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ENHANCING THE PRECISION OF THE CELL TRANSMISSION MODEL FOR UBRAN MOBILITY PLANNING

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GABRIEL ROSSI FIGLARZ

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This Master Thesis has been submitted in partial fulfillment of the requirements for the degree of Master in Computer Science, of the Computer Science Graduate Program, School of Technology of the Pontifical Catholic University of Rio Grande do Sul

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APRIMORAMENTO DA PRECISÃO DO MODELO DE TRANSMISSÃO CELULAR PARA PLANEJAMENTO DE MOBILIDADE URBANA

RESUMO

No gerenciamento de mobilidade urbana, rotas de ônibus devem ser modificadas e até mesmo adicionadas novas. Para isso, identificar e entender o comportamento de tráfego é proporcionado pela simulação de trânsito usando ferramentas computacionais. Modelos matemáticos usados nas simulações aproximam-se do comportamento do trânsito. Este trabalho aplica modificações do Modelo de Transmissão Celular (CTM) para simular comportamento de trânsito para implementação de gerenciamento de rotas de ônibus. O modelo, chamado CTM*, foi implementado em um *script* de *python* e adicionadas regras para simular interferências no trânsito e diferentes tipos de veículos. Além disso, o CTM* proporciona o tempo de viagem e a identificação de gargalos. O modelo foi validado em uma parte da cidade de Porto Alegre, Brasil. O tempo de viagem simulado foi comparado com dados do Google Maps e obtido uma diferença de 5.88%. Com o CTM* validado, um ônibus foi inserido no modelo. Adicionalmente a isto, um cenário com as condições completamente saturadas foi introduzido no modelo para simular uma situação de congestionamento. A simulação permitiu observar posições críticas no caminho e congestionamento devido aos atrasos do ônibus. O CTM demonstrou a simulação de diferentes condições do trânsito com êxito. O modelo permite a implementação de diferentes cenários e é influenciado por obstáculos e tipos de veículos.

Palavras-Chave: Simulação de Trânsito, Modelo de Transmissão Celular, Mobilidade Urbana.

ENHANCING THE PRECISION OF THE CELL TRANSMISSION MODEL FOR URBAN MOBILITY PLANNING

ABSTRACT

In urban mobility management, bus routes must be modified and added new ones. For this, identify and understand traffic behavior is proportionate by traffic simulation using computational tools. Mathematical models used in the simulation can approximate the actual traffic behavior and even predict it. This work applies modifications in the Cell Transmission Model (CTM) to simulate traffic behavior for bus routes management. The model, called CTM*, was implemented in a python script and added rules to simulate interference in traffic and different sizes of vehicles. The model's rules simulate different types of vehicles, the presence of traffic lights and bus stops to intervene in the traffic flow. Additionally, the CTM* is capable of providing the travel time of vehicles and generating a data frame for assessing the situation of the traffic flow during the simulation and identify bottlenecks. The model was validated in a district located in the city of Porto Alegre, Brazil. The simulated travel time was compared with Google Maps data and obtained a difference of 5.88%. Once the CTM* is validated, a bus was inserted in the model. In addition to that, a saturated scenario was introduced in the model to simulate a situation of extreme congestion. The simulation allowed the observation of critical spots in the path and congestion due the bus delays.The CTM* has demonstrated to simulate traffic conditions successfully. The model allows the implementation of different scenarios and is influenced not only by obstacles like traffic lights and bus stops, but different types of vehicles.

Keywords: Traffic Simulation, Cell Transmission Model, Urban Mobility.

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1. INTRODUCTION

According to the United Nations (UN), the world's population is expected to reach over 9 billion people by the end of this century [24]. Additionally, 68% of the total population is projected to live in urban areas. The process of urbanization affects all sizes of settlements, villages become small towns and small towns become big cities [33]. Expansion of city borders, driven by increases in population leads to expansion of these borders, swallowing up neighborhoods and urban areas, becoming a megacity.

Unplanned growth creates a sprawl of the population and increases the demand for services like water supply and sanitation, housing, health, and urban mobility [33]. Considering these facts, mobility is a topic that is worth being studied in order to improve the means of circulation operation. Besides providing the citizens with a life quality, but also improve the efficiency of the city.

The ideal definition of urban mobility is the possibility for safe, clean, reliable, and affordable ways to get from A to B and go back. Unfortunately, population growth and car dependence lead to congestion, CO2 emissions, and safety problems. Besides that, mobility problems are expensive. According to the European Joint Research Center, the cost of road congestion in Europe is equivalent to an estimated 1% of gross domestic product (GDP) [11].

Brazil is the 6^{th} most populated country in the world. The current population reaches more than 212.000.000, 0,72% more than 2019 [32]. Additionally, according to the Brazilian Institute of Geography and Statistics (IBGE), nearly 85% of Brazilians live in an urban area. It is furthermore reported by the UN that the country's rate of urbanization is estimated to reach 90 percent in the next five years [20].

Among the most populated Brazilian cities, Rio de Janeiro's population grew 18% since 2001, reaching 17.2 million people [29]. Consequently, the city has huge mobility challenges, both concerning improvements in the quality of public transport and improvements in urban planning to reduce traffic congestion. For example, the city of Rio de Janeiro currently has three different rush hours. Besides the usual in the beginning of the morning and in the end of the afternoon, noon became another congested period on the streets [28]. A study in 2014 [27] estimated that in Brazil, for every 4 inhabitants, there is one car, thus increasing the competition of space on the streets and consequently, causing congestion.

Glancing the statistics, the demand for mobility solutions in various cities in the world is prominent. Collective transportation has the potential to solve several issues that urban mobility encounters, if well planned. Besides the capacity to transport multiple people at once, which reduces congestion, electric buses reduces pollution and can be GPS-tracked to provide precise location and arrival estimation, and more.

An actual methodology used by city planners and traffic engineers to analytically assess the traffic behavior is simulation. Simulation allows to study complex models and analyzes the results using computational resources and it is widely used in traffic modelling research [15]. By simulating and assessing the impacts of different routes for buses, eliminates the need for *in situ* tests and expands the possibilities for experimentation.

The simulation of bus routes allows the improvement of the city's performance in traffic. Implementing new routes or changing existing ones using traffic simulation models, opens the possibility of investigating different solutions and allows positive alternatives to be discovered.

The proposed work aims to expand an actual model for traffic simulation to increase its accuracy and expand the possibility of different results. Consequently, the model will provide more realistic results and approximate an optimal alternative when planning bus routes.

1.1 Motivation

According to [26], simulation software tools have many challenges concerning traffic. The heterogeneous nature of the problem from roads network to data allows development in the area of developing solutions to approximate the simulation accurately.

This work proposes to expand a consolidated traffic simulation model known as Cell Transmission Model (CTM) and expands its results. The enhanced model considers heterogeneity between vehicle types and the interference of obstacles such as traffic lights and bus stops.

1.2 Objectives

The main objective of this work is to increment an existing model that can be used by city authorities to simulate the impacts of adding or changing bus routes. Among the strategic objectives are the following:

- Identify a solid method of modeling traffic behavior
- Validate the model for traffic condition prediction
- Simulate impact of a bus in traffic flow

1.3 Textual Organization

The following chapters are organized as follows. Chapter 2 contains the theoretical background and related work concerning traffic simulation and models. In Chapter 3 is the proposed model, with the methodology and the means of validation. Besides that, in this chapter the results are displayed and discussed. Finally, in Chapter 4, the conclusions of the study are described and future works are recommended.

2. THEORETICAL BACKGROUND AND RELATED WORK

This chapter is divided into the studied traffic flow models, explaining the Lighthill Witham Richards model and advancing until the Cell Transmission Model. Subsequently, the related works in the area of traffic simulation and hydrodynamic models.

2.1 Traffic Simulation

Traffic modelling corresponds to recreate real traffic behavior in an analytical model [10]. This allows monitoring and forecasting of situations that can be solved before happening. Most vehicles are guided by people, therefore they are limited by their driver's decisions. Thus, a great challenge is to describe human actions to model it.

Acquire exact results is generally unlike in science, furthermore, if the data is essentially composed by human actions. An alternative is to compare traffic with an already consolidated model in science to grasp an acceptable approximation with reality.

Physics models such as many-particle systems, hydrodynamics and classical Newtonian mechanics are the most considered in the literature for traffic dynamics modeling [18]. Models based in hydrodynamic theories to simulate traffic dynamics have been commonly studied in literature [13]. For that reason, in this work the hydrodynamic model was chosen to explore due to the resemblance between the concepts of the traffic dynamics and hydrodynamics systems. The essentials of the model is to compare traffic with a fluid. Number of particles per unity of length, velocity and capacity are some of the concepts found both in traffic dynamics and hydrodynamics systems.

Traffic simulation can be represented by Microscopic, Macroscopic or Mesoscopic models. Microscopic simulation focus individually on each component of the traffic from people to change of lanes [18]. In the other hand, the Macroscopic simulation considers the traffic as a fluid flow with density and vehicle distribution in the path in a continuous stream. Mesoscopic integrates both Microscopic and Macroscopic models and can assess attributes from them.

Macroscopic simulation has demonstrated efficiency in large-scale simulations [35]. Besides that, it does not require numerous variables as comparing to the other types of models and it generalizes traffic network successfully, which allows the view of the entire system [5]. Therefore, in the best of our knowledge, the Macroscopic model is the most adequate for this study. This model was chosen once it allows the simulation of several streets at the same time, what allows a better understanding of the traffic behavior as whole.

2.2 Traffic Flow Models

2.2.1 The Lighthill Whitham Richards (LWR) Model

The Lighthill Whitham Richards (LWR) model (Equation (2.1)) for macroscopic traffic simulation considers the number of vehicles passing per street and length of the road network. The model describes the temporal evolution of the density as a function of flow gradients [31].

$$Q(x,t) = \rho(x,t) * V(x,t) \tag{2.1}$$

Where Q is the flow in position x and time t, ρ is the traffic density represented by the number of vehicles per unit of length, in position x and time t, and V is the local velocity in position x and time t. The traffic density ρ can be obtained by empirical counting of vehicles, image detection or even sensors, while the velocity V can be measured by speed sensors. For example, considering the follow situation:

$$Q([-30.059, -51.172], 9:49) = \rho([-30.059, -51.172], 9:49)V([-30.059, -51.172], 9:49) \tag{2.2}$$

In the case exemplified by Equation (2.2), the flow Q, in the position represented by the coordinates -30.059,-51.172 at the time t 9:49, is obtained multiplying the traffic density ρ at this same location at this same time by the velocity V at this same location, at this same time.

The LWR Model is a robust mathematical model in terms of resources to approximate traffic behavior. However, there are gaps that do not allow to identify causes of increase or decrease of the vehicle's flow. The model's limitations include the incapability of identifying the reasons of congestion formation and dissipation. Different types of vehicles or obstacles as traffic lights are possible causes of interference in the traffic flow. Therefore, the traffic's vehicles heterogeneity and obstacles are subjects worth studying for a model enhancement.

2.2.2 The Cell Transmission Model (CTM)

The CTM model, proposed by [9], is derivative from the LWR model to prevent traffic based on evaluating flow at a finite number of carefully selected intermediate points. The model consist in divide the road into homogeneous sections (cells). The length of the cells is defined as the distance traveled by a vehicle in light traffic considering one clock tick.

Therefore, under light traffic, is assumed that each vehicle advances to the next cell, on the next clock tick, represented by Equation (2.3).

$$n_{i+1}(t+1) = n_i(t), \tag{2.3}$$

where $n_i(t)$ is the number of vehicles in cell i at time t. This concept is represented on Figure 2.1.

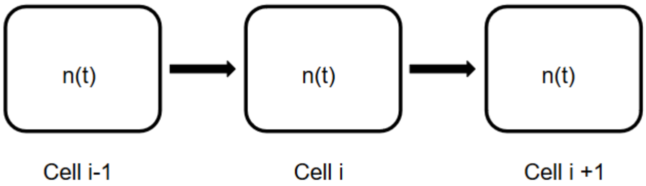

Figure 2.1 – Cell Model

Traffic jams are related to the formation of queues of vehicles, causing delays. If translated in the CTM, queues are formed by vehicles that want to advance to the next cell, but it is not available. To incorporate queues, two constants must be considered in the model, which is the maximum number of vehicles that can be present in cell i when the clock advances ($N(t)$), and the maximum number of vehicles that can flow into cell i when the clock advances ($Q(t)$) [9]. According to these parameters, the CTM is based on the number of vehicles in cell at time $t+1$ result of the occupancy at time t, plus the inflow ($y_i(t)$), and minus outflow ($y_{i+1}(t)$), as showing in Equation (2.4):

$$n_i(t+1) = n_i(t) + y_i(t) - y_{i+1}(t) \tag{2.4}$$

The flow ($y_i(t)$) represents the number of vehicles moving from cell i-1 to cell i in a time interval t (Equation (2.5)).

$$y_i(t) = min\{n_{i-1}(t), N_i(t) - n_i(t), Q_i(t)\} \tag{2.5}$$

There are some instabilities identified in the CTM. Drivers behavior can make the spacing between vehicles vary inside the cell. Complementing, is important to notice that the vehicles are not discretized by the type and size. Relying the status of occupancy of a cell exclusively on the number of vehicles is the same as considering that only cars circulate in a city. With the objective of making the CTM more precise, is proposed an expansion in the model. The expansion is called CTM* and introduces real world phenomena that interfere to the traffic flow. Vehicle's types heterogeneity is one of the model's expansions. As will be described in Section 3.1, a relation between the size of buses and cars can bring accuracy when determining if a section is congested. Along with the different types of vehicles, obstacles during the path like traffic lights and bus stops influence the flow as well.

2.3 Related Work

First, the state of the art regarding traffic simulation is presented in Section 2.3.1. Following in Section 2.3.2, relevant related works concerning hydrodynamic models are studied.

2.3.1 Traffic Simulation

A comparison from mathematical models for traffic simulation was studied by [12]. The study introduces usual concepts such as traffic flow, macroscopic and microscopic models and its formulas. It is approached that in most modeling approaches, road traffic is suitable for a fluid and therefore, automobiles are characterized by interacting particles. Subsequently, the authors test a study case using software SUMO (Simulation of Urban Mobility). In the work, the concepts of flow and vehicle's distribution on a network are explored. Considering a case study, the authors simulated traffic behavior with macroscopic hydrodynamic model and SUMO software. The work validates the use of hydrodynamic concepts simulating traffic with SUMO and comparing results. The validation reinforces hydrodynamic models relevance for traffic simulation.

Traffic simulation to analyze impacts in urban areas was studied by [40]. The construction of large scale projects attracts traffic to the surroundings and inevitably increases the flow of vehicles. Traffic history is used to forecast the behavior using techniques as regression analysis and trip generation model. For evaluating the traffic impact quantitative methods are considered, such as, service level of transport facilities and degree of surrounding roads and intersections of base development and construction. Complementing with rationality of the entrance, inside and outside architectural designing. The authors simulated the forecasting using a simulation software that input the community traffic distribution and evaluated the impact of new urban constructions in the traffic flow. The forecast feature in simulation demonstrates how important it is to assess impact in traffic.

The work presented by [1] brought the relevance of using mathematical techniques and computer simulation to understand traffic simulation. Developing a simulation software was possible to visualize graphically the behavior of traffic flow, what makes easier the understanding of mathematical concepts. Changing parameters as traffic flow and velocity and visualizing changes in the model, contributes with the idea of simulating models and try new approaches. The modelling flexibility shows to be useful to experimentation. Simulating different scenarios contribute for new approaches experimentation for urban planning.

The Water Flow Algorithm (WFA) was proposed by [34] with the objective of suggest decision for drivers in road traffic. The objective of the proposed algorithm with the suggestions to the driver is to re-engineer the road traffic. The model is based on traffic delay, density and degree of saturation, some different parameters from LWR model, but similar concepts of traffic situation. The methodology aims on finding a velocity of the flow that is considered satisfactory and update the optimal solution. Momentum caused by gravity as water flow is the main concept of the WFA. The model was validated comparing several decision alternatives of selected experimental parameters. Furthermore the results are successful on deriving the traffic delay decision in order to suggest route alterations for drivers. The evaluation of routes with an expanded model has demonstrated to be a resourceful approach in traffic modelling. Therefore, using a consolidated model and enhance features to achieve more precise results is a path worth exploring in the study.

A intersection simulation was made by [39] and analyzed the traffic behavior comparing with field data. In this paper the microscopic traffic simulation model was built to obtain the instantaneous vehicle behavior by transportation engineer theory and computer technology, and the inventory of traffic emission was calculated by IVE (International Vehicle Emission) model coupling with the model. The authors built an Urban Microscopic Traffic Simulation Model (UMTSM) that includes vehicle generation, network representation, traffic rule model, signal control and vehicle behavior model. Once the study case is simulated, became possible to obtain the emissions caused by traffic. The emissions values are coupled with the IVE model to obtain the emissions in the studied case. The model successfully represented quantitative evaluation between vehicle driving behaviors and vehicle fleet emission.

The *Open Street Maps* platform was explored by [37] to implement a prediction method in an specific area in China. The study focused on exporting the maps structure to a real time traffic broadcast platform. By integrating both, is possible to parse traffic information and using Machine Learning Techniques to predict approximately how is the traffic in the area.

Another study that aims to present a reliable travel time estimate system [17]. The authors refer to Smart Mobility an essential area of Smart Cities. Smart Mobility is considered a safe, reliable and efficient system. The Travel Time Reliability Estimation System proposed in this paper collects the data with sensors. The travel data calculation is based on traffic speed data collected from the loop-detector stations in a freeway corridor. Additionally, the system integrates multiple datasets to determine various time travel measures.

The presented studies related to traffic simulation have demonstrated adequacy in results approximate to reality. Besides that, according to the studies, simulation offers a level of customization in traffic features. These features allow new situations to be explored to experimentation and discover new alternatives.

2.3.2 Hydrodynamic Models

The foundation of every macroscopic traffic model are the hydrodynamic relation from Equation (2.1). The continuity equation describes the temporal evolution of the density as a function of flow differences or gradients [31].

A simulator based on the LWR model was built and validated by [23]. The validation is made by comparing the traffic performance with *Vissim*, a traffic simulation software. To make the comparison, the assessed parameters were percentage difference and linear regression and average delays. The model integrated macroscopic attributes with Petri Nets and microscopic attributes to provide vehicles platoon dynamics. This integration between microscopic and macroscopic modelling generates a mesoscopic model. The result was a simulation with a fixed 1000 vehicles per hour flow and varying the overloading of the street.

Considering the continuity equation, [6] proposed a 3 second prediction in traffic. Using Kalman filter to obtain traffic data in real time. For the traffic prediction, the authors model the traffic using LWR concepts. In this study, the probing data is particularly peculiar since it collects data from pairs of vehicles and computes based on the distance and time difference between them. The prediction technique appears promising since the prediction one step ahead presents 15% error. Additionally, is possible for the model to request more information since it works in real time.

Another study that contemplated the LWR model in order to simulate traffic was made by [38]. In the paper, the problem was focused to be discretized in the Lagrangian model. The state-space Lagrangian flow model was considered. Additionally, reformulating it and introducing an observation equation, gives the time-updates of the spacing, rather than the trajectories. Using as probe, GPS equipped vehicles, the Kalman filter was implemented in order to obtain real time data. The results were satisfactory and effective thanks to a pre linearization of the non linear model.

Based on the Equation of Continuity [25], transport flow is analyzed. It was proposed a method to approximate the observational data on the relationship between the flow density and the velocity of motion. To simulate a stochastic conditions, is supposed that some functions in the traffic model are random. Under these conditions, a mathematical model of traffic flow in stochastic conditions is proposed. It was proved that mathematical expectation of random solution is the solution of ordinary problem with initial, boundary conditions.

A study was made to demonstrate the credits and drawbacks of Cell Transmission Model (CTM) as a simulation model [7]. The studied case was in a disturbance and flow recovery scenario and evaluated the computational performance. Fictional road conditions were inserted in the CTM and a spreadsheet was built to simulate the traffic behaviour. Along with the data, the road disturbance is determined by the authors as well and the time it last. Analyzing the table, was inferred that the model is applicable for traffic network simulations, planning, monitoring and control due to its discrete and iterative updating nature. The possibility of changing the conditions of the cells, simulate sudden changes on road conditions. The authors suggest that the model can be implemented as a vehicular platform that integrates with *ad hoc* network communication.

A derivative from the Cell Transmission Model was proposed by [22]. With the objective to estimate traffic density on unmonitored locations, the study is based on standard linear systems. The model follows the conservation law and Continuity Equation. The addition to the CTM model that the proposed study offers is the description of the model as a hybrid system that switches between 5 sets of linear difference equations, depending on the congestion status of the cells. Although the results of density found with the proposed model and the CTM are similar, a challenge found during the work is the lack of available data.

Heterogeneity in Cell Transmission model was approached by [14]. The study proposed derivation of the cellular model in order to consider the behaviour of heterogeneous traffic under non-lane-based roadway conditions. Non linear equations are introduced to the original CTM in order to modify the behavior in a diagram. The data for this study is from a city's segment video cameras and were analyzed using an object detection algorithm. With the real data, was possible to compare with the proposed model. Speed, flow and density were simulated and validated according with the real data. It was proved that the proposed model can capture traffic behavior accurately since it considers vehicle's different speeds. However, capturing quality traffic data was one of the biggest challenges experienced during the study.

Driver's behaviour is also considered a heterogeneity in traffic. An improvement in the CTM by introducing merge ratio to describe the effect of the driver's behaviour at a merge and diverge section was proposed by [19]. The study case was a expressway in China with complicated geometry and mandatory lane changes what sources traffic congestion regularly. The modified CTM model proposes variable cells sizes and shapes to fit on the complex expressway geometry. The traditional CTM does not considers lane changing, so the modified model introduces a "merge area", which is a typical segment of the road that cars usually change lanes due a mandatory merge. Data was collected from traffic volume detectors and speed detectors installed on the expressway. Considering the data and proceeding to simulation allowed obtaining the cell density, delay and the spatiotemporal evolution diagram of the expressway traffic flow. The results of the modified CTM model provides the observation of the points of the road when merging occurs as dispersion as well. Along with the critical points, due the fact that the terminal cell has limited capacity, it was possible to observe that a queue is formed in some off-ramps, creating a bottleneck.

A Variable Cell Transmission Model (VCTM) is proposed by [36]. The modification in the original model is the introduction of different types of cell, as simple connection, merge connection, and diverge connection. Another modification is the possibility of changing the cell's length, what allows that large segments can be analyzed with less computational cost. The concept of the types of cell is differentiated from the original CTM by adjusting the Conservation Law and the relation between inflow and outflow from the cells. This translates the process of queuing, transmission and evacuation. The cell's length is not limited by the distance a vehicle travels in free stream in a time interval, which allows the cells to adapt to the road's geometry. The data to be used in the simulation, the authors used a traffic flow detection equipment and implemented in a simulation software to obtain the traffic flow on each cell. The simulation using the VCTM is compared with the same study case in the simulation software and considered suitable for traffic forecasting. The successful of the results is considered due the capacity of the model to offer different cell sizes, what permits suitability for different kinds of roads. However, the model considers that the traffic distribution inside the cell is uniform. This affirmative is not entirely accurate since spacing between vehicles and gaps can vary.

For a better understanding of the state of the art's gaps, the approaches are represented in Table 2.1. The numbers of each row represent a criteria that is covered in the respective author's study according to the used model either LWR or CTM. Number **(1)** being simulation with real data, **(2)** a validated model, **(3)** if the proposal assesses queue formation, **(4)** considers different vehicles, **(5)** if considers obstacles in the path and **(6)** if is a real time modelling.

Table 2.1 – State of the Art's Approaches

Authors	**(Model)**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
[23]	LWR	✓	✓				
[6]	LWR	✓	✓				✓
[38]	LWR			✓			
[25]	CTM	✓	✓				
[7]	CTM	✓					✓
[22]	CTM			✓			
[14]	CTM	✓		✓			✓
[19]	CTM	✓	✓	✓			
[36]	CTM		✓	✓			

Although the CTM is a derivative model from the LWR, it is widely studied and considered consolidated [13]. In order to choose between the LWR and the CTM, the considered parameters are: **(1)** Accuracy, **(2)** Allows differences among vehicle's velocities, **(3)** Allows to implement different types of vehicles, **(4)** Precise location of queue formation **(5)** Allows implement obstacles as accidents **(6)** Prediction, **(7)** Inexpensive computational resources, **(8)** Possibility to expand area, **(9)** Possibility of dynamic alterations during simulation and **(10)** Required data easily found. It will be compared the following simulation approaches presented in Table 2.2.

Table 2.2 – Hydrodynamic Models Comparison

Features										
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
LWR	✓					✓	✓	✓		
CTM	✓	✓	✓	✓	✓	✓	✓	✓	✓	

As Table 2.2 shows, both LWR and CTM models present accurate results, are capable of predicting traffic behavior, present inexpensive computational resources and allow expansion in the modeled area. The main difference between the methodologies is that CTM grants customization as differentiation between types of vehicles and implementation of obstacles in the path. Besides that, the CTM has a microscopic simulation feature that indicates the location of congestion and vehicle queues. However, none of the models' input data are easily found. Meaning that data acquisition is a challenge regardless of the model.

3. PROPOSED MODEL AND CASE STUDY

Section 3.1 demonstrates the improvements proposed in the original CTM, calling the modified model CTM*. In Section 3.2 the computation of cell's parameters are mentioned and also an example is described. The study case for this work is presented in Section 3.3. In this section all the characteristics and features extraction of the designated path are described. Section 3.4 describes the process of validating the CTM* implementing the model in the study case. The results can be assessed in Section 3.5. In Section 3.5.1 an individual vehicle is simulated and the model validated, followed by Section 3.5.2 where a bus is implemented in the CTM* and then, Section 3.5.3 where an extreme saturated scenario in considered in the simulation. Finally, in Section 3.6 the obtained results are summarized and discussed.

3.1 The CTM*

The dynamic of the flow in cells located previously traffic lights behave in a particular way. Therefore, one of the enhancements we proposed in the CTM traffic flow equation based on the lectures of Boyles [4] varies depending on the traffic light state. If the traffic light is red means that no vehicle shall be transmitted to the following cell, resulting in a null flow. The relation between the vehicle's flow whether the light is red or green is represented in Equation (3.1). If the light is red, no vehicle shall be transmitted to the following cell, if the light is green, the flow is computed by the second therm of the system of equations.

$$y_{light}(t) = \begin{cases} 0 & \text{if light is red} \\ min\{n_{i-1}(t), N_i(t), Q_i(t) & \text{if light is green} \end{cases} \tag{3.1}$$

In this case, the position i has no vehicles in the cell, once it represents the position of the traffic light. For that reason, it was considered $n_i(t)$ from Equation (2.5) to be equal to zero.

Although the original logic presented by [4] contributes to the traffic light insertion in the CTM, there are limitations. Besides not computing the travel time, the model considers only one traffic light at the end of the path whilst the CTM* allows multiple traffic lights. The traffic lights dynamic follows Equation 3.1 reproducing the behavior of red and green lights in the path. Thus, multiple traffic lights in the path are considered in simulation.

Another modification proposed to the model is to consider the size of different types of vehicles. According to Section 2.2.2, as previously discussed, the Cell Transmission Model does not differentiate the type of vehicle that occupies the cell. The objective of this feature of the CTM* is to offer this differentiation based on the size of the vehicles. Individual vehicles, like cars, occupy less space in the cell when comparing to buses, for example. The space occupied by vehicles is defined as the length of the vehicle plus a gap considered on the front as Figure 3.1. SUMO (Simulation of Urban Mobility) [16], a simulation software considers in the documentation [30] the following length for car and bus according to Table 3.1.

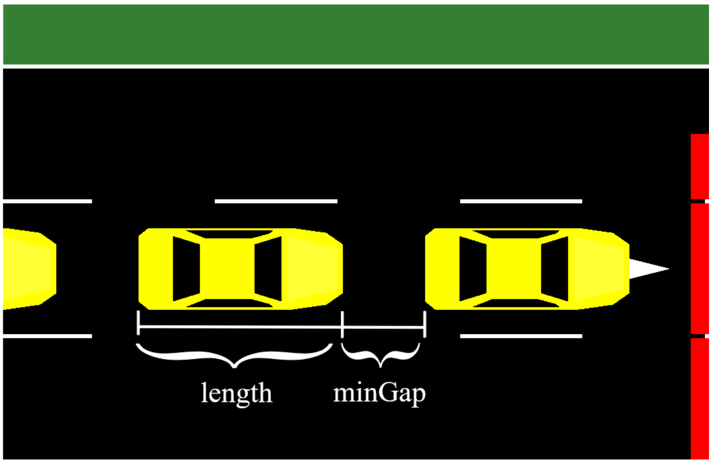

Figure 3.1 – Vehicle Length

Table 3.1 – SUMO's Vehicle Length.

Vehicle Class	**Length(m)**	**min Gap(m)**
Passenger	4.3	2.5
Bus	12	2.5

For this work, we will consider the total length for cars 7m and 15m for buses. Rounding this values, will be considered that a bus represents the occupied space by two cars. Subsequent to this relation is possible to understand the relevance of the differentiation of the vehicle type in the cell. In the original CTM, if the capacity of a cell is 2 vehicles and contains 2 cars, it is considered full, meanwhile, in the CTM*, the cell is considered full also with only one vehicle if this vehicle is a bus.

The procedure of calculations will follow the same as the example in Section 2.2.4, but with a discrimination of the type of vehicle. The heterogeneity of vehicles will be considered in the input parameter of the table classifying vehicles by type. The proposed relation between the length of a car and a bus is represented in the follow equation:

$$l_{bus} = 2l_{car} \tag{3.2}$$

Often buses have to stop to board and disembark passengers independently of the traffic lights. This generates an increase in bus travel time and the possibility of congestion.

Thus, to simulate these bus stops, the CTM* allows determining when a bus should make a stop through the path. When a cell that contains a bus stop is reached by a bus, it remains for one extra simulation time step in it. Considering $t_{busStop}$ as the time step that a bus arrives in a cell containing a bus stop, Equation 3.3 demonstrates how the flow is computed only for the bus. The flow is null in the time step the bus arrives the cell, meaning that it cannot advance for one time step. In the following time step, the bus' flow is computed normally and subsequently for the other vehicles as well.

$$y_i(t) = \begin{cases} 0 & \text{if t} = t_{busStop} \\ min\{n_{i-1}(t), N_i(t) - n_i(t), Q_i(t) & \text{if t} = t_{busStop}+1 \end{cases} \tag{3.3}$$

The proposed CTM* aims to simulate the influence on the vehicle's flow caused by different types of vehicles, traffic lights and bus stops through the whole path. The premise is to apply the Equations (2.4) and (2.5) in the cells between traffic lights to control the flow and the cell's occupancy depending on the traffic light condition and bus stops occurrences. Equation (3.1) is used to simulate the impact traffic lights do on the flow. Besides that, to obtain the travel time, a vehicle throughout the path is monitored.

3.2 Cell's Parameters

First, the studied street was divided in the adequate number of cells. According to Equation (3.4), the size of the cell Δx is determined by the distance a vehicle can travel at the maximum allowed speed v, in one simulation time step Δt.

$$\Delta x = v * \Delta t \tag{3.4}$$

With the size of the cells, through Equation (3.5), the number of cells in the street is obtained. Considering l the length of the street:

$$z_{cells} = l/\Delta x \tag{3.5}$$

The traffic flow Q is the maximum number of vehicles that can flow through the cell. Equation (3.6) multiplies the maximum flow of the street by the time step considered.

$$Q = q_{max} * \Delta t \tag{3.6}$$

The maximum capacity of a cell, N, is calculated in (3.7). Considering k_{jam} as the jam density and Δx from Equation (3.4). The jam density k_{jam} is the number of vehicles that fit in one kilometer, obtained dividing 1000m per the length of the considered vehicle. In the studied case, we are considering 7m as typical vehicle length.

$$N = \Delta x * k_{jam} \tag{3.7}$$

A table with storage, inflow and outflow information from each cell was built. With this table is possible to assess how the vehicles are distributed along the street and the formation of queues, evaluating the traffic behavior.

An example of CTM simulation [21], considers a 1.25km street with speed of 50km/h, the jam density k_j is 180 veh/km and the maximum traffic flow q_{max} = 3000 veh/h. Initially traffic is flowing at a rate of q = 2400 veh/h. Considering that a lane is blocked for 2 minutes and happening at $2/3^{rd}$ of the road's length and that this blockage restricts the flow to 20% of the maximum. After the 2 minutes, the flow in cell 3 reaches its maximum value of flow. According to [2], the average time a vehicle remains still in traffic lights is 27 seconds, which in this study, the clock tick is considered to be 30 seconds. Adding the time spent in traffic lights with the previous information, is possible to predict traffic evolution.

First is necessary to determine the cell's length and number of cells. Considering the clock's tick as $1/120^{th}$ of an hour (30s). So, cell length according to Equation (3.4), is the multiplication of 50 per (1/120) resulting in 5/12 km. Once the road length is 1.25km, according to Equation (3.5) dividing it by the size of the cell, results in 3 cells total.

The next step is to determine the Q and N. N, the maximum number of vehicles that can be in cell i at time t is determined by multiplying cell's length by jam's density, as is showed in Equation (3.7). By multiplying 180 per (5/12) is possible to affirm that 75 vehicles fit inside the cell.

Parameter Q, is the maximum number of vehicles that can flow to the next cell in the next time step, as showed in Equation (3.6), is result of the multiplication of q_{max} by the time, resulting in 25 vehicles from cell i from time t to $t+1$.

To determine the number of vehicles in the cell, we multiply the flow, by the time. In the example, for 20% of the flow capacity, multiplying 600 per 1/120 results in 5 vehicles,. In the other scenario, with 80% of the flow, the number of vehicles in the cell is 20 vehicles and flow with full capacity, is 25.

With this information in hand, the next procedure is create a table to follow the cells occupancy process. The occupancy is determined by the Conservation Law in Equation (2.4), translated as Occupancy = Storage + Inflow - Outflow. Analyzing cell 1 at time 2, the storage is 20 and the inflow and outflow results in 20 vehicles. The outflow results also in 20 vehicles. According to Equation 2.4 results in 20+20-20 = 20 vehicles in the cell.

Filling the table successively with the steps above, Table 3.2 shows the results found. Each row is a time step from 1 to 18. The entry column has a fixed rate of 20 vehicles entering the system at each time step. The following columns represent the number of vehicles at cells 1 to 3 as exemplified previously.

We can observe that the number of vehicles in cell 1 and 2 increases due the blockage at lane 3 and after, when the lane is not blocked, the situation normalizes. Another factor is the occupancy at cell 2 almost reaches the maximum capacity, which is 75, this represents the formation of a queue and decrease in the velocity in the traffic flow.

Table 3.2 – Example Solution's Table

time step	**Entry**	**Cell 1**	**Cell 2**	**Cell 3**
1	20	20	20	20
2	20	20	35	5
3	20	20	50	5
4	20	20	65	5
5	20	30	70	5
6	20	45	50	25
7	20	40	50	25
8	20	35	50	25
9	20	30	50	25
10	20	25	50	25
11	20	20	50	25
12	20	20	45	25
13	20	20	49	25
14	20	20	35	45
15	20	20	30	25
16	20	20	20	25
17	20	20	20	20
18	20	20	20	20

3.3 The Study Case

In order to validate the CTM*, a study case was analyzed in a determined path in the city of Porto Alegre, Brazil. The selected route for the simulation is located at Avenida Bento Gonçalves between numbers 8850 and 6992 as can be observed in Figure 3.2. The initial point is represented by A and the destination by B.

Besides the path, traffic lights were located and included in the model for a more accurate simulation. The traffic lights positions can be visualized in Figure 3.3. Additionally, lights are considered to remain green and red in a cycle of 30 seconds each.

For the system to be initialized, data with the flow of vehicles and a 5 seconds time step interval were implemented in the model. The Public Transportation and Circulation

Figure 3.2 – Road Network Map

Public Company (EPTC) from Porto Alegre's City Hall, has 45 detectors distributed in the city that monitor speed and counts the number of vehicles.

According to a report provided by EPTC, during the year of 2019, the average vehicles passing at 10 AM by the detector located at the begin of the selected path for the study is a rate of 3.79 vehicles at each time step.

3.3.1 Road Network

Data concerning the streets are available in Open Street Maps (OSM) [8] platform. Among the data, the length of the streets, direction, and maximum speed allowed were considered for the study case. The library *OSMnx* [3] from the programming language *python* was used to extract these data.

The street geometry from OSM is converted to a graph by *OSMnx* [3]. The library downloads the maps using OSM APIs and interprets it as nodes and links network. This transformation turns the streets into links and the intersections into nodes. Figure 3.4 demonstrates an example of the path representation where the blue dots are the nodes and the lines between them are the links.

The street data acquirement is important to calculate the cell's parameters. To locate the streets considered for the study case, the data set extracted from Open Street Maps was manipulated using another *python* library called *pandas*. The library allows to search, edit, query, among other features applied to data frames. Data concerning the

Figure 3.3 – Traffic light location. Source: Open Street Maps

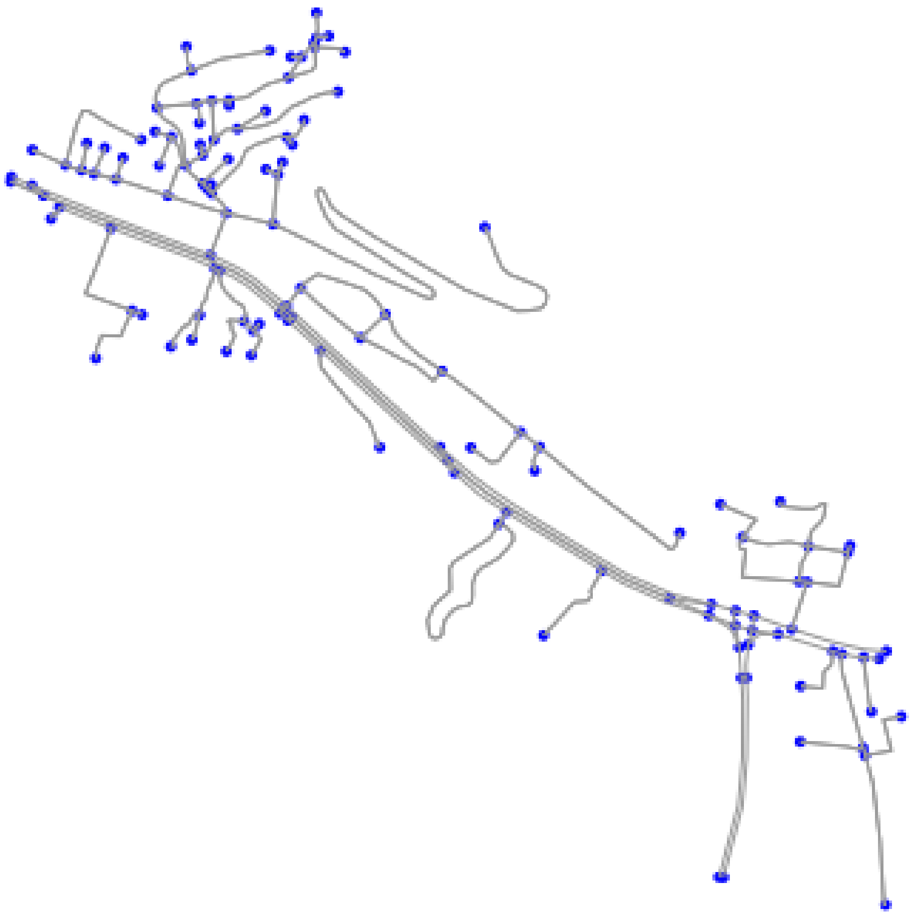

Figure 3.4 – Road Network Map

path's link numbers, name of the street, maximum speed, and length can be observed in Table 3.3. The length of one link to the following is considered to be the distance of each intersection. Therefore, since the traffic lights are not necessarily in every intersection, but can also be located in between nodes such as the origin and destination points, the length was not considered in this study. Nevertheless, the maximum speed allowed in the street is essential information to compute the following cell's parameters.

Table 3.3 – Street Data. Source: Open Street Maps

Link	Name	Max. Speed(km/h)	Length(m)
16684	Avenida Bento Gonçalves	60	45.53
16687	Avenida Bento Gonçalves	60	233.16
21247	Avenida Bento Gonçalves	60	274.83
17236	Avenida Bento Gonçalves	60	89.95
26372	Avenida Bento Gonçalves	60	42.718
26374	Avenida Bento Gonçalves	60	1434.31
13959	Avenida Bento Gonçalves	60	601.89
17230	Avenida Bento Gonçalves	60	93.50

3.4 Validation

The CTM* validation is described in this section. Data concerning traffic flow from the city of Porto Alegre, Brazil, was incorporated in the model and compared to Google Maps travel time information.

3.4.1 EPTC

The steps to be taken in order to put the CTM* in use are divided in data collection and the modelling itself. EPTC (Empresa Pública de Transporte e Circulação de Porto Alegre) has 45 sensors that collect the number of vehicles passing on determined intersections.

This data provides the traffic flow. Additionally, with the data, as explained in Section 3.3, the number maximum of vehicles that can flow in one cell and the cell capacity as well with Equations (3.6) and (3.7) is obtained.

To simulate the traffic flow between the cells the table was filled. The increase and decrease of the of vehicles in each cell is expected to be observed. This information allows to analyze if the street has more demand than supply, resulting in congestion.

To validate the model using EPTC's data, the results were compared with information provided by a Google Maps API. In the condition of the traffic flow in a determined street behaves similarly to the traffic behavior provided by Google API, is possible to infer that the model is correct.

3.4.2 Cells and Street Parameters

Specific parameters were calculated for the cells. Equation (3.4) computes the cell's size by multiplying 60 km/h which is the maximum speed allowed on the street v by the time step Δt, which is a time step of 0.0014 hour (5 seconds). The computation results in a cell with 83m of size.

After computing the size of the cells, they were distributed in the pathway. As mentioned in Section 3.3.1, the length obtained in Open Street Maps is the distance between intersections and is not suitable for this study. Thus distance between traffic lights was computed manually with Google Maps (shown in Table 3.4). The distance of each path between traffic lights is divided by the size of the cell. Table 3.4 contains the round number of cells that each path contains and results in a total number of 29 cells.

Table 3.4 – Cells Division

Traffic Light	Distance(m)	Number of Cells
1	140	2
2	260	3
3	170	2
4	170	2
5	270	3
6	70	1
7	530	6
8	70	1
9	490	6
10	270	3
Total	2440	29

An example of the first traffic lights division is represented in Fig 3.5. The gray rectangles represent the cells that fit in the distance between the four first traffic lights. This division inside the path allows to coordinate the flow between cells according to the color of the traffic light.

The density of the congested traffic is represented by k_{jam}. This means the maximum amount of vehicles that can be accommodated in one kilometer. As mentioned in Section 3.1, an individual vehicle occupies a 7 meters space. Therefore this value is considered for computing k_{jam} resulting in 142.86 vehicles/km.

To determine the maximum flow that the network supports, the q_{max} parameter was computed. The maximum flow is obtained multiplying k_{jam} by the maximum speed allowed on the street. The maximum flow in the network results in 8571.42=3 vehicles/hour

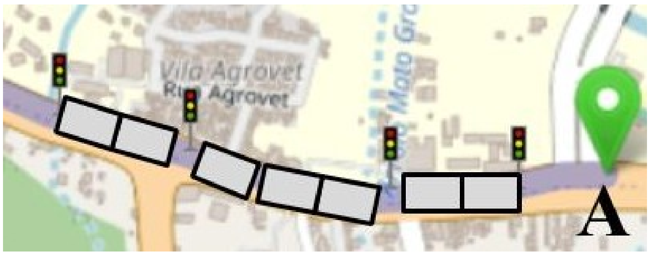

Figure 3.5 – Example of cells division Source: Open Street Maps

The maximum flow between cells was determined. Equation (3.6) describes that this value is obtained multiplying the maximum flow in the network by the time step. Therefore, by multiplying q_{max} by the time step results in 12 vehicles per time step allowed to be transferred.

The following parameter to be obtained was the cell capacity. Equation (3.7) multiplies the previously calculated size of the cell Δx by the density of the street in a traffic jam scenario k_{jam} resulting in 11.85 vehicles per cell. The value will be rounded to 12 during the simulation.

With the parameters computed, the next step is to create a system that applies the CTM's equations in every cell at each time step. In order to simulate traffic lights interference, Equation (3.1) is considered to compute the flow in its correspondent cells.

3.5 Results

Section 3.5.1 describes the process to validate the model comparing the travel time with Google Maps data. In Section 3.5.2 a bus is incremented in the CTM* and bus stops influence in its trajectory through the path. To simulate the capacity of the CTM* to consider different states of the traffic condition, Section 3.5.3 demonstrates the impact of a saturated initial scenario to the vehicles flow.

3.5.1 Car Simulation

Initially, the cell's parameters were calculated. Subsequently, traffic light positions and time cycles were applied in the CTM*. Figure 3.6 represents the system divided in 29 cells according to Table 3.4 in their empty initial condition and with the traffic lights positioned in their equivalent cells. Every line represents a time step of 5 seconds. The columns with the letter y represent the flow calculated by Equation (2.5) or Equation (3.1) that will enter the cell of the respectively number. For example, in column *y1* is the number of vehicles that will enter cell *1* in the next time step and column *yLight1* is the number of vehicles that will be transferred through the first traffic light called *Light1* if the light is green. To visualize the cell's occupation, elements from columns with numbers are composed by a list of size equal to the maximum capacity computed by Equation (2.4). Every number on the list represents the slot's situation inside the cell. When the position is equal to 0, the slot is empty, if it has 1, is occupied by an individual vehicle.

Besides that, at each time step of 5 seconds, a rate of 3.79, according to EPTC data mentioned in Section 3.3 was rounded to 4 for simplification and inserted into the system. To compute the travel time of the path, a vehicle enters the system in the first time step and its position was monitored during the modeling.

	y1	1	y2	2	yLight1	Light1	y3	3	y4	4	...	yLight9	Light9	y27	27	y28	28	y29	29	yLight10	Light10
0	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green

Figure 3.6 – CTM in time step 0

Figure 3.7 shows an example that in time step 1, cell 1 has a line of 4 cars and, according to *y2*, 4 vehicles will be transferred to cell 2 in the next time step. In time step 2, since cell 2 already had 8 vehicles, the 4 vehicles that entered the cell are lined up behind them forming a queue and cell 1 is updated with more 4 vehicles according to *y1*.

	y1	1	y2	2
0	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
1	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]
2	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]

Figure 3.7 – Example

The CTM* was implemented in a *python* application. The program creates a data frame and calculates the traffic flow, number of vehicles, and its position inside each cell during a determined number of iterations. In Figure 3.8 there is a representation of a segment of this data frame. At each time step, the system iterates and updates the flow and the resulting situation of vehicles in every cell. The CTM* application features the queue of vehicles formation rule mentioned previously and demonstrated in Figure 3.7. Figure 3.8 shows the flow of vehicles behavior when the light is green in time steps 0 to 3. When the light is red, as in time steps 56 to 59, a line of vehicles in cell 1 is formed occupying the maximum capacity, which indicates congestion.

	y1	1	y2	2	yLight1	Light1	y3	3	y4	4	...	yLight9	Light9	y27	27	y28	28	y29	29	yLight10	Light10
0	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
1	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
2	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
3	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
56	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
57	4	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
58	4	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
59	4	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	...	0	Red	0	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red

Figure 3.8 – Example of data frame from application

The same logic exemplified is repeated at each time step. The control of the vehicle's position was monitored to obtain the travel time until the final destination. The vehicle reached the last cell of the system at a time step 51 corresponding to 255 seconds (4 minutes and 15 seconds).

The travel time throughout the proposed path, obtained from Google Maps during the year of 2019 at 10 AM, was on average 240 seconds (4 minutes) long. Table 3.5 compares the travel time obtained with the original CTM, the CTM*, and Google Maps travel time. Since the obtained travel time with the CTM* is corresponding to 255 seconds, the difference between both results is 5.88%. This means that the model is validated.

Table 3.5 – CTM Comparission with and without traffic lights

CTM (s)	CTM* (s)	Google Maps(s)
145	255	240

Moreover providing the travel time, the CTM* offers another important traffic information: queue formation. As represented in this section, is possible to monitor not only the vehicle trajectory, but the cell's occupancy. This indicates critical positions in the path that occurs vehicle's congestion and can aid in route planning avoiding critical streets.

3.5.2 Bus Simulation

In order to simulate a bus in the system, its length was considered. As proposed in Equation (3.2), the space of a bus is two times an individual vehicle's. It means that it is supposed to occupy two slots in the system's cells. The example in Figure 3.9 shows that a bus is represented in the cell as the number 2 and is doubled in order to occupy two slots. In time step 0, is possible to observe that cell 2 has three free slots and *y2* computed that in the next time step, 4 vehicles should be transferred from cell 1 to 2. Therefore, one of the rules programmed in the CTM* verifies if the space available is adequate to the type of the vehicle as Equation (3.8) demonstrates. The equation does not compute any flow for buses if the available space in the following cell is smaller than 2, which is the bus size. The flow is computed normally if the verified available space is greater than 2. Therefore, in time step 1, only two vehicles were transferred to cell 2 and the bus stayed in the same position in cell 1 due lack of space. In time step 2, cell 2 transferred 4 vehicles to cell 3, allowing enough space to receive the bus from cell 1.

	y1	1	y2	2	yLight1	Light1	y3	3
0	4	[0, 0, 0, 0, 0, 0, 0, 0, 2, 2, 1, 1]	4	[0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
1	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 2, 2]	4	[0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
2	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 2, 2, 1, 1, 1, 1, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]

Figure 3.9 – Example of bus in the system

$$y_i(t) = \begin{cases} 0 & \text{if N - } n_i < 2 \\ min\{n_{i-1}(t), N_i(t) - n_i(t), Q_i(t) & \text{if t = N - } n_i \geq 2 \end{cases} \qquad (3.8)$$

Another rule in the CTM* is to simulate eventual bus stops to board and disembark passengers. The rule makes the bus to remain in determined cells for one extra time step. This imitates the bus behavior when it has to halt for a bus stop during the path and blocks vehicles from behind it. The bus stops position were manually localized in Google Maps and considered to be in cells 3,7,14 and 20. When the simulated bus reaches the correspondent cell, it takes one extra time step to cross it.

The model was implemented exactly like in the car simulation in Section 3.5.1 but with a bus input in the first cell. As can be observed in 3.10, in cell 1, the bus was located between one car and a line of other two cars. Additionally, when the bus reaches the cells corresponding to the bus stops location, it does not move for one-time step.

Figure 3.10 demonstrates in a segment of the data frame how the bus stop rule works. Since there is a bus stop located in cell number 3, the bus in that cell does not advance to the next one in time step 3. The two cars located in front of this bus are free to be transferred to the next cell. However, there is one car located behind the bus and thus, cannot advance since the passage is blocked by the bus.

An important feature of the CTM* is the capacity to recognize congestion. In time step 4 from Figure 3.10, is possible to identify that the permanence of the bus in cell 3 causes a line of vehicles behind it. In the following time step, once the bus is transferred to cell 4, the line is unobstructed and the flow occurs normally until the next cell that contains a bus stop.

	y1	1	y2	2	yLight1	Light1	y3	3	y4	4	y5
0	4	[0, 0, 0, 0, 0, 0, 0, 1, 2, 2, 1, 1]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0
1	4	[0, 0, 0, 0, 0, 0, 0, 1, 2, 2, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0
2	4	[0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 1, 2, 2, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0
3	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 0, 1, 2, 2, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0
4	4	[0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 2, 2]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	4
5	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	Green	4	[0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 2, 2]	4

Figure 3.10 – Bus stop simulation

The dynamic proposed by the CTM* that considers the space that a bus requires in the cell and compares it with the availability as Equation (3.8) demonstrated. Additionally, the presence of not only traffic lights, but bus stops has not delayed the result of the travel time. However, it generated bottlenecks and traffic congestion as Figure 3.11 shows a congestion in cell 19 caused by the bus.

The exemplified CTM* features such as the consideration of types and sizes of different vehicles and interruptions in the flow caused by bus stops and traffic lights impacted directly the simulation. The CTM* achieved a level of trajectory detail that allows to identify bottlenecks location with precision and visually monitor vehicles individually.

	y19	19	yLight7	Light7	y20	20	yLight8	Light8	y21	21
36	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	11	Green	11	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
37	10	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	Green	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	11	Green	11	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
38	2	[0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	10	Green	10	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2]	11	Green	11	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]
39	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	Green	2	[0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	10	Green	10	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2]

Figure 3.11 – Congestion Example

3.5.3 Saturated Scenario

In the simulation so far, the system initial condition throughout the whole path is represented with zeros. However, it does not necessarily mean that the path is clear, but it means that there is no congestion. The traffic condition may vary and be more congested on some occasions. Thus, another scenario was simulated considering an extreme situation where the traffic is completed saturated.

Figure 3.12 represents the initial CTM* system condition when fully saturated. In this case, every cell is fully occupied by individual vehicles. The purpose of this is to exemplify the possibility to intervene in the system to create different scenarios. In this particular case, the bus travel time was delayed by the heavy traffic congestion. Due to the initial complete cell's occupation, the bus only managed to leave cell 1 after 145 seconds (2 minutes and 25 seconds) and arrived at the final destination at 550 seconds (9 minutes and 10 seconds). This is a considerable difference from the previous simulation that considered the traffic flow occurring normally. Therefore the state of the system introduces impact to the simulation and CTM* offers the possibility to edit it according to the desired simulation scenario.

The CTM* allows the user to manipulate the system's condition. Meaning that not only an empty path or a saturated one, as exemplified in this section, can be simulated. For example, an occasion where a street outside the system is blocked, for a determined segment of the path, vehicles are directed to the system. This particular case can be simulated by the user using the CTM* in any segment of the path. This CTM*'s feature provides the user to evaluate streets individual particularities, increasing its flexibility and adaptability.

3.6 Discussion

In Section 3.5.1, results indicated an approximate travel time comparing Google Maps and the CTM*. The collected data from Google Maps and EPTC is from the average

	y1	1	y2	2	yLight1	Light1	y3	3	y4	4	...	yLight9	Light9	y27	27	y28	28	y29	29	yLight10	Light10
0	4	[0, 0, 0, 0, 0, 0, 0, 1, 2, 2, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Green	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	...	0	Green	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	4	Green
1	4	[0, 0, 0, 1, 1, 1, 1, 1, 2, 2, 1, 1]	1	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	12	Green	12	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	...	12	Green	12	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	4	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]	8	Green
2	4	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	1	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	12	Green	12	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	...	12	Green	12	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	4	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]	8	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	Green
3	4	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	1	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	12	Green	12	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	...	8	Green	8	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	8	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]	8	Green

Figure 3.12 – Initial Saturated Scenario

travel time and passing vehicles during the year 2019 at 10 AM. Considering that the initial condition of the system represents that the flow of vehicles is occurring normally, the 5.88% difference between the real data and the travel time simulation is understood that the model is validated.

With the model validated, in Section 3.5.2, buses were inserted in the model to simulate the traffic behavior and its interactions with cars. In this case, queue formation was identified, as Figure 3.11 shows due to the increment of bus stops. However, although the presence of the bus impacted significantly the traffic flow creating queues, the travel time did not change compared to the previous simulation.

The reason for that is exemplified in Figure 3.13 where a segment of the car and bus simulation is compared. The monitored vehicle in car simulation and the bus are identified in the figure by the red line. The monitored car reaches cell 19 at time step 30 and encounters the red light. While the bus reaches cell 19 at time step 32 since it was delayed by the bus stops in the way. Regardless of the time step that the car or the bus reached the cell, due to the red light, both leave the cell at time step 36. Meaning that from that point on, both car and bus are synchronized until the next bus stop in cell 20 that delays the bus. The same event repeats at the next traffic light and synchronizes again the car and the bus. Once both vehicles are in the same cell at the same time one more time and there are no bus stops anymore, they reach the final cell at the same time.

Car Simulation

	17	y18	18	y19	19	yLight7	Light7
27	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
28	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
29	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]	8	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
30	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1]	8	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	Red
31	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
32	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	8	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
33	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
34	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
35	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	Red
36	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	12	Green
37	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	12	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
38	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	12	Green
39	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]	4	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green

Bus Simulation

	17	y18	18	y19	19	yLight7	Light7
27	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
28	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
29	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	Green
30	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2]	11	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	0	Red
31	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2]	11	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	0	Red
32	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	10	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	0	Red
33	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	0	Red
34	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	0	Red
35	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	0	Red
36	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	0	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	2	[1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 1]	11	Green
37	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	[0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	10	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	Green
38	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	[0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	10	Green
39	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]	0	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]	2	Green

Figure 3.13 – Car Simulation vs. Bus Simulation

Another case was studied in Section 3.5.3 where the CTM* was introduced to a complete saturated scenario. Every cell was fully occupied by vehicles, interfering in the vehicles' transmission. This implicated in a travel time much greater than the previous simulations resulting in 550 seconds. The saturated scenario means that the whole path is in a congestion state, which makes it difficult for the traffic to flow between the occupied cells and must wait until a vacant space. This scenario was able to exemplify that the CTM* can simulate cases considering a predisposition and biased condition. Meaning that the user can insert different situations in the system to evaluate how traffic is impacted. For example, as mentioned previously, a street blockage can dissipate vehicles to different paths, increasing the demand for different streets.

4. CONCLUSIONS AND FUTURE WORKS

The presented study proposed an enhancement in the original Cell Transmission Model. The goal of the enhanced model, called CTM* is to provide to traffic planners and authorities a reliable simulation tool for bus lines management. The CTM* allows to simulate the addition and modification of bus routes and its impacts on the current traffic conditions in the city. This methodology optimizes the decision of which streets the bus should pass through based on the travel time and the congestion that it would encounter. Therefore, the CTM* not only reflects the impact of the traffic to the bus, but also transfer the impact of the bus presence to the rest of the traffic components.

The CTM* was implemented in a *python* application. In this application, a data frame is generated according with every row representing the time step of the simulation and the columns represent the cells and traffic lights positions. The vehicles are transferred between cells according to the original CTM criteria but have to follow rules added to the CTM*. One of them successfully only allows transfers of vehicles between traffic lights if the light is green. Another programmed rule assess the available space in the cell to be transferred to. The model allows only the transmission of vehicles suitable for that space. If there is no vehicles transmission, a queue is formed behind the vehicle. Additionally, periods of traffic lights and bus stops are considered and influence in the traffic flow generating delays.

The model was validated using data provided by EPTC and compared to travel time acquired from Google Maps. In this part, the traffic lights were mapped in the path and a vehicle was monitored during the designed path. The travel time result obtained differs 5.88% from the real information and thus, was considered validated.

The CTM* has demonstrated to be flexible for editing and grants the possibility for the traffic planner to create different scenarios in the traffic. As exemplified in Section 3.5.3, extreme cases can be introduced to the model to simulate specific events. This feature can be used to understand the impact of a bus travel in predetermined schemes as in days of sports matches in the city or other events, for example.

Aside from the mentioned rules that the CTM* follows, a relevant improvement was the model programmed in *python*. This allowed the model to be scalable and replicable. Meaning that the model works with any path in any city. Since the CTM* requires a small number of inputs, it is successfully capable of generalize the bus path in different scenarios with a feasible amount of data.

The proposed enhancement in the CTM has demonstrated to require inexpensive computational resources, to be self-adaptive, and to abstract real situations during the simulation process. The model output is a data frame with text that can be easily assessed using the mentioned *python* libraries. The rules in the program that concern the size of the vehicle consideration during the transmission and the influence of the bus stops and traffic lights are functional independently of the streets sizes and order. Therefore, the CTM* presents itself as a reliable solution for traffic planners to simulate the impact of bus routes on traffic requiring few resources and data.

Though the model was tested in a limited path, it can be implemented in the future in larger segments of city. The results of this study and the methodology can be used by any organization like EPTC to simulate different strategic areas of the city to make data-driven decisions for urban mobility.

The introduction of real traffic conditions in simulation approximates it to reality. Traffic lights and bus stops are phenomena proven in this study to influence traffic flow. However, more conditions have this impact as well. Enter and exit ramps in the streets and other vehicle types as motorcycles and trucks are example of conditions that can be added to the CTM* and increment its simulation capability. Therefore, although the CTM* already enhanced some aspects of the original CTM, new improvements can be made. For that reason, for future studies, rules implementation in the CTM* regarding the acceleration and deceleration during the flow and adding other types of vehicles are recommended.

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