janeiro, despite the good infrastructure for rail transport and subway, bus trips represent 73% of travel by public transport. The absence of incentives for rail transport strengthens the predominance of bus trips and it affects the traffic congestion level. This impact can be seen when comparing the reduction in the traffic congestion level in the two cities after the fully BUMP implementation, as the city with the largest bus trip share (Rio de Janeiro) showed the lower reduction in traffic congestion level.

With this changes, the $CO_2$ emissions decrease throughout the years (Figure 3.24). Over the years, 49.66 million tons of $CO_2$ were accumulated in Rio de Janeiro and 78.46 million tons of $CO_2$ in São Paulo. In São Paulo, $CO_2$ emission grows at an average rate of 0.49% in the first 11 years, emitting 2.91 million tons in the eleventh year. However, after Year 12, the emissions decrease, reaching a total of 1.88 million tons of $CO_2$ in 2050. Despite an increase of 10% in the total number of trips, the emissions in 2050 represents approximately 68% of the emissions in 2018. The annual $CO_2$ emission curve in Rio de Janeiro undergoes a sudden change in the $20^{th}$ year. This variation is due to the reduction of traffic congestion in the system. This change is also seen in São Paulo after Year 21.

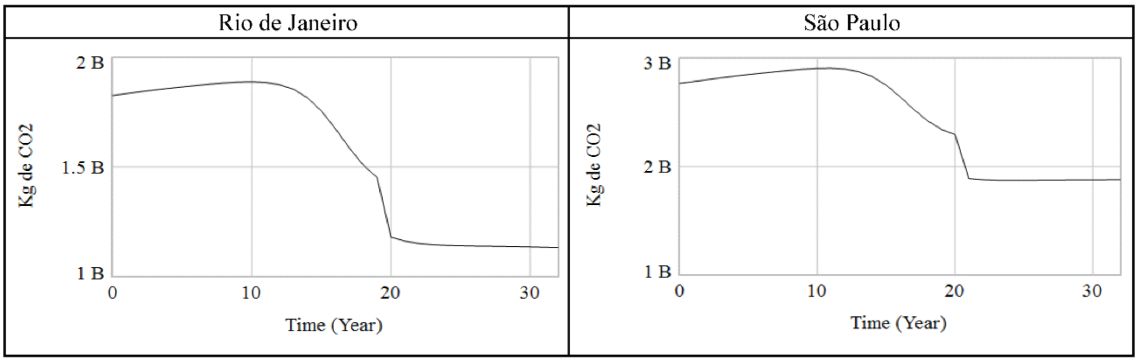


Figure 3.24 – Air pollution in Brazilian megacities

Finally, we verified the effects of the BUMP implementation in the urban mobility indicators (RTR and Covered Area). Due to the population growth and the lack of investments for the expansion of metro-rail systems, the indicators decrease over the years in both cities. The reduction is approximately 5% in the megacities.

## 3.4 Final remarks of the chapter

This chapter presented a SD model to assess the effects of BUMP, focusing on the prioritization of non-motorized transport and public transport. In the case study, the results show the importance of the BUMP to reduce the negative effects of transport and increase the efficiency of urban transport systems. It is observed that, despite population growth and economic development, the BUMP implementation reduces traffic congestion and air pollution. This is because, after the full BUMP implementation, the share of non-motorized trips and public transport trips increase. Furthermore, it is proven that the continuity of the current travel pattern will increase the externalities of transport, resulting in an unsustainable system. Regarding specific measures, rideshare is pointed out as a great strategy to reduce traffic congestion. Therefore, initiatives that stimulate the mobility management strategies, such as rideshare, have proved to be efficient.

Regarding the comparison between Brazilian megacities, the BUMP reduces the externalities of transport in both cities. However, despite obtaining similar results, the effects are different for some variables. The factor that most influenced this difference was the projection for the share of non-motorized transport, which is a scenario close to the current share in São Paulo. Other factors such as population size, trends before implementation and the share of each public transport mode also influenced the BUMP effects. São Paulo invests more in transport infrastructure and is more attractive to public transport. On the other hand, there is a predominance of bus trips among public transport in Rio de Janeiro, which affects the traffic congestion. Despite the infrastructure for high-capacity transport, the bus trip is quite used in this city. Therefore, there are also cultural factors involved.

Future research should consider the potential effects of electric vehicles in the transportation systems. Another suggestion is to address other points covered by the BUMP such as noise pollution, travel safety, land use, quality of life of human beings, among others. These suggestions were implemented in a second model which is presented in the next chapter.

# 4 SYSTEM DYNAMICS FOR SUSTAINABLE URBAN MOBILITY PLANS: AN ANALYSIS OF THE BRAZILIAN URBAN MOBILITY POLICY

Despite being able to show the effects of BUMP, the model presented in Chapter 3 does not address important factors such as land use, traffic safety, noise pollution, health, new technologies, accessibility, among others. Therefore, based on Fontoura *et al.* (2020), this chapter presents a SD model to assess the effects of BUMP, considering human health, land use efficiency and new technologies.

Like the model presented in the last chapter, it was carried out a case study in the city of Rio Janeiro to test the proposed model and evaluate the effects of the BUMP. For the dynamic simulation, a period of 32 years was chosen again, with 2018 as the base year (Year = 0) and 2050 the last one (Year = 32). One more time, the software Vensim® PLE (Personal Learning Edition) was used to model and simulate the proposed model. It is worth noting that the model proposed in this chapter is published in Fontoura et al. (2023a).

## 4.1 Proposed model

As already discussed, some important BUMP topics are not normally covered by the SD models, or they are covered separately. Therefore, in addition to the common topics (congestion, air pollution and modal share), the proposed model addresses traffic safety, noise pollution, health (deaths and hospitalizations caused by Particulate Matter - PM), new technologies and land use efficiency. The details of this model and the description of the study area are presented in the next section.

### *4.1.1 Causal Loop Diagram*

The model proposed by Fontoura *et al.* (2020) presents the relationship between the BUMP and nine sectors (Population, Economy, Travel Demand, Non-Motorized Transport, Public Transport, Private Transport, Congestion, Transport Supply and Air Pollution). To better describe the urban transport systems and to address others BUMP issues, six sectors (Health, Land Use Efficiency, Hybrid Electric Vehicles, Traffic Speed, Traffic Accidents and Noise Pollution) were created. The selection of the new sectors was based on Law 12,587 which establishes the guidelines of the BUMP (Brazil, 2012). These six sectors are addressed by this policy. Therefore, in Brazil, they are mandatory in sustainable urban mobility plans. However, these issues were not addressed in SD applications to assess the effects of the BUMP, as it was discussed in Section 2.3.

The Health sector shows how the reduction of motorized trips caused by the BUMP positively impact the human health. The Land Use Efficiency sector illustrates how the integration of land use and transport impacts on trips distance. Innovations in the transportation sector appear every day. In this study, hybrid electric vehicles (HEVs) were chosen to represent these innovations. Therefore, the Hybrid Electric Vehicles sector presents BUMP's incentives to replace conventional cars by HEVs. The Traffic Speed sector shows how congestion impacts in traffic speed, changing private transport attractiveness. The Traffic Accidents sector addresses the relationship between traffic speed and traffic accidents. Finally, the Noise Pollution sector shows the effects of traffic volume on noise pollution.

The new sectors were inserted into the Causal Loop Diagram (CLD) proposed by Fontoura *et al.* (2020). Figure 4.1 shows the new CLD proposed which highlights in green the new sectors. In addition to the new sectors, the Private Transport sector (highlighted in blue) was improved, adding the incentive for carpooling, which was identified as a good measure in Chapter 3. These sectors are connected in the CLD, forming several loops. The 12 main ones are presented below.

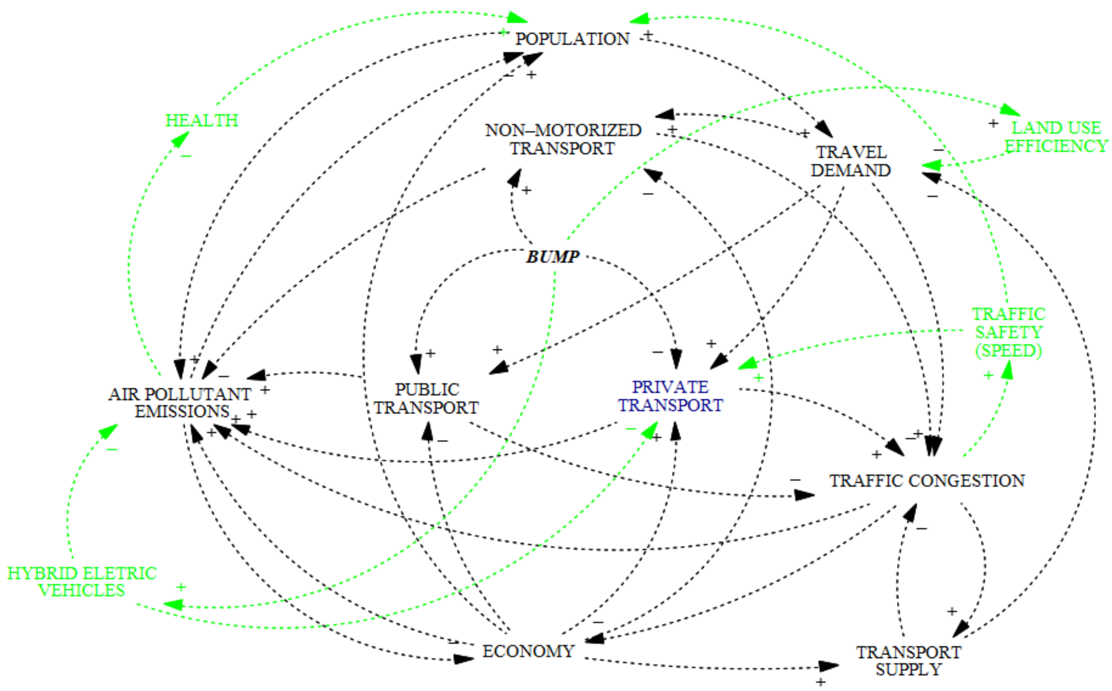


Figure 4.1 − Causal loop diagram for the second model

Source: Based on Fontoura *et al.* (2020).

Feedback loop i:

i. Private Transport $\xrightarrow{+}$ Congestion $\xrightarrow{-}$ Traffic Speed $\xrightarrow{+}$ Private Transport **(B1)**.

Increasing the number of trips using private transports raises congestion (Fiedler *et al.*, 2017). A high level of traffic congestion reduces traffic speed (Mondschein and Taylor, 2017), reducing the attractiveness of individual motorized transport. Thus, it is a balancing loop (B1) because an increase in any variable in the loop results in a decrease of the same variable.

Feedback loop ii:

ii. Private Transport $\xrightarrow{+}$ Congestion $\xrightarrow{-}$ Traffic Speed $\xrightarrow{+}$ Traffic Accidents $\xrightarrow{-}$ Private Transport **(R1)**.

As discussed above, trips by private transport raises congestion, reducing traffic speed. Slow vehicles speed turns down the number of traffic accidents (Elvik, 2013). The roads become safer with this reduction, increasing the attractiveness of individual motorized transport (Gruel and Stanford, 2016). Thus, it is noted that it is a reinforcing loop (R1) since the change feeds back to reinforce the original change.

Feedback loop iii:

iii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Congestion $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(B2)**.

Population growth increases travel demand (Metz, 2012). Due to new demand, there is an increase in the number of trips with individual motorized transport, increasing the traffic congestion. According to Jia *et al.* (2018), traffic congestion increases the pollutant emissions, which is harmful to human health. The air pollution is one of the major causes of diseases and deaths, reducing quality of life and, consequently, the population growth (Darçin, 2014). Therefore, it is noted that the third feedback is a balancing loop (B2).

Feedback loops iv - v:

iv. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Congestion $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(R2)**.

v. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Congestion $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(R3)**.

An increase in the number of trips using non-motorized transport or public transport reduces the congestion and, consequently, the air pollution (Kwan and Hashim, 2016). This reduction in pollutants emissions is beneficial to human health, increasing the quality of life of people and making the urban space more attractive to new residents. Therefore, loops (iv) and (v) are reinforcing loops (R2 and R3).

Feedback loops iv - vii:

vi. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Congestion $\xrightarrow{-}$ Traffic Speed $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(B3)**.

vii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Congestion $\xrightarrow{-}$ Traffic Speed $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(B4)**.

As already discussed, the population growth increases the travel demand. The increase in non-motorized trips reduces traffic congestion, increasing the traffic speed. As a result, trips by private transport become more attractive. This change in travel patterns raises air pollution and pollution-related diseases cases, reducing the quality of life in the population. As with non-motorized transport, the public transport reduces traffic congestion. Therefore, the sixth and the seventh feedback are balancing loops (B3 and B4).

Feedback loops viii - ix:

viii. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Non-Motorized Transport $\xrightarrow{-}$ Congestion $\xrightarrow{-}$ Traffic Speed $\xrightarrow{+}$ Traffic Accidents $\xrightarrow{-}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(R4)**.

ix. Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{-}$ Congestion $\xrightarrow{-}$ Traffic Speed $\xrightarrow{+}$ Traffic Accidents $\xrightarrow{-}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Health $\xrightarrow{+}$ Population **(R5)**.

Adding traffic accidents in loop (vi) and (vii) results in loops (viii) and (ix), respectively. As discussed, traffic accidents and private transport have an inversely proportional relationship, i.e., an increase in the first leads to a decrease in the second. Thus, loops (vii) and (viii) present a growth behavior, reinforcing a change.

Feedback loops x - xii:

x. Population $\xrightarrow{-}$ Land Use Efficiency $\xrightarrow{-}$ Travel Demand $\xrightarrow{+}$ Non-motorized Transport $\xrightarrow{-}$ Air Pollution $\xrightarrow{-}$ Population **(B5)**.

xi. Population $\xrightarrow{-}$ Land Use Efficiency $\xrightarrow{-}$ Travel Demand $\xrightarrow{+}$ Private Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Population **(R6)**.

xii. Population $\xrightarrow{-}$ Land Use Efficiency $\xrightarrow{-}$ Travel Demand $\xrightarrow{+}$ Public Transport $\xrightarrow{+}$ Air Pollution $\xrightarrow{-}$ Population **(R7)**.

In the proposed model, Land Use Efficiency sector represents the BUMP measures to make cities more compact, coordinated and connected, reducing trips distance. Population growth causes urban sprawl, increasing travel distances (Liu and Meng, 2020). Thus, the increase in trips distance negatively impact land use efficiency. In addition to increase trip distance, reducing land use efficiency increases travel demand, also increasing the number of non-motorized trips. Enhancing the number of trips with this mode reduces air pollution, reducing risks to human health. Therefore, loop (x) is a balancing one. Loops (xi) and (xii) are like (x), but the mode of transport is replaced by private transport and public transport, respectively. Despite emitting less than private transport, public transport also emits polluting gases. Therefore, the increase in travel with these modes increases pollution. Then, (xi) and (xii) are reinforcing loops.

Like the BUMP, Hybrid Electric Vehicles are not in the loops discussed above. However, it is relating to other sectors, impacting the whole system.

### *4.1.2 Stock and Flow Diagram*

Based on the CLD (Figure 4.1), it was developed the Stock and Flow Diagram (SFD), shown in Figure 4.2. The SFD presents all variables in the model, relating them by equations. Table 4.1 shows the main assumptions used to relate the variables of the new sectors by equations, which are detailed below. The equations of the other sectors can be seen in Chapter 3. In addition, the data collection and the considerations to carry out the case study are also presented below.

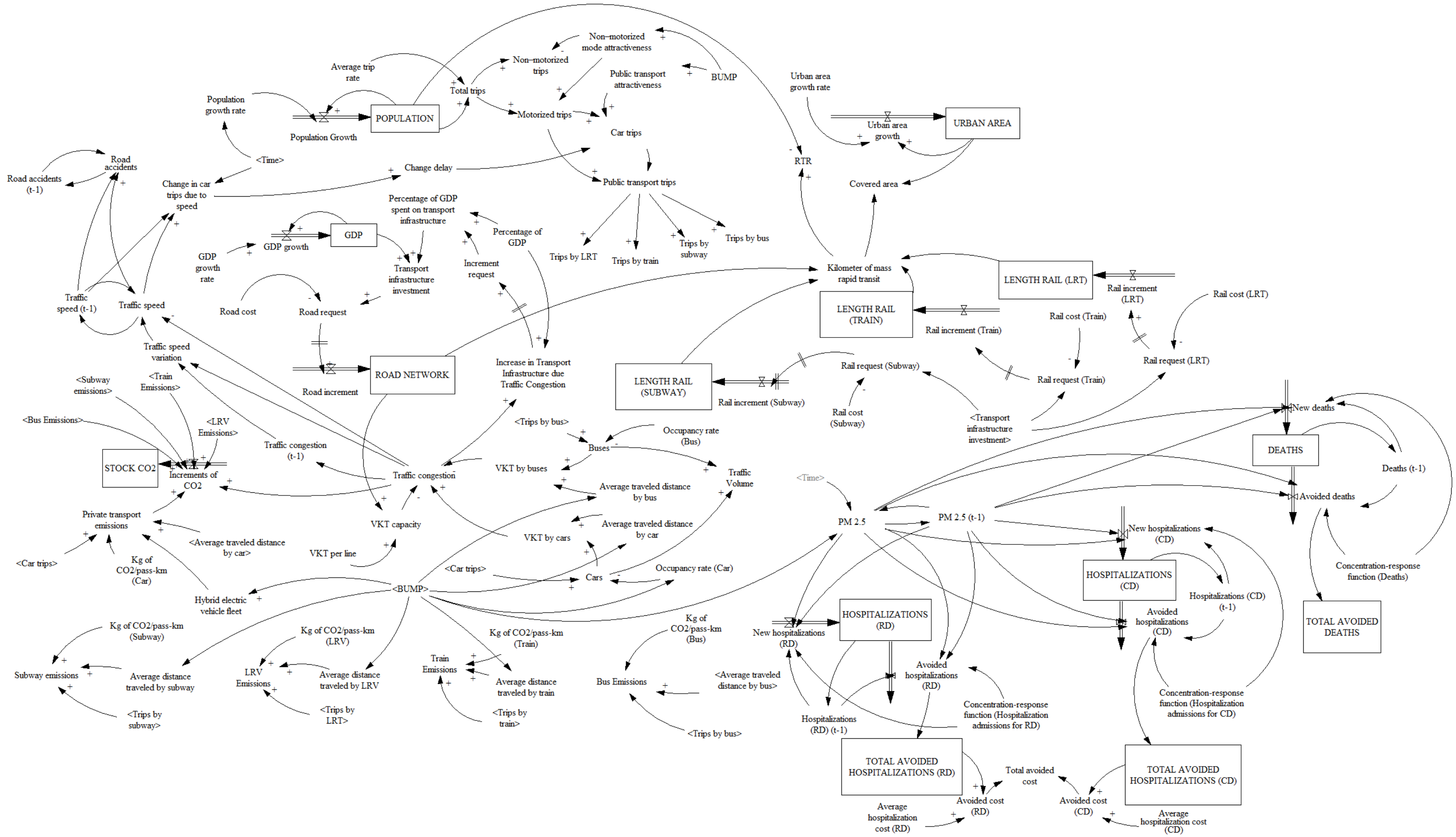


Figure 4.2 − Stock and Flow Diagram

Table 4.1 − New sector's assumptions and indicators

| Sectors | Assumptions | Indicators |
|---|---|---|
| Private Transport | The BUMP has a set of measures (carsharing, rideshare, among others) that encourage an increase in the occupancy rate of private vehicles. | Occupancy rate of private vehicles |
| Land Use Efficiency | The BUMP measures aim compact and connected cities, reducing travel distances. | Km |
| Noise Pollution | The BUMP discourages motorized transport. This measure reduces traffic volume, reducing noise pollution. | dB |
| Health | The BUMP has set of measures that reduces $PM_{2.5}$ emissions, reducing the number of deaths and hospitalizations. | $PM_{2.5}$ |
| Traffic Speed | The BUMP seeks to reduce congestion. This measure increases traffic speed. | Traffic speed |
| Traffic Accidents | Traffic speed increases traffic accidents. | Number of accidents |
| Hybrid Electric Vehicles | The insertion of HEVs in the urban transport systems reduce $CO_2$ emissions. | $CO_2$ emissions |

*4.1.2.1 Private Transport sector*

In Fontoura *et al.* (2020), the occupancy rate of private vehicles remains the same over the years. However, to reduce the number of vehicles on urban roads, the BUMP encourages the conscious use of car, stimulating car sharing, shared travel, among others (Coelho and Abreu, 2019). Therefore, in addition to changing the demand for car trips, the proposed model presents the relationship between the BUMP and the occupancy rate of cars, as can be seen in Figure 4.3.

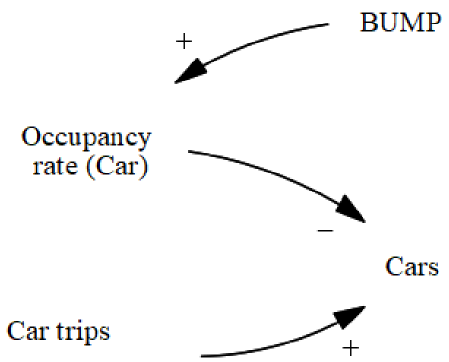


Figure 4.3 – BUMP and car occupancy rate

Brand *et al.* (2019) analyzed the impact of changes in lifestyle related to transport and socio-cultural factors. Through forecasts for 2050, the authors conclude that such changes could increase the occupancy rate of cars by 11.4% over a 30-year period. As mentioned before, the average occupancy rate in large Brazilian cities is 1.3 passengers/vehicle (CNT; NTU, 2017). Based on Brand *et al.* (2019), we developed an

S-Shaped curve, shown in Figure 4.4, to represent the increase in the vehicle occupancy rate according to the level of BUMP implementation, which means the percentage of BUMP measures implemented. Thus, the vehicle occupancy rate is defined by Equation (4.1).

$$Ocuppancy\ rate\ cars = 0.075 \times \tanh[(10 \times BUMP) - 5] + 1.375 \quad (4.1)$$

In this context, the vehicle occupancy rate is 1.3 while the BUMP is not implemented and it will reach 1.44 when this policy is fully met. In addition, at the beginning, this value changes slowly. After overcoming the initial difficulties in implementing the policy, the growth becomes exponential until an inversion in the implementation rate that stabilizes at the end of the BUMP implementation.

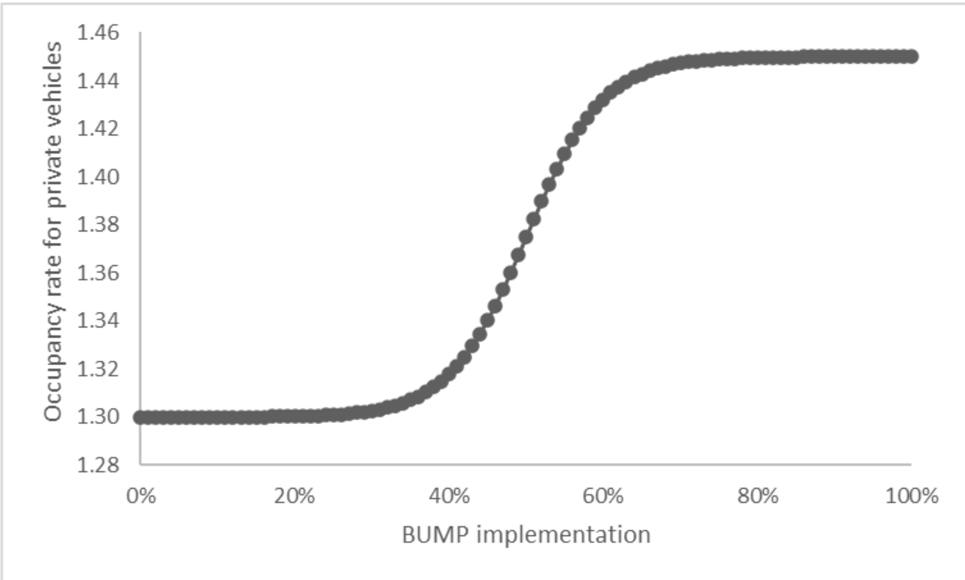

Figure 4.4 − Shaped for occupancy rate for private vehicles

Like Fontoura *et al.* (2020), the BUMP is defined by the RAMP function. Therefore, the BUMP implementation level will increase linearly until reaching 100% in 2050. As already mentioned, for cities with more than 250 thousand inhabitants, the deadline to start the BUMP implementation is 2022 (Brazil, 2020b), i.e., the fourth year simulated in this study. Therefore, as can be seen in Equation (4.2), the RAMP function is defined by the slope of the change, the initial period and the final period of the BUMP implementation.

$$BUMP = RAMP(0.0357, 4, 32) \quad (4.2)$$

*4.1.2.2 Land Use Efficiency sector*

The Land Use Efficiency sector (Figure 4.5) addresses the impact of creating compact cities on travel demands. According to Gaigné *et al.* (2012), compact, connected and coordinated cities reduces commuting distance. This reduction changes the travel demand, as some motorized trips are replaced by non-motorized trips, due to the reduced distance. Thus, to represent the effects of land use, the average trip distances will reduce according to the level of BUMP implementation.

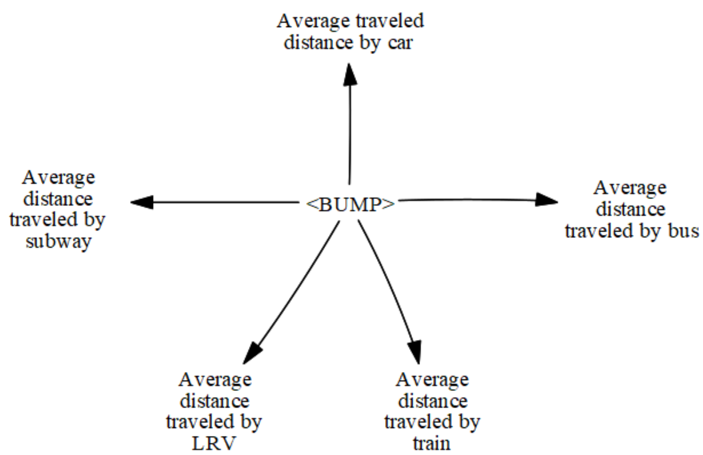


Figure 4.5 – Land Use Efficiency sector

When compared to widespread development, a set of policies increases the land use efficiency, reducing land consumption per capita by 60 to 80% and the displacement of motor vehicles by 20 to 60% (California Air Resources Board, 2014). According to Kuzmyak (2012), a higher density can reduce the distances of business and shopping trips by 36% and 25%, respectively. Based on this information and the opinion of consulting experts in Rio de Janeiro City Hall, in this study, we consider a 30% reduction in trips distance due to the high land use efficiency.

The average distance of trips by car, bus, subway, train and LRT in Rio de Janeiro is 7.4 km, 10.2 km, 11.6 km, 20.5 km and 3.25 km, respectively (ANTP, 2016; Government of Rio de Janeiro, 2015; VLT Carioca, 2018). As in private transport sector, we use a sigmoid function to represent the reduction of the average distance trip (for each mode) due to the level of BUMP implementation. The curves that represent the average distance of trips by car, bus, subway, train and LRT are represented by Equations (4.3), (4.4), (4.5), (4.6) and (4.7), respectively. Figure 4.6 shows the curve for private transport and Figure 4.7 the curves for public transport.

$$Average\ distance\ traveled\ by\ car = -1.11 \times \tanh[(10 \times BUMP) - 5] + 6.29 \quad (4.3)$$

$$Average\ distance\ traveled\ by\ bus = -1.53 \times \tanh[(10 \times BUMP) - 5] + 8.67 \quad (4.4)$$

$$Average\ distance\ traveled\ by\ subway = -1.74 \times \tanh[(10 \times BUMP) - 5] + 9.86 \quad (4.5)$$

$$Average\ distance\ traveled\ by\ train = -3.075 \times \tanh[(10 \times BUMP) - 5] + 17.425 \quad (4.6)$$

$$Average\ distance\ traveled\ by\ LRT = -0.4875 \times \tanh[(10 \times BUMP) - 5] + 2.7625 \quad (4.7)$$

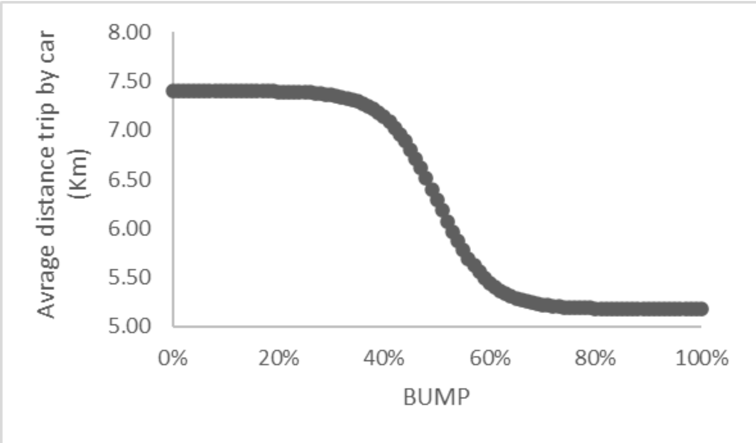


Figure 4.6 – Average distance trip for private vehicles

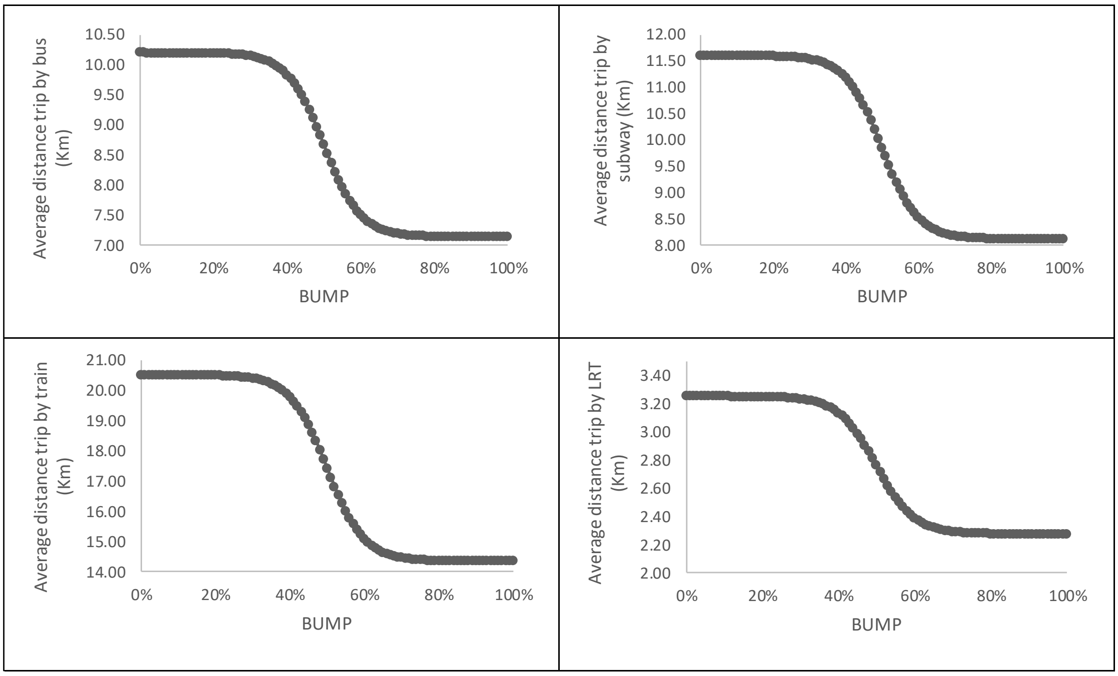


Figure 4.7 – Average distance trip for public transport

*4.1.2.3 Noise Pollution sector*

Bendtsen *et al.* (2004) shows a relationship between the reduction in traffic volume and the reduction in noise, as can be seen in Table 4.2. Thus, as can be seen in Figure 4.8), it was added the variable "Traffic Volume" (Equation (4.8)) which is used to analyze the effects of BUMP measure on noise pollution.

Table 4.2 − Noise reductions in decibels (dB) caused by reductions in the traffic volume

| **Reduction in traffic volume** | **Reduction in noise** |
|---|---|
| 10% | 0,5 dB |
| 20% | 1,0 dB |
| 30% | 1,6 dB |
| 40% | 2,2 dB |
| 50% | 3,0 dB |
| 75% | 6,0 dB |

Source: Bendtsen *et al.* (2004).

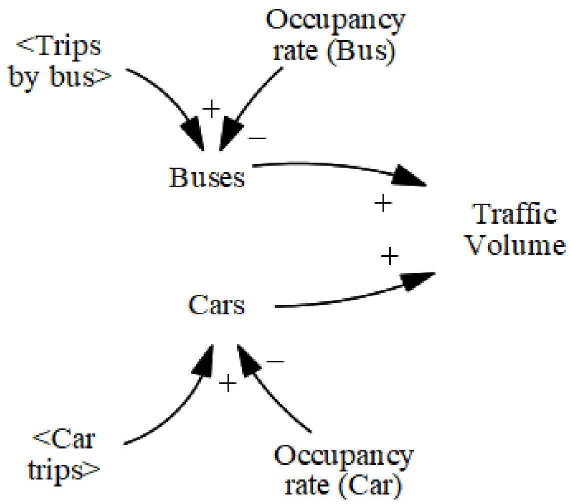


Figure 4.8 – Noise Pollution sector

$$Traffic\ volume = \text{Buses} + \text{Cars} \tag{4.8}$$

Where:

$$Buses = \frac{Trips\ by\ bus}{Occupancy\ rate\ (Bus)} \tag{4.9}$$

$$Cars = \frac{Trips\ by\ car}{Occupancy\ rate\ (car)} \tag{4.10}$$

*4.1.2.4 Health sector*

Using health impact functions, the health sector (Figure 4.9) assesses the effects of air pollution on human health. These functions estimate the effects of air pollutants, providing the number of premature deaths, hospitalizations, or other morbidities, due to changes in the pollutant concentration (Martenies et al., 2015). According to Milando et al. (2016), these functions are typically log-linear or logistic, depending on the model used to determine the coefficient that describes the relationship between the change in the pollutant concentration and the effects on human health. The log-linear impact function, which is used in this study, is defined by Equation (4.11).

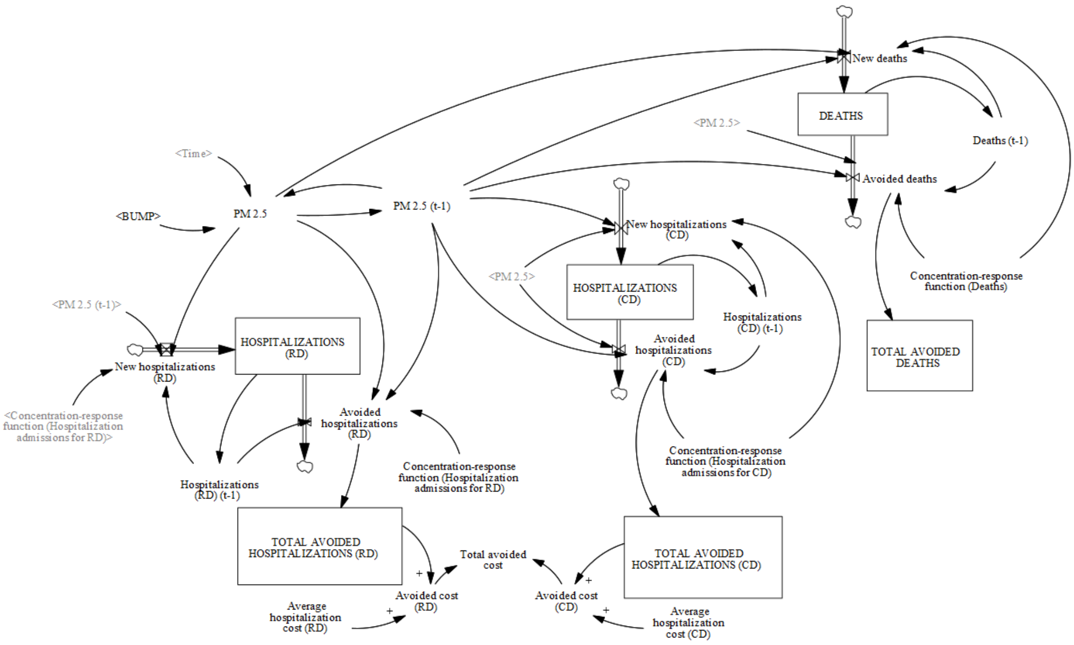


Figure 4.9 – Health sector

$$\Delta y = y_0(1 - e^{-\beta \Delta x}) \tag{4.11}$$

Where:

- $\Delta y$: Change in the incidence of adverse health effects;
- $y_0$: Baseline incidence rates;
- $\beta$: Concentration-response coefficient; and
- $\Delta x$: Change in air quality (μg/m$^3$).

Particulate matter (PM) is a global public health concern, as it is related to most pulmonary and cardiac morbidity and mortality (Pope III *et al.*, 2019). Therefore, it was chosen the $PM_{2.5}$ to determine the number of hospitalizations and deaths avoided by the BUMP implementation. For hospitalizations, it is analyzed the cases for respiratory diseases (RD) and cardiovascular diseases (CD). Table 4.3 presents all equations for RD hospitalizations. The equations for CD hospitalizations and deaths are similar. The difference between those equations is the concentration-response function.

The concentration-response coefficient for hospital admissions due to respiratory and cardiovascular diseases are 0.021761 and 0.012916, respectively (Li *et al.*, 2013; Qiu *et al.*, 2013). For the number of deaths of people over 30 years, $\beta$ is 0.1222218 (Pope III *et al.*, 2019). In 2018, the number of hospitalizations in Rio de Janeiro for respiratory and cardiovascular diseases were 5423 and 5266, respectively (Brazil, 2020b). In addition, the average cost of these hospitalizations is US$ 502.6 and US$ 499.96 for RD and CD, respectively (Brazil, 2020b). Finally, in 2018, the number of deaths of people over 30 years was 14,489 in Rio de Janeiro, which represents 93% of the deaths in this year (Brazil, 2020b).

Table 4.3 – Hospital admissions for respiratory diseases

| Variable | Equation |
|---|---|
| Hospitalizations (RD) | $\int_{t_0}^{t} \text{New hospitalizations (RD)} - \text{Avoided hospitalization (RD)}\, dt + Hospitalizations\ (RD)\ (t_0)$ |
| New hospitalizations (RD) | $IF\ THEN\ ELSE\ (PM_{2,5} - PM_{2,5(t-1)} > 0, Hospitalizations(RD)_{(t-1)} \times (1 - e^{(-Concentration-response\ function\ (Hospitalizations\ RD) \times (PM_{2,5} - PM_{2,5(t-1)}))}), 0)$ |
| Avoided hospitalizations (RD) | $IF\ THEN\ ELSE\ (PM_{2,5} - PM_{2,5(t-1)} < 0, Hospitalizations(RD)_{(t-1)} \times (1 - e^{(-Concentration-response\ function\ (Hospitalizations\ RD) \times (PM_{2,5} - PM_{2,5(t-1)}))}), 0)$ |
| Hospitalizations $(RD)_{(t-1)}$ | DELAY FIXED (Hospitalizations (RD), 1, 0) |
| Avoided cost (RD) | Total avoided hospitalizations (RD) × Average hospitalization cost (RD) |
| Total avoided hospitalizations (RD) | $\int_{t_0}^{t} \text{Avoided hospitalization (RD)}\, dt + Total\ avoided\ hospitalizations\ (RD)$ |
| Total avoided cost | Avoided cost (RD) + Avoided cost (CD) |

As already mentioned, the BUMP establishes a set of guidelines to help municipal managers to develop measures for the urban mobility plans. To reduce pollution, these plans usually address the following measures: renewal buses, renewal private vehicle fleet, renewal commercial fleet, new infrastructure, incentive carsharing, improving public transport, among others (Nocera *et al.*, 2015). According to Pisoni *et al.* (2019), the implementation of this set of measure improves the urban air quality, resulting in an annual reduction of up to 2% $PM_{2.5}$ concentration. In 2018, the $PM_{2.5}$ concentration was 11.19 µg/m$^3$ in Rio de Janeiro (INEA, 2019). Therefore, in the first four years of simulation (without BUMP implementation) this concentration follows the growth presented in the last years. For this purpose, historical data on $PM_{2.5}$ emissions from Rio de Janeiro were used (INEA, 2013; INEA, 2015a; INEA, 2015b; INEA, 2015C; INEA, 2016; INEA, 2017). After starting the implementation of BUMP (2022), the $PM_{2.5}$ concentration reduces by 2% per year.

*4.1.2.5 Traffic Speed sector*

Traffic Speed sector (Figure 4.10) presents the relationship between congestion, traffic speed and private transport attractiveness. Urban transport systems have different types of roads (local, arterial and collector), each one with a speed limit. In the proposed model, if the roads are not congested, the traffic speed is the maximum speed allowed on urban roads. Otherwise, the traffic speed changes according to traffic congestion variation. However, it is worth mentioning that this maximum speed is an average value that must be adopted according to the characteristics of the urban system. In other words, the speed adopted in the model must be an average value that represents the speed usually performed in the system. Thus, the traffic speed is determined according to Equation (4.12). It is worth mentioning that, according to Fontoura *et al.* (2020), the traffic congestion is defined by the ratio of vehicle kilometer traveled (VKT) and the VKT capacity and values above 1 represent a congested system.

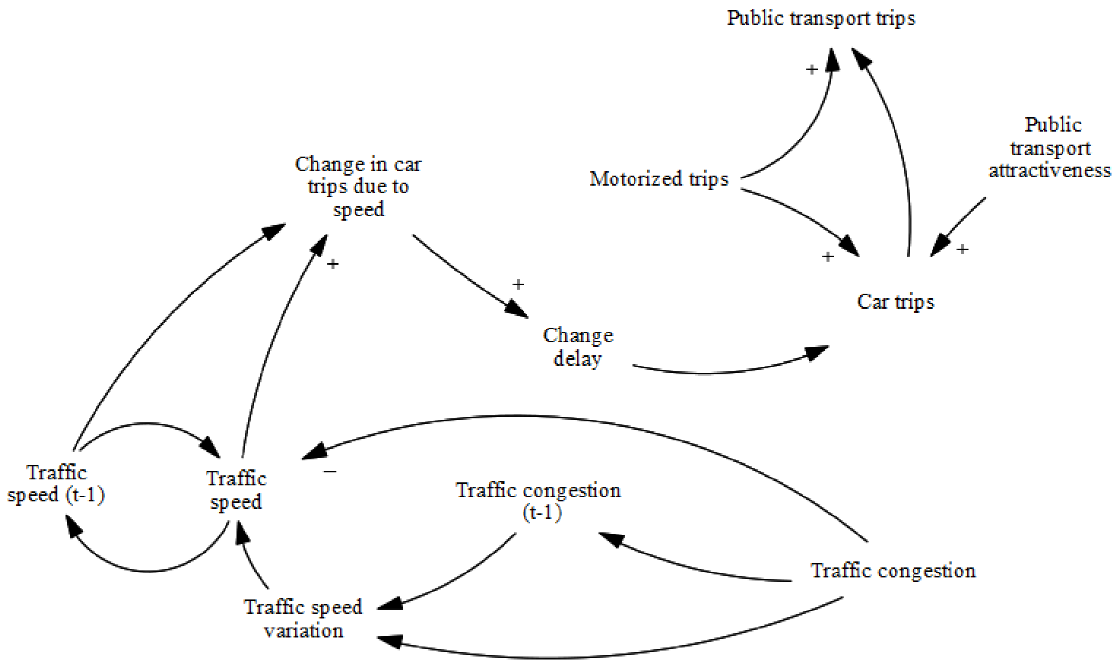


Figure 4.10 – Traffic Speed sector

$$Traffic\ speed = IF\ THEN\ ELSE(Traffic\ congestion_{(t)} > 1, IF\ THEN\ ELSE(Traffic\ speed_{(t\text{-}1)} \times Traffic\ speed\ variation < Maximum\ speed, Traffic\ speed_{(t\text{-}1)} \times Traffic\ speed\ variation, Maximum\ speed), Maximum\ speed) \quad (4.12)$$

Where:

$$Traffic\ speed_{(t\text{-}1)} = DELAY\ FIXED(Traffic\ speed_{(t)}, 1\ , Initial\ value) \quad (4.13)$$

The traffic speed variation is determined by congestion variation and it is represented by Equation (4.14).

$$Traffic\ speed\ variation = F(\frac{Traffic\ congestion_{(t)}}{Traffic\ congestion_{(t\text{-}1)}}) \quad (4.14)$$

Where:

$$Traffic\ congestion_{(t\text{-}1)} = DELAY\ FIXED(Traffic\ congestion_{(t)}, 1\ , Initial\ value) \quad (4.15)$$

Traffic speed impacts directly on trip time, changing the attractiveness of private motorized transport. The elasticity of travel volume for travel time in a short term (less than two years) and long term (more than two years) are -0.5 and -1.0, respectively (SACTRA, 1994 *apud* Litman, 2019). In other words, an increase in speed by 20% causes an increase in travel by 10% in the short term and an increase of 20% in the long term. The variable “Change in car trips due to speed” presents this relationship, as can be seen in Equation (4.16).

$$Change\ in\ car\ trips\ due\ to\ speed = 1 + \left\{\left[\left(\frac{Traffic\ speed_{(t)}}{Traffic\ speed_{(t\text{-}1)}}\right) - 1\right] \times 0.5\right\} \quad (4.16)$$

The change in travel demand, due to speed is not automatic. Therefore, it is necessary to include a delay to represent this change. So, the change delay is determined according to Equation (4.17).

$$Change\ delay = DELAY\ FIXED\ (Change\ in\ vehicular\ trips\ due\ to\ speed, 1, 1) \quad (4.17)$$

In the model proposed by Fontoura *et al.* (2020), the car trips and public transport trips are determined only by number of motorized trips and public transport attractiveness, which is changed by BUMP implementation. Because of the effects of traffic speed on car attractiveness, it is necessary to change the equation of those variables. So, Equations (4.18) and (4.19) present the formulation of car and public transport trips.

$$Car\ trips = Motorized\ trips \times (1 - Public\ transport\ attractiveness) \times Change\ delay \quad (4.18)$$

$$Public\ transport\ trips = Motorized\ trips - Car\ trips \quad (4.19)$$

It was used the data made available by Waze to identify the relationship between traffic speed and traffic congestion in Rio de Janeiro. The level of traffic congestion can change by some factors such as weekday, time, maximum speed allowed on the road, weather, accidents, among others (Chung and Recker, 2013; Soriguera *et al.*, 2017). Thus, it was select a time range for a specific weekday to perform the analysis. Therefore, using data for January and August 2018 from one of the city's main roads, it was analyzed the period between 16:00 and 19:00 on Fridays.

It is worth mentioning that we chose Fridays and this time, because it is a period with high travel demand and, consequently, high congestion. Using data of secondary roads or other time periods would make it difficult to obtain the relationship between traffic congestion and traffic speed, as the level of congestion would be low or zero.

Comparing the speed and level of traffic congestion of every Friday, it was obtained the variation in traffic speed and the variation in congestion. After obtaining these variations, it was developed a function (Equation (4.20)) that express the traffic speed variation due the traffic congestion variation, as can be seen in Figure 4.11.

$$Traffic\ speed\ variation = -0.645 ln\left(\frac{Traffic\ congestion_{(t)}}{Traffic\ congestion_{(t\text{-}1)}}\right) + 1.0133 \quad (4.20)$$

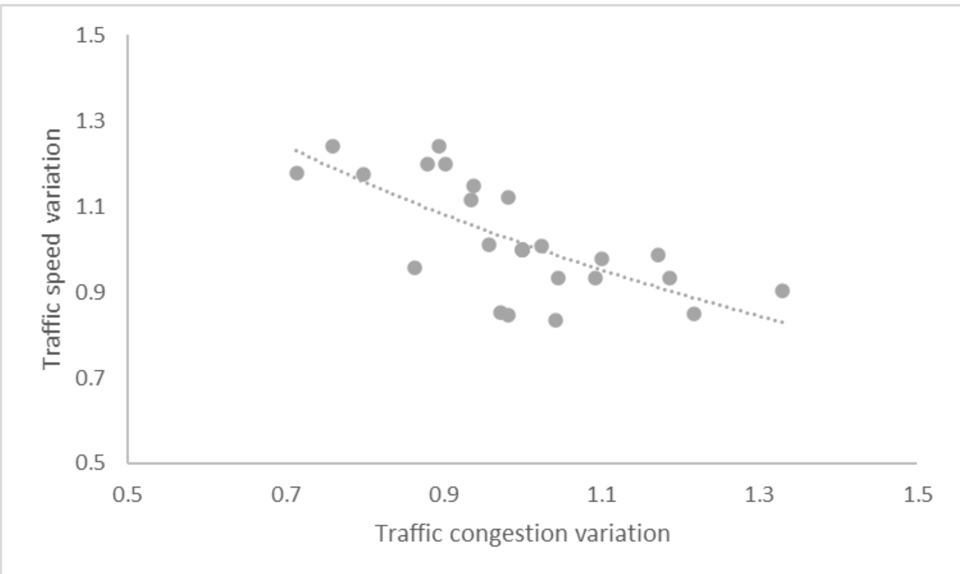


Figure 4.11 − Traffic speed variation due traffic congestion variation

There are different types of roads in Rio de Janeiro and each one has a speed limit. According to INRIX (2020), the average traffic speed in Rio in 2017 at peak and off-peak hours was 34 km/h and 39 km/h, respectively. In addition, at free flow times the average speed was 50 km/h. Therefore, it was used an intermediate value in this study. It was adopted 50 km/h as the maximum speed and 39 km/h as initial traffic speed. Since each road in the city has its own characteristics, it is worth mentioning that this maximum speed represents an average value. In addition, the traffic congestion level in Rio de Janeiro was 40% in 2017 (TomTom, 2021).

*4.1.2.6 Traffic Accidents sector*

There are several factors that influence traffic accidents. In this study, it was chosen traffic speed to analyze them, as can be seen in Figure 4.12. To represent this relationship, it was adopted the exponential model proposed by Elvik (2013). Thus, the Equation (4.21) presents the formulation used to calculate the number of road accidents based on the traffic speed.

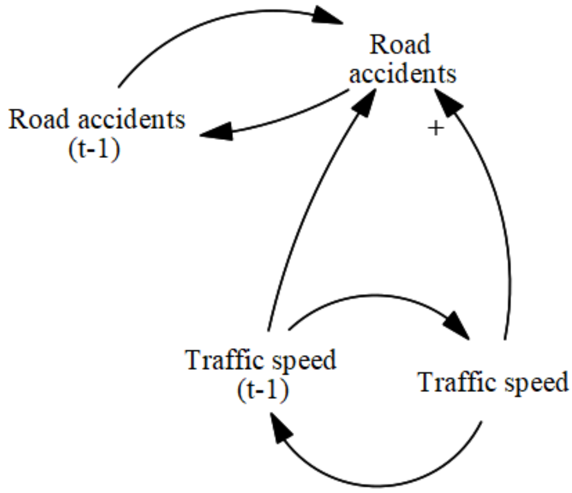


Figure 4.12 – Traffic Accidents sector

$$Road\ accidents = Road\ accidents_{(t\text{-}1)} \times e^{\beta(Traffic\ speed_{(t)} - Traffic\ speed_{(t\text{-}1)})} \quad (4.21)$$

Where:

$$Road\ accidents_{(t\text{-}1)} = DELAY\ FIXED(Road\ accidents\ , 1\ , Initial\ value) \quad (4.22)$$

In Equation (4.21), β is a coefficient that changes according to the type of accident (fatal injury, fatal crash, serious injury, slight injury and all crashes). In this study, all types of accidents are addressed. Therefore, $\beta = 0.034$ was adopted (Elvik, 2014). Finally, according to DETRAN-RJ (2019), Rio de Janeiro recorded 13,764 traffic accidents in 2017.

*4.1.2.7 Hybrid Electric Vehicles sector*

Focusing on the air pollution, Hybrid Electric Vehicles sector (Figure 4.13) presents the impact of the change in the energy matrix of the Brazilian fleet. Comparing to other countries, Brazil still has incipient policies to encourage electric vehicles (Delgado *et al.*, 2017). Due to the absence of effective policies, hybrid electric vehicles (HEVs) and full electric vehicles (FEV) have low representativeness in the Brazilian fleet, i.e., 0.025% of vehicles in 2018 (SINDIPEÇAS, 2019).

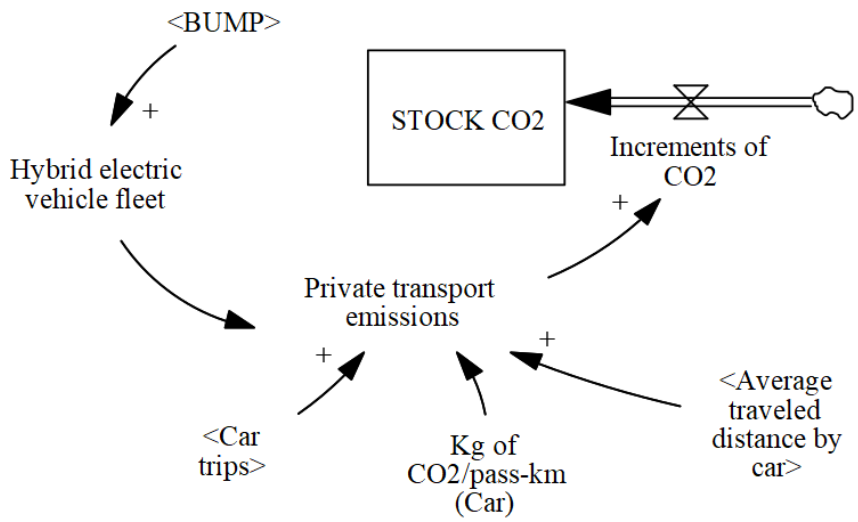


Figure 4.13 – Hybrid Electric Vehicles sector

According to Coelho (2019), the HEVs licensing will be 3.5% of the total licenses in 2030, resulting in a fleet of approximately 1 million vehicles. It is worth mentioning that of this total, there is a predominance of hybrid electric vehicles over full electric vehicles. Thus, Boston Consulting Group (BCG) predicts that in 2030 HEVs will be 5% of the Brazilian fleet (Moura, 2019). Due to the current growth of HEVs and the negligible share of FEVs, we chose to focus on the effects of HEVs.

As data about Rio de Janeiro were not found, so national projections were used. Therefore, we consider that, due to policy incentives, HEVs will represent 10% of Brazilian fleet in 2050. Thus, Equation (4.23) represents the growth of the HEV fleet according to the level of BUMP implementation which is shown in Figure 4.14.

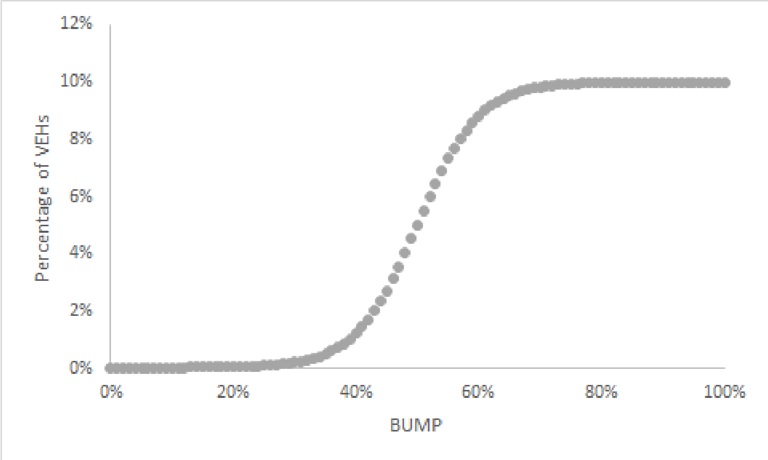


Figure 4.14 − Percentage of HEVs on Brazilian fleet

$$HEV\ fleet = 0.049875 \times \tanh[(10 \times BUMP) - 5] + 0.050125 \qquad (4.23)$$

According to Choi *et al.* (2020), the air pollution generated by HEVs represents 70% of the amount emitted by conventional vehicles. Thus, the private transport emissions will be calculated according to Equation (4.24).

$$\textit{Private transport emissions} = (\textit{Hybrid electric vehicle fleet} \times \textit{Car trips} \times \textit{Kg of } CO_2\textit{/pass-km (Car)} \times \textit{Average travelled distance (Car)} \times \textit{\% share of HEV air pollution}) + [(1 - \textit{Hybrid electric vehicle fleet}) \times \textit{Car trips} \times \textit{Kg of } CO_2\textit{/pass-km (Car)} \times \textit{Average travelled distance (Car)})] \qquad (4.24)$$

After the development of the new sectors, the proposed model was tested to ensure that the results represent the real system properly. Therefore, tests commonly used to validate system dynamics models were performed, such as boundary adequacy, structure assessment, dimensional consistency, integration error and extreme condition. After checking the model, the proposed model was simulated and the results are presented in the next section. It is worth mentioning that, like the equations, the parameters of the other sectors are available in the previous chapter.

### 4.2 Dynamic simulation results

To highlight the effects of BUMP, it is presented at the same time the results for two scenarios: business-as-usual (BAU) and BUMP. Thus, it is presented the system's behavior for the next three decades with and without BUMP implementation. For the BAU scenario, the variable "BUMP" is equal to 0.

Considering the total trips in Rio de Janeiro, 1.48 billion (28%) were non-motorized and 3.81 billion (72%) were motorized in 2018. With BUMP implementation, the share of non-motorized trips increases, resulting in 1.95 billion trips, i.e., 35% of the total trips in 2050. In addition, comparing to the BAU scenario, the BUMP implementation reduces 800 million motorized trips only in 2050 (year 32), as can be seen in Figure 4.15.

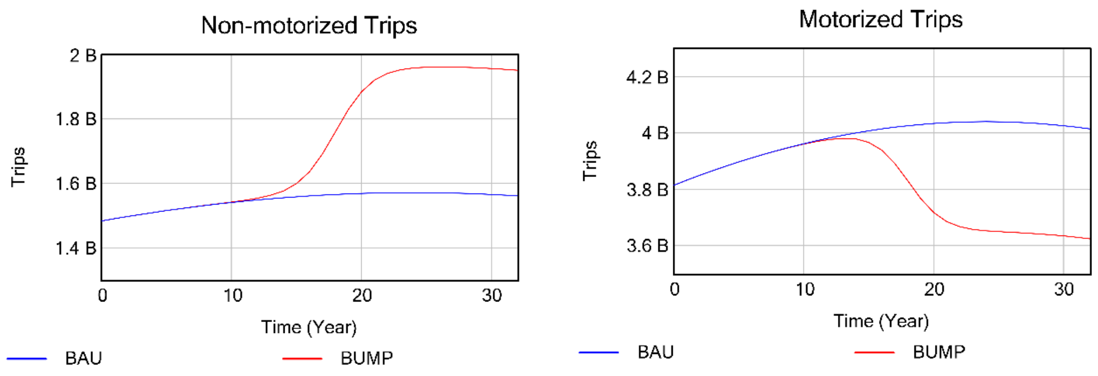


Figure 4.15 – Non-motorized and motorized trips

Regarding motorized trips, in BUMP scenario, there is a reduction in car trips and an increase in public transport trips. Car trips drops from 1.30 billion in 2018 to 827 million in 2050. However, as shown in Figure 4.16, in the first years of simulation, there are small peaks during this reduction. These peaks occur because the reduction in the level of traffic congestion leads to an increase in traffic speed and, consequently, an increase in the attractiveness of car trips.

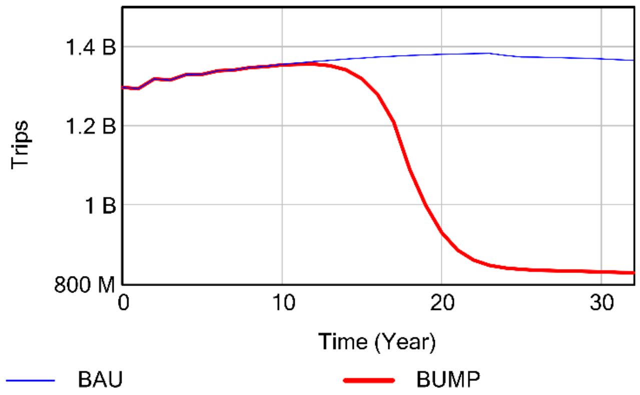


Figure 4.16 – Car trips

As can be seen in Figure 4.17, in BUMP scenario, the public transport trips increase from 2.52 billion in 2018 to 2.80 billion in 2050. Like car trips, in the first years this growth fluctuates somewhat due to the variation in the traffic speed that impacts the attractiveness of private transport.

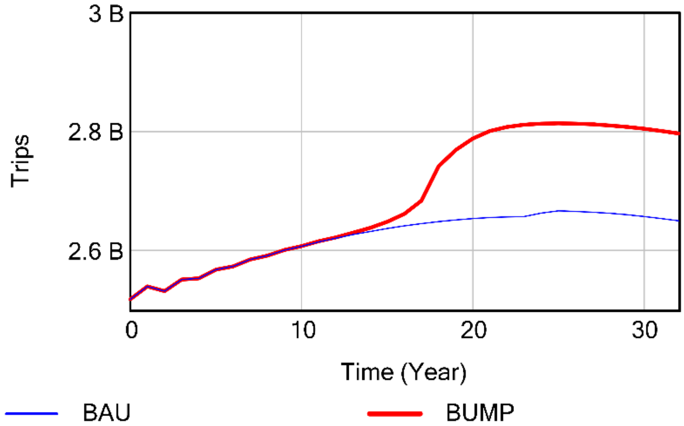


Figure 4.17 – Public transport trips

In 2018 the traffic congestion level is 1.46, i.e., the travel demand is 46% greater than the system's capacity. As can be seen in Figure 4.18, in BAU scenario, this level remains over 1.46 during the 32 years. In other hand, in BUMP scenario, the congestion level is below 1.00 in the 18$^{th}$ year (0.997651). From that year, the traffic congestion level keeps decreasing, reaching 0.59 in 2050. Therefore, the results show that encouraging non-motorized, public transport and efficient land use help to reduce the traffic congestion.

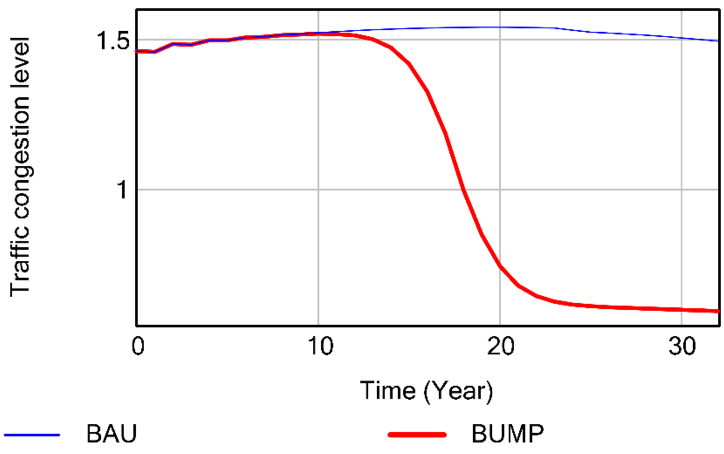


Figure 4.18 – Traffic congestion

As previously discussed, traffic congestion directly influences traffic speed. As can be seen in Figure 4.19, due to the reduction in the traffic congestion level in BUMP scenario, the traffic speed enhances in the first 15 years, rising from 38 km/h to 48 km/h. Due to the maximum speed, the traffic speed is 50 km/h in the 16$^{th}$ year. Besides that, since the traffic congestion level is less than 1.0, after the 18$^{th}$ year, the traffic speed keeps at the maximum speed (50 km/h), remaining constant until 2050. Once the number of accidents is determined based on traffic speed, this variable presents a behavior like traffic speed. Therefore, in 2018 the number of accidents is 13,497, reaching 18,516 in 15$^{th}$ year.

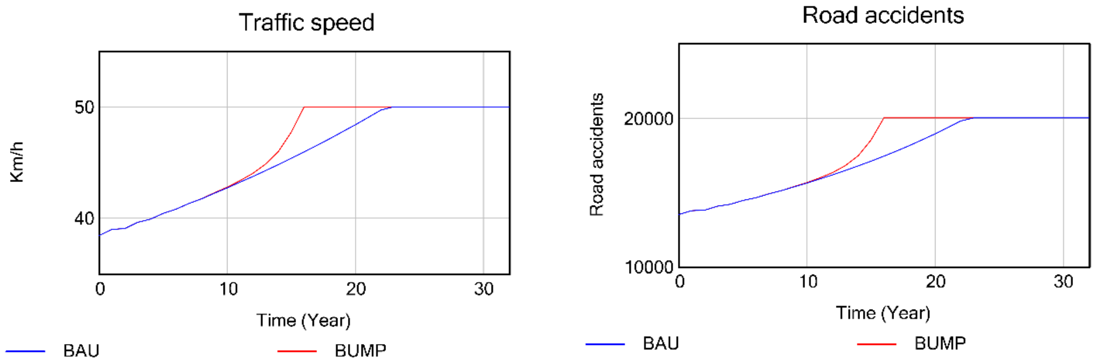


Figure 4.19 – Traffic speed and road accidents

The BUMP measures to change travel patterns and to integrate renewable energy sources, such as electric vehicles, significantly reduce pollution. As can be seen in Figure 4.20, the $CO_2$ emissions in 2018 is 1.85 billion Kg, reaching 1.94 billon and 785 million

Kg of $CO_2$ in BAU and BUMP scenarios, respectively. Therefore, with BUMP implementation, the emission in 2050 represents 42.4% of the emissions in 2018.

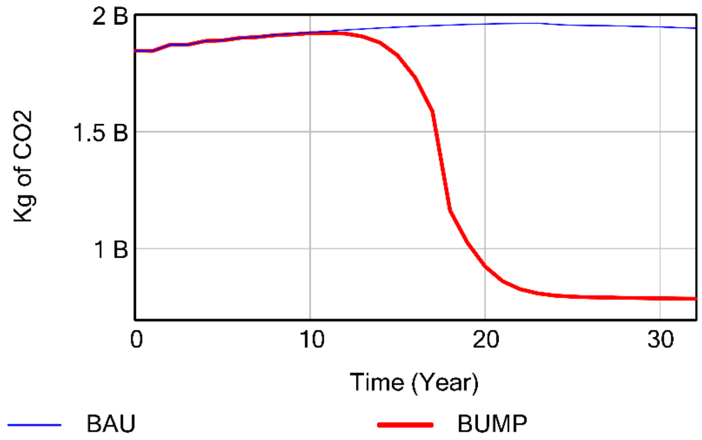


Figure 4.20 − $CO_2$ emissions

To assess the effects of the BUMP on noise pollution, it is necessary to check the variation in the traffic volume. Compared to 2018, in BUMP scenario, the traffic volume (total of cars and buses) reduces 40% in 2050, as can be seen in Figure 4.21. According to Table 4.2, this change in traffic volume results in a 2.2 dB noise reduction. This reduction provides several benefits to the population because the exposure to traffic noise can increase the risk of developing type 2 diabetes, affect people's memory and behavior, cause damage to pregnancy, create psychiatric disorder, among others negative effects (Stansfeld *et al.*, 2000; Dzhambov, 2015).

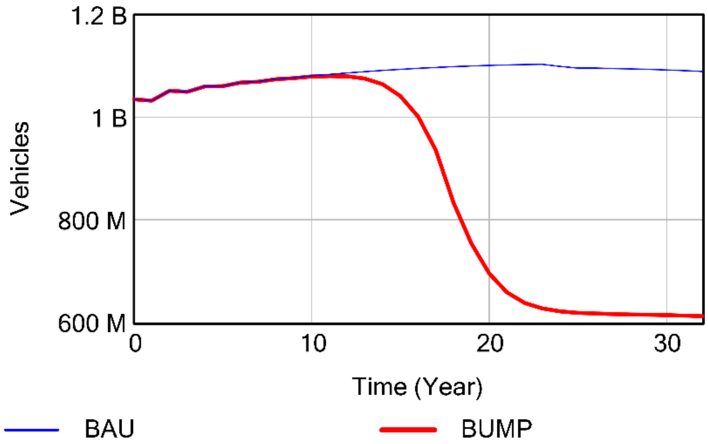


Figure 4.21 − Traffic volume

In 2018, the $PM_{2.5}$ concentration in Rio de Janeiro was 11.19 µg/m$^3$. In BUMP scenario, this concentration decreases, reaching 7.09 µg/m$^3$ in 2050. The reduction of approximately 37% in the $PM_{2.5}$ concentration avoided 954 hospitalizations due respiratory and cardiovascular diseases in 32 years. In financial terms, this new travel pattern resulted in savings of almost US$ 500,000 to the government. The effects of Health sector become more evident when analyzing the number of avoided deaths. As can be seen in Table 4.4, more than 8,000 deaths are avoided, impacting thousands of families and the local economy.

Table 4.4 – Effects on health

| Effect on health | Avoided | Avoided cost |
|---|---|---|
| Hospitalization of respiratory disease | 603 | US$ 303,068 |
| Hospitalization of cardiovascular disease | 351 | US$ 175,486 |
| Death (Age > 30) | 8042 | - |

The simulation results show that the proposed model is capable to show how the BUMP implementation reduces the negative externalities of the transport. In addition, the proposed model present factors that are not commonly addressed in other SD models, further evidencing the reduction of these externalities through BUMP measures. The Hybrid Electric Vehicles and Land Use Efficiency sectors highlight the importance of sustainable transportation measures to reduce air pollution. In addition, with the Land Use Efficiency sector, it is possible to see how avoiding urban sprawl helps to reduce congestion and air pollution. The Health sector shows how BUMP can improve well-being and, consequently, the population's quality of life. Finally, the results about Traffic Accidents sector point to the need to address factors other than speed to control traffic accidents, such as traffic rules and road safety education.

## 4.3 Final remarks of the chapter

This chapter sought to assess the effects of the BUMP on urban transport systems. To achieve this goal, it was developed a SD model and carried out a case study in the city of Rio de Janeiro. In addition to the factors addressed in Chapter 3, we added more components to this model, addressing more measures of this policy and, consequently, better capturing its effects. The results point out the importance of this policy to reduce the negative effects of transport and to increase the efficiency of these systems.

The results show how the BUMP increases non-motorized and public transport trips, reduces private transport trips and improve land use. All these changes combined reduce the traffic congestion and air pollution. In addition, despite not reducing traffic congestion, the use of electric vehicles points out as a great strategy to reduce the air pollution.

Air pollution is the world's largest environmental health threat. Regarding this global concern, the results show how BUMP can reduce the cases of diseases caused by air pollutants. Consequently, this policy avoids costs for the government that are responsible for providing health services to the entire population.

The BUMP reduces the traffic congestion, increasing traffic speed and consequently, private transport attractiveness. The results from the Traffic Accidents sector show how this increase in traffic speed raises the number of traffic accidents. Therefore, decision makers should take extra measures to ensure that the reduction of a negative externality does not increase or generate another negative externality. Also, there are other factors that influences traffic accidents such as traffic volume, infrastructure, human factors, among others. These factors should be included in future studies.

As in the model in Chapter 3, the attractiveness of non-motorized and public transport was determined based on projections. As shown in this chapter, the simulation results are sensitive to the attractiveness. Consequently, changes in these parameters will impact the results and may change their behavior. Although we adapted the attractiveness to the Brazilian reality, future studies should use projections based on Brazil data, because the attractiveness are the core of the model.

Despite showing the effects of the BUMP implementation, the proposed model has some limitations. The Transport Supply sector addresses only motorized transport (public and private), disregarding the infrastructure for non-motorized transport. Therefore, it will be interesting to expand this sector in future studies. The Traffic Accidents sector addresses the effects of traffic speed on traffic accidents. However, it is known that the number of accidents is also influenced by other factors such as travel demand, human factors and transport supply. Also, it is known that traffic speed affects air pollution (Tang *et al.*, 2020) and this relationship is not addressed in this study. Thus, it is suggested to include these factors in future studies.

Despite representing a small percentage of the vehicle fleet, freight vehicles are responsible for more than half of transport emissions (Agarwal and Kickhofer, 2016). In addition, this mode of transport generates other externalities. Therefore, it is suggested that, in addition to the passenger's transport, freight should be addressed in the future studies. The Hybrid Electric Vehicles sector encourages new technologies, but it prioritizes individual transport. We suggest including innovations for public or non-motorized transport. In addition, despite being practically non-existent in Brazil, full electric vehicles (FEVs) present better results and their use may become a reality in the future. Therefore, this type of vehicle should be addressed in future studies.

In the proposed framework, the social issues are represented by traffic safety and health. However, there are other ways to quantify the social costs from urban transport systems. Therefore, we suggest for future work the addition of other forms of social costs, such as fare policies and accessibility for people with limited mobility. The traffic accident sector considered all types of accidents. However, it is possible to analyse the different types of accidents by varying $\beta$. About $\beta$, we used the parameter provided by Elvik (2014), who calculated it based on data from the Norwegian context. Therefore, it is suggested for future studies the re-parameterisation of $\beta$ using data from the Brazilian context. We also suggest analysing the different types of accidents, using different values of $\beta$.

Despite the limitations, the proposed model has significant contributions to the literature, expanding the existing studies on the theme. It is observed that this model provides realistic results, improving the decision-making process. Although the model is focused on the BUMP, it can be adapted and applied to any city around the world, being a powerful planning instrument that can help the entire urban planning community. Finally, it can be concluded that the externalities of urban transport systems are manageable and reversible through sustainable transportation policies, making it possible to achieve sustainable development.

# 5 USING SYSTEM DYNAMICS TO UNDERSTAND LONG-TERM IMPACT OF NEW MOBILITY SERVICES AND SUSTAINABLE MOBILITY POLICIES: AN ANALYSIS PRE- AND POST-COVID-19 PANDEMIC

In addition to the challenge of adapting to the growing demand with its current structure and the externalities, transport systems are being impacted by the new modes and services that are emerging with the rapid growth of mobile and wireless communication technologies (Wang and Yang, 2019). Even in countries in economic crisis, new shared mobility business models have emerged, changing the travel pattern and, consequently, the transportation planning and operation approaches (Luna *et al.*, 2020; Cruz and Sarmento, 2020).

The number of studies about the effects of the new shared urban mobility services, especially about the replacement of traditional modes by these services, is growing, but there is still no consensus about the costs (Vanderschuren and Baufeldt, 2018). As a recent phenomenon, these new transport concepts are not yet regularized in several places, not being mentioned on the sustainable transport policies and transportation planning (Li and Hou, 2019; Kent and Dowling, 2016). In this context, it is important that governments address the new modes, services and vehicles into their sustainable policies to adequately manage the urban areas, combining public and private interests (Akyelken *et al.*, 2018; Lim and Taeihagh, 2018).

The COVID-19 pandemic showed that city administrations around the world were not prepared to manage urban transport during adverse scenarios, consequently, the effects are still being evaluated. In addition, this event changed how people live, work and play, impacting commuting trips. Therefore, it is important to study and learn from this event, allowing policymakers to develop measures that improve transport systems not only in adverse events, but also in daily routine. Therefore, in addition to new technologies, urban mobility plans must include guidelines for events like that.

New mobility services have been developed in recent years. Thus, laws and policies about these alternative modes are still under development in Brazil. The COVID-19 pandemic, on the other hand, aroused the need to develop a contingency plan for adverse situations. Both events are recent and are not addressed by BUMP, which was created in 2012. Consequently, these factors were not addressed in Chapters 3 and 4. However, they have a major impact on urban transport systems and must be included in this study. Therefore, considering the new urban mobility services and the effects of

COVID-19 pandemic, this chapter aims to develop a strategy support model, using the System Dynamics as a modeling and simulation tool, to assess the effects of sustainable mobility policies on the new travel pattern, focusing on traffic congestion and pollution.

The model proposed in this chapter seeks to help public managers in decision making on urban transport systems. In addition, it was carried out a case study in the city of Rio de Janeiro where the results are presented in two realities: pre- and post-pandemic. Finally, the model proposed in this chapter is published in Fontoura *et al*. (2023b).

## 5.1 Proposed model

The two models already presented in this study evaluate the effects of BUMP. The model proposed in Chapter 4 is an improved version of the model presented in Chapter 3. The model proposed in this chapter is not an improvement or adaptation of the models already presented. However, like them, the proposed model presents the effects of sustainable urban mobility measures. In addition, other factors such as the COVID-19 pandemic, mode choice analysis and new transport services are addressed in the model presented below.

### *5.1.1 Causal Loop Diagram*

The proposed model aims to analyze the effects of sustainable transport policies on the modal share and, consequently, on congestion and air pollution. As car trips raise these externalities, most sustainable transport policies encourage the use of public transport instead private transport (Zhou, 2012; Malayath and Verma, 2013).

The number of trips is determined according to the population size. Then, there are several factors that determine the distribution of these trips between modes, such as price, travel time, safety and comfort (Tonini *et al.*, 2021). Price and travel time are the factors that have a major impact on modal choice (Ertz *et al.*, 2016; Du and Cheng, 2018; Youssef *et al.*, 2021). Therefore, these two factors are considered in this study. Besides that, as can be seen in Figure 5.1, the model has eight sectors: Ride-hailing Trips, Car Trips, Bus Trips, Subway Trips, Train Trips, Congestion, Pollution and Road Capacity.

As already mentioned in this thesis, SD is a modelling and simulation tool that represent systems through feedback loops to identify its behaviors over time. Thus, the main loops pointed out in Figure 5.1 are detailed below.

Feedback loops i - iii:

i. Car trips $\xrightarrow{+}$ Congestion $\xrightarrow{+}$ Car trip time $\xrightarrow{-}$ Car trips **(B1)**.
ii. Ride-hailing trips $\xrightarrow{+}$ Congestion $\xrightarrow{+}$ Ride-hailing trip time $\xrightarrow{-}$ Ride-hailing trips **(B2)**.
iii. Bus trips $\xrightarrow{+}$ Congestion $\xrightarrow{+}$ Bus trip time $\xrightarrow{-}$ Bus trips **(B3)**.

An increase in car trips raises the level of traffic congestion, increasing car trips time (Nguyen-Phuoc *et al.* 2018). Consequently, the increase in travel time reduces the attractiveness of car trips, reducing the number of trips (Gruel and Stanford, 2016). Thus, it is balancing feedback loop (B1) because the change feeds back to oppose the original change. Loops B2 and B3 are obtained by substituting car trips for ride-hailing trips and bus trips, respectively.

Although replacing private trips by public transport trips is a strategy to reduce congestion, the polarity between bus trips and congestion is positive because growing the number of vehicles (buses) increases congestion. In other words, the polarity only evaluates the relationship between the two variables in the link, not considering the other ones of the model.

Feedback loops iv - vi:

iv. Subway trips $\xrightarrow{+}$ Subway Occupancy Rate $\xrightarrow{+}$ Subway trip time $\xrightarrow{-}$ Subway trips **(B4)**.
v. Train trips $\xrightarrow{+}$ Train Occupancy Rate $\xrightarrow{+}$ Train trip time $\xrightarrow{-}$ Train trips **(B5)**.
vi. Bus trips $\xrightarrow{+}$ Bus Occupancy Rate $\xrightarrow{+}$ Bus trip time $\xrightarrow{-}$ Bus trips **(B6)**.

Expanding public transport demand increases the occupancy rate of vehicles. Passenger boarding and transfers are longer in crowded vehicles, impacting travel time (Kim *et al.*, 2015). The increase in trip time reduces the attractiveness of these modes, reducing the number of trips. Thus, loops B4, B5 and B6 are balancing loops.

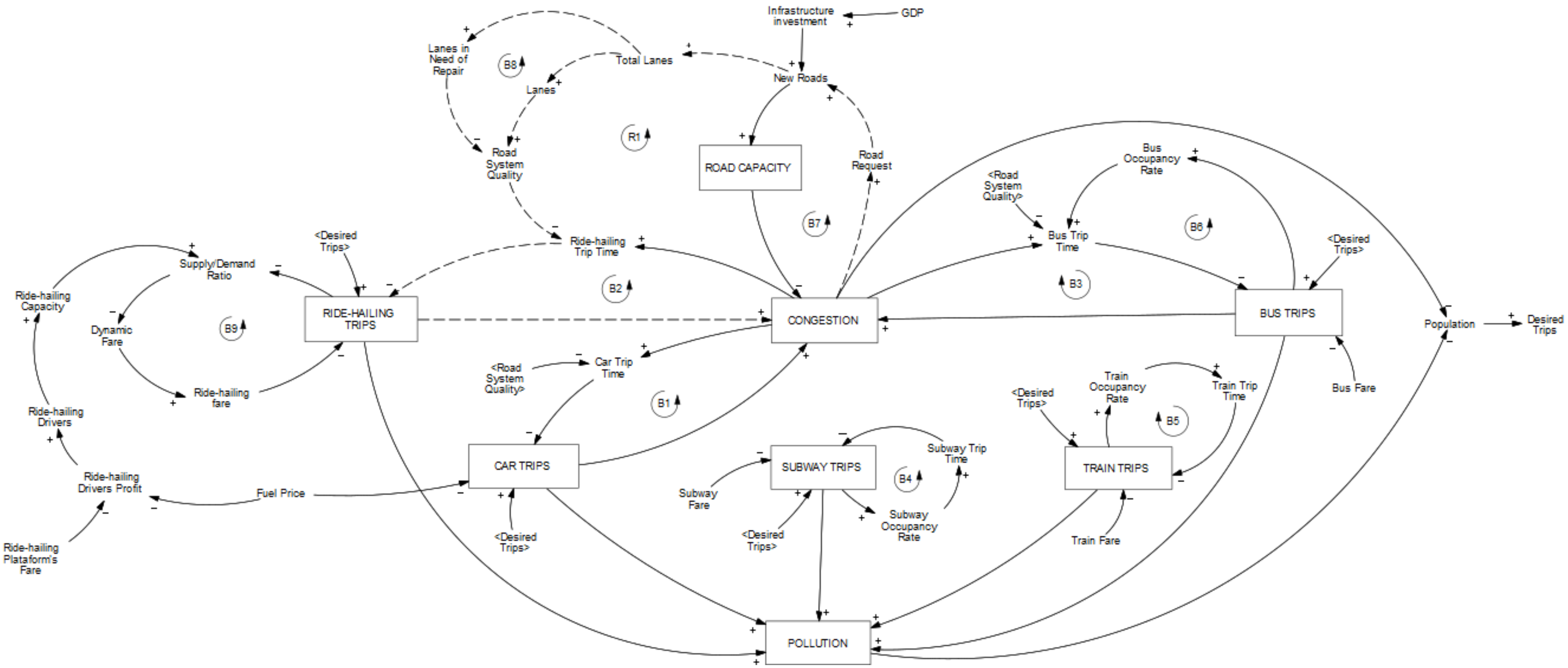


Figure 5.1 − Causal Loop Diagram for the third model

Feedback loop vii:

vii. Congestion $\xrightarrow{+}$ Road Request $\xrightarrow{+}$ New Roads $\xrightarrow{+}$ Road Capacity $\xrightarrow{-}$ Congestion **(B7)**.

Congestion is an urban transport externality that directly impact population. Therefore, the government is commonly pressured by the population to take measures to reduce traffic congestion (Armah *et al.*, 2010). Constructing new roads is a common measure to solve this problem, increasing the capacity of the system and, consequently, reducing congestion. Thus, it is balance loop (B7).

Feedback loops viii - ix:

viii. Congestion $\xrightarrow{+}$ Road Request $\xrightarrow{+}$ New Roads $\xrightarrow{+}$ Total Lanes $\xrightarrow{+}$ Lanes in Need of Repair $\xrightarrow{-}$ Road System Quality $\xrightarrow{-}$ Ride-hailing Trip Time $\xrightarrow{-}$ Ride-hailing Trips $\xrightarrow{+}$ Congestion **(B8)**.

ix. Congestion $\xrightarrow{+}$ Road Request $\xrightarrow{+}$ New Roads $\xrightarrow{+}$ Total Lanes $\xrightarrow{+}$ Lanes $\xrightarrow{+}$ Road System Quality $\xrightarrow{-}$ Ride-hailing Trip Time $\xrightarrow{-}$ Ride-hailing Trips $\xrightarrow{+}$ Congestion **(R1)**.

System capacity is determined by the total number of lanes. However, these lanes will gradually begin to show distress over time, requiring routine maintenance (Sharifi, 2019). These repairs are extremely necessary, as lanes in poor conditions can increase travel time (Zheng *et al.*, 2018). As already discussed, the increase in travel time reduces travel demand, reducing congestion and the request for new lanes. Therefore, this behavior is a balancing loop (B8). On the other hand, routine maintenance keeps the roads in good condition, not negatively impacting travel time. Thus, there is an increase in the attractiveness of travel, increasing congestion and, consequently, the request for new routes. In this case, it is a reinforcing loop (R1) because the change feeds back to reinforce the original change. Although Figure 5.1 only shows these feedback loop with ride-hailing trips, this behavior also happens with bus trips and car trips.

Feedback loop x:

x. Ride-railing trips $\xrightarrow{+}$ Supply Demand Ratio $\xrightarrow{+}$ Dynamic Fare $\xrightarrow{-}$ Ride-hailing Fare **(B9)**.

This loop represents the relationship between travel demand, price and ride-hailing trips. A common practice in this type of service is the dynamic pricing, which is applied when demand is greater than supply. The dynamic pricing increases the fare of this mode, reducing its attractiveness. Therefore, this relationship is a balance loop (B9).

Using different modes, Figure 5.1 presented the relationships between urban trips and two transportation externalities. However, pollution and congestion make cities less attractive, impacting on population growth and, consequently, on desired trips (Cirovic *et al.*, 2014; Wolch *et al.*, 2014). Thus, there is a balancing loop between each mode and these two externalities. Figure 5.2 presents these relationships for car trips.

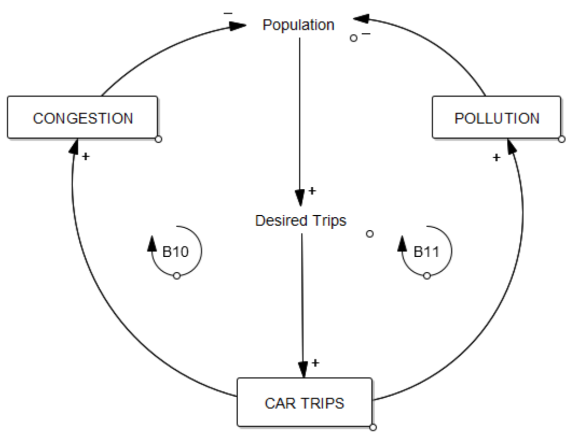


Figure 5.2 − Relationship between car trips, pollution and congestion.

All relationships described above were detailed in a Stock and Flow Diagram (SFD), where the variables are connected by equations, allowing the simulation.

### *5.1.2 Stock and Flow Diagram*

The five trip sectors, shown in Figure 5.1, have a similar structure. To explain the concept of these sectors, the ride-hailing sector is presented below. As can be seen in Figure 5.3, travel demand is determined according to population. The allocation of these trips is given according to the attractiveness of each mode. To represent this attractiveness, it is used the discrete choice utility approach developed by McFadden (2001; 2022). For that, the trip time and trip price of each mode were used to determine their utility function. Regarding trip time, it is used perceived trip time, which includes the waiting time and the travel time. Therefore, the attractiveness and the trip allocation of ride-hailing trips are defined by Equations (5.1) and (5.2), respectively.

$$Relative\ Attractiveness\ (Ride-hailing) = \left[Coef\ 1 \times \left(\frac{Perceived\ Time\ Per\ Trip}{Initial\ Perceived\ Time\ Per\ Trip}\right)\right] + \left[Coef\ 2 \times \left(\frac{Perceived\ Price}{Initial\ Perceived\ Price}\right)\right] \tag{5.1}$$

$$Allocation\ of\ Demand\ Among\ Modes\ (Ride-hailing) = \left[\frac{EXP\big(Relative\ Attractiveness\ (Ride-hailing)\big)}{\sum_{j=1}^{5} EXP\big(Relative\ Attractiveness\ (j)\big)}\right] \times (1 - Other\ Modes\ Share) \tag{5.2}$$

Where $j$ (1 = Ride-hailing, 2 = Car; 3 = Bus; 4 = Subway, 5 = Train) and other modes shares represent the share of modes that are not addressed in the model (non-motorized transport, boat, light rail, among others).

The total price of ride-hailing trips is usually determined by the sum of a fixed fare, a fare per kilometer traveled and a fare for each minute spend on the trip. However, several variables change the trip time. The waiting time increases when the trip demand is bigger than the number of available drivers. In addition, congestion and poor road conditions also increase trip time. Therefore, all these relationships are represented by non-linear relationships that change the trip time according to the value attributed to the variables “Supply-Demand Balance”, “Congestion” and “Road System Quality”. For bus, subway and train trips, the vehicle occupancy rate can change trip time once passengers spend more time to get on and off the in overcrowded vehicles. Therefore, it was also developed non-linearities to represent these relationships.

The trip price can be changed by the dynamic pricing, which is a practice commonly applied in ride-hailing services when demand is greater than supply. This tariff seeks to balance supply and demand by increasing the price. In addition, there is still the annual adjustment in the rates of all modes.

In addition to determining attractiveness and allocating trips to this mode, the ride-hailing trips sector also analyzes the system's capacity to meet the demand. The model considers the attractiveness of this job to determine the number of ride-hailing drivers, comparing the drivers' profits with the minimum wage, as can be seen in Figure 5.4. As already mentioned, the other trip sectors have a similar structure. The equations for each variable can be seen in APPENDIX B.

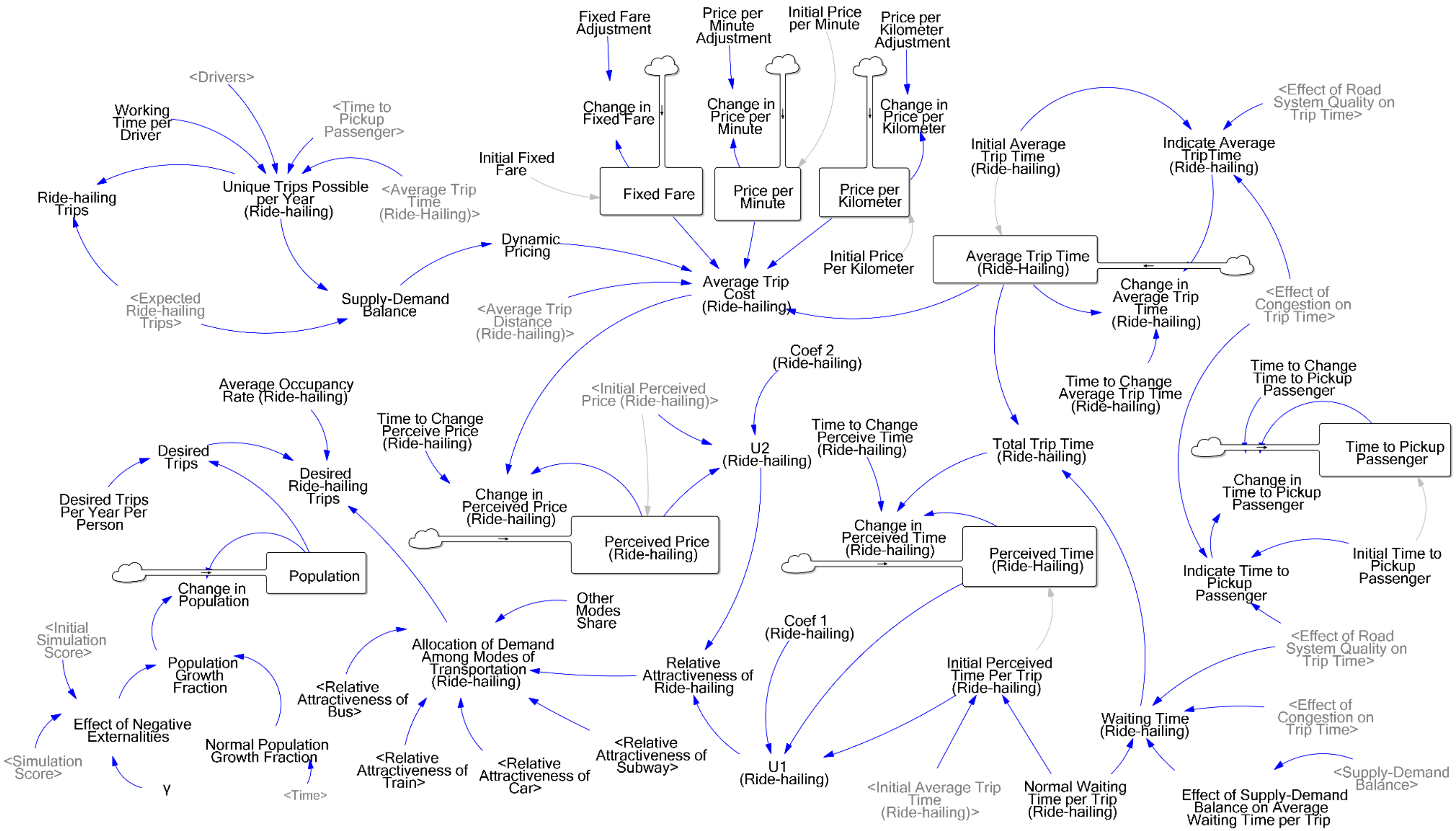


Figure 5.3 – Ride-hailing Sector (Trips Demand)

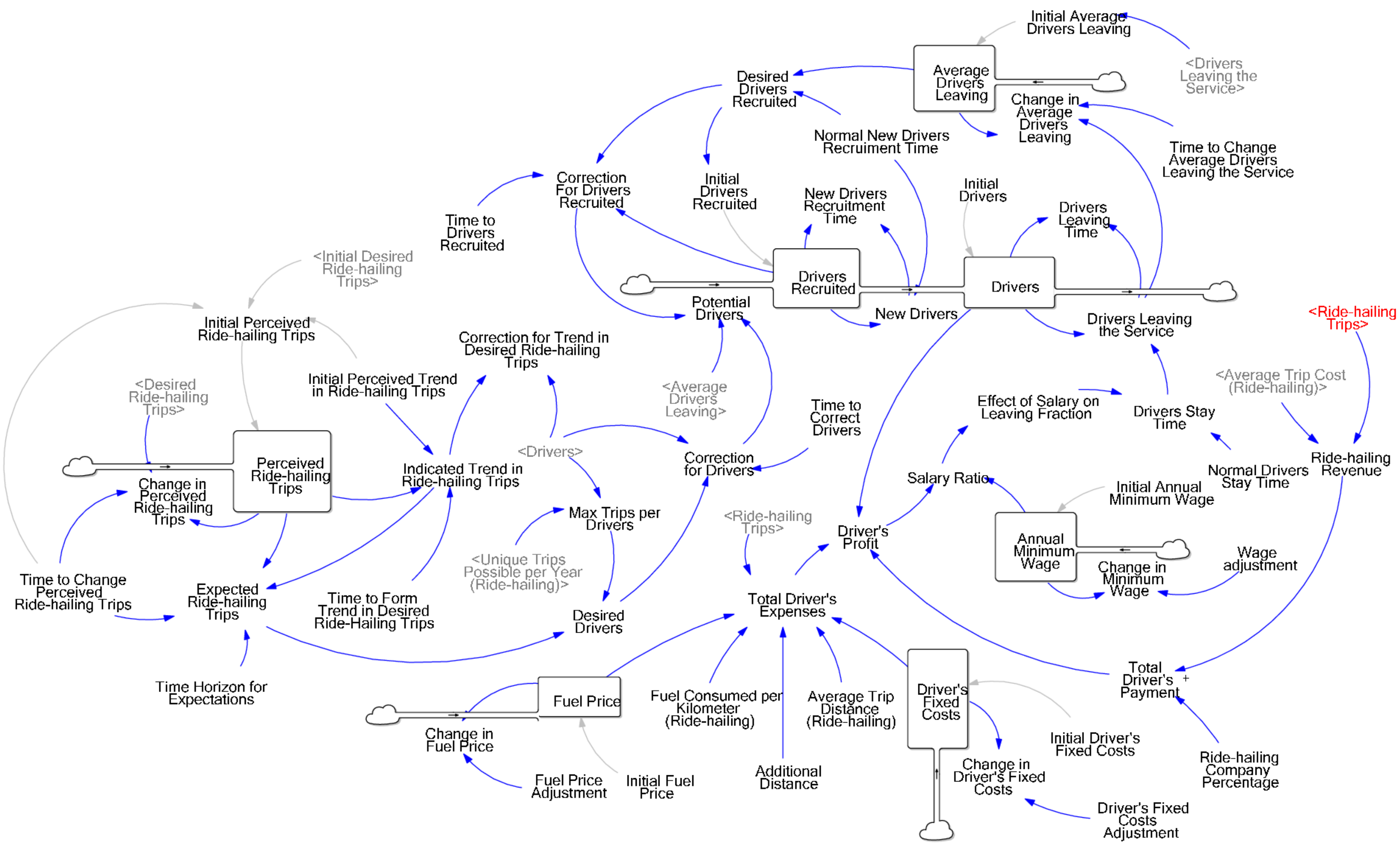


Figure 5.4 – Ride-hailing Sector (Trip Supply)

Based on Wang *et al.* (2008) and Sayyadi and Awasthi (2017), congestion is determined by the total vehicle kilometers traveled (VKT) and the system's capacity, as can be seen in Figure 5.5. In other words, congestion level is determined by the volume (V) over capacity (C) (V/C). The system capacity is determined in the road sector according to the number of lanes. The effect of congestion on trip time is obtained by the equation established by the Bureau of Public Roads (1964), which is presented in Equation (5.3). As will be explained later, congestion and pollution determine the simulation score in this model. Thus, as congestion gets worse, the smaller the variable "Effect Congestion (Score)" and, consequently, the simulation score.

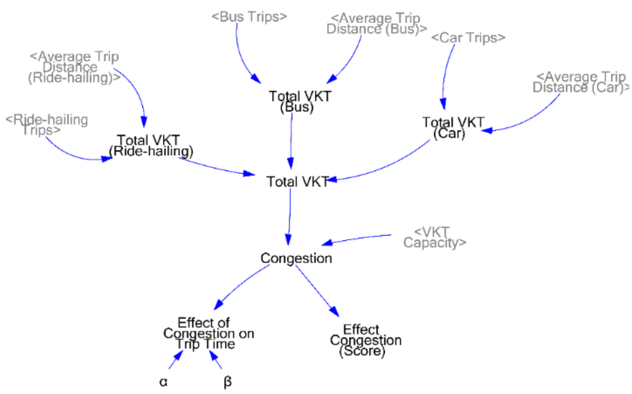


Figure 5.5 – Congestion Sector

$$t = t_0 \times \left(1 + \alpha \times \left(\frac{V}{C}\right)^{\beta}\right) \quad (5.3)$$

Where:

$t$: trip time with congestion;
$t_0$: trip time with free flow; and
$\alpha$ and $\beta$: calibration parameters (usually $\alpha$ = 0,15 and $\beta$ = 4).

To determine the VKT capacity in the road sector, it is used the total lanes and the VKT per lane, a measure provided by the Bureau of Transportation Statistics (2022). As can be seen in Figure 5.6, the desired lanes are obtained based on the desired congestion. However, there is a financial constraint. The percentage of GDP allocated to urban infrastructure is split between lanes maintenance and construction of new lanes, being maintenance a priority. To determine the number of lanes requiring a repair, the model uses the deterioration time for urban lanes. Based on the number of lanes in good condition, it is possible to determine the road system quality and, consequently, develop a function to represent its effect on trip time.

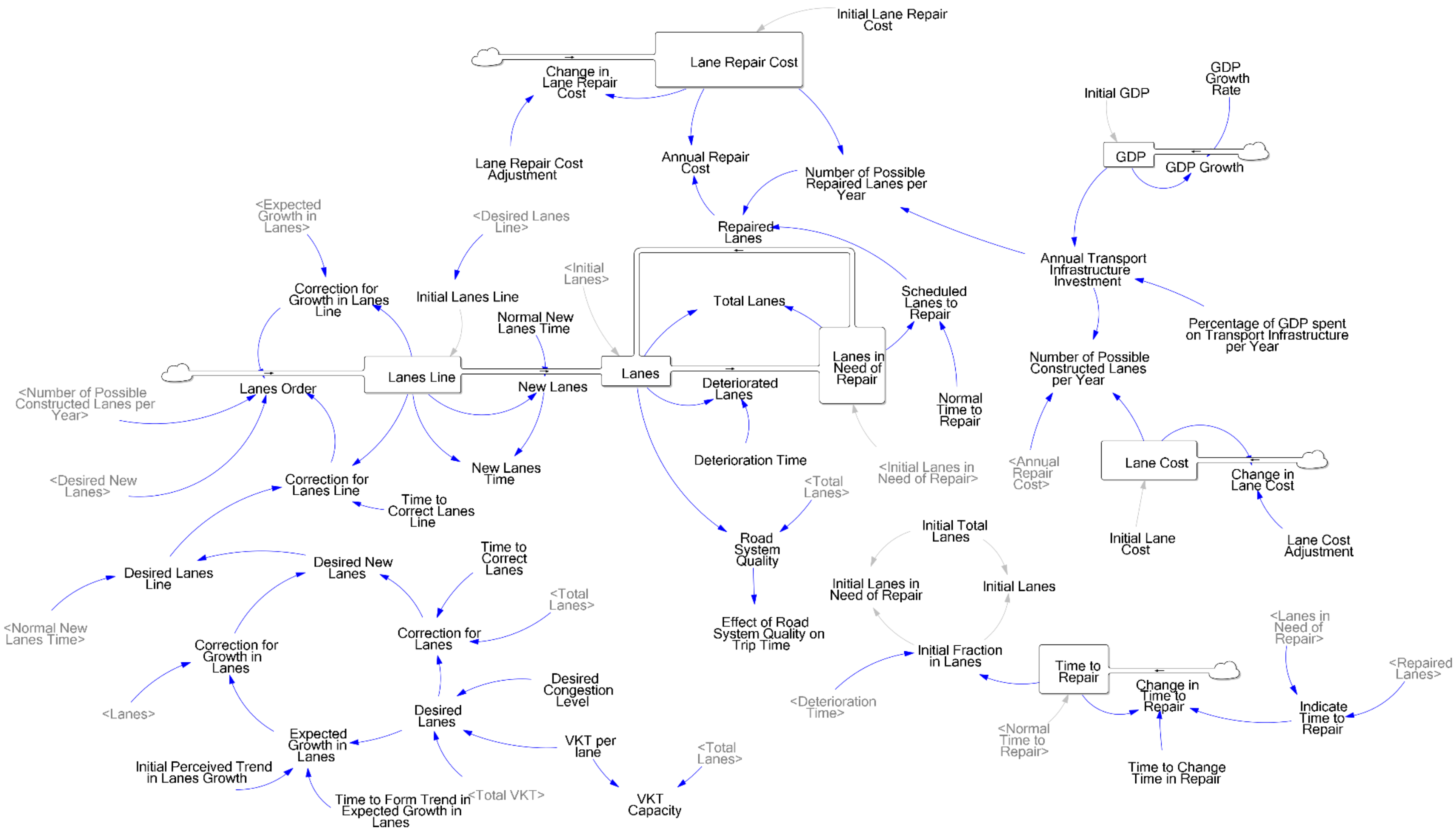


Figure 5.6 – Road Sector

The pollution sector calculates the emissions for each mode. To do so, the model uses the emission of $CO_2$ per kilometer (kg $CO_2$/km), the average trip distance and the total trips for each mode, as can be seen in Figure 5.7. As mentioned earlier, the simulation score is calculated based on the congestion and pollution. Therefore, the higher the pollution, the lower the “Effect Pollution (Score)” and, consequently, the simulation score. To obtain this effect, the model compares the annual emission with the initial emission.

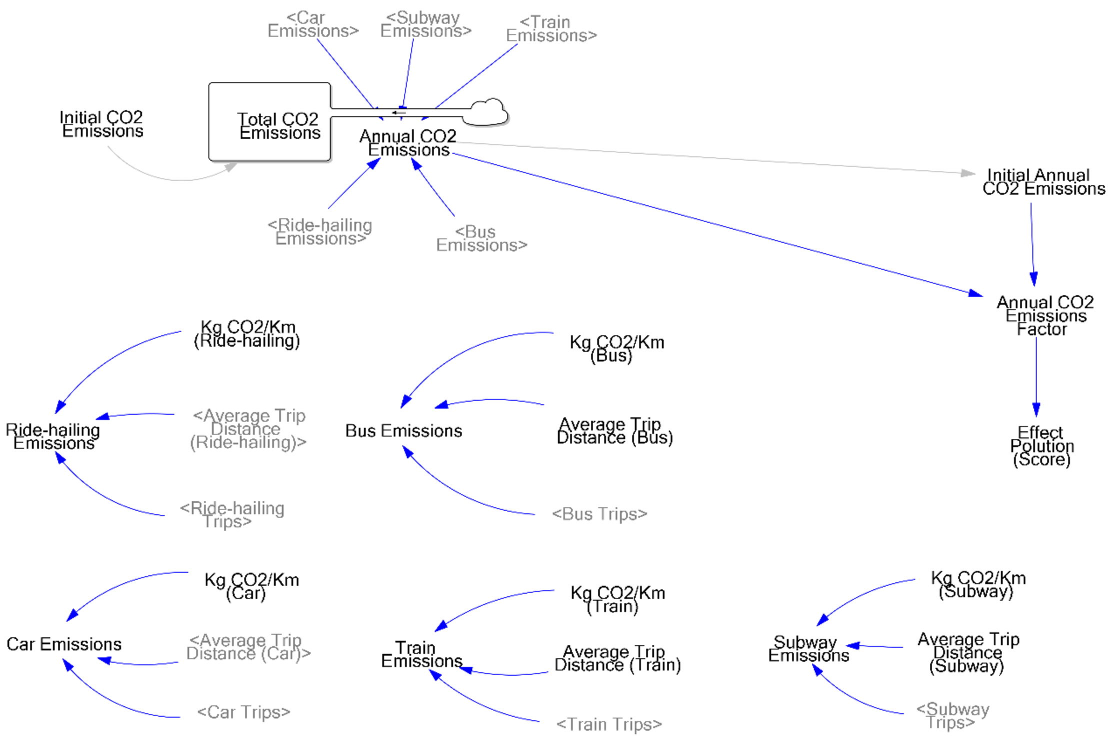


Figure 5.7 – Pollution Sector

Finally, the model has a simulation score that allows comparing the impacts of different sustainable transport policies. This score will be high when congestion and air pollution decrease. Therefore, it allows ranking different policies, highlighting the good measures that must be prioritized. In addition, the simulation score allows to compare a policy in different scenarios, such as pre- and post-COVID-19 pandemic. In this context, it is noted that this indicator is calculated based on two negative externalities, as can be seen in Equation (5.4).

$$\begin{aligned} Simulation\ Score \\ &= 100 \times [(Effect\ Pollution \times Pollution\ Weight) \\ &+ (Effect\ Congestion \times Congestion\ Weight)] \end{aligned} \tag{5.4}$$

Where “Pollution Weight” and “Congestion Weight” are weights assigned by policy makers according to their strategies and the sum of them is equal to 1.

In addition to being an indicator, the score impacts population growth since these negative externalities make cities less attractive. For this, we use the Cobb-Douglas Production Function, commonly used in economics to represent the relationship between outputs and inputs. In other words, this function denotes how the outputs of a system behave as a function of the inputs used to get those outputs (Goldberger, 1968; Sukono *et al.*, 2019). The application of this function can be seen in Equations (5.5) and (5.6).

$$\begin{aligned} Population\ Growth\ Fraction \\ &= Normal\ Population\ Growth\ Fraction \\ &\times Effect\ of\ Negative\ Externalities \end{aligned} \tag{5.5}$$

Where:

$$Effect\ of\ Negative\ Externalities = \left(\frac{Simulation\ Score^{-1}}{Initial\ Simulation\ Score^{-1}}\right)^{\gamma} \tag{5.6}$$

and γ is a calibration parameter that was established based on Forrester (1973) World Dynamics model assumptions.

Forrester’s model shows how population is controlled by four factors: crowding, food supply, pollution, and natural resources. For that, he developed assumptions to represent the variation in the population due to these factors. Therefore, based on the curves developed by Forrester to represent the impact of crowding and pollution, we set the parameter of the variable "$\gamma$", allowing the model to represent the impact of congestion and pollution on population growth.

After the construction of all the sectors presented above, tests were carried out to ensure that the model reproduces behaviors that represent reality. Thus, tests of extreme conditions, evaluation of the structure, dimensional consistency, evaluation of parameters and sensitivity analysis were performed. Furthermore, it was added noise on some variables simultaneously and the results showed the same behavior. Therefore, it was chosen the deterministic simulation.

## 5.2 Data Collection

To analyze and compare different policies in Rio de Janeiro, it is decided to simulate for 15 years, considering 2020 the first year. Therefore, all parameters related to this city were collected, which can be seen in APPENDIX C. In addition, it is important to note that it was used Vensim as a modeling and simulation tool and all experiments were performed using this software.

Due to the absence of some numerical data, it was carried out experiments to obtain the parameters for the following variables: “Fuel Price Adjustment”, “Driver's Fixed Costs Adjustment”, “Fixed Fare Adjustment”, “Price per Minute Adjustment”, “Price per Kilometer Adjustment”, “Lane Repair Cost Adjustment”, “Lane Cost Adjustment”, “Bus Fare Adjustment”, “Operational Costs Adjustment”, “Subway Fare Adjustment” and “Train Fare Adjustment”.

To determine the most appropriate annual growth rates for all costs address in the model, it was performed the Monte Carlo experiment. Based on historical data, it was selected a meaningful range for theses parameters (0.05% - 10%) and performed an experiment with 10,000 iterations. Then, we analyze the impact of these variations on the variable “Simulation Run Score”. As can be seen in Figure 5.8, the experimental results show robustness even for the minimum or maximum values.

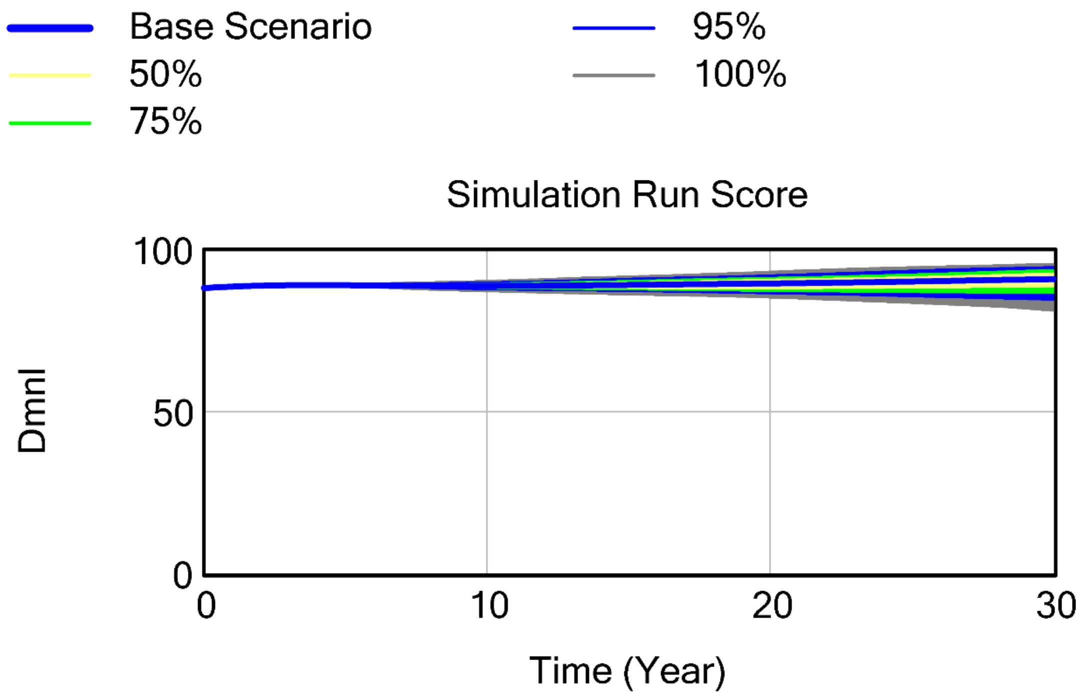


Figure 5.8 – Monte Carlo simulation results

It was not found historical data about the modal share in Rio de Janeiro, making it impossible to fit the simulation results with the historical data. To obtain the utility function for each mode, it was performed a sensitivity analysis. For this, we used a Vensim function called "Run simulation on each slider change". Instead of running a single simulation, this function allows to change the parameters of all auxiliary variables through sliders, automatically changing simulation results. Thus, with the model in equilibrium, the utilities were changed until the current modal split was obtained. In other words, with all variables constant over the years and all modes with the same modal share (20%), we change the coefficients (1 - time and 2 - price) used in the utility function of all modes. By moving the sliders of these coefficients, the system leaves the equilibrium state and the results are updated. Therefore, changing all coefficients and observing the change in modal split, we find a set of coefficients that represents the current modal share of Rio de Janeiro.

As congestion and pollution are two major concerns in transportation planning, it was assigned 0.5 to the variables "Pollution Weight" and "Congestion Weight". Finally, after collecting the data, it was developed policies, which are presented in the next section.

**5.3 Policies design**

The model testing, mentioned before, was performed with the Base Scenario. This scenario allows to visualize the most realistic system behavior (business as usual) and to compare policy spaces. Therefore, in addition to the to the Base Scenario, it was developed six scenarios to evaluate the effects of sustainable transportation policies. As can be seen in Table 5.1, the first five policy spaces are based on BUMP (Brazil, 2012) and the last one seeks to understand the effects of encouraging ride-hailing.

The first three scenarios aim to reduce car use. To simulate the fuel pricing policy (Scenario 1), the variable "Fuel Price Adjustment" was changed so that the fuel price increases more over the years, making car trips less attractive. There are several measures to reduce car ownership, such as the increase of tax on new vehicles. Therefore, in Scenario 2, the variable "Car Ownership Growth" reduces over the years. On the other hand, Scenario 3 increases the variable "Operational Costs Adjustment" to represent the impact of parking pricing on car attractiveness.

Table 5.1 − Policy spaces

| Scenarios | Policies |
|---|---|
| Base Scenario | None |
| Scenario 1 | Fuel Pricing Policy |
| Scenario 2 | Car Ownership Discouragement |
| Scenario 3 | Parking Policy |
| Scenario 4 | Encouraging High-capacity Transit |
| Scenario 5 | Transportation Infrastructure Policy |
| Scenario 6 | Encouraging Ride-hailing |

Sustainable transportation policies also encourage the use of public transportation, manly the high-capacity transit. To represent this measure, the subway and train fare adjustment were reduced in Scenario 4, making these modes more attractive. Transport infrastructure is also a major topic on urban mobility polices. Therefore, Scenario 5 represents the expansion of the road network. To do so, the parameter assigned to the variable "Desired congestion" was reduced, increasing the number of desired lanes. As a result, there is a request for new roads, which is higher than normal, increasing road network.

Finally, as there is still no consensus in the literature about the effects of ride-hailing, Scenario 6 shows the effects of encouraging this mode. For this purpose, the annual fare adjustment and the percentage that drivers pay the company were reduced, making this mode more attractive for drivers and passengers. The results of these scenarios are presented and compared below.

### 5.4 Policies evaluation

As discussed before, the COVID-19 pandemic has shown how events of this magnitude can change travel demand. Therefore, the policy spaces were simulated in two realities: pre-pandemic and post-pandemic. In pre-pandemic reality, the desired trips per person remains normal. On other hand, in post-pandemic reality, the desired trips per person drops abruptly (50%), remaining for two years, and then it increases, but now it represents only 80% of the initial demand. It is worth mentioning that this change in travel demand was determined based on news about urban trips during the COVID-19 pandemic and specialists. Finally, it is analyzed the effects of ride-hailing in both realities.

### *5.4.1 Pre-pandemic*

The Base Scenario shows that the trend is increasing bus trips while train, subway and ride-hailing trips decrease. As can be seen in Figure 5.9, the market share for car trips is almost the same over the 15 years. Unlike many Brazilian cities, private trips are not the biggest problem in Rio de Janeiro, but the bad allocation of public transport trips. Therefore, it is observed that the need to develop plans to boost mass rapid transit (train and subway).

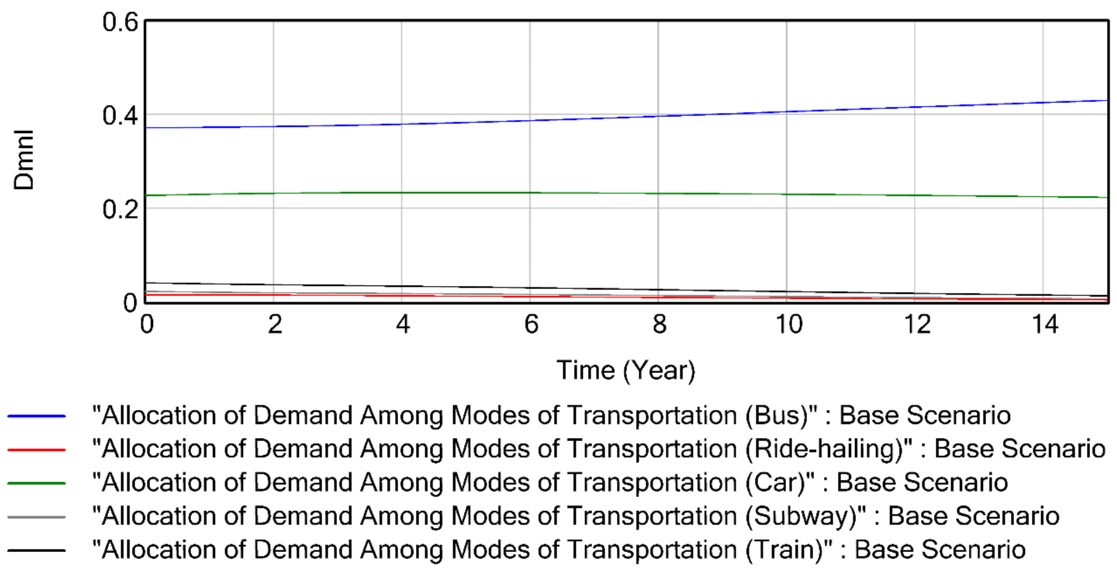


Figure 5.9 – Modal Share

Prioritizing bus trips will reduce air pollution and congestion in the first years. However, due to the low attractiveness of high-capacity transit and the increase in vehicle kilometer traveled by cars and bus, these externalities begin to grow after the fifth year, as can be seen in Figure 5.10. As the simulation score is determined by these two externalities, it increases in the first years, then starts to decrease, as can be seen in Figure 5.11

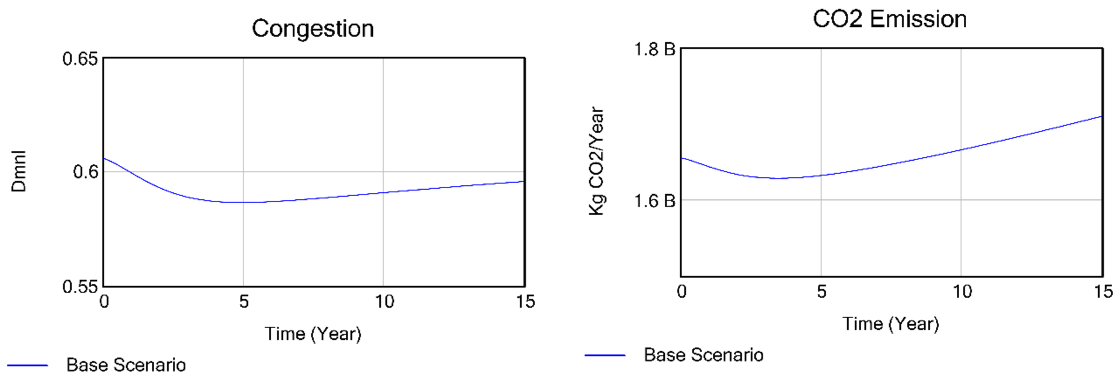


Figure 5.10 – Congestion and $CO_2$ emissions

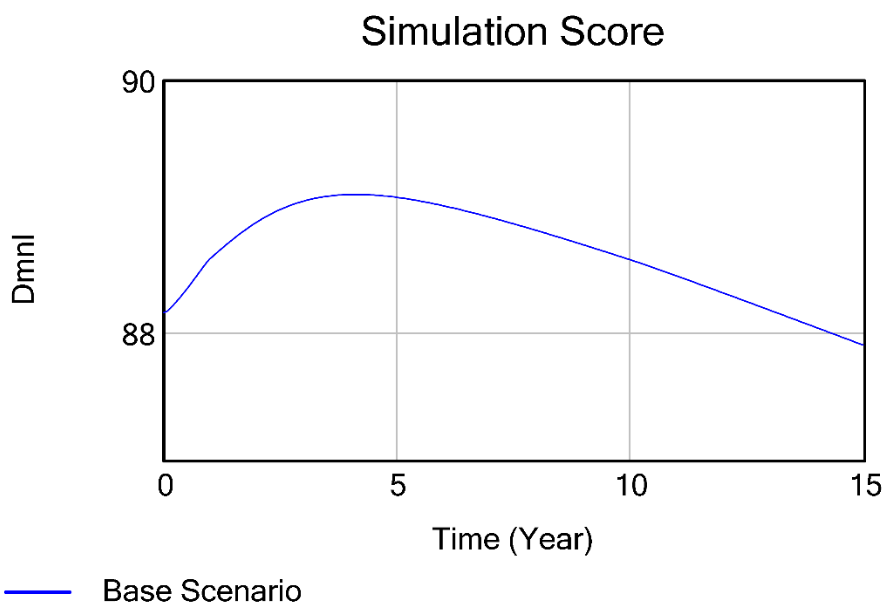


Figure 5.11 – Simulation Score

One of the assumptions of this study is that congestion and pollution impact the system on the same proportion. Then, we assign the same parameter (0.5) to the variables "Pollution Weight" and "Congestion Weight". Seeking to evaluate the impact of this premise on the results, Table 5.2 presents the simulation score for different sets of weights. Thus, it is observed that the simulation score increases as the weight of pollution decreases. Therefore, policy makers and public managers must pay attention to pollution due to its huge impact on urban transportation systems.

Table 5.2 – Simulation score for different sets of weights

| Congestion Weight | Pollution Weight | Simulation Score |
|---|---|---|
| 1 | 0 | 91.224 |
| 0.9 | 0.1 | 90.5589 |
| 0.7 | 0.3 | 89.2287 |
| 0.5 | 0.5 | 87.8986 |
| 0.3 | 0.7 | 86.5684 |
| 0.1 | 0.9 | 85.2382 |
| 0 | 1 | 84.5731 |

Among the three policies that aim to restrict the cars use (Scenarios 1, 2 and 3), the car ownership discouragement is the most effective, as can be seen in Figure 5.12, obtaining a score of 88.66 in year 15. So, it is the policy that most reduces car attractiveness, decreasing congestion and pollution. Fuel pricing and parking policies has a similar impact, being the first one a little bit more effective. In the last year, the simulation score for both scenarios are 88.48 and 88.43, respectively.

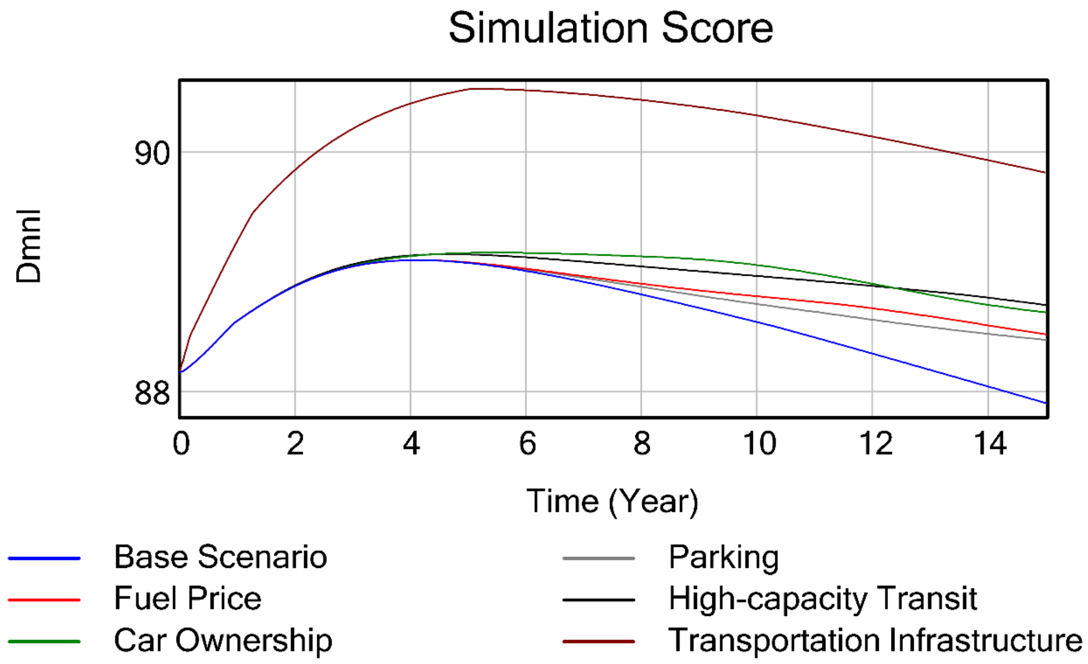


Figure 5.12 − Simulation Scores for pre-pandemic reality

Encouraging high-capacity transit (Scenario 4) and car ownership discouragement (Scenario 2) have a good impact. Comparing the score of these scenarios, Scenario 4 presents a lower initial growth, but is more stable over the years. As a result, Scenario 4 has the second highest score (88.72) in the last year.

Scenario 5 shows that the expansion of road network is an effective measure to reduce congestion. However, the $CO_2$ emissions increases in this scenario, as the new traffic congestion level makes car trips more attractive. Therefore, this scenario has the lowest congestion, but it is the only one with $CO_2$ emissions higher than the emissions on Base Scenario. Furthermore, the implementation of this policy has a high cost, because there is an unusual request for new lanes to achieve the new desired congestion. Therefore, this policy is efficient, but the financial and environmental costs of this scenario must be considered.

### *5.4.2 Post- pandemic*

The base scenario shows that only changing travel demand results in a better score than all pre-pandemic scenarios. As can be seen in Figure 5.13, excepting transportation infrastructure scenario, the scenarios results in a small improvement when compared to the base scenario. Therefore, it is noted that adopting transportation demand management (TDM) strategies is crucial to reduce urban transportation externalities. For this, urban mobility plans should focus on reducing the need to travel and link this strategy with other policies, resulting in efficient and sustainable urban transport systems.

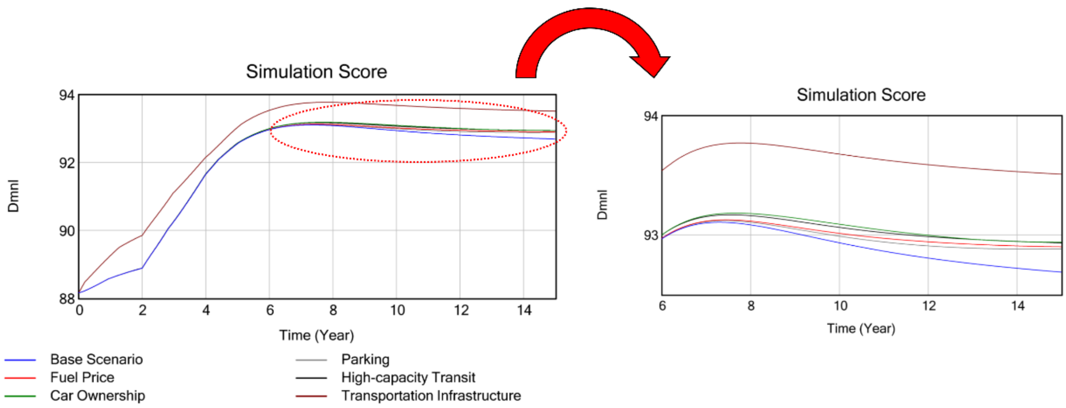


Figure 5.13 – Simulation Scores for post-pandemic reality

### *5.4.3 Ride-hailing*

Scenario 6 shows that, regardless of whether it is pre- or post-pandemic, encouraging ride-hailing increases congestion and air pollution. As can be seen in Figure 5.14, this scenario has the lowest score, showing that this measure is not a good sustainable transport policy. Therefore, the incentives to this mode must be associated with shared trips. In other words, it is important to increase the occupancy rate of these vehicles to reduce externalities.

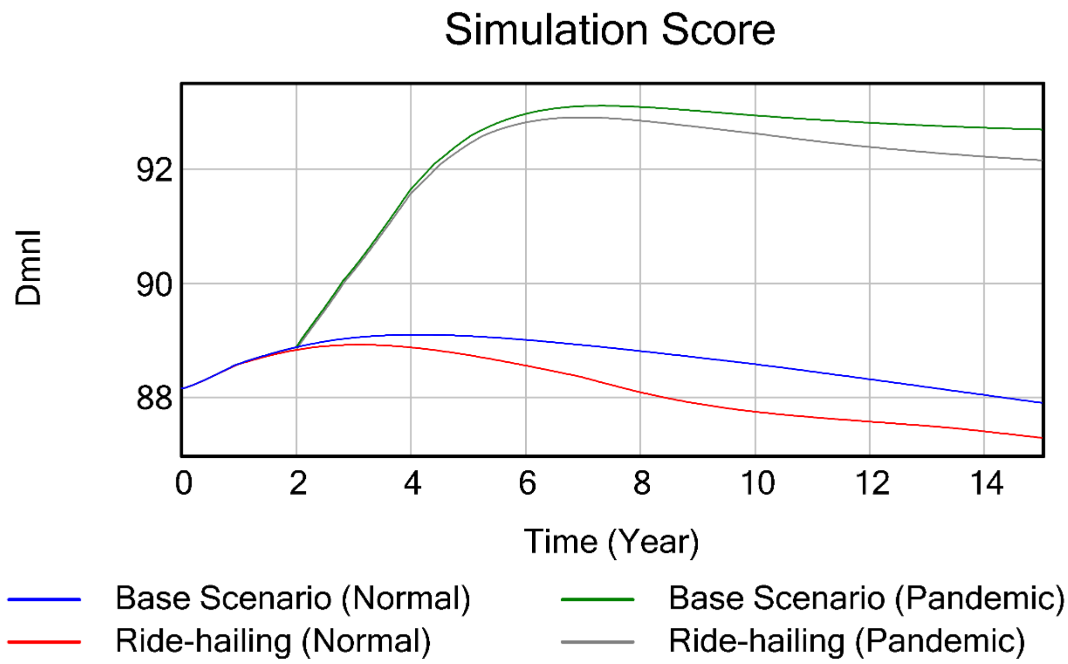


Figure 5.14 – Simulation Score in Scenario 6

### 5.5 Final remarks of the chapter

This chapter presented a System Dynamics model to evaluate the effects of sustainable transport policies, focusing on congestion and pollution. To achieve the objective of this study, the proposed model addresses several factors, including new modes of transport and road quality. In addition, the effects of the COVID-19 pandemic on travel demand were analyzed.

The results show the efficiency of policies in reducing urban transport externalities. Among the measures, encouraging high-capacity public transport stands out, as it reduces the number of vehicles on urban roads and, consequently, congestion and pollution. Regarding the policies to reduce the attractiveness of private transport, priority should be given to discouraging vehicle ownership.

Increasing transportation infrastructure is a measure that must be taken with caution, because, despite presenting a better score simulation, this scenario is expensive and it has the highest pollutant emission rate. Ride-hailing can provide practicality, security and comfort, becoming an attractive mode. However, this mode should be used in a conscious way. Therefore, shared trips with this mode should be encouraged, avoiding the exponential growth of vehicles on the roads.

Simulating the effects of COVID-19 pandemic highlighted the importance of transportation demand management, especially the ones to reduce and/or eliminate unnecessary travels. In this reality, the effects caused by the policies were very small when compared to the effects of changing travel demand. Therefore, the governments must rethink the urban configuration to change travel pattern and reduce the need of new trips.

Despite the results obtained, this study has some limitations. Therefore, it is suggested that future studies add more factors to determine the modes' attractiveness such as: safety, comfort, flexibility, among others. In addition, autonomous vehicles, non-motorized trips and the infrastructure for these modes should also be addressed.

In this model, we use the change in travel demand to simulate the effects of the COVID-19 pandemic. However, in addition to changing travel demand, the pandemic has impacted modes' attractiveness. During the pandemic, public transit usage reduced because contagion risk increases with the level of passenger occupancy in vehicles and stations. Consequently, private transport has become more attractive. Therefore, safety must be included in the formulation of mode attractiveness, allowing to determine the effects of COVID-19 pandemic on modal share.

Due to the numerous urban mobility problems faced by Brazilian cities, especially Rio de Janeiro, this study presents an important theme for the academic and governmental spheres. In addition, this study addressed the uncertain effects of new transportation services, which emerge daily and the COVID-19 pandemic.

# 6 CONCLUSIONS

The Brazilian Urban Mobility Policy (BUMP) establishes guidelines to improve accessibility and urban mobility in Brazilian cities. There are several studies in different fields to analyze the effects of this policy. However, it is noted that the few System Dynamics (SD) models that analyze the BUMP do not address fundamental aspects such as non-motorized transport, health, safety, land use efficiency, new technologies, among others. This thesis aimed to assess the impact of the BUMP using SD. For that, three SD models were developed, focusing on economic, environmental, social, traffic and land use variables. In addition, case studies were carried out in the city of Rio de Janeiro.

Chapters 3, 4 and 5 presented the three models proposed in this thesis. The first model (Chapter 3) stands out from the other SD models, as it presents the BUMP incentive for non-motorized transport. The model presented in Chapter 4 is an extension of the first model, addressing more factors related to BUMP such as health, land use, traffic safety, new technologies and noise pollution. Despite presenting similar results, the two models have different applications. The second model has more components and, consequently, it requires more data to carry out the simulation. As data collection can be difficult in some cities, the first model can be an option to effortlessly assess the BUMP effects. Finally, Chapter 5 presents the third model with a different structure from the first two. This model stands out for presenting the effects of new mobility services.

Dynamic simulation results show how BUMP measures can reduce the negative effects of transport, increasing the efficiency of urban transport systems. In addition to changing the travel pattern in Brazilian cities, the BUMP implementation improves land use, reducing travel distances and, consequently, congestion and air pollution.

The BUMP measures also reduce the number of hospitalizations and deaths. Therefore, this policy reduces the costs of the government, which is responsible for providing health services to the entire population. Despite not changing the congestion level, the results show that the use of electric vehicles reinforces measures to reduce the air pollution.

The results of this study highlight the factors that public managers should prioritize in the development of urban mobility plans. In addition, this study addressed current factors such as ride-hailing services, hybrid electric vehicles (HEVs) and the effects of the COVID-19 pandemic. These subjects are changing travel pattern around the world, being a current agenda among researchers and public managers. Thus, the models proposed in this study can be used to guide these discussions.

Besides the BUMP, new sustainable urban policies can be developed. However, these policies often fail to achieve their objectives due the complexity of several factors, such as environment, human behavior and the policy-making process. The proposed models can illustrate the sources of policy resistance in the system, allowing to overcome the issues to develop a new policy and help policymakers to find the best measure for a specific problem. Therefore, these models can be adapted and applied by the governments to improve urban transport systems and help the development of new public policies.

Despite showing the effects of the BUMP implementation, the proposed models have some limitations. They are complex and have several variables. Consequently, the dynamic simulations required huge data sets. However, we did not find all parameters. Then, we adopted some assumptions, such as the reduction of travel distance due to BUMP (percentage), the time to construct a road, the increase in investments due to congestion, among others. These assumptions were based on parameters for other countries and specialists. In addition, we performed tests, such as Monte Carlo experiment, which showed that the parameters estimation was robust.

In addition to the parameters, we make assumptions during model development. In Chapter 4, for example, BUMP's incentive for new technology is represented by HEVs. We chose this type of vehicle due to the tiny share of full electric vehicles (FEVs) in Brazil. However, encouraging FEVs would result in better results. Therefore, the model fails to compare and discuss these two types of vehicles, postponing the discussion for future studies. In Chapter 5, we considered that congestion and pollution have the same impact. However, the results shows that pollution has a larger impact in the system.

The proposed models consider only the motorized transport infrastructure (public and private), disregarding the infrastructure for non-motorized transport. In addition, there are other ways to quantify the social costs of urban transport systems besides safety and health. Therefore, we suggest that future studies address other factors, such as accessibility for people with limited mobility.

Given the above considerations, we also suggest that future studies improve the proposed models, focusing on their limitations. Therefore, new variables and sectors must be added to make them more realistic. In addition, new scenarios should be developed to verify more effects of this policy.

Given these limitations, this study takes a dynamic, feedback-rich, holistic and long-term approach, allowing to obtain comprehensive insights into a specific problem. Thus, the proposed models proved to be practicable and capable of capturing and measuring the effects of BUMP and they could be adapted to analyze any city around the world.

In addition to being tools for transport planning, the proposed models contribute to the literature, complementing the existing studies on the subject. Furthermore, it can be concluded that it is possible to achieve sustainable development and the externalities of transport systems are manageable and reversible through transport planning.

Finally, it is worth mentioning that this study has already resulted in several published papers. Most of these works are directly related to the subject of this thesis. In addition, studies related to other fields of Transportation Engineering were also developed. The scientific production resulting from this thesis are presented below:

- *Papers published in international journals*: Fontoura *et al.* (2019), Fontoura *et al.* (2020), Fontoura *et al.* (2022);
- *Papers under review*: Fontoura *et al.* (2023a) and Fontoura *et al.* (2023b);
- *Papers published in Brazilian journals*: Fontoura and Ribeiro (2021);
- *Papers published in Brazilian conferences*: Fontoura *et al.* (2019), Quadros *et al.* (2020) and Fontoura and Danielski (2022);
- *Abstracts published in Brazilian conferences*: Fontoura and Ribeiro (2019); and

In addition to these publications, this study received an award: The Fulbright-Hays Doctoral Dissertation Research Award (DDRA), provided by the Fulbright Commission Brazil. Thereby, part of this study was carried out in Department Social Science & Policy Studies at Worcester Polytechnic Institute (WPI), under the supervision of Professor Michael J. Radizicki. As a result, we developed the model presented in Chapter 5, which was submitted to a reputed journal in the field, Transportation Letters.

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## APPENDIX A – SYNTHESIS OF SYSTEMATIC LITERATURE REVIEW (SLR)

Table A.1 presents a synthesis of SLR, highlighting the main finds of each selected paper.

Table A.1. Synthesis of SLR

| Authors | Policies | Mode of Transport* | Sub-models** | Infrastructure | Simulation Time | Main Results |
|---|---|---|---|---|---|---|
| Yang and Chen (2000) | Exclusive Bus Lane; Free bus fare; Reschedule Bus Route Frequency in peak hours and off-peak hours; and compulsory Carpool | M | ECO, ENV, TC and TS | Not addressed | 1 day | Among the five policies, only compulsory carpool and bus fare compensation result in reducing both NOx and HC emissions |
| Wang *et al.* (2008) | Vehicle development | M | ECO, ENV and TC | Capacity | 50 years | The authors suggest restrict the use and the ownership of private vehicles |
| Bivona and Montemaggiore (2010) | Bus fleet maintenance policies | M | ENV | Not addressed | 1 year | The proposed model is an efficient tool to evaluate the sustainability of alternative strategies from a financial and customer satisfaction perspective. |
| Armah *et al.* (2010) | Government policy and planning; Travel demand management; and Supply management | M | ECO, ENV, SOC and TC | Capacity | Not performed | Proposed measures: development of a public transport system, road network expanding and enhancing and travel demand management alternatives |
| Han *et al.* (2010) | Promotion of more efficient vehicle's share; Extension of traffic network; Increase of Metro Rapid Transport Service (MRTS) passenger capacity; Increase of MRTS station number; Levy of fuel taxes; and decrease of fuel intensity | M | ECO and ENV | Capacity | 14 years | Accelerating the development of railway network is the most effective option. Decreasing the fuel intensity, slowing down road network extension and levying fuel taxes are also significant and useful policies for air pollution reduction. |
| Liu *et al.* (2010a) | Clean transportation; Bus priority; Subway priority; and Car trip restriction | NM and M | ECO, ENV and LU | Not addressed | 15 years | Pollutants, energy consumption and land demand for roads will exceed the capacity of Beijing in 2020, if nothing changes. The four policies have positive results, but the integration of the four measures shows better results |
| Liu *et al.* (2010b) | Congestion pricing policy | M | ECO and TC | Not addressed | Not performed | The proposed model allows for an initial qualitative evaluation of a congestion pricing policy that considers both the short-term and long-term effects |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

Table A.1. Synthesis of SLR

| Authors | Policies | Mode of Transport* | Sub-models** | Infrastructure | Simulation Time | Main Results |
|---|---|---|---|---|---|---|
| Bajracharya (2013) | Encouraging public transportation | M | ECO and TC | Not addressed | Not performed | The results highlight the need to design policies to encourage public transportation, reducing the large mass of car dependent population. |
| Bernardino and van der Hoofd (2013) | Parking policy | M | ECO, LU, TC and TS | Capacity | Unavailable data | The parking policy regulates the scarcity of parking and the traffic congestion. Thus, the system performs better, increasing the average speed in the network by up to 35% |
| Bisen *et al.* (2014) | Provision of pedestrian lane; User defined vehicle occupancy; Impact of telecommunication application; and Change in land use characteristics | NM and M | ECO, ENV, LU, TC and TS | Capacity | 20 years | Reduction of pollutant emissions and traffic congestion and increase of the average speed in the network |
| Guzman *et al.* (2014) | Road charge pricing policy | M | ECO, ENV, LU and TC | Not addressed | 30 years | Change in the modal split in radial trips. Speed increases and, consequently, the number of accidents also increases. Car travel has changed its destination pattern. Fuel consumption and pollutant emissions decreases |
| Li *et al.* (2014) | Land use management | M | ECO, ENV, LU and SOC | Not addressed | 5 years | The model has a good accuracy and can be used as the macro-scale model for estimating the aggregated urban land use demand |
| Sabounchi *et al.* (2014) | Congestion pricing policy | M | ECO and TC | Not addressed | 20 years | Congestion pricing scheme can effectively resolve congestion problems in short term but cannot be used as a policy to mitigate congestion in the long-term. |
| Cheng *et al.* (2015) | Fuel tax; Motorcycle parking management; and Free bus service | M | ECO, ENV, SOC and TC | Not addressed | 30 years | Fuel tax and motorcycle parking management policies are more efficient to restrict the growth of the number of cars, the fuel consumption and $CO_2$ emissions. However, fuel tax policy seems to be the most cost effective |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

Table A.1. Synthesis of SLR (Continued)

| Authors | Policies | Mode of Transport* | Sub-models** | Infrastructure | Simulation Time | Main Results |
|---|---|---|---|---|---|---|
| Haghshenas *et al.* (2015) | Increase in private infrastructure; Control of urban sprawl; Replacement of vehicles; Car sharing and carpooling; Travel demand management; Providing more mixed land use; and a set of policies to improve public and non-motorized transport | NM and M | ECO, ENV, LU, SOC and TS | Capacity | 13 years | Policy makers should prioritize the development of policies related to public and non-motorized transport infrastructure. In addition, they must prioritize the integration of modes with effective prices and control the use of cars |
| Liu *et al.* (2015b) | $CO_2$ emissions mitigation policy | NM and M | ECO, ENV and TS | Capacity | 25 years | Urban transport condition and $CO_2$ emissions would be more serious with the growth of vehicle ownership and travel demand. In addition, controlling the number of passenger cars the most effective measure to reduce $CO_2$ emissions |
| Wen *et al.* (2015) | Low-carbon policies | M | ECO and ENV | Not addressed | 13 years | Increasing the utilization of Liquefied Natural Gas vehicle (LNG) considerably reduces pollutant emissions. Vehicle quantity control helps to improve the sustainability of the transportation system |
| Yao and Chen (2015) | Increase the shares of public transit and expand the road capacity | M | ECO, ENV, LU and SOC | Capacity | 30 years | Increasing the shares of public transit reduces traffic congestion, while expanding the road capacity increases traffic congestion. |
| Ercan *et al.* (2016) | Public transportation policies; Alternative fuel options (public and private transport) | M | ECO, ENV and TC | Capacity | 60 years | The public policies must be supported by measures that are more aggressive. The prioritization of public transport and the improvements in the energy consumption of cars has the potential to reduce or even partially eliminate the current growth in $CO_2$ emissions |
| Macmillan *et al.* (2016) | Pro-cycling policies | NM and M | SOC | Capacity | 20 years | The model helps identifying effective policy levers to achieve sustained growth in cycling |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

Table A.1. Synthesis of SLR (Continued)

| Authors | Policies | Mode of Transport* | Sub-models** | Infrastructure | Simulation Time | Main Results |
|---|---|---|---|---|---|---|
| Alonso *et al.* (2017) | Cordon toll accompanied by public transport improvements; Teleworking; and Re-densification | M | ECO, ENV, LU, SOC, TC and TS | Capacity | 19 years | The three policies increase the efficiency of the system. However, teleworking is the most effective measure. Analyzing only energy consumption and pollution, re-densification showed better results |
| Caroleo *et al.* (2017) | Electric vehicles diffusion | M | ECO, ENV, NT and SOC | Not addressed | 15 years | The positive environmental performances attributed to the acceptance of EVs positively impact health, reducing public health expenditure and, consequently, freeing up resources that could become monetary incentives to further catalyze EVs. |
| Menezes *et al.* (2017) | Low-carbon policies | M | ENV | Not addressed | 30 years | Policies that promote the use of biofuels have the greatest potential to reduce pollutant emissions. The prioritization of public transport also stands out in reducing emissions |
| Procter *et al.* (2017) | Implementation of the Light Rail Transit (LRT) | M | ECO, ENV, LU and TC | Not addressed | 40 years | The implementation of the LRT will reduce emissions. Government targets on energy consumption will not be met without implementation |
| Barisa and Rosa (2018) | Promotion of public transport; Promotion of alternative fuel vehicles (AFVs); Promotion of vehicle fuel efficiency and the use of biofuels; Mode shift in passenger and freight transport. | M | ENV, NT, SOC and TC | Not addressed | 17 years | Improving the acceptance of public transport, implementation of a combined package of policies promoting alternative fuel vehicles and by improving the fuel efficiency and reducing the average age of the car stock are the measures that provide the best results. |
| Shen *et al.* (2018) | Strengthening urban road construction; Strengthening the public transport system; Limiting private cars | M | ECO and TC | Capacity | 10 years | The three policies are effective, but the authors emphasize the importance of implementing them simultaneously |
| Batur *et al.* (2019) | Supply management measures; Travel demand management (TDM) policies | M | ECO, ENV and LU | Not addressed | 10 years | Travel demand management based scenarios outperform supply management measures based scenarios. |
| Benvenutti *et al.* (2019) | Energy efficiency; Modal change and regulatory management; Renovation of the fleet; and biofuel increase. | M | ENV | Not addressed | 70 years | Energy efficiency and modal change policies are indicated as long-term strategies |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

Table A.1. Synthesis of SLR (Continued)

| **Authors** | **Policies** | **Mode of Transport*** | **Sub-models**** | **Infrastructure** | **Simulation Time** | **Main Results** |
|---|---|---|---|---|---|---|
| Fontoura *et al.* (2019) | Brazilian Urban Mobility Policy (BUMP) | M | ECO, ENV and TC | Capacity | 30 years | The BUMP implementation improves the share of public transit and reduces the pollutant emissions and traffic congestion. Besides that, the results show the importance of rideshare |
| Papageorgiou (2019) | Walking Mindset Strategies | NM | SOC | Not addressed | 10 years | Changing mindsets effectively requires an awareness strategy, which should be reinforced with the use of an Information and Communication Technology (ICT) |
| Papageorgiou and Demetriou (2019) | Public awareness of the sustainable habits | NM | SOC | Not addressed | 10 years | Social learning and motivation to change behaviors are effective in promoting sustainable active mobility. The introduction of Information and Communication Technology accelerates the shaping and diffusion of a walking mindset |
| Asasuppakit and Thieng-buranathum (2020) | Encouraging electric motorcycle and eco-car | NM and M | ECO, ENV and NT | Capacity | 30 years | The results show that the best measure is to reduce half of the growth rate of the motorcycle by electric motorcycle and to reduce half of the growth rate of the personal car by eco-car, reducing $CO_2$ emissions in 32.04%. |
| Emberger and Pfaffenbichler (2020) | Encouraging private Automatic Vehicles (AV), car-sharing-AV, ride-sharing-AV and public transport-AV | NM and M | ECO, ENV, LU, NT and TC | Capacity | 30 years | Automation will likely have a negative impact on the use of active and public modes of transport. In addition, the negative impacts of AV will occur if no mitigation policies are adopted. |
| Esfandabadi *et al.* (2020) | Car sharing services growth policy | M | ENV, NT SOC and TC | Capacity | Not performed | The proposed framework can help environment policy makers and shared mobility practitioners in long-term strategic decision-making |
| Fontoura *et al.* (2020) | Brazilian Urban Mobility Policy (BUMP) | NM and M | ECO, ENV and TC | Capacity | 32 years | The BUMP implementation reduces the negative externalities and, consequently, increases the efficiency of the urban transport system |
| Hu *et al.* (2020) | Urban passenger rail transit network (URFT) development | M | ECO, ENV, TA and TC | Not addressed | 28 years | URFT schemes with higher funding and capacity reduces traffic congestion, pollutant emissions and the number of accidents |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

Table A.1. Synthesis of SLR (Continued)

| Authors | Policies | Mode of Transport* | Sub-models** | Infrastructure | Simulation Time | Main Results |
|---|---|---|---|---|---|---|
| Keith *et al.* (2020) | Alternative fuel vehicles; Hybrid-electric vehicles; and Battery electric vehicles | M | ENV | Not addressed | 30 years | In order to obtain a low carbon transportation sector, it is necessary to integrate long-term policies, considering the different vehicles fuels, as well as vehicle platforms and their interactions |
| Khosravi *et al.* (2020) | Transport demand management policies | NM and M | ECO, ENV, TC and TS | Capacity | 10 years | The results show that completing metro network development simultaneously with cordon pricing has been the most effective combined policy to decrease air pollution and energy consumption and to increase traffic mobility in future. |
| Luna *et al.* (2020) | E-carsharing growth policy; and Retirement policy for conventional vehicles | M | ECO, ENV and NT | Not addressed | 40 years | E-carsharing reduces emissions and increases awareness of electric vehicles. The combination of the two policies presents the best results for reducing emissions and increasing electric vehicle adoption |
| Singh and Shukla (2020) | Encouraging public transport | M | ENV | Not addressed | 12 years | The results indicated a significant reduction in fuel consumption and fuel emission levels. In addition, the increase in public transport and restriction in private transport may be implemented on a pilot basis. |
| Wang *et al.* (2021) | Carsharing demand control (Incentives and surcharges) | M | NT | Not addressed | 1 day | The proposed method can increase revenues by 22.5% compared to a scenario without demand control and vehicle relocation policies. In addition, the proposed demand-based control policy can achieve higher revenues than operator-based relocation, whereas operator-based relocation could satisfy greater demand. |
| Tonini *et al.* (2021) | Brazilian Urban Mobility Policy (BUMP) | M | SOC and TC | Capacity | 30 years | The BUMP implementation is not sufficient to reverse the current modal share. The users' desire to own and use cars is a key point which needs to be addressed by more instruments to transform policy efforts into changes in user behavior. |
| Chen *et al.* (2022) | Driving restriction and purchase restriction | M | ECO, ENV and TC | Capacity | 30 years | The results show that the combination of public-transport development and driving-restriction policy is the most effective scenario to reduce traffic congestion, air pollution, improving air quality health |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

Table A.1. Synthesis of SLR (Continued)

| Authors | Policies | Mode of Transport* | Sub-models** | Infrastructure | Simulation Time | Main Results |
|---|---|---|---|---|---|---|
| Fontoura *et al.* (2022) | Brazilian Urban Mobility Policy (BUMP) | NM and M | ECO, ENV and TC | Capacity | 32 years | The BUMP implementation reduces the externalities in megacities. However, for some variables, this reduction occurred differently for each megacity. |
| Hu *et al.* (2022) | The long-term development and operating status of a city-wide the urban underground logistics system (ULS) project. | M | ECO, ENV, LU, TA and TC | Capacity | 25 years | ULS has significant competence with respect to service capacity and profitability, while enabling billions of dollars of external cost-saving annually. |
| Zhang (2022) | Control traffic congestion | M | LU and TC | Capacity | Not performed | The model is effective to test and find out the most reasonable and sustainable measures to control traffic congestion |

*NM = Non-motorized; M = motorized. **ECO = Economy; ENV = Environmental; LU = Land Use; NT = New Technologies; SOC = Social; TA = Traffic Accidents; TC = Traffic Congestion; TS = Traffic Speed.

## APPENDIX B – EQUATIONS OF CHAPTER 5

Table B.1 lists all variables present in the model, classifying the by type (stock, flow and auxiliary) and presenting their equations and units.

Table B.1. Variables

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | Population | Stock | $Population = \int_{t_0}^{t} (Population\ Growth)dt + Initial\ Population$ | People |
| | Change in Population | Flow | $Change\ in\ Population = Population \times Population\ Growth\ Fraction$ | $\frac{People}{Year}$ |
| | Population Growth Fraction | Auxiliary | $Change\ in\ Population = Normal$ Population $Growth\ Fraction \times Effect\ of\ Negative\ Externalities$ | $\frac{1}{Year}$ |
| | Effect of Negative Externalities | Auxiliary | $(\frac{Simulation\ Score^{-1}}{Initial\ Simulation\ Score^{-1}})^{\gamma}$ | Dimensionless |
| | Desired Trips | Auxiliary | $Desired\ Trips = Population \times Desired\ Trips\ per\ Year\ per\ Person$ | $\frac{Trip}{Year}$ |
| | Desired Ride-hailing Trips | Auxiliary | $Desired\ Ride-hailing\ Trips = \frac{Allocation\ of\ Demand\ Among\ Modes\ of\ Transportation\ (Ride-hailing)}{Average\ Occupancy\ Rate\ (Ride-hailing)}$ | $\frac{Ride-hailing\ Trip}{Year}$ |
| | Allocation of Demand Among Modes of Transportation (Ride-hailing) | Auxiliary | $Allocation\ of\ Demand\ Among\ Modes\ (Ride-hailing) = \left[\frac{EXP(Relative\ Attractiveness\ (Ride-hailing))}{\sum_{j=1}^{5} EXP(Relative\ Attractiveness\ (j))}\right] \times (1 - Other\ Modes\ Share)$<br>Where j (1 = Ride-hailing, 2 = Car; 3 = Bus; 4 = Subway, 5 = Train) | Dimensionless |
| | Unique Trips Possible per Year (Ride-hailing) | Auxiliary | $Unique\ Trips\ Possible\ per\ Year\ (Ride-hailing) = \frac{Drivers \times Working\ Time\ per\ Driver}{Average\ Time\ per\ Trip + Time\ to\ Pickup\ Passenger}$ | $\frac{Ride-hailing\ Trip}{Year}$ |
| | Supply-Demand Balance | Auxiliary | Supply-Demand Balance = ZIDZ (Expected Ride-hailing Trips, Unique Trips Possible per Year (Ride-hailing)) | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | Ride-hailing Trips | Auxiliary | Ride-hailing Trips = IF THEN ELSE (Expected Ride-hailing Trips < = Unique Trips Possible per Year (Ride-hailing), Expected Ride-hailing Trips, Unique Trips Possible per Year (Ride-hailing)) | $\frac{Ride - hailing\ Trip}{Year}$ |
| | Dynamic Pricing | Auxiliary | Dynamic Price = WITH LOOKUP (Supply-Demand Balance, ([(0,0)-(10,10)],(0,1),(0.5,1),(0.9,1),(1,1),(1.1,1.05),(1.2,1.1),(1.3,1.15),(1.4,1.2),(1.5,1.25),(1.6,1.3),(1.7,1.35),(1.8,1.4),(1.9,1.45),(2,1.5))) | Dimensionless |
| | Average Trip Cost (Ride-hailing) | Auxiliary | $Average\ Trip\ Cost\ (Ride - hailing) = [Fixed\ Fare + (Price\ per\ Kilometer \times Average\ Trip\ Distance\ (Ride - hailing)) + (Price\ per\ Minute \times Average\ Time\ Per\ Trip\ (Ride - hailing))] \times Dynamic\ Pricing$ | $\frac{\$}{Ride - hailing\ Trip}$ |
| | Fixed Fare | Stock | $Fixed\ Fare = \int_{t_0}^{t} (Change\ in\ Fixed\ Fare)\mathrm{dt} + Initial\ Fixed\ Fare$ | $\frac{\$}{Ride - hailing\ Trip}$ |
| | Change in Fixed Fare | Flow | $Change\ in\ Fixed\ Fare = Fixed\ Fare\ Adjustment \times Fixed\ Fare$ | $\frac{\$}{Ride - hailing\ Trip \times Year}$ |
| | Price per Minute | Stock | $Price\ per\ Minute = \int_{t_0}^{t} (Change\ in\ Price\ per\ Minute)\mathrm{dt} + Initial\ Price\ per\ Minute$ | $\frac{\$}{Minute}$ |
| | Change in Price per Minute | Flow | $Change\ in\ Price\ per\ Minute = Price\ per\ Minute\ Adjustment \times Price\ per\ Minute$ | $\frac{\$}{Minute \times Year}$ |
| | Price per Kilometer | Stock | $Price\ per\ Minute = \int_{t_0}^{t} (Change\ in\ Price\ per\ Kilometer)\mathrm{dt} + Initial\ Price\ per\ Kilometer$ | $\frac{\$}{Kilometer}$ |
| | Change in Price per Kilometer | Flow | $Change\ in\ Price\ per\ Kilometer = Price\ per\ Kilometer\ Adjustment \times Price\ per\ Kilometer$ | $\frac{\$}{Kilometer \times Year}$ |
| | Average Time per Trip (Ride-hailing) | Stock | $Average\ Time\ per\ Trip\ (Ride - hailing) = \int_{t_0}^{t} (\text{Change in Average Time per Trip (Ride} - \text{hailing))dt} + Initial\ Average\ Travel\ Time\ Per\ Trip\ (Ride - hailing)$ | $\frac{Minute}{Ride - hailing\ Trip}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | Change in Average Time per Trip (Ride-hailing) | Flow | $Change\ in\ Average\ Time\ per\ Trip\ (Ride-hailing) = \frac{Indicate\ Average\ Travel\ Time\ Per\ Trip\ (Ride-hailing) - Average\ Time\ Per\ Trip\ (Ride-hailing)}{Time\ to\ Change\ Average\ Time\ per\ Trip\ (Ride-hailing)}$ | $\frac{Minute}{Ride-hailing\ Trip \times Year}$ |
| | Indicate Average Travel Time per Trip (Ride-hailing) | Auxiliary | $\text{Indicate Average Travel Time Per Trip (Ride − hailing)} = Initial\ Average\ Travel\ Time\ Per\ Trip\ (Ride-hailing) \times Effect\ of\ Congestion\ on\ Trip\ Time \times Effect\ of\ Road\ System\ Quality\ on\ Trip\ Time$ | $\frac{Minute}{Ride-hailing\ Trip}$ |
| | Time to Pick up Passenger | Stock | $Time\ to\ Pick\ up\ Passenger = \int_{t_0}^{t} (\text{Change in } Time\ to\ Pick\ up\ Passenger)dt + Initial\ Time\ to\ Pick\ up\ Passenger$ | $\frac{Minute}{Ride-hailing\ Trip}$ |
| | Change in Time to Pick up Passenger | Flow | $Change\ in\ Time\ to\ Pick\ up\ Passenger = \frac{Indicate\ Time\ to\ Pick\ up\ Passenger - Time\ to\ Pick\ up\ Passenger}{Time\ to\ Change\ Time\ to\ Pick\ up\ Passenger}$ | $\frac{Minute}{Ride-hailing\ Trip \times Year}$ |
| | Indicate Time to Pick up Passenger | Auxiliary | $\text{Indicate Time to Pick up Passenger} = Initial\ Time\ to\ Pick\ up\ Passenger \times Effect\ of\ Congestion\ on\ Trip\ Time \times Effect\ of\ Road\ System\ Quality\ on\ Trip\ Time$ | $\frac{Minute}{Ride-hailing\ Trip}$ |
| | Perceived Time per Trip (Ride-hailing) | Stock | $Perceived\ Time\ per\ Trip\ (Ride-hailing) = \int_{t_0}^{t} \left(\text{Change in } Perceived\ Time\ per\ Trip\ (Ride-hailing)\right)dt + Initial\ Perceived\ Time\ per\ Trip\ (Ride-hailing)$ | $\frac{Minute}{Ride-hailing\ Trip}$ |
| | Initial Perceived Time Per Trip (Ride-hailing) | Auxiliary | $Initial\ Perceived\ Time\ Per\ Trip\ (Ride-hailing) = Initial\ Average\ Travel\ Time\ Per\ Trip\ (Ride-hailing) + Normal\ Waiting\ Time\ per\ Trip\ (Ride-hailing)$ | $\frac{Minute}{Ride-hailing\ Trip}$ |
| | Change in Perceived Time (Ride-hailing) | Flow | $Change\ in\ Perceived\ Time\ (Ride-hailing) = \frac{Total\ Trip\ Time\ (Ride-hailing) - Perceived\ Time\ per\ Trip\ (Ride-hailing)}{Time\ to\ Change\ Perceived\ Time\ (Ride-hailing)}$ | $\frac{Minute}{Ride-hailing\ Trip \times Year}$ |
| | Total Trip Time (Ride-hailing) | Auxiliary | $Total\ Trip\ Time\ (Ride-hailing) = Average\ Time\ Per\ Trip\ (Ride-hailing) + Waiting\ Time\ (Ride-hailing)$ | $\frac{Minute}{Ride-hailing\ Trip}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | Waiting Time (Ride-hailing) | Auxiliary | $\text{Waiting Time (Ride} - \text{hailing)} = Normal\ Waiting\ Time\ per\ Trip\ (Ride - hailing) \times Effect\ of\ Congestion\ on\ Trip\ Time \times Effect\ of\ Supply - Demand\ Balance\ on\ Average\ Waiting\ Time\ per\ Trip \times Effect\ of\ Road\ System\ Quality\ on\ Trip\ Time$ | $\frac{Minute}{Ride - hailing\ Trip}$ |
| | Effect of Supply-Demand Balance on Average Waiting Time per Trip | Auxiliary | Effect of Supply-Demand Balance on Average Waiting Time per Trip = WITH LOOKUP (Supply-Demand Balance, ([(0,0)-(10,10)],(0,1),(0.5,1),(0.9,1.02),(0.98017,1.03409),(1.06516,1.07955),(1.12748,1.11364),(1.21813,1.21591),(1.33196,1.34091),(1.43918,1.47727),(1.54227,1.59091),(1.64536,1.72727),(1.7567,1.89773),(1.85567,2.125),(2,2.5)) ) | Dimensionless |
| | Perceived Price (Ride-hailing) | Stock | $Perceived\ Price\ (Ride - hailing) = \int_{t_0}^{t} (\text{Change in } Perceived\ Price\ (Ride - hailing))\text{dt} + Initial\ \ Perceived\ Price\ (Ride - hailing)$ | $\frac{\$}{Ride - hailing\ Trip}$ |
| | Change in Perceived Price (Ride-hailing) | Flow | $Change\ in\ Perceived\ Price\ (Ride - hailing) = \frac{Average\ Trip\ Cost\ (Ride - hailing) - Perceived\ Price\ (Ride - hailing)}{Time\ to\ Change\ Perceive\ Price\ (Ride - hailing)}$ | $\frac{\$}{Ride - hailing\ Trip \times Year}$ |
| | Relative Attractiveness of Ride-hailing | Auxiliary | $Relative\ Attractiveness\ of\ Ride - hailing = U1\ (Ride - hailing) + U2\ (Ride - hailing)$ | Dimensionless |
| | U1 (Ride-hailing) | Auxiliary | $U1\ (Ride - hailing) = Coef\ 1\ (Ride - hailing) \times \left(\frac{Perceived\ Time\ Per\ Trip\ (Ride - hailing)}{Initial\ Perceived\ Time\ Per\ Trip\ (Ride - hailing)}\right)$ | Dimensionless |
| | U2 (Ride-hailing) | Auxiliary | $U2\ (Ride - hailing) = Coef\ 2\ (Ride - hailing) \times \left(\frac{Perceived\ Price\ (Ride - hailing)}{Initial\ Perceived\ Price\ (Ride - hailing)}\right)$ | Dimensionless |
| | Drivers Recruited | Stock | $Drivers\ Recruited = \int_{t_0}^{t} (\text{Potential Drivers} - \text{New Drivers})\text{dt} + Initial\ \ Drivers\ Recruited$ | Driver |
| | Potential Drivers | Flow | $Potential\ Drivers = MAX(\ 0, Correction\ for\ Drivers + Correction\ For\ Drivers\ Recruited + Average\ Drivers\ Leaving)$ | $\frac{Driver}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | New Drivers | Flow | $New\ Drivers = \frac{Drivers\ Recruited}{Normal\ New\ Drivers\ Recruiment\ Time}$ | $\frac{Driver}{Year}$ |
| | Drivers | Stock | $Drivers = \int_{t_0}^{t} (\text{New Drivers} - \text{Drivers Leaving the Service})\text{dt} + Initial\ \ Drivers$ | Driver |
| | Drivers Leaving the Service | Flow | $Drivers\ Leaving\ the\ Service = \frac{Drivers}{Drivers\ Stay\ Time}$ | $\frac{Driver}{Year}$ |
| | New Drivers Recruitment Time | Auxiliary | $New\ Drivers\ Recruitment\ Time = ZIDZ(\ Drivers\ Recruited, New\ Drivers\ )$ | Year |
| | Drivers Leaving Time | Auxiliary | $Drivers\ Leaving\ Time =\ ZIDZ(\ Drivers, Drivers\ Leaving\ the\ Service\ )$ | Year |
| | Initial Drivers Recruited | Auxiliary | $Initial\ Drivers\ Recruited = Desired\ Drivers\ Recruited$ | Driver |
| | Desired Drivers Recruited | Auxiliary | $Desired\ Drivers\ Recruited = Average\ Drivers\ Leaving \times Normal\ New\ Drivers\ Recruiment\ Time$ | Driver |
| | Average Drivers Leaving | Stock | $Average\ Drivers\ Leaving = \int_{t_0}^{t} (\text{Change in Average Drivers Leaving})\text{dt} + Initial\ \ Average\ Drivers\ Leaving$ | $\frac{Driver}{Year}$ |
| | Change in Average Drivers Leaving | Flow | $Change\ in\ Average\ Drivers\ Leaving = \frac{Drivers\ Leaving\ the\ Service - Average\ Drivers\ Leaving}{Time\ to\ Change\ Average\ Drivers\ Leaving\ the\ Service}$ | $\frac{Driver}{Year \times Year}$ |
| | Initial Average Drivers Leaving | Auxiliary | $Initial\ Average\ Drivers\ Leaving =\ Drivers\ Leaving\ the\ Service$ | $\frac{Driver}{Year}$ |
| | Correction For Drivers Recruited | Auxiliary | $Correction\ For\ Drivers\ Recruited = \frac{Desired\ Drivers\ Recruited\ -\ Drivers\ Recruited}{Time\ to\ Drivers\ Recruited}$ | $\frac{Driver}{Year}$ |
| | Correction for Drivers | Auxiliary | $Correction\ for\ Drivers = \frac{Desired\ Drivers - Drivers}{Time\ to\ Correct\ Drivers}$ | $\frac{Driver}{Year}$ |
| | Desired Drivers | Auxiliary | $Desired\ Drivers = \frac{Expected\ Ride - hailing\ Trips}{Max\ Trips\ per\ Drivers}$ | Driver |
| | Max Trips per Drivers | Auxiliary | $Max\ Trips\ per\ Drivers = \frac{Unique\ Trips\ Possible\ per\ Year\ (Ride - hailing)}{Drivers}$ | $\frac{Ride - hailing\ Trip}{Driver\ \times Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | Correction for Trend in Desired Ride-hailing Trips | Auxiliary | $Correction\ for\ Trend\ in\ Desired\ Ride-hailing\ Trips = Drivers \times Indicated\ Trend\ in\ Ride-hailing\ Trips$ | $\frac{Driver}{Year}$ |
| | Indicated Trend in Ride-hailing Trips | Auxiliary | $Indicated\ Trend\ in\ Ride-hailing\ Trips = TREND\ (Perceived\ Ride-hailing\ Trips, Time\ to\ Form\ Trend\ in\ Desired\ Ride-Hailing\ Trips, Initial\ Perceived\ Trend\ in\ Ride-hailing\ Trips)$ | $\frac{1}{Year}$ |
| | Initial Perceived Ride-hailing Trips | Auxiliary | $Initial\ Perceived\ Ride-hailing\ Trips = Initial\ Desired\ Ride-hailing\ Trips \times (1 + Time\ to\ Change\ Perceived\ Ride-hailing\ Trips \times Initial\ Perceived\ Trend\ in\ Ride-hailing\ Trips)^{-1}$ | $\frac{Ride-hailing\ Trip}{Year}$ |
| | Perceived Ride-hailing Trips | Stock | $Perceived\ Ride-hailing\ Trips = \int_{t_0}^{t} (\text{Change in Perceived Ride} - \text{hailing Trips})dt + Initial\ Perceived\ Ride-hailing\ Trips$ | $\frac{Ride-hailing\ Trip}{Year}$ |
| | Change in Perceived Ride-hailing Trips | Flow | $Change\ in\ Perceived\ Ride-hailing\ Trips = \frac{Desired\ Ride-hailing\ Trips - Perceived\ Ride-hailing\ Trips}{Time\ to\ Change\ Perceived\ Ride-hailing\ Trips}$ | $\frac{Ride-hailing\ Trip}{Year \times Year}$ |
| | Expected Ride-hailing Trips | Auxiliary | $Expected\ Ride-hailing\ Trips = Perceived\ Ride-hailing\ Trips \times (1 + Indicated\ Trend\ in\ Ride-hailing\ Trips \times (Time\ to\ Change\ Perceived\ Ride-hailing\ Trips + Time\ Horizon\ for\ Expectations))$ | $\frac{Ride-hailing\ Trip}{Year}$ |
| | Ride-hailing Revenue | Auxiliary | $Ride-hailing\ Revenue = Average\ Trip\ Cost\ (Ride-hailing) \times Ride-hailing\ Trips$ | $\frac{\$}{Year}$ |
| | Total Driver's Payment | Auxiliary | $Total\ Driver's\ Payment = Ride-hailing\ Revenue \times (1 - Ride-hailing\ Company\ Percentage)$ | $\frac{\$}{Year}$ |
| | Driver's Profit | Auxiliary | $Driver's\ Profit = \frac{Total\ Driver's\ Payment - Total\ Driver's\ Expenses}{Drivers}$ | $\frac{\$}{Driver \times Year}$ |
| | Total Driver's Expenses | Auxiliary | $Total\ Driver's\ Expenses = Driver's\ Fixed\ Costs + ((Average\ Trip\ Distance\ (Ride-hailing) \times Additional\ Distance) \times Fuel\ Consumed\ per\ Kilometer\ (Ride-hailing) \times Fuel\ Price \times Ride-hailing\ Trips)$ | $\frac{\$}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Ride-hailing | Driver's Fixed Costs | Stock | $Driver's\ Fixed\ Costs = \int_{t_0}^{t} (\text{Change in } Driver's\ Fixed\ Costs)dt + Initial\ \ Driver's\ Fixed\ Costs$ | $\frac{\$}{Year}$ |
| | Change in Driver's Fixed Costs | Flow | $Change\ in\ Driver's\ Fixed\ Costs = Driver's\ Fixed\ Costs\ Adjustment \times Driver's\ Fixed\ Costs$ | $\frac{\$}{Year \times Year}$ |
| | Fuel Price | Stock | $Fuel\ Price = \int_{t_0}^{t} (\text{Change in } Fuel\ Price)dt + Initial\ \ Fuel\ Price$ | $\frac{\$}{Liter}$ |
| | Change in Fuel Price | Flow | $Change\ in\ Fuel\ Price = Fuel\ Price \times Fuel\ Price\ Adjustment$ | $\frac{\$}{Liter \times Year}$ |
| | Annual Minimum Wage | Stock | $Annual\ Minimum\ Wage = \int_{t_0}^{t} (\text{Change in } Annual\ Minimum\ Wage)dt + Initial\ \ Annual\ Minimum\ Wage$ | $\frac{\$}{Driver \times Year}$ |
| | Change in Minimum Wage | Flow | $Change\ in\ Minimum\ Wage = Annual\ Minimum\ Wage \times Wage\ adjustment$ | $\frac{\$}{Driver \times Year\ \times Year}$ |
| | Salary Ratio | Auxiliary | $Salary\ Ratio = \frac{Driver's\ Profit}{Annual\ Minimum\ Wage}$ | Dimensionless |
| | Effect of Salary on Leaving Fraction | Auxiliary | $Effect\ of\ Salary\ on\ Leaving\ Fraction = WITH\ LOOKUP$(Salary Ratio, ([(0,0)-(10,10)],(-1,0.25),(-0.813031,0.257576),(-0.542268,0.287879),(-0.294845,0.378788),(-0.0651558,0.560606),(0.13881,0.712121),(0.31134,0.848485),(0.571134,0.939394),(0.793814,0.969697),(1,1),(1.26062,1),(1.5,1),(1.51,1.00758),(1.73654,1.02273),(1.9745,1.0303),(2.20412,1.06061),(2.40206,1.09091),(2.64948,1.12121),(2.84742,1.18182),(2.99588,1.30303),(3.1567,1.51515),(3.31753,1.83333),(3.49072,2.13636),(3.63918,2.43939),(3.73814,2.74242),(3.8102,3),(3.86186,3.21212),(3.92918,3.4697),(4.15014,3.75758),(4.4051,3.93939),(4.70309,3.9697),(5,4) )) | Dimensionless |
| | Drivers Stay Time | Auxiliary | $Drivers\ Stay\ Time = Normal\ Drivers\ Stay\ Time \times Effect\ of\ Salary\ on\ Leaving\ Fraction$ | Year |
| Bus | Desired Bus Trips | Auxiliary | $Desired\ Bus\ Trips = \frac{Trips\ to\ be\ allocated\ to\ Bus}{Average\ Occupancy\ Rate\ (Bus)}$ | $\frac{Bus\ Trip}{Year}$ |
| | Average Occupancy Rate (Bus) | Auxiliary | $Average\ Occupancy\ Rate\ (Bus) = MIN(Max.Occupancy\ Rate\ (Bus), (\frac{Trips\ to\ be\ allocated\ to\ Bus}{Unique\ Trips\ Possible\ per\ Year\ (Bus)}))$ | $\frac{Trip}{Bus\ Trip}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Bus | Trips to be allocated to Bus | Auxiliary | $Trips\ to\ be\ allocated\ to\ Bus = Desired\ Trips \times Allocation\ of\ Demand\ Among\ Modes\ of\ Transportation\ (Bus)$ | $\frac{Trip}{Year}$ |
| | Allocation of Demand Among Modes of Transportation (Bus) | Auxiliary | $Allocation\ of\ Demand\ Among\ Modes\ (Bus) = \left[\frac{EXP(Relative\ Attractiveness\ (Bus))}{\sum_{j=1}^{5} EXP(Relative\ Attractiveness\ (j))}\right] \times (1 - Other\ Modes\ Share)$ <br> Where j (1 = Ride-hailing, 2 = Car; 3 = Bus; 4 = Subway, 5 = Train) | Dimensionless |
| | Relative Attractiveness of Bus | Auxiliary | $Relative\ Attractiveness\ of\ Bus = \text{U1 (Bus) + U2 (Bus)}$ | Dimensionless |
| | U1 (Bus) | Auxiliary | $U1\ (Bus) = Coef\ 1\ (Bus) \times (\frac{Perceived\ Time\ Per\ Trip\ (Bus)}{Initial\ Perceived\ Time\ Per\ Trip\ (Bus)})$ | Dimensionless |
| | Initial Perceived Time Per Trip (Bus) | Auxiliary | $Initial\ Perceived\ Time\ Per\ Trip\ (Bus) = Initial\ Average\ Time\ per\ Trip\ (Bus) + Normal\ Waiting\ Time\ per\ Trip\ (Bus)$ | $\frac{Minute}{Bus\ Trip}$ |
| | Perceived Time Per Trip (Bus) | Stock | $Perceived\ Time\ Per\ Trip\ (Bus) = \int_{t_0}^{t} (\text{Change in } Perceived\ Time\ (Bus))dt + Initial\ Perceived\ Time\ Per\ Trip\ (Bus)$ | $\frac{Minute}{Bus\ Trip}$ |
| | Change in Perceived Time (Bus) | Flow | $Change\ in\ Perceived\ Time\ (Bus) = \frac{Total\ Trip\ Time\ (Bus) - Perceived\ Time\ Per\ Trip\ (Bus)}{Time\ to\ Change\ Perceived\ Time\ (Bus)}$ | $\frac{Minute}{Bus\ Trip \times Year}$ |
| | Total Trip Time (Bus) | Auxiliary | $Total\ Trip\ Time\ (Bus) = Average\ Time\ Per\ Trip\ (Bus) + Waiting\ Time\ (Bus)$ | $\frac{Minute}{Bus\ Trip}$ |
| | Waiting Time (Bus) | Auxiliary | $Waiting\ Time\ (Bus) = Normal\ Waiting\ Time\ per\ Trip\ (Bus) \times Effect\ of\ Congestion\ on\ Trip\ Time \times Effect\ of\ Road\ System\ Quality\ on\ Trip\ Time \times Effect\ of\ Average\ Occupancy\ Rate\ (Bus)$ | $\frac{Minute}{Bus\ Trip}$ |
| | Effect of Average Occupancy Rate (Bus) | Auxiliary | $Effect\ of\ Average\ Occupancy\ Rate\ (Bus) = WITH\ LOOKUP(\frac{Average\ Occupancy\ Rate\ (Bus)}{Max.Occupancy\ Rate\ (Bus)},$ ([(0,0)-(10,10)],(0,1),(0.7,1),(0.75,1),(0.8017,1.00455),(0.841237,1.01818),(0.874227,1.04091),(0.909278,1.06818),(0.940028,1.08636),(0.970711,1.09545),(1,1.1) )) | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Bus | Average Time Per Trip (Bus) | Stock | $Average\ Time\ Per\ Trip\ (Bus) = \int_{t_0}^{t} (\text{Change in } Average\ Time\ per\ Trip\ (Bus))dt + Initial\ Average\ Time\ per\ Trip\ (Bus)$ | $\frac{Minute}{Bus\ Trip}$ |
| | Change in Average Time per Trip (Bus) | Flow | $Change\ in\ Average\ Time\ per\ Trip\ (Bus) = \frac{Indicate\ Average\ Time\ per\ Trip\ (Bus) - Average\ Time\ Per\ Trip\ (Bus)}{Time\ to\ Change\ Average\ Time\ per\ Trip\ (Bus)}$ | $\frac{Minute}{Bus\ Trip \times Year}$ |
| | Indicate Average Time per Trip (Bus) | Auxiliary | $Indicate\ Average\ Time\ per\ Trip\ (Bus) = Initial\ Average\ Time\ per\ Trip\ (Bus) \times Effect\ of\ Congestion\ on\ Trip\ Time \times Effect\ of\ Road\ System\ Quality\ on\ Trip\ Time \times Effect\ of\ Average\ Occupancy\ Rate\ (Bus)$ | $\frac{Minute}{Bus\ Trip}$ |
| | U2 (Bus) | Auxiliary | $U2\ (Bus) = (\frac{Perceived\ Price\ (Bus)}{Initial\ Perceived\ Price\ (Bus)}) \times Coef\ 2\ (Bus)$ | Dimensionless |
| | Perceived Price (Bus) | Stock | $Perceived\ Price\ (Bus) = \int_{t_0}^{t} (\text{Change in } Perceived\ Price\ (Bus))dt + Initial\ Perceived\ Price\ (Bus)$ | $\frac{\$}{Bus\ Trip}$ |
| | Change in Perceived Price (Bus) | Flow | $Change\ in\ Perceived\ Price\ (Bus) = \frac{Bus\ Fare - Perceived\ Price\ (Bus)}{Time\ to\ Change\ Perceived\ Price\ (Bus)}$ | $\frac{\$}{Bus\ Trip \times Year}$ |
| | Initial Perceived Price (Bus) | Auxiliary | $\text{Initial Perceived Price (Bus)} = Initial\ Bus\ Fare$ | $\frac{\$}{Bus\ Trip}$ |
| | Bus Fare | Stock | $Bus\ Fare = \int_{t_0}^{t} (\text{Change in } Bus\ Fare)dt + Initial\ Bus\ Fare$ | $\frac{\$}{Bus\ Trip}$ |
| | Change in Bus Fare | Flow | $Change\ in\ Bus\ Fare = Bus\ Fare\ Adjustment \times Bus\ Fare$ | $\frac{\$}{Bus\ Trip \times Year}$ |
| | Bus Trips | Auxiliary | $Bus\ Trips = IF\ THEN\ ELSE(Expected\ Bus\ Trips \leq Unique\ Trips\ Possible\ per\ Year\ (Bus), Expected\ Bus\ Trips, Unique\ Trips\ Possible\ per\ Year\ (Bus))$ | $\frac{Bus\ Trip}{Year}$ |
| | Unique Trips Possible per Year (Bus) | Auxiliary | $Unique\ Trips\ Possible\ per\ Year\ (Bus) = \frac{Buses \times Bus\ Operational\ Time}{Duration\ of\ a\ Complete\ Bus\ Trip}$ | $\frac{Bus\ Trip}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Bus | Duration of a Complete Bus Trip | Stock | $Duration\ of\ a\ Complete\ Bus\ Trip = \int_{t_0}^{t} (\text{Change in Duration of a Complete Bus Trip})dt + Normal\ Duration\ of\ a\ Complete\ Bus\ Trip$ | $\frac{Minute}{Bus\ Trip}$ |
| | Change in Duration of a Complete Bus Trip | Flow | $Change\ in\ Duration\ of\ a\ Complete\ Bus\ Trip = \frac{Indicate\ Duration\ of\ a\ Complete\ Bus\ Trip - Duration\ of\ a\ Complete\ Bus\ Trip}{Time\ to\ Change\ in\ Duration\ of\ a\ Complete\ Bus\ Trip}$ | $\frac{Minute}{Bus\ Trip \times Year}$ |
| | Buses Line | Stock | $Bus\ Line = \int_{t_0}^{t} (Bus\ order - New\ Buses)dt + Initial\ Buses\ Line$ | Bus |
| | Bus Order | Flow | $Bus\ Order = MAX(0, Correction\ for\ Buses + Correction\ for\ Buses\ Line + Average\ Discarded\ Buses)$ | $\frac{Bus}{Year}$ |
| | New Buses | Flow | $New\ Buses = \frac{Buses\ Line}{Normal\ New\ Buses\ Time}$ | $\frac{Bus}{Year}$ |
| | Buses | Stock | $Buses = \int_{t_0}^{t} (New\ Buses - Discarded\ Buses)dt + Initial\ Buses$ | Bus |
| | Discarded Buses | Flow | $New\ Buses = \frac{Buses}{Bus\ Discard\ Time}$ | $\frac{Bus}{Year}$ |
| | Correction for Buses Line | Auxiliary | $Correction\ for\ Buses\ Line = \frac{Desired\ Buses\ Line - Buses\ Line}{Time\ to\ Correct\ Buses\ Line}$ | $\frac{Bus}{Year}$ |
| | Initial Buses Line | Auxiliary | $Initial\ Buses\ Line = Desired\ Buses\ Line$ | Bus |
| | Desired Buses Line | Auxiliary | $Desired\ Buses\ Line = Average\ Discarded\ Buses \times Normal\ New\ Buses\ Time$ | Bus |
| | Average Discarded Buses | Stock | $Average\ Discarded\ Buses = \int_{t_0}^{t} (Change\ in\ Average\ Discarded\ Buses)dt + Initial\ Average\ Discarded\ Buses$ | $\frac{Bus}{Year}$ |
| | Change in Average Discarded Buses | Flow | $Change\ in\ Average\ Discarded\ Buses = \frac{Discarded\ Buses - Average\ Discarded\ Buses}{Time\ to\ Change\ Average\ Discarded\ Buses}$ | $\frac{Bus}{Year \times Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
| --- | --- | --- | --- | --- |
| Bus | Initial Average Discarded Buses | Auxiliary | $Initial\ Average\ Discarded\ Buses = Discarded\ Buses$ | $\frac{Bus}{Year}$ |
| | Correction for Buses | Auxiliary | $Correction\ for\ Buses = \frac{Desired\ Buses - Buses}{Time\ to\ Correct\ Buses}$ | $\frac{Bus}{Year}$ |
| | Desired Buses | Auxiliary | $Desired\ Buses = \frac{Expected\ Bus\ Trips}{Max\ Trips\ per\ Bus}$ | Bus |
| | Max Trips per Bus | Auxiliary | $Max\ Trips\ per\ Bus = \frac{Unique\ Trips\ Possible\ per\ Year\ (Bus)}{Buses}$ | $\frac{Bus\ Trip}{Bus \times Year}$ |
| | Correction for Trend in Desired Bus Trips | Auxiliary | $Correction\ for\ Trend\ in\ Desired\ Bus\ Trips = Buses \times Indicated\ Trend\ in\ Bus\ Trips$ | $\frac{Bus}{Year}$ |
| | Indicated Trend in Bus Trips | Auxiliary | $Indicated\ Trend\ in\ Bus\ Trips = TREND\ (Perceived\ Bus\ Trips, Time\ to\ Form\ Trend\ in\ Bus\ Trips, Initial\ Perceived\ Trend\ in\ Bus\ Trips)$ | $\frac{1}{Year}$ |
| | Perceived Bus Trips | Stock | $Perceived\ Bus\ Trips = \int_{t_0}^{t} (Change\ in\ Perceived\ Bus\ Trips)dt + Initial\ Perceived\ Bus\ Trips$ | $\frac{Bus\ Trip}{Year}$ |
| | Change in Perceived Bus Trips | Flow | $Change\ in\ Perceived\ Bus\ Trips = \frac{Desired\ Bus\ Trips - Perceived\ Bus\ Trips}{Time\ to\ Change\ Perceived\ Bus\ Trips}$ | $\frac{Bus\ Trip}{Year \times Year}$ |
| | Initial Perceived Bus Trips | Auxiliary | $Initial\ Perceived\ Bus\ Trips = \frac{Initial\ Desired\ Bus\ Trips}{1 + Time\ to\ Change\ Perceived\ Bus\ Trips * Initial\ Perceived\ Trend\ in\ Bus\ Trips}$ | $\frac{Bus\ Trip}{Year}$ |
| | Expected Bus Trips | Auxiliary | $Expected\ Bus\ Trips = Perceived\ Bus\ Trips \times (1 + Indicated\ Trend\ in\ Bus\ Trips \times (Time\ to\ Change\ Perceived\ Bus\ Trips + Time\ Horizon\ for\ Expectations\ (Bus)))$ | $\frac{Bus\ Trip}{Year}$ |
| Car | Desired Car Trips | Auxiliary | $Desired\ Car\ Trips = \frac{Allocation\ of\ Demand\ Among\ Modes\ of\ Transportation\ (Car) \times Desired\ Trips}{Average\ Occupancy\ Rate\ (Car)}$ | $\frac{Car\ Trip}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Car | Allocation of Demand Among Modes of Transportation (Car) | Auxiliary | $Allocation\ of\ Demand\ Among\ Modes\ (Car) = \left[\frac{EXP(Relative\ Attractiveness\ (Car))}{\sum_{j=1}^{5} EXP(Relative\ Attractiveness\ (j))}\right] \times (1 - Other\ Modes\ Share)$ Where j (1 = Ride-hailing, 2 = Car; 3 = Bus; 4 = Subway, 5 = Train) | Dimensionless |
| | Relative Attractiveness of Car | Auxiliary | $Relative\ Attractiveness\ of\ Car = U1\ (Car) + U2\ (Car)$ | Dimensionless |
| | U1 (Car) | Auxiliary | $\mathrm{U1\ (Car)} = Coef\ 1\ (Car) \times \frac{Perceived\ Time\ Per\ Trip\ (Car)}{Initial\ Perceived\ Time\ Per\ Trip\ (Car)}$ | Dimensionless |
| | Initial Perceived Time Per Trip (Car) | Auxiliary | $Initial\ Perceived\ Time\ Per\ Trip\ (Car) = Initial\ Average\ Time\ Per\ Trip\ (Car)$ | $\frac{Minute}{Car\ Trip}$ |
| | Perceived Time Per Trip (Car) | Stock | $Perceived\ Time\ Per\ Trip\ (Car) = \int_{t_0}^{t} (Change\ in\ Perceived\ Time\ per\ Trip\ (Car))dt + Initial\ Perceived\ Time\ per\ Trip\ (Car)$ | $\frac{Minute}{Car\ Trip}$ |
| | Change in Perceived Time (Car) | Flow | $Chamge\ in\ Perceived\ Time\ (Car) = \frac{Average\ Time\ Per\ Trip\ (Car) - Perceived\ Time\ Per\ Trip\ (Car)}{Time\ to\ Change\ Perceived\ Time\ (Car)}$ | $\frac{Minute}{Car\ Trip \times Year}$ |
| | Average Time Per Trip (Car) | Stock | $Average\ Time\ Per\ Trip\ (Car) = \int_{t_0}^{t} (Change\ in\ Average\ Time\ Per\ Trip\ (Car))dt + Initial\ Average\ Time\ per\ Trip\ (Car)$ | $\frac{Minute}{Car\ Trip}$ |
| | Change in Average Time per Trip (Car) | Flow | $Change\ in\ Average\ Time\ per\ Trip\ (Car) = \frac{Indicate\ Average\ Time\ Per\ Trip\ (Car) - Average\ Time\ Per\ Trip\ (Car)}{Time\ to\ Change\ Average\ Time\ Per\ Trip\ (Car)}$ | $\frac{Minute}{Car\ Trip \times Year}$ |
| | Indicate Average Time Per Trip (Car) | Auxiliary | $Indicate\ Average\ Time\ Per\ Trip\ (Car) = Initial\ Average\ Time\ Per\ Trip\ (Car) \times Effect\ of\ Congestion\ on\ Trip\ Time \times Effect\ of\ Road\ System\ Quality\ on\ Trip\ Time$ | $\frac{Minute}{Car\ Trip}$ |
| | U2 (Car) | Auxiliary | $\mathrm{U2\ (Car)} = Coef\ 2\ (Car) \times \frac{Perceived\ Price\ (Car)}{Initial\ Perceived\ Price\ (Car)}$ | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Car | Perceived Price (Car) | Stock | $Perceived\ Price\ (Car) = \int_{t_0}^{t} (Change\ in\ Perceived\ Price\ (Car))dt + Initial\ Perceived\ Price\ (Car)$ | $\frac{\$}{Car\ Trip}$ |
| | Change in Perceived Price (Car) | Flow | $Change\ in\ Perceived\ Price\ (Car) = \frac{Average\ Trip\ Cost\ (Car) - Perceived\ Price\ (Car)}{Time\ to\ Change\ Perceived\ Price\ (Car)}$ | $\frac{\$}{Car\ Trip \times Year}$ |
| | Initial Perceived Price (Car) | Auxiliary | $Initial\ Perceived\ Price\ (Car) = Average\ Trip\ Cost\ (Car)$ | $\frac{\$}{Car\ Trip}$ |
| | Average Trip Cost (Car) | Auxiliary | $Average\ Trip\ Cost\ (Car) = ((Operational\ Costs \times Average\ Trip\ Distance\ (Car)) + (Average\ Trip\ Distance\ (Car) \times Fuel\ Consumed\ per\ Kilometer\ (Car) \times Fuel\ Price))$ | $\frac{\$}{Car\ Trip}$ |
| | Operational Costs | Stock | $Operational\ Costs = \int_{t_0}^{t} (Change\ in\ Operational\ Costs)dt + Initial\ Operational\ Costs$ | $\frac{\$}{Kilometer}$ |
| | Change in Operational Costs | Flow | $Change\ in\ Operational\ Costs = Operational\ Costs \times Operational\ Costs\ Adjustment$ | $\frac{\$}{Kilometer \times Year}$ |
| | Cars Line | Stock | $Cars\ Line = \int_{t_0}^{t} (Cars\ Order - New\ Cars)dt + Initial\ Cars\ Line$ | Car |
| | Cars Order | Flow | $Cars\ Order = MAX(0, Correction\ for\ Cars + Correction\ for\ Cars\ Line + Average\ Discarded\ Cars)$ | $\frac{Car}{Year}$ |
| | New Cars | Flow | $New\ Cars = \frac{Cars\ Line}{Normal\ New\ Cars\ Time}$ | $\frac{Car}{Year}$ |
| | Cars | Stock | $Cars = \int_{t_0}^{t} (New\ Cars - Discarded\ Cars)dt + Initial\ Cars$ | Car |
| | Discarded Cars | Flow | $Discarded\ Cars = \frac{Cars}{Cars\ Discard\ Time}$ | $\frac{Car}{Year}$ |
| | Correction for Cars Line | Auxiliary | $Correction\ for\ Cars\ Line = \frac{Desired\ Cars\ Line - Cars\ Line}{Time\ to\ Correct\ Cars\ Line}$ | $\frac{Car}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Car | Desired Cars Line | Auxiliary | $Desired\ Cars\ Line = Average\ Discarded\ Cars \times Normal\ New\ Cars\ Time$ | Car |
| | Initial Cars Line | Auxiliary | $Initial\ Cars\ Line = Desired\ Cars\ Line$ | Car |
| | Average Discarded Cars | Stock | $Average\ Discarded\ Cars = \int_{t_0}^{t} (Change\ in\ Average\ Discarded\ Cars) dt + Initial\ Discarded\ Cars$ | $\frac{Car}{Year}$ |
| | Change in Average Discarded Cars | Flow | $Change\ in\ Average\ Discarded\ Cars = \frac{Discarded\ Cars - Average\ Discarded\ Cars}{Time\ to\ Change\ Average\ Discarded\ Cars}$ | $\frac{Car}{Year \times Year}$ |
| | Initial Discarded Cars | Auxiliary | $Initial\ Discarded\ Cars = Discarded\ Cars$ | $\frac{Car}{Year}$ |
| | Correction for Cars | Auxiliary | $Correction\ for\ Cars = \frac{Desired\ Cars - Cars}{Time\ to\ Correct\ Cars}$ | $\frac{Car}{Year}$ |
| | Desired Cars | Auxiliary | $Desired\ Cars = \frac{Expected\ Car\ Trips}{Number\ of\ Trips\ per\ Car} \times Car\ Ownership\ Fraction$ | Car |
| | Correction for Trend in Desired Car Trips | Auxiliary | $Correction\ for\ Trend\ in\ Desired\ Car\ Trips = Cars \times Indicated\ Trend\ in\ Car\ Trips$ | $\frac{Car}{Year}$ |
| | Car Ownership Fraction | Stock | $Car\ Ownership\ Fraction = \int_{t_0}^{t} (Change\ in\ Car\ Ownership\ Fraction) dt + Initial\ Car\ Ownership\ Fraction$ | Dimensionless |
| | Change in Car Ownership Fraction | Flow | $Change\ in\ Car\ Ownership\ Fraction = Car\ Ownership\ Fraction \times Car\ Owership\ Growth$ | Dimensionless |
| | Unique Trips Possible per Year (Car) | Auxiliary | $Unique\ Trips\ Possible\ per\ Year\ (Car) = Number\ of\ Trips\ per\ Car \times Cars$ | $\frac{Car\ Trip}{Year}$ |
| | Car Trips | Auxiliary | $Car\ Trips = IF\ THEN\ ELSE(Expected\ Car\ Trips \leq Unique\ Trips\ Possible\ per\ Year\ (Car), Expected\ Car\ Trips, Unique\ Trips\ Possible\ per\ Year\ (Car))$ | $\frac{Car\ Trip}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Car | Expected Car Trips | Auxiliary | $Expected\ Car\ Trips = Perceived\ Car\ Trips \times (1 + Indicated\ Trend\ in\ Car\ Trips \times (Time\ to\ Change\ Perceived\ Car\ Trips + Time\ Horizon\ for\ Expectations\ (Car)))$ | $\frac{Car\ Trip}{Year}$ |
| | Indicated Trend in Car Trips | Auxiliary | $Indicated\ Trend\ in\ Car\ Trips = TREND\ (Perceived\ Car\ Trips, Time\ to\ Form\ Trend\ in\ Car\ Trips, Initial\ Perceived\ Trend\ in\ Car\ Trips)$ | $\frac{1}{Year}$ |
| | Perceived Car Trips | Stock | $Perceived\ Car\ Trips = \int_{t_0}^{t} (Change\ in\ Perceived\ Car\ Trips)dt + Initial\ Perceived\ Car\ Trips$ | $\frac{Car\ Trip}{Year}$ |
| | Change in Perceived Car Trips | Flow | $Change\ in\ Perceived\ Car\ Trips = \frac{Desired\ Car\ Trips - Perceived\ Car\ Trips}{Time\ to\ Change\ Perceived\ Car\ Trips}$ | $\frac{Car\ Trip}{Year \times Year}$ |
| | Initial Perceived Car Trips | Auxiliary | $Initial\ Perceived\ Car\ Trips = \frac{Initial\ Desired\ Car\ Trips}{1 + Time\ to\ Change\ Perceived\ Car\ Trips * Initial\ Perceived\ Trend\ in\ Car\ Trips}$ | $\frac{Car\ Trip}{Year}$ |
| Subway | Desired Subway Trips | Auxiliary | $Desired\ Subway\ Trips = \frac{Trips\ to\ be\ allocated\ to\ Subway}{Average\ Occupancy\ Rate\ (Subway)}$ | $\frac{Subway\ Trip}{Year}$ |
| | Average Occupancy Rate (Subway) | Auxiliary | $Average\ Occupancy\ Rate\ (Subway) = MIN(Max. Occupancy\ Rate\ (Subway), (\frac{Trips\ to\ be\ allocated\ to\ Subway}{Unique\ Trips\ Possible\ per\ Year\ (Subway)}))$ | $\frac{Trip}{Subway\ Trip}$ |
| | Trips to be allocated to Subway | Auxiliary | $Trips\ to\ be\ allocated\ to\ Subway = Desired\ Trips \times Allocation\ of\ Demand\ Among\ Modes\ of\ Transportation\ (Subway)$ | $\frac{Trip}{Year}$ |
| | Allocation of Demand Among Modes of Transportation (Subway) | Auxiliary | $Allocation\ of\ Demand\ Among\ Modes\ (Subway) = \left[\frac{EXP(Relative\ Attractiveness\ (Subway))}{\sum_{j=1}^{5} EXP(Relative\ Attractiveness\ (j))}\right] \times (1 - Other\ Modes\ Share)$<br>Where j (1 = Ride-hailing, 2 = Car; 3 = Bus; 4 = Subway, 5 = Train) | Dimensionless |
| | Relative Attractiveness of Subway | Auxiliary | $Relative\ Attractiveness\ of\ Subway = U1\ (Subway) + U2\ (Subway)$ | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Subway | U1 (Subway) | Auxiliary | $U1\ (Subway) = Coef\ 1\ (Subway) \times \frac{Perceived\ Time\ Per\ Trip\ (Subway)}{Initial\ Perceived\ Time\ Per\ Trip\ (Subway)}$ | Dimensionless |
| | Initial Perceived Time Per Trip (Subway) | Auxiliary | $Initial\ Perceived\ Time\ Per\ Trip\ (Subway) = Initial\ Average\ Time\ Per\ Trip\ (Subway) + "Normal\ Waiting\ Time\ (Subway)$ | $\frac{Minute}{Subway\ Trip}$ |
| | Perceived Time Per Trip (Subway) | Stock | $Perceived\ Time\ Per\ Trip\ (Subway) = \int_{t_0}^{t} (Change\ in\ Perceived\ Time\ Per\ Trip\ (Subway))dt + Initial\ Perceived\ Time\ Per\ Trip\ (Subway)$ | $\frac{Minute}{Subway\ Trip}$ |
| | Change in Perceived Time (Subway) | Flow | $Change\ in\ Perceived\ Time\ (Subway) = \frac{Total\ Trip\ Time\ (Subway) - Perceived\ Time\ Per\ Trip\ (Subway)}{Time\ to\ Change\ Perceived\ Time\ (Subway)}$ | $\frac{Minute}{Subway\ Trip \times Year}$ |
| | Total Trip Time (Subway) | Auxiliary | $Total\ Trip\ Time\ (Subway) = Average\ Time\ per\ Trip\ (Subway) + Waiting\ Time\ (Subway)$ | $\frac{Minute}{Subway\ Trip}$ |
| | Waiting Time (Subway) | Auxiliary | $Waiting\ Time\ (Subway) = (Normal\ Waiting\ Time\ (Subway)) \times Effect\ of\ Occupancy\ rate\ (Subway)$ | $\frac{Minute}{Subway\ Trip}$ |
| | Average Time per Trip (Subway) | Stock | $Average\ Time\ per\ Trip\ (Subway) = \int_{t_0}^{t} (Change\ in\ Average\ Time\ per\ Trip\ (Subway))dt + Initial\ Average\ Time\ per\ Trip\ (Subway)$ | $\frac{Minute}{Subway\ Trip}$ |
| | Change in Average Time Per Trip (Subway) | Flow | $Change\ in\ Average\ Time\ Per\ Trip\ (Subway) = \frac{Indicate\ Average\ Time\ Per\ Trip\ (Subway) - Average\ Time\ per\ Trip\ (Subway)}{Time\ to\ Change\ Average\ Time\ Per\ Trip\ (Subway)}$ | $\frac{Minute}{Subway\ Trip \times Year}$ |
| | Indicate Average Time Per Trip (Subway) | Auxiliary | $Indicate\ Average\ Time\ Per\ Trip\ (Subway) = Effect\ of\ Occupancy\ rate\ (Subway) \times Initial\ Average\ Time\ Per\ Trip\ (Subway)$ | $\frac{Minute}{Subway\ Trip}$ |
| | Effect of Occupancy rate (Subway) | Auxiliary | Effect of Occupancy rate (Subway) = WITH LOOKUP ($\frac{Average\ Occupancy\ Rate\ (Subway)}{Max.Occupancy\ Rate\ (Subway)}$, ([(0,0)-(10,10)],(0,1),(0.7,1),(0.760825,1.00455),(0.806186,1.008),(0.841237,1.01818),(0.874227,1.04091),(0.909278,1.06818),(0.940028,1.08636),(0.970711,1.09545),(1,1.1) )) | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Subway | U2 (Subway) | Auxiliary | $U2\ (Subway) = Coef\ 2\ (Subway) \times \frac{Perceived\ Price\ (Subway)}{Initial\ Perceived\ Price\ (Subway)}$ | Dimensionless |
| | Perceived Price (Subway) | Stock | $Perceived\ Price\ (Subway) = \int_{t_0}^{t} \big(Change\ in\ Perceived\ Price\ (Subway)\big)dt + Initial\ Perceived\ Price\ (Subway)$ | $\frac{\$}{Subway\ Trip}$ |
| | Change in Perceived Price (Subway) | Flow | $Change\ in\ Perceived\ Price\ (Subway) = \frac{Subway\ Fare - Perceived\ Price\ (Subway)}{Time\ to\ Change\ Perceived\ Price\ (Subway)}$ | $\frac{\$}{Subway\ Trip \times Year}$ |
| | Initial Perceived Price (Subway) | Auxiliary | $Initial\ Perceived\ Price\ (Subway) = Initial\ Subway\ Fare$ | $\frac{\$}{Subway\ Trip}$ |
| | Subway Fare | Stock | $Subway\ Fare = \int_{t_0}^{t} (Change\ in\ Subway\ Fare)dt + Initial\ Subway\ Fare$ | $\frac{\$}{Subway\ Trip}$ |
| | Change in Subway Fare | Flow | $Change\ in\ Subway\ Fare = Subway\ Fare\ Adjustment \times Subway\ Fare$ | $\frac{\$}{Subway\ Trip \times Year}$ |
| | Vehicles Line (Subway) | Stock | $Vehicles\ Line\ (Subway) = \int_{t_0}^{t} (Vehicle\ Order\ (Subway) - New\ Vehicles\ (Subway))dt + Initial\ Vehicles\ Line\ (Subway)$ | Vehicle (Subway) |
| | Vehicle Order (Subway) | Flow | $Vehicle\ Order\ (Subway) = MAX(0, Correction\ for\ Vehicles\ (Subway) + Correction\ for\ Vehicles\ Line\ (Subway) + Average\ Discarded\ Vehicles\ (Subway))$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | New Vehicles (Subway) | Flow | $New\ Vehicles\ (Subway) = \frac{Vehicles\ Line\ (Subway)}{Normal\ New\ Vehcicles\ Time\ (Subway)}$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | Vehicles (Subway) | Stock | $Vehicles\ (Subway) = \int_{t_0}^{t} (New\ Vehicles\ (Subway) - Discarded\ Vehicles\ (Subway))dt + Initial\ Vehicles\ (Subway)$ | Vehicle (Subway) |
| | Discarded Vehicles (Subway) | Flow | $Discarded\ Vehicles\ (Subway) = \frac{Vehicles\ (Subway)}{Vehicle\ Discard\ Time\ (Subway)}$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Subway | Initial Vehicles Line (Subway) | Auxiliary | $Initial\ Vehicles\ Line\ (Subway) = Desired\ Vehicles\ (Subway)\ Line$ | Vehicle (Subway) |
| | Correction for Vehicles Line (Subway) | Auxiliary | $Correction\ for\ Vehicles\ Line\ (Subway) = \frac{Desired\ Vehicles\ (Subway)\ Line - Vehicles\ Line\ (Subway)}{Time\ to\ Correct\ Vehicles\ Line\ (Subway)}$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | Desired Vehicles (Subway) Line | Auxiliary | $Desired\ Vehicles\ (Subway) Line = Average\ Discarded\ Vehicles\ (Subway) \times "Normal\ New\ Vehicles\ Time\ (Subway)$ | Vehicle (Subway) |
| | Average Discarded Vehicles (Subway) | Stock | $Average\ Discarded\ Vehicles\ (Subway) = \int_{t_0}^{t} \text{Change in Average Discarded Vehicles (Subway)dt} + Initial\ Average\ Discarded\ Vehicles\ (Subway)$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | Change in Average Discarded Vehicles (Subway) | Flow | $Change\ in\ Average\ Discarded\ Vehicles\ (Subway) = \frac{Discarded\ Vehicles\ (Subway) - Average\ Discarded\ Vehicles\ (Subway)}{Time\ do\ Change\ Average\ Discarded\ Vehicles\ (Subway)}$ | $\frac{\text{Vehicle (Subway)}}{Year \times Year}$ |
| | Initial Average Discarded Vehicles (Subway) | Auxiliary | $Initial\ Average\ Discarded\ Vehicles\ (Subway) = Discarded\ Vehicles\ (Subway)$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | Correction for Vehicles (Subway) | Auxiliary | $Correction\ for\ Vehicles\ (Subway) = \frac{Desired\ Vehicles\ (Subway) - Vehicles\ (Subway)}{Time\ to\ Correct\ Vehicles\ (Subway)}$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | Correction for Trend in Desired Subway Trips | Auxiliary | $Correction\ for\ Trend\ in\ Desired\ Subway\ Trips = Vehicles\ (Subway) \times Indicated\ Trend\ in\ Subway\ Trips$ | $\frac{\text{Vehicle (Subway)}}{Year}$ |
| | Desired Vehicles (Subway) | Auxiliary | $Desired\ Vehicles\ (Subway) = \frac{Expected\ Subway\ Trips}{Max\ Trips\ per\ vehicle\ (Subway)}$ | Vehicle (Subway) |
| | Subway Trips | Auxiliary | $Subway\ Trips = IF\ THEN\ ELSE(Expected\ Subway\ Trips \leq Unique\ Trips\ Possible\ per\ Year\ (Subway), Expected\ Subway\ Trips, Unique\ Trips\ Possible\ per\ Year\ (Subway))$ | $\frac{\text{Subway Trip}}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Subway | Unique Trips Possible per Year (Subway) | Auxiliary | $Unique\ Trips\ Possible\ per\ Year\ (Subway) = \text{Max Trips per vehicle (Subway)} \times \text{Vehicles (Subway)}$ | $\frac{\text{Subway Trip}}{Year}$ |
| | Expected Subway Trips | Auxiliary | $Expected\ Subway\ Trips = Perceived\ Subway\ Trips \times (1 + Indicated\ Trend\ in\ Subway\ Trips \times (Time\ to\ Change\ Perceived\ Subway\ Trips + Time\ Horizon\ for\ Expectations\ (Subway)))$ | $\frac{\text{Subway Trip}}{Year}$ |
| | Indicated Trend in Subway Trips | Auxiliary | $Indicated\ Trend\ in\ Subway\ Trips = TREND\ (Perceived\ Subway\ Trips, Time\ to\ Form\ Trend\ in\ Subway\ Trips, Initial\ Perceived\ Trend\ in\ Subway\ Trips)$ | $\frac{1}{Year}$ |
| | Perceived Subway Trips | Stock | $Perceived\ Subway\ Trips = \int_{t_0}^{t} \text{Change in Perceived Subway Trips dt} + Initial\ Perceived\ Subway\ Trips$ | $\frac{\text{Subway Trip}}{Year}$ |
| | Change in Perceived Subway Trips | Flow | $Change\ in\ Perceived\ Subway\ Trips = \frac{Desired\ Subway\ Trips - Perceived\ Subway\ Trips}{Time\ to\ Change\ Perceived\ Subway\ Trips}$ | $\frac{\text{Subway Trip}}{Year \times Year}$ |
| | Initial Perceived Subway Trips | Auxiliary | $Initial\ Perceived\ Subway\ Trips = \frac{Initial\ Desired\ Subway\ Trips}{(1 + Time\ to\ Change\ Perceived\ Subway\ Trips \times Initial\ Perceived\ Trend\ in\ Subway\ Trips)}$ | $\frac{\text{Subway Trip}}{Year}$ |
| Train | Desired Train Trips | Auxiliary | $Desired\ Train\ Trips = \frac{Trips\ to\ be\ allocated\ to\ Train}{Average\ Occupancy\ Rate\ (Train)}$ | $\frac{Train\ Trip}{Year}$ |
| | Average Occupancy Rate (Train) | Auxiliary | $Average\ Occupancy\ Rate\ (Train) = MIN(Max.Occupancy\ Rate\ (Train), (\frac{Trips\ to\ be\ allocated\ to\ Train}{Unique\ Trips\ Possible\ per\ Year\ (Train)}))$ | $\frac{Trip}{Train\ Trip}$ |
| | Trips to be allocated to Train | Auxiliary | $Trips\ to\ be\ allocated\ to\ Train = Desired\ Trips \times Allocation\ of\ Demand\ Among\ Modes\ of\ Transportation\ (Train)$ | $\frac{Trip}{Year}$ |
| | Allocation of Demand Among Modes of Transportation (Train) | Auxiliary | $Allocation\ of\ Demand\ Among\ Modes\ (Train) = \left[\frac{EXP(Relative\ Attractiveness\ (Train))}{\sum_{j=1}^{5} EXP(Relative\ Attractiveness\ (j))}\right] \times (1 - Other\ Modes\ Share)$<br>Where j (1 = Ride-hailing, 2 = Car; 3 = Bus; 4 = Subway, 5 = Train) | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Train | Relative Attractiveness of Train | Auxiliary | $Relative\ Attractiveness\ of\ Train = U1\ (Train) + U2\ (Train)$ | Dimensionless |
| | U1 (Train) | Auxiliary | $U1\ (Train) = Coef\ 1\ (Train) \times \frac{Perceived\ Time\ Per\ Trip\ (Train)}{Initial\ Perceived\ Time\ Per\ Trip\ (Train)}$ | Dimensionless |
| | Initial Perceived Time Per Trip (Train) | Auxiliary | $Initial\ Perceived\ Time\ Per\ Trip\ (Train) = Initial\ Average\ Time\ Per\ Trip\ (Train) + "Normal\ Waiting\ Time\ (Train)$ | $\frac{Minute}{Train\ Trip}$ |
| | Perceived Time Per Trip (Train) | Stock | $Perceived\ Time\ Per\ Trip\ (Train) = \int_{t_0}^{t} (Change\ in\ Perceived\ Time\ Per\ Trip\ (Train))dt + Initial\ Perceived\ Time\ Per\ Trip\ (Train)$ | $\frac{Minute}{Train\ Trip}$ |
| | Change in Perceived Time (Train) | Flow | $Change\ in\ Perceived\ Time\ (Train) = \frac{Total\ Trip\ Time\ (Subway) - Perceived\ Time\ Per\ Trip\ (Train)}{Time\ to\ Change\ Perceived\ Time\ (Train)}$ | $\frac{Minute}{Train\ Trip \times Year}$ |
| | Total Trip Time (Train) | Auxiliary | $Total\ Trip\ Time\ (Train) = Average\ Time\ per\ Trip\ (Train) + Waiting\ Time\ (Train)$ | $\frac{Minute}{Train\ Trip}$ |
| | Waiting Time (Train) | Auxiliary | $Waiting\ Time\ (Train) = (Normal\ Waiting\ Time\ (Train)) \times Effect\ of\ Occupancy\ rate\ (Train)$ | $\frac{Minute}{Train\ Trip}$ |
| | Average Time per Trip (Train) | Stock | $Average\ Time\ per\ Trip\ (Train) = \int_{t_0}^{t} (Change\ in\ Average\ Time\ per\ Trip\ (Train))dt + Initial\ Average\ Time\ per\ Trip\ (Train)$ | $\frac{Minute}{Train\ Trip}$ |
| | Change in Average Time Per Trip (Train) | Flow | $Change\ in\ Average\ Time\ Per\ Trip\ (Train) = \frac{Indicate\ Average\ Time\ Per\ Trip\ (Train) - Average\ Time\ per\ Trip\ (Train)}{Time\ to\ Change\ Average\ Time\ Per\ Trip\ (Train)}$ | $\frac{Minute}{Train\ Trip \times Year}$ |
| | Indicate Average Time Per Trip (Train) | Auxiliary | $Indicate\ Average\ Time\ Per\ Trip\ (Train) = Effect\ of\ Occupancy\ rate\ (Train) \times Initial\ Average\ Time\ Per\ Trip\ (Train)$ | $\frac{Minute}{Train\ Trip}$ |
| | Effect of Occupancy rate (Train) | Auxiliary | Effect of Occupancy rate (Train) = WITH LOOKUP ($\frac{Average\ Occupancy\ Rate\ (Train)}{Max.Occupancy\ Rate\ (Train)}$, ([(0,0)-(10,10)],(0,1),(0.7,1),(0.760825,1.00455),(0.806186,1.008),(0.841237,1.01818),(0.874227,1.04091),(0.909278,1.06818),(0.940028,1.08636),(0.970711,1.09545),(1,1.1) )) | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Train | U2 (Train) | Auxiliary | $U2\ (Train) = \ Coef\ 2\ (Train) \times \frac{Perceived\ Price\ (Train)}{Initial\ Perceived\ Price\ (Train)}$ | Dimensionless |
| | Perceived Price (Train) | Stock | $Perceived\ Price\ (Train) = \int_{t_0}^{t} (Change\ in\ Perceived\ Price\ (Train))dt + Initial\ Perceived\ Price\ (Train)$ | $\frac{\$}{Train\ Trip}$ |
| | Change in Perceived Price (Train) | Flow | $Change\ in\ Perceived\ Price\ (Train) = \frac{Train\ Fare - Perceived\ Price\ (Train)}{Time\ to\ Change\ Perceived\ Price\ (Train)}$ | $\frac{\$}{Train\ Trip \times Year}$ |
| | Initial Perceived Price (Train) | Auxiliary | $Initial\ Perceived\ Price\ (Train) = \ Initial\ Train\ Fare$ | $\frac{\$}{Train\ Trip}$ |
| | Train Fare | Stock | $Train\ Fare = \int_{t_0}^{t} (Change\ in\ Train\ Fare)dt + Initial\ Train\ Fare$ | $\frac{\$}{Train\ Trip}$ |
| | Change in Train Fare | Flow | $Change\ in\ Train\ Fare = \ Train\ Fare\ Adjustment \times Train\ Fare$ | $\frac{\$}{Train\ Trip \times Year}$ |
| | Vehicles Line (Train) | Stock | $Vehicles\ Line\ (Train) = \int_{t_0}^{t} (Vehicle\ Order\ (Train) - New\ Vehicles\ (Train))dt + Initial\ Vehicles\ Line\ (Train)$ | Vehicle (Train) |
| | Vehicle Order (Train) | Flow | $Vehicle\ Order\ (Train) = \ MAX(\ 0, Correction\ for\ Vehicles\ (Train) + Correction\ for\ Vehicles\ Line\ (Train) + Average\ Discarded\ Vehicles\ (Train))$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | New Vehicles (Train) | Flow | $New\ Vehicles\ (Train) = \frac{Vehicles\ Line\ (Train)}{Normal\ New\ Vehcicles\ Time\ (Train)}$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Vehicles (Train) | Stock | $Vehicles\ (Train) = \int_{t_0}^{t} (New\ Vehicles\ (Train) - Discarded\ Vehicles\ (Train))dt + Initial\ Vehicles\ (v)$ | Vehicle (Train) |
| | Discarded Vehicles (Train) | Flow | $Discarded\ Vehicles\ (Train) = \frac{Vehicles\ (Train)}{Vehicle\ Discard\ Time\ (Train)}$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Initial Vehicles Line (Train) | Auxiliary | $Initial\ Vehicles\ Line\ (Train) = \ Desired\ Vehicles\ (Train)\ Line$ | Vehicle (Train) |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Train | Correction for Vehicles Line (Train) | Auxiliary | $Correction\ for\ Vehicles\ Line\ (Train) = \frac{Desired\ Vehicles\ (Subway)\ Line\ - Vehicles\ Line\ (Train)}{Time\ to\ Correct\ Vehicles\ Line\ (Train)}$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Desired Vehicles (Train) Line | Auxiliary | $Desired\ Vehicles\ (Train)\ Line = Average\ Discarded\ Vehicles\ (Train) \times "Normal\ New\ Vehcicles\ Time\ (Train)$ | Vehicle (Train) |
| | Average Discarded Vehicles (Train) | Stock | $Average\ Discarded\ Vehicles\ (Train) = \int_{t_0}^{t} \text{Change in Average Discarded Vehicles } (Train)\text{dt} + Initial\ Average\ Discarded\ Vehicles\ (Train)$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Change in Average Discarded Vehicles (Train) | Flow | $Change\ in\ Average\ Discarded\ Vehicles\ (Train) = \frac{Discarded\ Vehicles\ (Train) - Average\ Discarded\ Vehicles\ (Train)}{Time\ do\ Change\ Average\ Discarded\ Vehicles\ (Train)}$ | $\frac{\text{Vehicle (Train)}}{Year \times Year}$ |
| | Initial Average Discarded Vehicles (Train) | Auxiliary | $Initial\ Average\ Discarded\ Vehicles\ (Train) = Discarded\ Vehicles\ (Train)$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Correction for Vehicles (Train) | Auxiliary | $Correction\ for\ Vehicles\ (Train) = \frac{Desired\ Vehicles\ (Train) - Vehicles\ (Train)}{Time\ to\ Correct\ Vehicles\ (Train)}$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Correction for Trend in Desired Train Trips | Auxiliary | $Correction\ for\ Trend\ in\ Desired\ Train\ Trips = Vehicles\ (Train) \times Indicated\ Trend\ in\ Train\ Trips$ | $\frac{\text{Vehicle (Train)}}{Year}$ |
| | Desired Vehicles (Train) | Auxiliary | $Desired\ Vehicles\ (Train) = \frac{Expected\ Train\ Trips}{Max\ Trips\ per\ vehicle\ (Train)}$ | Vehicle (Train) |
| | Train Trips | Auxiliary | $TrainTrips = IF\ THEN\ ELSE(Expected\ Train\ Trips \leq Unique\ Trips\ Possible\ per\ Year\ (Train), Expected\ Train\ Trips, Unique\ Trips\ Possible\ per\ Year\ (Train))$ | $\frac{\text{Train Trip}}{Year}$ |
| | Unique Trips Possible per Year (Train) | Auxiliary | $Unique\ Trips\ Possible\ per\ Year\ (Train) = \text{Max Trips per vehicle (Train)} \times \text{Vehicles (Train)}$ | $\frac{\text{Train Trip}}{Year}$ |
| | Expected Train Trips | Auxiliary | $Expected\ TrainTrips = Perceived\ Train\ Trips \times (1 + Indicated\ Trend\ in\ Train\ Trips \times (Time\ to\ Change\ Perceived\ Train\ Trips + Time\ Horizon\ for\ Expectations\ (Train)))$ | $\frac{\text{Train Trip}}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Train | Indicated Trend in Train Trips | Auxiliary | $Indicated\ Trend\ in\ Train\ Trips = TREND\ (Perceived\ Train\ Trips, Time\ to\ Form\ Trend\ in\ Train\ Trips, Initial\ Perceived\ Trend\ in\ Train\ Trips)$ | $\frac{1}{Year}$ |
| | Perceived Train Trips | Stock | $Perceived\ Train\ Trips = \int_{t_0}^{t} \text{Change in Perceived Train Trips dt} + Initial\ Perceived\ Train\ Trips$ | $\frac{\text{Train Trip}}{Year}$ |
| | Change in Perceived Train Trips | Flow | $Change\ in\ Perceived\ Train\ Trips = \frac{Desired\ Train\ Trips - Perceived\ Train\ Trips}{Time\ to\ Change\ Perceived\ Train\ Trips}$ | $\frac{\text{Train Trip}}{Year \times Year}$ |
| | Initial Perceived Train Trips | Auxiliary | $Initial\ Perceived\ Subway\ Trips = \frac{Initial\ Desired\ Train\ Trips}{(1 + Time\ to\ Change\ Perceived\ Train\ Trips \times Initial\ Perceived\ Trend\ in\ Train\ Trips)}$ | $\frac{\text{Train Trip}}{Year}$ |
| Road | Lanes Line | Stock | $Lanes\ Line = \int_{t_0}^{t} \text{Change in Perceived Train Trips dt} + Initial\ Lanes\ Line$ | Lane |
| | Lanes Order | Flow | $Lanes\ Order = MAX(0, MIN(Number\ of\ Possible\ Constructed\ Lanes\ per\ Year, Desired\ New\ Lanes + Correction\ for\ Lanes\ Line + Correction\ for\ Growth\ in\ Lanes\ Line))$ | $\frac{Lane}{Year}$ |
| | New Lanes | Flow | $New\ Lanes = \frac{Lanes\ Line}{Normal\ New\ Lanes\ Time}$ | $\frac{Lane}{Year}$ |
| | Lanes | Stock | $Lanes = \int_{t_0}^{t} \text{New Lanes + Repaired Lanes − Deteriorated Lanes dt} + Initial\ Lanes$ | Lane |
| | Deteriorated Lanes | Flow | $Deteriorated\ Lanes = \frac{Lanes}{Deterioration\ Time}$ | $\frac{Lane}{Year}$ |
| | Lanes in Need of Repair | Stock | $Lanes\ in\ Need\ of\ Repair = \int_{t_0}^{t} \text{Deteriorated Lanes − Repaired Lanes}\ dt + Initial\ Lanes\ in\ Need\ of\ Repair$ | Lane |
| | Repaired Lanes | Flow | $\text{Repaired Lanes} = MIN\ (Scheduled\ Lanes\ to\ Repair, Number\ of\ Possible\ Repaired\ Lanes\ per\ Year)$ | $\frac{Lane}{Year}$ |
| | Correction for Growth in Lanes Line | Auxiliary | $Correction\ for\ Growth\ in\ Lanes\ Line = Lanes\ Line \times Expected\ Growth\ in\ Lanes$ | $\frac{Lane}{Year}$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Road | Initial Lanes Line | Auxiliary | $Initial\ Lanes\ Line = Desired\ Lanes\ Line$ | Lane |
| | New Lanes Time | Auxiliary | $New\ Lanes\ Time = ZIDZ(Lanes\ Line, New\ Lanes)$ | Year |
| | Total Lanes | Auxiliary | $Total\ Lanes = Lanes\ in\ Need\ of\ Repair + Lanes$ | Lane |
| | Correction for Lanes Line | Auxiliary | $Correction\ for\ Lanes\ Line = \frac{Desired\ Lanes\ Line - Lanes\ Line}{Time\ to\ Correct\ Lanes\ Line}$ | $\frac{Lane}{Year}$ |
| | Desired Lanes Line | Auxiliary | $Desired\ Lanes\ Line = Desired\ New\ Lanes \times Normal\ New\ Lanes\ Time$ | Lane |
| | Desired New Lanes | Auxiliary | $Desired\ New\ Lanes = MAX(0, Correction\ for\ Lanes + Correction\ for\ Growth\ in\ Lanes)$ | $\frac{Lane}{Year}$ |
| | Correction for Growth in Lanes | Auxiliary | $Correction\ for\ Growth\ in\ Lanes = Lanes \times Expected\ Growth\ in\ Lanes$ | $\frac{Lane}{Year}$ |
| | Correction for Lanes | Auxiliary | $Correction\ for\ Lanes = \frac{Desired\ Lanes - Total\ Lanes}{Time\ to\ Correct\ Lanes}$ | $\frac{Lane}{Year}$ |
| | Desired Lanes | Auxiliary | $Desired\ Lanes = \frac{Total\ VKT}{Desired\ Congestion\ Level \times VKT\ per\ lane}$ | Lane |
| | Expected Growth in Lanes | Auxiliary | $Expected\ Growth\ in\ Lanes = TREND(Desired\ Lanes, Time\ to\ Form\ Trend\ in\ Expected\ Growth\ in\ Lanes, Initial\ Perceived\ Trend\ in\ Lanes\ Growth)$ | $\frac{1}{Year}$ |
| | Initial Lanes in Need of Repair | Auxiliary | $Initial\ Lanes\ in\ Need\ of\ Repair = Initial\ Total\ Lanes \times (1 - Initial\ Fraction\ in\ Lanes)$ | Lane |
| | Initial Lanes | Auxiliary | $Initial\ Lanes = Initial\ Total\ Lanes \times Initial\ Fraction\ in\ Lanes$ | Lane |
| | Initial Fraction in Lanes | Auxiliary | $Initial\ Fraction\ in\ Lanes = \frac{(\frac{1}{Time\ to\ Repair})}{((\frac{1}{Deterioration\ Time}) + (\frac{1}{Time\ to\ Repair}))}$ | Dimensionless |
| | Time to Repair | Stock | $Time\ to\ Repair = \int_{t_0}^{t} \text{Change in Time to Repair dt} + Normal\ Time\ to\ Repair$ | Year |
| | Change in Time to Repair | Flow | $Change\ in\ Time\ to\ Repair = \frac{Indicate\ Time\ to\ Repair - Time\ to\ Repair}{Time\ to\ Change\ Time\ in\ Repair}$ | $\frac{Year}{Year}$ |
| | Indicate Time to Repair | Auxiliary | $Indicate\ Time\ to\ Repair = \frac{Lanes\ in\ Need\ of\ Repair}{Repaired\ Lanes}$ | Year |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Road | Scheduled Lanes to Repair | Auxiliary | $Scheduled\ Lanes\ to\ Repair = \frac{Lanes\ in\ Need\ of\ Repair}{Normal\ Time\ to\ Repair}$ | $\frac{Lane}{Year}$ |
| | Number of Possible Repaired Lanes per Year | Auxiliary | $Number\ of\ Possible\ Repaired\ Lanes\ per\ Year = \frac{Annual\ Transport\ Infrastructure\ Investment}{Lane\ Repair\ Cost}$ | $\frac{Lane}{Year}$ |
| | Annual Repair Cost | Auxiliary | $Annual\ Repair\ Cost = Lane\ Repair\ Cost \times Repaired\ Lanes$ | $\frac{\$}{Year}$ |
| | Lane Repair Cost | Stock | $Lane\ Repair\ Cost = \int_{t_0}^{t} \text{Change in Lane Repair Cost dt} + Initial\ Lane\ Repair\ Cost$ | $\frac{\$}{Lane}$ |
| | Change in Lane Repair Cost | Flow | $Change\ in\ Lane\ Repair\ Cost = Lane\ Repair\ Cost \times Lane\ Repair\ Cost\ Adjustment$ | $\frac{\$}{Lane \times Year}$ |
| | Annual Transport Infrastructure Investment | Auxiliary | $Annual\ Transport\ Infrastructure\ Investment = GDP \times Percentage\ of\ GDP\ spent\ on\ Transport\ Infrastructure\ per\ Year$ | $\frac{\$}{Year}$ |
| | GDP | Stock | $GDP = \int_{t_0}^{t} \text{GDP Growth dt} + Initial\ GDP$ | \$ |
| | GDP Growth | Flow | $GDP\ Growth = GDP \times GDP\ Growth\ Rate$ | $\frac{\$}{Year}$ |
| | Number of Possible Constructed Lanes per Year | Auxiliary | $Number\ of\ Possible\ Constructed\ Lanes\ per\ Year = \frac{Annual\ Transport\ Infrastructure\ Investment - Annual\ Repair\ Cost}{Lane\ Cost}$ | $\frac{Lane}{Year}$ |
| | Lane Cost | Stock | $Lane\ Cost = \int_{t_0}^{t} \text{Change in Lane Cost dt} + Initial\ Lane\ Cost$ | $\frac{\$}{Lane}$ |
| | Change in Lane Cost | Flow | $Change\ in\ Lane\ Cost = Lane\ Cost\ Adjustment \times Lane\ Cost$ | $\frac{\$}{Lane \times Year}$ |
| | VKT Capacity | Auxiliary | $VKT\ Capacity = Total\ Lanes \times VKT\ per\ lane$ | $\frac{Kilometer}{Year}$ |
| | Road System Quality | Auxiliary | $Road\ System\ Quality = \frac{Lanes}{Total\ Lanes}$ | Dimensionless |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Road | Effect of Road System Quality on Trip Time | Auxiliary | Effect of Road System Quality on Trip Time = WITH LOOKUP (Road System Quality, ([(0,0)-(10,10)],(0,1.2),(0.0283286,1.15909),(0.0736544,1.11364),(0.11898,1.07273),(0.175258,1.05909),(0.240793,1.05),(0.325773,1.03636),(0.426804,1.03182),(0.525773,1.02727),(0.617564,1.02273),(0.711048,1.01364),(0.784703,1.00909),(0.858357,1.00909),(0.92068,1.00455),(1,1) )) | Dimensionless |
| Congestion | Congestion | Auxiliary | $Congestion = \frac{Total\ VKT}{VKT\ Capacity}$ | Dimensionless |
| | Total VKT | Auxiliary | $Total\ VKT = Total\ VKT\ (Bus) + Total\ VKT\ (Car) + Total\ VKT\ (Ride-hailing)$ | $\frac{\text{Kilometer}}{Year}$ |
| | Total VKT (Bus) | Auxiliary | $Total\ VKT\ (Bus) = Average\ Trip\ Distance\ (Bus) \times Bus\ Trips$ | $\frac{\text{Kilometer}}{Year}$ |
| | Total VKT (Car) | Auxiliary | $Total\ VKT\ (Car) = Average\ Trip\ Distance\ (Car) \times Car\ Trips$ | $\frac{\text{Kilometer}}{Year}$ |
| | Total VKT (Ride-hailing) | Auxiliary | $Total\ VKT\ (Ride-hailing) = Average\ Trip\ Distance\ (Ride-hailing) \times Ride-hailing\ Trips$ | $\frac{\text{Kilometer}}{Year}$ |
| | Effect of Congestion on Trip Time | Auxiliary | $Effect\ of\ Congestion\ on\ Trip\ Time = (1 + (\alpha \times Congestion^{\beta}))$ | Dimensionless |
| | Effect Congestion (Score) | Auxiliary | Effect of Congestion (Score) = WITH LOOKUP (Congestion, ([(0,0)-(10,10)],(0,1),(0.0913043,0.991979),(0.139679,0.989694),(0.189603,0.98585),(0.244064,0.98585),(0.295652,0.981283),(0.345652,0.975936),(0.395652,0.965241),(0.454348,0.954545),(0.507296,0.947413),(0.567391,0.927808),(0.6,0.91),(0.61,0.9),(0.645669,0.871122),(0.677165,0.837709),(0.698163,0.818616),(0.71,0.8),(0.732609,0.780749),(0.76087,0.751337),(0.778261,0.727273),(0.798479,0.697479),(0.815398,0.661098),(0.824147,0.625298),(0.838145,0.575179),(0.85,0.534759),(0.863043,0.473262),(0.880435,0.390374),(0.9,0.31),(0.917391,0.264706),(0.934383,0.214797),(0.96087,0.15508),(0.986957,0.0909091),(1.00217,0.0561497),(1.03043,0.0294118),(1.06304,0.0213904),(1.10061,0.0167064),(1.13911,0.0143198),(1.18285,0.0143198),(1.21785,0.0143198),(1.26334,0.0119332),(1.30009,0.0119332),(1.33508,0.00954654),(1.36658,0.00954654),(1.39783,0.00802139),(1.42826,0.00534759),(1.46522,0.00534759),(1.50217,0.0026738),(1.53261,0.0026738),(1.58913,0.0026738),(1.66522,0.0026738),(1.73913,0.0026738),(1.80652,0.00284759),(1.92391,0.0026738),(2,0.0005) ) ) | Dimensionless |
| Pollution | Total $CO_2$ Emissions | Stock | $Total\ CO_2\ Emissions = \int_{t_0}^{t} \text{Annual } CO_2 \text{ Emissions dt} + Initial\ CO_2\ Emissions$ | $Kg\ CO_2$ |

Table B.1. Variables (Continued)

| Sector | Variable | Type | Equation | Unit |
|---|---|---|---|---|
| Pollution | Annual $CO_2$ Emissions | Flow | $Annual\ CO_2\ Emissions = Bus\ Emissions + Ride - hailing\ Emissions + Car\ Emissions + Subway\ Emissions + Train\ Emissions$ | $\frac{Kg\ CO_2}{Year}$ |
| | Bus Emissions | Auxiliary | $Bus\ Emissions = Average\ Trip\ Distance\ (Bus) \times Bus\ Trips \times \frac{Kg\ CO_2}{Km}\ (Bus)$ | $\frac{Kg\ CO_2}{Year}$ |
| | Ride-hailing Emissions | Auxiliary | $Ride - hailing\ Emissions = Average\ Trip\ Distance\ (Ride - hailing) \times Ride - hailing\ Trips \times \frac{Kg\ CO_2}{Km}\ (Ride - hailing)$ | $\frac{Kg\ CO_2}{Year}$ |
| | Car Emissions | Auxiliary | $Car\ Emissions = Average\ Trip\ Distance\ (Car) \times Car\ Trips \times \frac{Kg\ CO_2}{Km}\ (Car)$ | $\frac{Kg\ CO_2}{Year}$ |
| | Subway Emissions | Auxiliary | $Subway\ Emissions = Average\ Trip\ Distance\ (Subway) \times Subway\ Trips \times \frac{Kg\ CO_2}{Km}\ (Subway)$ | $\frac{Kg\ CO_2}{Year}$ |
| | Train Emissions | Auxiliary | $Train\ Emissions = Average\ Trip\ Distance\ (Train) \times Train\ Trips \times \frac{Kg\ CO_2}{Km}\ (Train)$ | $\frac{Kg\ CO_2}{Year}$ |
| | Initial Annual $CO_2$ Emissions | Auxiliary | $Initial\ Annual\ CO_2\ Emissions = INITIAL\ (Annual\ CO_2\ Emissions)$ | $\frac{Kg\ CO_2}{Year}$ |
| | Annual $CO_2$ Emissions Factor | Auxiliary | $Annual\ CO_2\ Emissions\ Factor = \frac{Annual\ CO_2\ Emissions}{Initial\ Annual\ CO_2\ Emissions}$ | Dimensionless |
| | Effect Pollution (Score) | Auxiliary | Effect Pollution (Score) = WITH LOOKUP (Annual $CO_2$ Emissions Factor, ([(0,0)-(10,10)],(0,1),(0.203966,0.992424),(0.373938,0.988636),(0.560907,0.973485),(0.742268,0.939394),(0.884536,0.901515),(1.00825,0.856061),(1.11959,0.810606),(1.24948,0.738636),(1.34845,0.659091),(1.44742,0.587121),(1.54639,0.507576),(1.6701,0.42803),(1.76907,0.363636),(1.8866,0.276515),(1.99794,0.227273),(2.13402,0.162879),(2.33814,0.106061),(2.49278,0.0681818),(2.66598,0.0378788),(2.81443,0.00757576),(2.9134,0.00757576),(3,0.005) ) ) | Dimensionless |
| Score | Simulation Score | Auxiliary | $Simulation\ Score = 100 \times ((Effect\ Polution\ (Score) \times Pollution\ Weight) + (Effect\ Congestion\ (Score) \times Congestion\ Weight))$ | Dimensionless |
| | Initial Simulation Score | Auxiliary | $Initial\ Simulation\ Score = INITIAL\ (Simulation\ Score)$ | Dimensionless |

## APPENDIX C – PARAMETERS OF CHAPTER 5

Table B.2 shows the parameters used for the case study in the city of Rio de Janeiro.

Table B.2. Parameters for Rio de Janeiro

| Sector | Parameter | Value/Equation | Unit | References |
| --- | --- | --- | --- | --- |
| Ride-hailing | Initial Population | 6,775,561 | People | [1] |
| | Normal Population Growth Fraction | $Normal\ Population\ Growth\ Fraction = (-0.0002 \times Time) + 0.0043$ | $\frac{1}{Year}$ | Determined by the authors, based on [1] and [2] |
| | Γ | -0.005 | Dimensionless | Based on [3] |
| | Desired Trips Per Year Per Person | 792.05 | $\frac{Trip}{Year \times People}$ | Elaborated by the authors, based on [4] |
| | Average Occupancy Rate (Ride-hailing) | 1.1 | $\frac{Trip}{Ride-hailing\ Trip}$ | [5] |
| | Other modes | 0.325 | Dimensionless | [6] and [7] |
| | Working Time per Driver | 28,800 | $\frac{Minute}{Driver\ \times Year}$ | [5] |
| | Initial Fixed Fare | 2.57 | $\frac{\$}{Ride-hailing\ Trip}$ | [8] |
| | Fixed Fare Adjustment | 1.0% | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Initial Price per Minute | 0.14 | $\frac{\$}{Minute}$ | [8] |
| | Price per Minute Adjustment | 5.0% | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Initial Price per Kilometer | 1.27 | $\frac{\$}{Kilometer}$ | [8] |
| | Price per Kilometer Adjustment | 5.0% | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Initial Average Travel Time Per Trip (Ride-hailing) | 31.1 | Minute | [4] |
| | Time to Change Average Time per Trip (Ride-hailing) | 2 | Year | Determined by the authors |

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Ride-hailing | Initial Time to Pick up Passenger | 5 | Minute | [9] |
| | Time to Change Time to Pick up Passenger | 2 | Year | Determined by the authors |
| | Normal Waiting Time per Trip (Ride-hailing) | 5 | Minute | [9] |
| | Time to Change Perceive Time (Ride-hailing) | 2 | Year | Determined by the authors |
| | Time to Change Perceive Price (Ride-hailing) | 2 | Year | Determined by the authors |
| | Coef 1 (Ride-hailing) | -1.93284 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Coef 1 (Ride-hailing) | -2.04 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Initial Drivers | 100,000 | Driver | [10] |
| | Normal New Drivers Recruitment Time | 2 | Year | Determined by expert interviews |
| | Time to Change Average Drivers Leaving the Service | 2 | Year | Determined by the authors |
| | Time to Drivers Recruited | 2 | Year | Determined by the authors |
| | Time to Correct Drivers | 1 | Year | Determined by expert interviews |
| | Time to Form Trend in Desired Ride-Hailing Trips | 3 | Year | Determined by the authors |
| | Initial Perceived Trend in Ride-hailing Trips | 0 | $\frac{1}{Year}$ | Determined by the authors |
| | Time to Change Perceived Ride-hailing Trips | 2 | Year | Determined by the authors |
| | Time Horizon for Expectations | 0 | Year | Determined by the authors |
| | Ride-hailing Company Percentage | 0.25 | Dimensionless | [8] |

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Ride-hailing | Average Trip Distance (Ride-hailing) | 8.8 | $\frac{Kilometer}{Ride - hailing\ Trip}$ | [11] |
| | Additional Distance | 1.3 | Dimensionless | Determined by expert interviews |
| | Fuel Consumed per Kilometer (Ride-hailing) | 0.12 | $\frac{Liter}{Kilometer}$ | [12] |
| | Driver's Fixed Costs Adjustment | 0.03 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Initial Driver's Fixed Costs | 21,900 | $\frac{\$}{Year}$ | [13] |
| | Fuel Price Adjustment | 0.03 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Initial Fuel Price | 7.0 | $\frac{\$}{Liter}$ | [14] |
| | Wage adjustment | 0.1 | $\frac{1}{Year}$ | [15] |
| | Initial Annual Minimum Wage | 3,636 | $\frac{\$}{Driver \times Year}$ | [15] |
| | Normal Drivers Stay Time | 1.042 | Year | [16] |
| Bus | Max. Occupancy Rate (Bus) | 35 | $\frac{Trip}{Bus\ Trip}$ | [17] |
| | Coef 1 (Bus) | -0.5395 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Normal Waiting Time per Trip (Bus) | 20 | $\frac{Minute}{Bus\ Trip}$ | [18] |
| | Time to Change Perceived Time (Bus) | 2 | Year | Determined by the authors |
| | Initial Average Time per Trip (Bus) | 39.8 | $\frac{Minute}{Bus\ Trip}$ | [4] |
| | Time to Change Average Time per Trip (Bus) | 2 | Year | Determined by the authors |

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Bus | Coef 2 (Bus) | -0.225 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Time to Change Perceived Price (Bus) | 2 | Year | Determined by the authors |
| | Initial Bus Fare | 4.05 | $\frac{\$}{Bus\ Trip}$ | [19] |
| | Bus Fare Adjustment | 0.05 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Bus Operational Time | 350,400 | $\frac{Minute}{Bus \times Year}$ | Based on [20] |
| | Time to Change in Duration of a Complete Bus Trip | 2 | Year | Determined by the authors |
| | Normal Duration of a Complete Bus Trip | 60 | $\frac{Minute}{Bus\ Trip}$ | [20] |
| | Bus Discard Time | 5 | Year | [21] |
| | Time to Correct Buses Line | 2 | Year | Determined by the authors |
| | Normal New Buses Time | 5 | Year | [22] |
| | Initial Buses | 9,755 | Bus | [23] |
| | Time to Change Average Discarded Buses | 2 | Year | Determined by the authors |
| | Time to Correct Buses | 2 | Year | Determined by the authors |
| | Time to Form Trend in Bus Trips | 3 | Year | Determined by the authors |
| | Initial Perceived Trend in Bus Trips | 0 | $\frac{1}{Year}$ | Determined by the authors |
| | Time Horizon for Expectations (Bus) | 0 | Year | Determined by the authors |
| | Time to Change Perceived Bus Trips | 2 | Year | Determined by the authors |
| Car | Average Occupancy Rate (Car) | 1.3 | $\frac{Trip}{Car\ Trip}$ | [17] |

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Car | Coef 1 (Car) | -0.27 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Time to Change Perceived Time (Car) | 2 | Year | Determined by the authors |
| | Time to Change Average Time Per Trip (Car) | 2 | Year | Determined by the authors |
| | Initial Average Time Per Trip (Car) | 36.6 | $\frac{Minute}{Car\ Trip}$ | [4] |
| | Coef 2 (Car) | -0.9875 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Time to Change Perceived Price (Car) | 2 | Year | Determined by the authors |
| | Fuel Consumed per Kilometer (Car) | 0.11 | $\frac{Liter}{Kilometer}$ | [12] |
| | Average Trip Distance (Car) | 8.8 | $\frac{Kilometer}{Car\ Trip}$ | [11] |
| | Initial Operational Costs | 0.55 | $\frac{\$}{Kilometer}$ | [24] |
| | Operational Costs Adjustment | 0.025 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Car Discard Time | 10 | Year | [25] |
| | Initial Cars | 631,000* | Car | Determined by expert interviews and [1] |
| | Time to Correct Cars Line | 2 | Year | Determined by the authors |
| | Normal New Cars Time | 1 | Year | Determined by expert interviews |
| | Time to Change Average Discarded Cars | 2 | Year | Determined by the authors |
| | Time to Correct Cars | 2 | Year | Determined by the authors |

*Number of vehicles that circulate daily in Rio de Janeiro (30% of the total number of vehicles).

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Subway | Number of Trips per Car | 730 | $\frac{Car\ Trip}{Car\ \times Year}$ | Determined by expert interviews |
| | Initial Car Ownership Fraction | 0.47 | Dimensionless | [26] |
| | Car Ownership Growth | 0.01 | Dimensionless | [26] |
| | Time Horizon for Expectations (Car) | 0 | Year | Determined by the authors |
| | Time to Form Trend in Car Trips | 3 | Year | Determined by the authors |
| | Time to Change Perceived Car Trips | 2 | Year | Determined by the authors |
| | Initial Perceived Trend in Car Trips | 0 | $\frac{1}{Year}$ | Determined by the authors |
| | Max. Occupancy Rate (Subway) | 1080** | $\frac{Trip}{Subway\ Trip}$ | [27] |
| | Coef 1 (Subway) | -1.89 | Dimensionless | Determined by Sensitivity Analysis, based on [5] and [6] |
| | Normal Waiting Time (Subway) | 20 | $\frac{Minute}{Subway\ Trip}$ | [18] |
| | Time to Change Perceived Time (Subway) | 2 | Year | Determined by the authors |
| | Initial Average Time Per Trip (Subway) | 27.3 | $\frac{Minute}{Subway\ Trip}$ | [4] |
| | Time to Change Average Time Per Trip (Subway) | 2 | Year | Determined by the authors |
| | Coef 2 (Subway) | -1.7 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Initial Subway Fare | 5.8 | $\frac{\$}{Subway\ Trip}$ | [28] |
| | Time to Change Perceived Price (Subway) | 2 | Year | Determined by the authors |
| | Subway Fare Adjustment | 0.05 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |

**The average occupancy considers the different lines and its schedule. Therefore, the value assigned corresponds to 60% of the vehicle's capacity.

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Subway | Initial Vehicles (Subway) | 51*** | Vehicle (Subway) | [27] |
| | Vehicle Discard Time (Subway) | 30 | Year | [29] |
| | Normal New Vehicles Time (Subway) | 10 | Year | [28] |
| | Time to Correct Vehicles Line (Subway) | 2 | Year | Determined by the authors |
| | Time do Change Average Discarded Vehicles (Subway) | 2 | Year | Determined by the authors |
| | Max Trips per vehicle (Subway) | 2,190 | $\frac{Subway\ Trip}{Vehicle\ (Subway) \times Year}$ | [27] |
| | Time to Correct Vehicles (Subway) | 2 | Year | Determined by the authors |
| | Time to Form Trend in Subway Trips | 3 | Year | Determined by the authors |
| | Time Horizon for Expectations (Subway) | 0 | Year | Determined by the authors |
| | Time to Change Perceived Subway Trips | 2 | Year | Determined by the authors |
| | Initial Perceived Trend in Subway Trips | 0 | $\frac{1}{Year}$ | Determined by the authors |
| Train | Max. Occupancy Rate (Train) | 900**** | $\frac{Trip}{Train\ Trip}$ | [30] |
| | Coef 1 (Train) | -1.44 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Normal Waiting Time (Train) | 20 | $\frac{Minute}{Train\ Trip}$ | [18] |
| | Time to Change Perceived Time (Train) | 2 | Year | Determined by the authors |
| | Initial Average Time Per Trip (Train) | 35 | $\frac{Minute}{Train\ Trip}$ | [4] |

*** Number of vehicles used daily (not the fleet size).

***The average occupancy considers the different lines and its schedule. Therefore, the value assigned corresponds to 50% of the vehicle's capacity.

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Train | Time to Change Average Time Per Trip (Train) | 2 | Year | Determined by the authors |
| | Coef 2 (Train) | -1.55 | Dimensionless | Determined by Sensitivity Analysis, based on [6] and [7] |
| | Initial Train Fare | 5 | $\frac{\$}{Train\ Trip}$ | [31] |
| | Time to Change Perceived Price (Train) | 2 | Year | Determined by the authors |
| | Subway Train Adjustment | 0.05 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Initial Vehicles (Train) | 140***** | Vehicle (Train) | [30] |
| | Vehicle Discard Time (Train) | 30 | Year | [29] |
| | Normal New Vehicles Time (Train) | 10 | Year | [28] |
| | Time to Correct Vehicles Line (Train) | 2 | Year | Determined by the authors |
| | Time do Change Average Discarded Vehicles (Train) | 2 | Year | Determined by the authors |
| | Max Trips per vehicle (Train) | 1,825 | $\frac{Subway\ Trip}{Vehicle\ (Train) \times Year}$ | [30] |
| | Time to Correct Vehicles (Train) | 2 | Year | Determined by the authors |
| | Time to Form Trend in Train Trips | 3 | Year | Determined by the authors |
| | Time Horizon for Expectations (Train) | 0 | Year | Determined by the authors |
| | Time to Change Perceived Train Trips | 2 | Year | Determined by the authors |
| | Initial Perceived Trend in Train Trips | 0 | $\frac{1}{Year}$ | Determined by the authors |
| Road | Normal New Lanes Time | 6 | Year | Determined by expert interviews |
| | Deterioration Time | 20 | Year | [32] |

***** Number of vehicles used daily in the city of Rio de Janeiro (not the fleet size).

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Road | Normal Time to Repair | 3 | Year | Determined by expert interviews |
| | Time to Correct Lanes Line | 2 | Year | Determined by the authors |
| | Time to Correct Lanes | 2 | Year | Determined by the authors |
| | Desired Congestion Level | 0.6 | Dimensionless | Determined by expert interviews |
| | VKT per lane | 1,157,000 | $\frac{\text{Kilometer}}{Lane \times Year}$ | [33] |
| | Initial Perceived Trend in Lanes Growth | 0 | $\frac{1}{Year}$ | Determined by the authors |
| | Time to Form Trend in Expected Growth in Lanes | 3 | Year | Determined by the authors |
| | Time to Change Time in Repair | 2 | Year | Determined by the authors |
| | Initial Total Lanes | 7530 | Lane | [4] |
| | Percentage of GDP spent on Transport Infrastructure per Year | 0.00009 | $\frac{1}{Year}$ | Based on [1] and [34] |
| | GDP Growth Rate | 0.067 | $\frac{1}{Year}$ | [1] |
| | Initial GDP | 354,981,000,000.00 | $ | [1] |
| | Initial Lane Cost | 155,000 | $\frac{\$}{Year}$ | Based on [35], [36], [37], [38], [39] and [40] |
| | Initial Lane Repair Cost | 45,600 | $\frac{\$}{Year}$ | Based on [35], [36], [37], [38], [39], [40] and [41] |
| | Lane Cost Adjustment | 0.025 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| | Lane Repair Cost Adjustment | 0.025 | $\frac{1}{Year}$ | Determined by Monte Carlo experiments |
| Congestion | $\alpha$ | 0.15 | Dimensionless | [42] |
| | B | 4 | Dimensionless | [42] |
| Pollution | Initial $CO_2$ Emissions | 0 | Kg $CO_2$ | Determined by the authors |

Table B.2. Parameters for Rio de Janeiro (Continued)

| Sector | Parameter | Value/Equation | Unit | References |
|---|---|---|---|---|
| Pollution | Kg $CO_2$/Km (Bus) | 1.28 | $\frac{\text{Kg } CO_2}{Kilometer}$ | [43] |
| | Kg $CO_2$/Km (Ride-hailing) | 0.19 | $\frac{\text{Kg } CO_2}{Kilometer}$ | [43] |
| | Kg $CO_2$/Km (Car) | 0.19 | $\frac{\text{Kg } CO_2}{Kilometer}$ | [43] |
| | Kg $CO_2$/Km (Subway) | 3.16 | $\frac{\text{Kg } CO_2}{Kilometer}$ | [43] |
| | Kg $CO_2$/Km (Train) | 3.16 | $\frac{\text{Kg } CO_2}{Kilometer}$ | [43] |
| | Average Trip Distance (Bus) | 10.2 | $\frac{Kilometer}{Bus\ Trip}$ | [4] |
| | Average Trip Distance (Subway) | 11.6 | $\frac{Kilometer}{Subway\ Trip}$ | [4] |
| | Average Trip Distance (Train) | 20.5 | $\frac{Kilometer}{Train\ Trip}$ | [4] |
| Score | Pollution Weight | 0.5 | Dimensionless | Determined by the authors |
| | Congestion Weight | 0.5 | Dimensionless | Determined by the authors |

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