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Operational classification of urban roads for the development of intelligent traffic management schemes

Tesis que para obtener el grado de

Maestro en Infraestructura del Transporte en la Rama de las Vías Terrestres

presenta:

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Abstract

The main problems of large cities are associated to road congestion. The congestion is caused by multiple factors as lack planning and a deficient traffic management. This deficiency is encouraged by the absence of a criteria to hierarchize the operability of roads, especially in areas where the urban layout inhibits the complete connectivity. Most traffic management schemes are based on a hierarchy of movements that considers three main systems: arterial roads, collectors and local streets. However, due to the topology of a city, and other constraints, such schemes can not always be applied. This work presents an operational classification based on the definition of a road resistivity factor, computed from the speed and density observed in each segment of an urban network. To compute each resistivity value, a fuzzy inference system is proposed in which the macroscopic variables (speed and density), measured on road, are related by the reasoning of "the higher density and the lower speed, the greater resistance". Based on the paradigm of Parallel Transportation Management, the input variables for the inference system are calibrated through in-situ studies of traffic volumes and microscopic simulation. To validate the feasibility of the proposal, a microscopic simulation model was developed to reproduce the real behavior of a road subsystem located in the city of Morelia, Michoacán. From the simulation development, it was determined that the resistivity of the roads represents a new mesoscopic characteristic that describe the disturbances at each segment that consumes speed. Finally, an operational classification is proposed by establishing the resistivity factor of each segment of the road network.
Key words: *Operational classification, roads resistivity factor, parallel traffic management, Kirchhoff's laws*

Resumen

Los principales problemas de las grandes ciudades están asociados a la congestión vial. La congestión es causada por múltiples factores como la falta de planificación y una deficiente gestión del tránsito. Esta deficiencia es alentada por la ausencia de un criterio para jerarquizar la operabilidad de las vialidades, especialmente en áreas donde el trazo urbano inhibe la conectividad completa. La mayoría de los esquemas de gestión del tránsito se basan en una jerarquía de movimientos que considera tres sistemas principales: vialidades arteriales, colectoras y calles locales. Sin embargo, debido a la topología de una ciudad y otras limitaciones, dichos esquemas no siempre son aplicables. Este trabajo presenta una clasificación operacional basada en la definición de un factor de resistividad vial, calculado a partir de la velocidad y la densidad observada en cada segmento de una red urbana. Para calcular cada valor de resistividad, se propone un sistema de inferencia difusa en el que las variables macroscópicas (velocidad y densidad), medidas en la vialidad, se relacionan por el razonamiento de "a mayor densidad y a menor rapidez, existe una mayor resistencia". Basado en el paradigma de Gestión Paralela del Tránsito, las variables de entrada para el sistema de inferencia se calibran a través de estudios in-situ de volúmenes de tránsito y simulación microscópica. Para validar la factibilidad de la propuesta, se desarrolló un modelo de simulación microscópica que reproduce el comportamiento real de un subsistema vial ubicado en la ciudad de Morelia, Michoacán. A partir del desarrollo de la simulación, se determinó que la resistividad de las vialidades representa una nueva característica mesoscópica que describe las perturbaciones que consumen velocidad en cada segmento. Finalmente, se propone una clasificación operacional estableciendo el factor de resistividad de cada segmento de la red vial.

Palabras clave:*Clasificación operacional, factor de resistividad vial, gestión paralela del tránsito, leyes de Kirchhoff*

Contents

Chapter 1

Introduction

Medium and large Mexican cities (more than 700,000 inhabitants), presents an accelerated grow (between 5 and 7.8 times from 1980 to 2010), while their population densities have drastically decreased (until 67%) [OH15]. Due to the lack of a sustainable planning, the population dispersion has motivated the increase of the vehicle-based transportation. Just between 2000 and 2012, the motorization rate, for particular vehicles, was of 7.4%, which surpassing five times of the national population [dDS12]. These factors are the main precursors of the traffic jams and, consequently, of pollution and excessive expenses of time and money (more than 22% of daily income). It is estimated that by 2050 more than 70 % of the population will live in cities, so public and private transport will represent the main problems of cities, since their organization is directly related to the welfare and economy of the population [OH15]. In addition to the excessive increase of the vehicle fleet, traffic jams are produced by deficient management schemes, which impede the traffic flow and cause an occupancy increase.

Up to date, most of the traffic management schemes are supported by the functional classification of roads that compose an urban network. This classification is based on the characterization of each road according to their service levels, their accessibility, and a hierarchy of movements and components [Adm74, oSHO11, RCyM07]. This classification suggest that within a city there are identified three kind of roads : arterial, collector and local. Thereby, it is established how the traffic must be distributed along a city and the traffic regulator devices that must be considered for each case. The functional classification, however, does not include a criteria to evaluate the performance of the network and its elements, once the system is on operation. In addition, due to the constant generation of new trips attractors, that were not considered in the original planning of the city, it is difficult to directly apply this classification.

There are some exogenous and endogenous variables (socioeconomic activities, presence of multimodal transport, geometry of roads, etc.), which can be used to qualitatively diagnose a road system. However, due to the complexity of each city and the constant transformation in the use of each link, these variables are not useful for establishing traffic management schemes. Each element of a road system is associated with particular characteristics that represent different disturbances in mobility levels. Therefore, to make a coherent operational classification, an efficient traffic management system must consider such disturbances to prioritize the functionality of the elements of a road system.

In this work, it is proposed a functional classification which defines a resistivity factor to hierarchize the urban roads according to their operability. To obtain the resistivity factor of each road, a fuzzy inference system was developed that relates the macroscopic characteristics of density and speed through the reasoning: " the higher density and the lower speed, the greater resistance".

The input values for the FIS were obtained from the *in situ* data collection and through a microscopic simulation model that recreates the real conditions of a traffic system located in Morelia, Mexico. From the simulation development, each value for density and speed for individual segments were considered to determine each resistivity factor through the FIS. By establishing the resistivity factor of each segment an operational classification is proposed.

1.1 Objectives

1.1.1 The main objective

For this research work, the main objective is:

- To design and to develop an intelligent transportation system for the operational classification of roads, which allows to design intelligent traffic management schemes.

1.1.2 Specific objectives

- To characterize the current transport and infrastructure conditions in specific areas of an urban network.
- To determine the affluence in the elements of the urban network to identify centers of attraction and generation of trips.
- To determine the current use of the road for specific areas of an urban network, considering the traffic volume and the affluence.
- To classify the functionality of the roads from the volume of traffic and disturbances on the road to characterize in a scalar interval their performance.
- To analyze the influence of public transport on congestion problems to identify the degree of disturbance produced by the current logistic scheme.

1.2 Methodology

For this research, a methodology based on the prototype for the development of Intelligent Transport Systems for intelligent traffic management [GRLGSR17] is proposed. Based on this prototype, traffic behavior patterns will be determined by analyzing large volumes of data collected from multiple sources; what is known as crowd-sourcing. Mobility patterns were characterized by traffic volumes, traffic, indicators of origin and destination and the geometric characteristics of roads. The distribution of trips, for each element of the network, was determined by a nodal analysis based on the Kirchhoff law of currents, which allowed to recreate the road system conditions through a parallel traffic management approach [ZYC+13, ZLCX16]. Thus, the proposed methodology consider the following steps:

1. Crowd-sourcing. In this stage, a six-month traffic study was developed that considered vehicle counts retrieved by multiple sources such as video cameras, radars, automatic counters and manual collection. Also, Geo-statistical information from regional databases and GIS´s was consulted.

2. Information retrieval. From data obtained, through data mining techniques and knowledge representation, the main mobility patterns of the study case were identified.

3. Nodal analysis. With the traffic data and the identified patterns, an analysis was made in each node, based on the Kirchhoff´s current law to determine the flows in each element, as well as to establish the origin-destination trajectories.

4. Microscopic simulation. Using the SUMO simulator, a microscopic model simulation that reproduces the real behaviour of the study case was developed.

5. Fuzzy inference. Considering the performance parameters of the network, obtained from the simulation, an inference system based on fuzzy logic was developed. The Fuzzy Inference System (FIS) relates the macroscopic characteristics of density and speed to obtain a resistivity factor of each road.

6. Operational classification. By determining the resistivity factor of each road, an operational classification is proposed that qualify the performance of individual segments in a quantitative manner.

1.3 Document Organization

This document is organized as follows. Chapter 2 exposes the theoretical fundamentals of traffic engineering , microscopic traffic modeling, as well as some basic concepts of the electric circuit theory and fuzzy logic. In chapter 3 a review of most closely related work to the approach of the proposal is made. Chapter 4 details how the operational classification proposed is done. Finally, in chapter 5 conclusions and future work are presented.

Chapter 2

Background and definitions

2.1 Traffic engineering

Definition 1 Flow rate: *is the number of vehicles passing a reference point per unit of time, commonly expressed as vehicles per hour. In a single lane, the flow ratio, denoted by q, is defined as follows:*

$$q = \frac{N}{T_{int}}, \tag{2.1}$$

with N as the number of vehicles passing a reference point and T_{int}, as a time interval.

Due to the heterogeneous nature of traffic composition, the number of vehicles N are established in terms of Passenger Car Units.

Definition 2 Passenger Car Unit (PCU): *is a numerical factor associated to the impact that a mode of transport has on the traffic flow compared to a single standard passenger car.*

For convention, there are different PCU values according to the vehicle type e.g. motorcycle = 0.5, private car = 1 , bus = tractor = truck = 3.5 and so on.

Definition 3 Speed: *The average speed is the relationship between the distance traveled in a measuring section and the time taken to cover it completely, regularly* *expressed by kilometers per hour. Let l a distance where a vehicle speed does not change, and T_{int} is the time interval of the observation, the speed is computed by:*

$$v = \frac{l}{\delta t}, \tag{2.2}$$

Definition 4 Density: *is the number of vehicles over a stretch of roadway, commonly expressed as vehicle per kilometer. Let N be the number of vehicles occupying a roadway segment of length K, the vehicle density is computed by*

$$\rho = \frac{N}{K}. \tag{2.3}$$

Definition 5 Fundamental Relation of Traffic Flow: *density ρ, flow q and the average speed v can be related by:*

$$\rho = \frac{q}{v}. \tag{2.4}$$

From the fundamental relation, density describes the traffic flow demand on a stream and allows to empirically analyze the traffic behavior through three diagrams: *flow-density*, *speed-density*, and *speed-flow* (see Figures 2.1, 2.2, 2.3).

On the basis of the fundamental relation, Kerner [Ker14] analyzed the spatio-temporal behavior of traffic flow, focusing on three recurring patterns also called traffic phases: *free-flow*, *congested traffic* and *synchronized flow*.

Free-flow is usually observed, when the vehicle density in traffic is small enough. Thus, when density tends to zero vehicles can move with its maximum allowed speed. Otherwise, congested traffic phase describes when speed tends to zero and density grows until the flow is inhibited.

Synchronized flow is a continuous traffic flow, where vehicles move by the same average speed at the same space.

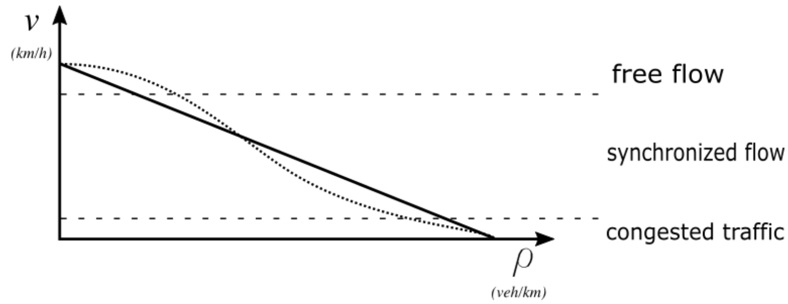


Figure 2.1: speed-density diagram

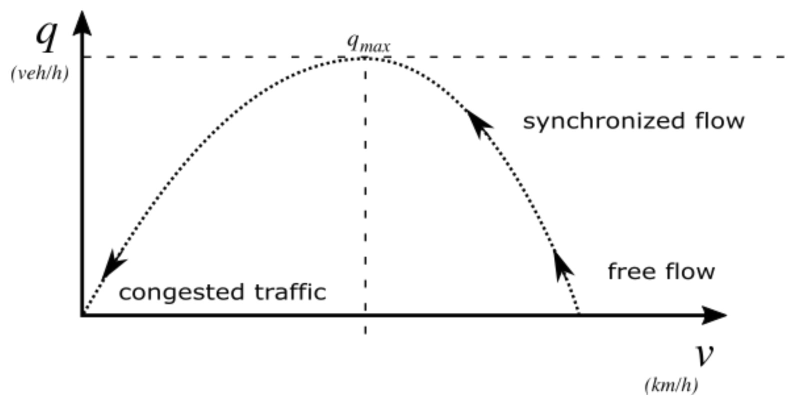


Figure 2.2: speed-flow diagram

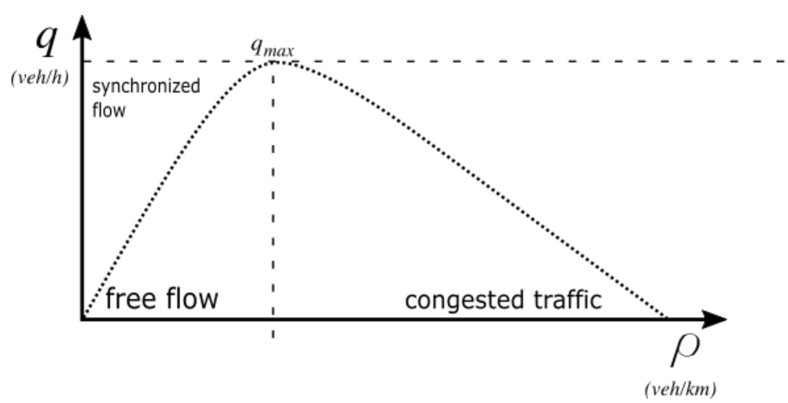


Figure 2.3: flow-density diagram

2.2 Microscopic traffic modelling

2.2.1 Modelling a vehicle

In the microscopic model the vehicles are modeled individually, considering the interaction between drivers and the individual behavior of each one. This type of model is very elaborate and its level of complexity is very high, because it is more similar to real behavior.

The variables that are considered in a microscopic traffic flow are:

- lenght, denoted by l_i
- longitudinal position:, denoted by x_i
- speed, denoted by $v_i = \frac{dx_i}{d_t}$
- acceleration, denoted by $a_i = \frac{dv_i}{dt} = \frac{d^2x_i}{dt^2}$

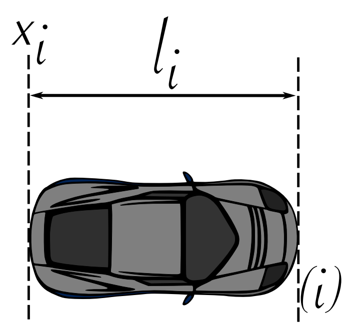


Figure 2.4: Individual characteristics of each vehicle

2.2.2 Car-following model

The base case is represented by two vehicles that circulate on the same road. (figure 2.5)

Where: (i) represents the follower vehicle and (i + 1) the leading vehicle.

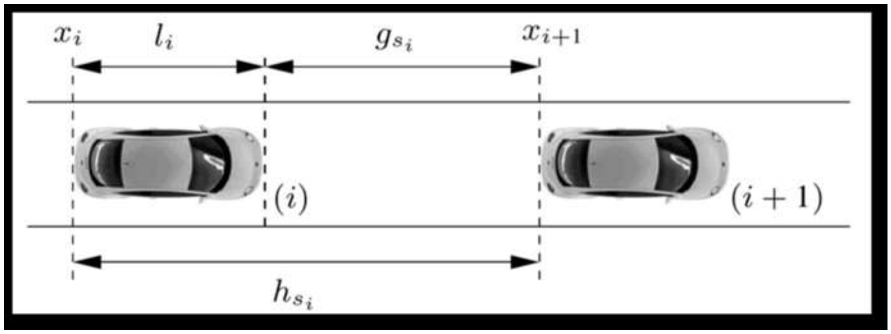


Figure 2.5: Base case of the car-following model

To analyze the traffic congestion, the base case is represented by a space-time diagram, it is considered that in a road the vehicles remain within the same lane following a FIFO order (first in-first out).(Figure 2.6)

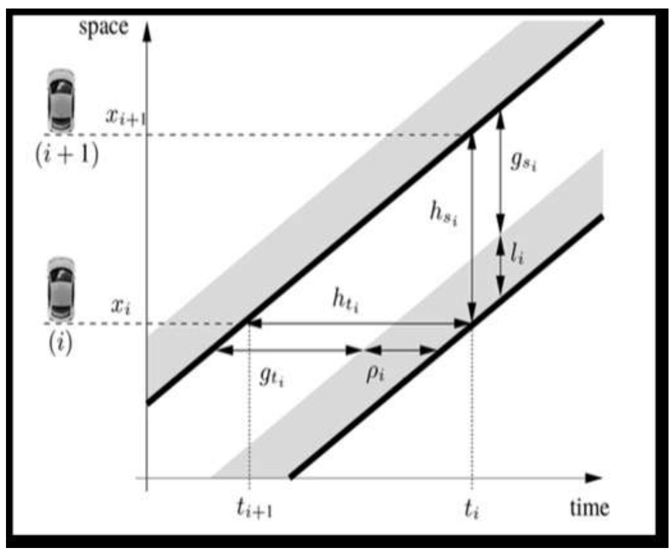


Figure 2.6: Space-time diagram

2.2.2.1 The Gipps model

Gipp´s model [Gip81] is a car-following model based on the safety condition derived from considering the braking distances of individual cars. It allows modeling the acceleration in a suitable way to avoid collisions. The interaction between vehicles, to avoid collisions, is described using the concept of maximum safety velocity V_{safe} defined by:

$$V_{safe}(gs, v_{i+1}) \tag{2.5}$$

This model is based on three assumptions:

1. Braking is always executed with a deceleration b and there is no difference between maximum deceleration and deceleration comfortable.
2. There is a reaction time Δtr.
3. The minimum space gap is always maintained, even when the leader stops completely.

To satisfy the first assumption, the braking distance for full braking is given by:

$$\Delta X_i + 1 = \frac{v_i^2 + 1}{2b} \tag{2.6}$$

In addition to the braking distance, each vehicle needs a reaction distance, so the stopping distance Δvt is given by:

$$\Delta X_i + 1 = \Delta vt + \frac{v_i^2 + 1}{2b} \tag{2.7}$$

The third condition is satisfied by the relationship 2.8, due to the difference $\Delta x_i - \Delta x_i + 1$ between the stopping and breaking distance.

$$gs \geq gs_0 + v\Delta t + \frac{v_i^2}{2b} - \frac{v_i^2 + 1}{2b} \tag{2.8}$$

In general, the simplified Gipp´s model is established by the equation 2.9.

$$v_i(t + \Delta t) = min[v_i + a\Delta t, v_0, v_{safe}(s, v_i + 1)] \tag{2.9}$$

In this model the reaction time is equal to a simulation step. The velocity of each vehicle is limited by the leading vehicle velocity or by the safety velocity, avoiding collisions. In this way, the Gipp´s model corresponds to a similar driving behaviour of an autonomous vehicle.

However, in the real world, the behavior of a human driver is influenced by different external factors such as reaction time, sensitivity to the context or the courtesy among drivers.

Krauß proposes a car-following model [Kra98], based on the same concept of the safety velocity, that discretizes the simulation time in such a way that the reaction time is equated to a simulation step.

For this work, the SUMO software [KEBB12] is used to develop microscopic traffic simulations. SUMO uses the Krauß model to recreate the microscopic characteristics of the traffic flow within an urban area. The main parameters implemented by the Krauß model in SUMO are the individual characteristics of vehicles such the minimum space gap, length, maximum speed among others. Also, the driver imperfection is modeled with a value $\varsigma \in [0, 1]$.

2.2.3 Modeling a road network

When a road network is modeled from a digital map, it is important to represent in a proper manner how the vehicles can travel from one intersection to another. Consequently, the model deals with two distinct set of objects: intersections and roads. One way to represent the relationship between this elements is by the concept of a graph. If E denotes the set of roads and V the set of intersections, the relation can be defined as $\mathbb{R}$ on V by $a\mathbb{R}b$ if the travel from a to b is allowed by using roads in E by one-way or two-way. That connection from a to b can be represented as an ordered pair of the form (V, E).

Definition 6 Graph. *Let be V a finite nonempty set, and let $E \subseteq V \times V$. The pair (V, E) is then called directed graph (on V), or digraph (on V), where V is* *the set of nodes, or intersections and E is the set (of directed) edges. The graph is denoted by:*

$$G = (E, V). \tag{2.10}$$

An urban network can be represented as a directed graph, which relates four entities: a set of intersections, a set of attractor or generator centroids, a set of lanes, and a set of connectors. A lane is a physical link between intersections. The centroids represents those points where vehicles enter or leave the system, being the connectors the different ways where the vehicles transit to arrive an intersection.

Definition 7 Road Network Graph (RNG). *Let be Y a set of intersections, K a set of centroids, L a set of lanes, and C a set of connectors; for the pair $G = (V, E)$, $E = L \cup C$ and $V = Y \cup K$, with $C \subseteq Y \times K$ and $L \subseteq Y \times Y$.*

For convention, the intersections are identified by natural numbers, the centroids are identified by capital letters, and the lanes and connectors are identified by ordered pairs (e.g. $(1, 2), (A, 1), etc.$) Figure 2.7 depicts a graph representing a traffic system composed by *two* intersections and *four* centroids.

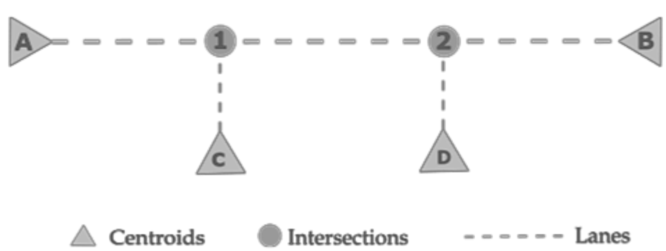


Figure 2.7: Traffic system representation

2.3 Electrical circuits theory

A network, in the context of electronics, is a collection of interconnected components. Network analysis is the process of finding the voltages across, and the currents through, every component in the network.

One of the fundamental laws presents in any electrical circuit is the Ohm's law, that allows to relate the magnitudes of voltage, current and resistance.

Definition 8 Current: *Electric current is the flow of an electric charge, that is the electrons moving across a conductor. Generally, knowing the electric charge in a period of time, the instantaneous current is expressed as:*

$$I = \frac{\delta Q}{\delta t}. \tag{2.11}$$

Resistance expresses the difficulty to pass an electrical current through a conductor. It shares some conceptual parallels with the notion of mechanical friction since is the inverse of the electrical conductance, i.e. is the ease with which the current passes through a conductor.

The way that the current flows through an electrical circuit is analyzed with the nodal analysis , which is based on the Kirchhoff's current law. This analysis is focused on to solve planar circuits for the currents at any place in the electrical circuit.

Definition 9 Kirchhoff´s current law (KCL): *At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node (see Figure 2.8).*

$$\sum_{k=1}^{n} I_k = 0. \tag{2.12}$$

The road network has some commons with an electrical circuit, that are useful when simulation models are developed from characteristics and measures retrieved

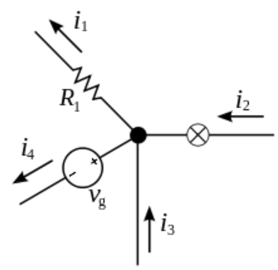


Figure 2.8: Current distribution in a node

from real scenarios. One of these characteristics is the distribution of the traffic flow through numerous intersections.

According to the KCL, in an electrical circuit the current flows in an assumed direction of polarity and is distributed along the circuit through the different nodes, in such a way the incoming current in a node is equal that all outgoing currents. In a similar way, on a road network the traffic flow is distributed on each intersection to the remaining system. For convention, by using the KCL, it is assumed that current flows from the highest potential to the lowest potential. Therefore, in the case of a road network, the traffic flow direction is determined by the trajectories and their origins and destinations, which are represented as centroids in the directed graph G (see figure 2.7).

Property 1 *Nodal analysis applied to the trips distribution modeling. Considering the RNG and representing the centroids with incoming traffic as electric source and the centroids with outgoing traffic as ground connections, the graph can be transformed into an electrical circuit, where each lane has associated a resistance and each intersection is a node.*

Based on the 1, the incoming and outgoing flows can be estimated at each node.

As an example consider the system depicted in figure 2.7. As the centroid A is the unique traffic input it is represented as electric source. Centroids B, C and D are the system's traffic outputs, therefore those centroids represents the ground connections. In this way the resultant circuit can be seen as the depicted in figure 2.9.

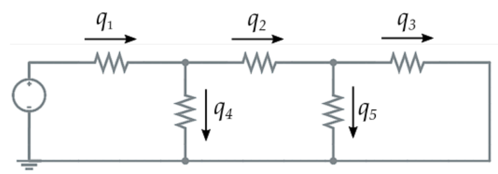


Figure 2.9: Traffic system represented as an electrical circuit

According to the resultant circuit, the currents of each link can be analyzed with equation 2.12, obtaining the following system of equations:

$$q_1 - q_2 - q_4 = 0 \tag{2.13}$$

$$q_2 - q_3 - q_5 = 0 \tag{2.14}$$

The centroid A, in figure 2.7 represents the voltage source of the circuit depicted in figure 2.9, therefore, the current I_1 that circulates through the resistance Ω_1 corresponds to the arrival flow q_1. This incoming flow is distributed after the first intersection (node), towards the whole traffic system (circuit).

2.4 Fuzzy logic

Fuzzy logic is a form many-valued logic which is able to handle the concept of partial truth, where the truth value may range between completely true and completely false [NMP99]. Fuzzy logic is based on the concept of fuzzy set, which is a class of objects with a continuum of grades of membership, ranging between zero and one [Zad65] .

Definition 10 Fuzzy sets. *A fuzzy set A is defined as a* membership function $f_A(x)$ *that maps the elements of a domain or universe* X *with the elements of the* *interval* $[0, 1]$*:* $f_A : X \to [0, 1]$*, representing the* grade of membership *of x in A. The closer the value of $f_A(x)$ to 1, the higher the grade of membership of x in A.*

A fuzzy set A can be represented as a set of pairs of values: each element $x \in X$ with its grade of membership in A.

$$A = \{(x, f_A(x)) | x \in X\} \tag{2.15}$$

Definition 11 Fuzzification *is the conversion of a precise quantity to a fuzzy quantity.*

Generally, the fuzzification of a real value is performed using intuition, experience and an analysis of the set of conditions associated to the system input variables. The most used fuzzifiers, are the based on triangular functions.

Definition 12 Triangular membership function: *let x be an element of a set A, its membership function is computed by:*

$$f_A(x) = max[min(\frac{x - L}{C - L}, \frac{R - x}{R - C}), 0], \tag{2.16}$$

where L, C and R are real scalar values that delimit A; being C the input value with the largest membership (see figure 2.10).

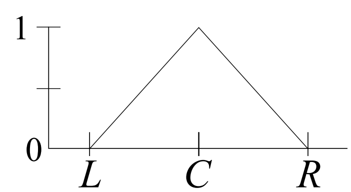


Figure 2.10: Triangular function

Definition 13 Defuzzification *is the process of producing a quantifiable result, given the fuzzy sets and the corresponding membership degrees.*

The defuzzification can be performed in several ways; however, the most used defuzzification methods are the based on the called centroid of area or center of gravity, which is the most prevalent and physically appealing of all the defuzzification methods [Sug85, Lee90].

Definition 14 Centroid of Area (COA) method. *Let x be the sample element and $f_A(x)$ be the continuous membership function of such a sample, the defuzzified value is computed by:*

$$COA = \frac{\int \bar{x}_l f_A(x)\,dx}{\int f_A(x)\,dx} \tag{2.17}$$

where $\bar{x}_l$ represents the area and centroid of area.

For a discrete membership function, the defuzzification may be carried out through the Weighted Average (WA) method.

Definition 15 Weighted Average (WA) method. *For a given sample element x and its discrete membership function $f_{A_i}(x)$, the defuzzified value is computed by:*

$$WA = \frac{\sum_1^n \bar{x}_{A_i} f_{A_i}(x)}{\sum_1^n f_{A_i}(x)}, \tag{2.18}$$

where n represents the number of sets to which the element belongs, and $\bar{x}_{A_i}$ is the element with maximum membership function in a set A_i.

The weighted average method is the most frequently used in fuzzy applications since it is one of the more computationally efficient methods [Ros95]. The only restriction is that the output membership functions must be symmetrical.

Definition 16 Linguistic variables. *The linguistic variables are those whose values are words or sentences in a natural or artificial language, called* linguistic terms. *A linguistic variable is characterized by the tuple (v, T, X, g, m); where v is the name of the variable, T is the set of linguistic terms of v, X is the universe* *of discourse of the variable v, g is a syntactic rule to generate linguistic terms, and m is a syntactic rule that assigns to each linguistic term t its own meaning $m(t)$, which is a fuzzy set in X.*

It is commonly to use expressions like *low*, *medium*, *high* and *very high*, as linguistic terms, and their meanings are determined through fuzzy sets.

2.4.1 Fuzzy inference system

A fuzzy inference system (FIS) is the process of mapping from a given input to an output using fuzzy logic. A FIS is an attempt to formalize the reasoning of human language. As depicted in Figure 2.11, a typical FIS is composed by four modules:

- *Fuzzification*: transforms the system inputs into memberships to fuzzy sets. This is done by applying a fuzzification function.
- *Knowledge base*: stores *if-then* rules provided by experts.
- *Inference engine*: simulates the human reasoning process by making fuzzy inference on the inputs and *if-then* rules.
- *Defuzzification*: transforms the memberships to fuzzy sets, obtained by the inference engine.

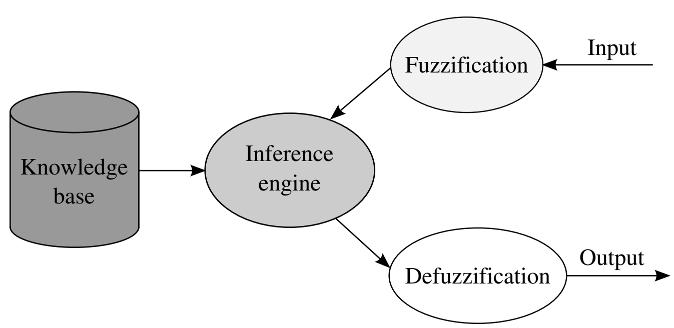


Figure 2.11: Typical FIS modules.

One of the most used FIS are the Mamdani type [MA75], where both the inputs and the outputs of the inference engine are fuzzy, while the knowledge base are composed by rules following the pattern:

$$If\ x\ is\ A\ and\ y\ is\ B\ then\ z\ is\ C.$$

Chapter 3

Related work

Intelligent Transportation Systems (ITS) are a set of technological solutions for telecommunications and information technology designed to improve the operation, efficiency and safety of land transport. They are the main tool for the development of intelligent traffic management solutions and for the planning of so-called "smart cities" [DD10]. The generalized ITS model is based on the identification of patterns from processing large volumes of data (*Big Data*) retrieved by multiple sources(*Crowd-sourcing*), such as: mobility patterns, land use, affluence and detection of centers of attraction and generation of trips [GRLGSR][FJM+01]
.

The second module of the ITS development prototype is information retrieval, which consists of the use of a knowledge representation model, as well as data mining techniques and pattern recognition. This allows to systematically manage and analyze the mobility data of the selected study area.

As a last step model intelligent traffic management is performed by simulations in which different optimization schemes are evaluated. The proposed schemes can offer solutions for the intelligent management of traffic oriented to physical modifications in the network, or to improvements in the current signage (traffic lights reconfiguration, horizontal and vertical signaling, among others). The prototype worldwide adopted for the ITS development is depicted in figure 3.1. In this work it has been identified two main approaches based on crowd-sourcing and recognition of mobility patterns used for intelligent traffic management: on the one hand, the analysis of large volumes of data (Big Data) and on the other hand the Parallel Transportation Management (PTM), see figure 3.2.

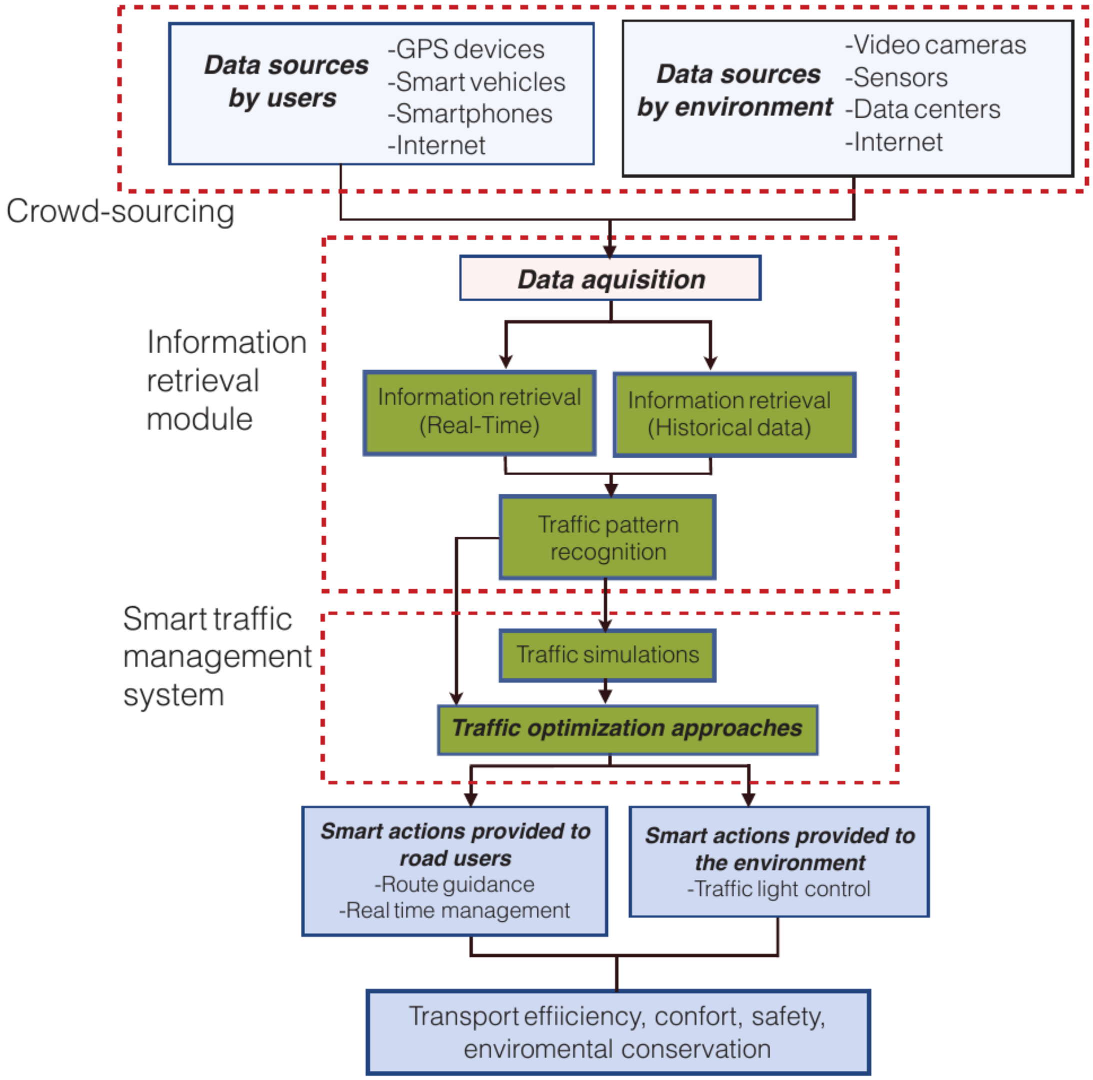


Figure 3.1: Prototype of ITS development for traffic management and control

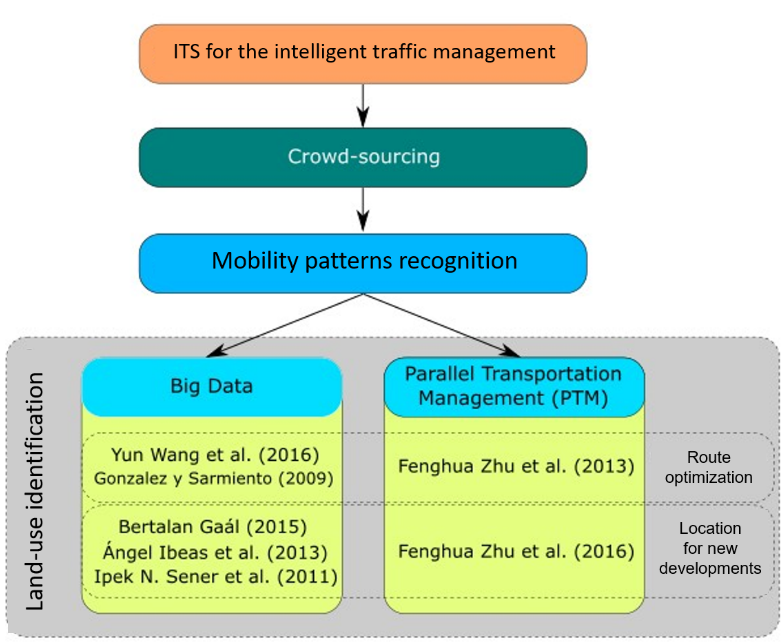


Figure 3.2: Taxonomy of solutions for intelligent traffic management, based on crowdsourcing and pattern recognition

Some of the approaches mentioned in the taxonomy of the figure 3.2 are described in the following sections.

3.1 *Parallel transportation management (PTM)*

A parallel system is a set composed of a system of naturalness real and one or more artificial systems that correspond to [ZYC+13, ZLCX16]. Such systems are oriented modeling of complex systems to predict the actual performance by the interaction of a computer system and data collected in the environment of the problem. Currently the methodology based on PTM is mainly applied in two cases: route optimization and construction of new developments (smart cities).

3.2 *Big Data*

The concept of big data refers to the analysis of voluminous sets of data, harvested through multiple sources, such as sensors, cameras, smart devices, historical records, among others. Big data has been applied in traffic engineering since is useful to identify different precursors of traffic jams, identify origin and destination centroids, crowded trajectories and determine whether the road geometrical design is insufficient for the current demand.

Gonzalez and Sarmiento [yIS09] proposed a big data approach to model the trips distribution within an urban area, establishing the involved cost for each trip. For this approach, authors analyze geo-statistical surveys to identify traffic patterns such as trajectories and trips typification accordingly to their origins and destinations.

Wang et. al. [WRC+16] proposed an approach for smart transportation management focused on bus networks. The proposed approach consists of a three layer data analytic strategy. In the first layer, sets of GPS signals and Automated Fare Collection (AFC) records are processed to compute bus travel times and passenger boarding locations. In the second layer, the data harvested by the first layer are processed to obtain networks metrics and chart data. Finally, in the third layer, the processed data are visualized. From this approach, regions of high mobility demands and delay level for routes can be determined. Authors shown that the results can be useful for smart city urban mobility programs such as bike sharing.

3.3 Land use-transport interaction

The current urban infrastructure can be understood as the result of the interaction between land use and transport, this interaction is identified as a bilateral process [Cha06]. There are numerous studies focused on determining this interaction, considering two main components:

- -Exogenous. Such as demography, regional economy, government, policies and external factors, among others.
- -Endogenous. Represent the supply and demand system, which is directly related to human activities, services and travel patterns.

The land use-transport interaction has been one of the main research topics of transport studies. However, given the exogenous and endogenous components, the model to represent and analyze such interaction depends on the objectives of each study. Thus, four types of approaches are mainly identified: a) urban planning; b) identification of mobility patterns; c) identification of main human activities and d) evaluation of traffic management policies.

3.4 Land use-transport interaction models

The land use-transport interaction models integrate socioeconomic theories, as well as human activities, land uses and transport systems, with the aim of resolving mobility problems in an integral way and considering the alterations that may occur in periods of time defined. According to Wegener [Weg], the housing location and employment centers determine the way in which the population moves (origin-destination) and the activities carried out. Thus, the activities of an area demand certain transport systems. In this way, transport systems allow to estimate the accessibility and connectivity between zones. Finally, connectivity and accessibility between zones shapes the land use. These interactions are cyclically repeated, as shown in figure 3.3.

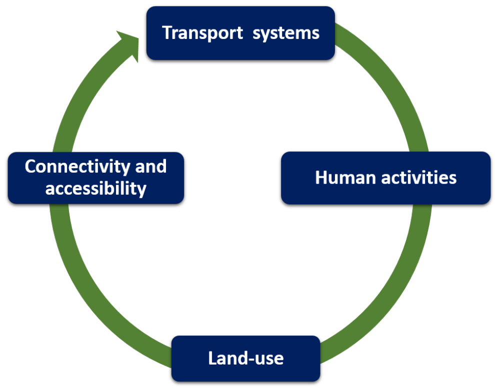


Figure 3.3: Land use-transport interaction cycle

Some of the most influential models in recent years are described in the following sections, classifying them according to their theoretical basis

3.4.1 *Spatial interaction models*

Spatial interaction models are focused on determining the number of trips by area (affluence) and represent the flow between each origin-destination. The main variables considered in the analysis are: operating costs and the level of activities in each region. The model assumes an inversely proportional relationship between the activities level and the impedance generated by the transport systems, so analogously it is usually compared with Newton's gravitation model and some authors call it a gravitational model. This group of models was originated by Lowry [Low64] and have been applied in numerous studies related to the land use- transport interaction, due to its simplicity and the coherence of the results obtained. In addition, these models are very flexible and can be adapted to the need of each case study. One of the advantages of using this type of models is that it allows quantifying the influx of certain centroids attractors or travel generators. However, in a strict sense, the model does not allow to determine the fundamental relationship between land use and transport explicitly, because it fails to represent the intrinsic characteristics of the centroids.

3.4.2 *Mathematical programming models*

The mathematical programming models are designed to optimize the development of urban infrastructure. The main objective is ordering the spatial efficiency of the infrastructure, achieving a balance between growth urban area and the activities carried out, as well as transport systems available [MPDMV10]. Most of these models are made with help of linear and non-linear optimization programs. Its main advantage is that allow visualizing the impedance produced in transport, by varying the interaction with land use. These models allows a partial quantification of the interaction between land use and transport, obtaining a greater number of mobility patterns. It can be applied to planning, policy evaluation and traffic management.

3.4.3 *Random utility models*

Random utility models explain the relationship between land use and transport looking to maximize the utility of the space according to users of transport infrastructure. In general terms, the theory describes the social processes as a set of decisions made by individuals. The selection of each individual will depend on the degree of satisfaction that a region provides, according to its potential or utility. Mathematically, utility is represented according to the individual and the possible options, using variables that contain measurable attributes for each option. In this way, if the user faces a set of options, it can be assumed that he will evaluate the options with the same level of utility in a random way. However, there are many sources of variability as the groups grow, as explained by Domencich and McFadden [Dom75]. For this reason, these types of models are little used to solve traffic engineering problems.

3.4.4 *Bid-rent models or discrete choice approach*

The bid-rent theory was proposed for the first time by Alonso [Alo]. According to this theory, each actor in a system generates a supply of land with different characteristics, so that the consumer begins to choose their settlements according to the best available offers. This generates the distribution of land uses in each population. However, although this type of analysis offers many advantages, it is not easy to calibrate the model with transport systems, since transport is only added as a part of the formulation. On the other hand, discrete choice approach models commonly calculate the utility of land based on a decision model, but it is only fulfilled if there is good urban planning. Therefore, if land use changes over a period of time, the relationship provided by the model is not guaranteed.

3.5 Tools for the analysis of the land use-transport interaction

There are currently several tools and methodologies that facilitate the analysis of the interaction between land use and transport, based on one or more of the models mentioned above. Here are some of the tools that most closely match to our study approach.

3.5.1 *Sketck planning*

These types of models are currently widely used as an aid in urban planning and for the analysis of population censuses [CL01]. Generally these models are assisted by Geographic Information Systems (GIS). Normally they are not integrated with travel distribution models, but they are useful to visualize population distributions. The basic principle of these models is the analysis of thematic maps by empirical inferences, which depend on the experience of the analyst.

3.5.2 *TELUMI (Transport-Efficient Land Use Mapping Index)*

It is a methodology aimed at visualizing the interaction between land use and transport in a graphic way [MSKM11]. It uses cartographic modeling methods that allows to generate maps of a particular area and associating land uses with travel behaviors. It also relies on geographic information systems to delimit the road network in regions according to land use.

TELUMI is a multifunctional tool that presents a series of maps to analyze the relationship between current land use and the behavior of the elements of a network, as well as identify patterns of mobility from the influx in specific areas. In addition, it is useful to evaluate current mobility conditions and associate them with models based on service levels; facilitating decision making to implement mobility schemes in metropolitan areas.

3.5.3 TRANUS

The TRANUS system is a tool based on the model proposed by de la Barra [Bar89] that allows to simulate in an integral way the location of activities as well as the interaction between land use and transport. It is particularly aimed at simulating the likely effects of the implementation of policies and projects in various cities or regions, and evaluate them from a social, economic, financial, energy and environmental view.

The most outstanding feature of the TRANUS system is the way in which the main components of the urban or regional system are represented, such as the location and interaction of activities, the real estate market and the transport system. All these components are related to each other explicitly and according to a theory clearly developed for this purpose. In this way the phenomenon of the movement of people and goods is explained by the economic and spatial relationships between the activities that generate them. Although it is in the integrated planning where the TRANUS system yields its maximum potential, the system can be used as an exclusive model for transport analysis, assigning demand matrices, which can be useful for the evaluation of traffic management policies short term. The integrated approach also allows estimating origin-destination matrices at a reduced cost.

3.5.4 Summary

Over the years, several researchers have proposed different approaches to characterize an urban network, intended to improve the urban mobility. Most of these models have been focused on the urban development, routes optimization for public transport and logistics. These models commonly are based on an interaction between the land use and the transportation (determined by government policies) with a close dependence on the human activities produced in the neighboring areas the roads. In general, these approaches are oriented towards the recognition of mobility patterns, the location of human activities and the evaluation of policies for the traffic management. The recognition of patterns consists in the analysis of data from different sources to identify the characteristics associated with the current mobility conditions, within an urban area. Some of these patterns are trajectories of origin-destination, socioeconomic activities, demand in the current infrastructure, among others. Through the recognition of mobility patterns, some models allow determining the most suitable location for the construction of new developments, as well as planning the way in which new human settlements are established, that is, they determine the land use in specific zones.The tools that incorporate these models, as a basis for their formulation, are aimed at evaluating policies for urban development by displaying the effects produced by transportation or activities promoted by the land use. In this way, the evaluation that is carried out helps the planners in the decision making process. However, these models do not allow to qualify the performance of a road network and its operation under its current configuration and demand in each segment. Table 3.1 summarizes the approaches identified, according to their theoretical basis.

Table 3.1: Approaches

Approach / Theoretical basis	**Recognition of mobility patterns**	**Location of human activities**	**Policy evaluation for traffic management**
Spatial interaction Models [Low64, yIS09, CL01, MSKM11, Bar89]		×	×
Mathematical Programming Models [MPDMV10]	×	×	×
Random Utility Models[Bar89, Dom75]	×	×	
Bid-Rent Models[Bar89, Alo]	×	×	

Chapter 4

Operational classification of urban roads

4.1 The flow resistance of a road

As depicted in section 2.3 the current flow behavior, in an electrical circuit, is mainly affected by the resistances, which represent the difficulty for the electrons to circulate trough a wire, and it consumes a charge provided by the voltage source. On a road system there is an intrinsic perturbation on each link that affect the traffic flow conditions, this variability is commonly evaluated by the speed-density fundamental relation. However, such a relation is a general-empirical form to evaluate the performance of a road system that may hide specific space-time conditions in a bounded area. One example of this effect can be seen on an intersection with an inadequate signal timing and inefficient geometry whose may produce a disturbance in a specific point of the network. To analyze this effect consider the system depicted in figure 4.1.

By considering the scenario depicted in figure 4.1, if the turn lane do not have the length to safeguard the turning vehicles during the red light, or the light phase is too long, the backward stream is affected and a queue is produced. Such a disturbance can be seen as a resistivity of the road which negatively affects the flow conditions. It is necessary to known the resistivity of a road to identify specific problems and quantify the efficiency of mobility, such as how the queue

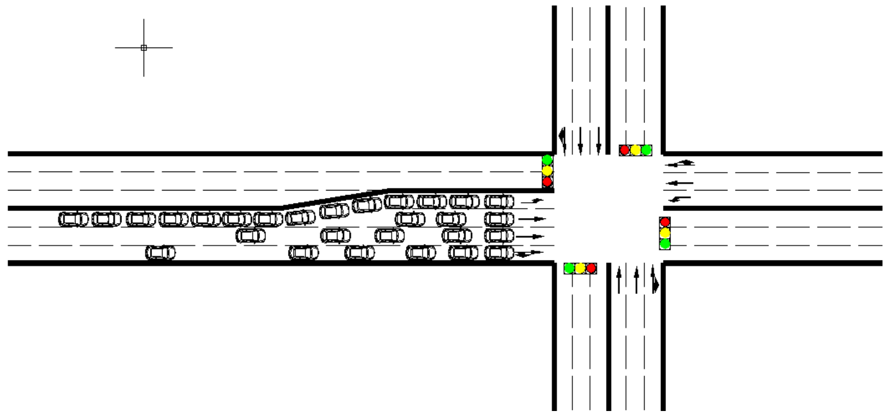


Figure 4.1: Intersection with disturbances produced by geometry and signal timing

is affected when the signal timing changes or hierarchize the operating conditions of each link.

4.2 Problem definition

Empirically the resistance of a road consumes speed and produces some disturbances on the traffic flow such as traffic jams.

According to the fundamental relationship, at homogeneous flow conditions, the speed is inversely proportional to the density, it means, when the density increases, the speed decreases. Nevertheless, the speed and the density have no a persistent decreasing condition as a function to the flow. The flow decreases proportionally to the density in two cases: when density decreases and when density rises above the road capacity. Therefore the resistance of a road is not directly analogous to the resistance in an electrical circuit, in terms of the fundamental relationship, since there are no a characteristic with a similar behavior to voltage. Thus, there is not a precise formulation that allows to determine that resistivity factor.

4.3 Computation of the road´s resistivity factor

Due to the lack of an accurate formulation to describe the resistance of a road in terms of speed, density and flow, in this work it is proposed a fuzzy inference system (FIS). Through the proposed FIS, the tree characteristics of the fundamental relationship are related in such a way that the resistance increases directly proportional to the density and inversely proportional to the speed.

4.3.1 Fuzzy sets to describe the resistivity factor

To fuzzify the density, a universe of discourse P is defined by the interval $[\rho_{min}, \rho_{max}]$, where ρ_{min} and ρ_{max} are the lower and upper bounds of the density expressed in veh/km/lane. The set P is divided into m subsets, each one related to a linguistic term x_i, $i \in [1, m]$, that qualifies the density with sentences such as *very low, low, mean, high* and *very high.* In a similar way, the average speed is related to the universe of discourse V, defined by the interval $[v_{min}, v_{max}]$, where v_{min} and v_{max} are expressed in km/hr. The set V is divided into l subsets, each one related to a linguistic term y_j, $j \in [1, l]$, such as *very slow, slow, average, fast* and *very fast.*

The output variable *Resistivity* is related to the universe of discourse Ω defined by the interval $[\Omega_{min}, \Omega_{max}]$. The set Ω is divided into p subsets, each one related to a linguistic term z_k, $k \in [1, p]$, such as *very conductive, conductive, steady, resistive* and *very resistive.*

According to the limit values, observed from in-situ measurements, five fuzzy sets were defined for each variable as is shown in Table 4.1. For density, a range between 0.03 and 222.22 PCU/lane/km was determined, and for the speed between 0.9 and 72.75 km/h. The value of 222.22 for density results for the maximum number of PCU occupying a section of one kilometer in a single lane, and considering a space gap of 0.5 m between vehicles.

The interval for speed was established by considering the 85th percentile of the group of measures retrieved in the most representative operative schedule, which occur during 05:00 and 22:00, from Monday to Friday.

Table 4.1: Scalar values for the fuzzy sets

Density	**(PCU/lane/km)**	**Speed**	**(km/h)**
Very low (VL)	0 – 55.58	Very slow (VS)	0.0 – 18.86
Low (L)	55.58 – 111	Slow (S)	18.86 – 36.82
Mean (M)	111 – 167	Average (A)	36.82 – 55.54
High (H)	167 – 222.22	Fast (F)	55.54 – 72-75
Very High (VH)	222.22 – 277.78	Very Fast (VF)	72.75 – 91.61

The fuzzy sets for each variable were established with triangular membership functions (see definition 10) as depicted in figures 4.2 and 4.3.

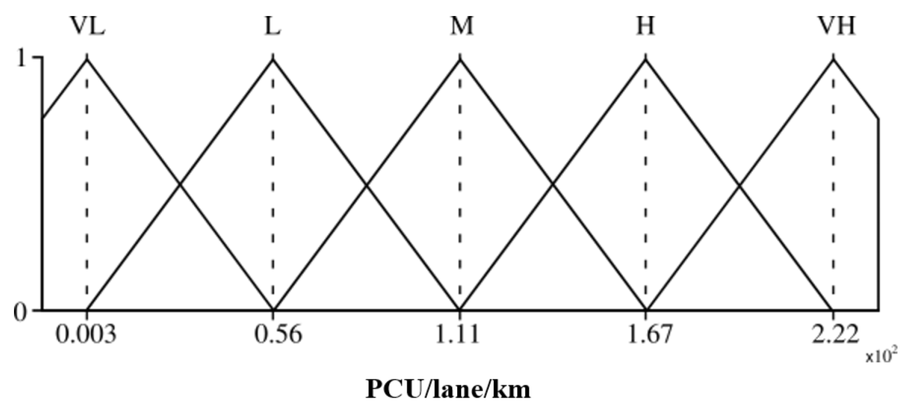


Figure 4.2: Fuzzy sets for density

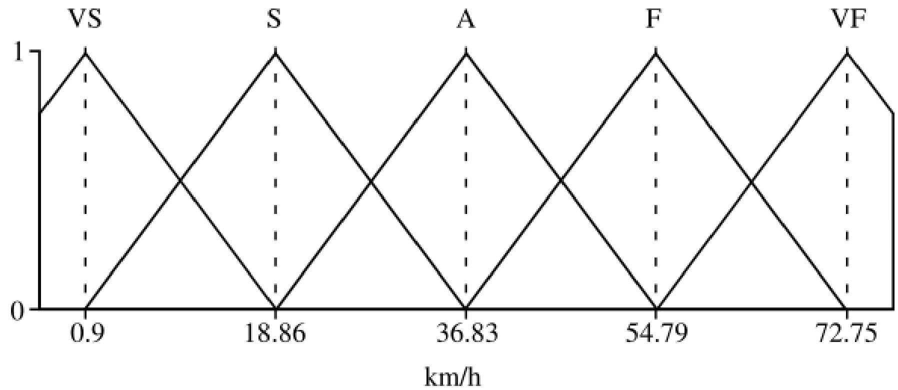


Figure 4.3: Fuzzy sets for speed

The output variable was defined as Ω (Omega) with fuzzy values between 0 and 1 defined by five fuzzy sets with triangular membership functions, as shown in figure 4.4. The linguistic terms for omega are Very Conductive (VC), Conductive (C), Steady (S), Resistive (R) and Very Resistive (VR).

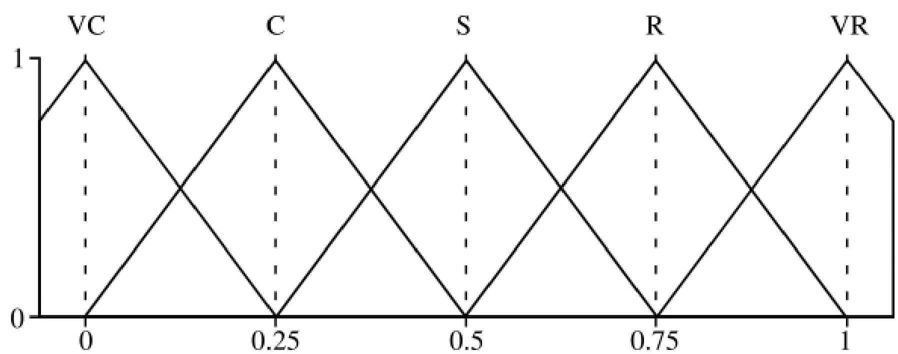


Figure 4.4: Fuzzy sets for resistivity

4.3.2 Fuzzy inference system to compute the resistivity factor

Since the traffic characteristics, related to the road performance, are defined in antagonistic domains, a fuzzy inference system (FIS) was proposed to relate the density and the speed to the resistivity.

By considering the fundamental relation speed-density, the higher density expresses greater disturbances on the network. However, the resistivity does not depends only on the density. There are some cases where the density on the roads is very high without producing decreasing on the speed. Otherwise, some local streets have very low operating speed although the density is low. These considerations need to be described according to qualitative characteristics observed in real-world scenarios and are the result of the experience acquired from traffic studies.

To achieve a formal relation among resistivity, speed, and density, in such a way that the human experience about the road performance can be included, a Mamdani FIS is proposed. This FIS maps the fuzzy sets, specified for the density and the speed, to a given resistivity factor by using twenty-five *if-then* rules of the form:

If *density* is x_i and ... *speed* is y_j then the *resistivity* is z_k.

The twenty-five inference rules, that have been defined to consider all the conditions observed on the road network, are depicted in Table 4.2.

The twenty five if-then rules enumerated in table 4.2 describes all the possible combinations between density and speed that produce road resistivity or allows steady and free traffic conditions. Since, the rules are defined on the basis of degrees of memberships to fuzzy sets, these twenty five combinations can be depicted with the surface of figure 4.5. Therefore, the resultant membership surface depicts all the possible conditions that promote the raising of resistivity.

In the surface of figure 4.5, the lowest points represent the most conductive conditions, defined by the rules number 5 and 25 in the table 4.2. In real scenarios this condition occurs in local streets with low density and arterial roads with very high speed of operation. The first plain of the surface represents the optimal operating conditions, in other words, speed of operation is maintained fast without reaching the limit of the density. The intermediate zone of the surface, represented

Table 4.2: If-Then rules for the Mamdani FIS

Rule	If Density	and Speed	then Omega
1	VL	VS	R
2	VL	S	R
3	VL	A	S
4	VL	F	C
5	VL	VF	VC
6	L	VS	R
7	L	S	R
8	L	A	S
9	L	F	C
10	L	VF	C
11	M	VS	R
12	M	S	R
13	M	A	S
14	M	F	C
15	M	VF	C
16	H	VS	R
17	H	S	R
18	H	A	S
19	H	F	C
20	H	VF	C
21	VH	VS	VR
22	VH	S	R
23	VH	A	S
24	VH	F	C
25	VH	VF	VC

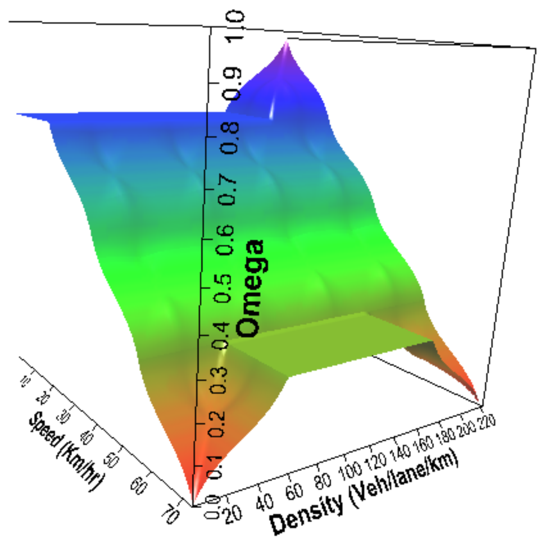


Figure 4.5: Omega values for an urban network

in green, describes the synchronized flow conditions in which the output value for omega was defined as steady. The second plain of the surface shows the traffic jam state on the roads. This condition was defined by the rules with the value for omega as resistive. Finally, the highest peak of the surface, depicts the over-saturation condition. That is the worst case when the road capacity has been surpassed.

4.4 Case study

In order to show the utility of the resistivity factor, as an alternative to hierarchize the operation of urban roads; a road subsystem of the city of Morelia, Michoacán, Mexico was selected as a case study. The study zone was selected due to the current demand and the number of activities that take place in the vicinity of the roads. In addition, the lack of connectivity between some roads make difficult to hierarchize the system according to the traditional functional classification.

4.4.1 Characterization of the study area

The city of Morelia, capital of the state of Michoacán de Ocampo, is the largest and most populated city in the state, which is the eighteenth nationwide, with an area of 10,120 hectares and a population of 829,625 inhabitants [OH15]. The figure 4.6 shows the macro location of the study case.

Figure 4.6: Macro location of the study area

The area selected as an object of study is located in the southeast of Morelia, demarcated by the colonies "Félix Ireta", "Ventura Puente", "La Loma" and "Alberto Oviedo Mota", in the vicinity of the shopping mall "Fiesta Camelinas ". The study area includes the road subsystem of Camelinas avenue, from the intersection with the Ventura Puente roadway to the intersection with Jesús Sansón Flores boulevard, as well as the streets that intersect the Camelinas avenue along the entire stretch, as shown in the figure 4.7.

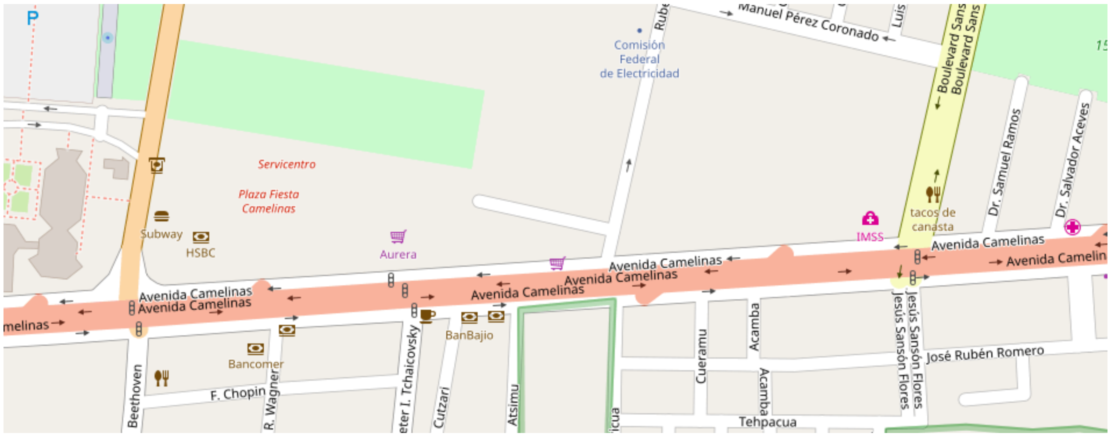


Figure 4.7: Micro location of the study zone

4.4.2 System model

For the microscopic analysis of the study area, the road network was described as follows:

- An eight-lane dual arterial road with west-east and east-west traffic.
- Two four-lane dual collector roads with north-south and south-north traffic, connected to the arterial road by two signal-controlled intersections based on pre-timed traffic lights.
- Nine two-lane dual local roads with north-south and south-north traffic, connected to the arterial road by seven yield-controlled intersections.

By employing the notation stated in Definition 7, the system model is depicted through the road network graph (RNG) of figure 4.8. In the RNG, the nodes 1, 2 and 3 represents the intersections with the highest traffic and corresponds to the junctions of Camelinas Av. with Ventura Puente (node 1), Camelinas Av. with Tchaikovsky (node 2), and Camelinas Av. with Sansón Flores Blvd. (node 3).

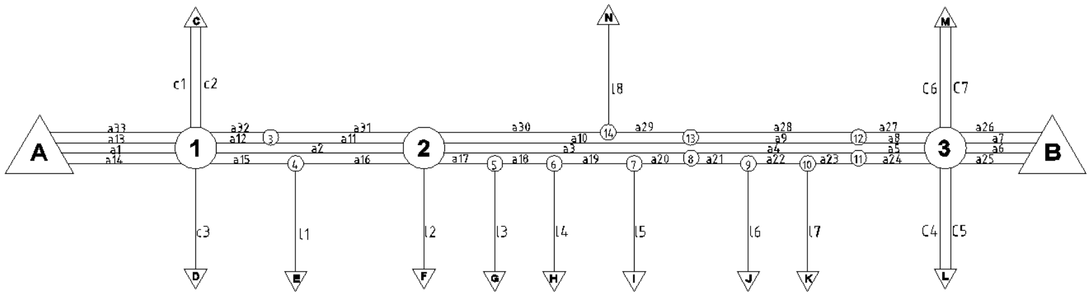


Figure 4.8: Road network graph of the study zone

4.5 Simulation model

Due to the spatio-temporal nature of the density, it is difficult to retrieve in-situ measurements to determine it. To facilitate the determination of the density, for this work, such a characteristic is computed through a microscopic simulation, based on the Parallel Transportation Management scheme. Therefore, based on the Simulator of Urban Mobility (SUMO), a simulation model was calibrated by using digital maps and traffic data retrieved from traffic counters and video recordings.

4.5.1 Digital map

The simulation model is based on a digital map of the urban network obtained through open street maps (OSM). However, it was necessary to make some modifications in the configuration to use it in the SUMO simulator. According to the representation of the network described in the figure 4.8, the static model was built considering the useful lanes for each section, as well as the geometry of the streets and the way direction (see figure 4.9).

In the real scenario, the secondary segments of the main artery are limited to the use of only one lane, because the other lanes are occupied as a parking. Therefore, the occupied lanes were removed from the map, leaving only the useful

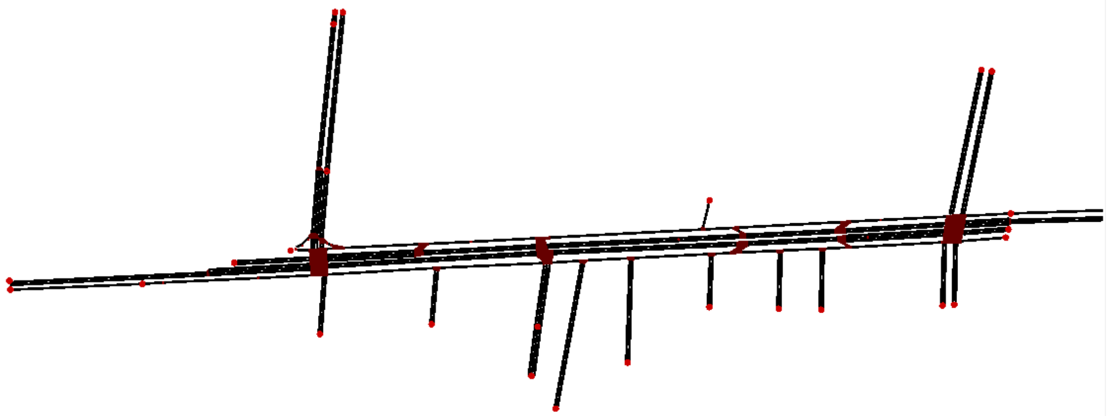


Figure 4.9: Digital map o f the network

lanes. In addition, according to the regional regulations, the maximum permitted speeds on each type of road were bounded as depicted in table 4.3.

Road type	Max Speed (Km/h)
Arterial	55
Collector	40
Local	30

Table 4.3: Maximum permitted speed by road type

The three main intersections (1, 2 and 3) of the arterial road are managed by synchronized pre-timed traffic lights, whose signaling are adjusted within a cycle of 130 seconds, preserving an offset of 5 seconds one with respect to another. The phase configuration, depicted through the diagram of figure 4.10, has the following characteristics:

- In the west-east direction, the cycle starts with the green phase at the intersection 1 (Camelinas-Ventura Puente). Then it has an offset of 65 seconds before the green phase starts at the intersection 2 (Camelinas-Tchaikovsky). Finally between the second and the third intersection, there is an offset of 5 seconds before the green phase begins.

- In east-west direction the cycle starts with the green phase at the intersection 3 (Camelinas-Sansón Flores). Then, there is an offset of 30 seconds before the green phase starts at the intersection 2 (Camelinas-Tchaikovsky) . Finally, between the intersections 1 and 2, there is an offset of 30 seconds before the green phase begins.

Total cycle has a duration of 130 seconds for all intersections.

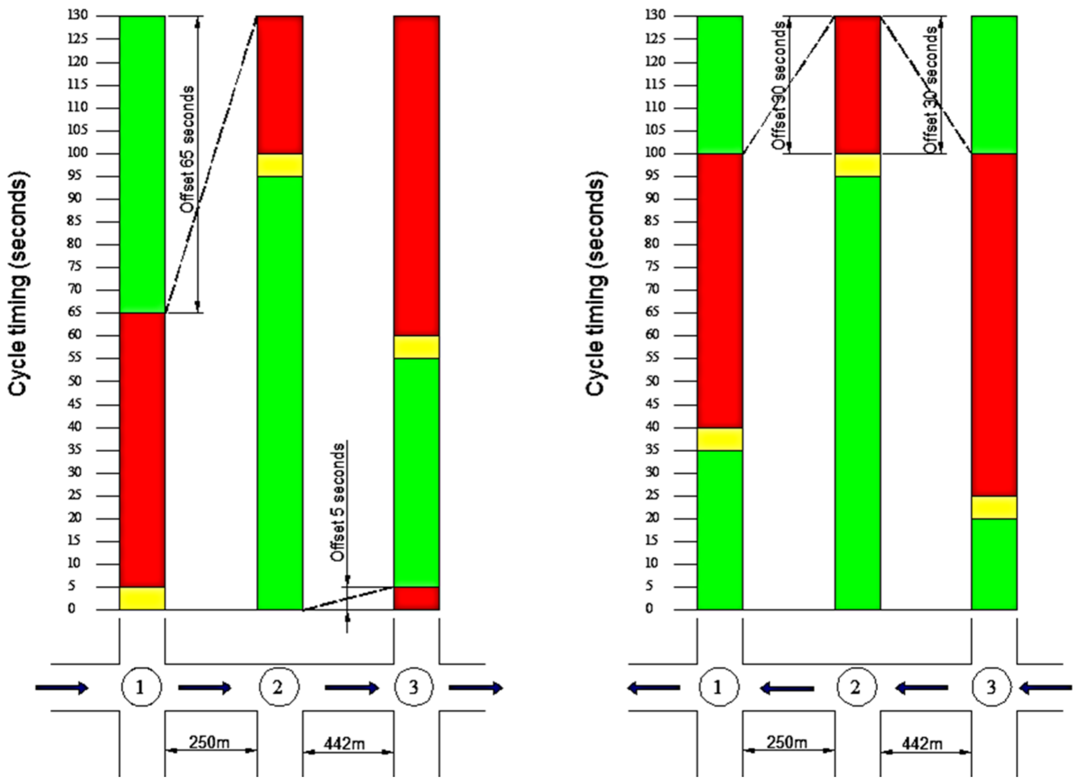


Figure 4.10: Phase diagram configuration

Additionally, each phase is configured with the corresponding allowed turns for each lane. An example of the turns for each phase is represented in the figure 4.11, which corresponds to the Camelinas-Ventura Puente intersection.

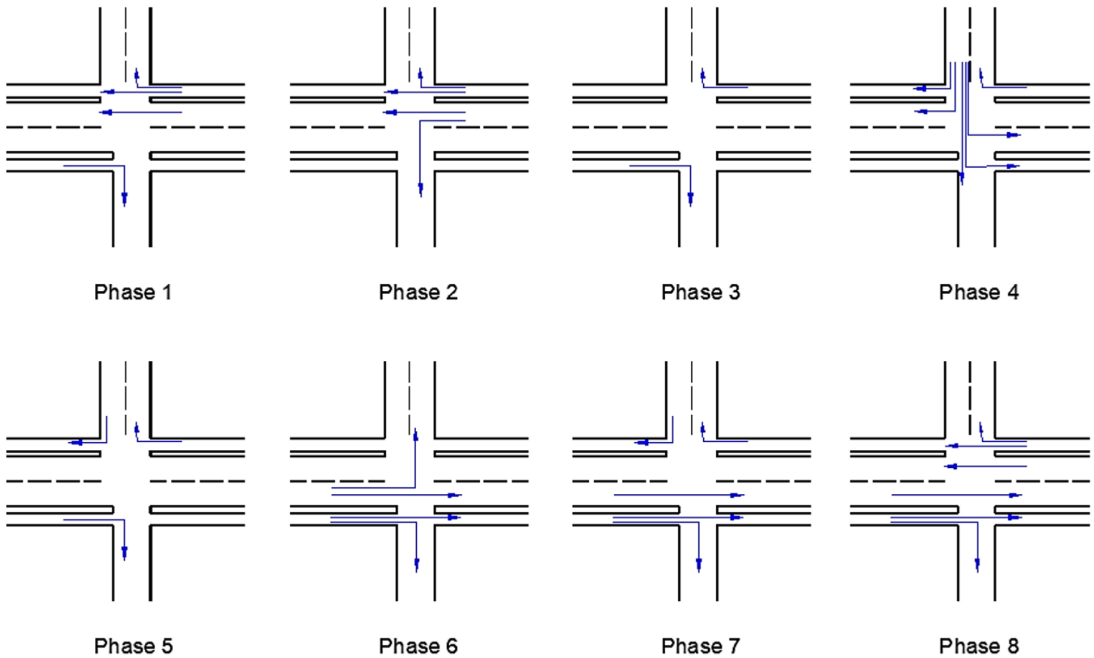


Figure 4.11: Allowed movements by phase

4.5.2 Traffic information retrieval

To retrieve the traffic volumes, rubber tubes and radar sensors were deployed on the roads with high traffic volumes. To improve the accuracy in travel distributions, several video recordings were retrieved at the intersections. Moreover, in the segments with obstacles or local streets, where the sensor deployment was unfeasible, the traffic volumes were determined by manual counts. Table 4.4 describe the basic characteristics of each road and the counting/classification methods used on each case.

Vehicle counting was performed in order to determine the hourly traffic, daily traffic and weekly traffic volumes, respectively. The hourly traffic volume was retrieved in intervals of fifteen minutes. Table 4.5 summarize the hourly, daily and weekly traffic volumes retrieved from the segment $c2$ of the RNG, which corresponds to the Ventura Puente road in south-north direction. As it can bee seen, the total weekly traffic volume is of 150,728 vehicles.

Table 4.4: Traffic data collection methods

Road or segment	Lanes	Orientation	Method
Camelinas avenue, central lanes	4	east-west/west-east	radar, rubber tubes, video
Camelinas avenue, secondary lanes	4	east-west/west-east	radar , video
Ventura Puente	4	north-south/south-north	radar, rubber tubes, video
Jesus Sansón Flores	4	north-south/south-north	rubber tubes
Tchaikovsky	2	north-south	radar ,rubber tubes , video
Beethoven	2	south-north	radar ,rubber tubes , video
Wagner	2	south-north	manual count
Cutzari	2	south-north	manual count
Atzimu	2	south-north	manual count
Uricua	2	south-north	manual count
Cueramu	2	south-north	manual count
Acamba	2	south-north	manual count
Rubén C. Navarro	2	south-north	manual count

From the weekly traffic volume, the most representative time intervals were identified. Therefore, it was established the day of week by considering the day with the greatest traffic volume along a full operative week. Figure 4.12(a) shows the hourly volumes of the days of week.

From the daily traffic volume, in the day with the greatest demand, it was identified the most representative time of days by considering samplings of fifteen minutes (see figure 4.12(b)). These time of days are the time intervals in which the most representative traffic conditions take place, i.e., the greatest and the lowest demand along an operative day.

By considering the TODs, identified from the weekly traffic volume, a whole operational day is reproduced through a sequence of five hours of simulation, each hour associated to the average volume in a TOD. The five TODs considered for the microscopic simulation are the following:

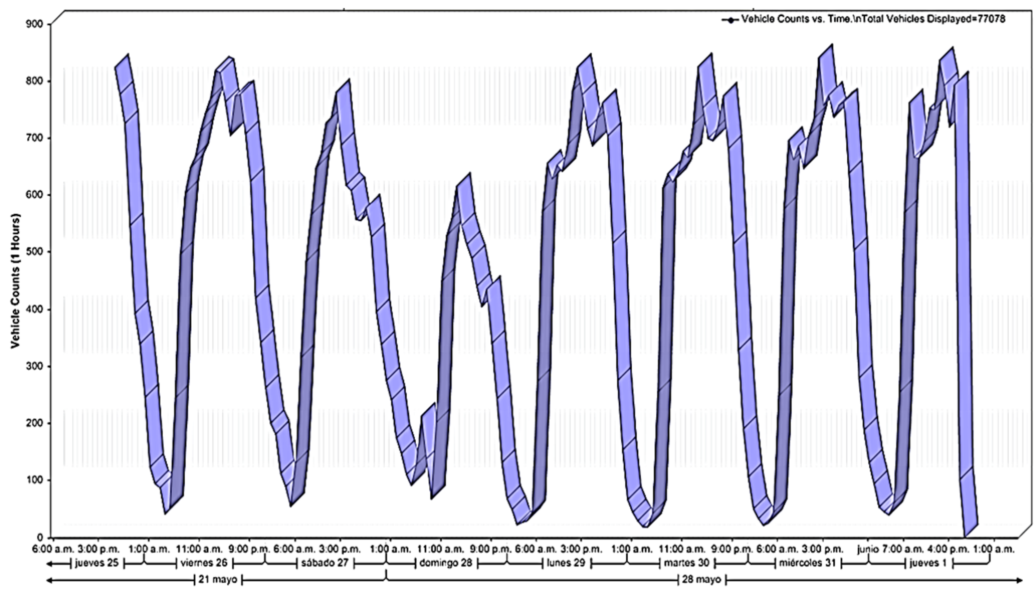
- From 04:00 to 05:00, the lower demand observed, related to the average time in which the activities in the study zone begins.
- From 07:00 to 09:00 , the greater demand during the morning.

Table 4.5: Weekly vehicle count on a road

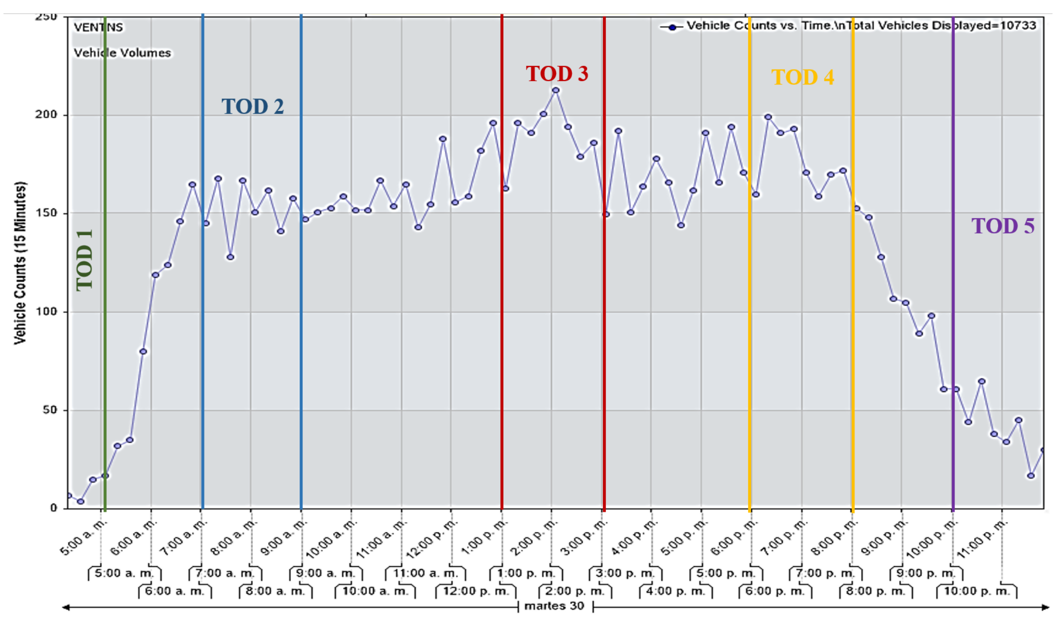
Day/hour	M	T	W	T	F	S	S	Avg.
0 - 1	305	412	381	418	444	602	856	392
1 - 2	173	169	172	272	317	508	638	221
2 - 3	107	78	120	186	196	351	509	137
3 - 4	74	70	72	157	184	291	454	111
4 - 5	87	82	106	121	160	193	344	111
5 - 6	243	229	257	239	266	247	275	247
6 - 7	848	733	787	781	751	546	363	780
7 - 8	1690	1661	1653	1460	1694	1190	170	1632
8 - 9	1555	1455	1496	1570	1586	1642	133	1532
9 - 10	1330	1370	1403	1364	1544	1533	177	1402
10 - 11	1236	1284	1223	1236	1215	1311	83	1239
11 - 12	1259	1233	1316	1283	1253	1530	81	1269
12 - 13	1281	1335	1307	1491	1345	1524	321	1352
13 - 14	1289	1327	1389	1423	1369	1494	1561	1359
14 - 15	1453	1484	1530	1466	1467	1655	1702	1480
15 - 16	1523	1523	1321	1606	1412	1765	1643	1477
16 - 17	1462	1564	1463	1525	1473	1834	1444	1497
17 - 18	1410	1486	1527	1489	1450	1677	1478	1472
18 - 19	1445	1450	1547	1337	1446	1639	1522	1445
19 - 20	1455	1576	1532	1534	1586	1810	1629	1537
20 - 21	1467	1565	1553	1539	1419	1634	1396	1509
21 - 22	1361	1349	1354	1303	1014	1410	1263	1276
22 - 23	929	952	1018	1070	1007	1234	870	995
23 - 24	595	603	689	749	782	940	574	684
Totals	24577	24990	25216	25619	25380	28560	19486	150728
% of Total	14.14%	14.38%	14.51%	14.74%	14.60%	16.43%	11.21%	

- From 14:00 to 16:00, the greater demand during the day.
- From 18:00 to 20:00 , the greater demand during the afternoon, associated with the schedule in which people leave their workplaces.
- From 22:00 to 24:00 , the time in which the flow is decreasing because the local activities ends.

To achieve a behavior with a maximum similitude to the real conditions of the case study, the trip distribution was computed by considering the the TODs and the directional distribution within each intersection. These two measurements were used along with a RNG to perform a nodal analysis based on the Kirchhoff´s



(a)



(b)

Figure 4.12: (a) Days of week, (b) Times of day

current law. In each intersection, it is considered that the incoming volume is equal to the volume that comes out. This condition represents what happens in the real scenario, which can not exist vehicles parked on an intersection and each node is balanced by distributing the flow to other network segments. Thus, the outgoing volume of each node may represent a new incoming volume for subsequent nodes. As an example, let consider the values depicted in figure 4.13. Cells with letters represent the network nodes in which there must be an equilibrium condition according to incoming and outgoing flows. The values in the blue cells shows the in-situ flow measurements, and the values in green cells are the present flow in each lane according to the trips distribution.

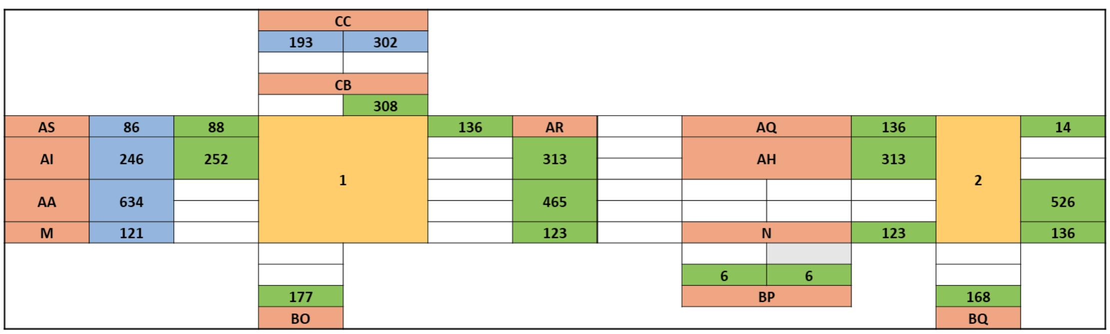


Figure 4.13: Trips distribution of the centroids between the intersections 1 and 2 at the first TOD

The directional distribution was retrieved by several video recordings, determining the turns percentage at each intersection. Table 4.6 shows the directional distribution for the intersection 1 (Camelinas-Ventura Puente).

By applying this distribution, iteratively throughout the RNG, all the possible trips, performed in the system, were established.

4.5.3 Dynamic model

The calibration of the SUMO simulation model was carried out by satisfying the parameters required by the lane change model [XH13] and the car-following model

Table 4.6: Directional distribution at intersection 1

		Destination					
		a33	**a13**	**a2**	**a15**	**c2**	**c3**
Origin	**a1**			63%		37%	
	a14				70%		30%
	a12		62%		6%		32%
	a32	46%				54%	
	c1	30%	3%	34%	12%		21%

of Krauss [Kra98], which is a model derived from Gipps´s model. This parameters were obtained through the registered flows and the queue length observed.For vehicle dynamics, the average speed was calculated from the corresponding records at the 85th percentile of the entire sample. In this way, by considering the trip distribution obtained from the traffic information retrieval, several routes were defined. In the SUMO simulator each route is established from a projected vehicle type, denotes as *Vtype*. In this sense three *Vtypes* were defined: *Car*, *Combi* and *Bus*.The *Vtype Car* represents the private vehicles characterized with a bumper to bumper (b2b) length of 4.5 m, an acceleration of 2.6 m/s^2, a deceleration of 4.5 m/s^2, and a maximum speed of 20.20 m/s (72.75 km/h). The *Vtype Combi* is characterized with a b2b length of 5.2 m, an acceleration of 2.6 m/s^2, a deceleration of 4.5 m/s^2, and a maximum speed of 20.20 m/s (72.75 km/h). The *Vtype Bus* is characterized with a b2b length of 12.5 m, an acceleration of 2.6 m/s^2, a deceleration of 4.5 m/s^2, and a maximum speed of 20.20 m/s (72.75 km/h). In addition, for the three *Vtypes* were considered a standard deviation of 20 % up and down to the maximum speed, to reproduce the fluctuations of the real world, as well as a sigma value of 0.5 to describe the driver imperfection. The values considered for each Vtype are presented in the table 4.7.

Table 4.7: Definition of Vtypes for the road network

Vtype ID	**accel** (m/s^2)	**decel (m/s^2)**	**length (m)**	**maxSpeed (m/s)**	**sigma**	**minGap (m)**	**speedFactor**	**speedDev**	**guiShape**
Car	2.6	4.5	4.5	55.55	0.5	0.5	1.1	0.1	passenger/sedan
Combi	2.6	4.5	5.2	55.55	0.5	0.5	1.3	0.3	passenger/van
Bus	2.6	4.5	12.5	55.55	0.5	0.5	1.3	0.3	bus

In order to reproduce the volume distribution, in the road network, for each $Vtype$, so many routes were defined as possible trips exist on the study zone.

The definition of routes for public transport was carried out according to the trajectories established in the study area, as well as the corresponding volume according to the frequency observed. Table 4.8 summarizes the flows for public transport.

Table 4.8: Route definition and flows for public transport

Route ID	From	To	Flow (veh/h)	VType
Amarilla	ventNS3	sanSN2	10	Combi
Gris1PO	latPO11	latPO24	20	Combi
Gris1OP	latOP22	latOP12	20	Combi
Gris2	latOP22	ventSN6	12	Combi
Gris4PO	latPO11	latPO24	15	Combi
Gris4OP	latOP22	latOP12	15	Combi
Roja3APO	ventNS3	latPO24	15	Combi
Roja3AOP	latOP22	ventSN6	15	Combi
Roja3BPO	ventNS3	latPO24	15	Combi
Roja3BOP	latOP22	ventSN6	15	Combi
Roja3PO	ventNS3	latPO24	12	Combi
Roja3OP	latOP22	ventSN6	12	Combi
Ruta1PO	latPO11	latPO24	20	Bus
Ruta1OP	latOP22	latOP12	20	Bus
Ruta2PO	ventNS3	sanSN2	8	Bus
Ruta2OP	sanNS2	ventSN6	8	Bus
CentrosPO	ventNS3	latPO24	5	Bus
CentrosOP	latOP22	ventSN6	5	Bus

From the trips distribution and the Vtype definition, the dynamic model was developed considering five consecutive hours of simulation according to the TODs. In this way the simulation time is limited to 18000 seconds, which represent the most representative operational characteristics of a full average operating day.

Figure 4.14 depicts the resulting dynamic model for the entire network considering all Vtypes.

Finally, with the input data and the record of the observed data, the validation of the model is done through a sensitivity analysis, until the real behaviour of the network is reproduced.

Figure 4.14: Dynamic model of the network

The simulator was configured to obtain the measures of density and average speed in samplings of fifteen minutes. The results for each segment are presented in table 4.9.

4.5.4 Resistivity factor for the roads of the case study

From the measures of density and average speed, obtained from the microscopic traffic simulation, each road was evaluated with the FIS and their resistivity values were obtained for each segment. Considering the fuzzy sets for density and fuzzy sets for speed (see section 4.3) the numeric values were fuzzyfied into a linguistic terms according to their membership function, by using the equation 2.16, explained in section 4.3.1. Therefore, by applying the Mamdani FIS, stated through the rules of table 4.2, the output value for omega were established. Finally, the linguistic term of the output value for each segment were defuzzificated to know the numeric value of their resistivity.

As a functional description of the FIS, let consider the segment a2 depicted in figure 4.8. According to the traffic survey, in such a lane there are an average daily density of 26.43 veh/km/lane and an average daily speed of 26.38 km/hr. Considering the corresponding fuzzy sets, the density has a membership of 0.58 to the set VL (Very Low) and 0.42 to the set L (Low). The speed has a membership of 0.4 to the set VS (Very Slow) and 0.6 to the set S (Slow). Therefore, by applying the Mamdani FIS, the daily resistivity factor of the segment $a2$ Ω_{a2} is S. By defuzzificating, the membership to the set S, the numeric value of Ω_{a2} is 0.64 that represents a steady condition.

The resistivity factor also can be computed for hourly intervals. For example, let consider an interval defined by the TOD 3, where the segment $a2$ has a density of 30.79 PCU/km/lane and a speed of 20.08 km/h, then by applying the previous process, the resistivity value is 0.65.

This process was applied at each segment of the road network and the different values of resistivity are summarized in Table 4.9.

4.6 Operational classification of the urban roads

The operational classification corresponds to a hierarchical form of the urban roads according to the performance characteristics produced by the current demand and the disturbances present in each segment. In this way the operational classification is done by establishing the resistivity value for each road.

Based on the values of resistivity, computed for each road (see table 4.9), a corochromatic map (see figure 4.15) was built to graphically depicts the resultant classification. For the corochromatic map, a color scale was established to represent four different scales for resistivity. The green color represents resistiv-

Table 4.9: Daily density, average speed and resistivity of each segment of the network

Road or segment	Density (PCU/lane/km)	Speed (km/hr)	Resistivity (Omega)
a1	190.62	4.68	**0.86**
a10	15.17	31.248	**0.59**
a11	50.02	10.152	**0.75**
a12	167.98	5.04	**0.76**
a13	13.64	52.74	**0.29**
a14	30.33	14.364	**0.75**
a15	16.5	25.056	**0.65**
a16	37.53	11.016	**0.75**
a17	21.85	22.068	**0.68**
a18	23.04	19.908	**0.72**
a19	30.58	14.364	**0.75**
a2	26.43	26.388	**0.64**
a20	42.32	12.708	**0.75**
a21	37.63	12.06	**0.75**
a22	45.02	10.08	**0.75**
a23	62.95	7.848	**0.75**
a24	69.82	6.048	**0.75**
a25	9.98	39.744	**0.44**
a26	91.56	5.4	**0.75**
a27	10.64	38.268	**0.47**
a28	19.27	21.06	**0.69**
a29	49.78	17.712	**0.75**
a3	15.21	53.424	**0.28**
a30	57.35	13.68	**0.75**
a31	68.52	14.22	**0.75**
a32	57.81	11.232	**0.75**
a33	8.68	41.184	**0.42**
a4	15.59	53.964	**0.27**
a5	100.91	8.316	**0.75**
a6	14.1	51.876	**0.31**
a7	222.22	4.824	**0.92**
a8	18.58	47.196	**0.36**
a9	54.36	16.2	**0.75**
c1	100.9	5.58	**0.75**
c1	111.24	5.22	**0.75**
c1	222.22	2.34	**0.97**
c1	222.22	1.728	**0.98**
c2	12.57	54.18	**0.27**
c2	11.83	55.548	**0.22**
c2	15.08	40.5	**0.43**
c3	17.5	29.664	**0.61**
c4	12.53	29.016	**0.61**
c5	19.73	4.104	**0.75**
c6	7.49	8.676	**0.75**
c7	5.81	39.924	**0.44**
l2	142.91	2.448	**0.75**
l2	170	2.16	**0.78**

ity values between 0 and 0.25, the yellow values between 0.25 and 0.50, orange between 0.50 and 0.75 and red for values between 0.75 and 1.0.

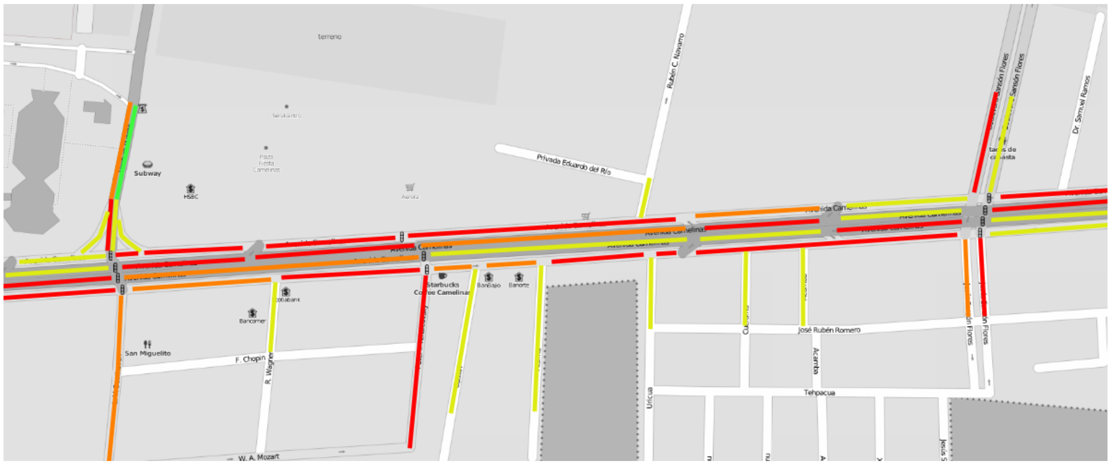


Figure 4.15: Operational classification of the studied zone

According to the corochromatic map of figure 4.15, the links represented on red color are the most resistive sections of the road network. Such a condition is produced for the disturbance induced by the traffic lights on each intersection, which indicates that the cycle times are not adequate for the current demands. The green and yellow links represents the most conductive sections that could be used to equilibrating the flows within the road network. An example of this phenomenon is the edge a1 to a6 where the stop lights produce more resistivity at the segments near to the intersections and the value for Ω decreases considerably when vehicles are driven after the traffic light.

4.7 Findings and discussion

In this work, an operational classification of roads was established by considering the traffic performance of each element, expressed by a resistivity factor. In this way, an urban network is hierarchized according to the traffic performance, achieved by each road. The resistivity factor Ω can be used to evaluate the efficiency of the road network, as well as to identify road segments that require modifications to improve the traffic flow conditions.

The resistivity factor Ω is introduced as a new mesoscopic parameter, oriented to evaluate solutions for traffic management, public transport route planning, as well as to determine the feasibility of new geometric projects and to guide the decision-making, involved in the proposals of new urban development policies.

In order to show the application of the resistivity factor, two experiments were conducted, evaluating two different modifications to the current deployment in the case study.

4.7.1 Experiment one: quantifying the resistivity factor induced by the public transport

For this experiment, two traffic conditions were modeled. The first condition was configured with the current characteristics, depicted through sections 4.5.1, 4.5.2, and 4.5.3. The second condition, is an hypothetical deployment, configured from the discarding the routes of the public transport, trying to reproduce an scenario where there are no public transport vehicles, i.e., Vtypes *Combi* and *Bus*.

By computing the resistivity factors of the forty seven segments, for the two proposed conditions, a comparison between the resistivity from current scenario (Omega) and the hypothetical scenario (Omega STP) was achieved. This comparison is depicted in the histogram of figure 4.16. As can be seen in the histogram, the average resistivity, induced by the public transport, is of 0.18.

4.7.2 Experiment two: quantifying the resistivity factor of a geometrical project modification

For this experiment, the segment $a1$ of the RNG, corresponding to the west branch of the Camelinas-Ventura Puente intersection, was evaluated by considering two configurations. The first configuration corresponds to the current geometrical condition, where there is an auxiliary lane, for the channelization of the left turning, with a length of 105 m (see figure 4.17(a)). The second configuration was performed by an hypothetical modification of the geometry that considers an extension of 45 m on the auxiliary lane, in order to host all the vehicles that produce a queue (see figure 4.17(b)). By computing the resistivity factors of this two configurations it was determined that the resistivity factor can be reduced from 0.62 to 0.58, while the density is reduced from 190.79 to 59.96 and the speed is increased from 27.79 to 32.07. It can be note that the resistivity factor remains in the same interval since for this experiment the traffic light timing was not modified. However, by analyzing the current deployment and their resistivity a low-intrusive traffic management solution was identified.

4.7.3 Relation of the resistivity factors with the socioeconomic characteristics of the study zone

In order to contrast the flows obtained with the zone activities, Geo-statistical data of the National Institute of Statistic and Geography (INEGI) database were consulted, integrated in thematic maps at the National Statistical Directory of Economic Units (DENUE)[dEyG17].

In figure 4.18(a) can be seen the density of activities. The buffer on the map corresponds to the location of the main employment centers and their influence area. Thus, the analyzed road network is influenced by three main zones in the vicinity of the road network.This information is consistent with the results of the distribution of trips and the origin-destination trajectories observed.

Figure 4.18(b) shows the main economic corridors at the study zone that corresponds to the number of jobs per kilometer, i.e., the level of activities by segment. It is observed that there is a correlation between the number of jobs in each segment and the resulting resistivity in some lanes in the proximity of the intersections. However, in the intermediate segments there are few jobs per kilometer and high resistivities. This condition shows that the resistivity depends not only on the current demand, but also on other factors such as geometric characteristics and traffic management in the road network.

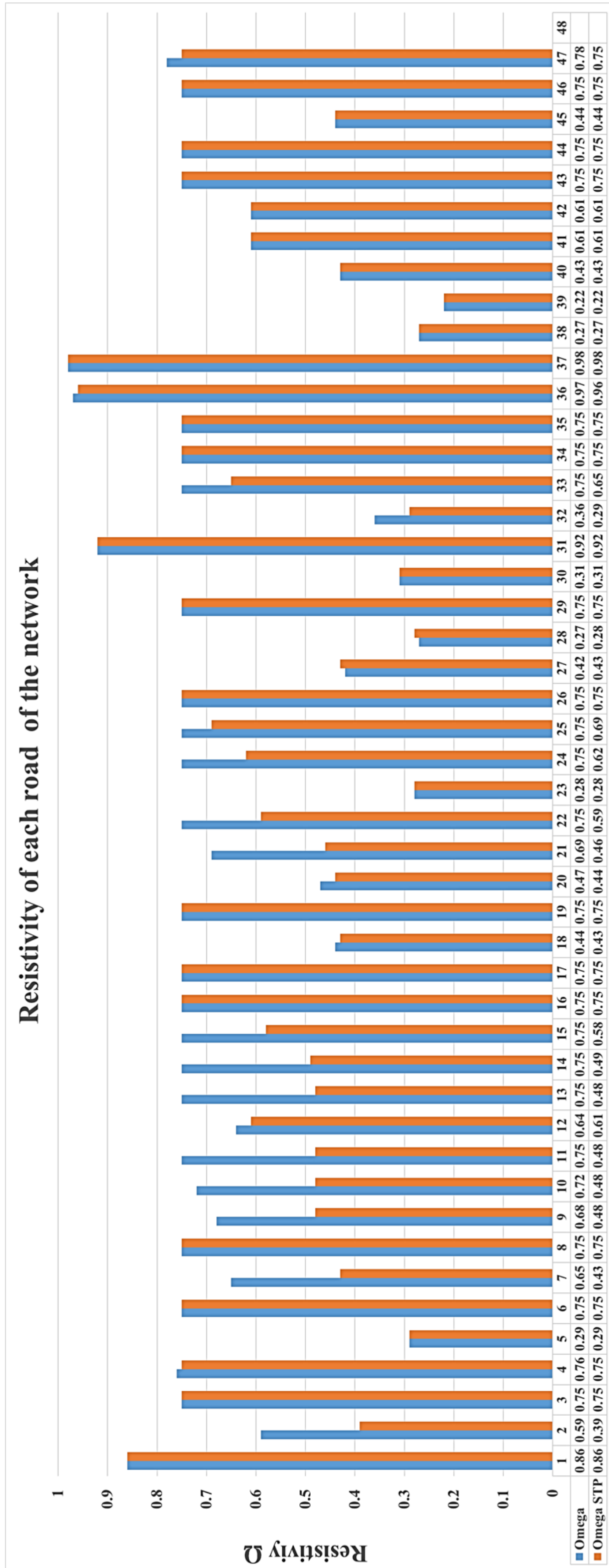
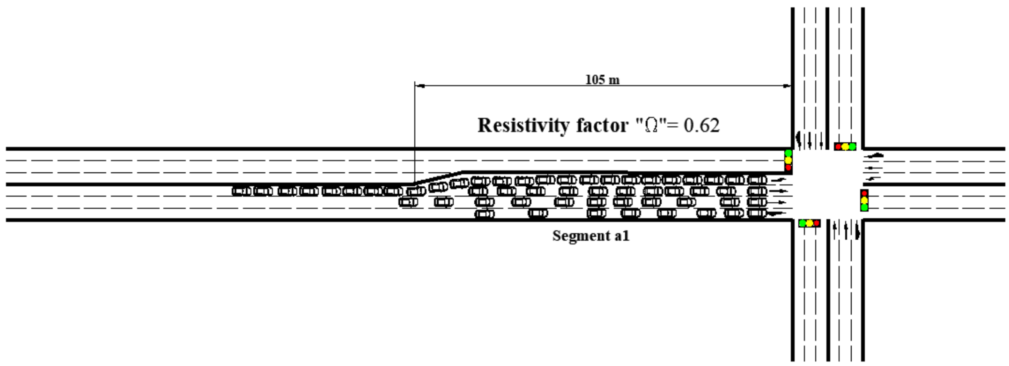
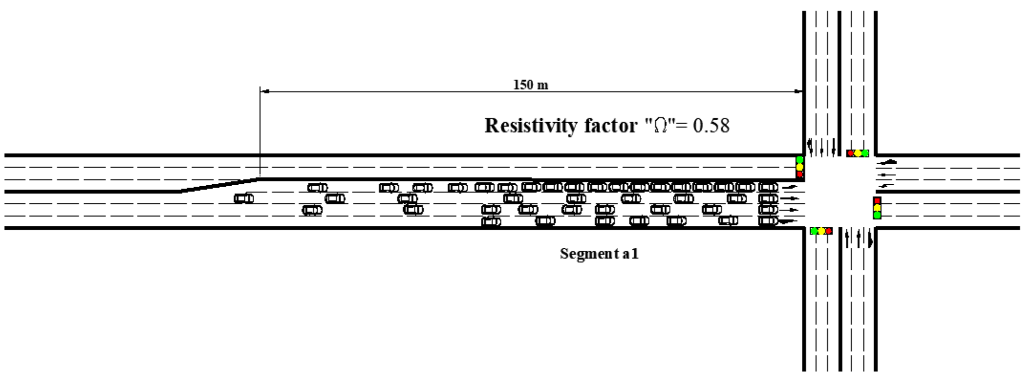


Figure 4.16: Resistivity values for each road of the network



(a)



(b)

Figure 4.17: (a) Current geometrical configuration, (b) Geometrical modification

(a)

(b)

Figure 4.18: (a) Activity density (jobs/hectare), ESRI shape by CONURBA; (b) Economic corridors (jobs/kilometer), ESRI shape by CONURBA [CON18]

Chapter 5

Conclusions and future work

5.1 Summary

In this work, it was formally described an operational classification of urban roads based on a resistivity factor. This classification is characterized by establishing a numeric value that indicates the resistance that a road imposes over the speed, on each segment within an urban road network. To establish the resistivity factor, the density and the speed, measured on road, are related through a fuzzy inference system. The fuzzy system maps the density and the speed to a resistivity value following the reasoning "the higher the density and the lower the speed, the greater the resistance". Due to the space-time nature of the traffic density, such a characteristic is difficult to retrieve through on-road measurements. Therefore, based on the Parallel Transportation Management paradigm, this work proposed the development of microscopic simulation models to retrieve the density measurements.

The operational classification according to the resistivity factor, is done by establishing the resistance values of each segment defined between intersections. In this way, the resistivity factor represents the disturbances that directly affect on the decreasing of the speed, for each segment of the network. Therefore, by establishing the different resistivity factors, the different segments of a road can be classified according to their operational performance.

The main finding of this work argues that the resistivity of a road represents a mesoscopic characteristic useful to evaluate the efficiency of the mobility or planning management schemes. In this sense, the design of efficient traffic management schemes could be focused on to reduce the values of resistivity at the most resistive segments.

The feasibility of the proposed classification is shown by establishing a resistivity-based operational classification of a road network located in the city of Morelia, Michoacan, Mexico. Based on the achieved classification, there were conducted two experiments that depict how the resistivity factor can be used to evaluate the performance of an urban network.

5.2 Future work

Urban roads catalog.

In order to create new road planning schemes for a city, it is necessary to extend the operational classification to the entire grid of the network. In this way, the segments with the highest resistivity factors could be improved, by designing particular solutions focused on to reduce such a mesoscopic characteristic.

Traffic management through PTM approach.

To achieve efficient traffic management based on the operational classification of roads, it is necessary to evaluate the possible improvements according to the resistivity factors, obtained through simulation, and validate them by an implementation in a real scenario.

Roads resistance definition through compressible flow theory.

Because the resistivity of a road has some similarity with the concept of friction of the materials, the disturbances present in an urban network, could be analyzed from a hydraulic approach considering the roughness coefficient analogously to the resistivity factor described in this work.

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