

AN ANALYSIS OF MODELS IN TRANSPORT SIMULATION PROBLEMS

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To the ones who kindly found a space in their lives to embrace my journey.

<i>Por este rio acima</i>	<i>Up this river,</i>
<i>Isto que é de uns</i>	<i>What is owned by some</i>
<i>Também é de outros,</i>	<i>So it is by others,</i>
<i>Não é mais nem menos,</i>	<i>No more, no less,</i>
<i>Nascidos foram todos.</i>	<i>We were all born.</i>
<i>Aquilo que uns tratam</i>	<i>What one treats</i>
<i>Não hão-de tratar</i>	<i>Others will treat</i>
<i>Outros de outra coisa</i>	<i>Nothing more</i>
<i>Na terra em harmonia</i>	<i>On earth in perfect</i>
<i>Perfeita e suave</i>	<i>And sweet harmony</i>
<i>das margens do rio</i>	<i>Of the river shores</i>
<i>Por este rio acima</i>	<i>Up this river</i>

Fausto Bordalo Dias – Por Este Rio Acima

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ABSTRACT

Modern society and polis demand frequent daily population movements, with a wide variety of distances, routes and vehicles. The logistics involved in the lives and routes of citizens and in the transport of commercial goods require planning and organising in such a way as to ensure efficiency and widespread accessibility.

This document identifies the problems associated with traffic in its various formats, starting with an historical overview of the evolution and creation of the modes of transport we know today or that were used in the past. In a second part, it is studied the materialisation and evaluation in a modelling approach, using simulation and numerical calculus software aiming to analyse road and pedestrian issues, based on theoretical models.

This dissertation seeks to define a comparison between the modelling tools available on the market, assigning different problems and approaches to the various software. The practical scope is focused on the pedestrian study of an Intermodal Terminal, describing the modelling process, the obtaining of results and their presentation and comparison. The software used for this analysis is LEGION, from Bentley Systems, which proved to be challenging but with well-defined utility.

The work in question has made it possible to create a historical-theoretical basis for associating challenges with tools and ways of studying solutions. It has also made it possible to explore the approaches that pedestrian reality requires of the analyst and the development of the knowledge on LEGION Software.

KEYWORDS: Transports, Transport Modelling, Transport Software, LEGION, Pedestrian Simulation.

RESUMO

As sociedades e as pólis modernas exigem das suas populações movimentos diários frequentes, com distâncias, percursos e veículos utilizados variáveis. A logística envolvida na vida e nos trajetos dos cidadãos, mas também na deslocação de matéria comercial, requer um planeamento e estruturação definidos visando a eficácia e a acessibilidade generalizadas.

Neste documento são identificados os problemas associados ao tráfego, nas suas distintas formas, partindo de um traçado histórico, da evolução e criação dos modos de transporte que hoje conhecemos ou que vigoravam outrora. Numa segunda parte, estuda a materialização e avaliação em ambiente de modelação, recorrendo a softwares de simulação e cálculo numérico orientados à análise de problemas rodoviários e pedonais, baseados em modelos teóricos.

A presente dissertação procura definir uma comparação entre as ferramentas de modelação disponíveis no mercado, atribuindo diferentes problemas e abordagens a softwares, também eles diversos. O âmbito prático é particularizado no estudo pedonal de um Terminal Intermodal, descrevendo o processo de modelação, de obtenção de resultados e sua exposição e comparação. O software utilizado para aquela análise é o LEGION, da Bentley Systems, que se mostrou desafiante, mas de utilidade bem definida.

O trabalho em causa permitiu criar uma base histórico-teórica para a associação de desafios a ferramentas e caminhos de estudo de soluções, permitiu também explorar as abordagens que a realidade pedonal solicita ao analista e o desenvolvimento de conhecimento no Software LEGION.

PALAVRAS-CHAVE: Transportes, Modelação de Transportes, Software de Transportes, LEGION, Simulação Pedonal.

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

A_j	Number of trip attractions in zone j
C	Number of Counting Points
D	Average Density
F	Average Inter-Person Spacing
F_{ij}	Friction factor (accessibility factor associated with impedance)
h	Hour
K_{ij}	Optional adjustment factor (socio-economic or physically related factor)
km	Kilometre
L	Lift
M	Pedestrian Area Module – Square Feet Area per Pedestrian
m	Metre
n	Total Number of Observations
P	Flow Volume
P_i	Number of trip productions in zone i
Q	Flow Rate, depending on the position (x) and time (t) in the Greenshields Linear Model
S	Average Speed
S	Speed
s	Second
s	Journey Time
T	Reaction Time of the driver vehicle system
T_{ij}	Number of trips from zone i to zone j
t	Time
t_0	Average Journey Time on the affected network
t_{aux}	Auxiliary Time for Total Travel Time calculation
$t_{boarding}$	Boarding Time for Total Travel Time calculation
t_{travel}	Travel Time for Total Travel Time calculation
t_{wt}	Wait Time for Total Travel Time calculation
V_0	Observed Traffic Flow in one hour
V_M	Modelled Traffic Flow in one hour
v	Velocity
veh	Vehicle

W_{aux}	Auxiliary Time Weight for Total Travel Time calculation
$W_{boarding}$	Boarding Time Weight for Total Travel Time calculation
$W_{transfer}$	Transfer Weight for Total Travel Time calculation
W_{wt}	Wait Time Weight for Total Travel Time calculation
x_i	Simulated Traffic Flow for Time i
y_i	Observed Traffic Flow for Time

ρ Density

3D	Three Dimensional
AON	All or Nothing Assignment
API	Application Programming Interface
BC	Before Christ
BS	Base Scenario
CAD	Computer-Aided Design
CAVs	Connected and Autonomous Vehicles
CCAM	Cooperative, Connected and Automated Mobility
CO ₂	Carbon Dioxide
DUE	Dynamic User Equilibrium
FDS	Fire Dynamics Simulator
FPM	Feet per Minute
GEH	Geoffrey E. Havers
GIS	Geographic Information System
IB	Information Board
IDM	Intelligent Driver Model
ITS	Intelligent Transport Systems
LoS	Level of Service
MPZ	Multipath Zone
MSA	Method of Successive Averages
MTZ	Mesoscopic Transit Zone
NE	Northeast
NTR	Number of Transfers
NW	Northwest

OD	Origin-Destination
PFM	Pedestrians per Foot width of the walkway or stairway per Minute
RDS	Real Data Set
RMSE	Root Mean Squared Error
SE	Southeast
SFP	Square Feet per Person
SRC	Stochastic Route Choice
SSG	Signal State Generator
SW	Southwest
TAZ	Traffic Analysis Zones
TraCI	Traffic Control Interface
TTT	Total Travel Time
UTS	Underground Ticketing System
XML	Extensible Markup Language

1

INTRODUCTION

1.1. CONTEXT AND SCOPE

Humanity and its ways of organizing have come to a state in which people's activity relies on at least one transport mode. Pendular movements as home to work (and work to home) or home to school (and school to home) trips fulfil the roads of the metropolitan areas.

The high flow and demand the road network system experiences has led to a continuous expansion of the infrastructure and a constant upgrading and creation of transport modes. This evolution and the increasing offer implicate the identification of the problems, challenges and needs of the transportation reality, which can be more efficient when applying theoretical models and implementing them into the analysis. The materialisation, detailing and refining of the theoretical models, created with a generic perspective based on a standard scenario, can be helpfully managed through the usage of a properly chose suitable software.

The history of transportation has been associated with the evolution of society, with remarkable events as the introduction of the wheel by the Sumerians in 3500 BC or the first engineered car by Karl Benz, during the Industrial Revolution. Nowadays, those events are easily recognised in the available modes of transportation but are still being improved to respond to modern concerns, such as the widespread implementation of electric vehicles.

The modelling as a transport planning tool is more recent. Greenshields presented the first flow traffic model in 1934 and Gerlough conceptualised the first transport simulation in 1955, relying on binary language. Currently, models are based on statistical concepts and divided into their characteristics, for example the level of detail and time representation.

The computational advances helped the development of various transport simulation software, based on distinct theoretical models with different interfaces and outputs. It is important to understand the applicability of each software for the associated purpose.

LEGION is a Pedestrian Simulation Software, it is a useful tool to understand the pedestrian dynamics and the connection with the involving system. In this document, a LEGION simulation of an Intermodal Terminal is carried out, aiming to understand how the changes in the system affect the pedestrian movements.

This dissertation was realised in the Faculty of Engineering of the University of Porto.

1.2.AIM AND STRUCTURE

The main ambition of this work is to gather historical knowledge of transportation and its models, aside the evolution of the software and its availability, to choose the more suitable one for each case, regarding its characteristics. Other aim of this project is to acquire knowledge in a particular simulation software, LEGION, through the study of a practical pedestrian scenario and to understand the importance of some factors of the systems and the modelling process.

The structure of this dissertation is related to the specific aims, whose are distributed by 5 Chapters, described below.

In Chapter 1:

- Definition of proposals and ambitions, as well as the dissertation importance;
- Description of the document structure.

In Chapter 2:

- Description of the transportation evolution, since the beginning to the modern times;
- Identification of modern concerns regarding transportation;
- Historical description of the transport modelling rise and development;
- Identification of the types of models and its hypothesis;
- Identification of different approaches in modelling;
- Gathering of theoretical formulations related to Pedestrian analysis;
- Identification of the Pedestrian analysis key elements and parameters.

In Chapter 3:

- List some software available in the market;
- Identification of the characteristics and tools of each software, as well as its outputs;
- Comparison of software, according to some factors, such as type of models.

In Chapter 4:

- Description of the Case Study;
- Description of the modelling process in LEGION;
- Elaboration of different scenarios;
- Description of the implementation of the scenarios in the software;
- Description of the conducted analysis;
- Presentation and discussion of the results.

In Chapter 5:

- Drawing the main final conclusions;
- Description of the challenges faced during the process;
- Drawing the specific conclusions;
- Suggesting further developments on this work.

2

LITERATURE REVIEW

2.1. EVOLUTION OF THE TRANSPORTATION

For many years in the history of mankind, the only means available to people was nature, but as the world began to develop and people began to communicate with other civilizations, the need for transportation became urgent in order to move goods and people and to trade. The introduction of the wheel (3500 BC), through the work of the Sumerians, promoted the development of means of transport, those improved the usage of wagons and carriages pulled by horses (Rossi et al., 2016).

A great development in the transportation field, according to some historical information, was the first recorded paved road in the world, built in 2500 BC by the Egyptians with the aim to help building the Great Pyramids. Even though the Egyptians were the first to build roads, the Roman Empire is very relevant in the history of roads, starting from 300 BC, the Romans improved the quality and increased the number of roads, mostly for military and commercial purposes along Europe and Great Britain (Albano, 2016).

Before the construction of roads, a mode of transportation was already evolving, the boat. The Pesse canoe is the oldest boat discovered and dates to 7600 BC [1]. The earliest known boats were simple log boats that were made by hollowing out a tree trunk. Starting in 1450 and for several centuries, wooden ships with three or four masts were in use by several different countries, mainly to explore, to trade and for battleships [2].

During the 18th and 19th centuries, the Industrial Revolution conducted to significant upgrades and discoveries in transportation. Beginning in Britain, the Industrial Revolution saw the rising of advanced machinery and manufacturing changing the way the world produced and traded goods. Alongside this industrial evolution, more advanced modes of transport were created to cater for a never stopping progressing world. During the Industrial Revolution, the first bicycle was made, the first motorways were invented, and the first car was engineered by the German inventor Karl Benz, Figure 1 [3].

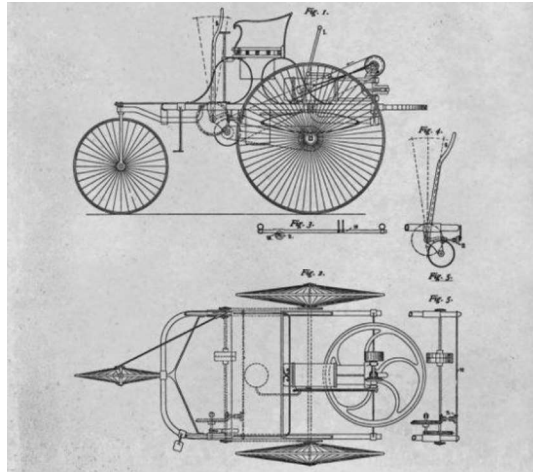


Figure 1 – First car by Karl Benz [4]

In the 1820's, the first modern trains were built using steam locomotives, and trains became a regular mode of transport for many, it developed railway networks allowing people and goods to travel and be transported at greater distances at a quicker speed [5]. By that time in history, in Portugal, the major development in terms of infrastructure took place when the engineer, politician and Minister of Public Works of that time, Fontes Pereira de Melo, made a significant investment, building around 460 kilometres of roads and 17 bridges; he also introduced the railways in 1856. By the day of his death, in 1887, Portugal was crossed by 6500 kilometres of road (Pereira, 2021). Trains served as the most important mode of transportation during the called “The Golden Age” of rail roads, which lasted from the 1880's until the 1920's, after being invented their popularity grew quickly, but in the 1920's, cars and planes would replace trains as the primary means of transportation [5].

Even though the traffic lights appear to be a very modern and technological tool, traffic lights were introduced in 1868, in London, at a very busy intersection (Figure 2) and consisted of a revolving gas lantern with only red and green colours (Sánchez et al., 2006). Electricity only became widespread 40 years later, and that is when the first two-colour traffic light appeared, the yellow light was added in 1920, in New York. Traffic lights including pedestrians were put into service in 1933, in Copenhagen [6].



Figure 2 – First Traffic Light Police Notice [10]

In 1901, Wilbur Wright addressed a distinguished group of Chicago engineers on the subject of “Some Aeronautical Experiments” that he had conducted with his brother Orville Wright over the previous two years, after several tests Orville and Wright took the Flyer for a 12-second, in 1903, it was the first successfully powered and piloted flight in history. The outbreak of World War I, in 1914, led to many companies and governments expediting aircraft design for military purposes. The after-war era saw plenty of experimentation in aircraft types, Dornier Do X, launched in 1929, was the largest aircraft at that time with a capacity of 169 passengers and had a range of up to 1700 kilometres. The developments in aircraft, since the 1970’s, has been the improvement of performance and safety [7].

The ambition to make railway faster conducted to the first high-speed rail, with a 515-kilometre extension, the Shinkansen line, was inaugurated in 1964 in Japan, connecting Tokyo and Ōsaka. Its inauguration was greeted by widespread international acclaim, and the Shinkansen was quickly dubbed the “bullet train” for the great speed obtained and for the aerodynamic bullet shape of their noses. Europe’s first high-speed line opened in Italy in 1977, between Rome and Florence [8].

In the 1980’s, container ships began to be more widely used to transport cargo, designed to carry the containers stacked on the deck, can hold up to one thousand containers at a time (D. Knowles, 2006). In the 1990's boats ushered in an era of luxurious passenger cruise ships, reshaping leisure travel, with amenities like shops, restaurants and entertainment [9].

In the 21st century, the concerns in environmental issues engaged the investment and research in electric cars (Baran & Legey), however, electric vehicles were created back in the 1880’s, but their use declined significantly due to the high cost and short range of the battery at that time (Rajashekara, 1994).

2.2. HISTORY OF TRAFFIC MODELLING AND SIMULATION

In 1934, Bruce Greenshields presented the first traffic flow model at the Annual Meeting of the Highway Research Board, he carried out some tests to measure traffic flow, traffic density and speed using photographic measurement methods for the first time. The Greenshields model is a linear speed-density

relation that converts into a parabolic relation between speed and traffic flow. This achievement inspired researchers around the world and after that, many models and simulation tools were developed, Figure 3 (Kuhne, 2014).

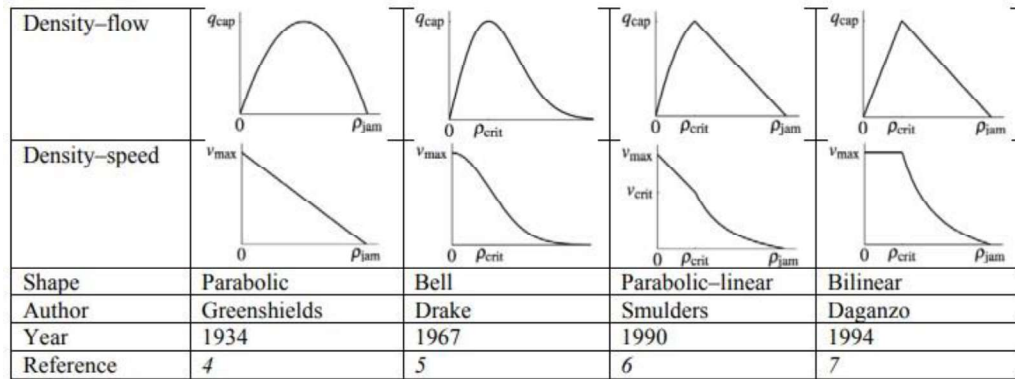


Figure 3 – Different Shapes of Fundamental Diagram of Density-Flow-Speed (Kuhne, 2014)

In 1955, Gerlough applied computer technology to simulate the freeway traffic. This simulation used binary language as physical and mathematical representation, where the “1’s” were the vehicles and the “0’s” the spaces between vehicles, Figure 4 (Gerlough, 1955).

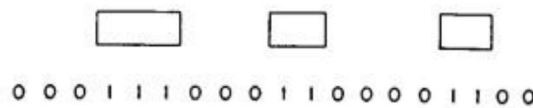


Figure 4 – Representation of vehicles by binary digits (Qiao et al., 2021)

In the decade of the 1960’s, the macroscopic traffic simulation software, NPL, the traffic control simulation software, LWEIS, and the vehicle delay simulation software, KELL, were created and the simulation program, TRANS, for T-shaped intersections and a traffic signal configuration model emerged. In 1966, the SIGOP simulation system was developed by the Federal Highway Administration for the signal timing optimization (Qiao et al., 2021).

In the 1970’s, the emerge of the Smalltalk computer language, the first integrated development environment, has fuelled the advancement of traffic simulation. With the increase of computer technology, the accuracy of the traffic simulation model improved rapidly, and the functions of the simulation model were diversified. A macroscopic model, SATURN, for signal control at intersections, was developed by the University of Leeds in 1976, this software is still used by some transportation planners (Qiao et al., 2021).

In the 1980’s, with the development of object-oriented language, a macro-micro simulation model DYNEMO, was proposed by Schwerdtfeger, in the simulation experiment under the condition that the vehicle is being driven out of the expressway (Qiao et al., 2021).

The appearance of Java provided a new method for simulation software. In the 1990's, many countries began to upgrade or develop traffic simulation software based on the Intelligent Transport Systems (ITS), some of them are widely used, like PARAMICS, VISSIM, and AIMSUN (Qiao et al., 2021).

In the 2000's, two significant simulation systems DYNAMIT and DYNASMART and some other systems like DYNAMIQ, MEZZO, TRANSMODELER were all visual simulation systems (Qiao et al., 2021).

2.3. TRANSPORTATION NOWADAYS

The world is growing at a rapid pace and so it is the need for movement and the urge to attend to many different activities, whether for necessity or leisure. This contributes to the road traffic overloading and transport demand booming, which causes transportation and environmental problems, such as congestion, accidents and pollution (Rodrigues, 2014).

Traffic flows can negatively affect the ability of pedestrians and cyclists to use the road space and its facilities, as pedestrians and cyclists can affect the capacity of road for vehicles. It is important to obtain the best solution for each case, according to the activities and the surroundings, these types of modes should always be taken into account when modelling a network (Morgan & Veysey, 2013).

Another problem that unplanned transportation systems have created is regarding the safety - it is expected that road traffic accidents will be the fifth cause of deaths in the world by 2030. With an ageing society, transportation systems must improve the accessibility of their services to be more inclusive and reach the whole population, but, since it involves additional costs, in most cases these changes only happen imposed by legal requirements (Karekla et al., 2011).

Although Public Transportation is quite effective at reducing the externalities of driving private vehicles, the low investment in this field does not attract all kinds of urban dwellers to use it (Cheng & Chen, 2015). In addition, accessible public transport lacks accessible pedestrian infrastructure, such as sidewalks, traffic signals, street crossings and travel information for people with sensory, cognitive or linguistic impairments (Suen & Mitchell). Mobility is reduced even more for public transport users because it tends to operate in most congested arteries (Gakenheimer, 1999).

The greatest megacities around the world are facing overcrowding public transit systems, with the addition of environmental and traffic complications, thus Intermodalism is gaining more relevance (Bernal, 2016). Intermodal transportation can be defined as the transportation of a person or goods from its origin to its destination by a sequence of at least two transportation modes which includes at least one transfer from one mode to another, realized in an intermodal terminal (Crainic & Kim, 2007).

According to the New Zealand Transport Agency (2009), deficits in the physical environment are the most common factor preventing the population from walking, such as insufficient footpaths or sections of footpath, poor-quality walking surfaces, obstacles and minimal maintenance on the footpath, poor quality lighting, speeding traffic and absent shelter from inclement weather. The social and perceptual deterrents factors are a perceived longer journey time, the perception that other modes of transport are more convenient and safer and the perception that pedestrians generally have a low social status, especially in relation to car drivers. The institutions and local authorities have planned (or have not planned) cities in a way that can make walking very difficult for the population, with long distances between origins and destinations through insufficient walking infrastructure and priority given to other modes of transport. The where, why and who walks questions needs to be addressed in order to understand the current situation of walking trips. A summary of a travel survey from 2000 in New Zealand is shown in Table 1.

Table 1 – New Zealand travel survey (NZ Transport Agency, 2009)

Trip Purpose	Trip purpose as a percentage of all walking trips	Walking trips of all modes for each trip purpose (%)
To home	31.2	16.7
Work (to job)	10.0	16.0
Work (employer's business)	2.2	8.1
Education	7.7	31.8
Shopping	14.2	20.9
Personal business/services	6.1	18.3
Social/recreation	24.5	20.7
Accompanying someone else	4.2	8.3
Total	100.0	-

According to the results, the majority of walking trips are home-bounded journeys, from work or educational buildings (31.2%); however, when compared with other modes, its percentage have very low values, being the highest ones associated with the educational buildings (31.8%). Other important data gathered that is not shown in the table above is that females make 22% more walking trips than males, but the average time walking is similar in both genders, 11 to 12 minutes per trip.

To summarise, the transportation problems identified above are the environmental issues due to the high level of car usage, lack of planning and investment in transportation, mainly in public transportation, no planning when it comes to pedestrian spaces and the poor investment in intermodal solutions.

Human mobility behaviour is a complex issue, involving many decisions taken at different levels, taking into consideration of one's own needs, capabilities, and constraints. Transport problems cannot be solved as an independent variable, it must always be approached with a context. Models contribute to identifying the problems and selecting ways to address them in a more solid basis; nevertheless, a case by case study is necessary.

2.4. TRANSPORTATION MODELS

The main focus of the Transportation Models is to represent the real world and the problems existing in a network as precisely as possible. The demand and supply interaction models play a central role in the quantitative analysis of a transportation system. Demand models represent how users choose among all alternatives, based on the departure time and the path, the supply performances according to a network flows or costs (Cascetta & Cantarella, 19991).

The models can be classified by the level of detail, time representation and the uncertainty of the perception of the population.

2.4.1.LEVEL OF DETAIL

The models are an approximated reproduction of the successive changes of the traffic system over time and they can be Macroscopic, Mesoscopic and Microscopic, depending on the level of detail required, the resolution. A scheme of the level of detail of a network is shown in Figure 5 (Gomes, 2003).

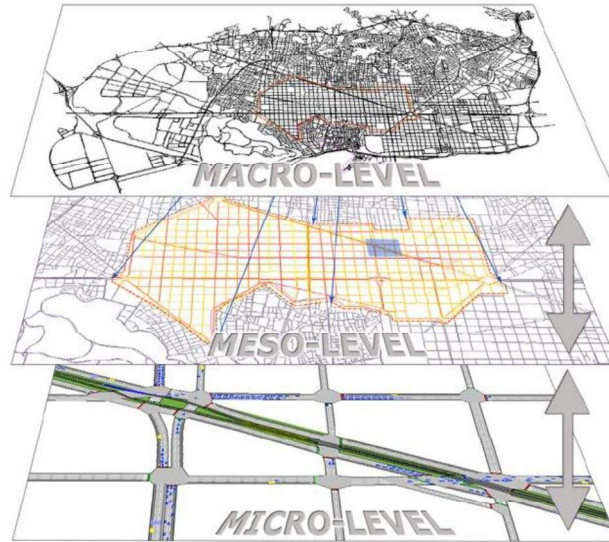


Figure 5 – Level of Detail of a Network (Marcelo & García, 2003)

2.4.1.1. MACROSCOPIC MODELS

Macroscopic models deal with aggregated characteristics of transportation elements, such as aggregated traffic flow dynamics and zonal-level travel demand analysis. They are based on deterministic relationships between the quantities characterizing the traffic flow such as: flow rate (veh/h), density (veh/km) and average speed (m/s), that can relate to each other as it can be seen in the equation 2.1 relative to the Greenshields Linear Model (Dias, 2021).

$$Q(x, t) = \rho(x, t) * v(x, t) \quad (2.1)$$

These models do not characterise the individual behaviour of vehicles, such as changing lanes. They are more commonly used to model very extensive networks and are widely used at a strategic level. The calibration and validation procedure are quicker than in the other models. Some disadvantages associated can be the lower detail level, incapacity to translate an individual vehicle and to show the delays in the intersections and the aggregated presentation of the results (Dias, 2021).

2.4.1.2. MESOSCOPIC MODELS

Mesoscopic models analyse transportation elements in small groups, within which elements are considered homogeneous. There are some advantages comparing this type of model to the others such as requiring less effort for network building and calibration than microscopic simulation and generating

more detailed simulation results in terms of traffic conditions than macroscopic simulation. These models do not distinguish between vehicles or driver behaviour because they don't recognise vehicles as individual elements, but as a collective (Dias, 2021).

In the Mesoscopic Models there are three models that are more usual, the Headway distribution models, the Cluster models and the Gas-kinetic model. The first models are based on the statistical properties of time intervals, starting from an observation of the time intervals distribution, or spacing of vehicles, considering them as independent variables, equivalent and randomly distributed, are based on the definition of density functions. The Cluster models can describe the dynamics of traffic flow through clusters of vehicles that have a specific property in common. The gas-kinetic model is the most widely used mesoscopic model, able to describe velocity distributions and localisations at specific moments in time, the dynamics of these distributions are usually guided by methods individual driver behaviour methods, such as changing lanes, accelerating or the interaction between vehicles (Dias, 2021).

2.4.1.3. MICROSCOPIC MODELS

Microscopic models study individual elements of transportation systems, such as individual vehicle dynamics and individual traveller behaviours, separate units in the traffic flow (different types of vehicles, pedestrians) and mutual interactions between them. They are usually applied for the detailed analysis of limited segments of transportations systems.

These type of models' main characteristics include high level of detail, capacity of giving a number of results and possibility to analyse the behaviour of an individual vehicle. However, it can have some disadvantages like the need for greater computing power, a lot of input data for its execution and extensive calibration and validation processes (Dias, 2021).

The microscopic models can be sub-divided into other four models, the Car-following, Lane Changing, the Gap Acceptance and the Free-flow (Dias, 2021).

Car-following models consist of differential difference equations giving the acceleration of a vehicle with respect to the behaviour of the preceding ones. The general form of car-following models can be represented by the equation 2.2, where T is the reaction time of the driver-vehicle system (Hildebrand & Hörtin, 2014).

$$response(t + T) = sensitivity * stimulus(t) \quad (2.2)$$

In the Lane Changing models, decision depends on three questions: the necessity, the desirability and the possibility of changing lanes. According to that, there can be three different reasons for drivers to change lanes: Mandatory change, Change without Restrictions and Change in Advance. Trying to simulate the driver decisions is very hard because the motivations and decision makers' behaviour are also very complex (Oliveira, 2014).

The Gap Acceptance models represent the action of waiting until the right time for the driver to change lane or direction, so the interval between the vehicles is enough to complete the manoeuvre in security, this minimum time is named the Critical Interval. The parameters that affect this model are the acceleration, the maximum critical interval and the visibility distance (Oliveira, 2014).

The Free-flow models are used when the spacing between the vehicles is very high that the following vehicle does not impact the behaviour of the previous vehicle, the drivers can choose the speed

considering that it does not exceed the required speed and the distance never goes beyond the safe recommended (Dias, 2021).

2.4.2. TIME REPRESENTATION

In terms of time representation, transportation models generally can be classified as Static, Dynamic and Quasi-dynamic models (Casas et al., 2016).

2.4.2.1. STATIC MODELS

The Static Model is a simplified representation of journey in a given time period that does not take into account neither the fluctuations of demand, nor the interactions between the time and distance steps (Tchappi Haman et al., 2016). The demand is evenly distributed over time (Silva, 2022). Static models are still preferred over the others in strategic transportation planning because of the simplicity, fast speed and the ability to handle large networks.

Some assignments of static models are the All or Nothing Assignment (AON), the Incremental Assignment, the Stochastic Traffic Assignment, System Optimum Assignment and the User Equilibrium Assignment (Saw et al., 2015).

All or Nothing Assignment is classified as not applying capacity restrictions, defining that all drivers consider the same attributes when choosing a route, with the perceived generalised cost of the links being the same for every driver. The Incremental Assignment introduces a significant improvement that can result in more realistic allocations, by considering the capacity restriction of the links and the allocation carried out in an iterative process. In the Stochastic Assignment, the network elements are not subject to capacity restrictions, so the route choice mode is based on the perceived variable generalised costs of the links, instead of the real generalised costs, thus becoming independent of the overall flow. The system optimum assignment meets an ideal of network system optimisation, assuming that users cooperate to minimise the total cost of the system or network, rather than minimising their individual cost. User Equilibrium methods require iterations and the recalculation of journey times. There is a dependency between the traffic volumes on the links and their generalised perceived costs, it is characterised by more reliable results (Silva, 2022).

2.4.2.2. DYNAMIC MODELS

There is a representation of time and a temporal relationship between all the processes. The outcomes can evolve over time, so it is possible to get the evolution of the congestion and the delays (Casas et al., 2016). This model is most used to forecast networks with high congestion variations over time, and it also can provide real-time traffic simulation. Dynamic Models can be classified into Analytical Based Models and Simulation Based Models (Saw et al., 2015).

These variations can be continuous or discontinuous and are specially advantageous when there are large changes in traffic over a period, such as the end of sporting events (Silva, 2022).

2.4.2.3. QUASI-DYNAMIC MODELS

It is a middle model, between the dynamic and the static models, it uses some static models that are temporally linked to improve the accuracy of the static model (Casas et al., 2016).

2.4.3. UNCERTAINTY

Other way to classify the models is according to the uncertainty, Figure 6, models can be Deterministic or Stochastic (Casas et al., 2016).

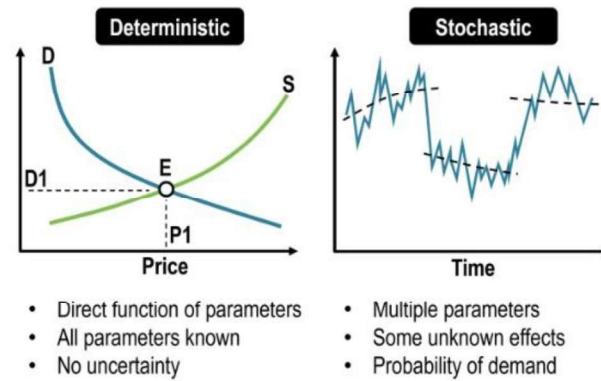


Figure 6 – Uncertainty Models [11]

2.4.3.1. DETERMINISTIC MODELS

These models do not take into account the uncertainty and tries to represent the average conditions (Casas et al., 2016). This model assumes that the users know the cost of each path (Cascetta, 1988). A spatial interaction model is a standard example of deterministic demand, which is a general function of the attributes of at least two locations pondered by a function of their distance.

2.4.3.2. STOCHASTIC MODELS

The stochastic models assume the uncertainty, considering the errors in user's generalised cost perceptions, for the assignment in a Stochastic model the models generally used are the Logit or the Probit (Russo & Vitetta, 2003). For instance, freight demand and rates can have substantial variations, including surges and crashes associated with the volatility of commodity and energy prices, transportation prices, geopolitical events, and currency fluctuations.

2.5. TRANSPORT MODELLING

Transport systems can be represented by a network, that is a set composed of nodes, arcs and flows. Transportation nodes are locations with a concentration of outgoing and incoming travel demand whereas arcs are routes connecting two nodes and flow refers to the means of movement that use arcs to arrive to nodes (Costa, 2019).

Modelling an infrastructure gives a valid representation of the current situation that helps in understanding what is happening, the existing infrastructure bottlenecks or shortcomings can be identified and explained, the modelling can be a very important tool to aid decision-making. Further, traffic models usually come with a visualization component which helps in presenting the situation on the road or found issues to a broader audience and they are capable of predicting what happens if the given system is changed.

Model calibration and validation are important steps in the development of a valid simulation model, and crucial for ensuring reliable information gathered from these models (Ozbay et al., 2014).

Models are based on travel behaviour of the population, so it is important to distinguish the main two models of travel behaviour, the Activity-based and the Trip-based.

2.5.1. ACTIVITY-BASED MODEL

Activity-based models are based on the principle that travel demand is generated by the daily activity patterns. Activity-based models predict which activities are conducted when, where, for how long, for and with whom, and the travel choices they will make to complete them. Most of these models share the same two-step structure, first the generation of the population and then the schedules. The utility-based model, that simulate the human decision process to select the best route alternative, was the first activity-based model to predict full-scale mobility plans (Adenaw & Bachmeier, 2022).

Activity-based models are particularly suited for allowing a continuous distribution of value-time-savings, a typical analysis when driving in highways, and a clarified accounting of the full range of costs and utilities associated with both activity and travel, which improves transit mode choice estimation [12].

2.5.2. TRIP-BASED MODEL

In the trip-based models, also known as four-step models, the primary unit of analysis is the trip interchange, Origin-Destination, between two geographic locations.

The Four-Step-Model is one of the oldest and widely models used for replicating the mobility patterns within a city including the resulting traffic state of the transportation network. This model uses a representation of the modelled region divided into areas called Traffic Analysis Zones (TAZ) and provides a mechanism to determine equilibrium flows for networks, direct demand functions can be estimated and, together with standard link performance functions and path enumeration, can provide the desired flows (McNally, 2000).

It is a macroscopic model built around four main steps, the Trip Generation, the Trip Distribution, the Mode Choice and the Route Assignment (Figure 7).

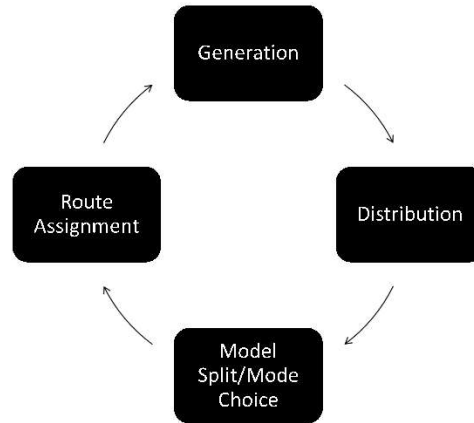


Figure 7 – Four Step Model [13]

In the Trip Generation step it is important to gather the information regarding the frequency of origins or destinations in each trip, to have an idea of what trips are being generated, for that its useful to have data about the population, such as demographic, economic or social, it is also very important to understand the land use.

After that, there is the Trip Distribution, in this step it is done the Origin-Destination Matrix, each cell represents the number of trips from origin, in row, to the destination, in column, following some models such as the Growth Factor Method, the Gravity Model, Intervening Opportunities Model, the Choice Model and the Entropy Model (Rodrigues, 2014). The most used is the Gravity Model, which is inspired in the Newton's Gravitational Law stating that the attractiveness between two bodies is related to their mass (positively) and also to the distance between them (negatively), the equation 2.3 shows how the model works.

$$T_{ij} = P_i * \frac{A_j F_{ij} K_{ij}}{\sum_{j=1}^n (A_j F_{ij} K_{ij})} \quad (2.3)$$

With:

T_{ij} - Number of trips from zone i to zone j

P_i - Number of trip productions in zone i

A_j - Number of trip attractions in zone j

F_{ij} - Friction factor (accessibility factor associated with impedance)

K_{ij} - Optional adjustment factor (socio-economic or physically related factor)

The next step is the Mode Choice where the means of travelling is adjusted to each trip, these different modes can be private automobile, walking, bicycling, public transportation and others. Three major factors can influence the modal choice, the character of the trip maker, the character of the trip and the characteristics of the competing transportation networks (Morgan & Veysey, 2013).

The last step is the Route Assignment and can be seen as the combination of the other steps, it allocates each origin and destination to a route and a mode of transportation. It can follow three different approaches such as the Diversion Curves, the Minimum Time Path or the Minimum Time Path (Alkaissi).

2.5.3.MODEL CALIBRATION AND VALIDATION

The calibration of a model is a process that aims to obtain the confidence level desired, after the calibration, the output must be validated.

When comparing the real network and model output data, if there are substantial differences in the comparison, some correction factors are added in the input data, then the comparison must be done again, this is an iterative procedure of input modification to meet the target output (Ozbay et al., 2014). To compare it is necessary to have real data, this data can be found in Official Demographic Statistics, the data can also be gathered with counts in the field.

When it comes to validation, there are a few methods for validating the results produced by the traffic model, some examples are the GEH (Geoffrey E. Havers) index and the RMSE (Root Mean Squared Error) (Morgan & Veysey, 2013).

The GEH index was developed at London City Hall by Geoff Hovers and can be considered as a parameter based on the chi-squared statistical test, consisting of a comparison between modelled and observed volumes (Silva, 2018). This index can be calculated individually for each section or for the entire network (Tavares, 2003). The following equation 2.4 and equation 2.5 shows how to calculate the GEH.

$$GEH = \sqrt{\frac{2(x_i - y_i)^2}{(x_i + y_i)}} \quad (2.4)$$

Or

$$GEH = \frac{1}{n} \sqrt{\sum_{i=1}^n \frac{2(x_i - y_i)^2}{(x_i + y_i)}} \quad (2.5)$$

With:

x_i - Simulated traffic flow for time i ;

y_i - Observed traffic flow for time i ;

n - Total number of observations.

The RMSE is a statistical measure of the correlation between the entire set of metering data and the total volumes that the model predicted. Unlike the GEH index (which applies to individual flows), the RMSE applies to the entire set of comparison data and is expressed as a single value (Morgan & Veysey, 2013). The application of this measure is represented in the equation 2.6.

$$RMSE = \sqrt{\frac{\frac{\sum (V_0 - V_M)^2}{C-1}}{\frac{\sum V_0}{C}}} * 100 \quad (2.6)$$

With:

V_0 - Observed traffic flow in one hour;

V_M - Modelled traffic flow in one hour;

C- Number of counting points.

2.6. PEDESTRIAN ANALYSIS

Understanding the use of space by pedestrians is crucial for the design of the buildings and the transport facilities used every day. However, most studies have considered pedestrians as a flow, except Fruin, who also focused on individuals, only a few studies have looked at the detailed behaviour of individual pedestrians. Agent-based pedestrian simulations have included sophisticated characteristics of individual pedestrians, but often these are limited to simplistic descriptions of particular aspects of the agent's behaviour (Fujiyama & Tyler 2008).

Pedestrian simulation is crucial for perceiving crowd behaviour, optimizing the design of public spaces, and ensuring safety and efficiency in areas with high foot traffic. This topic is still depreciated since the concerns about it are very recent for the society. Results are of interest to various institutions and companies, such as constructors of buildings, airplanes and ships; operators of large public constructions or mass events; or providers of public transport systems. Such system models allow simulating evacuation scenarios in advance, discovering possible existing problems and optimizing plans (Zsifkovits & Pham, 2016).

The space inside Stations should be planned to minimise congestion and be resilient to surges in demand and train service disruption. It is based on parameters such as the Level of Service. All the components inside the Station must be determined by the space requirements according to the activity, either access to platforms or ticket purchase shops. Certain precautions must be taken, routes with minimum travel distance should be free from obstacles, the avoidance of dead ends and also hiding places. The station and the platforms should be planned thinking of people with reduced mobility, putting ramps and lifts in order to have access to all of the places. The entrances and exits of the building must show an easy interchange between modes and the street (Powell, 2012).

A plan for hazard situations must be done, creating evacuation emergency exits. The space must be prepared for evacuating people inside into a safe place, in a maximum period of 6 minutes (Powell, 2012).

2.6.1.FUNDAMENTALS OF TRAFFIC DESIGN

Some fundamentals of traffic design can be categorized by the Flow Volume, the Speed, the Density, the Headway and the Queue (Fruin, 1971).

The following information contains measurements in inches and in feet, for better understanding of numbers some converting tools were needed, and the information got was that the equivalent of 1 foot is approximately 0.305 meters and the equivalent of 1 inch is approximately 0.025 meters.

2.6.1.1.FLOW VOLUME

Flow Volume (P) is the number of traffic units passing a certain point in a unit of time, it is expressed as pedestrians per foot width of the walkway or stairway per minute (PFM) and can be calculated according to the equation 2.7 (Fruin, 1971).

$$P = S * D \quad (2.7)$$

Where:

S- Average Speed

D- Average Density

The pedestrian volume is the most important parameter when designing a walkway, if the demand exceeds the capacity, it can cause delays and crowding in a very sensitive section. Fruin developed a time-lapse photography study on walkways, it shows that the flow volume increases as pedestrian area decreases, until it reaches a critical point due to the lack of space, so the flow volume starts to decline. The results of time-lapse photography studies of pedestrian flow got to lower flow volumes of the upward direction are the determinant of stairway width and design quality, as with walkway volumes, maximum stairway flow occurs in the region of minimum pedestrian area occupancy. The maximum flow volume of 18.9 pedestrians per minute per foot of stairway width is representative of design values used by many authorities (Fruin, 1971).

2.6.1.2.SPEED

Speed (S) is expressed in distance per unit of time, feet per minute, when in a section the speed is the average speed of all pedestrians passing through the section during the design interval. A survey with a sample of 1000 non-baggage-carrying pedestrians inside the Port Authority Bus Terminal and Pennsylvania Station in New York City gathered information about the Frequency Distributions and Walking Speeds of the passengers in a free flow analysis, it concluded that the most frequent walking speed is around 250 FPM, the average walking speed for the Bus Terminal is 257 FPM and the average walking speed for the Pennsylvania Station is 272 FPM (Fruin, 1971).

Locomotion speeds on stairs have a direct relationship to height of the step, with the faster speeds, in both ascending and descending directions, occurring on stairs with lower step heights.

2.6.1.3.DENSITY

Density represents the number of traffic units per unit of area, it is expressed in tenths of pedestrian per square foot, which can be hard to visualise, so Pedestrian Area Module (M) or the square feet of area per pedestrian is often used. A time-lapse photography analysis of pedestrian flow was conducted by Fruin, it showed the effect of increased traffic density, or decreasing area occupancy, on pedestrian walking speeds for one-directional commuter traffic flow, to note that similar studies of two-directional commuter resulted in only small variations from this curve. The curve indicated that mean speeds for dense pedestrian flows are approximately normal, up to an average pedestrian area occupancy of 25 square feet, after that the walking speed declines as the area to move decreases. The limit of normal

walking speed, established in the interval between 140 and 150 FPM, is reached at an area occupancy of about 7 square feet per person. Beyond this point, when it gets to zero at an area occupancy of slightly less than 3 square feet, it represents a crowded and immobile queue (Fruin, 1971).

Pedestrians must leave additional space for manoeuvring and to avoid oncoming and crossing pedestrians. The spacing of pedestrians in a traffic stream is a function of density, as it increases, pedestrians are forced to maintain constrained spacing patterns to allow for pacing room, and to avoid the conflict with others. Another aspect of typical pedestrian interaction on walkways is the possibility of conflicts with pedestrians crossing the main stream of flow. A study of conflicts was conducted by time lapse recording, with a camera above the location where pedestrians usually cross a main traffic stream, it identifies the probability of conflicts existing over a wide range of pedestrian densities. The probability of pedestrian conflict is 100 percent at 15 square feet.

2.6.1.4. HEADWAY

Headway is the time and distance separation between traffic units. This concept is useful for evaluating the design of doors and other entrance devices. When a pedestrian opens a door, there must be a sufficient time-headway separation between that pedestrian and the following pedestrian. By assuming a traffic lane equal to the entrance width, the designer can translate pedestrian traffic volumes into time-headway separations (Fruin, 1971).

2.6.1.5. QUEUE

Queue is defined by one or more traffic units waiting for service, queue lengths and durations will vary according to traffic flow characteristics. Queues can be divided into lineal/ordered, with conventional first-come first-served priority or into a bulk queue, which is unordered and with no discipline (Fruin, 1971).

2.6.2. LEVEL OF SERVICE

A correlation can be done between the Level of Service and the quality of the passenger's space. The Level of Service is divided into six groups, from A to F, considering A the best quality scenario and F the worst scenario (Powell, 2012). When the designer is required to use maximum capacity volumes in bigger events such as sports stadium design, the adequacy of holding areas at the approaches to the critical section must be examined. Standards provide the tools to determine the quality of corridor design, walkways and entrances (Fruin, 1971).

2.6.2.1. WALKWAY STANDARDS

The width of corridors should be reduced by 18 inches on each side of the corridor, to take into consideration the human tendency to keep this separation of objects from fixed objects and walls, except in the most crowded conditions. When designing walkways, the effective width should be reduced by 2 feet or more to take into account the constricting effects of street obstacles such as parking meters, lighting standards, fire hydrants and bins (Fruin, 1971).

The description of the Walkways Level of Services is shown in the Table 2, the evaluation is made according to the Average Pedestrian Area Occupancy, in the dimension of Square Feet per Person (SFP) and the Average Flow Volume, in Pedestrians per Foot width of walkway per Minute (PFM).

Table 2 – Level of Service Walkways (Fruin, 1971)

Level of Service Walkways	Average Pedestrian Area Occupancy [SFP]	Average Flow Volume [PFM]
A	≥ 35	≤ 7
B	25-35	7-10
C	15-25	10-15
D	10-15	15-20
E	5-10	20-25
F	≤ 5	≥ 25

In level A, the pedestrians have sufficient area to choose freely their walking speed, bypass slower pedestrians and avoid crossing conflicts. In level B, the available space is enough to select normal walking speed, and bypass other pedestrians in one-directional flow, yet some minor conflicts can occur if there is a reverse-direction or pedestrian crossing movements, slightly lowering the mean speed and volumes. In level C, the freedom to select the speed and freely pass other pedestrian is restricted and there is a higher probability of conflict. The level D results in a restricted and reduced speeds of the majority of pedestrians, due to the difficulty to bypass slower pedestrians and avoiding conflicts. In level E all pedestrians have their walking speed restricted, the area is insufficient to bypass other pedestrians and the volume is close to the maximum attainable capacity of the walkway, resulting in frequent stoppages and interruptions of flow. The last level, F, conducts to an extremely restricted speed, with difficulties to perform reverse or crossing movements, above the level of 5 SFP, it is considered a queue over a traffic flow, this is not recommended for walkway design (Fruin, 1971).

2.6.2.2. STAIRWAY STANDARDS

When it comes to design stairs, the human characteristics must be taken into consideration because of the greater safety hazard and energy expenditure required, so these are some factors that must be attended (Fruin, 1971):

- Stairs should be located to be visible and identifiable as a mean of direct access to other levels;
- In the approach of the stairways there must be a clear area large enough to allow queuing;
- The stairs should be well lighted;
- When the stairs are placed in the middle of a corridor the lower capacity is the controlling factor for the design of the structure.

The description of the Stairway Level of Services is shown in the Table 3.

Table 3 – Level of Service Stairways (Fruin, 1971)

Level of Service Stairway	Average Pedestrian Area Occupancy [SFP]	Average Flow Volume [PFM]
A	≥ 20	≤ 5
B	15-20	5-7
C	10-15	7-10
D	7-10	10-13
E	4-7	13-17
F	≤ 4	≥ 17

In level A, representing a space 5 steps long and 3 to 4 feet wide, the pedestrians have sufficient area to choose freely their walking speed, bypass slower pedestrians, no difficulties are associated with reverse traffic flows. In level B, representing a space with 5 steps long and about 3 to 4 feet wide, the available space is enough to select normal walking speed, but with a slight difficulty in bypassing other pedestrians, and reverse flows can cause a minor conflict. In level C, representing a space 4 to 5 steps long and 3 feet wide, the freedom to select the speed and to pass other pedestrian are slightly restricted and reverse-traffic flows deal with some difficulties. The level D, representing a space 3 to 4 steps long and 2 to 3 feet wide, results in a restricted and reduced speeds to the majority of persons, due to the difficulty to bypass slower pedestrians and reverse-traffic flows deal with significant difficulties and traffic conflicts. In level E, representing a space 2 to 4 steps long and 2 feet wide, all pedestrians have their walking speed restricted, the area is insufficient to bypass other pedestrians and the area is the minimum possible for locomotion on stairs, resulting in frequent stoppages and critical pedestrian density is exceeded, the reverse traffic flow experiences serious conflicts. The last level, F, representing a space 1 to 2 steps long and 2 feet wide, perform the complete breakdown in traffic flow and many stoppages, this level is not recommended for design (Fruin, 1971).

2.6.2.3. QUEUING STANDARDS

The designer must apply queuing standards for not only areas that is common to have queues like elevators, but also in areas where it is likely to result from service stoppages, the approach to stairs and other critical sections should also be designed to hold waiting pedestrians. In the Table 4 the Level of Services associated to the Queuing can be consulted, in this analysis the factors to evaluate the Level of Service are the Average Pedestrian Area Occupancy, in SFP, and the Average Inter-Person Spacing, in feet (Fruin, 1971).

Table 4 – Level of Service Queuing (Fruin, 1971)

Level of Service Queuing	Average Pedestrian Area Occupancy [SFP]	Average Inter-Person Spacing [F]
A	≥ 13	≥ 4
B	10-13	3.5-4
C	7-10	3-3.5
D	3-7	2-3
E	2-3	≤ 2
F	≤ 2	≈ 0

At level A the space provided is enough to stand and circulate easily through the queuing area without disturbing other pedestrians. In the level B the queuing space is provided for standing and restricted circulating through the queue without disturbing the other pedestrians. In the level C the queuing space is provided for standing and restricted circulating through the queue, but disturbing the other pedestrians, it is within the personal space range of comfort body buffer zone established by psychological experiments. In the level C, there is space for standing without personal contact with other pedestrians, but the circulation through the queue area is restricted and movement is only possible as a group. In the level E there is space for standing but the personal contact with other pedestrians is unavoidable, the circulation through the queue is impossible, thus this level can cause physical and psychological discomfort for longer periods of time, it is only recommended for the design of elevators. In the last level, F, the space is equivalent to the human body area, which makes standing possible but with contact with other pedestrians that causes discomfort, no movement is possible, in large crowds it is potential to panic (Fruin, 1971).

2.6.3. PEDESTRIAN MOVERS

The Pedestrian Movers concept is associated with the Elevators and Escalators, some useful information about the design of these structures is explained in the following paragraphs.

2.6.3.1. ELEVATORS

The standing capacity of an elevator assumes an average area occupancy of 2 square feet per person, even though the crowded situation can lead to a 1.5 square feet per person. If the value of the average area occupancy is below 2.75 SFP there is an unavoidable contact between pedestrians. To feel comfortable most persons, require an area occupancy of 3 square feet or more, inside the elevator (Fruin, 1971).

The quality of service of the usage of the elevator depends also on the waiting time, the tolerance level acceptable for the waiting time is around 30 seconds in commercial buildings and 60 seconds for residential buildings (Fruin, 1971).

2.6.3.2. ESCALATORS

The normal angle for the inclination of the escalators is settled at 30 degrees, as the value for the operating speed can vary between 90 to 120 feet per minute.

A comparison of the standing areas provided for pedestrians on escalator steps demonstrates the range of potential for personal space interaction. The 32-inch escalator (width) has a projected tread length of 15 inches and a tread width of 24 inches, which provides an average footprint of 2.7 square feet per pedestrian, with the occupancy assumed by the manufacturer of 1.25 people per step. The 48-inch escalator, with a tread width of 40 inches, allows 2.1 square feet standing area per person, according to the theoretical assumption of the double-step occupancy (Fruin, 1971).

2.6.4. OTHER PERSPECTIVES

Powell (2012) states that the planning of the Levels of Service in the Normal Operation, Guidance for Special Events and Guidance for Construction Work of a Station should be approximately the following discriminated in Figure 8. Figure 9 shows what are the Level of Services for each scenario of Normal Operation.

Station area	Category of station operation							
	Normal operation		Guidance for special events up to three days		Guidance for special events over three days		Guidance for construction work	
	LoS	Quantitative measure	LoS	Quantitative measure	LoS	Quantitative measure	LoS	Quantitative measure
Open concourses	B	1.0m ² per person	D	0.45m ² per person	C	0.8m ² per person	C	0.8m ² per person
Queuing for ticket hall facilities	C	0.8m ² per person	E	0.28m ² per person	D	0.45m ² per person	D	0.45m ² per person
Passageways- one-way	D	50 passengers /minute/m width	E	80 passengers /minute/m width	D	65 passengers /minute/m width	D	65 passengers /minute/m width
Passageways- two-way	C	40 passengers /minute/m width	E	65 passengers /minute/m width	D	50 passengers /minute/m width	D	50 passengers /minute/m width
Stairs- one-way	D	35 passengers /minute/m width	E	43 passengers /minute/m width	E	43 passengers /minute/m width	E	43 passengers /minute/m width
Stairs- two-way	C	28 passengers /minute/m width	E	43 passengers /minute/m width	D	35 passengers /minute/m width	D	35 passengers /minute/m width
Escalators		100 passengers /minute		120 passengers /minute		110 passengers /minute		110 passengers /minute
Platforms	B/C	0.93 m ² per person	E	0.28 m ² per person	D	0.45 m ² per person	D	0.45 m ² per person

Figure 8 - Planning criteria and levels of service in a Station (Powell, 2012)

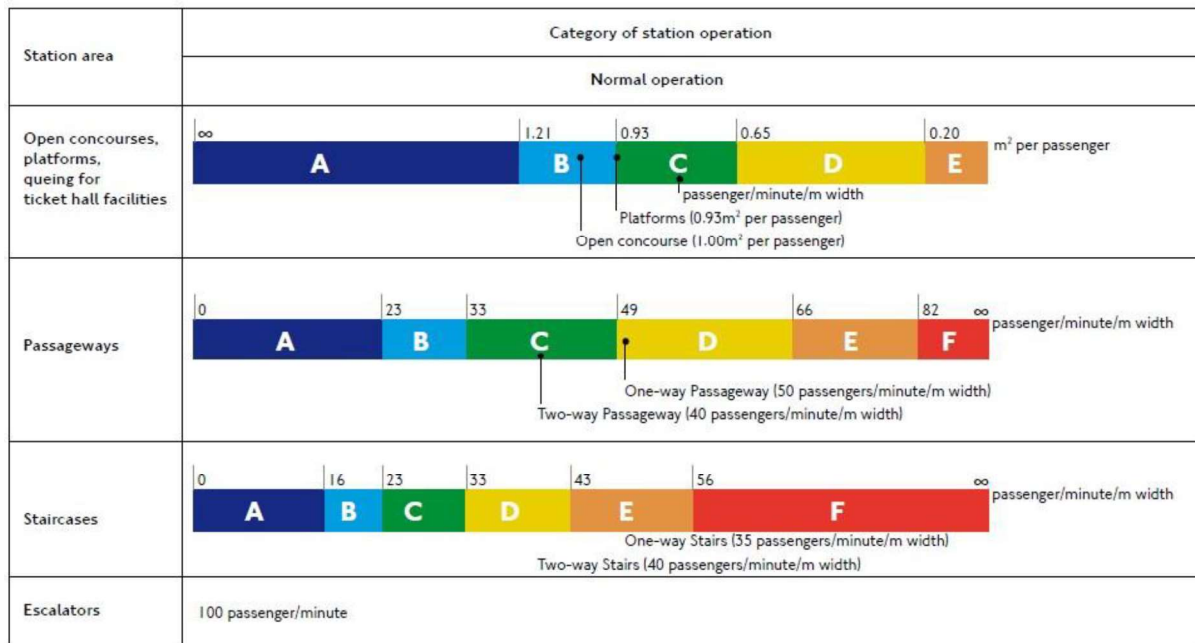


Figure 9 – Levels of Service for Normal Operation (Powell, 2012)

2.6.5. PLANNING FOR HAZARD SITUATIONS

The emergency path should remain the same as the route for normal conditions because passengers will evacuate more easily and quickly if the route is familiar and because there is no additional cost in making a specific route for emergencies only (Powell, 2012).

The design of a station must be prepared for two worse hypothetical scenarios, the case of a train being on fire and fire within the station structure. In the case of emergencies, the lifts shall not be used to evacuate, and the escalators shall continue to work in the same direction as it is in normal operation (Powell, 2012).

The evacuation time for the case of a train being on fire can be calculated through the equation 2.8, if this time is greater than four minutes, the station does not have the capacity to evacuate in security (Powell, 2012).

$$\text{evacuation time} = \text{platform clearance time} + \text{pinchpoint clearance time} + \text{free flow walk time} \quad (2.8)$$

In the case of a fire in the station structure, the evacuation must be calculated in parts, the first parameter is the maximum evacuation flow per minute for each platform, the equation 2.9 demonstrates how that parameter is calculated. The next step is to calculate the required width of passageways and stairs and the required number of escalators, dividing the evacuation flow per minute by the capacity flow rates present in Figure 10. Lastly the passenger walking speed must be applied to the last passenger in remaining on the platform, Figure 11, to check if the period of six minutes or less for evacuation is achieved.

$$\text{maximum evacuation flow per minute} = \text{width of exits} * 80 \text{ passengers per minute per metre width} \quad (2.9)$$

Means of escape	Capacity
Horizontal circulation elements – passageways and stopped passenger conveyors	80 people per minute per metre width
Vertical circulation elements – stairways	56 people per minute per metre width. (The width is measured between the innermost part of the handrails.)
Working escalators and passenger conveyors	120 people per minute per metre width
UTS gates	50 people per (UTS) gate per minute. Evacuation capacity required in excess of that achievable through the UTS gates shall be provided by emergency gates in the gateline.

Figure 10 – Evacuation capacities of Station (Powell, 2012)

Circulation	Passenger walk speed
Horizontal circulation	38m per minute.
Vertical circulation	12m vertically per minute

Figure 11 – Passenger Walk Speed (Powell, 2012)

3

SOFTWARE

3.1. INTRODUCTION

One of the goals of this Dissertation is linking the problems of transportation with some existing transportation software, which requires information on software. There is a variety of software in terms of the field of simulation as it can be seen in each description, some are microscopic and other macroscopic, some are only vehicle oriented, others only can simulate pedestrian movements and other can do both.

The software that are going to be explored are EMME, CUBE, Vissim, Visum, SUMO, Aimsun, LEGION and DYNAMIQ. These software were chosen due to the easy access, the information found and because of the agreements with companies and universities for research that make these more discussed and known.

The sources for this work were based on available information of the websites of the software, from dissertations related to this subject, some articles also found about transportation and simulation software and some books that were consulted.

In the end of this chapter a summary table to summarize the similarities, differences and additional information about the software was added.

3.2. EMME

EMME, *Equilibre Multimodal, Multimodal Equilibrium*, was developed at the Centre for Research on Transportation at the University of Montreal, by INRO, in the late 1970's as a Macroscopic Transportation Software (EMME, 2020).

It has been suffering some changes and updates, standing now at the fourth version with new features, such as the EMME Modeller replacing and supplementing the Prompt, as a command-line and macro programming.

In EMME the supply is defined by the road and transit network and the performance is characterized by the delay or cost functions. The demand is a result of matrix operations and demand functions.

EMME is organized in three dimensions, the Network Data, the Matrices and the Functions, Figure 12. The Network Data can be divided in various scenarios, inside each one there is a characterization of the Base Network with the modes, nodes and links and the turns, then the Transit Vehicles allowed, also including the transit lines connected to the base network. There are some important Matrices to complete the demand information such as by O-D pair, by origin, by destination and scalar. The functions carry a

lot of information, very important to the results of the study, such as the volume-delay, transit time, turn penalty, demand and user defined (EMME, 2020).

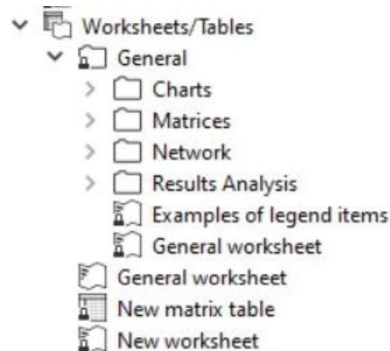


Figure 12 – Explorer Organisation

The visualisation of the scenario can be done in the General Worksheet, and the edition of the network in the Network Editor worksheet, Figure 13, by add or delete modes, nodes and links, it is also possible to edit and modify the attributes of the turns, transit vehicles and the transit lines itineraries.

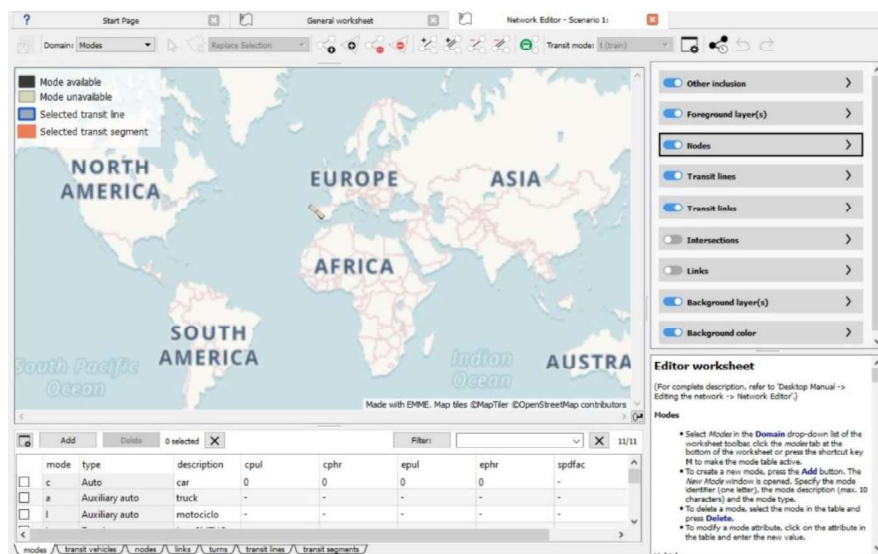


Figure 13 – Network Editor

The equilibrium traffic assignments with fixed and variable demand that are implemented in EMME are based on the John Glen Wardrop's second principle, the "system optimal", that states that at equilibrium, the average journey time is at a minimum. That implies that all users behave cooperatively in choosing their routes to ensure the most efficient use of the whole system (Hildebrand & Hörtin, 2014).

The transit assignment algorithm aims to minimize the total travel time (TTT) containing the wait time, the auxiliary time, the boarding time and the in-vehicle time. The time components are weighted to

compare these times with the in-vehicle time so the total travel time is converted into a general cost. The formula for the total expected travel time (TTT) is shown below in equation 3.1 (Hildebrand & Hörtin, 2014).

$$TTT = w_{aux}t_{aux} + w_{wt}t_{wt} + w_{boarding}t_{boarding} + t_{travel} \quad (3.1)$$

The standard traffic assignment uses the linear approximation method to obtain a solution, the Second-Order Linear Approximation traffic assignment uses a variant of the linear approximation, and the path-based traffic assignment uses the projected gradient method. The most used assignment in EMME is the Multimodal with direct demand functions.

In EMME there are six function classes, volume delay, turn penalty, transit time, auto demand, transit demand and user, it also provides a function editor to edit, delete or modify the functions. (Yu, Yue & Teng, 2003)

In terms of results, EMME can provide the visualization of some variables directly in the scenario, all the results that this software can deliver are link volumes, travel times and turning volumes at intersections, an example of results can be seen in Figure 14. One specific and interesting tool of this software is that it is possible to compare the results between two different scenarios. Other results can be checked in the Results group (Yu et al., 2003).



Figure 14 – Example of Link Volumes

3.3. CUBE

CUBE software is a set of modules that support transportation modelling and planning, it is a comprehensive suite for passenger, freight, land use and traffic simulation (Bentley, 2021).

The System Interface is the CUBE Base, it is used for data editing, mapping, reporting, model development and the creation of the scenario. It operates in two modes, the Developer Mode, where it

manipulates the data and the model structure, and the Applier Mode, here it is possible to see the flow chart, edit inputs and run the whole model. In the CUBE Base, the complete software interface is composed by the CUBE GIS, this software integrates GIS using ESRI geodatabase technology; in CUBE Model Builder, a flow-chart system for model design, coding and documentation can be visualised, also a visual creation of the model, it gives direct access to data and scripts; in CUBE Scenario Manager, Figure 15, highlights key model parameters and data for easy creation and tests the existing scenarios, it has a run menu for running the scenarios and provides easy links to main output data for viewing and comparing; and CUBE Reports, containing charts and tables integrated in model and it is also where it is possible to view and compare scenario specific statistics (Bentley, 2021).

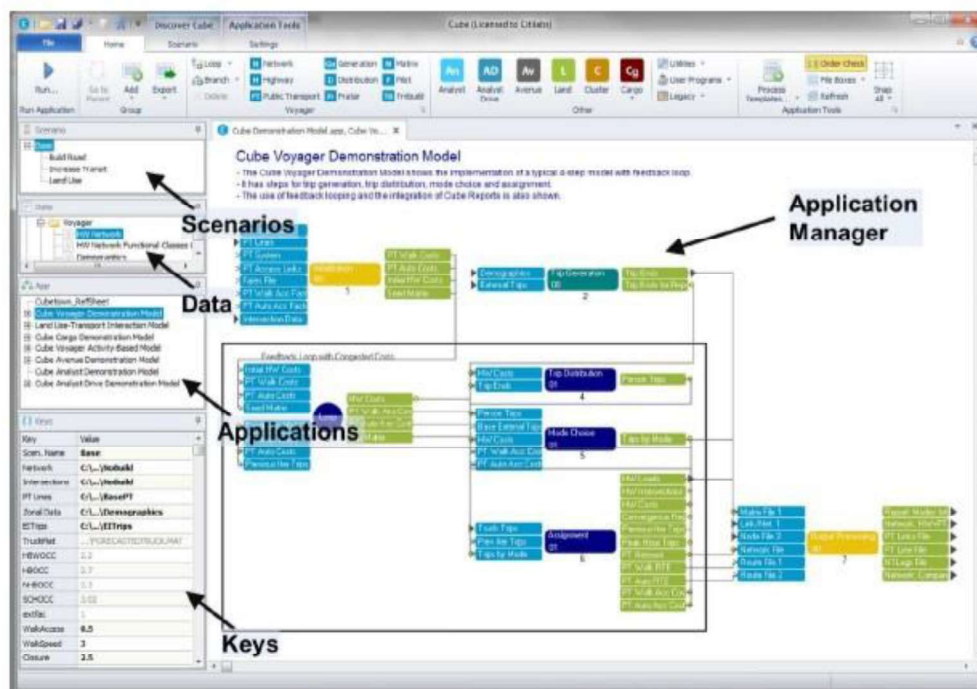


Figure 15 – Scenario Manager (Bentley, 2021)

The Demand Modelling is divided into the CUBE Voyager, the CUBE Land and the CUBE Cargo, the full organization of the software can be found in Figure 16.

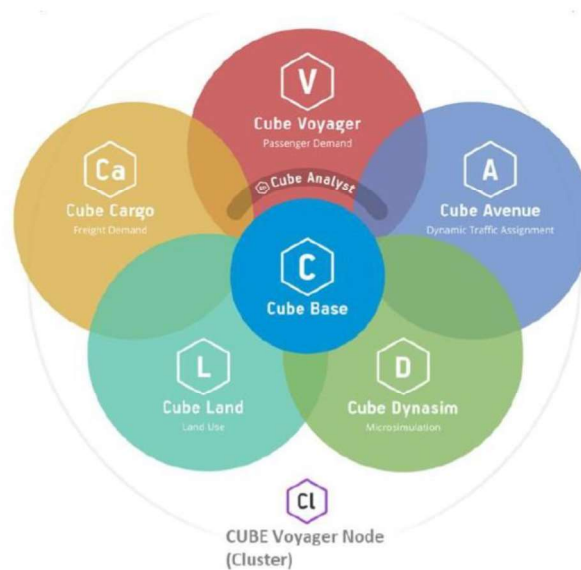


Figure 16 – Structure of the software (Bentley, 2021)

The CUBE Voyager is oriented to urban, regional and long-distance demand forecasting and assignment, it is possible to incorporate any modelling methodology in this structure, such as the Four Step Model, Discrete Choice Models and Activity Based Models. In this module the calculation of travel demand and the comparison of scenarios in detail can be done. There are two extensions from the CUBE Voyager, the CUBE Voyager Node or CUBE Cluster, which provides functions for running the model across multiple computer processors, and the CUBE Analyst, that estimates and updates statistically optimized trip matrices for base-year automobile, truck and public transit trips, it can manipulate extensive data sets and upgrade constantly the origin destination matrices, one of the most valued data for transportation simulation (Bentley, 2021).

The CUBE Land covers the land use model for combined transport-land use modelling. It models the interaction between land use and transportation taking into account the real estate supply, transportation accessibility, economic incentives and other factors (Bentley, 2021). The model is based on the bid-rent theory, Figure 17, a geographical economic theory created by William Alonso in 1964, that refers to the amount of rent a user is willing to pay for a more central location (Narvaez et al., 2013). Two types of simulation can be done, the Fixed-supply, the supply of real estates in the different zones is a fixed scenario input, and the Variable-supply that uses the supply to know the quantity and type of new development in each zone based on profit maximization, which in turn depends on the rent model and cost function (Bentley, 2021).

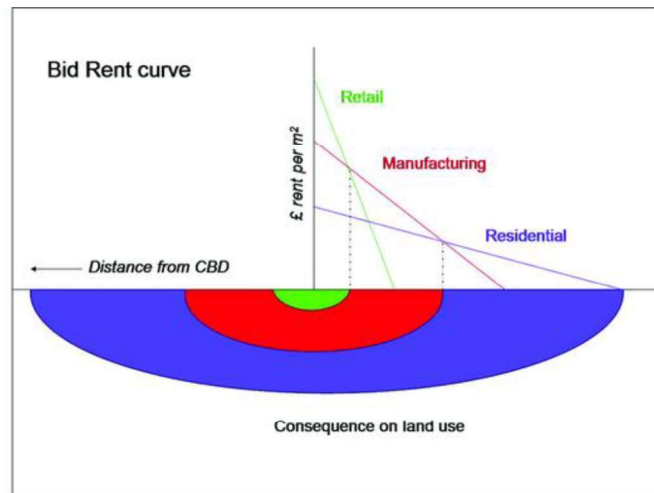


Figure 17 – Bid Rent Curve [14]

The CUBE Cargo studies the commodity-based freight forecasting, which can test a wide variety of policies and infrastructure improvements and evaluate the changes in level of services according to the change of the costs of a railway. This module has three steps to go through, the first is to compute network costs and times by mode, then to estimate zone-to-zone commodity and truck matrices and finally to compute peak-hour trucks. It can deliver results about the flow of goods and the truck vehicle flows. If the CUBE Land and the CUBE Voyager are integrated, the interaction of the real estate markets and transportation system can be analysed (Bentley, 2021).

In this software, the simulation is done in two modules, the CUBE Avenue, which is directed to mesoscopic traffic simulation, and the CUBE Dynasim, related to multimodal microsimulation (Bentley, 2021).

CUBE has a great integration with ArcGIS as it contemplates a map with the geographic information stored in shapefiles and geodatabases, leaving space for the creation of other map elements. The exchange of files between CUBE and ArcGIS is easy as it can be uploaded back into the software after some geographical changes (Bentley, 2021).

In terms of analysis of results, CUBE allows to compare the same subject in different scenarios, so it can be easier to detect the influence of the changes in the network or the data that has been made in more than one approach to the problem (Bentley, 2021). An example of results this software can deliver can be seen in Figure 18.

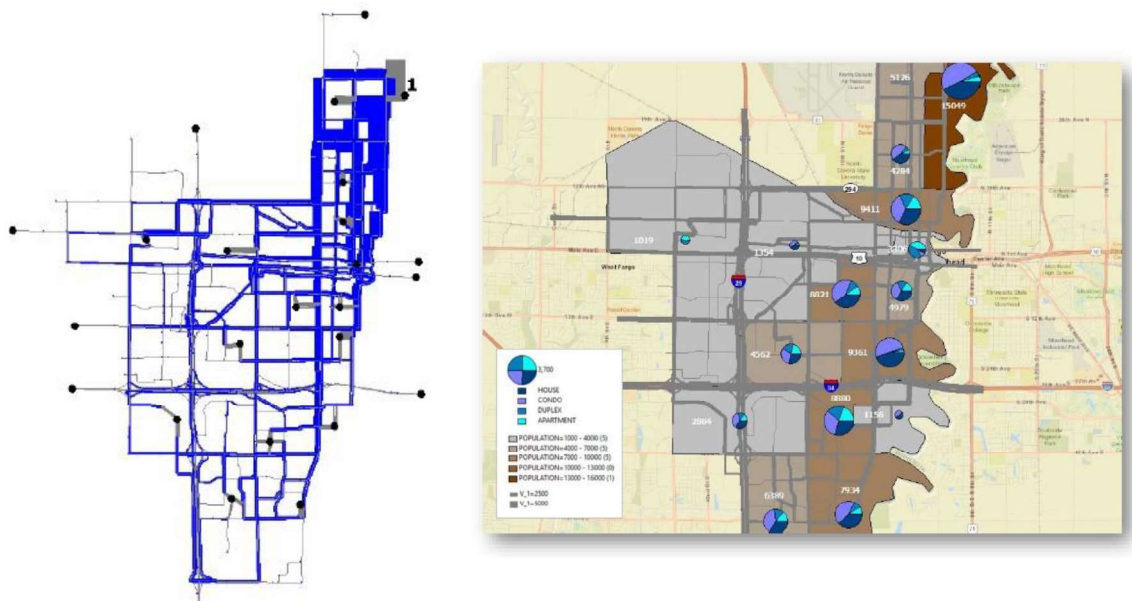


Figure 18 – Example of Results (Bentley, 2021)

3.4. VISSIM

ViSSim is a software developed in 1992 belonging to the PTV Group, a Germany-based global software company for traffic planning, simulation, and real-time management with more than 40 years of experience.

Its main domain is the microscopic level, as it offers the highest level of detail, as it simulates individual vehicles and pedestrians, but it is also capable of some mesoscopic analysis, although in a lower level of detail.

The tool bar has the Network Objects, it selects insertion mode types and visibility for network objects, edits graphic parameters for network objects and shows or hides labels for network objects, it has also the Levels, it selects visibility and editing option for levels and visibility for vehicles and pedestrians per level, and finally the Backgrounds, it selects visibility for the background (Mora & Viana).

After having the network built with the nodes and links needed, it is time to input the number of lanes, the behaviour type, the display type, the level and some features such as the width, the Blocked Vehicle Classes and the lane change restrictions (Mora & Viana).

In ViSSim there are five types of vehicle routes: Static; Partial Route; Partial Public Transportation Route; Parking Lot; Managed Lanes. The Static Routes start from a departure point and end at arrival points, using statistical percentages for each destination; these are not applied to public transport vehicles. The Partial Route is used for local distribution of vehicles as it defines a section of one or several static routes, after leaving the partial route, the vehicles continue their original route, this route is also not applicable for public transport vehicles. The Partial Public Transportation Route defines a section of one or several routes, the routes of all the vehicles relevant to the public transport lines are reassigned according to the part of the partial route of that section and after leaving the partial route, the vehicles continue their original route. The Parking Lot is only for parking areas and defines a route decision point used to automatically generate routes for each parking space and then return to the network, selecting a parking area instead of a destination section. The Managed Lanes are vehicle routes

via two parallel routes, from a start section to a destination section, for a route decision, it must define the settings from the pricing model and decision model tools (Mora & Viana).

In this software, it is possible to determine and analyse priority rules, conflict areas, reduction speed areas, signal heads and signal controllers. Traffic signals can be simulated and programmed by the Signal State Generator (SSG), a separate module from Vissim traffic simulation module (Mora & Viana).

The pedestrians follow the social-force model of pedestrian movement (Vortisch, 2017). It suggested that the motion of pedestrians can be described as if they would be subject to social forces that are a measure for the internal motivations of the individuals to perform certain actions (Helbing & Molnár, 1998).

The results in this software related to the queue length can be defined through the Queue Counters or with the Nodes. The Queue Counters measures the queue starting with its own location and only in the link that it is fixed. The Nodes start checking the signal head or the zone that is stuck and measures the queue in every direction and also other attributes like the number of vehicles, level of service in the lane, delay and others (Mora & Viana).

In the Figure 19, an example of a Vissim general overview and some results it can generate can be seen.

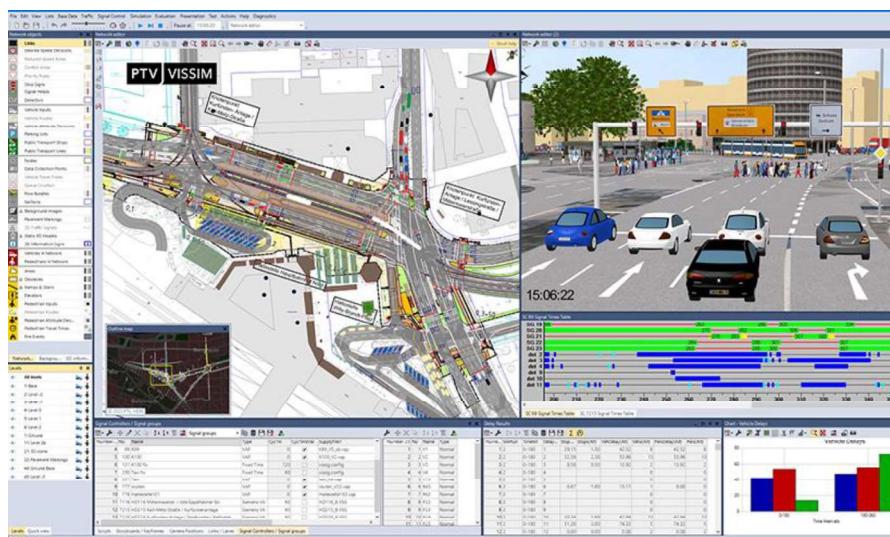


Figure 19 – Software Overview [15]

3.5. VISUM

Visum is a transport planning software, developed by PTV Group in Karlsruhe, Germany, for macroscopic simulations, macroscopic modelling of transport networks and transport demand, public transport planning, and for the development of transport strategies and solutions.

This software enables a lot of features like the forecast of traffic flow, the estimation of traffic flows in the absence of some data, establishment of transport policies, correlation of behavioural link of user and transport systems, planning routes for transport corridors, regulation of the modes of using the area, the influence of new infrastructure designed elements, the development of scenarios related to traffic organisation and others (Andreescu & Clenci, 2015).

Bellow, in Figure 20, it is possible to see a software overview.

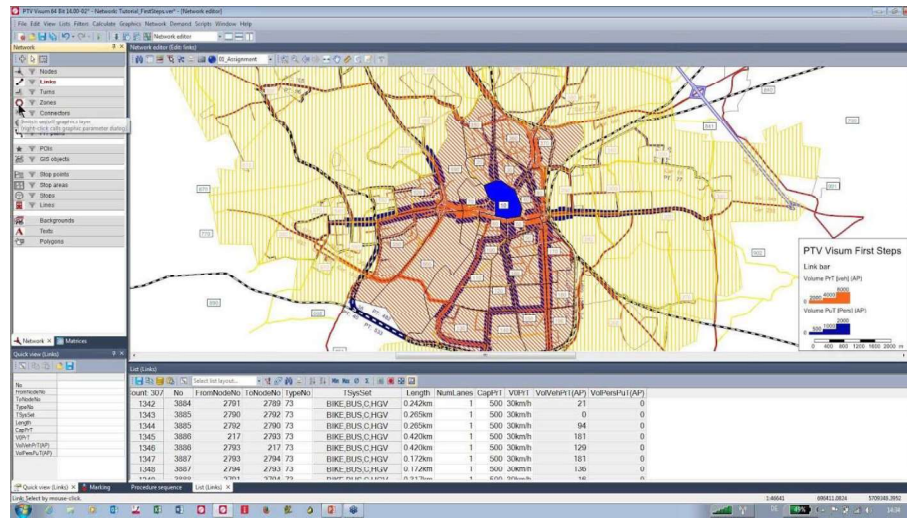


Figure 20 – Software Overview [18]

It follows a four step model, in the trip generation it is focused on the construction of the traffic zones defining origins and destinations used to estimate the number of trips produced and attracted to each area, then the trip distribution which builds the OD Matrix that determine the number of shifts between two traffic zones, the models used are the rearing factor method and the gravitational model, next the modal distribution the decomposition of the total travel demand in OD Matrix, the models used are the Probit and the Logit models, and the final step the route assignment, to establish a balance between the supply and the demand, the model used is based on the Wardrop balance (Andreescu & Clenci, 2015).

The accessibility of the network is determined by the shortest path, the characteristics used are the t_{Cur} , average journey time on the affected network, t_0 , average travelling time in free regime, Distance, average distance of the journey, Impedance, and AddValues 1 to 3, other attributes that can be edited to complement the existing ones (Gonçalves, 2016).

In this software a perceived journey time (s) is calculated in the headway-based model to minimize the expected travel time for the demand. The impedance is a measure of how much the perceived journey time is weighted, so the Total Expected Travel Time is calculated according to the equation 3.2 ((Hildebrand & Hörtin, 2014).

$$s = w_{aux}t_{aux} + w_{wt}t_{wt} + w_{boarding}t_{boarding} + t_{travel} + w_{transfer}NTR \quad (3.2)$$

The most used parameters to calibrate the network are the GEH, Geoffrey E. Havers Statistic and the RMSE (Gonçalves, 2016).

The results in Visum can focus on statistical data containing the attributes of the network and public transport routes, matrix indicators including travel times, frequency of vehicles circulation and graphical representation of traffic flows, isochronous, shortest path and traffic relationships diagram. (Oliveira).

In the Figure 21, a visual result of volumes generated by Visum is shown.

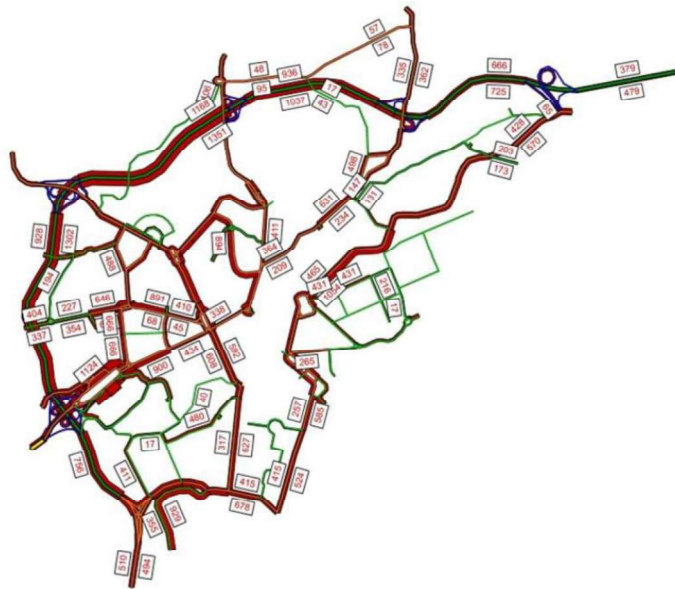


Figure 21 – Example of results (Gonçalves, 2016)

3.6. SUMO

SUMO, Simulation of Urban Mobility, is an Open-Source Software developed in C++ language to execute microscopic transport simulations, it also allows multimodal pedestrian simulations. This software was invented in German Aerospace Centre by Institute of Transportation Systems in 2000 [16].

This software hosts a small number of traffic simulation models, such as the Intelligent Driver Model (IDM), the Wiedemann model, Kerner's three phase models and others fewer known models. The IDM is a model where a set of Ordinary Differential Equations are used to determine the positions and the velocities of single vehicles according to parameters for the vehicles such as the desired velocity, the safe time headway, the maximum acceleration of the vehicle and the comfortable deceleration. The Wiedemann model was developed by Rainer Wiedemann, in 1974, for motorway traffic and the main goal is that cars want to avoid collision with the leader vehicle while aiming to maintain the desired speed if the normal conditions prevail. In the three-phase model traffic theory features of spatial-temporal congested patterns are based on the transition between the three phases, Free Flow, Synchronized Flow and Wide Moving Jar (Mai et al., 2017).

To run a simulation, first the user must have the network file and the demand information, it can be in several formats as the XML format, the NETCONVERT that imports digital road from OpenStreetMap, Visum, Vissim and Shapefile. Once the network it is built the next step is to get the information about the demand through a O-D matrix, the OD2TRIPS disaggregates O-D matrices into individual vehicles departing at a specific point in time (Schweizer, 2014).

In order to make the model closer to reality, the Calibration of the model must be done, in SUMO this step uses the speed data to find the optimal value of parameters, the main criteria to choose the best set of parameters are according to the Root Mean Square Error function (Jariwala & Gujar, 2020).

SUMO supports the extensibility to its core and control through TraCI (Traffic Control Interface), which is an API that allows the traffic simulation to interact with an external application via a socket connection

in runtime, there are already Python scripts available that will be integrated into the SUMOPy framework (Schweizer, 2014).

The results this software produces are the Information based on the vehicle, such as its position, speed and emissions, the name of this analysis is Full-Output; Values for the Lanes, such as performance measures (edgelane traffic), total pollution emissions (edgelane emissions), noise created by the vehicles (edgelane noise) and the time and length of the queue (queue-output); Aggregated vehicle information, like the routes with the stops (vehicle routes information), the loading and unloading (stop-output) and the battery used for the electric vehicles (battery usage); Information based on the simulation network, such as the number of cars entering, waiting time, journey time, number of cars in the simulation and vehicles that have reached their final destination (summary-output); finally reports about the Traffic Lights, about the state (traffic light state) and the cycles for a certain intersection (stream-based traffic light switches) (Floriani, 2017).

A simple demonstration of the software overview can be seen in Figure 22.

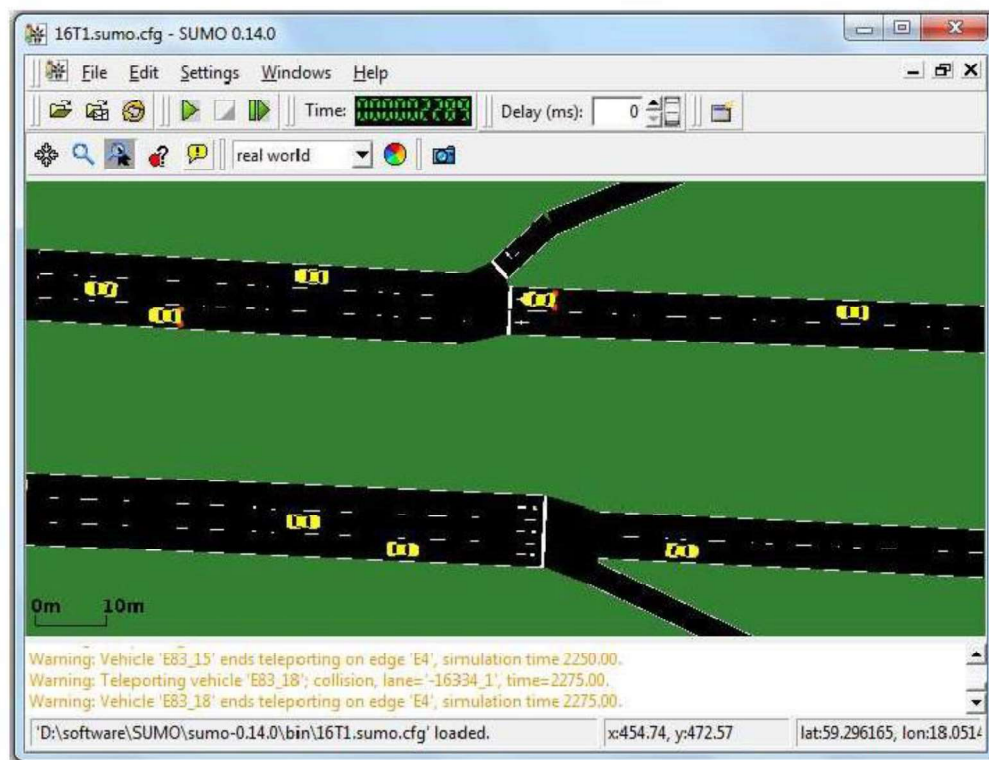


Figure 22 – Software Overview (Ronaldo & Ismail, 2012)

Initially, this software was simpler than it is nowadays, regarding intersection, it only answered whether a vehicle should pass an intersection and this vehicle would then instantly continue driving on the other side of the intersection, acting such as it jumped across the intersection. In the current versions, there are some changes that improves the driving dynamics, the gap time necessary when turning left, also the concept of impatience is implemented where vehicles may enter the junction even if it means that vehicles with priority must slow down. The lane-changing behaviour is needed to simulate the changing of lane in roads with more than one lane, the model rules the motivation for changing lanes and it is the

responsible for the speed adaptation to take the changing lane manoeuvres, it is based in four points (Erdmann, 2015):

- i. Strategic – another lane must be used to continue the current route;
- ii. Cooperative – the vehicle would like to clear the lane for another vehicle;
- iii. Speed Gain – the vehicle speeds up its travel by changing to a faster lane;
- iv. Keep Right – the vehicle should keep the left lanes clear for faster vehicles.

SUMO was implemented in the European Union project, CityMobil, from 2006 till 2011, to achieve a more effective organisation of urban transport, resulting in a more rational use of motorised traffic with less congestion and pollution, safer driving, a higher quality of living and an enhanced integration with spatial development [17].

3.7. AIMSUN

Aimsun, which means Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks, is a very diversified transport simulation software, it can provide analysis on a macroscopic, mesoscopic and microscopic level, it also provides outputs from 3D animation, Figure 23, to transport analysis and contains tools to assist in managing a project with a base model and multiple, multi-faceted option tests. It was developed in 1997, in the Universidad Politecnica Catalunya and Transportation Simulation System of Barcelona, Spain, but it operates in France, Australia, United States of America, Singapore, United Kingdom and United Arab Emirates. In 2018 it was acquired by Siemens, as part of the company in the unit of Mobility Intelligent Traffic Systems that now is named Yunex Traffic [19].



Figure 23 – 3D Animation [20]

In terms of research, the Aimsun team is divided into four main activities, Driving Behaviour, the aim is to improve the driving behaviour models of the software by creating new models or improving the calibration of the existing algorithms; Multi-modal Transport Planning, it believes that the future belongs to the multimodal transportation; Cooperative, Connected and Automated Mobility (CCAM), working with universities and research institutes, in this way testing cutting-edge technologies to integrate connected and autonomous vehicles (CAVs) into the transportation network; Network Demand and Traffic Management, facilitates the development of traffic simulation frameworks, including data streams of connected transport systems, modules for pattern detection and modules for demand and supply management (Makridis et al., 2020).

Aimsun is a dynamic simulator, it means that it can create and modify the scenarios through parameters that defines the simulation. A scenario is composed of four different data, the description of the network, the traffic control plans, the traffic demand data and public transport plans (Kober, 2015).

The microscopic simulation considers the continuous behaviour of each vehicle, so it uses models such as the car-following, the change-lane and the gap-acceptance.

To build a model in Aimsun it is necessary to input the base network topology and the travel demand. The base network is the core of the modelling project, it holds the vehicle types, trip purposes and the user classes that describe the vehicles in the network. The traffic demand describes the trips either from a set of Traffic States or through OD Matrices (RONALDO, 2012).

There are some optional inputs that improves the base network such as the Master Control Plans, that specify the control parameters applied to signalized junctions, and the Transit Plan, that creates a collection of routes and the timetables chosen for each transit route. Other optional components that interfere in the network topology or model parameters are the Attribute Overrides, this allows to change parameters such as the speed limits and lane restrictions without changing the layout of the network and the Geometry Configurations, that contains the geometric differences between the base network and the network to be tested in a scenario.

Aimsun has two mechanisms for simulation sub-areas in a network, for example in a hybrid meso-micro model or a macro-meso model.

This software has three environmental models inside its functions, a fuel consumption model and two pollution emission models (Neves & Galhardi, 2017).

For calibration of the OD Matrix, Aimsun uses external detection data, with real data set (RDS) that contains data for detectors, detector stations, sections, turns and transit stops.

Vehicle-based simulators include support for traffic management operations to solve a problem or achieve a goal, modifying the traffic network conditions, to affect driver behaviour or to simulate events on the traffic network.

For the microscopic simulation of the pedestrians, Aimsun offers the Pedestrian Simulator, it is designed to model the movement of pedestrians on sidewalks, the interaction between pedestrians and traffic crosswalks and boarding and alighting process at transit stops.

Each dynamic scenario can have two modes of dynamic traffic assignment, the Stochastic Route Choice (SRC) and the Dynamic User Equilibrium (DUE). Regarding the Travel Demand, this software uses the Four-Step Model [21].

The outputs of the simulation can be analysed in terms of speed, flow, the travel time between origin and destination and the network wide accumulated values and average values, an example of output can be consulted in Figure 24.



Figure 24 – Example of Outputs [22]

To validate the results of the simulation there are some measures like the Theil's U and the GEH Statistic.

3.8. LEGION

LEGION is a pedestrian simulation software founded in the United Kingdom in 1997, but in 2018 it was acquired by Bentley Systems. This software analyses and simulates people's movements in a variety of environments, such as stadiums, shopping centres, metro and rail stations and airports and the results can help with crowd management or even to establish safety strategies.

In 2000, LEGION was used to assist the organization of Sydney Olympic Committee, the case study carried out used the software to compare the real pedestrian density between the scenario without traffic organization and the scenario with traffic organization. It was concluded that the duration of peak hour was reduced, the level of service raise in the exits area and some potential safety problems were prevented (Zhonghua et al.).

LEGION contains three core modules that in combination enable modelling, simulation and analysis of movements within any CAD defined spaces:

- i. Model Builder;
- ii. Simulator;
- iii. Analyser.

The Model Builder allows the creation of the model. First it is necessary to import an Autocad drawing of the space to model, with all the physical information such as the obstacles, stairs and others. Then, the Demand Data must be imported, and some information like the total quantity of pedestrians and the origins and destinations is essential to have a complete database. In this module it is possible to output an .ORA file.

The .ORA file is opened in the Simulator (Figure 25), in this step it allows the user to see the virtual space in action and record the entities in real time, moving according to the data imported and created before. The output file is an .RES format file.

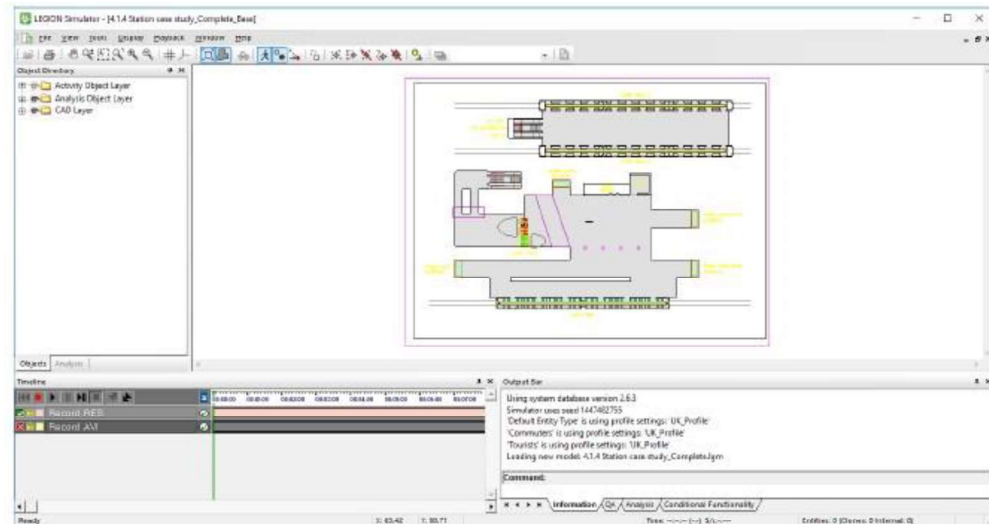


Figure 25 – Software Overview (Bentley Systems)

The .RES file can be uploaded in the Analyser, it supports quantitative and visual analysis of a recorded simulation, using a combination of pre-set map views and graphic tools.

LEGION enables the users to see the simulation in a 3D environment, through LEGION 3D, resulting from the merge of an .3DS file and the .RES file, result of the simulation done before in the Simulator.

The entity decisions are based on three levels, a Strategic that is basically a choice of target, either intermediate or final destination, then a Tactical, macro navigation, being the shortest path to target in general and finally an Operational, micro navigation, going through the optimal next step going from the local location. Each entity moves towards the final destination trying to minimize the perceived objective cost function, which is a weighted sum of three components, the Inconvenience, the Frustration and the Spatial Discomfort (Berrou et al., 2005).

The outputs of this software can be in maps or in graphs, some variables that can be analysed are the Space Utilisation, Density and Evacuation Time.

3.9. DYNAMIQ

DYNAMIQ, DYNAMIC Equilibrium, a product of INRO, is a mesoscopic and microscopic software based on traffic simulation model that was designed to produce accurate results with a minimum number of parameters and a minimum of computational effort, it is designed to capture the effects of car following, it was developed in Canada by the University of Montreal (Snelder, 2009).

The traffic flow model is based on car-following behaviour and micro-scale gap acceptance and lane-changing behaviour (Gliebe & Bergman, 2011). This software enables the visualisation of the congestion due to traffic signals, conflicting intersections movements, flow capacity, lane changing and heavy vehicles. It has the capacity to re-route in response to critical location's incidents (Snelder, 2009).

The inputs to execute the simulation are the traffic demand, by a time-dependent OD Matrix for each vehicle type, the network definition, with the lane's specifications and the turns, it is also needed the traffic control plans (Snelder, 2009).

The generation of the traffic can be done according to three methods, the Poisson, the Conditional and the Constant. In the Poisson both number of vehicles generated and departure times are random and the variability in the number of vehicles that are generated can be higher than desired. In the Conditional the number of vehicles generated does not vary, this number is obtained by multiplying the flow rate by the duration of the corresponding matrix interval. In the Constant it produces the same number of vehicles as in the Conditional, but only the first departure time for each OD pair is random, following a uniform distribution. (Snelder, 2009).

The path choices are modelled according to iterations and the assignment can be done with two different algorithms, the Regular Method of Successive Averages and the Flow Balancing Method of Successive Averages. The Regular MSA adjusts the path flow through the shortest path for each OD pair, and the Flow Balancing MSA adjusts the path flows by evaluating the travel times on all the paths used and doing the average path travel time (Snelder, 2009).

To converge the model, it divides the difference the average travel time with the shortest travel time for each OD pair and each assignment interval by the shortest travel time, this is called the Relative Gap (RGap) (Snelder, 2009).

In terms of Network information, it is organized into nodes, centroids, links, movements and transit lines (Bentley Systems, 2023). Regarding the Traffic Signals, in DYNAMIQ it can be represented as fixed time signal plans and coordinated signal timing (Gliebe & Bergman, 2011).

All the DYNAMIQ outputs can be divided into vehicle classes, since it is a multiclass model, and it is possible to give data for each vehicle type. The simulation results can be represented in animated plots and in time-series charts. Some analysis that can be done are traffic measurements, including flows, densities, speeds, travel times, vehicle counts and queues. It is possible to compare the scenarios side-by-side and to compare the results in scattergrams and histograms (Snelder, 2009). The main outputs are the Vehicle Trajectories, Simulation results, Transit Line results, Path-based results and Matrix results (Bentley Systems, 2023).

In Figure 26, a general overview of the software can be seen.



Figure 26 – Software Overview [23]

3.10. COMPARISON TABLE

The Table 5 summarises the capabilities and specific functionalities of each software. The information used was based on research exposed above but also gathered from given enterprises contact.

The table was filled in in a way that the “✓” symbol corresponds to the affirmative case of a software holding that capacity or information, and the “○” symbol corresponds to the case in which the software can indirectly or through the compatibilization with other elements or extensions contain or provide the given information.

Table 5 – Software Comparison Table

Classification		EMME	CUBE	Vissim	Visum	SUMO	Aimsun	LEGION	DYNAMEQ
Resolution	Microscopic		○	✓		✓	✓	✓	✓
	Mesoscopic	○	✓				○		○
	Macroscopic	✓	○		✓		○		
Time	Static	○	○		✓				
	Dynamic	✓	✓	✓	✓	✓	✓	✓	✓
	Quasi-dynamic	○		○		○	○	○	○
Uncertainty	Deterministic	✓	✓		✓		✓		✓
	Stochastic		○	✓		✓	✓	✓	
Demand	Activity Based							✓	
	Trip Based	✓	✓	✓	✓	✓	✓		✓
Public Transportation		✓	✓	○	✓	○	✓		○
Pedestrian		○	✓	○	✓	○	✓	✓	○
File Format	DWG/DXF	✓	✓	✓			✓	✓	
	SHP	✓	✓	✓	✓		✓	✓	✓
	CSV	✓	✓	✓	✓	✓	✓	✓	✓
	DBF	✓	✓	✓	✓		✓		✓
	XML	✓	✓	✓	✓	✓	✓	✓	✓
	OSM	✓	✓	✓		✓	✓		
	KML	✓	✓	✓	✓		✓	✓	✓
	TXT	✓	✓		✓	✓	✓	✓	✓
	XLSX	✓	✓	✓	✓		✓		✓
3 Dimensional			✓	✓	✓		✓	✓	
Outputs	Travel Time	✓	✓	✓	✓	✓	✓		✓
	Vehicle Emissions	✓	✓	✓	✓	✓	✓		✓
	Mode Share	✓	✓		✓		✓		
	Congestion Levels	✓	✓	✓	✓	✓	✓		
	Volumes	✓	✓	✓	✓	✓	✓	✓	✓
	Density					✓		✓	✓
	Evacuation					✓		✓	
	Accessibility				✓				
	Space Utilisation		✓	✓	✓		✓	✓	
Price Range	Low					✓		✓	
	Medium		✓						✓
	High	✓							

In terms of resolution, a diverse range of representations is observed within the selected software, this includes macroscopic, microscopic, and mesoscopic approaches, each with its own distinctive features and capabilities. All software operates within a dynamic temporal framework, enhancing the simulation's realism and applicability.

Concerning demand modelling, it is noteworthy that only LEGION adopts the Activity-based model approach, which simulates individual travel behaviours and activities. While nearly all software platforms directly or indirectly support Public Transportation and Pedestrian analysis, LEGION exclusively focuses on pedestrian-oriented simulations and does not incorporate public transportation representation.

Compatibility with various file formats is another notable aspect, with XML format standing out as universally supported across all software. Furthermore, CUBE, Visum, Vissim, Aimsun, and LEGION offers capabilities for representing three-dimensional space, primarily through result maps.

Regarding output features, Volume measurement emerges as a common metric present across all software, whether for traffic or crowd. Accessibility evaluation is associated with Visum, which offers dedicated tools for assessing accessibility within the transportation network.

Lastly, the classification of software into price range categories exhibits a degree of variability, although complete information was not attainable within the available timeframe despite attempts to contact the respective companies for this information.

In general, assessing software proves to be a challenge due to its significant differences and diverse approaches to the transport network. The complexity of the evaluation also depends on the variables considered. However, it can be inferred that Aimsun and CUBE stand out as software that offer a wide-ranging representation and results across a broad spectrum.

4

LEGION AND A PEDESTRIAN CASE STUDY

4.1. INTRODUCTION

Pedestrian simulation is increasing in number and advancing in quality, so the aim of this case of study is to gather knowledge regarding a pedestrian simulation software, to emphasise its capabilities and explore the importance of this type of analysis, when building the spaces that will integrate, but also shape the way society operates.

In this chapter, a Case of Study of an Intermodal Terminal will be presented and modelled in the LEGION Software.

The Intermodal Terminal was inspired by some existing infrastructures, and it should be mentioned that the design does not intent to represent the total integrity of the existing building but was used as a comparison and inspiration for the created scenario.

In this analysis the software chosen was LEGION, previously presented, as it is a frequently used pedestrian simulation software.

Although the interaction between the modes of transportation and the crowd around the station is the focus of this study, there is also a component that is part of the daily routine of the users, that is the time spent in the shops and coffees, and also the time that is necessary to buy the tickets, so that parameters are represented and considered in this analysis.

To explore and obtain the most optimal usage of the software, every step was done within the software environment, except for the drawing of the layout. Some information regarding the Entities and the OD Matrix could be done in an Excel Worksheet, Data Template, and later uploaded in the software into the Data Import Manager, as it can be a quicker and more efficient way to develop the scenario around the simulation.

For this analysis some cases are going to be tested, using the same layout, with a slight difference, the vertical circulations in Case 1 are realized using stairs and escalators, in the Case 2 some lifts are placed beside the stairs and escalators, whereas other cases have an increasing demand to compute, with the addition of some entrances in the network throughout the tests.

In the end of this chapter, a discussion about the differences and the specific aspects of this simulation work and the results for each case created is shown.

4.2. LEGION CONCEPTS

Along with the information given in the Software Chapter, strengthening the knowledge of this software is needed to make an accurate simulation that best represents real and ideal conditions.

The Accessible Space is the area that is walkable for the entities. If the model has an error of boundaries that are not closed, it can result in a wrong scope of the Accessible Area, that can lead to an imprecise simulation.

The default grid on the software represents a scale of 0.1m, it has a bigger division of 1 meter subdivided into 10 minor divisions.

The typical functionalities of other drawing software like the trim, move, copy, mirror, scale, measure and rotate exists in LEGION, so it is possible to change the layout and some configurations along the preparation of the simulation. This can be done using some tools, but also in the command bar.

The Entities represent the population of the simulation, displayed in the shape of a circle in the model, that try to be representative of the size a person occupies. It is possible to choose if the entity carries a luggage and its size, small, medium or large.

The movement decisions in LEGION are done by the Entities, as it has an auto navigation system, however the inputs selected suggest a path or preference. This software uses “Minimum Cost” or “Maximum Utility” concept, and entities try to minimise their personal dissatisfaction, the physically and psychologically quality of the journey, when choosing the next step to take. This dissatisfaction can be a result of frustration in the congested places, inconvenience when the path is very different from the shortest path and discomfort related to the personal space.

The Final Destination is the final goal of an Entity’s journey, it is usually an Exit, but it can be a Waiting Zone. It can be imported using the Data Template Spreadsheet through the OD Matrix or directly in the model, in the Data Profiles. Before reaching the Final Destination, Entities can have Intermediate targets, like shops, ticket shop and information boards.

In the Data Profiles, it is possible to detail information regarding Population Profile, Arrival Profile, Availability Profile, Delay Profile, Event Profile, Exit Profile, Gate Control Profile, Passenger Distribution Profile, Speed Profile, Size Profile of the Entity and Size Profile of the Luggage. The Population Profile is a profile used with Populated Zones and Evacuation Zones, it informs the destinations of the entities leaving a zone. The Arrival Profile is used to define the movement of entities in the Entrances. The Availability Profile is required to specify if an object is available to use or not, like the platforms. The Delay Profile is used to model the delays over a period of time. The Event Profile is used with a Direction Modifier and enables a certain number of Entities respond to events in a specific time. The Exit Profile is used with Exits, it controls the rate of egress from a model. The Gate Control Profile is used with gates to control the direction, in and out, for example. The Passenger Distribution Profile is a histogram that indicates the preference of entities to distribute along the platforms and inside a vehicle, the default is the Uniform Distribution. The Speed Profile contains the preferred walking speeds used by Entities. The sizes Profiles are also a histogram or distribution that specifies the physical area occupied by the entities and luggage.

The Direction Modifiers have a very important role in the improvement of the simulation as they re-target the entities that are affected by one intermediate activity, like the queues for shops. It is also important to make sure that the model contains the essential Focal Nodes, it ensures that entities approach targeted objects from any direction.

LEGION enables the creation of Queues, it simulates the activity of people queuing for services like cash machines, or ticket counters, it is possible to see the distribution through the space available, the queues can be grouped into Queue Groups.

The Mesoscopic Transit Zone (MTZ) represent areas that are immaterial and does not require a lot of information to the study so it doesn't show the dynamic inside the Mesoscopic Transit Zone when entities arrive to that spot, some cases that this can be applied are the existence of lifts, shops, holding areas or internal transit services.

The Multipath zone (MPZ) enables to create an area on the model where entities can choose between different routes according to their preferences for distance and time.

There are some Social Distance parameters that can be consulted directly in the model such as the Capacity Calculator, the Socially-Distanced Waiting Area, the Socially-Distanced Queue Tool and the Occupancy Estimator.

It is possible to check the state of the model before going into the Analyser in the tool QA Model, giving the results, such as information, warnings or errors, in the Output Bar, in the lower section of the window.

Maps can be checked inside the Model Builder package, such as the Environment Maps that display the conditions registered and the entities in case of fire, it needs the integration of files generated by the FDS (Fire Dynamics Simulator) fire software and it displays factors such as temperature, visibility and toxicity.

The LEGION Simulator can also produce Maps that provide colour-coded representations enabling the visualisation of the crowd dynamic metrics or the entity experience such as density and space utilisation. There are two types of range, the value range like the Level of Service, and the colour ranges, that list in ordered colours that describe the conditions from excellent (blue) to bad (red).

To analyse the simulation the following metrics can be used:

- Count Inside: number of entities inside an area;
- Egress: number of entities exiting an area;
- Ingress: number of entities entering an area;
- Space Density: size of an area divided by number of entities within it;
- Distance: in an analysis zone (distance travelled in the zone); two lines (distance travelled from one line till the other); one line (distance between an entity's entrance into the model and the moment that it reaches the line);
- Entity Count/Flow Rate: number of entities crossing a line;
- Entity Density: density perceived by entities within an area;
- Journey Time: time taken for one entity to cross two lines or to cross an analysis zone area;
- Normalised Flow: number of entities crossing a line averaged over time and divided by the length of the line;
- Speed: speed of an entity crossing a line.

Other metrics that can be considered are the Inconvenience, Frustration, Discomfort and Dissatisfaction, but this can be hard to assess since their evaluation is not provided in a mathematical way.

4.3. MODELLING OF THE INTERMODAL TERMINAL

4.3.1. BUILD THE LAYOUT GEOMETRY OF THE SCENARIO

The first step to start the process is to build a scenario, in this case the software used to draw was Autocad by Autodesk, with the student version.

The layout was entirely drawn, but the vehicles, train and metro, resulted as an adaptation from the LEGION documents, from the Tube Station Simulation, given as template by Bentley to help users understand the operation of the software.

In Figure 27 it is possible to visualise the layout of the Intermodal Terminal, as it is composed by a train station, a metro station and a bus terminal, all of them connected to each other. The plant is divided into floor levels by colour, the dark lines representing the ground floor, the purple lines express the first underground floor and the red lines are related to the second underground floor.

To connect the floors in all of the buildings, different elements can be used, such as stairs, lifts (L) and escalators. All of them are going to be modelled in these examples to try to replicate real situations and challenges of the movement of people.

The train station has a ticket office at the entrance, some commercial shops along the whole length and a coffee shop in the east part, it has also a waiting room, outside the station is composed by nine platforms connected by a corridor on the lower level, with 4.7m width, what can be seen in Figure 28, as well as the highlighted parts (platform 3, train 4 and 5, corridor 1 and 3) that are the main zones of observation and analysis of the case study.

The metro station owns one platform in each side, it also has a ticket office in the entrance of the building, Figure 29.

The bus terminal is a compact structure in terms of operation since it has only five platforms, in addition, it offers a lot of commercial shops, a waiting room and a bathroom, all of this in the upper level of the building. To connect these different floors there is a number of options like escalators, lifts and stairs, Figure 30.

All of the obstacles that people have to go through are also a part of the layout as it is an important parameter to consider because of the delays and the shape of the route to be taken by the users, the main element that incorporates this are the walls of the buildings. Another obstacle that is present in the layout is the Information Board (IB).

The main entrances and exits defined are divided into the streets and each mode of transportation, metro, train and bus. From the streets there is an entrance and exit in the Northwest (NW), Northeast (NE), Southwest (SW) and Southeast (SE).

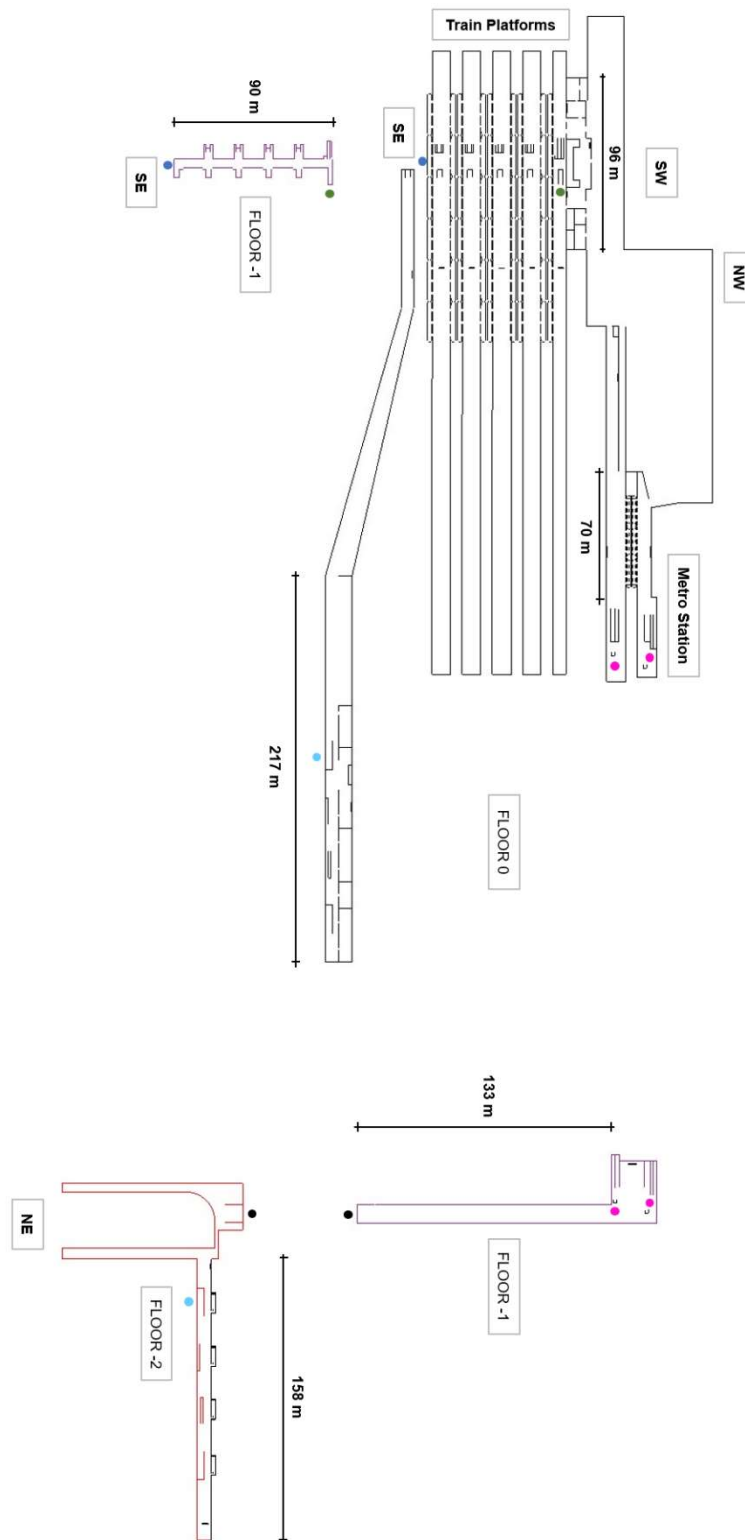


Figure 27 – Whole Model Layout

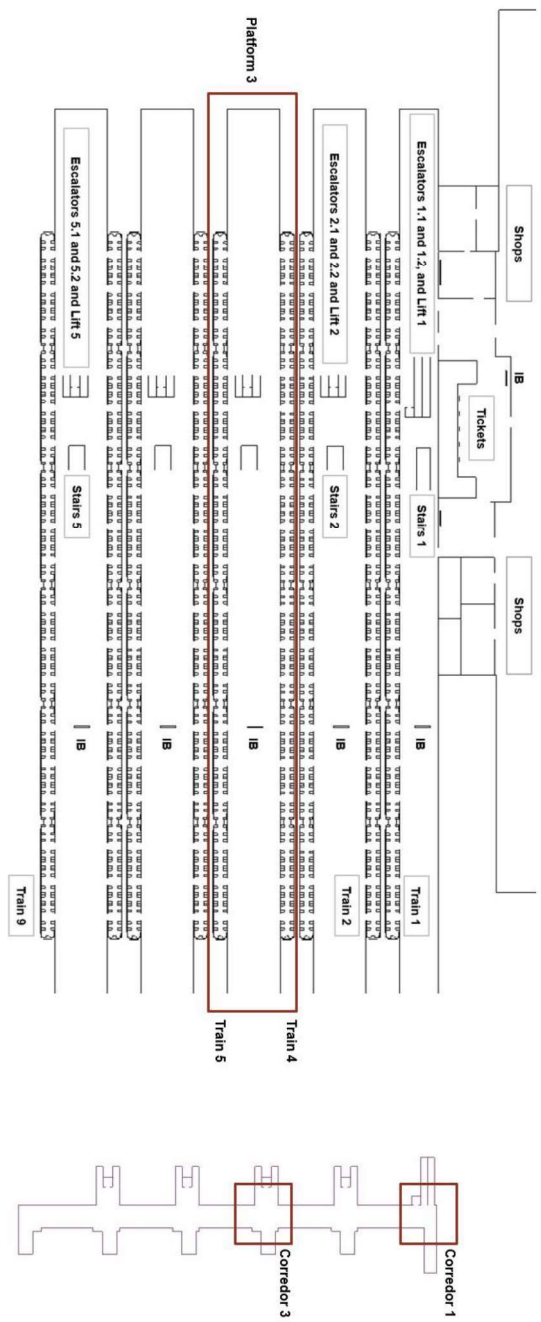


Figure 28 – Train Station Layout

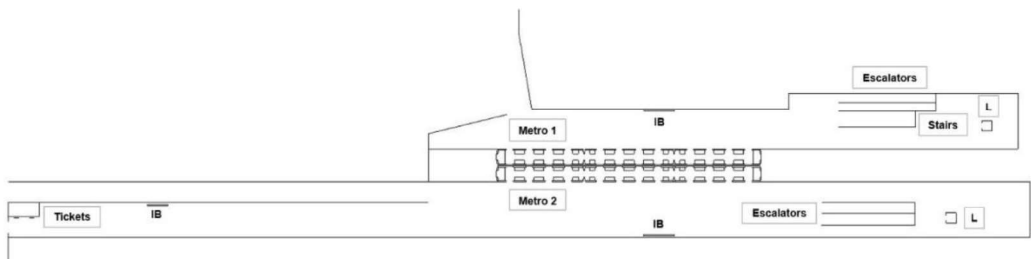


Figure 29 – Metro Station Layout

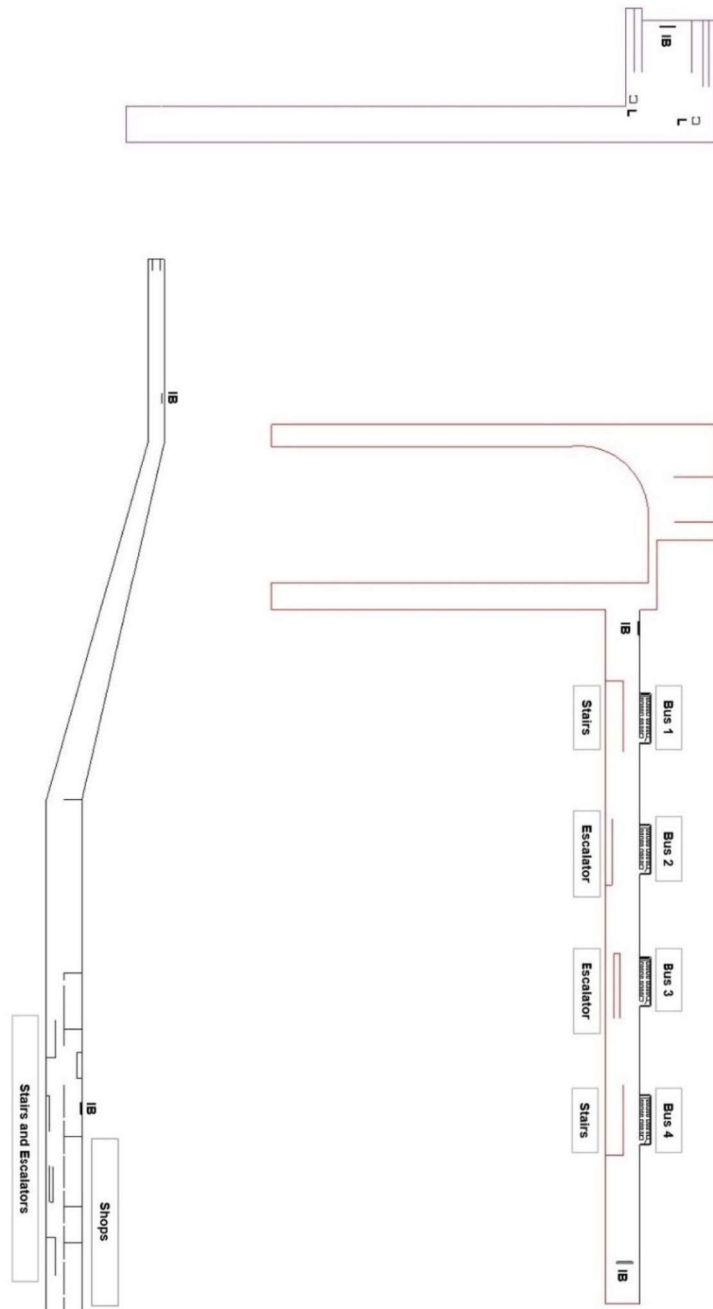


Figure 30 – Bus Terminal

4.3.2. IMPORT THE SCENARIO

To import the Autocad layout in the Model Builder can be an easy task if the drawings are simple structurally and operationally, if the layout is very detailed, some elements must be hidden or deleted, not to manipulate the experience in the simulation software.

In this case of study, the components in the layout are quite simple so they are easily imported to the LEGION software.

Through the tool Import CAD, it navigates into the layout done in Autocad, it is important to select the measures corresponding to reality for the right importation of the file. In this case the draw was done in proportions 1:1, in meters.

The layout is finally ready for the next steps of the simulation, the result of the importation can be seen in the Figure 31.

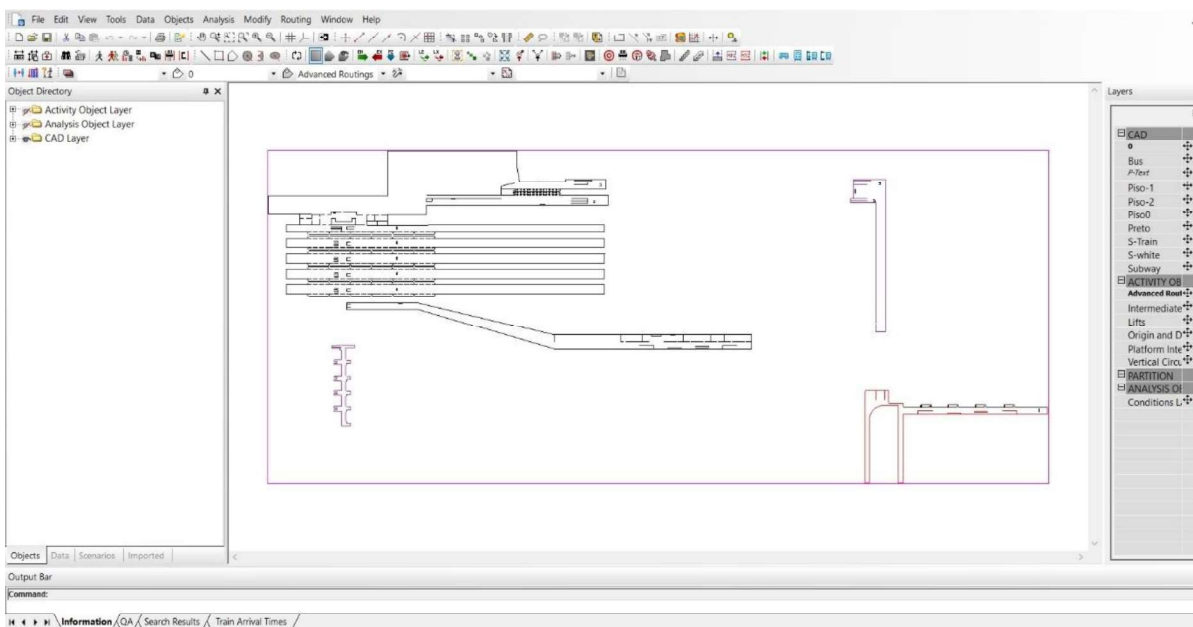


Figure 31 – Software after CAD Importation

4.3.3. CHARACTERISATION AND DEFINITION OF THE SCENARIO DATABASE

Firstly, the definition of the simulation duration must be defined, the time chosen was 10 minutes, from 8:00 am to 8:10 am, based on previous tests and the assumption that the majority of entities could get to their final destination during this period of time.

It is mandatory to define some parameters to describe and characterise the scenario, first using the Entity Profile Tool, it was decided to divide the population only in two types, the Residents and the Tourists. To detail this information other parameters were filled, regarding for example the size of the luggage used by the Tourists, in this case small, and the distribution according to the gender, the division used was 50% male and 50% female entities like the standard suggestion. More details can be given, like the entity colour that is going to represent visually, the Resident entities is in color red and the Tourist entities are represented in the color yellow.

The next tool is the Supply Type, which is going to divide the supply for each entity type in percentage. The Supply was divided into Bus_R, considering that it would take routes with more Resident interest, and Bus_T, considering that it would take routes with more interest from Tourists than the other bus, Metro_1 and Metro_2, also with a slight difference in the distribution of the population, and Street and Train, which was decided not to get into more detail and split into different options. The percentage attributed into each supply type can be seen in Figure 32.

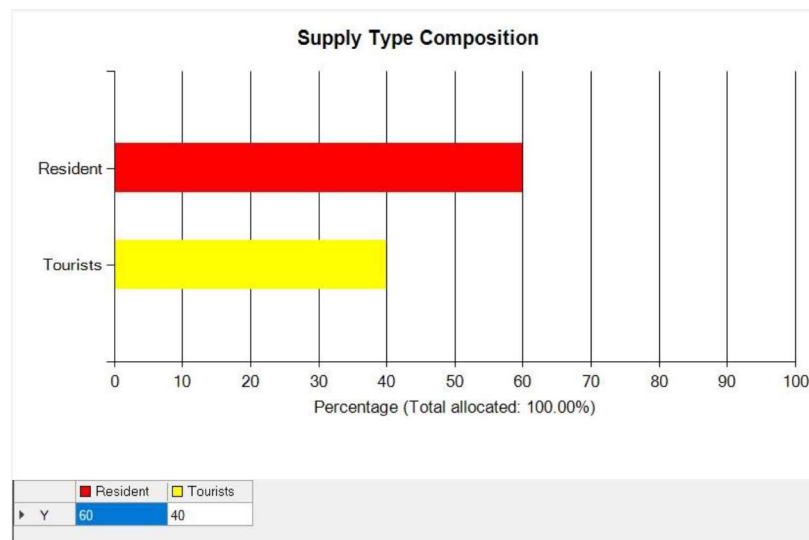


Figure 32 – Supply Type Composition

After these two parameters, the next tool is the Edit Data Profile, which is responsible for the attribution of the number of Arrivals and Exits in a period of time, as it would be in an OD Matrix. It can also include the Availability that controls arrival-dependent events, it indicates the time available for entities to board and controls the exit of entities in the vehicles. The last one used was the Delay Profile, there are two different delays, the delay caused by people going to the shops and the delay to buying tickets, the delay time considered for the Tourists was a little higher than the delay of the Residents entities in both Delay Profiles.

4.3.4. DEFINING BOUNDARIES

The main Entrances and Exits in this project are the following:

- Street NW
- Street NE
- Street SW
- Street SE
- Train 1 – 9
- Metro 1 – 2
- Bus 1 – 4

To define the Entrance, filling the entity/supply type, the profile and the final destinations is required. To increase the accuracy, it is possible to link the entrance to a focal node which orients the entities to a certain point. To define the Exits it is not necessary to fill any information, just to draw it in the right place. In Figure 33, it is possible to check an example of Entrances and Exits boundaries.

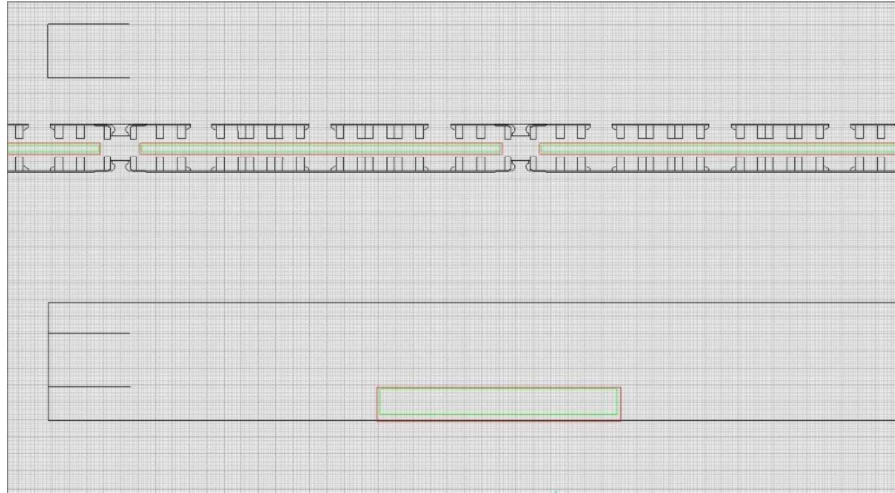


Figure 33 – Definition of Entrances and Exits

4.3.5. VERTICAL CIRCULATIONS

The next task was the definition of the stairs and the escalators to connect each floor along the extension of the terminal, to access all of the modes of transportation integrated in the project.

For the stairs, the bidirectional was the direction used and the distance factors were left as the standard suggestion, 1.98m up direction and 1.49 down direction. In this project it was defined the total of 10 different stairs.

The escalators resulted in a simple process, only needing to define the direction, up or down. The speed and slope were left as the standard suggested, tangential speed 0.59m/s, slope 30 degrees and distance factor 0.20m. It was also defined that the entities would stand on the right side of the escalator, this can facilitate the flow, that can not always represent the reality, but as it isn't possible to define a halfway walk or stand attitude, since the dimension of the escalators is not enough to make people walk in both sides.

An example of both stairs and escalators design can be shown in Figure 34.

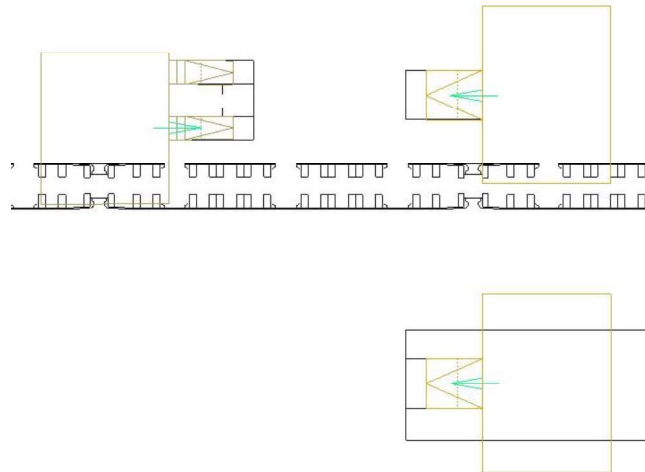


Figure 34 – Stairs and Escalators

4.3.6. DELAYS AND QUEUE

To make the simulation closer to reality it is important not to forget the delays and the queues generated by the delays or just by the normal flow of the pedestrian movement.

The delays considered were the delay to check the information boards that are located in many points of the platforms and buildings and the delay to buy the tickets in the ticket offices, one for each mode of transport. Around seventeen delays to check the information boards were created, connected to a structure that represents its placement, some could be checked only in one direction, but others could be seen in two directions, front and back. Nine delays were created for the tickets purchase or information request in the ticket office. In this case, the average time spent that was considered for the tourist was higher than the time for the Resident profile.

The queues created are linked to the delays to buy tickets, the information of the direction of growth of the queue was changed according to the available space, but the alignment factor the rigidity and the proximity factor was kept the same as the suggested by the software, 0.5 alignment, 0.5 rigidity and 0.25 proximity. Some queues can be grouped, so the entity can choose which queue is going into according to the shortest distance or the shortest queue, for this project it was chosen the shortest queue.

An example of groups of queues and delays in information boards can be found in Figure 35.

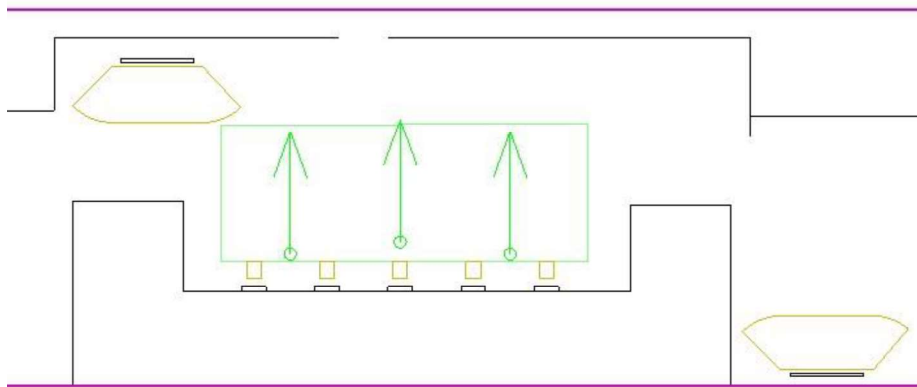


Figure 35 – Queues and Information Boards

For each delay is needed a direction modifier to make sure that the entities don't get lost and that they follow to their final destination after getting the delays.

4.3.7. MESOSCOPIC TRANSIT ZONE

In this next step, the Mesoscopic Transit Zone was created to simulate spaces that are part of the structure but do not require a lot of detail for the simulation, like Shops and WC, these spaces are present in the train building and in the bus terminal.

It also requires the direction modifier, for the same reason as the delays and queues, for entities don't get lost and continue to their final destination.

4.3.8. WAITING ZONE

The next step is improving the operation of the platform interfaces, for that a Waiting Zone was created in front of each train, metro and bus, so when entities arrive to the platform can wait until their destination is available for boarding, this allows entities to distribute through the waiting zone space using dispersion points.

For the waiting zone to be well implemented, direction modifier is needed to help guide the entities to their final destination when it is time to leave the waiting zone.

4.3.9. ADVANCED ROUTING

The next topic regarding the construction of the simulation is to compute advanced routings, using the Route Guide tool, it is possible to define certain routes and directions that must be followed by the entities that come from one origin or that go to one final destination. It can be a good tool to design a corridor with only one direction or a stair with only one way, and it is useful to make the system more organized. In case of congestion, it can lead the entities to choose one path over the congested one.

Matching the route guide tool with the direction modifier, entities can be distributed according to the preference given in the links, for example, it can be set that 90% of entities will go to the escalator and only 10% will go to the stairs to reach the upper floor, to reach the bottom floor the coefficients

associated are slightly different, considering that 75% of the entities are going to the escalator and 25% of the entities choose the stairs.

4.3.10. LIFTS

In this last step, the input of lifts were added, located in every train platform and in the metro platforms to access the different floors and create another path for the entities to reach their final destinations.

To define the lifts only with a two-floor layout, information about the Delay inside the lift, the time that takes until people enter into the lift and leave in the other floor, must be given in the Data Profile, in this case a period of 20 seconds was adopted. In the Data Profile, the information about the availability of the lifts is needed, in the up direction and the down direction, this means to define when the lifts go up and go down, these times must not overwrite each other, so there is a controlled up and down movement, so they don't match in time.

The construction of lifts can be done through a Microscopic or Mesoscopic way. In this simulation, the Mesoscopic way was chosen. For that, a waiting zone outside the lifts is needed, in the upper and in the lower floor, with the capacity defined. Then a mesoscopic transit zone must be created in the lift entrance and exit, upper level and lower level, in this point the capacity of the lift should be written, in this case it was considered that the lift can move 4 people inside, and the delay profile of the lift should be applied to all the entities. The next step is to create a direction modifier in the upper and lower levels right in front of the lift, it can be overlapped with the waiting zone area, information about the availability profile must be filled, the entity filter should match the waiting zone that corresponds to the level and the links must be connected to the mesoscopic transit zone in each floor. The last step is to connect the lifts to the direction modifier created before, which divides the entities through the stairs and the elevators, so in the lower to the upper direction the distribution considered was 82% escalator, 15% stairs and 3% lift, from the upper to the lower level the distribution chosen was 77% escalator, 20% stairs and 3% lift. An example of the appearance of a lift can be seen in the Figure 36.

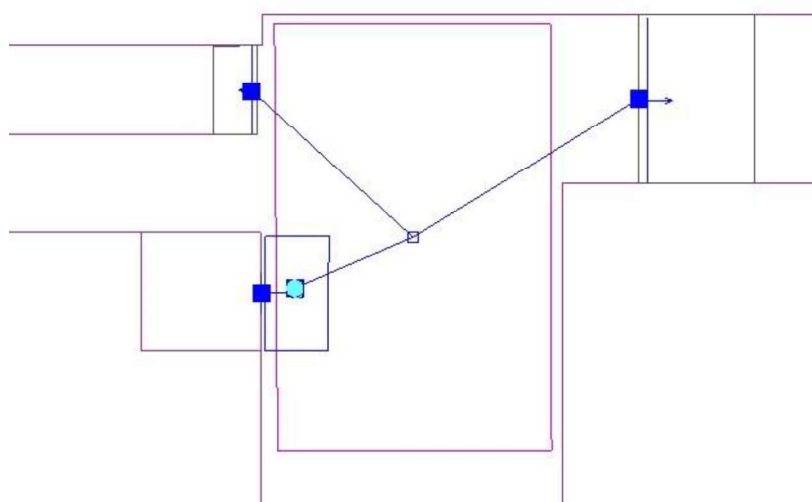


Figure 36 – Lift and Advanced Routings

4.3.11. SIMULATION SCENARIOS

Different simulations were performed in order to understand how the model reacts over the changes, according to different origin, destinations and vehicles that are integrated (Table 6). The scenario II was considered the Base Scenario, useful to analyse the impact of changes in the other scenarios. The only scenario that has not the lifts operating is the first scenario (I).

Table 6 – Summary of the Scenarios

Schedule	08:00				08:01		08:02	
Case/ Supply	Train 5	Train 4	Street SW	Metro 1	Train 4	Street SW	Street SE	Bus 1
I	288							
II	288							
III	288	270						
IV	288				270			
V	204		70		216		60	
VI	192			90	210	70	60	
VII	210			80	192			48

- i. The first simulation was very simple, only with one train arriving, train 5, at 8am and spreading the entities according to their final destinations, as it can be visualised in the Table 7. The train was tested at full capacity, with 294 entities. To try to understand the difference between the existence of lifts and a model without lifts and the influence of the lifts or not, the first simulation was done without lifts.

Table 7 – OD Matrix Scenario I

	Street SW	Street SE	Metro 1	Metro 2
Train 5	86	86	58	58

- ii. In this simulation the utilisation of the lifts was restored, the rest of the model was exactly the same, with only train 5 and the same entities and final destinations. The information can be seen in the previous Table 7.

- iii. The next simulation considered the previous train 5, at 8am and with the same conditions, but with the addition of another train, train 4, also with full capacity, arriving in the same platform at the same time. The OD matrix and quantities can be visualised in the Table 8.

Table 8 – OD Matrix Scenario III

	Street SW	Street SE	Metro 1	Metro 2
Train 5	86	86	58	58
Train 4	81	81	54	54

- iv. The following simulation is exactly the same as the third simulation but the train 4 arrives with an interval of 1 minute after the train 5 arrives. The distribution of the OD matrix can be seen in the Table 9.

Table 9 – OD Matrix Scenario IV

	Street SW	Street SE	Metro 1	Metro 2
Train 5	86	86	58	58
Train 4	81	81	54	54

- v. In this simulation, other elements were added, in the origin, so entities could enter in the model through the entrances in the Street NW and Street SW, and carry on to their final destinations, the distribution of the entities can be checked in the Table 10.

Table 10 – OD Matrix Scenario V

	Street SW	Street SE	Metro 1	Metro 2	Train 4	Train 5
Train 5	61	61	41	41		
Train 4	65	65	43	43		
Street SW			14	14	21	21
Street SE			12	12	18	18

- vi. This simulation is similar to the previous simulation with the addition of the metro 1 contributing with entrances in the model, the origin destination table can be seen in the Table 11.

Table 11 – OD Matrix Scenario VI

	Street SW	Street SE	Metro 1	Metro 2	Train 4	Train 5
Train 5	58	58	38	38		
Train 4	63	63	42	42		
Metro 1	23	23			23	23
Street SW			14	14	21	21
Street SE			12	12	18	18

- vii. The last simulation considers the train 4 and train 5, the metro 1 and the bus 1 for the first time. The entity's number entering the model and its distribution of origin destinations can be visualised in the Table 12.

Table 12 – OD Matrix Scenario VII

	Street SW	Street SE	Metro 1	Metro 2	Bus 1	Train 4	Train 5
Train 5	42	42	42	42	42		
Train 4	29	29	38	38	58		
Metro 1	16	16			16	16	16
Bus 1	5	5	7	7		12	12

4.4. SPECIFIC ASPECTS OF MODELLING

Regarding the train and metro boundaries, it was decided to create an entrance and an exit according to the different carriages, to have better control on the distribution of the entities throughout the vehicle doors. This option was not mandatory and turned out to require an intensive work, because each train had 6 carriages and each metro had 3 carriages, so the information had to be repeated that number of times.

The display of the layout made it difficult to follow all the entities and visualise if the path is being accomplished as planned, the connections between floors must be separated so it creates some divisions that can be hard to manage.

The design chosen for the train was very detailed, this made the simulating task more difficult, because the seats were not representing an available and usable space, which do not represent reality. The solution was to duplicate the train cad layer and turn the seats into an only visual object and not a barrier, this was not done because it was crashing the software over and over, so the solution found was to make the seats smaller, so entities does not get stuck while trying to leave the vehicle.

The creation of lifts represented a very challenging step, since there is not a lot of official information about it, and it requires a lot of knowledge and experience in the software. The contact with Bentley professionals was needed to execute this task.

4.5. RESULTS

The run of the simulation is operated in the LEGION Simulator, and the results can be prepared in the analysis tab.

During the process it is possible to visually inspect the changes in the space by the entities, slowing down or accelerating the time flow, in the timeline window. It allows the user to detect obstacles, modelling errors and entities preferential routes. The entity's moves are tracked generating a colour map showing the distribution of parameters values chosen by the user, for example speed, density and space utilisation. The user can create maps with the value ranges of the default maps. This value ranges are based on Fruin's literature and on the Highway Capacity Manual.

The results data, besides the maps, are organised in an excel workbook containing the chosen parameters values, it also provides graphical plots of these results. The software outputs can be Crowd metrics and Entity metrics. The Crowd metrics are Count Inside, Egress, Ingress and Space Density. The Entity metrics are the Discomfort, Dissatisfaction, Distance, Entity Density, Frustration, Inconvenience, Journey Time and Speed. It is possible to separate the results according to different entities using the Entity Filter.

In the timeline window the creation of graphs and maps can be controlled during the time defined for the simulation. The movements in the layout can be recorded during this time, and with focus on different views, it allows to separate the whole perspective into smaller parts, for example, a section of the corridor or a platform.

To evaluate the whole layout, a simple analysis can be done, but if the goal is to gather more detailed information, an analysis line or an analysis zone must be drawn, in this way the results are generated in that delimited space.

The results from all the scenarios described previously were collected. The main variations from each scenario were observed and detached with the support of graphs and maps generated in the software. For each scenario some analysis zones were created, mainly along the corridors, the exits of the vehicles, queue zones and in the proximity of the escalators, stairs and lifts. Although the simulation is comprised of 10 minutes, in three moments, minutes 1, 4 and 7, it was interrupted for the instant disposal graphical recording, correspondent to the instant disposal, in the end the software automatically outputs a graph and a map with the whole process. As the routes of entities are quite different from each other, some are affected by the lifts or the shops, and others walk directly to their final destination, the values considered in the graphs were evaluated in intervals found significant for the correspondent analysis.

To complement the results, two new maps were created, the Average Speed and Density over the Level of Service C, this particular map followed the Level of Service intervals values of Fruin. Other maps and graphs made for the evaluation of this simulation are shown in the Table 13.

Table 13 – Main Graphs and Maps extracted from LEGION Simulator

Graphs					
Count Inside	Space Density	Distance	Entity Density	Journey Time	Speed
Maps					
Cumulative High Density	Cumulative Mean Density	Space Utilisation	Evacuation	Average Speed	Density over LoS C

4.5.1.1.BASE SCENARIO – SCENARIO II

In the Base Scenario (BS), entities start to reach their Final Destinations in the minute 00:52, in the end of the 10 minutes of simulation almost all entities left the model, 235 entities, 82% of the total, these values can be seen in the excel worksheet and in the following Figure 37.

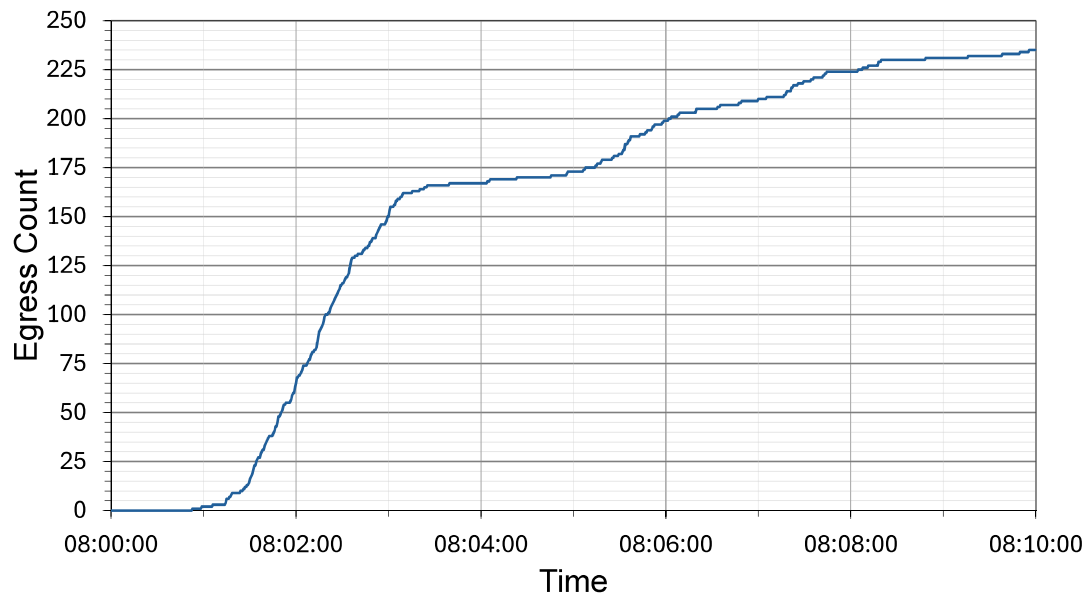


Figure 37 – Egress

In minute 00:08, 102 entities share the space inside the Train 5 Exit analysis zone, Figure 38. The maximum value of space density in the exit of the train is 0.53 persons/square metre, 8 seconds after the simulation starts, Figure 39, this validates the previous affirmation. The highest speed registered in this zone is 1.39 m/s, in the first second of the exiting the train 5, Figure 40. The perception of the average density by entities registered a higher value of 0.73 persons/square metre in the minute 00:13; between the minutes 00:04 and 1:12 the average entity density is 0.49 persons/square metre, Figure 41.

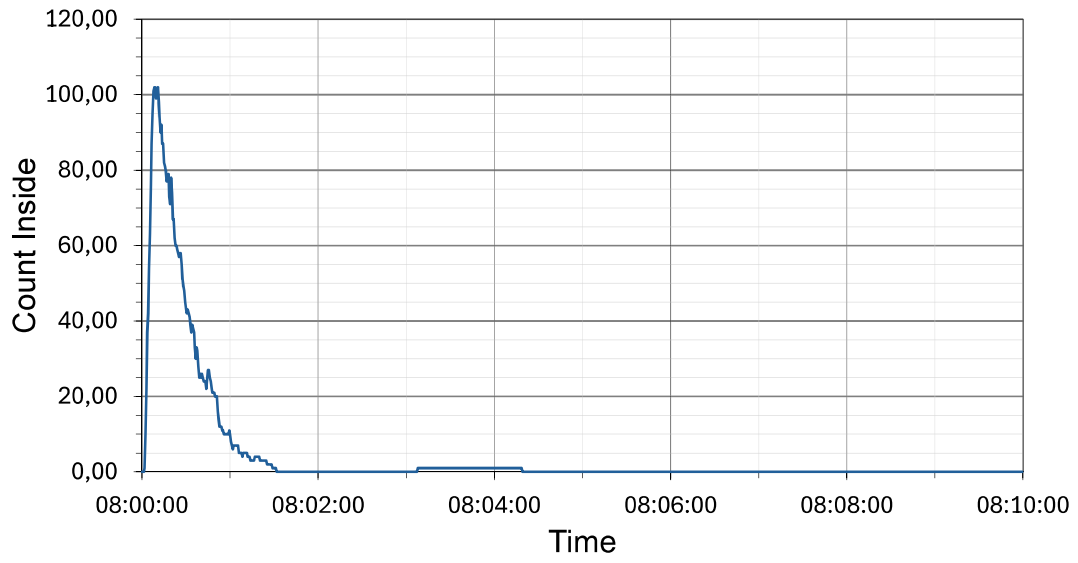


Figure 38 – Count Inside Exit Train 5

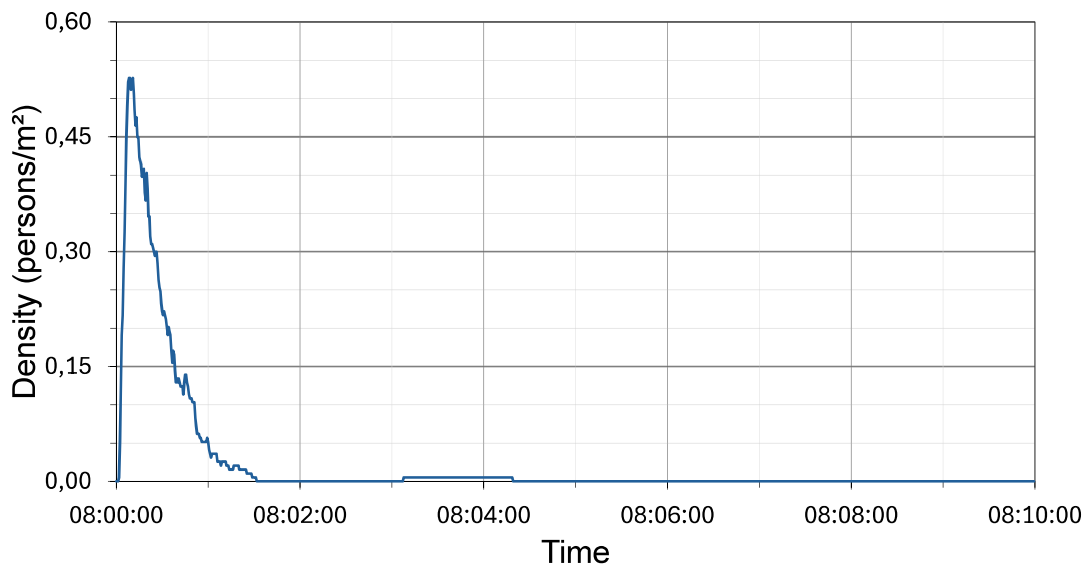


Figure 39 – Space Density Exit Train 5

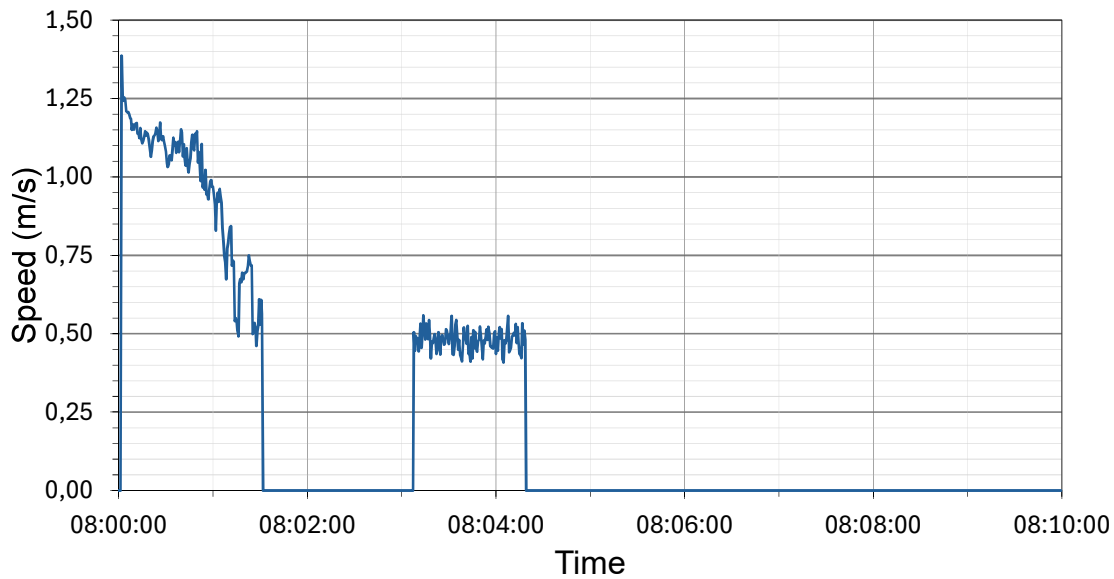


Figure 40 – Speed Exit Train 5

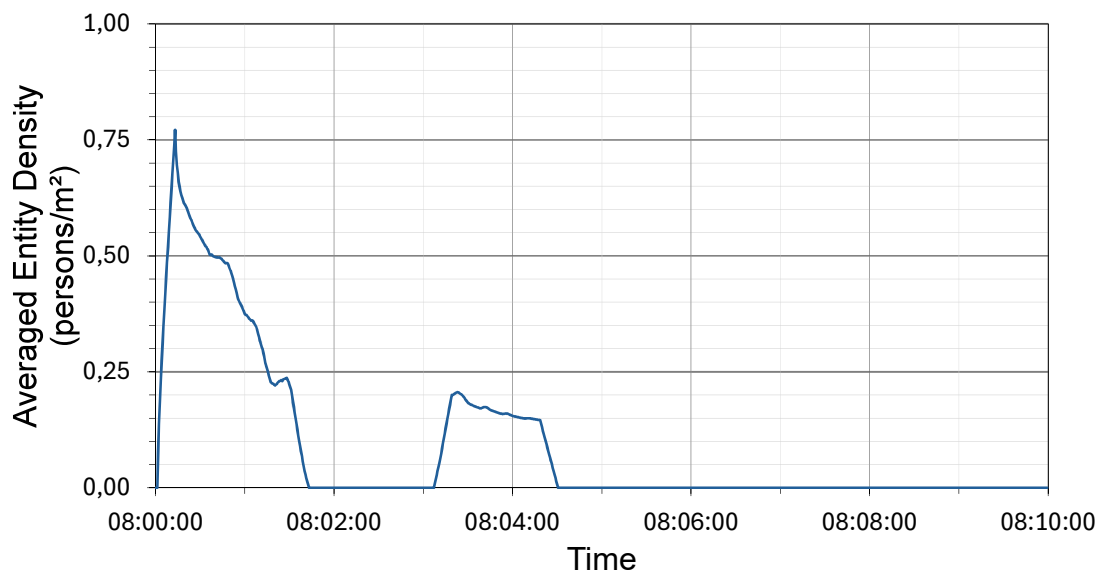


Figure 41 – Averaged Entity Density Exit Train 5

In the platforms, near the stair 3, the Space Density registered was 0.29 persons/square metre, Figure 42, but the maximum Average Entity Density outputted was 0.74 persons/square metre, Figure 43, the highest speed was 1.47m/s. In the zone of entrance of escalator 3, the Space Density was 0.26 persons/square metre, Figure 44, while the Averaged Entity Density was 0.86 persons/square metre, Figure 45, the highest speed was 1.72m/s in the first seconds.

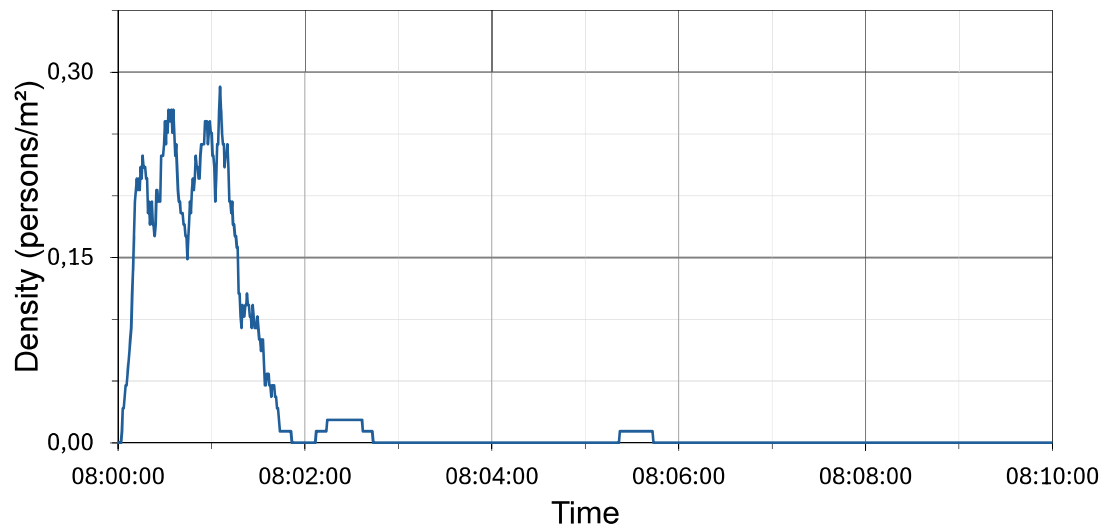


Figure 42 – Space Density Platform Stair 3

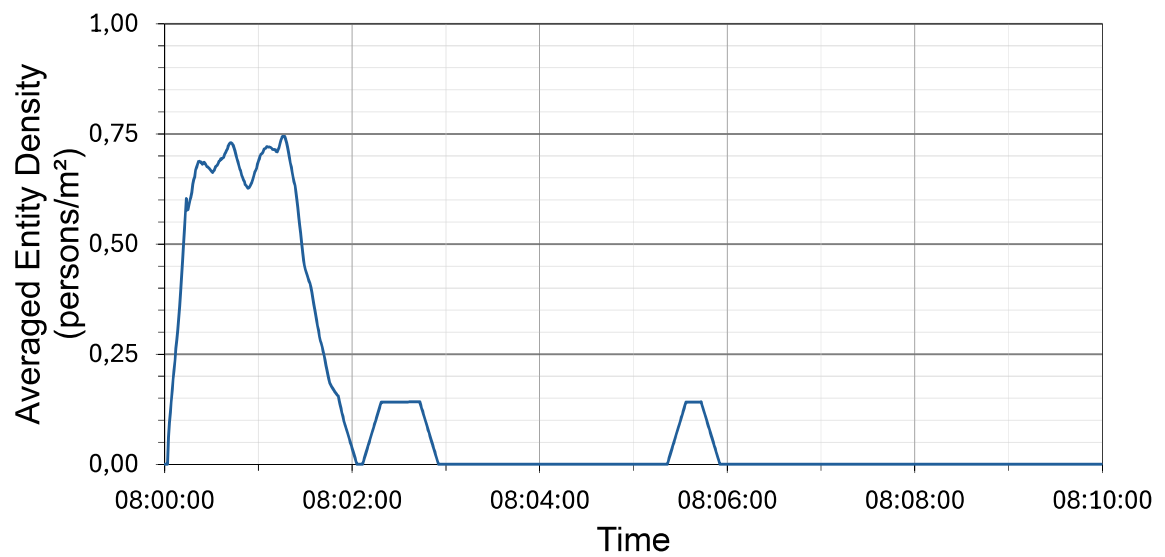


Figure 43 – Averaged Entity Density Platform Stair 3

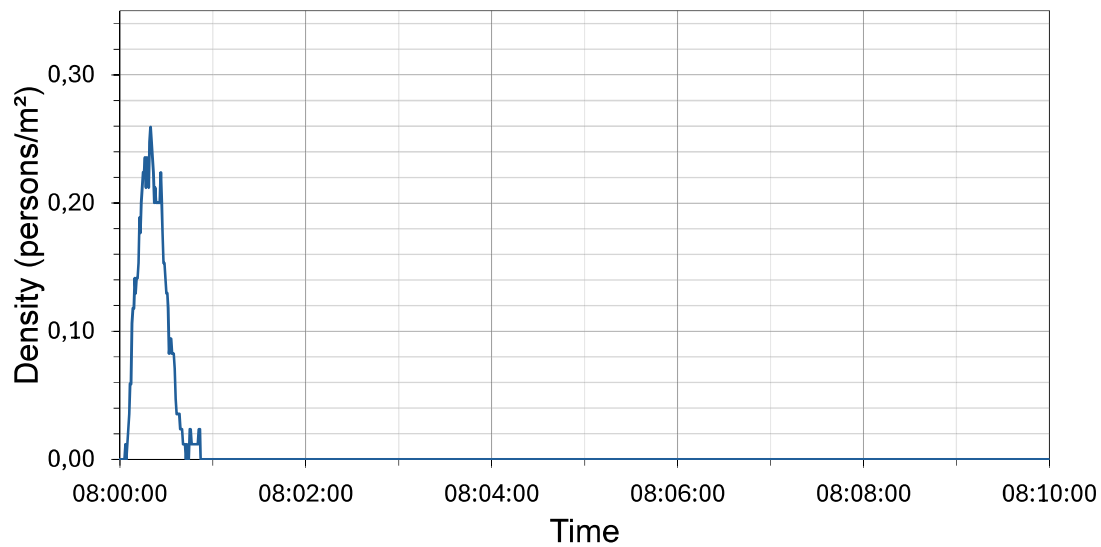


Figure 44 – Space Density Platform Esc 3

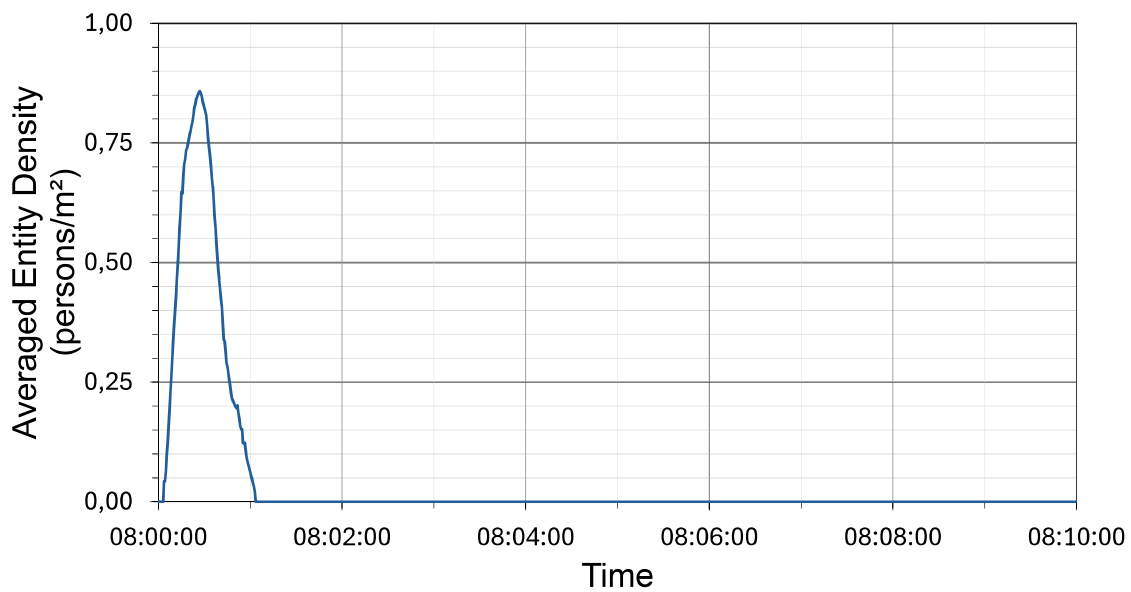


Figure 45 – Averaged Entity Density Platform Esc 3

The existence of lifts, calls for the evaluation of the effects in the surrounding perimeter. In the analysis of the platform near the lift 3 the space density reaches the higher value of 0.64 persons/square metre during the period of 00:48 to 1:10 (Figure 46), when entities start to arrive to this point coming from the train, the entity's perception of density (average entity density) during this period is 0.67 persons/square metre, which is similar to the real value of space density (Figure 47).

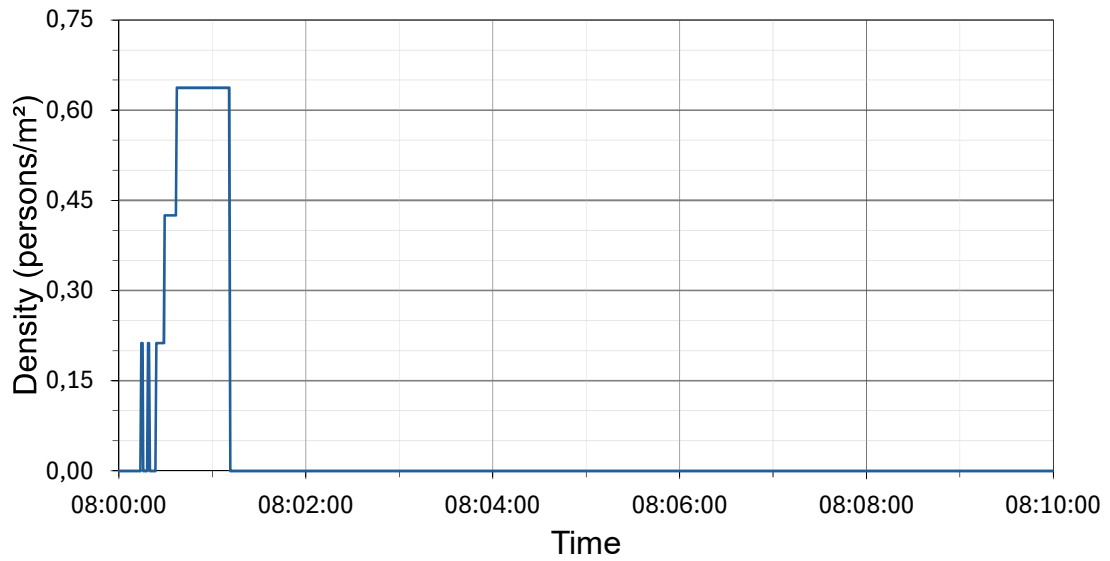


Figure 46 – Space Density Lift 3

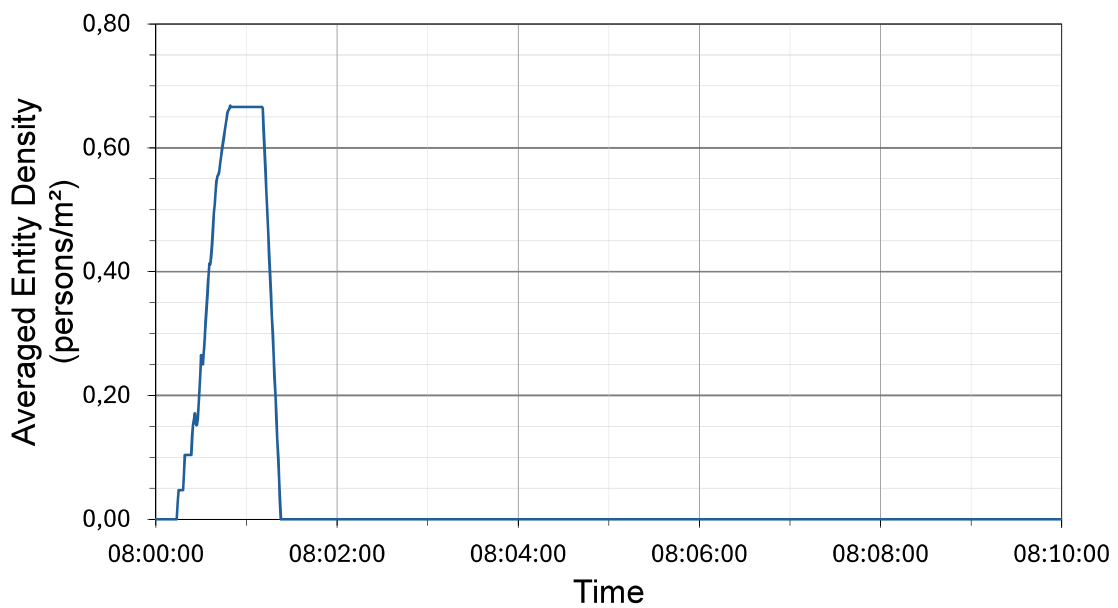


Figure 47 – Averaged Entity Density Lift 3

In the corridor 3, the count of entities maximum is 10 people in the minute 00:48, Figure 48, and the highest space density is around 0.35 persons/square metre is recorded in the minute 00:54, Figure 49. The fastest entity going through this zone walks at 1.81 m/s in the minute 00:18, Figure 50. In this case the interval that gathers most of all averaged entity density is from 00:31 to 02:00, the averaged entity density reveals a perception of 0.64 persons/square metre, with the maximum value of 0.8 persons/square metre, Figure 51.

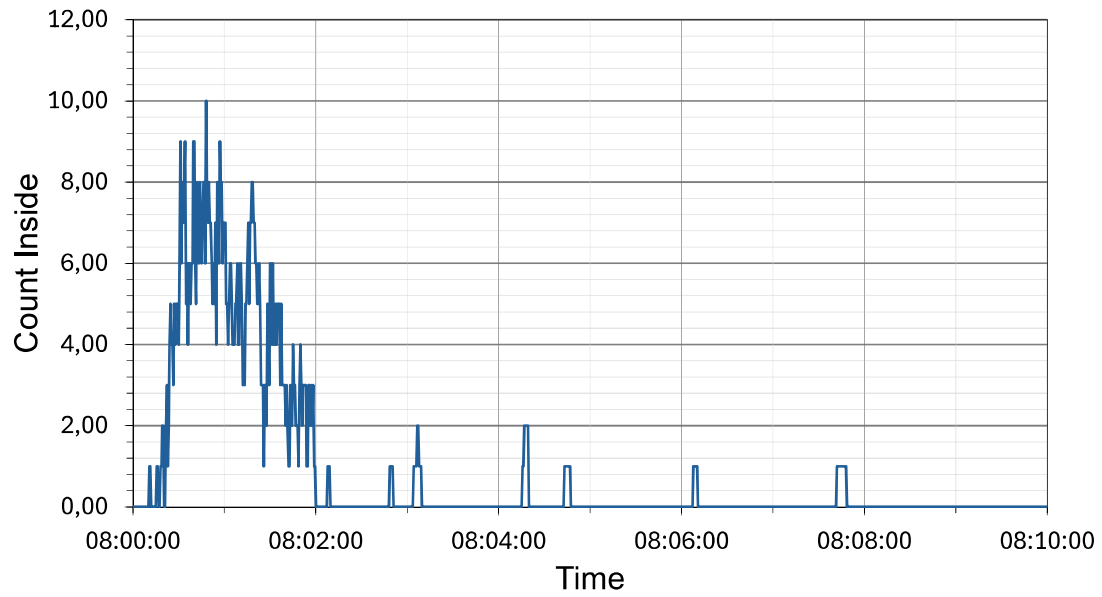


Figure 48 – Count Inside Corridor 3

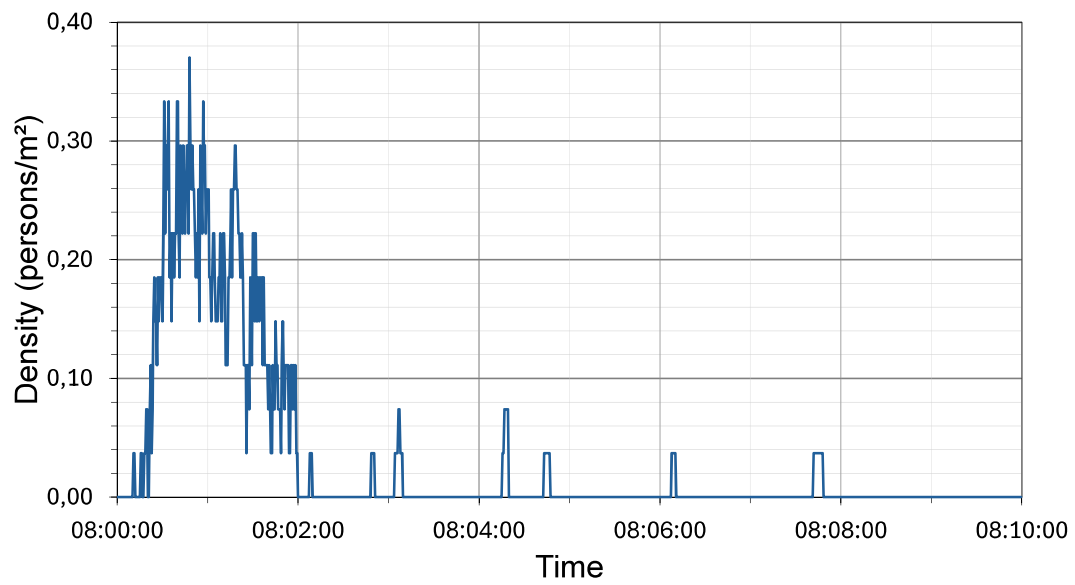


Figure 49 – Space Density Corridor 3

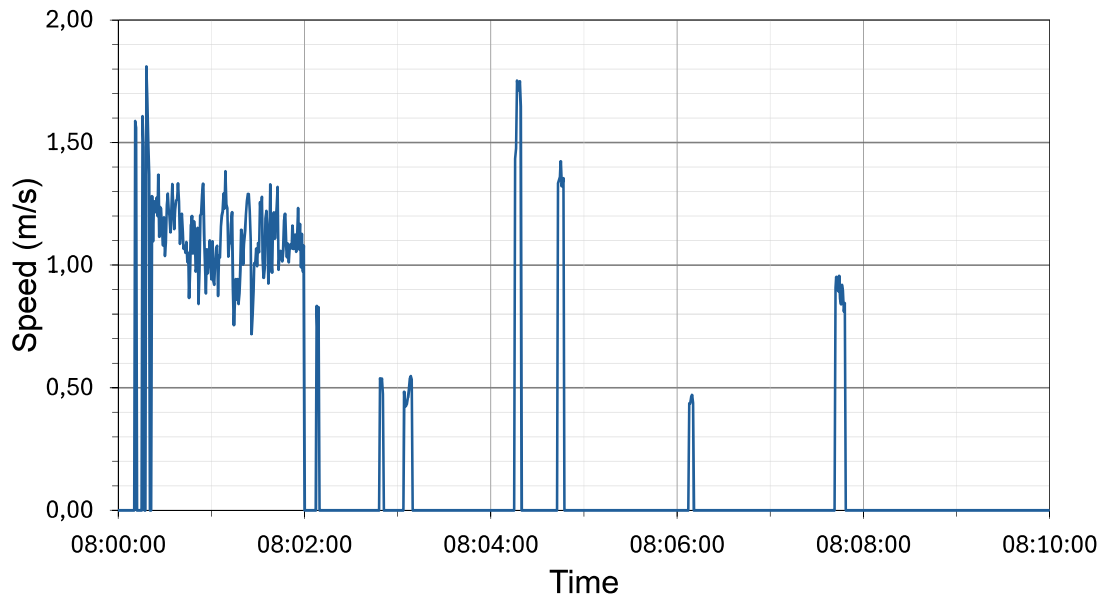


Figure 50 – Speed Corridor 3

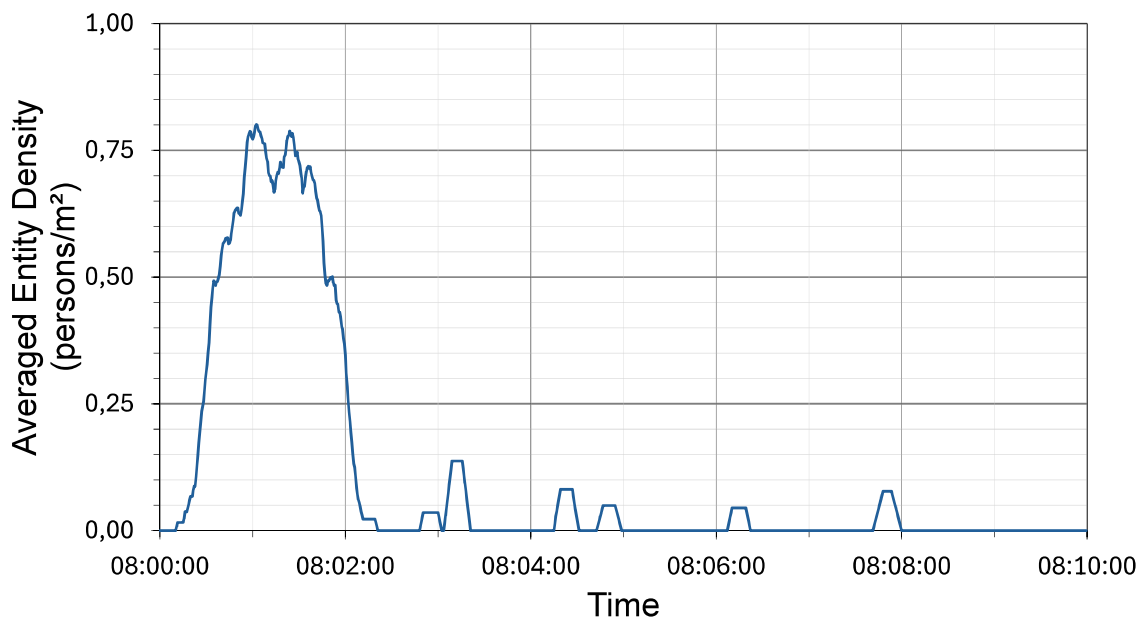


Figure 51 – Averaged Entity Density Corridor 3

In the corridor 1, the count of entities inside of the analysis zone is equal to or higher than 5 between the minutes 1:00 and 2:18, getting to 21 entities in the minute 1:31, Figure 52. In this zone, the space density reaches its higher value of 1.30 persons/square metre after 1:31 minutes from the start of the simulation, that verifies the parameter shown before, in this point the number of entities inside the zone is the highest so the density reaches its maximum value, Figure 53. In terms of speed, the highest registered was 1.83 m/s in 4:01 minutes of simulation, Figure 54, this can represent an entity that was not following the crowd right after the train opened the doors, or an entity that came back to the corridor, at this time emptier, after making an intermediate activity, such as shopping. The interval between 00:38

and 2:27 accumulates an average entity density of 0.60 persons/square metre, with the maximum value of 1.63 persons/square metre, Figure 55.

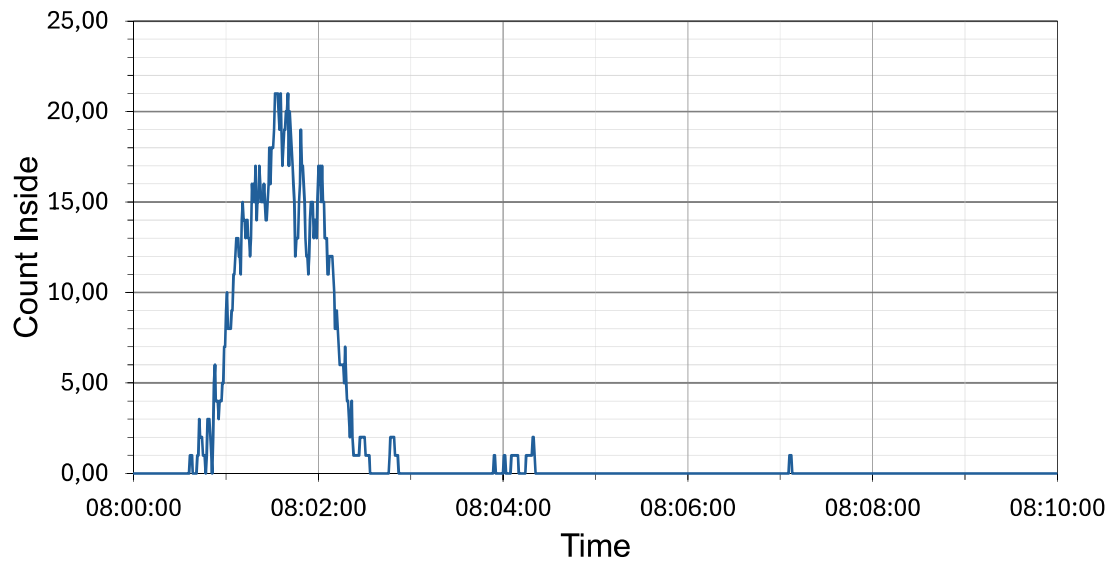


Figure 52 – Count Inside Corridor 1

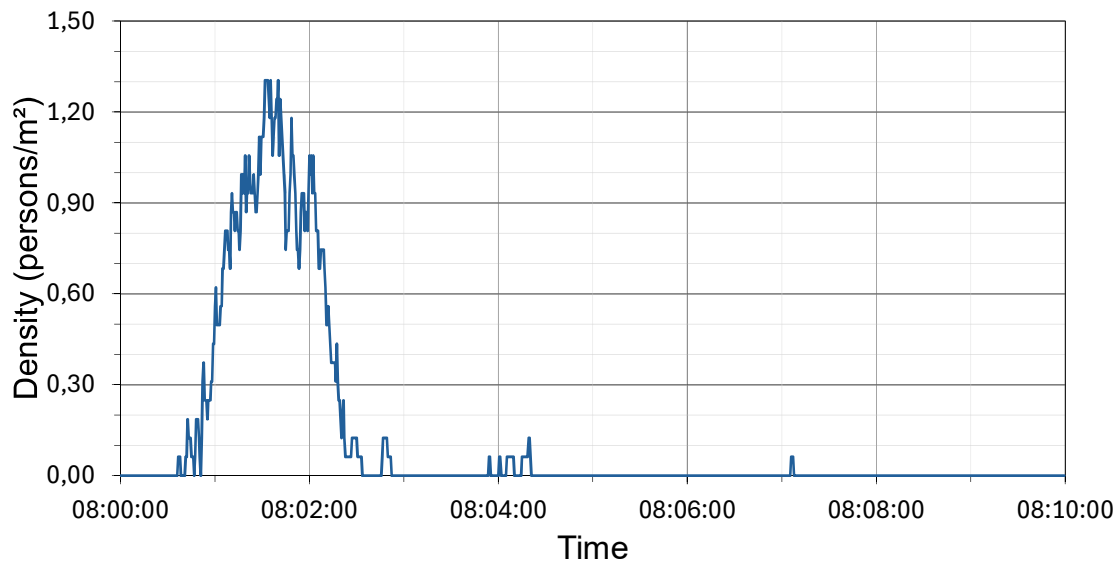


Figure 53 – Space Density Corridor 1

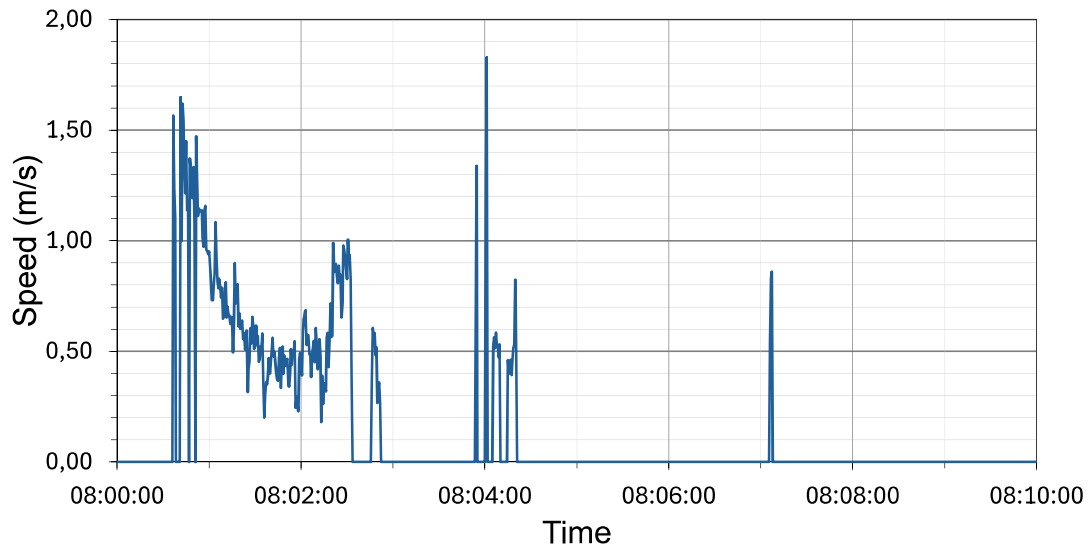


Figure 54 – Speed Corridor 1

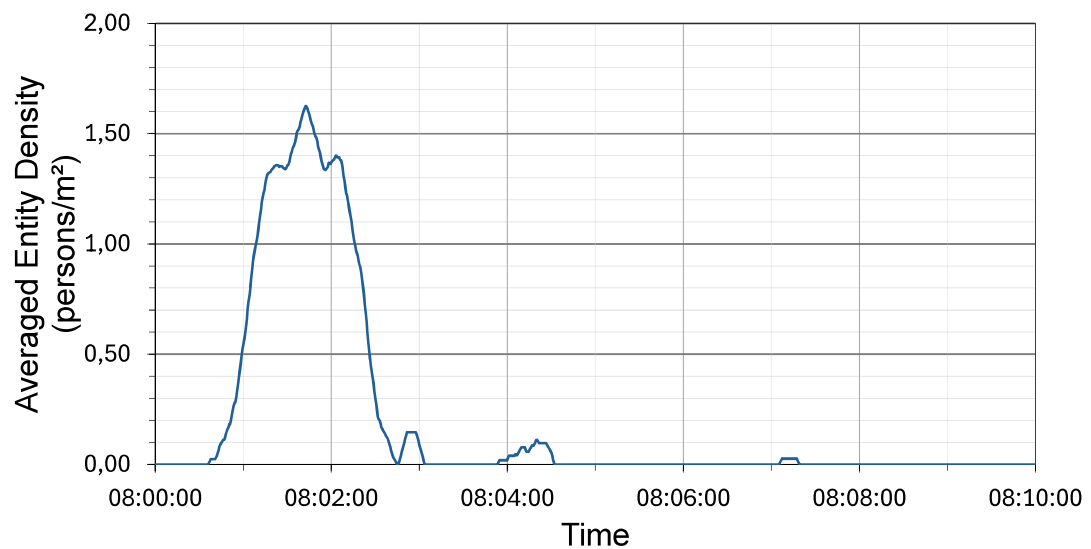


Figure 55 – Averaged Entity Density Corridor 1

In terms of maps generated in the software, some were found more representative of the data described.

The maps that can be related to the Fruin level of service factors are the Cumulative Mean Density, which are represented according to the weight and colour assigned in Figure 56.

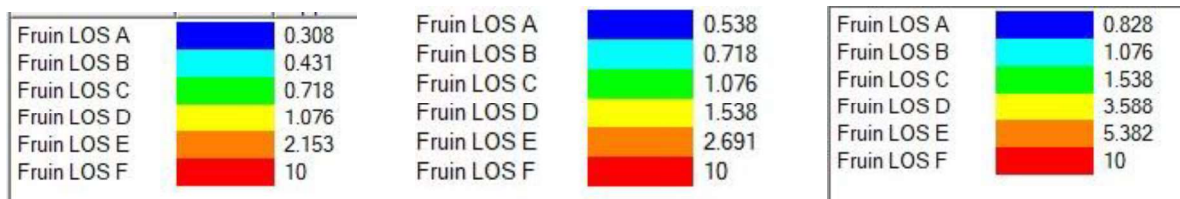


Figure 56 – Fruin LoS Walkways, Stairs and Queues, respectively

In the beginning of the Scenario II, the maps showed that the stairs escalators and the space inside the train 5 is in Level E, Figure 57. In this map it is also visible that in the platform Level is C, therefore confirming the analysis did before in the graphs.

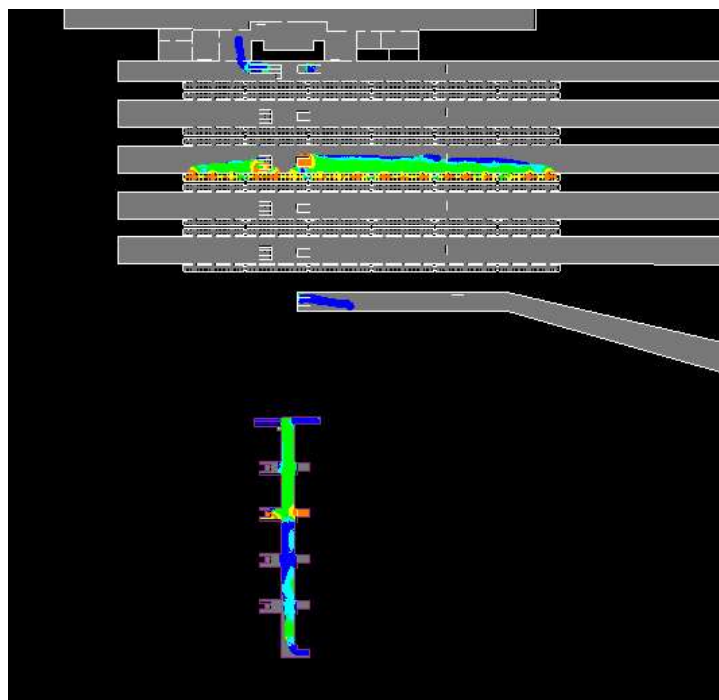


Figure 57 – Cumulative Mean Density, minute 1

The speed can be evaluated according to the Figure 58. In the simulation of the scenario II, the speed did not show to be a problem because it delivered high numbers even in the most crowded instants of simulation, what can be observed in Figure 59. The stairs and escalators must not be evaluated with the same speed factor intervals.

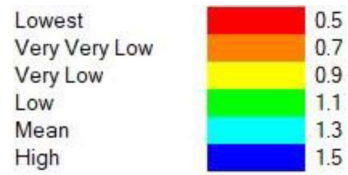


Figure 58 – Speed [m/s]

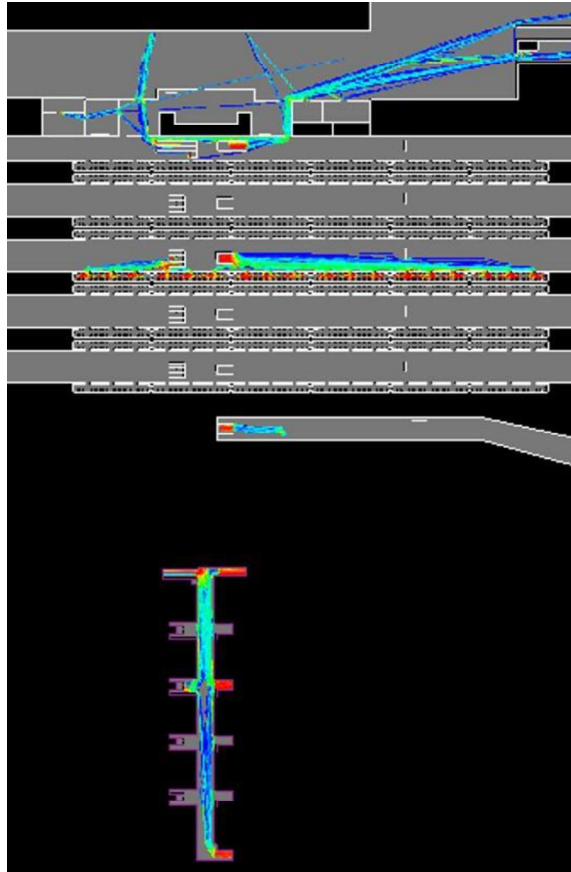


Figure 59 – Average Speed, minute 4

The map of Density turns red over LoS C, if at any time, the density of the area belongs to level D or worse, it was defined a minimal value of 0.72, corresponding to the value ranges of Fruin. It can be verified, in Figure 60, that in the end of the simulation time almost all the entities routes are equivalent to Level D or worse.

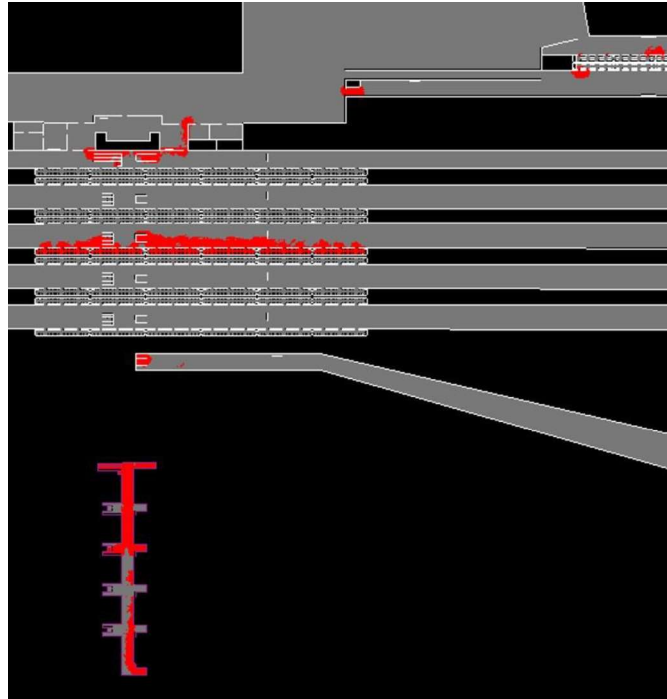


Figure 60 – Density over LoS C, minute 10

4.5.1.2. SCENARIO I

In the Analysis Zone positioned in the Exit of the Train 5, the Count inside reaches the maximum value of 110 entities in that analysis zone at the same time, in the minute 00:11. In this scenario the space density gets to 0.57 persons/square metre in the minute 00:11, in this case a higher density than in the BS. The fastest speed recorded, 1.44m/s, is right in the beginning of the simulation, minute 00:01, a speed slightly lower than the BS. In terms of average entity density, the value is higher than 0.38 persons/square metre between minutes 00:13 and 00:39, the perception of density by the entities shows to be lower in this case. In this zone, it was not captured a significant variation of the results.

Analysing the corridor 3, overall, the values are similar to the ones output in the previous analysis zone, the count of entities maximum is 9 people in the minute 00:40 and the highest entity density is 0.37 persons/square metre, recorded in the minute 00:43. The fastest entity going through this zone walks in 1.68 m/s and that speed is registered in the minute 00:21, in the minute 00:41 the speed is 1.16 m/s. In this case the interval that gathers most of all average entity density is from 00:31 to 01:43 the average entity density reveals a perception of 0.51 persons/square metre, with the maximum value of 0.63 persons/square metre, slightly better than the results of the BS, as the registered results of Space Density, Figure 61.

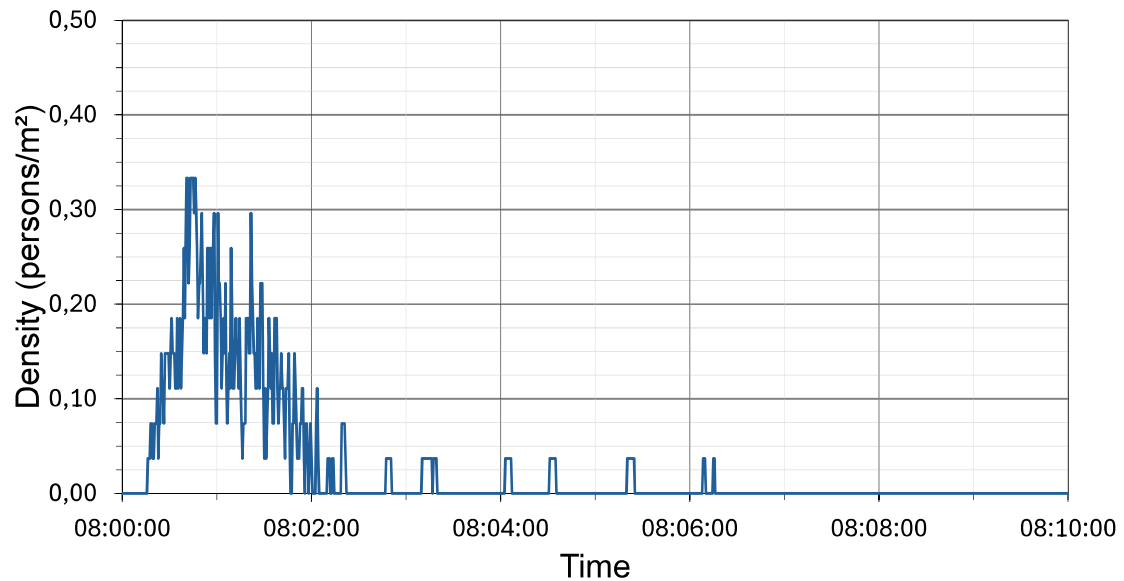


Figure 61 – Density Corridor 3

In the corridor 1, the count of entities inside of the analysis zone is equal or higher than 5 between the minutes 1:00 and 2:11, getting to 24 entities in the minute 1:21. In this zone, the space density reaches its higher value of 1.49 persons/square metre after 1:21 minutes from the start of the simulation, worse than in the BS, it also verifies the parameter shown before, that as in this point the number of entities inside the zone is the highest the density reaches its maximum value. In terms of speed, the highest registered was 1.50m/s in 41 seconds of simulation. The interval between 00:38 and 3:51 accumulates an average entity density, the perception of density by entities, of 0.60 persons/square metre, with the maximum of 1.64 persons/square metre. The parameters in this zone are similar to the BS but slightly worse.

The maps resulting from this scenario were very identical to the BS.

4.5.1.3. SCENARIO III

With the addition of another train in this scenario, the exit zone of Train 5 shows a slightly bigger space density number than in the BS, in terms of the perception of the entities, the number increased a lot with the addition of a new train arriving at the same time, Figure 62. Regarding the speed performed, the values are lower. These values were expected due to the increase of entities sharing the same space.

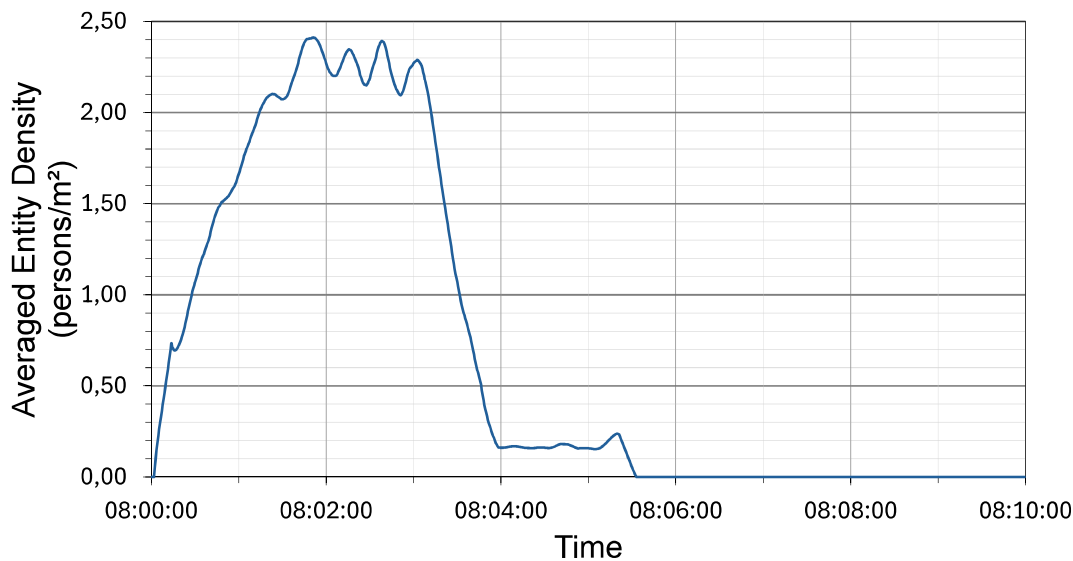


Figure 62 – Averaged Entity Density Exit Train 5

The exit zone on the Train 4 is implemented for the first time, the higher space density registered is 0.38 persons/square metre, although the value of average entity density was 0.68 persons/square metre, it represented a bigger value than the one for the train 5. The fastest movement was done at 1.35m/s in the minute 00:58 of the simulation.

The main differences of the Lift 3 in the upper zone are in the space density, which has a maximum value of 0.21 persons/square metre, lower than the one in the BS. The average entity density is also lower, 0.27 persons/square metre. This analysis can show that in the case of two trains arriving in the same platform the entities prefer to take stairs or escalators instead of lifts.

In the platforms, the variation from the BS were a higher space density in both cases (stairs and escalator 3), a considerable increase in the average entity density, approximately 1.95 persons/square metre, and a lower speed, 1.45m/s.

The analysis zone in the corridor 3 expressed lower values in density space, but the averaged entity density has almost all values above the 0.35 persons/square metre, the speed was higher than in the BS, 1.81m/s.

The corridor 1 had some variations, but mainly in the speed, although the highest speed was near 1.8 m/s, the other values seem to be quite low comparing to the BS.

The main differences in this scenario are the increase of density in the platform when the trains arrive and the decrease of average speed during the same time period. It can be seen in the map of Cumulative Mean Density, Figure 63, that the area of exit of Train 5 as well as the zone near the escalators have an increased LoS compared to the BS and that in the map of Average Speed, Figure 64, the average speed decreased in that area.

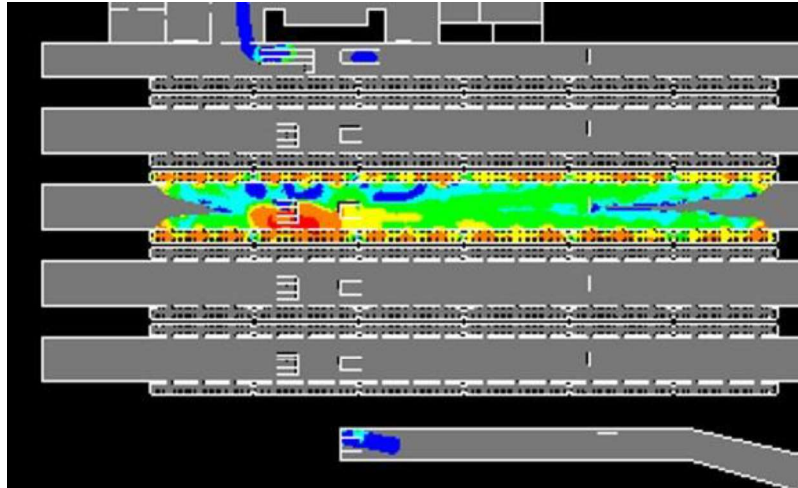


Figure 63 – Cumulative Mean Density, minute 1

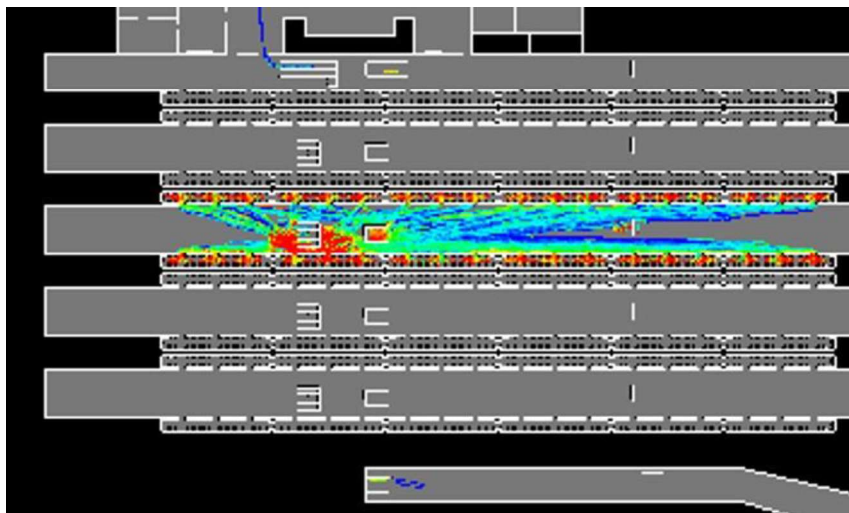


Figure 64 – Average Speed, minute 1

4.5.1.4. SCENARIO IV

This scenario is like the third one, but the trains arrive with an interval gap of 1 minute.

The analysis zone right outside the Train 4 showed similar results of density and speed to the previous scenario.

The exit of Train 5 presented results very alike comparing to the BS, what means that the 1 minute gap resulted in better quality of service than in the previous scenario in this zone.

The analysis on the corridor 1 showed a higher Space Density of 2.1 persons/square metre (Figure 65), a slightly slower speed of 1.67m/s. The Average Entity Density reaches the 2.1 persons/square metre (Figure 66), equal to the Space Density. In the third minute, 33 entities were inside the analysis zone at the same time. In this scenario the density registered higher values than in the BS and in the scenario III.

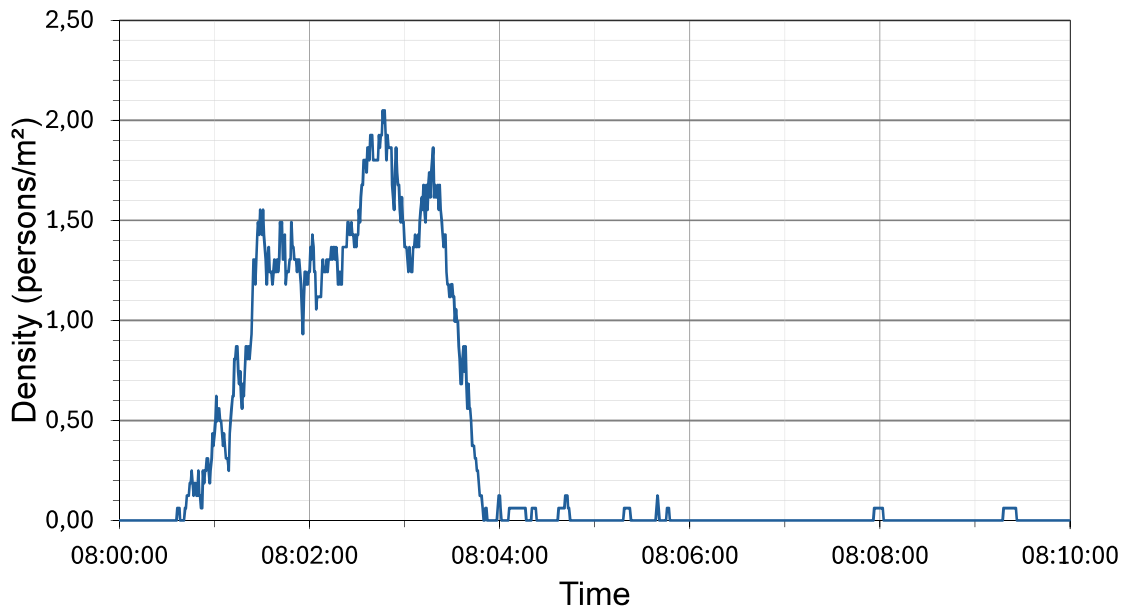


Figure 65 – Space Density Corridor 1

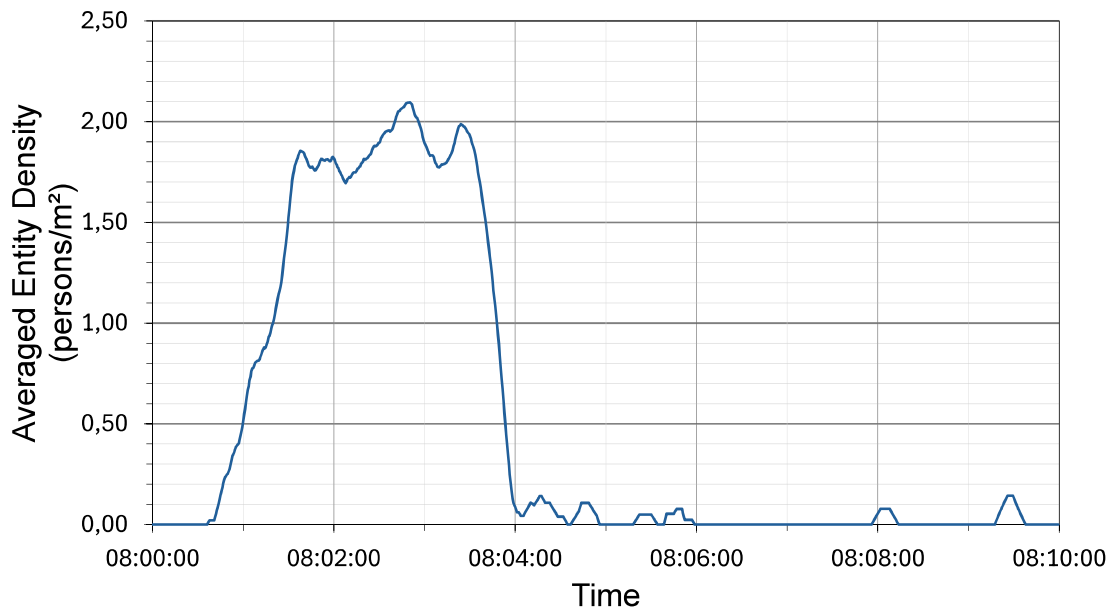


Figure 66 – Averaged Entity Density Corridor 1

The corridor 3 registered a maximum entity number of 13 around minute 01:00, a higher value comparing to the BS was detected in the Space Density, 0.48 persons/square metre, the other values did not change significantly.

In the platforms, near the stairs 3, the speed parameters matched the BS, the Space Density delivered a higher value, 0.47 persons/square metre, also the averaged entity density were significantly higher than it was in the BS, with 1.45 persons/square metre. Still in the platform, near the escalators 3, the numbers are quite similar to the ones obtained in the BS.

Any differences in the lifts were found.

The reproduction of this scenario did not show large differences comparing to the BS, but in general delivered better results comparing to the scenario III.

4.5.1.5. SCENARIO V

In this scenario the train 4 and 5 are distributed as they were in the previous scenario, with the addition of entities entering through the Street SW and Street SE.

Train 4 produced lower Space Density, 0.29 persons/square metre, very constant and higher maximum speeds, and a little lower Averaged Entity Density, 0.57 persons/square metre.

In the Train 5, the major difference relies on the Averaged Entity Density, with 2 persons/square metre.

In the corridor 1, the maximum of entities sharing the space of the analysis zone is 36, in the minute 03:12. The space density turned out very different, 2.2 persons/square metre (Figure 67), comparing to 1.30 persons/square metre in the BS, this value can demonstrate the increase of density with the addition of street entrances in the model, that blend together in the extension of the corridor. The Averaged Entity Density reproduced higher values, bigger than 1.5 persons/square metre between minute 02:00 and 05:00, with maximum value of 2.3 persons/square metre.

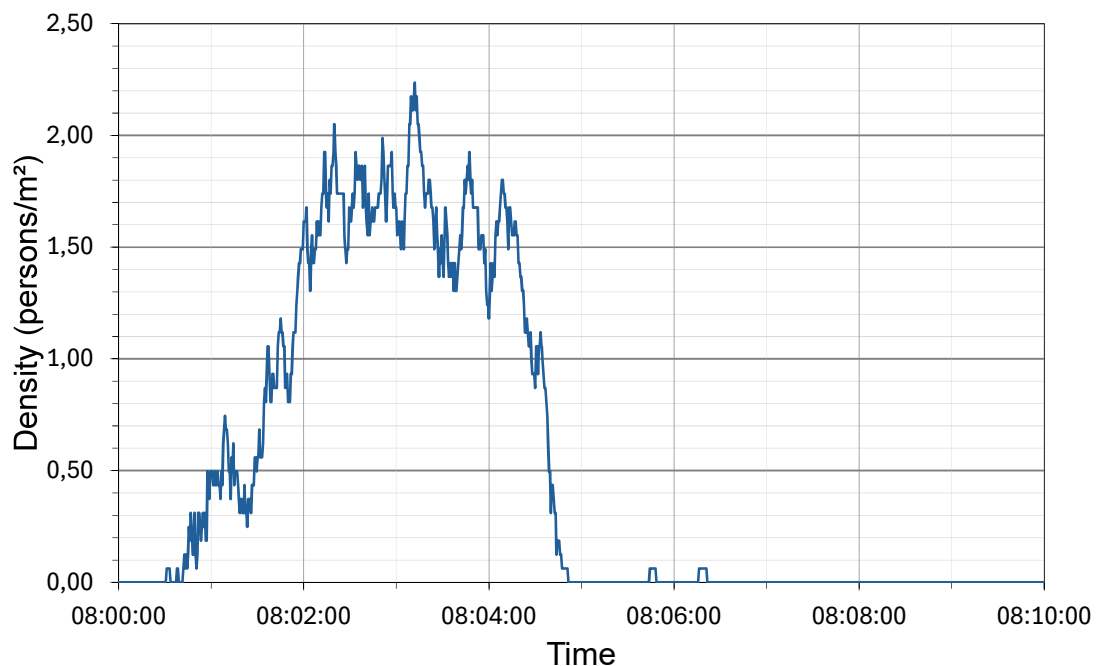


Figure 67 – Space Density Corridor 1

The values in the corridor 3 showed some variations from the BS. The space density assumed the maximum value of 0.4 persons/square metre; in Figure 68 it is possible to visualise that the density is very spread in time.

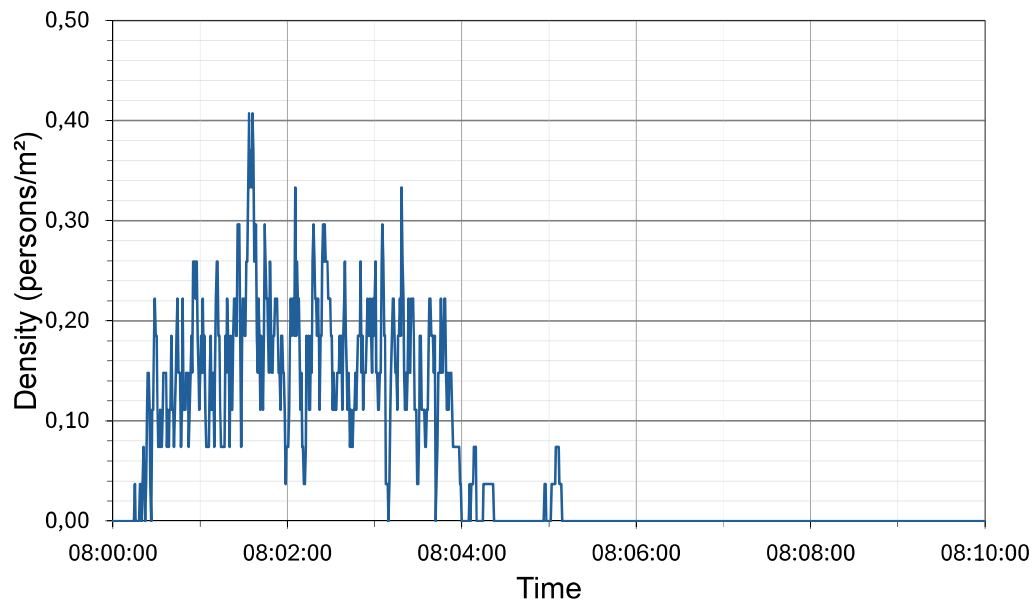


Figure 68 – Space Density Corridor 3

In the platforms, near the escalator 3, the Space Density had higher results, 0.39 persons/square metre, and the Averaged Entity Density registered a higher value, 1.80 persons/square metre, comparing to the BS. The zone near the stairs 3 in the platforms showed values closer to the BS, but the Averaged Entity Density appeared to be lower, with a maximum value of 0.53 persons/square metre.

Through the maps, it is possible to visualise the main difference in this scenario from the BS, mainly in the density in the corridor 1, a comparison of maps of cumulative mean density, in Figure 69, can show the disparities of both scenarios, in the minute 4.

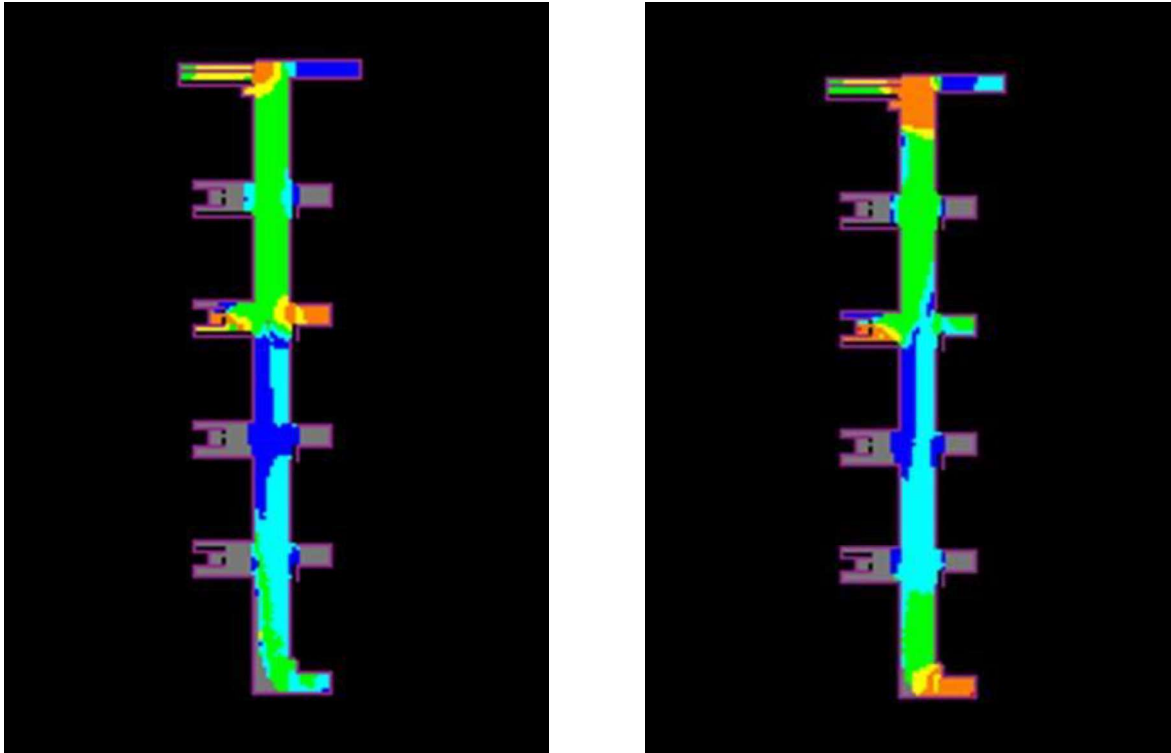


Figure 69 – Cumulative Mean Density minute 4, BS (left) and Scenario V (right)

4.5.1.6. SCENARIO VI

In scenario VI, some entities start to enter the model through metro 1, so that parameter must be analysed.

In the exit zone of Train 5, the speed values are generally higher and for a longer period of time, it shows that there are always entities inside the zone, either for arrival or departure.

In the exit zone on the Train 4, the highest space density registered is 0.25 persons/square metre, this corresponds to the arrival of the train itself. The fastest movement was done at 1.8 m/s, around minute 04:00 of the simulation.

In the platforms, was observed a variation from the BS density in the stairs nearby, it is possible to see a considerable increase in the averaged entity density of space close to the stairs, 0.95 persons/square metre.

The corridor 1 had some variations, but mainly in the speed, although the higher speed was near 1.5 m/s, the other values seem to be quite low comparing to the BS. The Space Density reached a maximum value of 1.90 persons/square metre, Figure 70, almost all values are above the 0.8 persons/square metre. In the Averaged Entity Density, the values were very high, almost all above 1 persons/square metre, Figure 71.

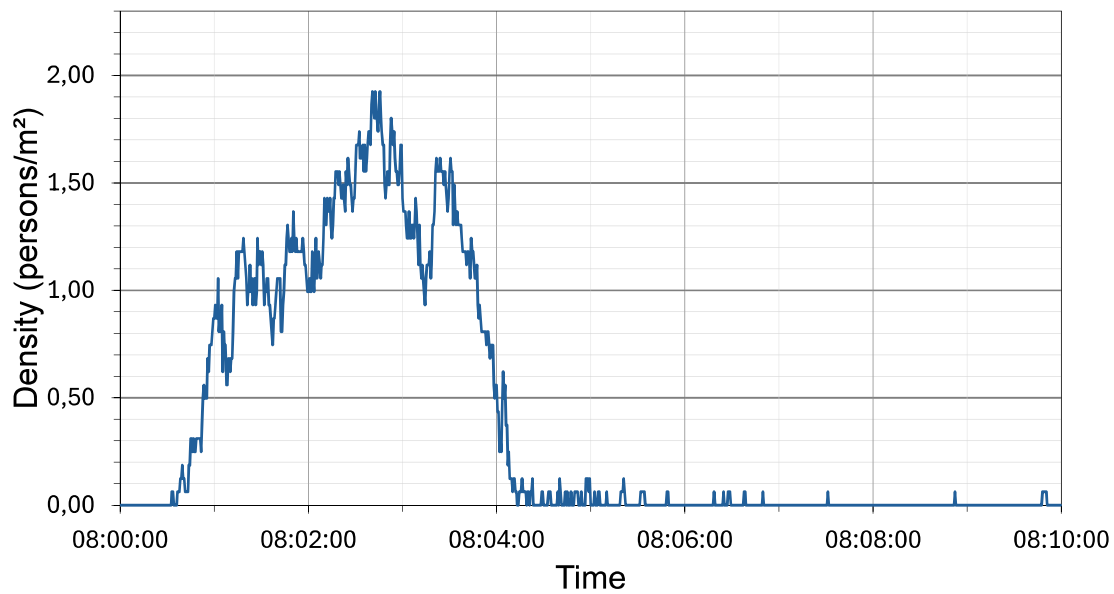


Figure 70 – Space Density Corridor 1

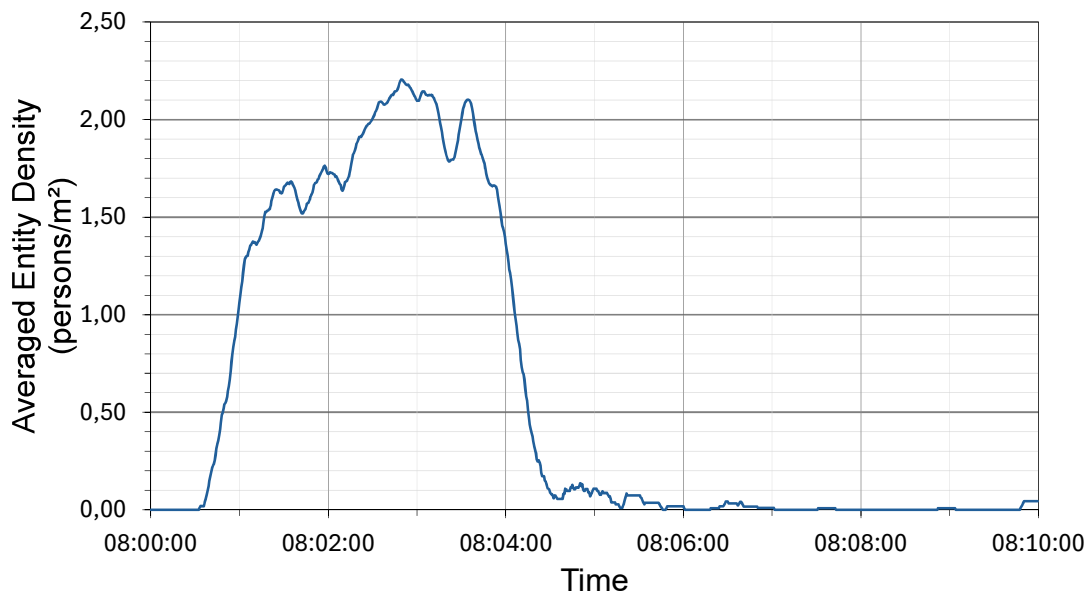


Figure 71 – Averaged Entity Density Corridor 1

Regarding the corridor 3, it held 14 entities sharing that space in the minute 01:39. The Space Density revealed a very low peak value, 0.52 persons/square metre.

Finally, the influence of the metro supply led to a maximum Space Density of 0.57 persons/square metre, Figure 72, right in the metro platform, in the time of arrival the Speed practised was around 1.4 m/s. In the case of the Averaged Entity Density, the highest value is also in that period, with 0.62 persons/square metre.

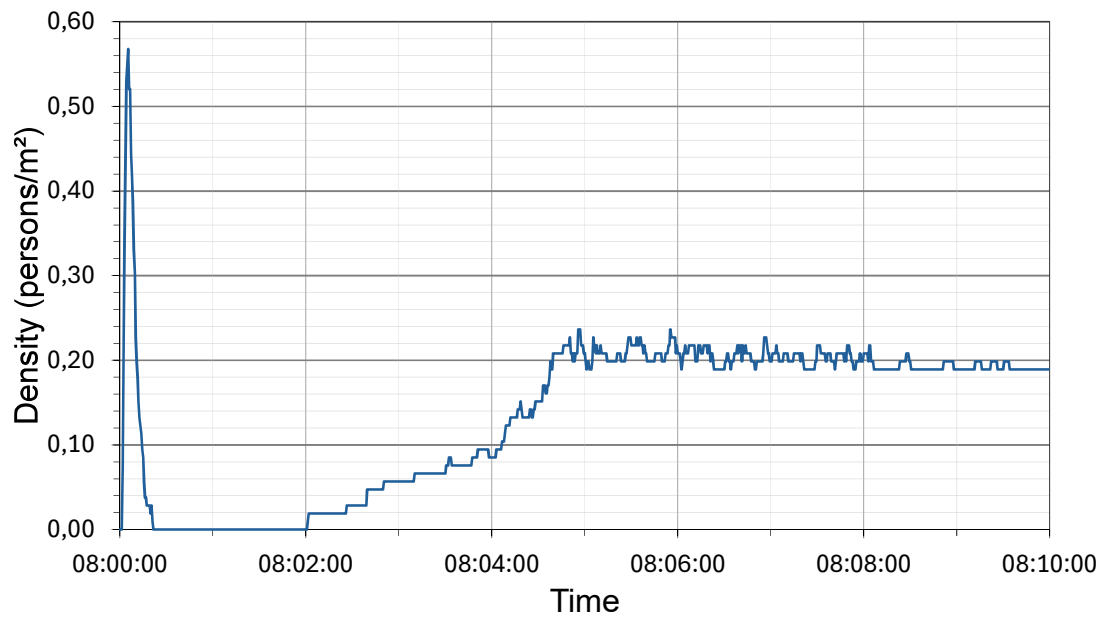


Figure 72 – Space Density Metro

In the map presented in Figure 73 it is possible to see the Average Speed in the Metro Station 1 minute after the arrival of the Metro 1.

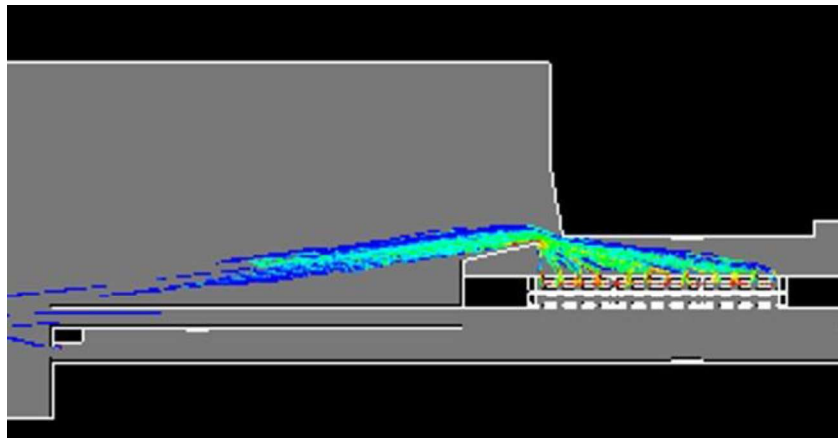


Figure 73 – Average Speed in minute 1

This input only decreased a little the LoS in the end of the Simulation, which can be seen in Figure 74.

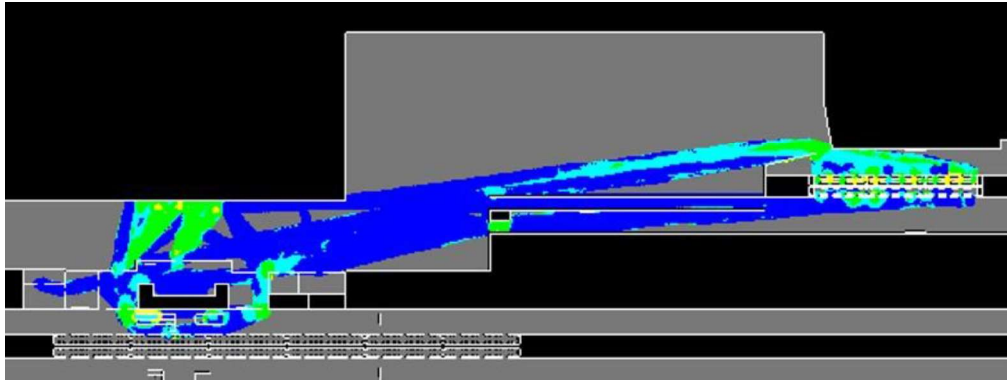


Figure 74 – Cumulative Mean Density, minute 10

4.5.1.7. SCENARIO VII

The last scenario represents the arrival of entities through all modes of transportation, in this case with the addition of the bus, and also through the entrances of the streets.

In the corridor 3, the maximum Space Density detected was 0.37 persons/square metre, similar to the rate presented in the BS. The Speeds reached were all high, the majority above 1m/s.

The number of entities in the corridor 1 got to 40, by the minute 02:32, by this period of time, the maximum Space Density reached values higher than 2.4 persons/square metre (Figure 75), and the speed became very low, less than 0.5 m/s, the Averaged Entity Density increased to its highest value of 2.3 persons/square metre.

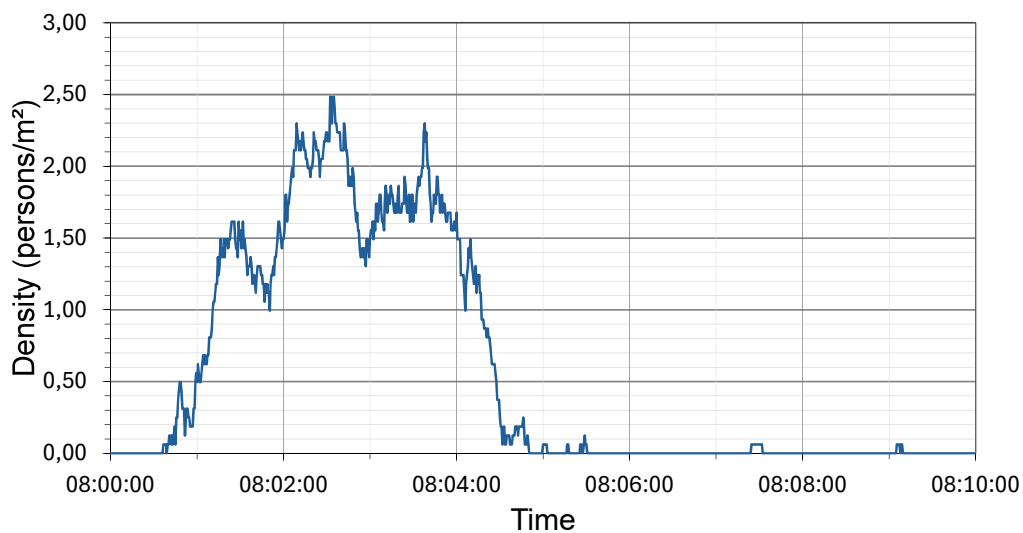


Figure 75 – Space Density Corridor 1

In the platform, closer to the escalator 3, the maximum value registered for the Space Density was 0.26 persons/square metre.

Next, evaluating the results about the analysis zone outside the train 4, the Space Density had a smaller value than in the BS, 0.27 persons/square metre.

In train 5, the Entity Density reached its maximum value right after the opening of the doors of the train, with 0.39 persons/square metre, lower value comparing to the BS. Also, the maximum perception of density by the entities showed to be smaller, 0.57 persons/square metre.

The corridor 3 did show major variations from the BS.

The metro arrival zone registered a high speed of 1.9m/s, in its maximum. The highest value for the Averaged Entity Density was around 0.47 persons/square metre.

With the addition of the Bus 1, the values next to it and affected by it must be analysed. The Space Density, right in front of the bus, reproduced good results, with maximum of 0.42 persons/square metre, Figure 76, it happened very close to the end of the simulation, when the demand from other vehicles arrived at the platform. The Speed in average is higher than 1m/s during the presence of entities and the fastest value showed was 1.9m/s. The Averaged Entity Density reached its maximum among the Space Density, with the value of 0.39 persons/square metre.

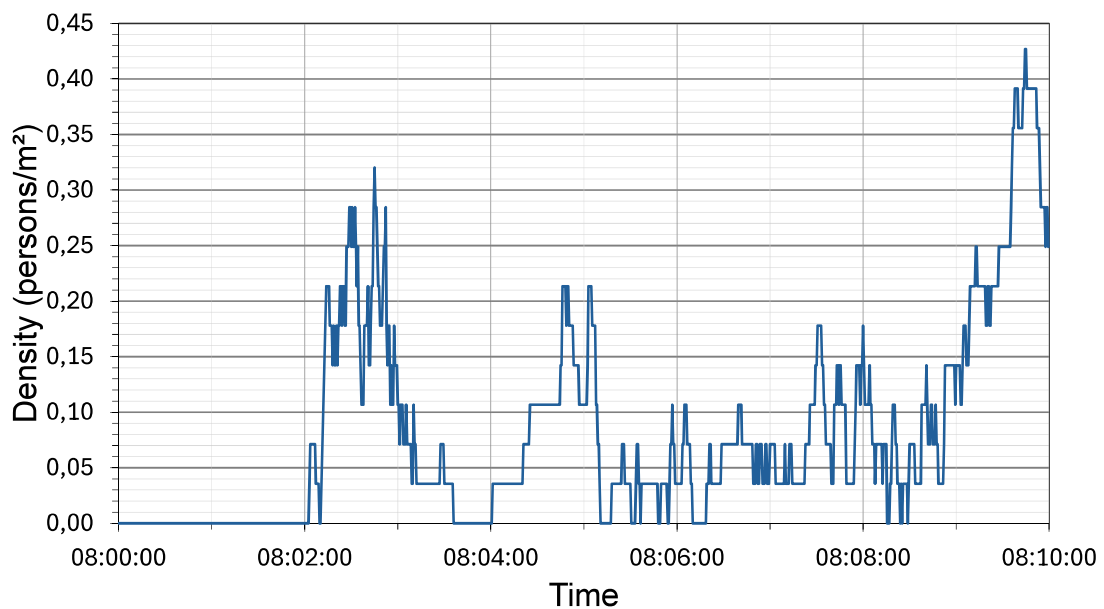


Figure 76 – Space Density Bus 1

In the end of the simulation, it is possible to visualise that the zone with more space utilisation is the corridor 1, Figure 77, highlighted with a lighter blue colour.

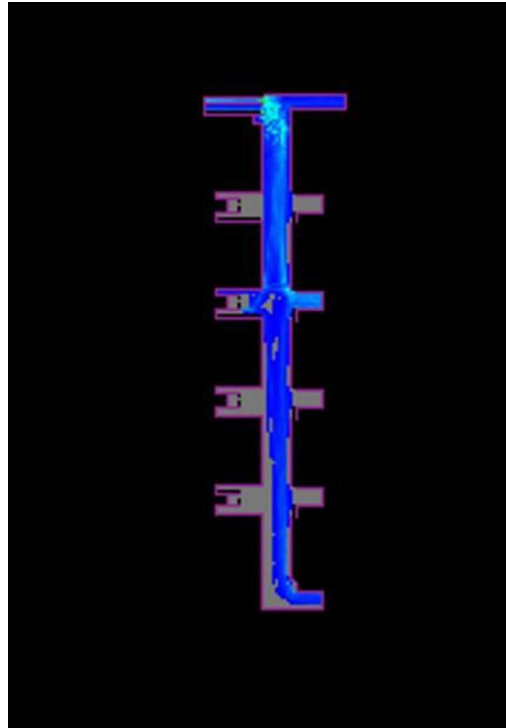


Figure 77 – Space Utilisation Corridor

It is also possible to conclude that in this scenario the majority of spaces the LoS was equal or lower to C, Figure 78 and Figure 79, except in some stairs, escalators and in corridor 1.

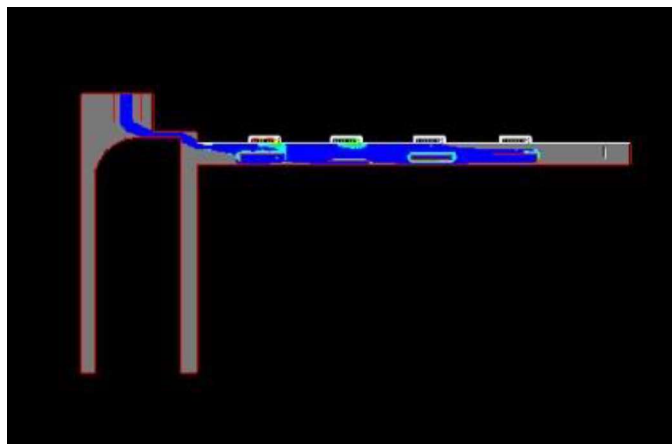


Figure 78 – Cumulative Mean Density

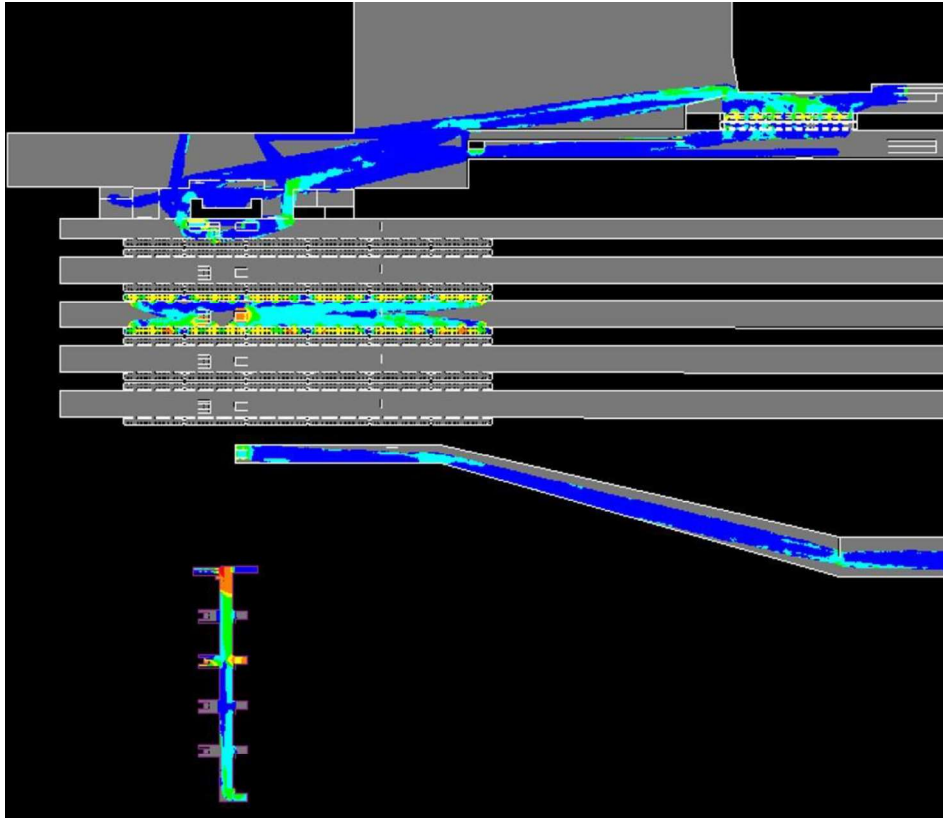


Figure 79 – Cumulative Mean Density

4.5.1.8. QUEUES

Throughout the simulation of the various scenarios, the queues were an area that always caused some congestion and interrupted the entities' flow, the queue that generated most problems was the metro ticket office. Some examples that show its influence can be seen in Figure 80 and Figure 81.

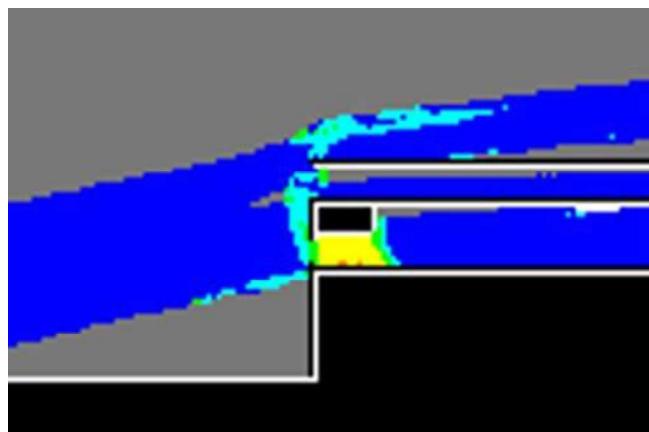


Figure 80 – Cumulative Mean Density, Scenario 4

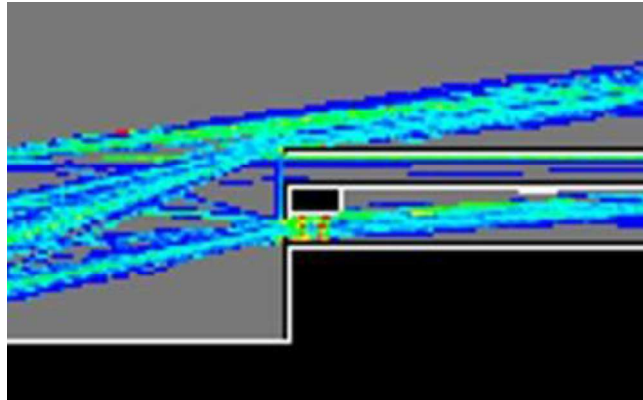


Figure 81 – Average Speed, Scenario 4

4.6. DISCUSSION OF THE RESULTS

Comparing the outputs between the Base Scenario and Scenario I, it can be inferred that the removal of the lift did not exert a significant impact on the network. Conversely, the presence of the lift marginally exacerbated the congestion in Corridor 3, possibly due to variations in route patterns adopted by entities utilizing it.

The staggered arrival of two modes of transport at the same platform has proved remarkably effective, resulting in an improvement in the quality of service. Alternatively, optimising the distribution of arrivals over longer distances could also serve to improve the quality of service.

In this last scenario the results highlight the low influence that the bus had on the network. In this case the values did not change a lot from the BS, attributed to the considerable distances separating the bus from other origins and destinations, preventing entity collisions.

The maps showed that the Corridor 1 was the zone most used by the entities, which derives from the paths chosen by the entities and the Origin and Destination set for each one.

Overall, all maps showed similar distributions, but adjusted to the content they represented according to the different scenarios.

5

CONCLUSION

5.1. GENERAL CONCLUSIONS

This dissertation seeks to attend the ambitions described in 1.2, also contemplated along the document content.

The collection of the historical background of transportation is crucial to understand how the problems were solved along the time and the reasons that led to the creation and development of the transports into the nowadays form. It is perceptible that the introduction of the wheel, the creation of the motor or the construction of a large road network shape the today's society functioning.

The identification of the theoretical models is mandatory to elaborate an approach to analyse a system of transportation. This combined with the choice of the most suitable software provides a more cohesive and adjusted analysis. In this particular case the work of investigation of Fruin, related to pedestrian analysis, was an excellent component to carry out the study of the Intermodal Terminal.

The transportation planning process, involving problem definition, modelling and simulation, plays a crucial role in communities by aiding decision-making and problem-solving. Through data-driven analysis, planners can anticipate future trends and evaluate strategies, ensuring transportation infrastructure meets evolving needs while maximizing benefits for all.

5.2. SPECIFIC CONCLUSIONS

The summary of each software's capabilities in Table 5 proved highly beneficial for comprehending the range of products available in the market. It also facilitated an easy evaluation to determine which software was best suited for addressing specific transportation problems.

In the analysis of the Intermodal Terminal the characterisation of a Base Scenario, as a comparison scenario, allowed a better relationship between the space and supply changes and the entity's behaviour.

The temporal proximity of the supply had a notable effect on both the results and the flow of entities. Furthermore, the origin of the supply significantly influenced the outputs. This emphasizes the importance of considering the potential distribution of various supplies in conjunction with the available routes for entities when planning infrastructure such as the Intermodal Terminal.

LEGION proved to be an extremely valuable software, effectively fulfilling the objectives outlined for the case study. Its ability to visualise the movements of entities and generate information maps greatly facilitates the interpretation and visual understanding of the results. Furthermore, this feature simplifies comparisons with standardised values, such as those proposed by Fruin.

The software information is not always of easy access online. For those who do not subscribe the software license it can be difficult to understand and reach the capabilities and the theoretical formulations of the software, as well as the outputs and the costs.

The modelling in a software is very useful and helpful for the study analysis, however it still requires a lot of time spending, either for the learning process or for its implementation and output gathering. In this specific case, it demanded at least 80 hours of software learning and at least 200 hours of modelling and output generating.

The computational nature of the software adds numerical obstacles, sometimes without obvious solutions. Bentley Support Team provided valuable support on these adversities.

5.3. FURTHER DEVELOPMENT

This work accomplished its aiming, yet it left some possible further developments opened, to complement and continue the started approach, for example:

- Explore software compatibilization tools in a way that a multidisciplinary case study is attended on multiple dimensions at the same time;

For LEGION Intermodal Terminal simulation:

- Test a scenario with bigger simulation time;
- Increase and redistribute the supply;
- Study of evacuation emergency;
- Create a scenario for reduced mobility people;
- Change the layout dimensions, for example the corridor width and length;
- Addition or reduction of the lifts, stairs and escalators;
- Explore the compatibility of Aimsun;
- Addition of different supply, such as taxi;
- Evaluate other output parameters;
- Study the impact of different supply and its distribution.

REFERENCES

- Bachmeier, Q. (2022). *Generating Activity-Based Mobility Plans From Trip-Based Models And Mobility Surveys*. Applied Sciences, 2022-08-24, Pg. 386-403, Mdpi, Taiwan, Roc.
- Albano, J. F. (2016). *Evolução Das Vias: Uma Visão Geral*. Masters Dissertation, Universidade Federal De Rio Grande Do Sul, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Alkaissi, Z.. *Route Assignment. Masters Dissertation*, A Comparison Between Dynameq And Indy, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Baran, R., Legey, L. F. L. (2011). *Veículos Elétricos: História E Perspectivas No Brasil*. Bndes Sectorial, 2011-03-01, Pg. 207-224, Bndes, Rio De Janeiro.
- Bentley Systems (2021). *Discover Cube Tutorial*. Department Of Civil Engineering, University Of Minnesota.
- Berrou, J. L., Beecham, J., Quaglia, P., Kagarlis, M. A., Gerodimos, A. (2005). *Calibration And Validation Of The Legion Simulation Model Using Empirical Data*. Pedestrian And Evacuation Dynamics, 2011-03-01, Pg. 167-181, Bndes, Berlin.
- Camillo, E. (2013). *A Brief History Of The Evolution Of Transportation Over Time*. Masters Dissertation, Centro Studi Subalpino, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Casas, J., Aymami, J. M., Breen, M., Perarnau, J., Delgado, M. (2016). *Quasi-Dynamic Model In Aimsun. Comparison To Static And Dynamic Models*. Cit2016 – Xii Congreso De Ingeniería Del Transporte, January 12, 2014, Valencia, Universitat Politècnica De Valencia, Pg. 92-122, Procedia Computer Science.
- Cheng, Y., Chen, S. (2015). *Perceived Accessibility, Mobility, And Connectivity Of Public Transportation Systems*. Transportation Research Part A, 2015-05-27, Pg. 386-403, Crossmark, Taiwan, Roc.
- Costa, Á. (2019). *Transport Networks*. Masters Dissertation, Universidade Federal De Santa Catarina, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Crainic, T. G., Kim, K. H. (2007). *Chapter 8. In Intermodal Transportation*, Pg. 468-537, C. Barnhart And G. Laporte.
- D. Knowles, R. (2006). *Transport Shaping Space: Diverential Collapse In Time–Space*. Journal Of Transport Geography 14, 2011-03-01, 407–425, Bndes, Manchester, Uk.
- Erdmann, J. (2015). *Sumo'S Lane-Changing Model*. Modeling Mobility With Open Data, 2011-03-01, 105-123, Crossmark, Manchester, Uk.
- Floriani, E. G. (2017). *Análise De Propostas Para Melhoria Do Tráfego De Uma Região Central Utilizando O Software De Simulação Sumo*. Masters Dissertation, Universidade Federal De Santa Catarina, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Fruin, J. (1971) *pedestrian planning and design*. ELEVATOR WORLD, INC., Alabama.
- Gakenheimer, R. (1999). *Urban Mobility In The Developing World*. Transportation Research Part A 33, Pg. 468-537, Pg. 671-689, Pergamon, Cambridge, Usa.
- Gliebe, J., Bergman, A. (2011). *Case Study Evaluation Of Dynamic Traffic Assignment Tools*. Oregon Department Of Transportation Transportation Planning Analysis Unit, 2011-03-01, Pp. 12–25, Bndes, Salem, Oregon.

- Gomes, G. (2015). *Análise Comparativa Das Características De Tráfego Calculadas Pelo Hcm-2010 E Pelo Microsimulador Aimsun Para Uma Área De Estudo Em Santa Catarina*. Masters Dissertation, Universidade Federal De Santa Catarina, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Gomes, G., May, A., Horowitz, R. (2003). *A Microsimulation Model Of A Congested Freeway Using Vissim*. 2004 Conference Of The Transportation Research Board In Washington D.C., November 15Th, 2003, Washington, Dc, Usa, Crossmark, Manchester, Uk.
- Gonçalves, L. A. P. J. (2016). *Modelação De Uma Rede De Transporte Individual. Estudo De Caso Guimarães*. Masters Dissertation, Universidade Do Minho, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Helbing, D., Molnar, P. (1998). *Social Force Model For Pedestrian Dynamics*. Physical Review A, Atomic, Molecular, And Optical Physics, 1998-05-01, Pg. 386-403, Mdpi, Taiwan, Roc.
- Hugo Silveira, P. (2021). *Appropriation, Integration, And Nation Building: Portuguese Railways In The Second Half Of The Nineteenth And Early Years Of The Twentieth Century*. Social Science History 45.2, 2011-03-01, 391-416, Bndes, Manchester, Uk.
- Jariwala, J., Gujar, R. (2020). *Development Of Red Light Violation Detection System For Heterogeneous Traffic*. Recent Advances In Traffic Engineering, 2011-03-01, 139-149, Crossmark, Manchester, Uk.
- Krajzewicz, D., Heldt, B., Nieland, S., Cyganski, R., Gade, K. (2019). *Guidance For Transport Modelling And Data Collection*. Sustainable Urban Mobility And Commuting In Baltic Cities, 2011-03-01, Pg. 207-224, Bndes, Berlin.
- Krajzewicz, D., Rossel, C.. *Sumo (Simulation Of Urban Mobility) - An Open-Source Traffic Simulation*. Department Of Civil Engineering, University Of Minnesota.
- Kuhne, R. D. (2014). *Foundations Of Traffic Flow Theory I: Greenshields' Legacy – Highway Traffic*. Masters Dissertation, German Aerospace Center, Transportation Studies, Berlin, Germany, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Ling Suen, S., G.B. Mitchell, C. (2000). *Accessible Transportation And Mobility*. Transportation In The New Millennium, Pg. 468-537, Pg. 1-8, Trb.
- Mai, M., Wangb, L., Prokop, G. (2017). *Advancement Of The Car Following Model Of Wiedemann On Lower Velocity Ranges For Urban Traffic Simulation*. Transportation Research Part F, 2011-03-01, 391-416, Crossmark, Manchester, Uk.
- Makridis, M., Mattas, K., Mogno, C., Ciuffo, B., Fontaras, G. (2020). *The Impact Of Automation And Connectivity On Traffic Flow And Co2 Emissions*. A Detailed Microsimulation Study. Atmospheric Environment, 2011-03-01, 105-123, Crossmark, Manchester, Uk.
- McNally, M. G.. *The Four Step Model*. In *Handbook Of Transport Modeling*, Pg. 468-537, Pergamon.
- Mora, P., Vianna, F.. *Guia Ptv Vissim*. Ninth International Space Syntax Symposium, 2011-03-01, 391-416, Bndes, Manchester, Uk.
- Narvaez, L., Penn, A., Griffiths, S. (2013). *Spatial Configuration And Bid Rent Theory: How Urban Space Shapes The Urban Economy*. Ninth International Space Syntax Symposium, 2011-03-01, 391-416, Bndes, Manchester, Uk.
- Neves, G. R., Galhardi, A. C. (2017). *Uma Abordagem Teórica Do Simulador Aimsun Aplicado Na Emissão De Co2*. Xxxvii Encontro Nacional De Engenharia De Producao, 13 De Outubro De 2017, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.

- Oliveira, J. L. D. (2014). *Verificação Da Qualidade Da Representação Do Tráfego No Simulador Aimsun A Partir De Metodologia De Calibração*. Masters Dissertation, Faculdade De Tecnologia E Ciências Sociais Aplicadas - Fatecs, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Oliveira, V. M. D.. *Passo A Passo Inicial Para O Começo Rápido Da Utilização Do Software Ptv Visum*. Masters Dissertation, Universidade Mackenzie, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Ozbay, K., Yang, H., Morgul, E. F., Mudigonda, S., Bartin, B. (2014). *Big Data And The Calibration And Validation Of Traffic Simulation Models*. Traffic And Transportation Simulation, January 12, 2014, Washington, Dc, Usa, Pg. 92-122, Procedia Computer Science.
- Qiao, F., Liu, T., Sun, H., Guo, L., Chen, Y. (2021). *Modelling And Simulation Of Urban Traffic Systems : Present And Future*. International Journal Of Cybernetics And Cyber-Physical Systems, 2011-03-01, Pg. 1-32, Bndes, Berlin.
- Rajashekara, K. (1994). *History Of Electric Vehicles In General Motors*. Ieee Transactions On Industry Applications, 2011-03-01, 407–425, Bndes, Manchester, Uk.
- Ronaldo, A., Ismail, T. (2012). *Comparison Of The Two Micro-Simulation Software Aimsun & Sumo For Highway Traffic Modelling*. Atmospheric Environment, 2011-03-01, 105-123, Crossmark, Manchester, Uk.
- Rossi, C., Chondros, T. G., Milidonis, K. F., Savino, S., Russo, F. (2016). *Ancient Road Transport Devices: Developments From The Bronze Age To The Roman Empire*. Front. Mech. Eng., Spring 2015, Pp. 12–25, Bndes, Berlin.
- Saw, K., Katti, B. K., Joshi, G. (2015). *Literature Review Of Traffic Assignment: Static And Dynamic*. International Journal Of Transportation Engineering, Spring 2015, Pp. 339-347, Bndes, Berlin.
- Schweizer, J. (2014). *Sumopy: An Advanced Simulation Suite For Sumo*. First International Conference, Sumo 2013, 2011-03-01, 71–82, Crossmark, Manchester, Uk.
- Snelder, M. (2009). *A Comparison Between Dynameq And Indy*. Masters Dissertation, A Comparison Between Dynameq And Indy, Joinville, Sc, Brasil, Pg. 92-122, Procedia Computer Science.
- Systems, B. *Create the Station case study Data Template*.
- Systems, B. *Introduction to LEGION software and Workflow (Create, Simulate and Analyse your First model)*.
- Systems, B. *LEGION Analyser*.
- Systems, B. *LEGION Model Builder*.
- Systems, B. *Pedestrianise a CAD file*.
- Systems, B. *Understand Entity movements*.
- Tchappi Haman, I., Galland, S., Kamgang, J. C. (2017). *Towards An Multilevel Agent-Based Model For Traffic Simulation*. 6Th International Workshop On Agent-Based Mobility, Traffic And Transportation Models, Methodologies And Applications (Abmtrans'17), May 2017, Washington, Dc, Usa, Pg. 887-892, Procedia Computer Science.
- Xiao, H., Ambadipudi, R., Hourdakis, J., Michalopoulos, P. (2005). *Methodology For Selecting Microscopic Simulators: Comparative Evaluation Of Aimsun And Vissim*. Department Of Civil Engineering, University Of Minnesota.

Yu, L., Yue, P., Teng, H. (2003). *A Comparative Study Of Emme/2 And Qrsii For Modeling A Small Community*. 82Nd Annual Meeting Of The Transportation Research Board, January 2003, Washington, Dc, Usa, Crossmark, Manchester, Uk.

Zsifkovits, M., Pham, T. S. (2017). *Modelling And Parameterizing Pedestrian Behaviour In Public Places: A Review*. International Journal Of Simulation Modelling, Spring 2015, Pp. 630-643, Bndes, Berlin.

- [1] <https://www.marineinsight.com/maritime-history/when-were-boats-invented/>. 2023-10-10.
- [2] <https://www.hmy.com/a-timeline-of-ships-boats-and-yachts/>. 2023-10-19.
- [3] <https://www.britannica.com/event/Industrial-Revolution>. 2023-10-19.
- [4] <https://aoghs.org/transportation/benz-patents-first-car/>. 2023-10-28.
- [5] <https://intrans.iastate.edu/news/trains-a-history/>. 2023-11-16.
- [6] <https://magazine.wsu.edu/web-extra/traffic-signals-a-brief-history/>. 2023-11-16.
- [7] <https://simpleflying.com/the-evolution-of-the-airplane/>. 2023-11-20.
- [8] <https://www.britannica.com/topic/Shinkansen>. 2023-12-05.
- [9] <https://www.cruisenation.com/blog/cruise-lines/a-history-of-cruise-ships-from-past-to-present/>. 2023-12-06.
- [10] <https://londonist.com/london/history/here-s-what-the-world-s-first-traffic-lights-in-westminster-looked-like>. 2023-12-09.
- [11] <https://fh777.org/index-133.html>. 2023-12-17.
- [12] https://tfresource.org/topics/00_Table_Contents.html. 2023-12-17.
- [13] https://png.toolbox.com/pikp?p=hJxwiox_4-step-model-for-traffic-assignment-4-step/. 2023-12-17.
- [14] <https://www.townandcountryplanninginfo.com/2020/08/land-use-and-land-value-theory-of.html>. 2024-01-04.
- [15] <https://company.ptvgroup.com/nl/resources/pers/laatste-nieuws/ptv-group-celebrates-30th-anniversary-of-the-ptv-vissim-traffic-simulation-software>. 2024-01-06.
- [16] <https://sumo.dlr.de/docs/index.html>. 2024-01-06.
- [17] <https://sumo.dlr.de/docs/Tutorials/CityMobil.html>. 2024-01-19.
- [18] https://www.youtube.com/watch?v=t5deCVvei-k&ab_channel=PTVMobility. 2024-01-28.
- [19] <https://www.aimsun.com/>. 2024-01-28.
- [20] <https://docs.aimsun.com/next/22.0.2/UsersManual/AdvancedAimsun3D.html>. 2024-02-02.
- [21] <https://docs.aimsun.com/next/23.0.0/UsersManual/SRCAndDUE.html>. 2024-02-03.
- [22] <https://docs.aimsun.com/next/23.0.0/UsersManual/MapOutputs.html>. 2024-02-04.
- [23] <https://www.transportmodelling.com.au/services/mesoscopic-modelling>. 2024-02-04.
- [24] <https://diyhomeschooler.com/the-steam-locomotive-a-mini-unit/>. 25-01-2024.

- [25] <https://londonist.com/london/history/here-s-what-the-world-s-first-traffic-lights-in-westminster-looked-like>. 13-12-2023.
- [26] <https://www.nicepng.com/maxp/u2q8u2u2o0t4q8q8/>. 12-12-2023.
- [27] <https://kids.britannica.com/students/article/roads-and-streets/276743>. 20-12-2023.
- [28] <https://fh777.org/index-133.html>. 16-10-2023.
- [29] https://tfresource.org/topics/Activity_based_models.html. 21-11- 2023.
- [30] <https://www.thoughtco.com/history-of-transportation-4067885>. 09-01-2024.

