BUILDING A SIMULATOR OF A TRAFFIC ASSIGNMENT MODEL FOR THE USE OF PUBLIC TRANSPORTATION IN THE SECTOR "CORREDOR CALLE 5"

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ABSTRACT

Worldwide, the rise in the population has created the need to develop efficient transportation systems in order to facilitate the movement of citizens. Nowadays the main public transportation in the city of Cali is called "Masivo Integrado de Occidente" MIO. The waiting times on the system are high and the capacity of the buses is often exceeded. For this reason, it is necessary to analyze the system to create different scenarios where the current situation could be improved.

This project was designed to develop a simulator for the use of public transportation in "Corredor Calle 5", one of the main sectors in the city, in order to support the decision-making process on the traffic assignment for the MIO system.

Throughout the simulations it was possible to determine that it is necessary to change the synchronization of traffic lights prioritizing the buses traffic, with the purpose of reduce the users waiting time.

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ACRONYMS

BRT Bus Rapid Transit

MIO Masivo Integrado de Occidente

ETL Extract, Transform and Load

1 INTRODUCTION

This document outlines an approach to build a traffic assignment model for the public transportation in Cali and develop a simulator for the "Sector Calle 5". In Chapter 1, the problem, the justification, the scope, along with general and specific objectives of the project are exposed.

Additionally, the rest of the document can be roughly divided into two parts. The Chapter 2, Chapter 3 and Chapter 4 contain the theoretical part of this work and the Chapter 5, Chapter 6 and Chapter 7 describe the implementation of the simulator.

Chapter 2 contains the reference framework, which supports the project development, including literature review on traffic assignment models, concurrency message passing and BRT systems. The state of art is also included in this chapter.

Chapter 3 presents the description of the current MIO system and includes the definition of the components that are considered in the simulation. The traffic assignment model defined for this approach is presented on Chapter 4 and it is also included an integrally description on how the implementation for the simulator is made.

In Chapter 5 the concurrency message passing model for the defined MIO system is presented. In Chapter 6 the graphical interface created for the user of the simulator is presented. The Chapter 7 contains the coherence tests that were made on the simulator, explains how was processed the available information to perform the tests, the creation of the scenarios and the results.

1.1 PROBLEM STATEMENT

Cali, the third biggest city in Colombia, has since 2009 a public Bus Rapid System (BRT) called "Masivo Integrado de Occidente", better known as MIO, operated by the private company METROCALI. By 2014 the MIO system had a spatial coverage of 91% of the city of Cali (O. d. C. Metrocali, 2014) and its operation is currently divided in 7 sectors of the city demarcated by Metrocali. Six of those sectors are called main corridors, where the bus traffic is given mainly by articulated buses and a dedicated lane for them (BRT). The other sector corresponds to zones of the city where the buses travel in the same roads as particular vehicles.

The road network of Cali is not enough to contain just private transportation for the entire city, the congestion presented in private transportation is common and high in some important sectors in peak hours everyday. Therefore an efficient public transportation is needed and even though the MIO System has been working in the city for about seven years, and the spacial coverage is high, the frequency of the routes is not enough to cover the current demand, the waiting times are long, the amount of people in a single bus normally is above its capacity and some stations turn out to be not enough to hold all the users waiting for buses.

As the MIO system is not an isolated system, instead of it is a part of the transportation of the city, the performance should also consider external factors as the control of traffic lights in the system, which interrupt the continuous flow of the buses.

Traffic assignment models are used to shape and guide the distribution of traffic in a network according to a set of constraints, related to the capacity, time and cost (Möller, 2014). Therefore, a traffic assignment model is analyzed on this project, with regard to the assignation of routes frequencies and the traffic light intersections in order to build a simulator based on concurrency message-passing, which could support the decision-making process in traffic assignment for the MIO system.

1.2 PROPOSAL JUSTIFICATION

Nowadays, the MIO system is turning into the only public transportation in Cali and carries about 500.000 people per day, according to the report given by the operational chief of Metrocali by the end of 2015 (Redacción de El Pais, 2015). Unfortunately, the system presents a lot of problems by the moment and a lot of citizens prefer to take particular transportation instead of the public one.

For the development of scenarios for this project, the sector "Corredor Calle 5" was selected because it is an important sector of the city that connects the center with the south of Cali, which extension is approximately 11 km with 16 stations. The importance of this sector lies in the existence of important health care centers, commercial centers and also that it provides a connection with the universities located on the south of Cali, such as the Universidad del Valle, Universidad Pontificia Javeriana, Universidad Icesi, among others. Hence, this part of the system is daily used by many citizens and a large amount of students. Therefore, it is believed that a better performance of the routes belonging to this sector (i.e. decrease in the travel times and better coverage of the demand) may increase the preference of the use of public transportation.

Cali, as the third biggest city of the country, with a fast growing economy due to the amount of industry in the city and the surrounding areas, needs a better mobility for the citizens. Consequently, this project is aimed to search possible scenarios, which can lead to improve the performance of the MIO system in the "Corredor Calle 5" sector; with regard to the frequencies and times required by the operating routes and the assignment of the traffic lights in this sector.

The MIO system is composed of a set of elements or agents, which have an important role in the performance of the system and interact between them. On the other hand, the concurrency message-passing paradigm allows the modeling of scenarios where the agents communicate with each other. Therefore this paradigm was used in the process of building the simulator for the MIO System.

1.3 SCOPE OF PROPOSAL

This project is delimited to the analysis, modeling and the implementation of a simulator of the MIO system in Cali. The scenarios and instances that were performed are limited specifically to the sector called "Corredor Calle 5" due to the economical and spatial importance of the sector. Only the main routes, called "expresas" and "troncales", which operate in the stations on the sector were considered.

The scenarios of analysis are specified in the analysis phase considering the available information of frequencies of the routes and the assignation of the traffic lights in the sector. The implementation was performed in Mozart through the concurrency message-passing paradigm.

1.4 OBJECTIVES

1.4.1 *General Objective*

To build a simulator for a traffic assignment scenario for the frequency of routes and operation of traffic lights in the Cali's MIO system.

1.4.2 *Specific Objectives*

1. To analyze the actual MIO system in order to extract the characteristic elements of the system.
2. To define a traffic assignment model to calculate performance measures and user flows for each supply element (network link) resulting from:
    a) Origin-Destination pairs
    b) Path choice behavior
3. To define a concurrency message-passing model for the MIO System, that depicts the mutual interactions between the system components.
4. To implement the traffic assignment model for the actual system behavior.
5. To implement a graphical interface to visualize the simulations.
6. To instantiate and run the model with the current conditions of the sector "Corredor Calle 5" in order to identify aspects to be improved.
7. To define and run alternative instances for the model with different assignments for route frequencies and traffic lights in the sector "Corredor Calle 5".
8. To analyze the results obtained from the execution of the model with the different instances to present some recommendations for the traffic assignment in the sector "Corredor calle 5".

2 REFERENCE FRAMEWORK

2.1 THEORETICAL FRAMEWORK

2.1.1 *Transportation Network*

A transportation network can be expressed as a directed graph G = (A,N), where A is the set of links like roads, railway rails, among others, and N is the set of nodes like airports, bus stops, etc. Flows are also part of the transportation network, they represent actual patterns of movement on networks (Xie and Levinson, 2011). The transportation networks can be divided by the space it took place, namely Industrial zones, Urban motorways and residential zones (Möller, 2014).

As time goes by, transportation networks have to grow alongside with the city growth. It is not enough to develop a transportation network, that supplies the current needs of the population. It is necessary to think about the growth of demand and go further in the evolution of current transportation systems. Network growth requires comprehensive consideration of demand, supply, space, and time (Xie and Levinson, 2011).

2.1.2 *Traffic Assignment*

On Patrikson, 2015, traffic assignment is defined as a process, which designates a determined set of trips to a transportation network. The input of this process is a full description of the transportation system to be analyzed and the possible trip movements and the output of the process is in general an estimate of traffic volumes, traffic times or costs on the system.

Furthermore the traffic assignment is part of the transportation planning process and its purpose is to evaluate the flaws on an evaluated transportation system by using an approximate future trips (increasing current demand), evaluate changes by using future trips on a system with the improvements and test alternative proposals to the transportation system.

2.1.3 *Traffic assignment model*

Traffic assignment in a transportation network is considered as the distribution of traffic, taking into account the demand between nodes and the transport supply. Therefore, traffic assignment models aim to simulate the demand-supply interaction within a transportation network based on some constraints like transport capacity, time and cost (Rodrigue, 2013). These constraints can be described as follows: network measures derived from traffic volume of links inside the network, travel costs and traffic pattern between origin-destination (O-D) pairs.

The main objective of this type of models is to identify a possible selection of trips between links within a network considering the demand between different pair of nodes (Möller, 2014). Therefore, a traffic assignment could be the tickets bought for a specific mean of transportation, since they make feasible a measurement of the demand in the system.

As it is known, transportation is composed by links and each one of them has a direction and a value (or capacity) and represents the union between nodes. In a transportation network, should exist nodes where the traffic can be generated and concluded.

An O-D matrix is used to have a ratio of trips between origin and destination pairs, and it is important to consider the maximum capacity between each pair of nodes in the transportation network.

According to Möller, 2014, some of the relevant trip assignment models in transportation analysis, modeling and simulation are:

- **All-or-nothing assignment for uncongested networks:** it is focused on the selection of the shortest path. Therefore assign all the travels to the shortest path between an O-D pair.

- **User equilibrium:** the idea is that each passenger/user chooses always the shortest path to its destination.

- **Stochastic travel assignment:** this model assumed that it is not possible to have a perfect real-time information with regard to costs, then the selection of routes have uncertain factors.

- **Dynamic assignment:** this model assumes that early decisions have an impact in later congestion situations, then interactions over time are considered.

2.1.4 *BRT Systems*

Bus Rapid Transit (BRT) is one of the fastest growing public transport system in the century. BRT systems are integrated bus-oriented public transport services composed of six basic elements (Henke, 2013):

1. Higher-quality buses.

2. A structured service plan, including a well defined route structure, regularly transit service is faster and more frequent than the one experienced with regular route local bus service.

3. Organized and well design bus stations.

4. Roadway infrastructure, which normally consist on exclusive lanes, that gives the buses priority and separate them from mixed traffic, or giving them priority over mixed traffic ensuring shorter travel times.

5. New and intelligent transportation technologies, like real-time passenger information and vehicle tracking to ensure a more accurate service schedule.

6. Distinct branding and marketing.

Even though the cost of the implementation of a BRT system in a city is lower compared to other types of transportation systems like rail systems, travel times are briefer than in normal bus systems and the satisfaction level is considerably high. Problems commonly found in this type of transport system are (Hidalgo, 2013):

- Insufficient user education in the early stages of the implementation of the system.
- Budget planning deficit – user fares are not well defined.
- High occupancy levels.
- Early deterioration of the new infrastructure due to design problems.

2.1.5 *MIO: Masivo Integrado de Occidente*

The development of the urban arquitecture of Cali, as well as other cities in Colombia, is strongly related with the development of a mass public transit system. By 2009 the BRT "Masivo integrado de Occidente" MIO started its operation, with aiming not only to provide mobility to the city but also improve life quality of citizens and promote the development of the city (Gonzales Escobar, 2010).

The system counts with three different type of routes: the main routes, also called "expresas" and "troncales", secondary routes called "pretroncales" and auxiliary routes called "alimentadores". The main routes take place in different stations of the city and have a exclusive lane. Secondary routes can also take place in the normal traffic, alongside with the private transportation. Finally, the auxiliar routes took place in the normal traffic and are short routes.

The operation of MIO is divided in seven sectors demarcated by Metrocali. Six of this sectors are called main corridors where the bus traffic is given mainly by articulated buses and a dedicated lane for them; the other sector corresponds to zones of the city where the buses travel in the same roads as particular vehicles.

Namely in the corridor "Corredor Calle 5", 5 express routes take place, 4 main routes (troncales) and 15 secondary routes. It is possible to locate them in the Figure 1 from the station Santa Librada (middle with green colour) to the station Universidades (in the bottom of the image with brown colour).

Specifically, the sector Calle 5 is composed by the following bus stations: Santa Librada, Manzana del Saber, Estadio, Tequendama, Lido, Terminal Cañaveralejo, Plaza de toros, Pampalinda, Refugio, Caldas, Capri, Melendez, Buitrera, Univalle, Estación Universidades.

Additionally, the routes that take place in this corridor are:

- **Express Routes:** E21, E31, E37, E27, E27B
- **Main Routes:** T31, T47A, T47B, T57A
- **Secondary routes:** P10A, P10B, P27D, P47A, P72, P17

2.1.6 *Traffic lights assignment in Colombia*

The traffic lights operation in Colombia is currently regulated by the Transportation Ministry "Ministerio de Transporte Colombiano". The regulations of traffic lights are part of the road sign manual (Ministerio de Transporte, 2004).

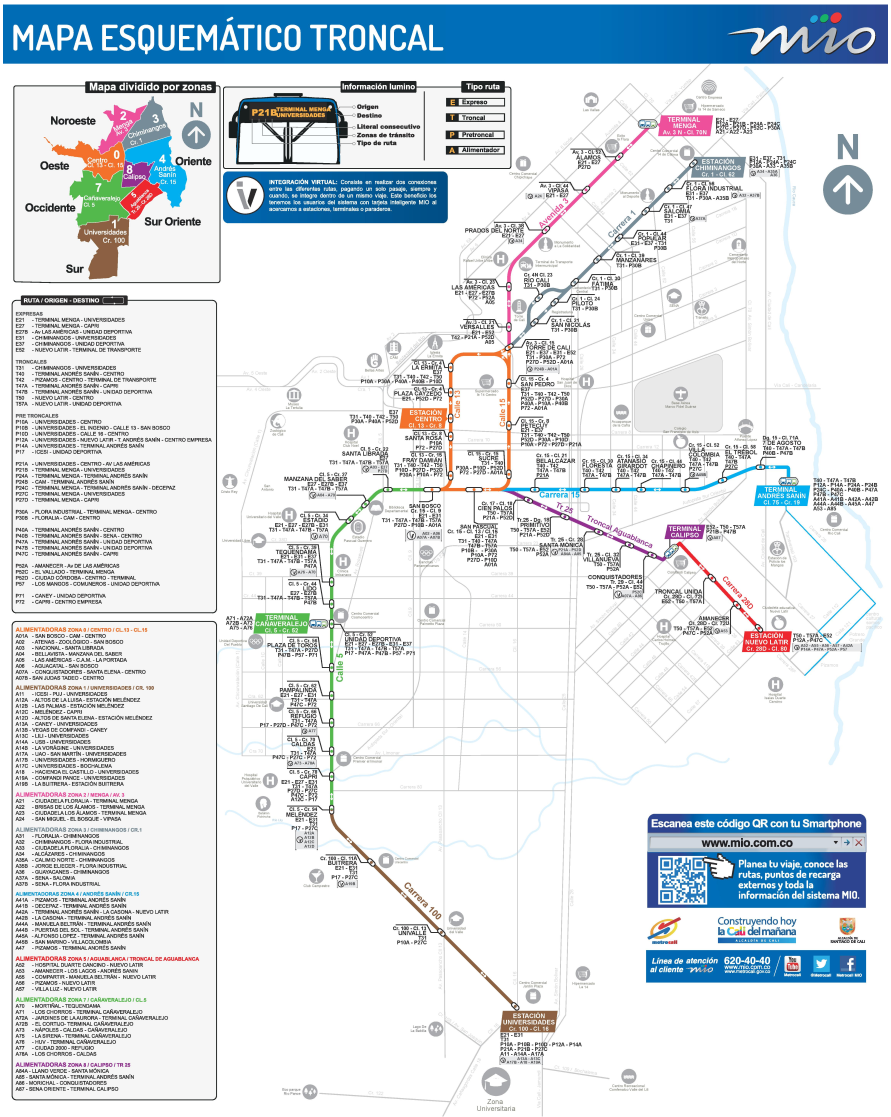


Figure 1: Map of the MIO system Metrocali, n.d.-a

Colombia has three types of traffic lights: vehicular, pedestrian and special. The vehicular transit lights can also be classified in fixed time or time dependent, and transit dependent.

The light bulbs should be red, yellow and green. In case an arrow is needed, it should be also red, yellow or green over a black background. The traffic lights' color interpretation is as follows:

- **Green:** Drivers shall go ahead and turn if it is possible.
- **Yellow:** Warns the driver, that the green period is over and the red period is about to start.
- **Red:** Vehicles should stop before the stop line or two meters before the traffic light.

The sequence of vehicular traffic lights could be Red-Green-Yellow-Red or Red-Red and Yellow-Green-Yellow-Red and the synchronization of the traffic lights depends on the type of traffic light. For the time dependent lights, the cycle should be (90-45, 120-60) or equivalent cycles. For the transit dependent lights it is necessary to consider the number of lanes, pedestrian needs, speed of cars, among others.

2.1.7 *Computational Simulation*

"Simulation is the art and science of constructing models of systems for the purpose of experimentation. In particular, computer simulation is a technique used to imitate, on computers, systems exhibiting complex, time-dependent behavior." Tyszer, 1999

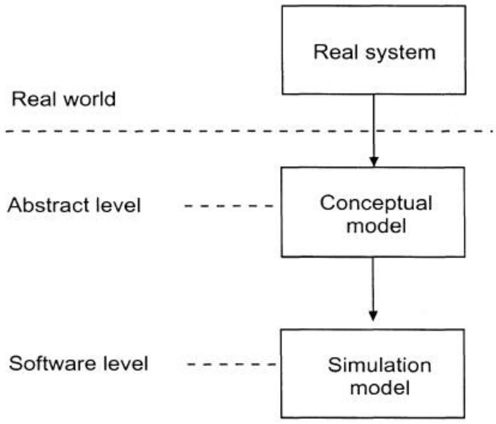


Figure 2: Computational Simulation from Garrido, 2001

In Figure 2 an abstraction of the real world is necessary to create a simulation model of the real system. In general, the main reason to develop a simulation are the high costs that implies to simulate new changes in the real system.

A model is useful when the user can manipulate the system by making changes in the system input, observe its behavior or outputs and be able to predict the variations of the system under specific circumstances (Garrido, 2001).

2.1.8 *Concurrency message-passing paradigm*

Concurrent programming is a programming paradigm, in which a program executes two or more sequential programs that could be executed as parallel processes. Furthermore, message-passing is a programming style in which the program is compound of independent entities interacting with each other via an asynchronous message sending.

Consequently, concurrent programming with message passing is an extension of the concurrent model, including an asynchronous channel for communication, which means, that every client could send a message to a channel at anytime and can be redirected to the destination client to be read. Therefore this model, concurrent programming with message passing, is not deterministic (Van Roy and Haridi, 2003).

2.1.9 *Mozart*

Mozart is a programming system, developed by the Mozart Consortium and released for the first time in January 1999 (Smolka, 2005). Mozart is product of constant research. It implements the programming language Oz, which supports several programming paradigms like logic, functional, concurrent, among others.

2.2 STATE OF THE ART

Computational simulation in transportation is an important tool to make decisions over the future operation of the system and it is safer and cheaper than performing a simulation on a real system. Some relevant work made in the simulation of transportation systems are as follow:

- Simulation Model of Bus Rapid Transit Gunawan, Suharjito, and Gunawan, 2014

  Mathematical model for the Bus Rapid Transit system based on the discrete-event approach to evaluate the system performance, considering important factors that affects the performance of the system like station design, infrastructure, service planning, passenger information systems, integration and access.

- Microscopic Simulation Approach to Capacity Analysis of Bus Rapid Transit Corridors (Siddique and Khan, 2006)

  For this work a simulator for the BRT system in Ottawa (Canada) was created in order to evaluate the capacity of the exclusive bus lanes (also called transitways) to handle high volumes of transit buses using as comparison the traffic of 2001 and a scenario for possible traffic in 2021. NETSIM was used as a microsimulator.

- A multi-agent learning-based approach to the transit assignment problem (Wahba and Shalaby, 2005)

  An operational prototype of a framework for the transit assignment problem is presented, which is structured in a multi-agent and learning-base approach and represent the learning and decision-making activities of the passengers. For the implementation a hypothetical transit network was used and the microsimulation platform used was Paramics©. Reinforcement learning is used to represent the adaptation of the passengers and the dynamic of the system. With this approach is possible to predict the behavior of the passenger and calculate the passenger travel cost in a congested network.

3 MIO SYSTEM

On this Chapter, the MIO system is introduced and it is broadly describe as a set of structural and functional elements. The sector "Corredor calle 5", where the simulation was held is also described and the elements of the system that were used to simulate are introduced.

3.1 MIO SYSTEM

The MIO System can be broadly described as the union of structural elements like: roads, bus stations, bus stops, bicycle parking stops, bus "garage". For the functionality of the system, there are three different type of buses, namely: "Articulado", "Padrón" and "Complementario" which are used depending on the road, the route and the demand of the route. Additionally, another elements of the system are the people interacting within: drivers, personal for selling tickets, security personal and passengers.

Considering the functionality of the system it is possible to identify some process which are performed in the system as the following:

1. Users buy a single trip card, buy a user card or recharge a user card in a bus station.
2. Users get inside of the system by using the card in the entrance of each station or in the bus when the bus stop is on the street.
3. Buses get out of the "garage" and start a route, which is basically a list of stops where the bus stops, opens the doors to allow the user flow and close them after.
4. Users decide a proper route(s) for reaching the destination and wait for a bus with the selected route, when the doors are opened, they get inside the bus and out when they reach the destination.

For the sake of simplicity, in this project the attention was restricted to the following elements:

- Structural elements: the exclusive roads for the MIO, the bus stations and the garages.
- The buses Articulados, which have a capacity of 160 passengers.
- The processes of the buses making a route, users deciding a route, taking a bus and get off the bus.

It is assumed that the user is inside of one stations once he/she is included in the system. All the stops, which are not in a bus station are not considered because private traffic is not part of the project scope. Therefore, the processes which are part of the traffic assignment model are the execution of bus routes, decision process of the users and interaction between the users and the buses.

3.2 CORREDOR CALLE 5

On the sector Corredor calle 5 was possible to identify the punctual elements, which were used to configure the modeled system, like the routes on the sector, the stations and their wagons and the traffic lights, these are shown on the map presented on Figure 3 created on Google Maps and the elements marked are explained below.

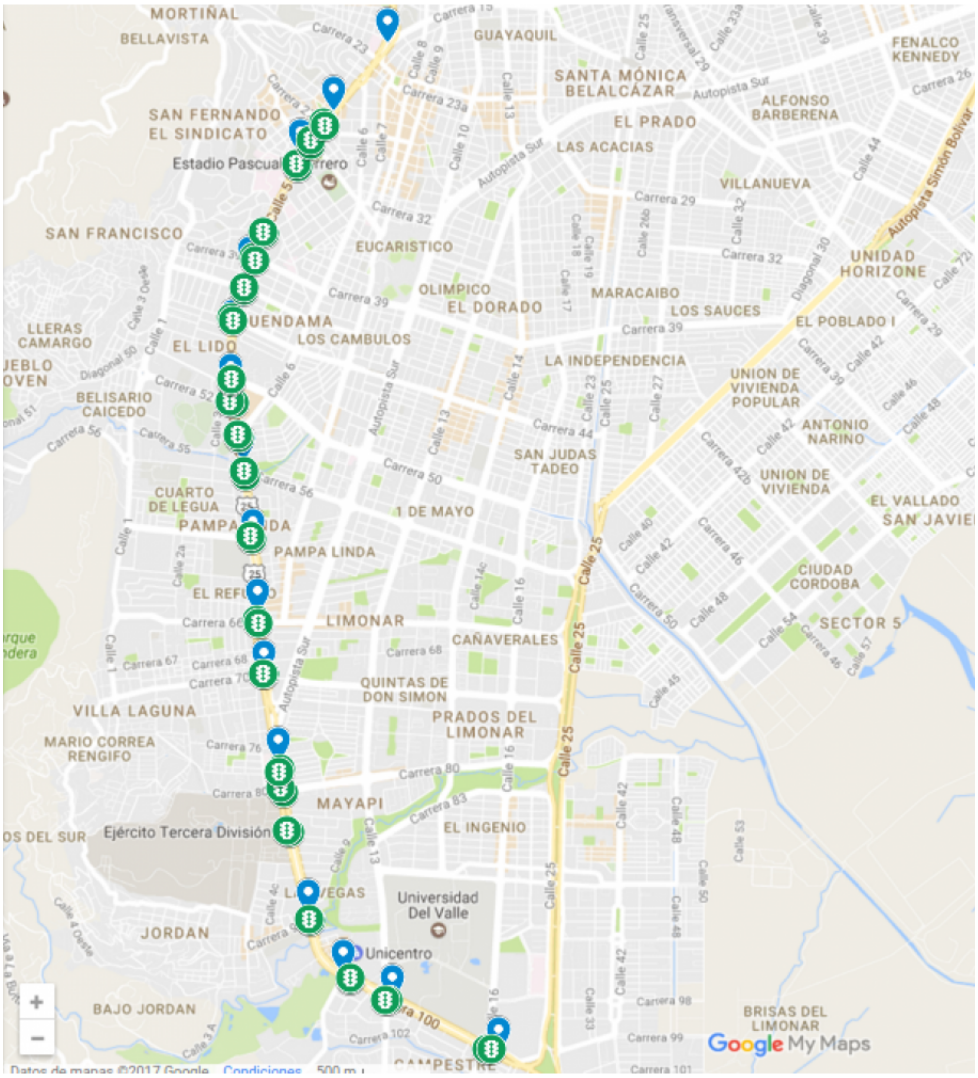


Figure 3: Corredor Calle 5 Map

3.2.1 *Stations*

The stations on the sector are signalized with blue markers on Figure 3 and their names (from north to south) are:

- **Santa Librada**: This station has 4 wagons (A1,A2,B1 and B2)
- **Manzana del Saber**: This station has 4 wagons (A1,A2,B1 and B2)
- **Estadio**: This station has 4 wagons (A1,A2,B1 and B2)

- **Tequendama**: This station has 4 wagons (A1,A2,B1 and B2)
- **Lido**: This station has 2 wagons (A1 and A2)
- **Unidad Deportiva**: This station has 6 wagons (A1, A2, A3, B1, B2 y B3)
- **Plaza de Toros**: This station has 2 wagons (A1 and A2)
- **Pampalinda**: This station has 2 wagons (A1 and A2)
- **Refugio**: This station has 2 wagons (A1 and A2)
- **Caldas**: This station has 2 wagons (A1 and A2)
- **Capri**: This station has 4 wagons (A1, A2, B1 and B2)
- **Melendez**: This station has 2 wagons (A1 and A2)
- **Buitrera**: This station has 2 wagons (A1 and A2)
- **Univalle**: This station has 2 wagons (A1 and A2)
- **Universidades**: This station has 4 wagons (A1, A2, B1 y B2)

3.2.2 *Traffic Lights*

The traffic lights on the sector are signalized with green markers on the Figure 3. The traffic lights are divided on:

- **Pedestrian traffic lights**: Carrera 70, Pedestrian traffic light on station Capri and Pedestrian traffic light on station Buitrera.
- **Vehicular traffic lights**: Carrera 27, Carrera 34, Carrera 36, Carrera 38d, Carrera 39, Carrera 42, Carrera 44, Carrera 50, Carrera 52, Calle 6, Carrera 56, Carrera 62, Carrera 66, Carrera 80, Battalion traffic light, Carrera 94, Calle 13 and Calle 16.

3.2.3 *Routes*

The selected routes on the sector and their respective stops on the corredor Calle 5 are:

- **E31**: this route stops in the stations Estadio, Tequendama, Unidad Deportiva, Pampalinda, Capri, Melendez, Buitrera, and Universidades.
- **E21**: this route stops in the stations Estadio, Tequendama, Unidad Deportiva, Pampalinda, Caldas, Capri, Melendez, Buitrera, and Universidades.
- **E27**: this route stops in the stations Santa Librada, Manzana del saber, Estadio,Lido, Unidad Deportiva, Pampalinda and Capri.
- **E27B**: this route stops are Manzana del Saber, Estadio, Lido and Unidad Deportiva.
- **E37**: this route stops in the stations Manzana del Saber, Tequendama and Unidad Deportiva

- **T47A**: this route stops in the stations Manzana del Saber, Estadio, Tequendama, Lido, Unidad Deportiva, Plaza de Toros, Pampalinda, Refugio, Caldas and Capri.
- **T47B**: this route stops in the stations Manzana del Saber, Estadio, Tequendama, Lido and Unidad Deportiva.
- **T57A**: this route stops in the stations Manzana del Saber, Estadio, Tequendama, Lido and Unidad Deportiva.
- **T31**: this route stops in the stations Santa Librada, Manzana del Saber, Estadio, Tequendama, Lido, Unidad Deportiva, Plaza de Toros, Pampalinda, Refugio, Caldas, Capri, Melendez, Buitrera, Univalle and Universidades.

4 TRAFFIC ASSIGNMENT MODEL

The traffic assignment model used for this project is introduced on this chapter. Some complex elements of the model are also explained later and at the end of this Chapter a general view of the implementation of the proposed traffic assignment model is presented.

4.1 DESCRIPTION OF THE TRAFFIC ASSIGNMENT MODEL

For the Traffic assignment model of the considered MIO system an agent-based approach was chosen, based on the model presented by the Department of Transport Science of the KTH Royal Institute of Technology (Cats, 2013), where the assignment model is aimed to reduce the waiting times of the users in general and it consists on a day to day simulation in which the inputs are supply elements from the MIO System, a metric to determine the maximum time a user should wait in her/his journey and the configuration of the traffic light. The interaction of demand and supply is presented with the load of passenger and decision of routes, and the dynamics of the transit is presented on the within-day and could be affected by the traffic lights.

Three main groups of agents were designed: vehicles, travelers and traffic lights. Even though the traffic lights are not properly part of the MIO system, these are considered on the development of a traffic assignment model due to the impact of its configuration on the dynamics of the buses inside the system.

A framework of the simulation is shown in the Figure 4. The inputs, represented by parallelograms, are the agents i.e. buses, users (created by a generator) and the traffic lights with their respective inner characteristics and the topology of the transit network. For the within-day component the rectangles are models and the ovals are processing components.

The traffic lights dynamics emulate the configuration of periods of red and green time of the traffic lights and affects the transit dynamics. Transit dynamics imitates the behavior of the buses on the network collecting automatic data about the position of the buses, users inside the buses and waiting times, among others.

All the users have an origin and a destination and for the travel decision model is assumed that all the users have the same knowledge on the buses routes and based on this knowledge a set of feasible routes are defined by the user.

The loading process of the users in the buses is influenced by the user decision, the transit dynamics and the availability of the buses. The loading process directly affects the future availability of the buses for other users.

The day to day simulation has as input the data collection of the transit dynamics. The data collection process and the planning of the frequency of the routes can change every day as well as the planning of the traffic lights. The day to day simulation should be performed manually repeatedly until the maximum time a user should wait for her/his journey is minimized or until it is determined that it is not possible to optimize the waiting time for the users.

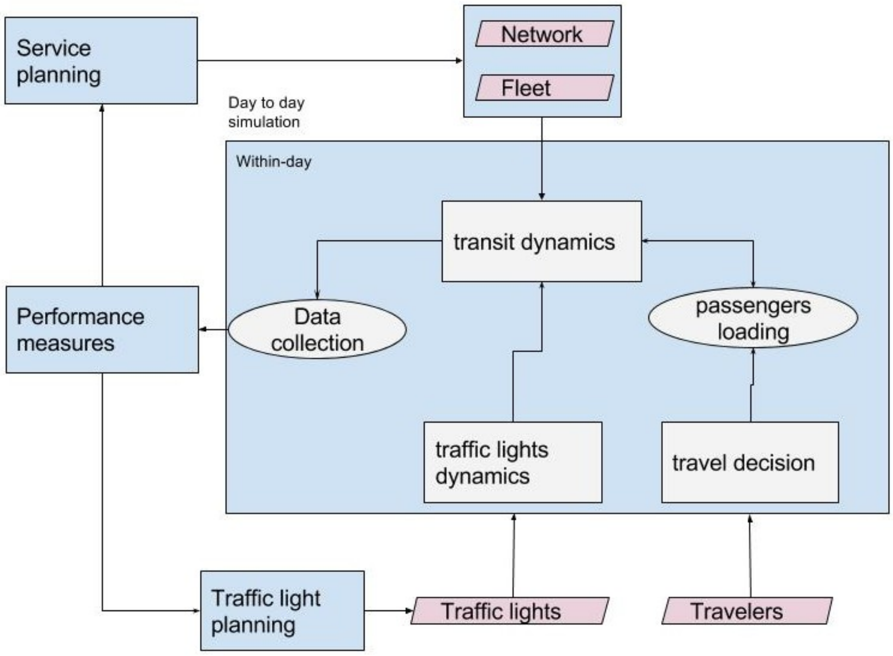


Figure 4: Traffic Assignment Model

4.2 MODEL COMPONENTS

Some of the processes of the traffic assignment model mentioned above are complex and require a broader explanation. Therefore, the following processes are described: how the simulation was done, how the users were created on the system and the path choice to determine the flow of users in the system.

4.2.1 *Transit Simulation*

The transit simulation was performed in the within-day part of the model. The implementation of this simulation was carried out through the Mozart language based on a concurrency message-passing model, with which is possible to simulate the three main groups of agents as concurrent entities and create the metrics needed for the day to day simulation. In the Chapter 5 is explained the design of the Concurrency message-passing model.

4.2.2 *User generation*

For the user creation in the simulation, an origin-destination matrix is defined on the Chapter 7. The matrix was used as one of the inputs of the users generation program done on R called `userGeneration`.

The `userGeneration` program receives an origin destination matrix, the total time of simulation and the number of users and based on the probabilities on the matrix creates the amount of users distributed on the time of simulation.

4.2.3 *Users Path Choice*

As the users have all the same knowledge on the system the path choices is made by choosing the direct routes from the user's origin to the destination. Each user selects a maximum of three feasible routes and waits on the origin station until one of those routes arrives to the station.

4.2.4 *Service planning*

When the model is launched by an application, a planning of the routes, traffic lights and number of buses should be set with the initial configuration of the system by the final user. Afterwards, when a within-day simulation is done a number of performance measures are delivered to the user and he/she has the capacity to work on the re-planning of the configuration by means of a graphical interface of the application in order to achieve the expected results.

4.3 IMPLEMENTATION OF THE MODEL

The implementation of the model was made as a web application, where all the elements of the traffic assignment model are integrated. On Figure 5 is possible to observe the different components that creates the application.

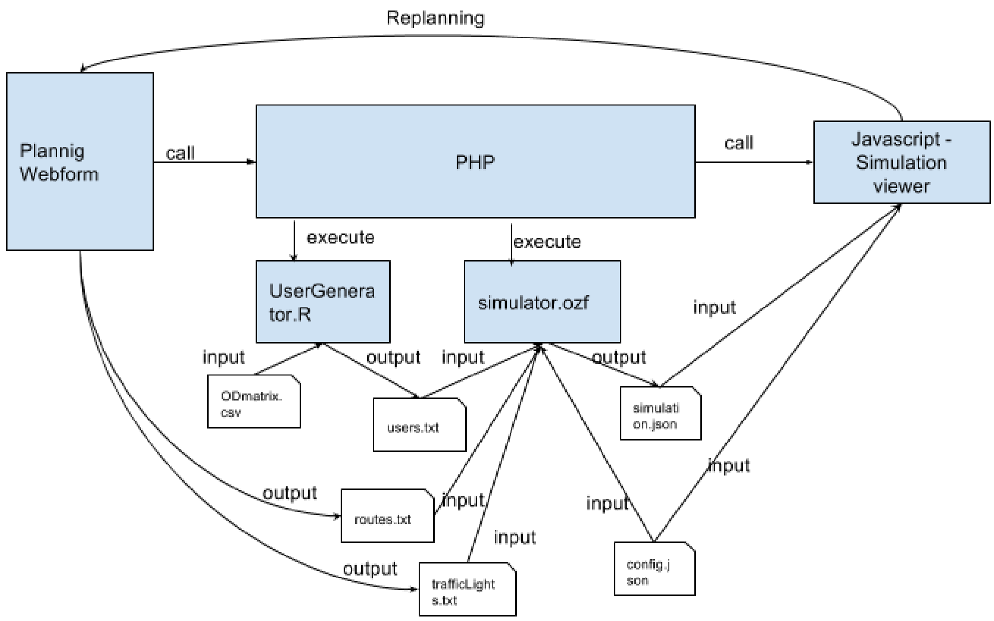


Figure 5: Map of the implementation of the Traffic Assignment Model

Initially, a Webform is displayed (Planning Webform) where the user can include the frequencies of the routes, determine the number of buses on the simulation and the configuration of the existing traffic lights. The webform is fully explained on the Chapter 6.

After the user includes the initial configuration, the information is stored on the files `routes.txt` and `trafficlights.txt` and afterwards a PHP application is invoked; its function is to execute the R program (`UserGenerator.R`), which receives as the input the Origin-Destination Matrix (`ODmatrix.csv`) and creates as output the users on the file `users.txt`.

The next step for the PHP application is to call the simulator created on Mozart, which receives as input the information of users, routes and traffic lights (files `routes.txt`, `trafficlights.txt`, `users.txt`) and the configuration file (`configuration.json`) which contains the information of stations, wagons with the names and physical location.

When the simulation on Mozart is running a log of the simulation is written on the file `simulation.json`, which is used by the simulator viewer (program made mainly on Javascript). This viewer is invoked by the PHP application and shows visually the behavior of the buses, traffic lights and users on the stations during the simulation. The viewer also displays the performance measures and it is fully explained on the Chapter 6.

Finally, based on the performance measures the user could use the planning webform to modify the inputs he/she gave on the first place and execute the whole process again.

5 CONCURRENCY MESSAGE-PASSING MODEL FOR THE MIO SYSTEM

For the development of the transit simulator, a concurrency message-passing model was created to be later implemented in Mozart Oz. The methodology followed was the one described on (Van Roy and Haridi, 2003), the considered elements of the system are described by a components diagram and the state diagrams for each one of the elements.

5.1 CONCEPTUAL ELEMENTS

The conceptual elements are used in the design phase to make a model of the application and the implementation; each element corresponds to the definition of a function, a set of states and a port, where the element could receive messages and process them. In total 5 components were defined:

- Traffic Light
- Station
- Wagon
- Bus
- User

The interaction among system components is described in the components diagram on Figure 6.

5.1.1 *Traffic Light*

The traffic lights have three states: `inactive`, `green` and `red`. For this system the yellow phase in a traffic light is not relevant, because it does not represent a different state. The traffic light has two variables `RedPeriod` and `GreenPeriod` which contain the amount of time corresponding to the states `green` and `red` respectively.

Initially the traffic lights are inactive, to activate the traffic lights the controller sends the message `activate_light(StartState InitialTime)` and the traffic light is activated on the `StartState` state, which could be `green` or `red`; for an initial period of time (InitialTime). This `InitialTime` allows the user to synchronize the traffic lights.

When the traffic light is `green` and a bus is arriving, the traffic light should inform whether the bus can pass through it by the message `move_bus` or if the bus should be included in a queue of buses to pass through the traffic light. When a queue exists the traffic light should inform the buses, that they can move if the state is `green`.

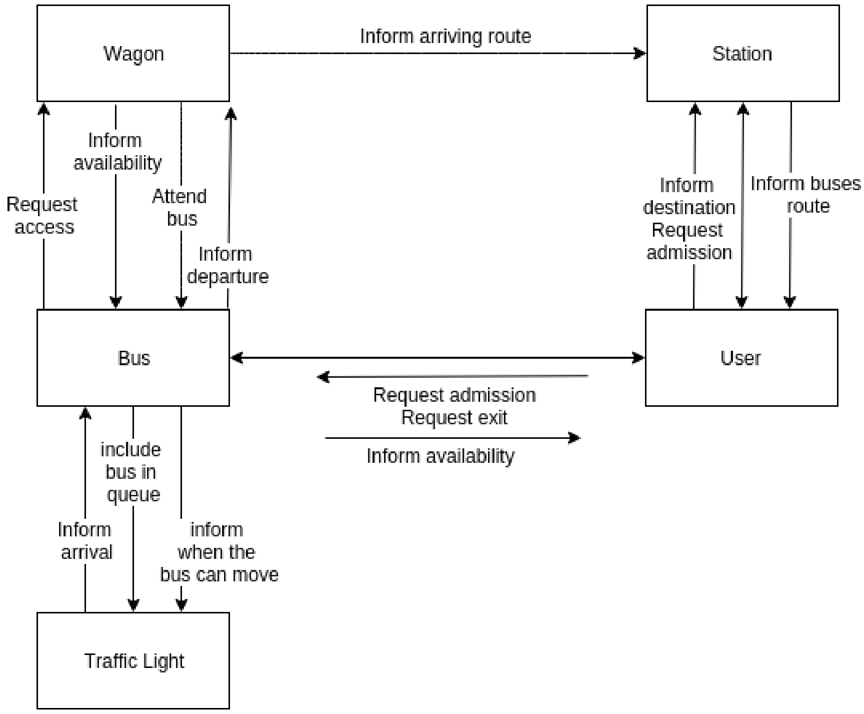


Figure 6: Components diagram

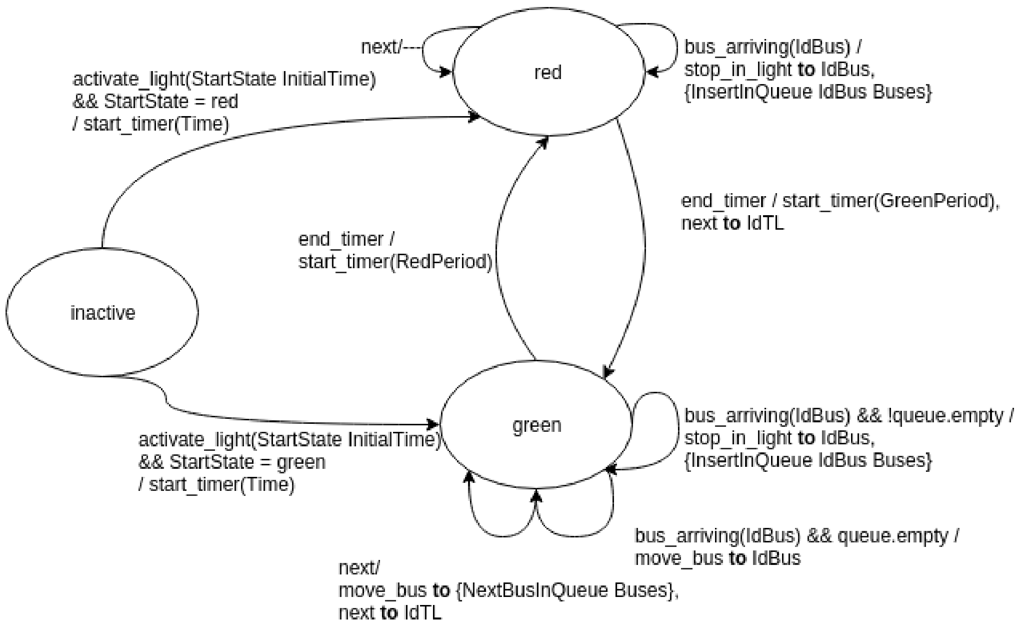


Figure 7: Traffic light state diagram

When the state of the traffic light is `red` all the buses arriving should be included in the queue until the `move_bus` message is sent by the traffic light after changing the traffic light's state from `red` to `green`.

5.1.2 *User*

A user always has an origin and a destination, which determine how he/she moves inside the system. The user counts with 4 states, namely: `inactive`, `in_station`, `waiting_availability` and `in_bus`. Additionally, a user preserves

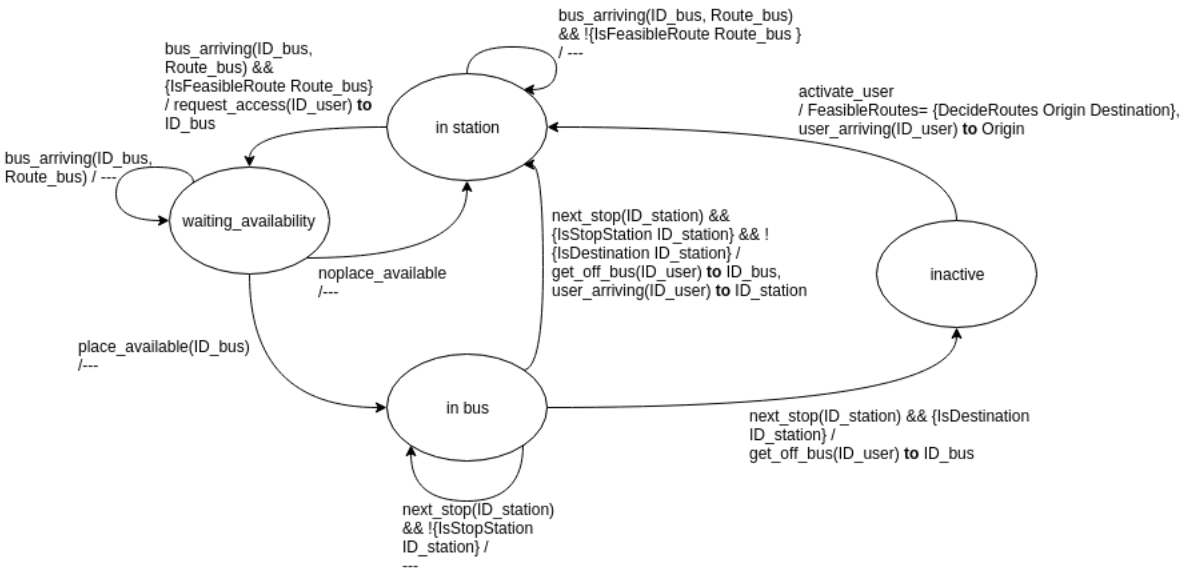


Figure 8: User state diagram

her/his current location by saving the ID of the station or bus he/she is at the moment.

The activation of a user in the system is made by the controller with the message `create_user`, which leads the user to define feasible routes for her/his journey between origin and destination through the function `DecideRoute` and the user arrives to the origin station. When a user is `in station` and a bus with a feasible route arrives, the user requests access to the bus by the message `request_access` and changes her/his state to `waiting_availability`. This intermediate state between `in_station` and `in_bus` ensures that a user request access to one bus at a time.

When the state `waiting_availability` the user receives the message `place_available` from a bus, then the user proceeds to take the bus and changes her/his state to `in_bus`. Otherwise if the user receives the message `noplace_available`, then the user changes his/her state to `in_station` and waits for the next bus with a feasible route.

While the user is `in_bus`, he/she will receive a message every time the bus arrives into a station (`next_stop`) and wait until a right stop is reached. If the stop is the final destination of the user, he/she will get off the bus and change the state to `inactive`. Conversely, if the stop is not the final destination, the user get off the bus and arrives into a station and wait for the next connection, changing the users status to `in_station`.

5.1.3 *Wagon*

A wagon is defined as a part of a station, where the buses arrive, pick up and drop travelers. A wagon could be `busy` or `free`. A wagon is considered `busy` when a bus is on the wagon and its doors are open, so people is going inside and outside the bus. A wagon is `free` when no bus is in the wagon and the queue of the wagon is empty.

An important attribute of a wagon is its station called `Station` to whom the wagon sends messages.

When a wagon is `free` and a bus is arriving, it attends the bus and informs to the station of the bus arrival through the message `bus_arriving_wagon`. Attending the bus means that a wagon changes the state to `busy` and waits until the bus leaves. When a wagon is `busy`, all the arriving buses will remain in the wagon's queue. When a bus is leaving a wagon, the wagon receives a `bus-leaving` message and the wagon attends the next bus in the queue and when the queue is empty and no bus is arriving the wagon changes its state to `free`.

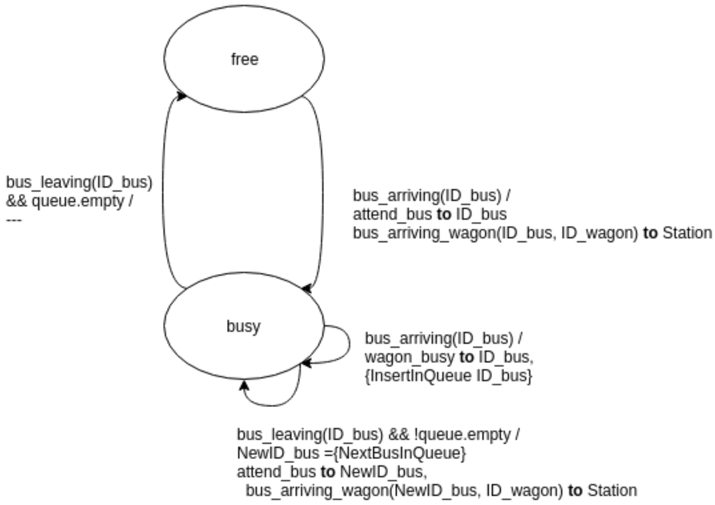


Figure 9: Wagon state diagram

5.1.4 *Station*

A station has two states, namely: `empty` and `non-empty`. A station is empty when there are no users inside the station and non-empty when at least one user is waiting for a bus in the station.

When a user arrives to a station, the user sends a `user-arriving` message to the station and the station includes the user into a list called `Users`, which represents the users inside of the station. When a user leaves the station a `user-leaving` message is sent to the station and the list of users inside of the station is updated. Once a bus arrive to a wagon of the station, the station receives a message `bus-arriving` and the station informs all the users on its list about the arrival. If the state of the station is `empty` and a bus arrives into a wagon, no procedure is needed to be made by the station.

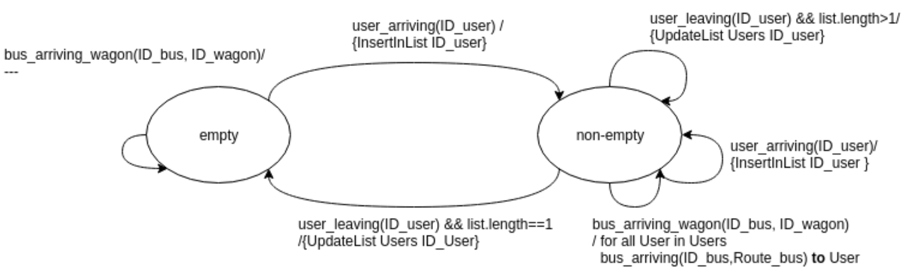


Figure 10: Station state diagram

5.1.5 *Bus*

A bus has five different states: inactive, in_wagon, waiting_in_station, moving and waiting_in_traffic_light. A bus has as attributes a list of users inside the bus, the current position; it means, the last known position of the bus, which could be the ID from the wagon or the ID from the Traffic light where the bus was and the bus also contains the time it would have the doors open in a wagon. Additionally, after activation each bus follows a route, which contains the stops in the route and time between each pair of stops.

Initially, a bus changes its state from inactive to moving, when the controller sends the message activate_bus and starts a timer with the time needed to reach the first stop. When the timer ends and the bus reaches a stop, the bus sends the message bus_arriving to the ID of the stop, which could be a wagon or a traffic light. If the stop is a wagon the bus can receive a wagon_busy message or an attend_bus message from the station. In the first case, the bus must wait in line to be attended by the wagon and changes its state to waiting_in_station. In the second case, the wagon is free and the bus changes its state to in-wagon.

Otherwise, when the bus arrives to a traffic light, the bus sends it a bus_arriving message. After that, the bus should receive a stop_in_light message or a move_bus message from the traffic light. In the first case, the bus can not go through the traffic light an has to wait in line. In the second case, the bus moves through the light and stays in moving state".

When the bus changes its state to in_wagon, a period of time is open for receiving requests from the users. This period of time is controlled via a timer started for TimeInWagonr units of time. Users can send two kind of messages to the bus: get_off_bus messages or request_acces messages. In the first case, the bus reacts updating the list of users to exclude the user from the list. In the second case the bus sends back a place_available message to the user if there is a place for the user in the bus; otherwise, a noplace_available message is sent back to the user.

When a bus sends the message place_available to an user, the bus updates the list of users inside the bus to include the user in it.

5.2 ADDITIONAL AGENTS OF THE MODEL

Besides the previously described agents, additional agents were used to control the execution of simulations, calculate the performance measures and to create the output file for a simulation.

On the following component diagram (Figure 12) it is described the additional agents and their communication. Furthermore the existing agents so far are delimited by dotted lines to show the communication of the additional agents with the preview defined agents.

5.2.1 *Controller*

The controller is a stateless agent, which is in charge of start the simulation by activating the traffic lights, creating the wagons with an empty state, creating stations with a free state and starting the execution of the agents BusGenerator,

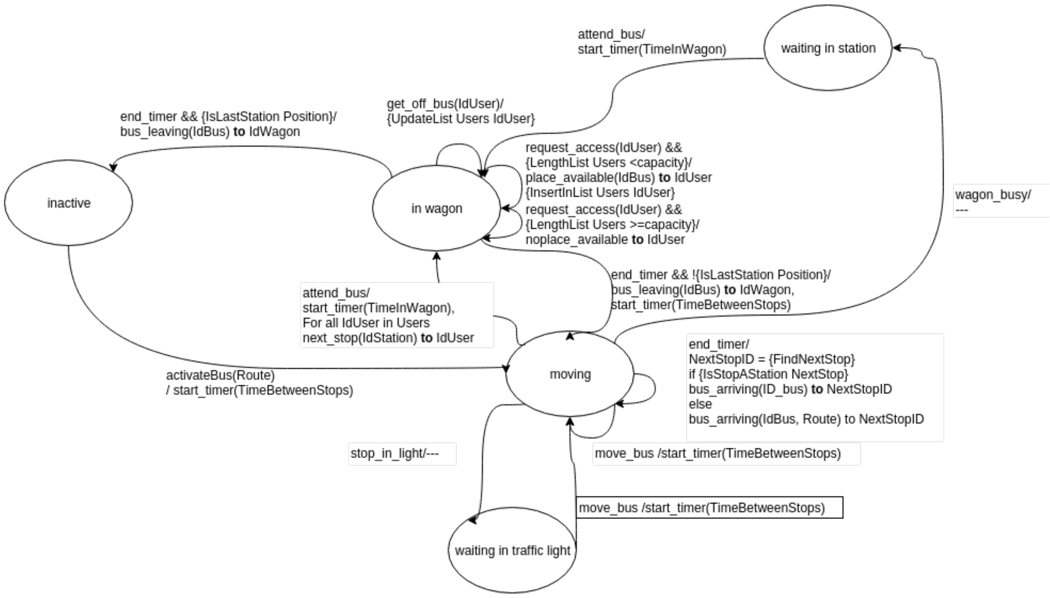


Figure 11: Bus state diagram

`UserGenerator`, `Writer`, `PerformanceMeasuresBus`, `PerformanceMeasuresTL`, `PerformanceMeasuresWa` and `PerformanceMeasuresUsr`.

Additionally the controller has a timer to control the end of the simulation time. When the time is over, the controller is in charge to finish the execution of the simulation by inactivating the traffic lights, wagons and stations and ending the execution of the `BusGenerator` agent, the `UserGenerator` agent and the `Writer` agent.

5.2.2 *Users Generator*

The users generator is a stateless agent, which receives a list of users from the Controller. Each user has an origin and destination and an inter arrival time, i.e. the time lapse between the last user arrival and the arrival time of the current user.

The User Generator agent activates each user on the respective origin. The time in which the activation for the user starts, is calculated as the time where the previous user started plus the inter arrival time of the user.

5.2.3 *Bus And Route Generator*

The Bus and Route Generator is a stateless agent in charge of creating and activating buses. The agent take under consideration the frequency of each route; every time a route should start the agent search for an inactive bus to assign the route to it.

5.2.4 *Performance Measures TL*

The performance Measures TL is a stateless agent created to collect relevant information of each traffic light, used for calculating the performance measures (average queue of buses on the traffic light and Average waiting time of the

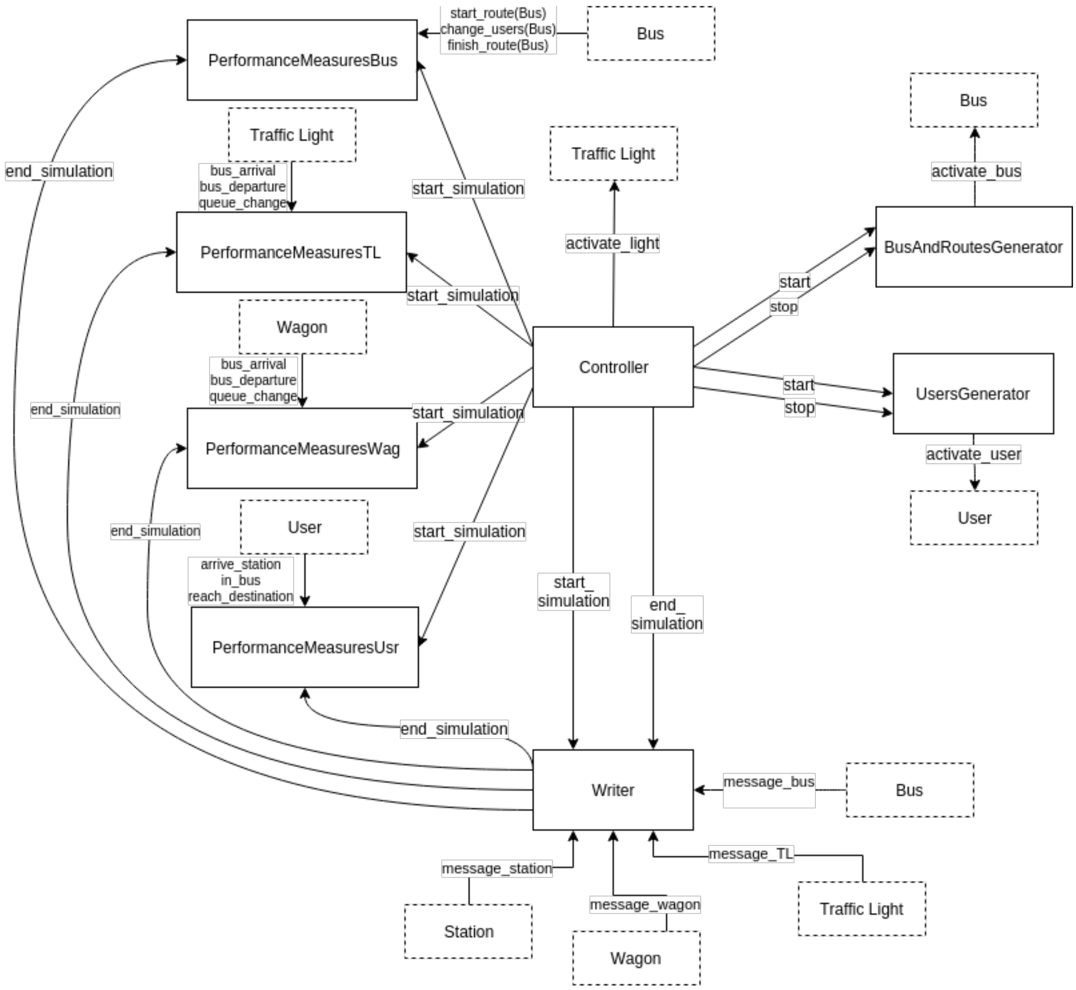


Figure 12: Component diagram of additional agents

buses on each traffic light). Each traffic light sends the following messages to the PerformanceMeasuresTL agent:

- `bus_arrival`: This message is sent every time a bus arrives to a traffic light.
- `bus_departure`: This messages is sent when a bus leaves the traffic light.
- `queue_change`: It is sent when the queue of the traffic light changes (a bus is added to the queue or leaves the queue).

5.2.5 *Performance Measures Bus*

The Performance Measure Bus is a stateless agent which collects useful information of buses to calculate the related performance measures of buses (Average number of users in the buses, Average speed of buses and average time of routes). The agent receives the following messages from each bus on the system:

- `start_route`: This message is sent when a route is assigned to the bus and its state changes from inactive to moving.
- `change_users`: When the bus leaves a station, this message is sent to update the number of users on the bus.

- `finish_route`: This message is sent when the bus finish the assigned route and its state go from moving to inactive.

5.2.6 *Performance Measures Wag*

This stateless agent is in charge to calculate the performance measures related to the wagons: average queue of buses on the wagon and the average waiting time of the buses on each wagon. The information to make the calculations is received by each wagon by the following messages:

- `bus_arrival`: This message is sent from each active wagon, every time a bus arrives to a wagon.
- `bus_departure`: This messages is sent from each active wagon, when a bus leaves the wagon.
- `queue_change`: It is sent from each active wagon when its queue changes (a bus is added to the queue or leaves the queue).

5.2.7 *Performance Measures Usr*

The performance Measusers Usr is the stateless agent that collects information of the users and calculate the performance measures related to the users: average waiting time, average time of trip from origin to destination. The agent receives the following messages from each user:

- `arrive_station`: This message is sent when a user arrives to the origin and its state change from inactive to in_station.
- `in_bus`: This messages is sent when a user takes a bus with a feasible route an its state changes from in_station to in_bus .
- `reach_destination`: This message is sent to the agent when a users reaches its destination and its state changes from inactive.

5.2.8 *Writer*

The Writer is an agent with two states, namely on-simulation and end-simulation (Figure 13). The Writer agent is in charge to collect information about buses, traffic light, wagon and station to write the log of execution that is going to be used afterwards to present graphically the execution of the simulation.

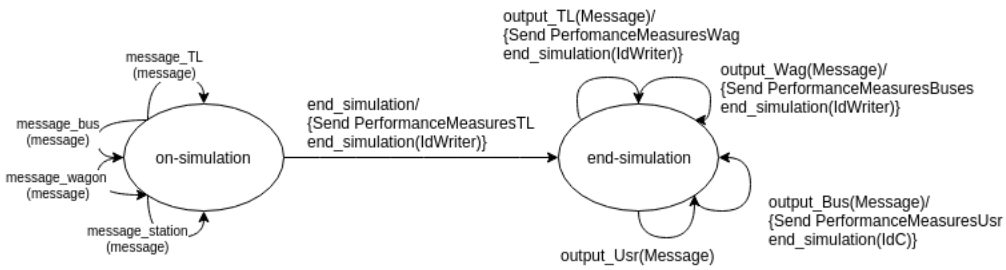


Figure 13: State diagram Writer

After the Controller sends the message end_simulation to the Writer, the writer collect the output of the performance measures agents one by one, by sending the message end_simulation to each performance measures agents.

6 GRAPHICAL INTERFACE

The graphical interface of the project is performed by a web application built on PHP and Javascript using the `d3.js` library to visualize the output of the simulator in Mozart Oz. The framework AngularJS was also used for the presentation of the information in the web page.

The graphical interface has two main parts, namely: the form to adjust the simulation parameters and the results page with a visualization of the simulation and the resulting performance measures.

6.1 INITIAL FORM

On this first webpage the user has the possibility to change the following simulation parameters:

- Frequency of routes
- Time in green for each traffic light
- Time in red for each traffic light
- Number of buses

On Figure 14 is shown the form. First the list of routes is displayed with the current frequency and the user has the possibility to change it to the desired frequency. The frequency is expressed on minutes.

Below the routes a list of traffic lights is shown with the green and red time for each one. The user can change the amount of seconds that a traffic light stays on red and green or use the configuration that is displayed.

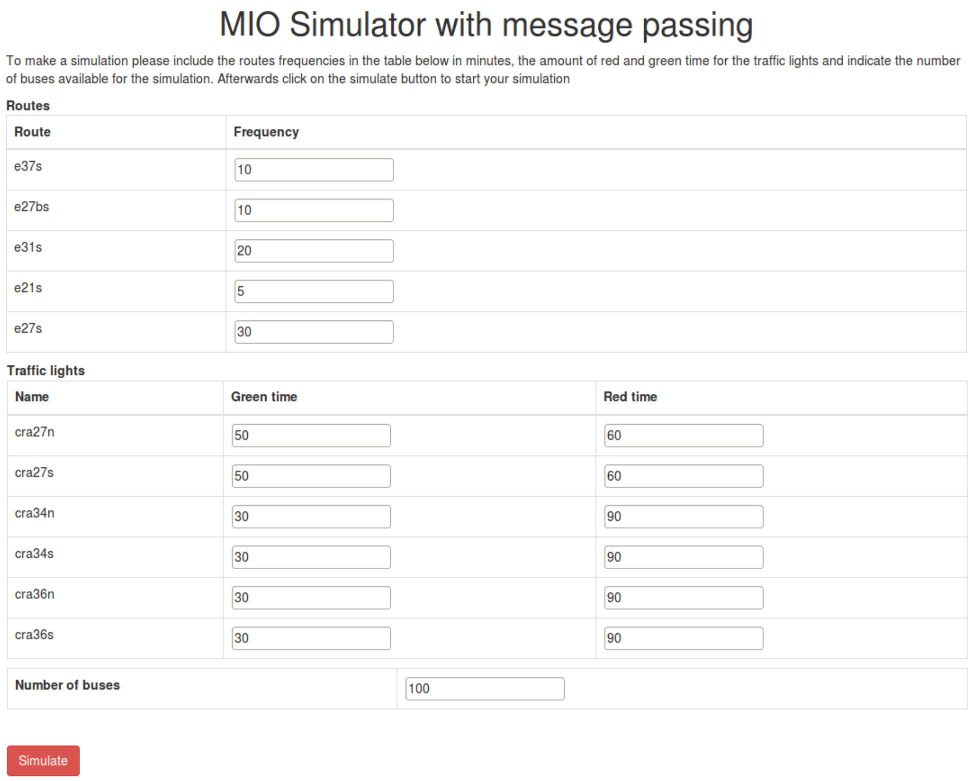
At the end of the form the number of available buses is displayed and the number of buses could be changed. The maximum amount of buses is set to 600. Finally the user has to click the button "simulate" to perform the simulation and get the results.

The information of the routes on the form is read from the routes.json file and the information of the traffic lights is read from the `trafficLights.json` file via Javascript. All the changes made by the users are sent to the server where it is stored on the same files using PHP.

6.2 SIMULATIONS RESULTS

After the user changes the configuration for the simulation, and the new information is saved on the `routes.json` file and the `trafficLights.json` file, the simulator in Mozart is called and the results of the simulation are shown in the results webpage (see Figure 15 and Figure 16).

On the first section of the results webpage (Figure 15) a "start" button on the left side allows the user to start the animation below. On the right side a new



MIO Simulator with message passing

To make a simulation please include the routes frequencies in the table below in minutes, the amount of red and green time for the traffic lights and indicate the number of buses available for the simulation. Afterwards click on the simulate button to start your simulation

Routes

Route	Frequency
e37s	10
e27bs	10
e31s	20
e21s	5
e27s	30

Traffic lights

Name	Green time	Red time
cra27n	50	60
cra27s	50	60
cra34n	30	90
cra34s	30	90
cra36n	30	90
cra36s	30	90

Number of buses	100

Simulate

Figure 14: Initial form

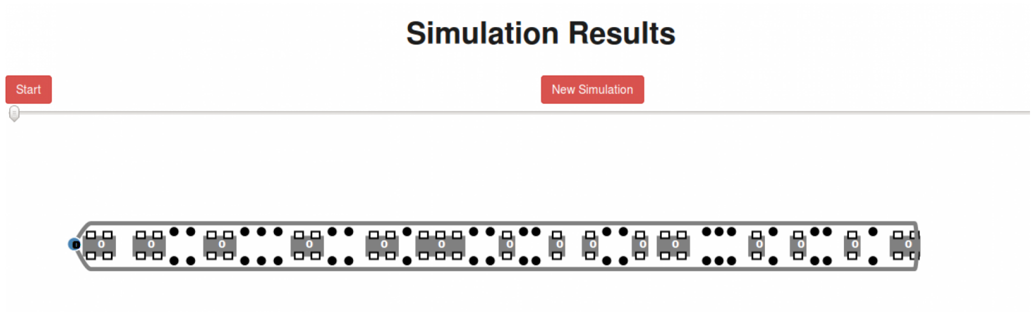


Figure 15: First section Webpage results

simulation button lead the user to the Initial form to change the parameters and make a new simulation.

The animation on this section has a gray line, which represents the corridor: the black points are the traffic lights; the gray rectangles are the stations, which contains white rectangles representing the wagons. Each station has a number on it, which represents the amount of users in a specific moment. The blue points are the buses, which also have a number on them representing the amount of users in a certain point of time.

This animation was made with the d3 library from javascript, where the log created at the end of the simulation by Mozart is read and displayed with the described elements.

The stations are from left to right: Santa Librada, Manzana del Saber, Estadio, Tequendama, Lido, Unidad Deportiva, Plaza de Toros, Pampalinda, Refugio, Caldas, Capri, Melendez, Buitrera, Univalle and Universidades.

When the start button is clicked, the traffic lights start to work, the users arrive to the station and the buses start the respective routes. On Figure 16 it is possible to take a look of the animation working. The buses move from left to right, simulating a route going from north to south.

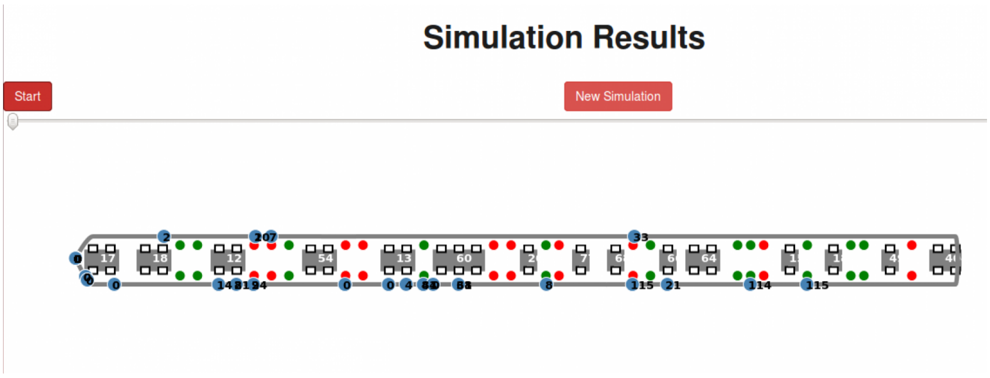


Figure 16: Animation

On the second section of the webpage (Figure 17) the performance measures are displayed as follows. First, on the left side:

- Average waiting time users
- Average travel time users
- Average bus speed
- Average number of users in bus
- Average waiting time of buses in traffic lights
- Average queue size of buses in traffic lights

On the right side:

- Average waiting time for each route
- Average route time
- Average waiting time of buses in wagons
- Average queue size of buses in wagons

The results are given in minutes for the time performance measures. The average bus speed is given on km per hour. The average queue size of traffic lights and wagons is given in number of buses at any moment of time.

The name of the traffic light ends with n when the traffic light is part of the routes in the direction south to north. Likewise the name of the traffic light ends with s when the traffic light is part of the routes in the direction north to south. The name of the routes is presented in the same way as the name of the traffic lights. When the routes are in the direction south to north the name ends in N and when the direction is north to south, the name ends in S.

For the performance measure Route time, the time is given only on the routes end on N. This happens because the route time is calculated once the buses finish a route on the northernmost station.

Performance Measures

Average Waiting Time Users:

5.1386

Average Travel Time Users:

11.489

Average bus speed:

18.231

Average number of users in bus:

38.386

Average queue size and average waiting time in traffic lights:

Traffic Light	Average Waiting Time	Average Queue
batallonn	0.77031	0.2247
batallons	0	0
buitrerapn	1.3938	0.10164
buitreraps	0.25667	0.083105
calle13n	0.425	0.086904
calle13s	0	0
calle16n	0.42353	0.13127
calle16s	0.85429	0.27256
calle6n	0.83007	0.3859

Average waiting time for route and total route time:

Route	Waiting time	Route Time
e21n	6.1563	49.196
e21s	3.3552	---
e27bn	3.0308	20.783
e27bs	3.3233	---
e27n	5.0613	38.888
e27s	2.9729	---
e31n	7.0047	47.713
e31s	3.5138	---
e37n	4.1009	19.758
e37s	3.6955	---
t31n	8.4889	59.326
t31s	3.2336	---
t47bn	3.7445	22.775
t47bs	3.3194	---
t47n	5.6478	39.9
t47s	3.4303	---
t57an	3.631	23.343
t57as	2.7012	---

Average queue size and average waiting time in Wagons:

Wagon	Average Waiting Time	Average Queue
buitreraA1	0	0
buitreraB1	0.22778	0.0062027

Figure 17: Second section Webpage results

7 TESTS OF THE SIMULATOR

For testing the implementation of the Concurrency message-passing model from Chapter 5 a test plan was made, in which the expected results were included. The configuration of the simulator was based on the available information from Metrocali. Results are shown later on this chapter.

The tests made on the simulator were just to prove the coherence of the system. No further tests like comparing the results with another simulation tools were made. Due to the abstraction level used on the model it is not possible to compare the results with a commercial tool, because it is possible to find that users in some tools are model as a flow and not as an agent who make decisions. Additionally each tool has its own performance measures and it is necessary to generate the same measures.

At the end of this chapter the current MIO conditions were defined and executed and some alternative instances for the model were defined and tested.

7.1 TEST PLAN

The main purpose of the test on the simulator was to prove if the interactions among agents on the system were appropriate.

The tests were divided into two groups. The first group is composed of tests changing the buses's frequencies; the second group is composed of tests changing the traffic lights's green and red times. On Table 1 tests are described.

Some performance measures were used to determine whether the simulator was behaving as expected. The performance measures considered were: average number of users per bus, average bus speed, average waiting time users, average time between origin and destination, average queue size on traffic light, average waiting time on traffic lights, average queue size on wagons, average waiting time on wagons and average route time.

On Table 2 it is included the expected results with respect to the reference test, for each performance measure for each test of the type "Change on routes frequencies". Likewise, on Table 3 it is included the expected results for each performance measure for each test of the type "Change on traffic lights".

The test 1 is considered as reference for the performance of the tests 2, 3, 4 and 5 as all of them change only on the frequency of the routes. The test 6 is also considered as a reference for the tests 7, 8 and 9. These reference tests (1 an 6) are taken as a baseline point to compare the evolution of the performance measures.

The expected results are given in terms of how the results varies with regard to the previous test. For the first 5 tests the followed methodology was to increase progressively the frequency of all of the routes. Therefore, it is expected that the performance measures average queue size on traffic lights, average queue size on wagons, average waiting time on traffic lights and average waiting time on wagons increase due to the increment on the amount of buses in use. On

Nr.	Test	Type of test
1	Frequency for all routes is set to 20 minutes	Change on routes frequencies
2	Frequency for express routes is set to 20 minutes and for other routes is 10 minutes	
3	Frequency for all routes is set to 10 minutes	
4	Frequency for all routes is set to 5 minutes	
5	Frequency for all routes is set to 1 minute	
6	All traffic lights are set to green the whole simulation	Change on Traffic lights
7	The green time for all traffic lights is set to 1:30 and the red time is set to 0:30	
8	The green time for all traffic lights is set to 1:00 and the red time is set to 1:00	
9	The green time for all traffic lights is set to 0:30 and the red time is set to 1:30	

Table 1: Test plan

the other hand, performance measures like number of passenger in bus and the average waiting time for users would decrease.

For the test 6 to 9, the followed methodology was to decrease progressively the amount of green time for all the traffic light and increase progressively the amount of red time for the traffic lights. Therefore, it is expected that the performance measures related to the waiting times for buses and users increase. It is also expected that the number of users inside the buses decrease and the speed of the bus decrease progressively.

7.2 AVAILABLE MIO INFORMATION

For this project, information about the routes and users on the MIO system were used. This information corresponds to the days with more demand on March and April 2014 (Gomez Moreno and Jaramillo Molina, 2016).

The information corresponds to files from Metrocali, from which the files related to the users in the system are called "Usos_Detallados" and contains the daily registrations of users in the system with a card in stations or direct in a bus. The amount of files given were 6, from March 25th, March 26th, March 27th, April 1st, April 2nd and April 3rd. The files corresponding to the routes and buses are on the file "Semana_Abril", which contains the information of time between stops for each bus on the first week of April 2014.

Performance Measure	Test 1	Test 2	Test 3	Test 4	Test 5
Number of users per bus	Reference	Equal or lower	Equal or lower	Equal or lower	Equal or lower
Average bus speed	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher
Average waiting time users	Reference	Equal or lower	Equal or lower	Equal or lower	Equal or lower
Average time between origin and destination	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher
Average queue size in traffic lights	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher
Average waiting time in traffic lights	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher
Average queue size in wagons	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher
Average waiting time in wagons	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher
Average route time	Reference	Equal or higher	Equal or higher	Equal or higher	Equal or higher

Table 2: Expected results of tests type of test Change on routes frequencies

The information was transformed in order to determine the peak hours, create an Origin-Destination matrix and obtain the average time between stops for the routes on the Corredor Calle 5. The transformations were made on the ETL tool Spoon from Pentaho. Based on the size of the files and the nature of the transformations (mostly filters) this tool offers an user-friendly interface and small processing time.

7.2.1 *Peak Hours*

Peak hours are the time slots with the highest demand on a day, which are frequently used for the evaluation of a system for planning the service with the highest users volume. To determine those peak hours on the MIO system all the six files of daily users registration were used. The information was filtered to exclude the workers of the system of the analysis.

To visualize the user arrivals behavior, a user arrivals versus time graphic was made with the filtered information. The user arrivals were calculated by obtaining the average number of users going inside the system per minute of the system service (approximately from 4:30 am to 11:00 pm) for the six available days.

On Figure 18 it is possible to observe the behavior of user arrivals. It is possible to determine three peaks between 6:00 am and 8:00 am, 12:00 pm and 2:00 pm and from 5:00pm until 7:00 pm

Performance Measure	Test 6	Test 7	Test 8	Test 9
Number of users per bus	Reference	Equal or lower	Equal or lower	Equal or lower
Average bus speed	Reference	Equal or lower	Equal or lower	Equal or lower
Average waiting time users	Reference	Equal or higher	Equal or higher	Equal or higher
Average time between origin and destination	Reference	Equal or higher	Equal or higher	Equal or higher
Average queue size on traffic lights	Reference	Equal or higher	Equal or higher	Equal or higher
Average waiting time on traffic lights	Reference	Equal or higher	Equal or higher	Equal or higher
Average queue size on wagons	Reference	Equal or higher	Equal or higher	Equal or higher
Average waiting time on wagons	Reference	Equal or higher	Equal or higher	Equal or higher
Average route time	Reference	Equal or higher	Equal or higher	Equal or higher

Table 3: Expected results of tests type of test Change on traffic lights

7.2.2 *Origin-Destination Matrix*

For the creation of the Origin-Destination matrix the files "Usos Detallados" were used. Each of these files contains a row for each user registration in the system with the following information: arrival time, entrance point (bus or station where the user get inside the system) and type of card used (single trip card, user card, Metrocali workers, etc.).

In order to create an origin-destination matrix it was necessary to determine not only the origin of the passenger (the place where the user get inside the system) but the destination (station inside the corridor where the user goes). Therefore in the followed strategy just the users that register more than once per day in the system were considered. For example, when a user register twice in a day, the first time in the station Estadio and the second time in Universidades, then it is assumed that the origin is Estadio and the destination is Universidades.

As the files contain information of the whole system and this work is focused on the Corredor Calle 5, the following steps were made in order to extract the useful information:

1. The selected users had as entrance points just the stations part of the Corredor Calle 5. Therefore, all the rows representing users entering in stations and buses that are not part of the corridor were deleted.

2. All the users, which are employees from Metrocali like bus drivers and operators were not considered.

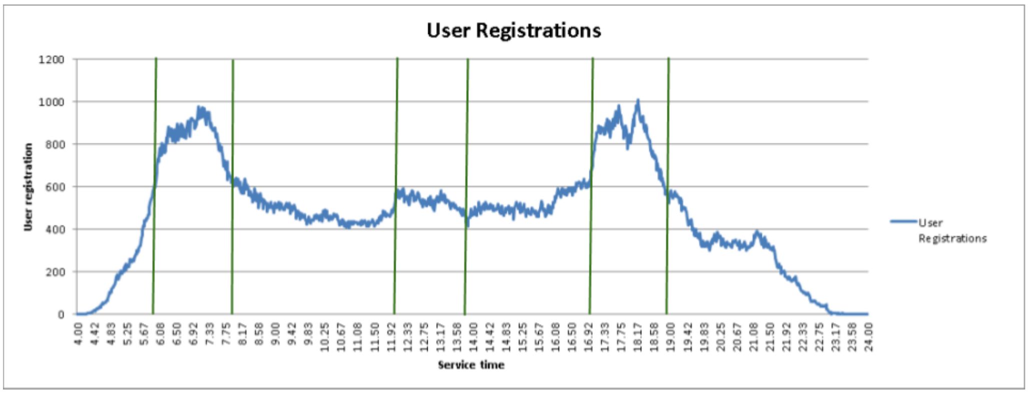


Figure 18: User arrivals versus Service time

3. Only the users using a user card and not a single trip card were considered. This decision was made because it is not possible to determine the destination of the users with single trip cards.

4. Only the users registering more than one time in the system are taken.

After choosing the useful information of the files, Table 4 was made with the amount of users registration per day. The file dates are in the first column; the second column has the day of the week corresponding to the date; the total users registration is in the third column; fourth to sixth columns contains the users registration on peak hours.

Date	Day of the week	Total Number of User	6:00 am to 8:00 am	12:00 pm to 2:00 pm	5:00 pm to 7:00 pm
25/03/2014	Tuesday	116332	16826	15423	26006
26/03/2014	Wednesday	111837	15855	14798	25049
27/03/2014	Thursday	112789	15884	14539	24778
01/04/2014	Tuesday	114541	16177	14731	25142
02/04/2014	Wednesday	113544	16055	14668	25773
23/04/2014	Thursday	110171	15708	14379	23731

Table 4: Users per day

After the analysis from Table 4 the chosen date for the creation of the origin-destination matrix was the March 25th because on that day the total amount of registration is the highest.

With the information of March 25th, an NxN matrix was created, where N is the number of stations in the "Corredor Calle 5" and each position (i,j) corresponds to the percentage of users, who has as origin the station i and as destination the station j. The positions (i,i) are 0 and the sum of all the elements of the matrix is equals 1. The results are on Table 5.

Origin/ Destination	Santa Librada	Manzana del Saber	Estadio	Tequendama	Lido	Unidad Deportiva	Plaza de toros	Pampalinda	Refugio	Caldas	Capri	Melendez	Buitrera	Univalle	Universidades
Santa Librada	0	0.00148	0.00513	0.00902	0.00315	0.00531	0.00154	0.00469	0.00204	0.00216	0.00296	0.00284	0.00704	0.00426	0.01062
Manzana del Saber	0.00284	0	0.00173	0.00519	0.00241	0.00587	0.00136	0.00407	0.00148	0.00160	0.00247	0.00136	0.00463	0.00191	0.00716
Estadio	0.00290	0.00204	0	0.00358	0.00136	0.00587	0.00136	0.00685	0.00173	0.00303	0.00333	0.00306	0.01062	0.00432	0.01328
Tequendama	0.00599	0.00463	0.00321	0	0.00123	0.00593	0.00148	0.00617	0.00309	0.00371	0.00531	0.00303	0.00722	0.00204	0.01210
Lido	0.00173	0.00296	0.00247	0.00136	0	0.00154	0.00043	0.00278	0.00068	0.00130	0.00179	0.00129	0.00370	0.00154	0.00562
Unidad Deportiva	0.00222	0.00296	0.00438	0.00463	0.00074	0	0.00086	0.00315	0.00198	0.00247	0.00340	0.00173	0.00587	0.00142	0.01235
Plaza de Toros	0.00049	0.00111	0.00259	0.00309	0.00056	0.00080	0	0.00043	0.00043	0.00068	0.00117	0.00099	0.00204	0.00049	0.00321
Pampalinda	0.00204	0.00290	0.00710	0.00550	0.00216	0.00494	0.00062	0	0.00068	0.00127	0.00321	0.00309	0.00722	0.00191	0.01321
Refugio	0.00222	0.00340	0.00735	0.00821	0.00272	0.00605	0.00043	0.00327	0	0.00111	0.00278	0.00167	0.00550	0.00154	0.01037
Caldas	0.00315	0.00438	0.00692	0.00790	0.00296	0.00562	0.00123	0.00235	0.00136	0	0.00099	0.00266	0.00957	0.00265	0.01853
Capri	0.00327	0.00383	0.00963	0.01118	0.00346	0.00550	0.00105	0.00463	0.00142	0.00068	0	0.00160	0.00729	0.00136	0.01420
Melendez	0.00840	0.00735	0.01822	0.02056	0.00685	0.00790	0.00235	0.01056	0.00296	0.00352	0.00383	0	0.00296	0.00148	0.02865
Buitrera	0.00370	0.0030	0.01062	0.00932	0.00290	0.00617	0.00099	0.00568	0.00185	0.00352	0.00432	0.00204	0	0.00037	0.01272
Univalle	0.00093	0.00068	0.00327	0.00160	0.00074	0.00093	0.00049	0.00086	0.00016	0.00062	0.00037	0.00031	0.00080	0	0.00272
Universidades	0.01093	0.01155	0.02989	0.03545	0.00920	0.01489	0.00272	0.02464	0.00568	0.01081	0.01136	0.01396	0.02575	0.00364	0

Table 5: Origin Destination Matrix

7.3 RESULTS

For all the tests proposed previously on this chapter. A 2 hours simulation were used. The number of buses available on the simulation were assumed to be enough to perform each test. Therefore the number of buses were set to 1000.

In addition the origin-destination matrix used for the test was the result of processing the information available from Metrocali. The number of users generated for each test was 25000. The time that a bus stays in a wagon with open doors was set to 30 seconds and the running time for the buses was 50 km/h

For each test the simulator was ran 5 times, because some random aspects has been considered, as the generation of users made on R, also as the simulator in Mozart is concurrent, the agents could send messages at the same time and the answers to the messages could variate from one simulation to another.

The results presented on Table 6 and Table 7 were calculated as the average of the times that the test was executed.

Performance Measures	Results				
	Test 1	Test 2	Test 3	Test 4	Test 5
Number of users per bus	61.5198	51.6993	39.5063	22.0908	10.4544
Average bus speed	26.7558	26.0395	25.8410	24.8242	12.7202
Average waiting time users	8.7424	6.6523	4.7114	2.8707	2.6455
Average time between origin and destination	8.5152	8.7553	8.9098	9.6144	11.8410
Average queue size in traffic lights	0.0473	0.0523	0.0790	0.1562	0.3422
Average waiting time in traffic lights	0.3677	0.3874	0.4061	0.4201	0.3888
Average queue in wagons	0.0102	0.0142	0.0210	0.0637	6.9767
Average waiting time in wagons	0.1751	0.1845	0.2016	0.3019	2.5275
Average route time	24.9306	25.0678	25.8039	27.0604	53.2638

Table 6: Results type of test Change on routes frequencies

On Table 6 the results for the first five tests are presented, corresponding to the type "Change on routes frequencies". As the frequencies of the routes are increased from test 1 to test 5, the number of users per bus and the average waiting time of the users, as it was expected, decreases from test 1 to test 5.

As the routes frequencies increase on each test, the number of buses on the system at the same time for a test is higher than the previous test. Therefore the average queue size in traffic lights and wagons should be higher. As a consequence, the waiting time in traffic lights and wagons is higher on each test as it is evidenced on the table.

Consequently the buses needed more time to finish a route. Therefore the average route time increased from test 1 to test 5 and the bus speed decreased on each test.

In the same way, on Table 7 the results for the test 6 to test 9 are presented, corresponding to the type "Change on traffic lights". The amount of time in green for each traffic light decreased by each test. Therefore the amount of time in red increased, which represents an increase of the waiting time for buses.

Performance Measures	Results			
	Test 6	Test 7	Test 8	Test 9
Number of users per bus	39.7810	40.6424	41.3242	40.8716
Average bus speed	31.0894	28.5772	25.0240	17.7330
Average waiting time users	4.3089	4.4460	4.9842	5.8441
Average time between origin and destination	7.4239	7.9556	9.2070	11.6094
Average queue size in traffic lights	0	0.0322	0,0930	0,2702
Average waiting time in traffic lights	0	0.1802	0.3227	0.6171
Average queue size in wagons	0.0160	0.0193	0.0245	0.0300
Average waiting time in wagons	0.1043	0.1846	0.1934	0.2776
Average route time	21.5370	23.2703	26.5250	36.2748

Table 7: Results type of test Change on traffic lights

As a consequence the waiting time and queue size in traffic lights increased from test 6 to test 9. Consequently the average queue size and waiting time in wagons increased, as well as the waiting time for the users. As the waiting time for users increased the number of users per bus increased from test 6 to test 9 as well.

The average bus speed decreased from test to test due to the amount of time that the buses should wait on traffic lights and wagons. Also the average route time increased by each test and the number of users per bus was higher by each test.

7.4 Scenario generation

After testing the simulator some scenarios were created in order to analyze a representation of the current MIO situation and to analyze how changes on the configuration affects the performance measures.

To configure a simulation the following information is needed:

- Red and green time for traffic lights
- Initial state for each traffic light and the time for the initial state
- Routes frequencies
- Number of buses
- Origin - destination matrix
- Number of users

7.4.1 *Current Situation*

The current situation was simulated based on the available information, i.e. the origin - destination matrix used was the one calculated earlier on this chapter. The number of users was 25773 users, as it was the highest amount of users registered on the available time.

The total time for the simulation was 2 hours from 5:00pm to 7:00pm. The number of available buses for the simulation was assumed to be 120. As the calle 5 is one of the main sectors of the city and the speed limit is 60km/h; it was assumed that the traffic lights are synchronized for a car to go through them without stopping at a 60km/h speed.

The traffic light cycle was assumed to be 2 minutes, 1 minute in red and 1 minute in green. Finally the routes frequencies was taken from the "Planea tu viaje" (Metrocali, n.d.-b) application from the MIO, as shown on Table 8

Route	Frequency (minutes)
E21	5
E31	10
E37	12
T31	11
E27	10
E27B	9
T47A	10
T47B	9
T57A	9

Table 8: Routes frequencies current MIO situation

The results of the simulation were included on Table 9. The Performance measures used were: Number of users per bus, average bus speed, average waiting time users, average waiting time from users per route, average time between origin and destination, average queue size in traffic lights, average waiting time in traffic lights, average queue size in wagons, average waiting time in wagons and average route time.

It can be observed that the waiting time for the users are not high, but some consideration should be made: All the buses start without users, which is not consistent with the reality, because the simulation considers just a portion of the routes, not the whole routes. Also the amount of time a bus stops in a station for the simulation is always 30 seconds, which variate on the reality.

The average waiting times per route are very different between each other, i.e. for some routes the waiting time of users is much lower than the waiting time for other routes. For example the waiting time for the route T31 from South to North is 8.7104 minutes and the waiting time for the route E27B from South to North is 2.9645 minutes, when the frequencies are very similar; 11 minutes for T31 and 10 minutes for E27B.

Performance Measures	Results
Number of users per bus	37.0160
Average bus speed	23.9498
Average waiting time users	4.8132
Average waiting time per route:	
T31 South - North	8.7104
T31 North - South	4.4951
T47A South - North	5.2263
T47A North - South	3.5086
T47B South - North	3.4573
T47B North - South	3.3326
T57A South - North	3.2818
T57A North - South	3.17846
E31 South - North	5.4902
E31 North - South	3.3881
E21 South - North	4.4779
E21 North - South	2.3441
E27 South - North	4.7719
E27 North - South	3.3061
E27B South - North	3.3250
E27B North - South	2.9645
Average time between origin and destination	9.7797
Average queue size in traffic lights	0.1350
Average waiting time in traffic lights	0.5610
Average queue size in wagons	0.0275
Average waiting time in wagons	0.2856
Average route time	28.0146

Table 9: Results simulation of current situation

7.4.2 *Scenarios*

As it was mentioned on Chapter 4 the aimed of the assignment model is to optimize the waiting times for the users. Therefore based on the current MIO situation, some scenarios were defined to define a configuration with a better performance than the current situation.

The scenarios were created by changing the traffic lights configuration and the routes frequencies is order to search a better performance for the execution of the system.

The scenarios created are described on Table 10. The scenario 1 represents the current situation of the MIO system described above. On the scenarios 2 and 3 the configuration of the traffic lights were changed and for the last two scenarios (scenario 4 and 5) the frequencies were changed. For the scenario 5 the frequencies were changed for the four routes with the highest waiting times.

Scenario	Characteristics
Scenario 1	Current situation
Scenario 2	All the traffic lights starts on the state red. The frequencies don't change
Scenario 3	The traffic lights are synchronized for a car to go through them without stopping at a speed of 40km/h and the car stops 30 seconds on each station. The frequencies don't change.
Scenario 4	The traffic lights are synchronized for a car to go through them without stopping at a speed of 40km/h and the car stops 30 seconds on each station. The frequencies of all routes is set up to 8 minutes.
Scenario 5	The traffic lights are synchronized for a car to go through them without stopping at a speed of 40km/h and the car stops 30 seconds on each station. The frequencies of the routes change: T31 change to 10 minutes, E27 to 9 minutes, T47A to 9 minutes, E31 to 9 minutes.

Table 10: Scenarios

Each scenario was run five times and the average results are available on the Table 11. The cells in green represents improvements on the performance measures over the scenario 1, which is the reference.

On scenario 2, the waiting times for the users in some of the routes was improved, but the average waiting time for the users is higher than in the first scenario. The average bus speed is lower on scenario 2 than in the first scenario.

On scenario 3, both the average waiting time for the users and the waiting time for each routes have improvements compared to scenario 1. The bus speed is higher and the average waiting times on traffic light and wagons decreased with regard to scenario 1.

On scenarios 2 and 3 it is possible to observe that changes on the traffic light configuration affects directly the waiting time in traffic lights and could lead to a improvement on the user's waiting times.

Scenario 4 represents an improvement on the average waiting times of users over the first three scenarios and an improvement on the waiting times per route. The waiting time on traffic lights are shorter than in scenario 1. On this scenario all the routes had the same frequency (8 minutes), this represents the increase of the frequency for almost all the routes and the decrease on the frequency of the route E21. The results presents an increase on the size of the queue of buses on the wagons and the waiting time on wagons.

Finally scenario 5 has the lowest average waiting time of all of scenarios. This scenario has improvements on the waiting times per routes with regard to scenario 1 and the waiting times on traffic lights and wagons are shorter than in the scenario 1.

Considering that the main purpose is to optimize the waiting time for the users, it could be concluded that the best scenario for the simulated system is

Performance Measures	Scenario				
	1	2	3	4	5
Number of users per bus	37.0160	37.5288	38.2506	37.096	34.7632
Average bus speed	23.9498	22.5634	24.9530	24.5422	24.5326
Average waiting time users	4.8132	4.8465	4.6436	4.42362	4.3009
Average waiting time per route:					
T31 South - North	8.7104	8.5499	7.9768	7.72006	7.0388
T31 North - South	4.4951	4.2819	4.2779	4.2083	2.9940
T47A South - North	5.2263	5.5665	5.1776	4.7284	4.27458
T47A North - South	3.5086	3.4382	3.3688	3.2025	3.3030
T47B South - North	3.4573	3.4358	3.3953	3.3068	2.8838
T47B North - South	3.3326	3.0635	3.1654	2.8813	2.7010
T57A South - North	3.2818	3.3893	3.5309	3.2633	2.9480
T57A North - South	3.17846	3.1155	3.1409	3.2331	2.5194
E31 South - North	5.4902	5.85732	5.3748	5.0851	4.8382
E31 North - South	3.3881	3.4932	3.3741	2.8997	2.9421
E21 South - North	4.4779	4.9795	4.2873	4.2732	5.3014
E21 North - South	2.3441	2.4606	2.2941	2.24812	2.9579
E27 South - North	4.7719	4.9632	5.0587	4.7404	4.3525
E27 North - South	3.3061	3.2180	3.0707	3.1626	3.0288
E27B South - North	3.3250	3.2879	3.5293	3.6494	2.9885
E27B North - South	2.9645	3.4771	3.3302	3.8413	3.2771
Average time between origin and destination	9.7797	9.9716	9.48002	9.6511	9.9317
Average queue size in traffic lights	0.1350	0.1769	0.1221	0.1277	0.1233
Average waiting time in traffic lights	0.5610	0.5063	0.3725	0.3814	0.3567
Average queue size in wagons	0.0275	0.02846	0.0225	0.0289	0.0406
Average waiting time in wagons	0.2856	0.2751	0.2668	0.3121	0.2784
Average route time	28.0146	29.4077	27.0146	27.4644	27.7282

Table 11: Results simulation of scenarios

the scenario 5, with the highest improvement on users waiting times with regard to the current situation.

8 CONCLUSIONS AND FUTURE WORK

8.1 conclusions

- The abstraction level used on our approach enables us to capture the most representative features of the MIO system, the most important operation processes of the buses and users are included and performed on the simulator, which allows us to represent and evaluate interesting scenarios. Moreover, our model can be easily extended to incorporate more detailed and realistic characteristics.
- The traffic assignment model defined on this document had an agent-based approach and the main purpose was to optimize the waiting times of the users in the system by the execution of day to day simulations and the use of performance measures of the within day simulations. This approach made it easier to simulate as many times as possible to reach a scenario where the waiting times of the users is reduced.
- The concurrency message passing paradigm allows the implementation of a simulator on a detailed level, representing all the interactions between the components of the simulated system. The implementation represents the core of the interaction between the elements of the system and made it easier to include new agents and interactions between them.
- For the execution of this project several languages were used. Mozart has a good support for multithreaded programs, which made it ideal for the simulation done on this project. Similarly R, as a statistical software facilitated the creation of random users considering an O-D matrix. Furthermore, Javascript allowed us to create a visual representation of the simulation for the final user. Nevertheless, this languages are not easy to connect, and because of this, a PHP program was built to create a bridge to integrate the programs in the different languages. The association made on PHP was synchronized and well structured, which allows the final users to has a unified program.
- The information use for the execution of the web application was saved on files. This decision made the interaction between the languages a relatively easy process, due to the simplicity of the manipulation of files in all the languages used.
- The creation of a webpage makes the access for users easier to configure the simulation parameters and obtain the results on a browser, without the need to install software on their devices and without the need to train the user.
- The current synchronization of traffic lights has a negative impact on the performance of the system. Therefore, to optimize the MIO system on the

corridors it is necessary to create a traffic light configuration that prioritize the transit of the buses.

- When all the frequencies for the routes increase, the waiting time on wagons could increase as it is presented on scenario 4 on Chapter 7. Therefore to improve the performance on the MIO system, increasing the frequencies could not be properly a solution. This action could lead to higher waiting times for users and decrease of the average speed of the buses.

8.2 FUTURE WORK

This work was a first approach to the creation of a simulator of the MIO system using a concurrency message passing paradigm. In order to recreate a system closer to the reality, it is necessary to make some changes on the defined system:

- So far the users just take direct routes. Therefore, it is necessary to give them the possibility to make transfers to go from their origins to their destinations.

- New users can be included on the design like box offices on the stations to sell tickets to the users. And it should be possible to create different type of routes like "pretroncales" and different buses besides "articulados" buses used at the moment.

- The period of time a bus stops in a station should not be static as it is right now. It should variate depending on the number of users going outside and inside the bus. Therefore a function to calculate this time should be implemented.

- Real-time information should be deliver to the user, like the information available on incoming routes and it should be possible to recalculate the user routes based on real-time information.

- The final user of the simulator should be able to change more aspects than the traffic light period and the the bus frequencies. More meaningful changes should be defined and implemented on the first web form of the application.

- At the moment the simulated routes represents do not imitate the entirely routes and the number of users on the first selected station is always zero. Therefore the reality of the situation inside the buses is not presented. Two approaches that could be used to represent the real users on the buses are:

  1. Only entire routes should be considered for making simulations.
  2. The number of users for the first selected station should not be zero and a number of users inside the bus should be calculated based on the stations, that are not included in the simulated routes.

So far the interaction between the programs made in different languages is by the execution of those programs via PHP. The creation of a web service to connect the application is desired. This change could allow the users to interact with the simulation being processed instead of waiting for the simulation to be finished. Some examples of this interaction could be the incorporation of users in stations to observe how the simulation behaves with more users in a specific station; or the inclusion of buses on a station with a specific route.

To allow the final user to receive suggestions about different configurations for the MIO system, it is desired to incorporate a function based on heuristic to determine different configurations that could lead to a decrease on waiting times for users.

To create a wider traffic model, the private traffic in the city should be included. Therefore more information of the traffic in the city is needed for integrating the whole city transportation. Some aspects like intelligent traffic lights, which are driven not by selected periods of time, but they are driven by the current traffic situation can be included.

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