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Public transport reorganization through rational territory management

Tesis que para obtener el grado de

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

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Resumen

En México, el Transporte Público Colectivo Concesionado (TPCC) surgió como una alternativa para compensar las necesidades de transporte urbano del siglo XX. A través de los concesionarios, el gobierno pudo delegar la explotación del servicio de transporte público a asociaciones privadas. Sin embargo, la falta de regulación ha motivado el crecimiento acelerado de las flotillas, bajo el precepto de cubrir el mayor número de destinos. Esta sobre-oferta del servicio se traduce en una alta redundancia de rutas, incrementando la densidad vehicular y obstaculizando la movilidad urbana. Un caso especial tiene lugar en la ciudad de Morelia, Michoacán, en donde en un segmento de una vialidad arterial coexisten 36 rutas, lo que induce hasta 374 vehículos de TPCC por km/h. En este trabajo se propone una metodología para identificar las trayectorias que permitan unificar la mayor cantidad de rutas; para lograr una reo-organización del TPCC orientada a disminuir la redundancia y mejorar la movilidad. Las trayectorias se identificaron mediante la construcción del árbol de expansión mínimo (AEM) del grafo de distribución de rutas actual. Basándose en el AEM, se planteó un esquema de re-organización del TPCC compuesto por tres sistemas: troncal, alimentador y local. El sistema troncal atraviesa la ciudad de oriente a poniente, conectando los tres principales centroides atractores y generadores de viajes. El sistema alimentador se compone de nueve rutas, diseñadas para permitir los traslados desde los centroides secundarios hacia el sistema troncal. Por último, el subsistema local, está orientado a facilitar el traslado desde el interior de diferentes ciudades dormitorio y complejos industriales, hacia los otros dos sistemas.

Palabras clave: transporte público, optimización de rutas, simulación microscópica, estadística GEH, movilidad urbana.

Abstract

In Mexico, the Concessioned Public Collective Transit (CPCT) arose as an alternative to compensate for the need for urban transportation in the 20th century. Through concessions, the government was able to delegate the exploitation of the public transit service to private associations. However, the lack of regulation has motivated the accelerated growth of the fleets as an attempt to cover the largest number of destinations. This service oversupply is traduced in a high redundancy of routes, increasing the vehicular density and inhibiting urban mobility. A special case takes place in the city of Morelia, Michoacán, where on a segment of an arterial road coexist 36 routes, which means up to 374 CPCT vehicles per km/h. In this work, it is proposed a methodology to identify the trajectories that allow unifying the most routes for a CPCT re-organization intended to reduce vehicular density and improve mobility. The trajectories were identified by constructing the maximum spanning tree (MST) of the graph of the current distribution of routes. Based on the MST, a CPCT re-organization scheme was proposed, consisting of three systems: backbone, feeder and local. The backbone system traverses the city from east to west, connecting the three main travel attractor/generator centroids. The feeder system is composed of nine routes, intended to allow the trips from the secondary centroids to the backbone. Finally, the local subsystem is intended to facilitate the trips from the inner of different bedroom cities and industrial complexes to the other two systems.

Key words: public transit, routes optimization, microscopic simulation, GEH statistic, urban mobility.

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Contents

Notation

- $Flow$: Number of vehicles transiting over a certain point per unit time
- Density: Number of vehicles into a certain length
- Speed: Transited length of a vehicle per unit time
- $CPCT$: Concessioned Public Collective Transit
- G_{road}: Representation of the road network through a graph
- G_{CPCT}: Weighted graph of the Concessioned Public Collective Transit
- MST: Minimum spanning tree
- $oai_i = \frac{1}{w_i}$ Overlapping avoidence index
- w_i: number of routes overlapped
- $Backbone$: Main proposed route for the unified CPCT
- $Hyperpath$: Representation of users' decision rules by lines
- $Compositehyperpath$: Two or more hyperpaths reach the same destination.
- $GEHS$: GEH statistic
- $SUMO$: Simulation of urban mobility

Chapter 1

Introduction

1.1 Motivation

According to the United Nations [gu11], 51% of the world population is established in urban areas. Medium and large Mexican cities (more than 700,000 inhabitants), presents an accelerated growth, while their population densities have drastically decreased (until 67%) [OH15]. Due to the lack of sustainable planning, the population dispersion has motivated the increase of vehicle-based transportation. Just between 2000 and 2012, the motorization rate was of 7.4%, which surpassing five times of the national population [INE15]. Within such a population is included most of the vehicles used to provide public transit (PT).

In Mexico, as a consequence of the rapidly growing of both population and urban surfaces, since the decade of 1930, the centralized public transportation services began to be insufficient. To compensate for this inadequacy, the government promoted the legal entity of *concession* for the collective public transit to delegate such a service to private organizations. Initially, the aim of the concessions was to improve the coverage of different origins and destinations by rising availability. However, from the end of the decade of 1980, the demand overcame this scheme, promoting that the government conceived a new legal entity to help *concessionaires* to satisfy the new requirements by themselves. This new entity, called *permissionaire*, allowed the holders of public transport units, enrolled to a concession, to increase the fleets and even to propose new service routes deployment.

1.2 Problem description

The combination of deficient urban planning with the weak regulations that support both concessionaires and permissionaires have motivated a greedy competition among the Concessioned Public Collective Transit (CPCT) holders, which triggered the accelerated growth of the fleets [Var15]. This competition has resulted in the service oversupply since many holders have attempted to cover the largest number of origins and destinations. The service oversupply has been traduced into a high redundancy among lines/routes since most of them share the same travel trajectories besides that their covered origins/destinations are close to each other in around one kilometer. This deployment has several repercussions on the urban mobility, being the rapid increase of vehicular density one of the most delicate since is directly related to jams formations, raising of operational/monetary transportation costs, degradation of the quality of life and environmental pollution [ZSHB09].

According to Hadas Yuval [Had13], the redundancy of routes must be minimized to increase the efficiency of public bus lines, due to the impact that the overlapping has in the mobility patterns such as speed and vehicular density. In addition, Chen et al. [CBL+18], argue that a separation of one kilometer between a couple of origins/destinations decreases the productivity of their trajectories.

1.3 Proposed solution

This work is focused on a case study located in the city of Morelia, Michoacán, known as *Obelisco a Lázaro Cárdenas*. The case study is the main traffic distributor of the city, where converge the two main arterial roads and spreads trips to the four cardinal points. These characteristics have attracted the economic interest of the CPCT because of the potential trip demand. Currently, in this zone co-occur 36 CPCT routes contributing with up to 374 transportation units per km/h. Unfortunately, the great population of vehicles inhibits mobility, transforming the zone into the major jam generator of the city. This situation is aggravated due to the constrained accessibility of the whole road network. According to Ortega and Vázquez [OMV17], Morelia has inefficient urban mobility, according to its population, since it has a morphology with a disorganized poly-centric structure, where there are just three vehicular axles, one internal traffic circuit and many local streets without connection among them.

This work proposes a methodology to identify the trajectories that allow unifying the most routes for a CPCT re-organization intended to reduce vehicular density and to enhance mobility.

The proposed methodology consists of four stages. The first stage is intended to retrieve a graph of the current distribution of routes, for which the geo-spatial characteristics of the origin-destination trajectories of all the CPCT lines, that coincide in the zone, were integrated into a Geographic Information System (GIS). Supported by the GIS, in the second stage, a weighted graph was retrieved, in which each edge is identified by the number of coincident routes. In the third stage, the maximum spanning tree (MST) of the graph is constructed by applying the Kruskal algorithm. Finally, in the fourth stage, the MST is trimmed considering the geometric and transitability characteristics of the roads, obtaining a condensed graph.

Supported by the resulting condensed graph, a CPCT re-organization scheme was proposed, consisting of three systems: backbone, feeder and local. The backbone system traverses the city from east to west, connecting the three main travel attractor/generator centroids. The feeder system is composed of nine routes, intended to allow the trips from the secondary centroids to the backbone. Finally, the local subsystem is intended to facilitate the trips from the inner of different bedroom cities and industrial complexes to the other two systems.

Analytically was proved that the proposed trajectories for unification accomplish the main characteristic of the *hyperpath* concept [TGBK13], which was proposed as one of the most equilibrated models to pre-trip en route choice for public transit networks. Specifically was proved that the trajectories of the backbone and the feeder system accomplish to the morphology of composite hyperpaths, while the trajectories of the local system accomplishes the concept of simply hyperpath.

Complementary to the formal analysis, a *naive* reorganization scheme, based on the trajectories for unification, was tested through a microscopic simulation of the case study. The simulation was shown that the reorganization reduces the traffic density up to 19% in comparison to the current deployment.

1.4 Research objectives

1.4.1 General objective

- To design and develop a reorganization strategy for the Concessioned Public Collective Transit through the rational management of the territory.

1.4.2 Specific objectives

To achieve the general objective, the following specific objectives are defined:

- To characterize an urban trip attractor and generator through traffic volumes and trips distribution.
- To identify the origins and the destinations of the public transit routes that converge in the characterized centroid.
- To determine the O-D trajectories by analyzing geo-statistical data.

- To optimize the O-D trajectories to determine the most profitable routes to define the arterial and the feeder system of the public transit.

- To propose a distribution scheme of the arterial and feeder system considering the most profitable routes.

1.5 Document organization

This document is organized as follows. Chapter 2 notes the theoretical and fundamentals of traffic engineering, traffic flow theory and modeling, as well graph theory. Chapter 3 presents a literature review about public transit management. In chapter 4, the proposed solution to reorganize the public transport is described. Finally, the chapter 5 notes the conclusions and the future work.

Chapter 2

Background and definitions

2.1 Traffic engineering

2.1.1 Traffic flow theory

Vehicles flow q can be expressed as a frequency, which it counts the total of vehicles N in a certain point of measure for a lapse of time $T_m p$, see the equation [Pip65].

$$q = \frac{N}{T_{mp}}. \tag{2.1}$$

2.1.2 Density

Density represents the vehicles quantity that circulate in a section of a road, it normally expresses as vehicles for kilometer [Kur09]. The density lets knowing the quantity of vehicles that circulate in a section, no matter their composition and individual characteristics.

Density k, in a road of a single direction, is compute through the following equation:

$$k = \frac{N}{K} \tag{2.2}$$

Where N denotes to the vehicles number and K es the length of the road.

2.1.3 Speed or mean celerity

Speed or mean V_s must not be confused with the term of velocity, such the speed is the scalar magnitude or the norm of the vector that expresses a velocity [Vla07]. Mean speed of a flow is the relation between the distance that it goes down in a section of measure, and the time that it takes to traverse that total distance regularly expressed by kilometers for hour.

There is an only relation between the three characteristics of the macroscopic model FT, where the flow, the density and the mean speed can be expressing as the following equation:

$$q = kV_s \tag{2.3}$$

2.1.4 Passenger Car Unit (PCU)

The PCU is a metric used to measure the impact that a concerned transportation mode has on the traffic behavior [PD19]. This variable consists of the comparison of a simple passenger vehicle with the diversity of vehicle types. In this way, the PCU looks for quantifying the traffic volume as accurately as possible, in terms of density (vehicles/km) and flow (vehicles/h). The concept of PCU can be summarized as a metric used to convert a scenario of heterogeneous traffic into a homogeneous flow, where is assumed that only passenger cars are transiting.

The traffic flows are made-up of different vehicles whose characteristics are different either geometric or mechanical, which mean disadvantages and advantages for each vehicle along the traffic flows. Due to this traffic behavior, there are different methods to estimate the value of the PCU associated with a specific type of vehicle, depending on the conditions of the study.

For convention, there are different PCU values according to the vehicle type:

- Motorcycle = 0.5

- Private car (passenger car) = 1
- Collective Van (Combi) = 1.2
- Bus = 2.82
- Tractor, truck = 3.5

2.2 Microscopic traffic modelling

2.2.1 Gipps model

Gipps model [Ni15] is based on a rule of security, which it says that the driver of the following vehicle i selects his speed $\dot{x}_i(t)$ to assure that he can carry on his vehicle to a sure stop, because of a sudden braked B_{i-1} of the leader vehicle $i-1$. So, in any moment the following driver most have to leave an enough distance of security $s_i(t) = x_{i-1}(t) - x_i(t)$ that depends of the behaviour of the leader driver. Furthermore, the vehicles position, as much from the leader $x_{i-1}(t)$ as from the follower $x_i(t)$, will be in time function.

The model works when the leader vehicle with a speed $\dot{x}_{i-1}(t)$, starts an emergency brake with an index of B_{i-1}. Aster that, the following vehicle, warned by the brake lights, with a certain speed goes to a process of perception-reaction of duration t_i and then the following driver decides to brake in an tolerable index b_i. So, The following vehicle starts to decelerate from $\dot{x}_i(t + t_i)$ until its total stop before the collision with the leader vehicle.

Therefore, the position of the leader and following vehicle, at the end of their braking are:

- Leader vehicle

$$x^*_{i-1} = x_{i-1}(t) - \frac{\dot{x}^2_{i-1}(t)}{2B_{i-1}} \tag{2.4}$$

- Following vehicle

$$x_i^* = x_i(t) + \frac{\dot{x}_i(t) + \dot{x}_i(t+t_i)}{2}t_i - \frac{\dot{x}_i^2(t+t_i)}{2b_i} \tag{2.5}$$

In the traffic behaviour can be that the space gap between the leader vehicle and the following vehicle will be considerable and would be establish a free flow in the road. For this case, Gipps suggests that is not necessary to do a distinction, due the model computes a speed for free flow and another one for the condition car-following, so, the lowest speed will be selected to determine if there is free flow or car-following. The speeds are computing with the following equation:

- Free flow

$$\dot{x}_i(t+T_i) = \dot{x}_i(t) + 2.5A_iT_i(1 - \frac{\dot{x}_i(t)}{v_i})\sqrt{0.025 + \frac{\dot{x}_i(t)}{v_i}} \tag{2.6}$$

- Car-Following

$$\dot{x}_i(t+T_i) = -b_iT_i + \sqrt{b^2{}_iT_i^2 - b_i[\dot{x}(t)T_i - \frac{\dot{x}_{i-1}^2}{B_{i-1}} + 2l_{i-1} - 2s_i(t)]} \tag{2.7}$$

2.2.2 Fundamental diagram

Fundamental diagram [KEKPP12] is a graphic representation of the traffic behaviour comparing variables as density, speed and flow. Where is possible to identify what phase is present: free flow, jam or synchronized flow. The diagram can be done comparing density-flow, speed-flow and density-speed.

On one side is the diagram done with density-flow (see Figure 2.1), where is possible to note that at higher density lower flow because is present the jam phase but also at lower density lower flow, that is possible because there are not vehicles circulating on the road; the local max of the diagram represents the synchronized flow phase, where is happening the most favorable condition for the operation of the network.

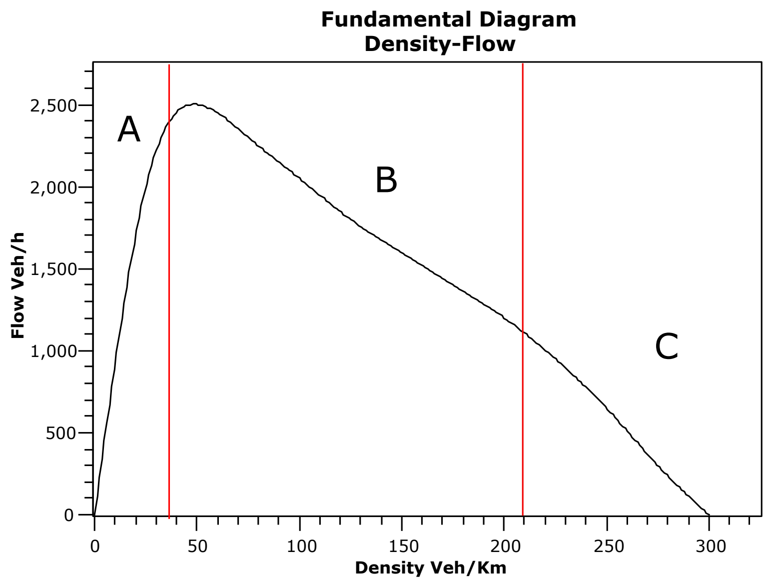

Figure 2.1: Fundamental diagram Density-Flow. A)Free flow; B)Synchronized flow; C)Jam flow.

On the other side, the diagram done with the relation density-speed (see Figure 2.2) represents at higher density lower speed. When the speed tends to zero the speed is unlimited while the speed tends to zero the density grows up until the jam phase.

Furthermore, the diagram flow-speed (see Figure 2.3) shows that a certain speed the flow gets synchronized and after that the flow is decreasing together with the speed. Also is possible to show the free flow in the interval where a certain speed, the flow increases lineally until the first deflection point of the curve.

2.2.3 Modelling a road network

The urban network can be represented as a weighted directed graph, where its graphical representation of the relation of correspondence G between two sets [MdCC+18]:

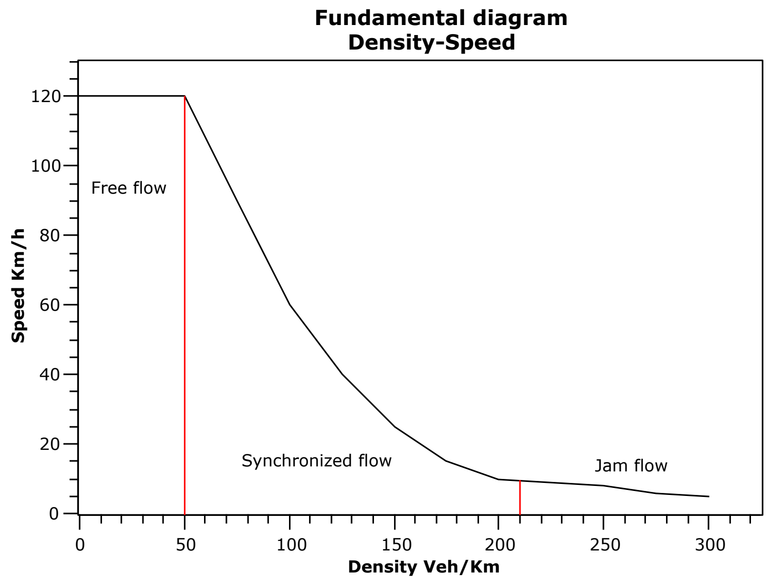

Figure 2.2: Fundamental diagram Density-Speed

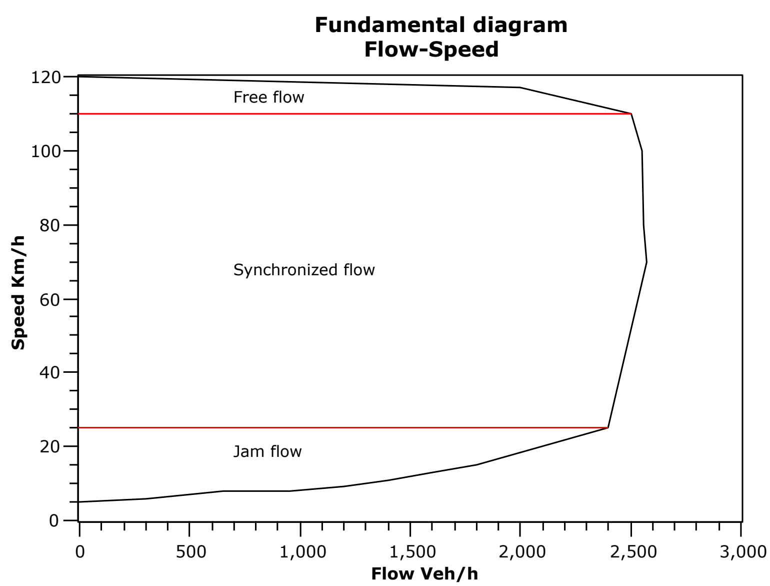

Figure 2.3: Fundamental diagram Flow-Speed

- Set of edges $E = L \cup C$
- Set of vertexes $V = Y \cup K$

They are denoted by the following ordered pair.

$$G = (E, V). \tag{2.8}$$

In the ordered pair G, the set E results from the union of a set of lanes L and a set of connectors C, $E = L \cup C$; and the set V is the union of a set of intersections Y and a set of centroids K, $V = Y \cup K$. A lane is the physical link between intersections. The centroids represents those points where vehicles enter to the system, being the connectors the different ways where the vehicles transit to arrive an intersection. For convention, the intersections are identified by natural numbers and the traffic lights by the abbreviation TL with its natural number, the centroids are identified by a capital letter in vertical sense and by double capital letters in horizontal sense, the lanes are identified by continuous lines with their sense and connectors are identified by discontinuous lines. Figure 2.4 depicts a geometric plant of the road with two intersections, and the figure 2.5 represents the graph of the traffic system composed by *two* intersections and *six* centroids.

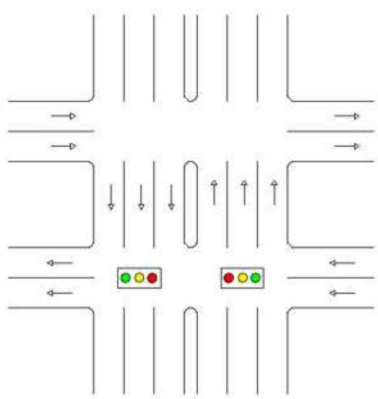

Figure 2.4: Geometric plant of the road

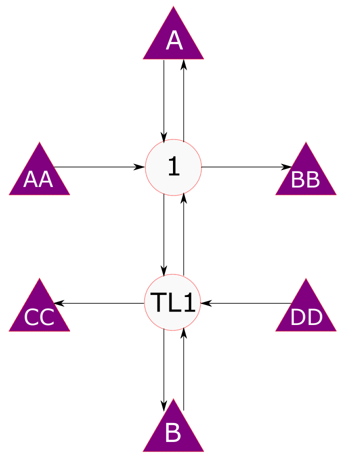

Figure 2.5: Graph of the system road

The weighted directed graph is going to be traversed using the function in-order [MR18]. The trip in-order is done by the following steps (see figure 2.6):

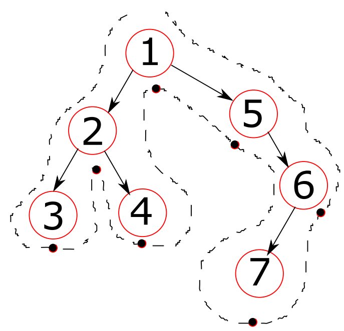

Figure 2.6: In-order function

- Check if the current intersection or centroid is empty or null.
- Traverse the left sub-tree by recursively calling the in-order function.
- Display the data part of the intersection or centroid node.
- Traverse the right sub-tree by recursively calling the in-order function.

2.2.4 Calibration of traffic microscopic models

The statistical expression GEH is a formula used by the traffic engineering, transportation and the traffic modeling to compare two traffic flow sets [DEE+13]. On one hand, the first flow is obtained by the traffic studies done in a case study. On the other hand, the second flow consists of the number of vehicles transiting in a certain period within a traffic micro-simulation of the case study.

The GEH formula is defined as follows:

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}} \tag{2.9}$$

where:

- M is the traffic flow of the traffic model
- C is the real traffic flow
- GEH must be ≤ 5

For traffic modeling, a GEH value less than 5 is considered an adequate relation between the model and the real flow. The traffic modeling of a certain stage is considered permissible if the 85% of the flows, in a traffic model, have a value less than 5.

2.3 Public transit routes optimization

2.3.1 Kruskal algorithm

It is a ravenous algorithm which objective is to obtain the minimum re-coating tree from a weighted graph, fig 2.7. It seeks that the total addition of the graph edges is the minimum possible [KN83].

The following list describes the algorithm application:

- Set of nodes V that contains the "n" nodes of the initial graph
- Set of edges E that is initially empty
- Set B that contains all of the original graph edges

- It recursively selects the lightest edge
- In each recursive step the lighter edge in set B is add to set E
- The algorithm ends when the set E cardinality is equal to n-1

Set V is the union of the addition or subtraction of routes in a point (I) and the different origins and destinations of the public transport routes (k).

- Set of nodes $V = I \cup K$

Set B, are edges weighted with the overlap evasion index. This index is the inverse of the number of routes that are overlapped.

Set E contains the selected edges using Kruskal algorithm. These edges will build the minimum re-coating tree.

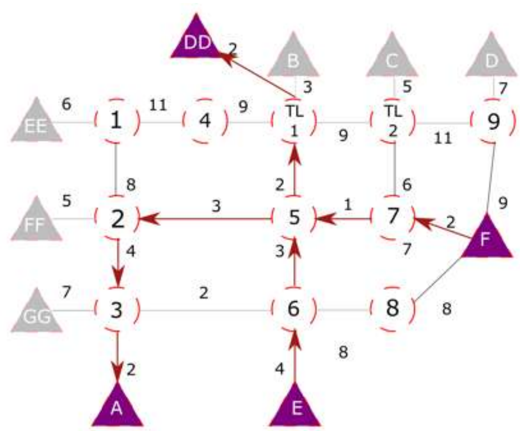

Figure 2.7: minimum re-coating tree

2.3.2 Pre-trip adaptive choice alternatives

The public transit service gets complicated when there is a diversity of route frequencies, which has impacted the pre-trip choice behavior of the users. This behavior consists of user decisions before undertaking the trip, which includes the comparison of several alternative strategies. These strategies can be selected by considering some decision rules, such as the probability to undertake a trip on a certain road where many routes offer the service.

The above user strategies are possible to be represented by constructing a line-based graph, where the edges represent the strategies and the nodes represent the forks of their trajectories. Those trajectories that connect the origin and the wished destination are called *hyperpaths*, that are associated with the probability to perform the trip along a certain road from the origin to the destination. The probability to ask the public transit service in a certain hyperpath is defined as follows, [Cas09]:

$$g_i r = \frac{f_i}{f_i + f_r} \tag{2.10}$$

where:

- $g_i r$ is the probability to perform the trip along the hyperpath i on the intersection of hyperpaths i and r.
- f_i is the frequency of public transit vehicles on hyperpath i
- f_r is the frequency of public transit vehicles on hyperpath r

Sometimes, the wished destination can be reached from the same origin by several hyperpaths along the urban network, defining a *composite hyperpath*. The *composite hyperpath* depicts the product probability pg_n of n hyperpaths to ask the public transit on a line-based graph. The product probability is defined as follows:

$$pg_n = (g_i r) * (g_r m) ... * (g_m n) \tag{2.11}$$

Chapter 3

Related work

World wide, there are distinguished two main modalities for urban collective transit supply: state-owned and private-owned. State-owned collective transit is the most popular modality in Europe since the low extension and the high density of the cities facilitated the deployment of centralized systems. In contrast, private-owned is the most popular schema in America and Asia.

Private-owned collective transit has opened the possibility to diversify the organization of the public transit supply. The most common schema consists on to delegate the operation of transit lines to individual concessionaires while the routes management and planning remain restricted to the transit authorities. This state-managed private-owned supply is widely adopted in the US and Asia.

State-managed private-owned and state-owned collective transit supply are kinds of centralized systems that continuously facing the problems of routes optimization and coordination to adapt the service to the constantly increasing demand. For this reason, in literature, there are several approaches intended to find solutions in these fields.

The weakness of regulations in which the private-owned collective transit schema was deployed in Mexico, referred to as Concessioned Public Collective Transit (CPCT), resulted in a decentralized system with particular characteristics. On the one hand, the owners individually manage their lines and routes, obeying their interests without any kind of coordination with other owners and lines. On the other hand, under this schema, the responsibilities of transport and transit authorities are limited to approve or deny permissions for new units and routes modifications, preserving a strong influence of the concessionaires [Var15]. So, these particular characteristics make difficult to directly apply the approaches for collective transit optimization reported in the literature.

With the ulterior aim to identify such approaches that can be useful to achieve an affordable solution for the reorganization of the public collective transit in some Mexican cities like Morelia, in this chapter a literature review is presented. Due to the predominance of the centralized state-owned and private-owned schemes, this survey is mainly centered on solutions for fleet and routes optimization. These solutions are focused on to reduce the transfer times, the waiting time at stops and of travel time from a stop to the other one.

Additionally, there are reviewed some approaches focused on to optimize sparse transit systems, where authors propose to dynamically modify the lines' routes to adapt the system to demand changes.

3.1 Public transit systems optimization

3.1.1 Hybrid predictive control for real-time optimization of public transport systems' operations

Cortés et al. [CSM+10] show a hybrid predictive control strategy based on evolutionary multi-objective optimization, in order to improve the efficiency of a bus system in a linear corridor with an uncertain passengers demand. This optimization is directed to the retention of units in the stations and the omission of these of a bus in route. The optimization is performed in a discrete event simulation environment to optimize the control operations in real time of the system.

The multi-objective approach is defined to minimize the waiting times and the impact of the application of control strategies over other actions. In this way, the authors establishes a variable that represents the penalty in those actions that impact over others, reflected by the extra travel and waiting times in stations and the omission of them. This variable helps the operator to regularize the gap times between the immediate units to his position that eventually could change depending of the demand variation in the route.

However, the approach is limited by the stages developed in order to support the authors' hypothesis, being these assumptions non-realistic. In this way, the authors aim the necessity to enrich this work by considering traffic variables that impact on the public transit operation. Nevertheless, the more variables are considered, the longer would be the computing time by using this approach. The latter due to the nature of the real time optimization approaches, explaining the tendency to develop fitted scenarios by this kind of approaches.

3.1.2 Stochastic optimization of public transport schedules to reduce transfer waiting times

Michel and Chidlovskii [MC16] proposed a stochastic optimization, oriented to attend the trouble of the transfer schedule modification in a multi-modal transportation system (MTS) to reduce the waiting times of passengers. For this, the retrieve a data collection about transfer times of a service to another inside of the public transit systems.

This research redefines the problem by proposing a more general solution, avoiding that the transfer travels and the conditions remain the same, after modifying the public transit lines schedule.

To simplify the problem formulation in terms of mathematics complexity, the authors defines a deterministic version of the optimization problem and subsequently he extends to a stochastic version.

The authors claim that is necessary to consider the spread of the current constraints of the problem, besides stage management for traffic data with different traffic effects and of each season. In addition, they seek a solution by executing cases in large stochastic optimization scale without using the commercial solvers.

3.1.3 Public transport optimisation based on traveller requests and network efficiency

Floudas,N. et al. [FDM+14] developed a collaborative optimization of PT through the visualization of an integer mobility system were passengers, drivers, vehicles, and infrastructure build a network in sustainable conjunction.

The main objective of this proposal is to improve the flexibility of the transport infrastructure to dynamically satisfy the demand of modern cities. Its application is mainly focused on a bus network, but it can be extended to be applied to several means of transportation in the same way, which is intimately related to the concept of transport sensitized to demand.

The proposed collaborative optimization algorithm is based on to compute a minimal cost of each route for each conveyor unit, satisfying the current demand of the users. The proposal is characterized to employ a system's simulation to obtain the most affordable parameters, with which later the real urban environment is configured.

3.1.4 Fuzzy multi-objective programming algorithm for vehicle routing problems

Dinc Yalcın et al. [DYE15] propose an algorithm based on fuzzy logic to solve the vehicle routing problems with backhauls. The algorithm has three phases: gathering, route and local search. The model assigns to the users to vehicles in the gathering phase and each vehicle is directed to route in the route phase of the model.

The proposal classifies the users and it always generates feasible gathers while the traveling salesman problem is remoulded to include users both from the backhaul network as from a transport line. In addition, the vehicle routing problem with backhauls could be solved by models of mathematics programing in the gathering and routing phases.

The primary contributions of the proposal are focused on the clustering phase, because of defining two objectives in that phase and becoming into feasible the concerned customers. The customer selection is based on fuzzy matrices that direct the weight of the objective functions in each phase. The fuzzy matrices allow an artificial perception of the algorithm about the environment, to define the vehicle route by selecting the customers as potential destinations.

Nonetheless, the authors mention that is necessary to consider more objective functions in the gathering phase to maximize the summit of the vehicles in the urban network, likewise to reduce the number of vehicles en route.

The authors state that of future extensions, additional properties could be considered, such as the travel distance and the time constraints for each vehicle and the different capacity of each kind of vehicle.

3.1.5 Robust routes for the fuzzy multi-objective vehicle routing problem

Oumayma Bahri et al. [BAT16] propose to find robust routes for a multiple-objective vehicle routing problem (VRP) with uncertain demands, where uncertainty is expressed by means of triangular fuzzy sets.

The basic vehicle routing problem, consists in finding a set of efficient routes for a fleet of identical vehicles to serve a number of geographically distributed customers subject to three main constraints: 1)that all routes start and end at a central depot; 2) that each customer is visited exactly once by only one vehicle; and 3) that each vehicle has a limited capacity that cannot be exceeded.

This approach uses fuzzy numbers to obtain a set of optimal routes that maximizes the robustness with respect to fuzzy-valued objectives. So, the objective of this research is to achieve robust routes that yield actual cost no worse than a given threshold level.

By considering the concept of B-robust routes, the authors determine such routes with a certain confidence level, that the cost in terms of total traveled distance and total tardiness time are within a given quality threshold. However, the approach tries to maximize the level of confidence that the traveled distance and tardiness time of each route would be less than the fixed threshold of the fuzzy sets.

The proposed robustness approach is intended to seeking optimal routes for this problem, by adopting the B-robustness concepts and extending them to their multi-objective context.

The authors assume a stage where the demand is uncertain, due to the uncertainty provoked by the demand of delivery for each customer. However, he did not consider time and space headways because each unit has its route being the only one circulating on it.

3.1.6 Evolutionary multi-objective optimization with uncertain travel time

Bederina and Hifi [BH16] claim that uncertainty can be modeled for the vehicle routing problem (VRP), by a set of scenarios where each scenario may represents the travel costs assigned to all edges of a graph.

Therefore, the travel cost is characterized by a set of discrete values. Hence, the VRP has to find a good solution that satisfies the majority of the established scenarios. Furthermore, VRP contains two usual objectives to minimize: the total travel cost of all the vehicles and the number of vehicles in the fleet.

The approach uses the multi-objective evolutionary optimization, because of many real world problems are multi-objective and including the optimization of opposed objectives. Into these objectives, the approach considers the number of vehicles and the total cost need to be minimized in the same proportion. This becomes the problem in robust and conflicting, so, the multi-objective evolutionary algorithm is the best option to tackle this kind of problems.

A disadvantage of the proposed algorithm is its computing time due to is not feasible neither easy to handle. The last due to the complexity of its genetic performance, the crossover and mutation process is determining results through a task of test and mistake; which that process extends significantly the execution time of the algorithm.

The authors develop the algorithm with arbitrary data to perform easier the research. They are not considering traffic features, such as density, flow, car-following condition, time tables, sorts of PT and the gathering to many holders that provide the PT service in the network.

3.1.7 Route optimization of urban public transportation

Álvarez et al. [PJA13] proposed an optimization process of urban public transportation routes based on the operation research techniques intended to develop a model that minimizes the transfer times.

On the side of the planning of urban PT, the authors suggest a task of prediction of future flows in the system, based on knowledge of human behavior, land use, economy, social-demographic information, and the current transport demand. They traduces the problem on to perform operational planning considering seven steps: 1) survey the demand of travels from origins to destinations in the city: 2) determine a modal split; 3) design of lines or routes; 4) set a frequency determination of passengers for each line; 5) determine the schedules; 6) set a vehicle scheduling; and 7) set a scheduling of drivers.

The proposed model includes additional features, such as minimizing transfer times. Regarding the solutions of the model, it suggests the application of meta-heuristic techniques as genetic algorithms. This aims the difficulty in terms of computational time, due to the large process that implies the application of metaheuristic and genetic algorithms.

Finally, the authors say that is advisable to include stochastic in some variables for future work, in order to obtain more robust models.

This research just makes a possible application of a optimization model through operation research techniques, which it is totally out of the reality being only a hypothesis without to be verified with an adequate quality data.

3.1.8 Multi-agent optimization model for multi-criteria regulation

Morri et al. [MHS15] proposed the construction of a regulation support system of public transport (RSSPT) for multimodal traffic. This RSSPT considers the punctuality, regularity and correspondence of the units that provide the service of public transport. Also, the approach deals with many disturbances at the same times by distributed decision. Moreover, the model treats many disturbances and considers some multimodal features, such as the sort of PT and type of vehicles.

The proposed system is subdivided into three modules: the disturbance acquisition, the regulation and the evaluation module. The first module supervises the network by collecting information from the the operating support system of the PT network locating the units. The second module analyzes detected disturbances by defining the risk of a vehicle and/or the risk of a gap. Furthermore, this phase establishes possibles actions, such as increasing or decreasing the number of vehicles in route and accelerating or decelerating the vehicles in route. Finally, the third module chooses the regulation action according to the feasibility of its application and this action will be controlled in the PT network.

The approach consider additional constraints, such as the working time driver do not exceed the work schedule of the drivers; in the same way, the working time vehicle has to be considered to keep the good state of vehicles, taking care to do not exceed the capacity load of each type of unit of the PT.

The research proposes to use the multi-agent approach for RSSPT, since the multi-agent is well adapted to multi-modal PT network activities; where autonomous entities interact between them in a distributed, open, dynamic, heterogeneous and complex environment. Hence, the RSSPT is based on agents that have different behaviors and able to communicate, cooperate and negotiate to detect and solve disturbances.

3.2 Analysis of traffic patterns for the transit systems improvement

3.2.1 Visualizing Mobility of Public Transportation System

Zeng et al. [ZFA$^+$14] proposed a system to visualize the passengers' mobility of PT that characterizes the passengers' activity and derived in methods to estimate mobility features, such as, waiting times, time in route, transfer times, and travel efficiency.

The estimation of these features is determined by the data collecting about passengers, since in the PTS is possible to do that task by using radio frequency ID as entry and exit pass of the system.

The system operation is visualized with three modules: iso-chronic maps, maps of iso-temporal flow and with the visualization of the O-D matrix. The maps of iso-temporal flow consist in a strategy of innovating visualization, which linearizes a vehicular flow map in a parallel iso-temporal layer, besides representing in a clear and friendly way the routes from an origin to the different destinations. These maps were compared with approaches of other transport experts, one of these works is the mobility wheel visualizing the O-D matrix; with that were able examining the temporal variation with all the mobility information.

The work is totally aimed to facilitate the pre-trip planning of the users through public transit systems, due to the premise that the visualization of the operation of public transit services is useful to enhance the productivity of the transportation system.

3.2.2 Assessing public transport systems connectivity based on google traffic data

Yuval Hadas [Had13] presents an unified methodology for extracting, storing and analyzing PT data as derived from the availability features of PT systems. These features are: spatial, where the service is provided; temporal, when the service is provided; information, how to use the service; capacity, space available for the passengers. Furthermore, the research enables relatively easy spatial and temporal analysis with GIS techniques. The approach is based on solely google traffic feeds and any available infrastructure layers with no need for additional data.

The author also adds and connects the stops to the network, creating a PT layer and relating it to the transportation layer. Furthermore, the author built routes based on a sequence of stops, reconstructing the routes in GIS format. Also, the time headway information through the scheduled departures associated with each route is retrieved. Subsequently, the author makes a network analysis using the stored spatial and temporal data to calculate the indicators, for assessing PT system connectivity.

The research aims a check of the data quality, where is necessary make a review in the elements of the transport network: direction, restricted turns and network connectivity. In the same way, it is done a check of general traffic feeds specification data, such as stops location, routes layout and time-tables.

After performing quality data check, this approach allows to get the following indicators:

- The transport network coverage and accessibility level indicator. It is able to compute the flow and the average speed of PT vehicles in route.
- The intersection coverage level indicator. This emphasizes the flow at the intersection level, thus enabling the node-level assessment of the network.
- The stop-transfer potential indicator. This indicator computes the possibility of a transfer from a trip of a route at a stop to all other routes, within a maximal walking distance of 100 meters.
- Route overlap indicator. It indicates the overlap between the routes of the PT service.

These indicators are gotten from PT systems from three different cities, where the author made the counting in a certain period, choosing the time of day period, day of the week and selecting the routes of the bus system.

3.3 Adaptability in sparse transit systems for dynamical demand changes

Errico et al. [ECMN13] have widely surveyed about approaches oriented to establish a semi-flexible public transit system. The author considers the contribution by Samuel Deleplanque and Alain Quilliot [DQ13] in their work about the dial-a-ride approach (DAR), where they use it as a personalized service, that modifies its schedule, itineraries and stop locations according to the needs of the users. This approach was developed in order to serve vulnerable society groups, as elder and disabled people. In this way, according to Posada and Anderson [PAH17], the integrated DAR (IDAR) approach that is a extended version of DAR. The main difference of this approach for the user, is the possibility to transfer to other transportation modes, and being able to be picked up again for a DAR line.

Finally, Crainic et. al[CEMN12], describe the demand adaptive system (DAS) approach like very similar to traditional transit service provided in many cities. This approach is constituted by a set of several compulsory stops and a set of time windows between such compulsory stops. DAS establishes that the requesting service at optional stops are allowed, so that the users requesting the service at optional stops are called active users, while those requesting exclusively at compulsory stops are identified as passive users. Finally, the fourth surveyed approach by the authors is the semi-flexible transit system. This system is a summary of the three above-mentioned approaches, since several authors defined them as types of semi-flexible transit systems. However, there is a classification of this kind of systems according to their operation features:

- Route deviation. Consists on the traditional public transit service with schedules and allows optional requests that could be serviced by deviating the route to pick up passengers. The passengers may ask for service at any point on the main path, by waving their hands when the vehicle approaches.

- Point deviation. The route is formed by a sequence of compulsory stops and the users cannot request the service anywhere. However, this semi-flexible system serves passengers in a given area between compulsory stops, working under the premise of demand responsive with the possibility to provide the service to neighborhood out of the path.

- Demand responsive connector. The vehicles serve a given area operating in a demand response mode. Th main difference with the latter system is the implementation of transfer points to connect with other public transit modes.

- Request tops. The line works with fixed-schedule, fixed-route, but the optional stops are allowed at points near of the main path.

- Flexible route segments. The fleet works as a public transit service, fixed-schedule and fixed-route. However, it could switch to demand-responsive operation to serve limited portions of the main path.

- Zone routes. This system works as demand-responsive covering a given zone. Usually there are just two compulsory stops, corresponding to initial and final station. Thus, the routes could be cyclic, because of the initial and end station could be located at the same place.

As were described, there are several alternatives to establish a semi-flexible pubic transit system. However, the authors aim that a framework unification is needed to facilitate the planning and developing of public transit. Thus, the unified framework consists on the consideration of the urban and economic features of each city, due to the different scopes of each semi-flexible transit systems.

The authors have established policies to follow in order to facilitate the planning of public transit in urban surfaces. These policies considerate operational features, which are described in the following:

1. The requests must be rejected if their acceptance makes the route deviation becoming unfeasible with respect to the time windows, if the request is accepted the passenger must be picked up and dropped off at the position where the user requests.

2. The users are always picked up at the point where they request, but they are going to be dropped off at a fixed stop near the position where the user requests.

3. The users must request both the pick up and drop off. If the user picks up or drops off at arbitrary point, the services pays penalty.

The work claims the necessity to optimize the public transit systems, proposing policies in order to achieve it. However, the authors just have surveyed the literature making a summary of the most aware works that tackle semi-flexible systems and some application cases.

Chapter 4

Public transport reorganization through rational territory management

4.1 Description of the study location

Morelia is the capital city of Michoacán state in Mexico, being the largest and most populated city of Michoacán. This urban surface has a population of 829,625 inhabitants [INE15], without consider the floating population coming from surrounding towns that is attracted by different human activities. In 2015, the urban agglomeration of Morelia was of 234km^2, where the dwelling expansion has been increasing more than the population rate [OH15]. Due to the unplanned expansion, the population dispersion has motivated the increasing of vehicle-based transportation, accelerating the growth of the motorization rate. This volume of circulating vehicles has aggravated the mobility conditions of the city, which has intrinsic constraints due to its morphology.

The urban mobility in Morelia has serious inhibitions due to the its disorganized poly-centric structure, where there are just three vehicular axles, one internal traffic circuit and many local streets without connection among them [OMV17]. This conditions directly impacts the traffic behavior since the user's movements overload specific centroids of the urban network. This issue can be depicted in the most important traffic distributor of the city called *Obelisco a Lázaro Cárdenas*, where the two main city axles converge, distributing trips to the four cardinal points.

4.2 Study context

For this research, the *Obelisco a Lázaro Cárdenas* is considered as a case study. This urban subsystem consists of a multiple-intersection which connects the main vial axle with four collector roads and four local streets. This centroid distributes an average of sixty-thousand vehicles daily. The choice of this case study was initially precipitated by its complex morphology and the great vehicular load.

This zone is characterized by a great population of public transport collective units, comprising a total of 48 routes/lines: 23 based on collective-based and 25 bus-based. These routes cover up to 96 origins and destinations deployed throughout the city, whose trajectories deployment is depicted in figure 4.1.

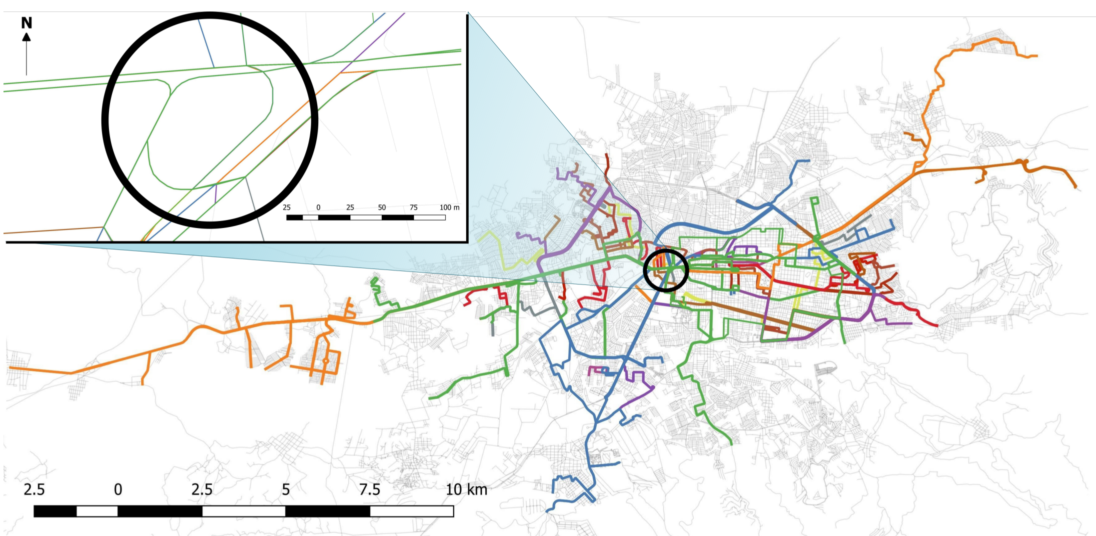

Figure 4.1: CPCT trajectories that converge in the zone of case study

4.2.1 Data collection and information retrieval

In order to characterize the case study, there were performed traffic volume studies and an origin-destination (OD) survey about the coverage of the CPCT. The traffic volume studies were performed to determine the vehicular density and the trips distribution of the studied intersection. Density reveals the over-saturation of the road network and it can be used to determine the imbalance between the population of both particular vehicles and CPCT. In addition, the CPCT OD survey was performed to determine all the routes that converge in the zone and how all the involved routes are deployed throughout the city.

4.2.1.1 Traffic volume studies

Due to the morphology of the centroid, traffic volumes were retrieved through the deployment of pneumatic traffic counters/classifiers and manual counting supported by video recordings. Weekly surveys were performed with pneumatic counters to determine the average volumes and to identify the most representative time-of-days (TOD). This raw data was refined by aggregating the transport mode volumes retrieved from video recordings of selected TODs.

4.2.1.2 Origin-destination distribution of the CPCT

OD distribution of the CPCT was performed through interviews with the schedulers located in different checkpoints along the CPCT trajectories. These schedulers control the appropriate time gaps among the CPCT vehicles of a line to keep an equitable spacing frequency. This frequency varies according to the number of vehicles in service, which in most of cases is independent of the passengers demand. In the case study, the time spacing employed by the CPCT lines varies between 3 and 30 minutes as is shown in Table 4.1 and Table 4.2. These frequency values means an average of 502 CPCT vehicles/hour that arrive to the centroid.

Traffic volume of bus routes of the CPCT				
Routes	Frequency (min)	CPCT flow (veh/h)	PCU	PCU/h
Panteón	12	5	2.84	14.2
Ruta 2	7	9	2.84	25.56
San Juanito It	6	10	2.84	28.4
Nueva Esperanza	6	10	2.84	28.4
El Pedregal	6	10	2.84	28.4
Circuito Carrillo	8	12	2.84	22.72
CC Leandro Valle	10	6	2.84	17.04
CC Lucio Cabañas	10	6	2.84	17.04
Ind Misión del Valle	8	8	2.84	22.72
Ind Mariel	8	8	2.84	22.72
Ind Hospitales	8	8	2.84	22.72
Paloma Azul Zimpanio	3.5	17	2.84	48.28
Paloma Azul Arquito	3.5	17	2.84	48.28
Paloma Azul Campiña	3.5	17	2.84	48.28
Villas del Pedregal 1	6	10	2.84	28.4
Villas del Pedregal 2	6	10	2.84	28.4
Villas del Pedregal 3	6	10	2.84	28.4
Villas del Pedregal 4	6	10	2.84	28.4
Villas de La Loma	15	4	2.84	11.36
Villa Magna	13	5	2.84	14.2
La Hacienda	10	6	2.84	17.04
Jardín Montaña	30	2	2.84	5.68
Lomas de la Maestranza	20	3	2.84	8.52
Capula	12	5	2.84	14.2
Tacícuaro	20	3	2.84	8.52

Table 4.1: Frequencies of CPCT bus-based routes

Traffic volume of collective routes of the CPCT				
Routes	Frequency (min)	CPCT flow (veh/h)	PCU	PCU/h
Azul A	4	15	1.2	18.0
Azul B	4	15	1.2	18.0
Azul C	9	7	1.2	8.4
Café 1	4	15	1.2	18.0
Café 1A	8	8	1.2	9.6
Café 2	4	15	1.2	18.0
Café 2A	4	15	1.2	18.0
Café 2B	4	15	1.2	18.0
Roja 1	9	7	1.2	8.4
Roja 2	9	7	1.2	8.4
Roja Oken	9	7	1.2	8.4
Roja 3	9	7	1.2	8.4
Roja 3A	9	7	1.2	8.4
Roja 4	9	7	1.2	8.4
Roja 4A	9	7	1.2	8.4
Roja 4M	9	7	1.2	8.4
Verde 1	3	20	1.2	24
Verde 2	3	20	1.2	24
Verde 3	3	20	1.2	24
Morada 1	2.5	24	1.2	28.8
Morada 2	3.5	17	1.2	20.4
Gris 3	3.5	17	1.2	20.4
Amarilla 2	4.5	13	1.2	15.6

Table 4.2: Frequencies of CPCT van-based routes

The trajectories of the 48 CPCT lines that converge in the centroid were spatially represented by using geographic information systems (GIS). The trajectories were traced in a GIS layer by using poly-lines for each route and feeding their relational data bases with the length, orientation and route name. The digital map of these trajectories shows the OD coverage of the CPCT lines. The lines' endpoints, are too close in some cases, which means distances less than one kilometer. According to Chen et al. [CBL+18], a separation of one kilometer between a couple of origins/destinations decreases the productivity of their trajectories.

Through the GIS analysis it was determined that on average the CPCT trajectories have a length of 15.58 km of which, in the worst case, in a corridor of 12.47 km coexist between 11 and 38 lines. This means that exists an important redundancy of the CPCT lines, which can be geometrically depicted through the overlapping of the OD trajectories. To quantify this overlapping, an additional GIS layer was created to identify the number of lines coexisting on each segment. Additional poly-lines was traced by using a chorochromatic scale to allow a hierarchical visualization of the overlapping as is shown in Figure 4.2. From this analysis, it was identified a critical case where 38 CPCT routes are overlapped in 1km which means up to 374 CPCT vehicles per km/h.

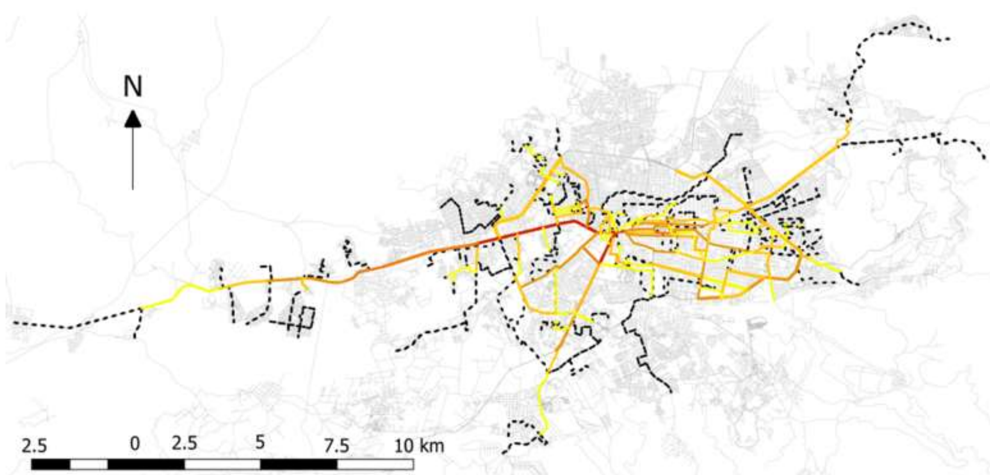

Figure 4.2: Chorochromatic poly-lines of the overlapping of CPCT trajectories

As can be seen in figure 4.2, the routes redundancy is higher on the edges represented by warmer colors, otherwise, the redundancy is lower. In addition, the black discontinuous lines represent the roads without redundancy, depicting the high routes overlapping of the CPCT along the urban network.

4.3 Theory/calculation

4.3.1 Modeling the CPCT network

When a road network is modeled from digital maps, 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 these elements is by the concept of a graph.

To represent the way the CPCT lines are distributed throughout the city, a subgraph of G_{road} is defined by considering those roads that matches with the lines trajectories. This directed sub-graph G_{CPCT} is formed by the set R_{CPCT} and the set I_{CPCT}. The elements of $R_{CPCT} \subseteq I_{CPCT} \times I_{CPCT}$ consist on the roads where the CPCT lines transit while the elements of I_{CPCT} are the intersections where those lines bifurcate.

Based on the sub-graph G_{CPCT}, the oversupply is depicted by assigning a weight w_i to each road $r_i \in R_{CPCT}$, where w_i means the number of the CPCT routes/trajectories that coexist on the same road. The value w_i allows to quantitatively establish how the trajectories of the CPCT are overlapped along determined segments of the road network. The figure 4.5 depicts a view of the weighted sub-graph.

The way that the weights are distributed throughout the graph can be used to identify the most profitable trajectories, since the most overlapped corridors

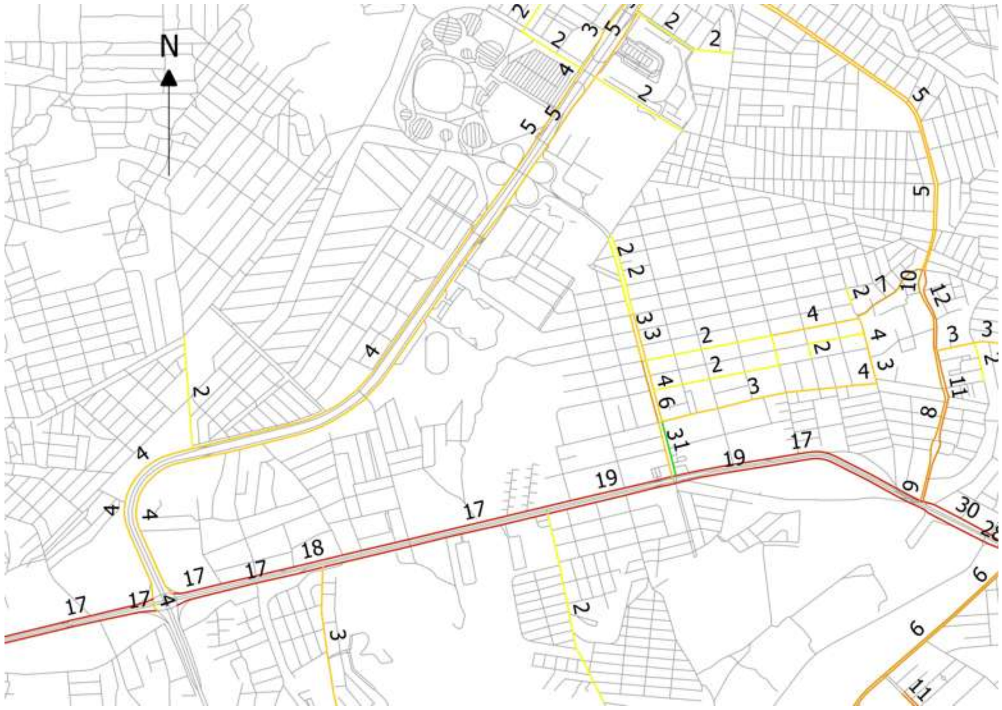

Figure 4.3: Weighted sub-graph

represent the segments of the road network where exist the major supply and demand.

In those cases, the concessionaires of the CPCT have tried to satisfy the high demand by providing multiple options, which at the same time, have been profitable for them. Nevertheless, the scheme followed by the concessionaires was focused by only considering the commercial competition and did not consider the traffic saturation either the productivity of the service.

For the mobility problems carried by the saturation of the CPCT, a solution towards the unification of the public transit lines is required. In this sense, a unification scheme can be supported by the weighted graph in an attempt to convert the overlapped segments into more productive trajectories while the urban mobility is improved.

4.3.2 Towards the unification of the CPCT

The main goal of this approach is to propose a methodology to re-distribute the CPCT routes, considering the roads where there are a high overlapping level. Those roads can be selected by constructing the backbone of new CPCT system. In this approach, the backbone is defined by the minimum spanning tree (MST) of the network.

The MST is formed by applying the Kruskal algorithm over the weighted graph depicted in section 4.3.1. Since the Kruskal algorithm is designed to find the subset of edges with the minimum weight that connect all the vertex in a graph, the overlapping level determined by each value w_i is normalized through an overlap avoidance index, defined as follows.

Definition 1 *Overlapping avoidance index. The overlapping avoidance index (oai) is defined as the inverse of the number of CPCT routes that coexist in the same road section* i*, expressed by* w_i*.*

$$oai_i = \frac{1}{w_i} \tag{4.1}$$

4.3.2.1 Construction of the minimum spanning tree of the CPCT graph

Supported by a new layer of a GIS, the MST of G_{CPCT}, denoted by T_{CPCT}, is constructed by performing the Kruskal algorithm as follows:

1. All the edges $r_i \in R_{CPCT}$ were sorted in ascending order according to their associated overlapping avoidance index oai_i.

2. Each new edge of T_{CPCT} is added by pick the edge $r_i \in R_{CPCT}$ with the minimum oai_i, if only and if r_i does not form a cycle in T_{CPCT}. Such the edges $r_i \in T_{CPCT}$ that are susceptible to form cycles, are discarded.

3. Step 2 is repeated until all the vertexes of I_{CPCT} are included in T_{CPCT} and the resultant MST is fully connected.

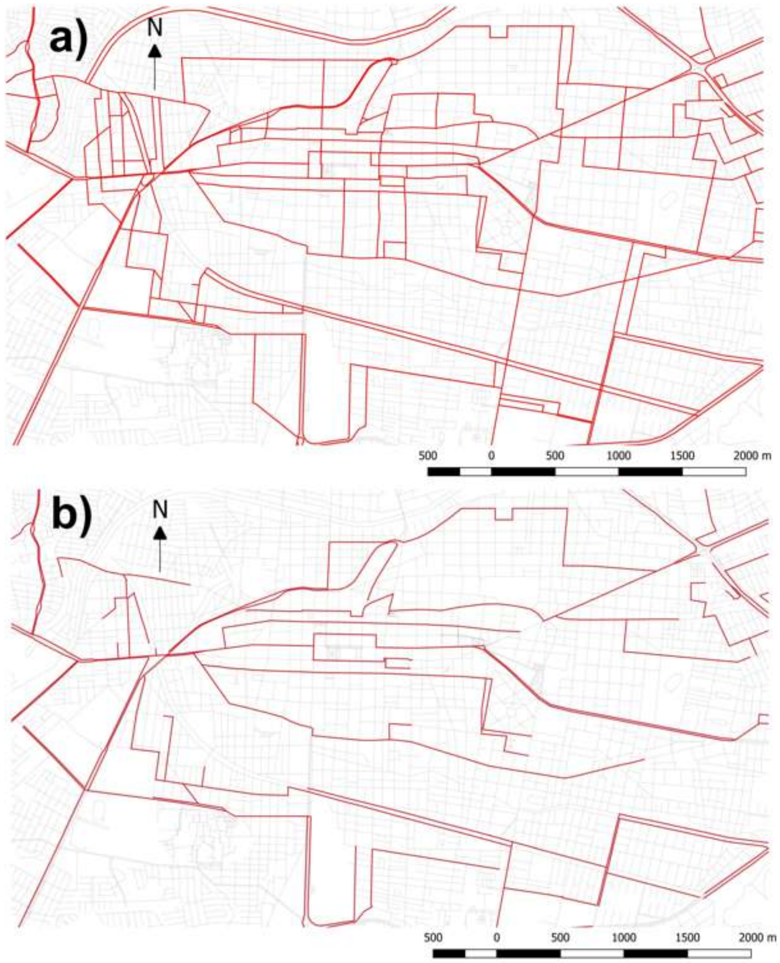

Figure 4.4: Close up of the most overlapped region. a)Weighted graph G_{CPCT}; b)Minimum spanning tree T_{CPCT} of CPCT

The resultant MST allows to identify all the roads that can be used to construct the backbone of an unified CPCT scheme. Due to the edges of the MST are the most overlapped roads, represent the trajectories with the highest demand and where in the current arrangement exists the major oversupply. Moreover, the roads with the highest overlapping level have the enough geometrical dimensions to establish massive modes of transportation, such as bus rapid transit (BRT).

As can be observed in figure 4.4, the MST discards the roads with the less demand which in most cases are short segments of the network where some lines have forks to justify the coverage of different destinations. Although different destinations are covered, these forks induce the oversupply on the remaining roads. Those shorts roads, where the forks are done, do not overpass one kilometer of length which several authors [NBM19] [MSS13] considers a walkable distance.

4.3.3 Construction of the backbone for the unified CPCT

The MST described in section 4.3.2.1 is a simplification of the CPCT deployment graph, which reduces the redundancy caused by the oversupply. However, to achieve a backbone for the CPCT unification, the MST T_{CPCT} needs to be adjusted to avoid some paths that could not be coherent due to the network morphology. In this way, the graph T_{CPCT} must be trimmed by considering the geometrical characteristics of the requested roads. In this way, a feeder sub-system can be formed by using the discarded edges by applying a trim process. The trim process is described through three stages as follows.

4.3.3.1 Stage 1: Discarding of the edges with the major *oai*

Although the Kruskal algorithm warranties that the MST T_{CPCT} has no redundancy in the interconnection of vertexes, it sill keeps some edges that result redundant according to a city morphology. In other words, in T_{CPCT} could be maintained some trajectories whose origins and destinations are covered by other trajectories with a greater overlapping of CPCT lines. A public transit backbone is intended to connect two extreme points of the city, without interruptions, like an arterial system. By using this premise, for the case study it was found that the edges that must be discarded are those whose *oai* value is between 0.020 and 0.16 ($6 \leq w_i \leq 48$) fig 4.5.

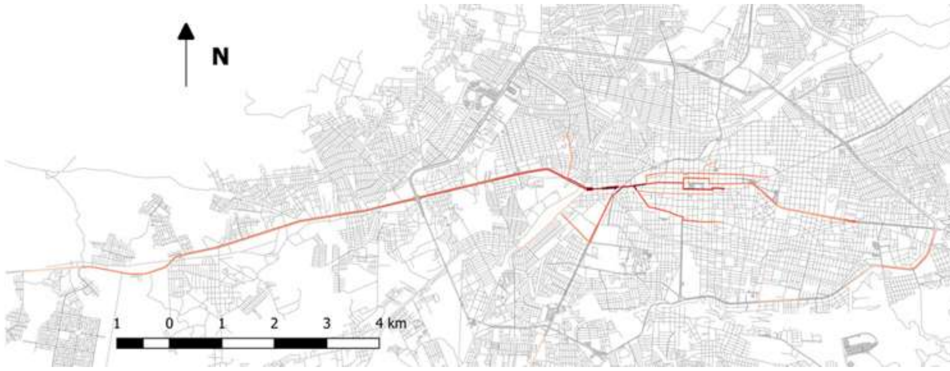

Figure 4.5: Edges of the MST with a *oai* value between 0.16 y 0.020 ($6 \leq w_i \leq 48$)

4.3.3.2 Stage 2: Calibration of the resultant trimmed sub-tree

After trimming T_{CPCT}, the resultant sub-tree contains the edges with the major oversupply and demand. However, there are some edges that could be changed or replaced by tracing new ones to improve the determined sub-tree for the CPCT unification, so that is necessary to perform a calibration of the trimmed sub-tree. The calibration, to get the backbone of the CPCT (fig 4.6), is based on the following:

- The concerned roads must be evaluated to verify their geometrical characteristics since there are segments on the net whose dimensions would not be enough to contain an arterial route.
- New edges were traced to extend some paths in order to propose the initial/final stations and cover some discarded origins/destinations.

4.3.3.3 Stage 3: Construction of the feeder system by using the discarded edges

The trimming process could disconnect some origins/destinations that must be served. These centroids are elements of disjointed graphs, which are used to determine the connection paths among these centroids and the backbone system. Thus, the trimming process is recursively applied in order to get the MST of the

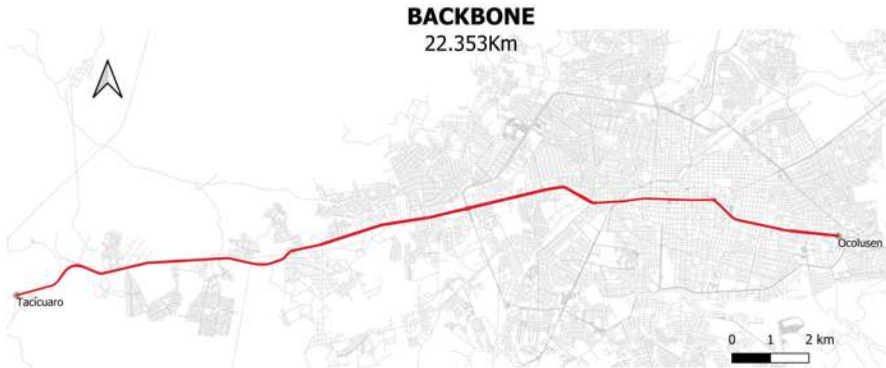

Figure 4.6: Determined backbone for the CPCT reorganization

isolated graphs. In this way, the determined MST, of each disjointed graph, must be used to construct the trajectories of the feeder system, fig 4.7. The resultant feeder system could be operated by the discarded routes of the CPCT, that were affected by the trimming process. This fact warranties the reorganization of the CPCT without affecting the concessionaries' interest while the performance of public transit is improved.

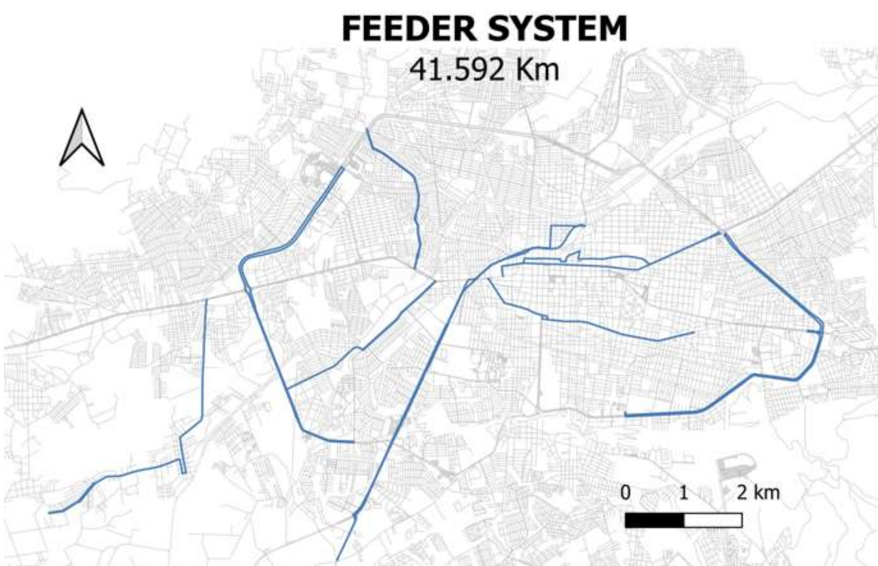

Figure 4.7: Determined feeder system for the CPCT reorganization

4.3.4 Validating the backbone and feeder systems

The proposal of this case study was validated by applying the concept of *hyperpath*, which consists of representing decision rules through edges connected by diversion nodes. The decision rule is based on the probability to ask the public transit service on a segment, by considering the CPCT routes frequencies that connect the origin O to destination D. The latter defines the diversion nodes as the locations where the probability changes due to the frequency variation of the CPCT routes that reach the concerned $O - D$.

In order to apply the hyperpaths, it was developed a stage with an origin and a destination connected by several CPCT routes on the road network (see fig 4.8). On one hand, the selected destination D is located at the intersection of the main arterial road of the urban network (*Francisco I. Madero* avenue) with a collector road (*Mariano Michelena* street). Moreover, the selected origin O is located at the intersection of an arterial road with the main collector road of the city (*Acueducto* avenue and *Lázaro Cárdenas* avenue). The above-defined destination D can be reached by several alternatives that the CPCT offers, however, there are just three coherent alternatives that a potential user could select to undertake a trip.

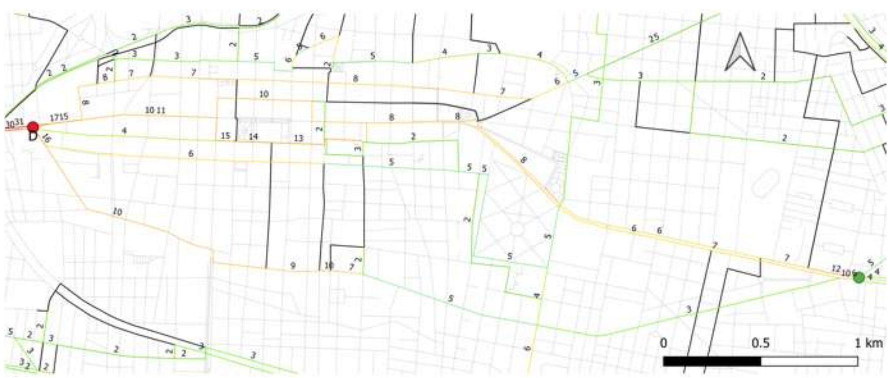

Figure 4.8: Location of the selected origin and destination over the CPCT weighted graph

The latter alternatives are represented as a composite hyperpath, which is constituted by three hyperpaths that are depicted in fig 4.9. The hyperpath A has a length of 4.70km, being the shortest path between O and D. The hyper-

Hyperpath	Length (km)	CPCT frequency (veh/h)
A	4.70	55
B	5.28	48
C	4.73	60

Table 4.3: Hyperpaths properties

paths B and C have lengths of 5.28km and 4.73km, respectively. The hyperpath characteristics are summarized in table 4.3.

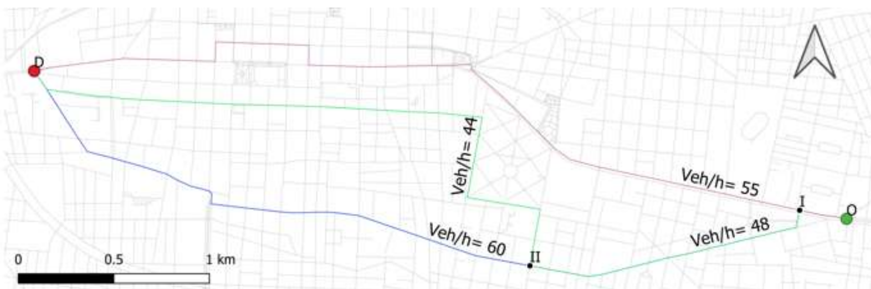

Figure 4.9: Composite hyperpath

The frequency of each hyperpath, is the maximum number of CPCT vehicles that transit through the involved roads from the origin O until destination D. However, the hyperpaths intersect among them in certain points, being these the diversion nodes of the composite hyperpath. As can be depicted in figure 4.9, the hyperpath A intersects with hyperpath B at diversion node I, and hyperpath B intersects with C at II. The computed probability of each hyperpath, after and before diversion nodes, is shown in figure4.10.

On the one hand, the obtained results show that the hyperpath A is the alternative with the major probability to be selected by a user. On the other hand, hyperpath C would be the second alternative since has more probability than hyperpath B, when D is reached from the origin O. Therefore, these hyperpaths are comparables with the backbone and feeder system proposed in this work, where the hyperpath A fits with the trajectory of the backbone while C matches with the trajectory of the feeder route number 7 (see figure 4.11). In this way, the

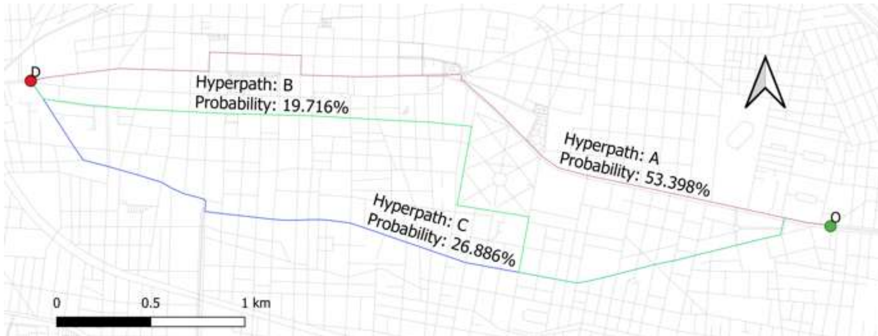

Figure 4.10: Probability of each hyperpath

CPCT unification method is able to determine trajectories in real stages, even in decentralized transit systems whose management could be hard by applying other approaches.

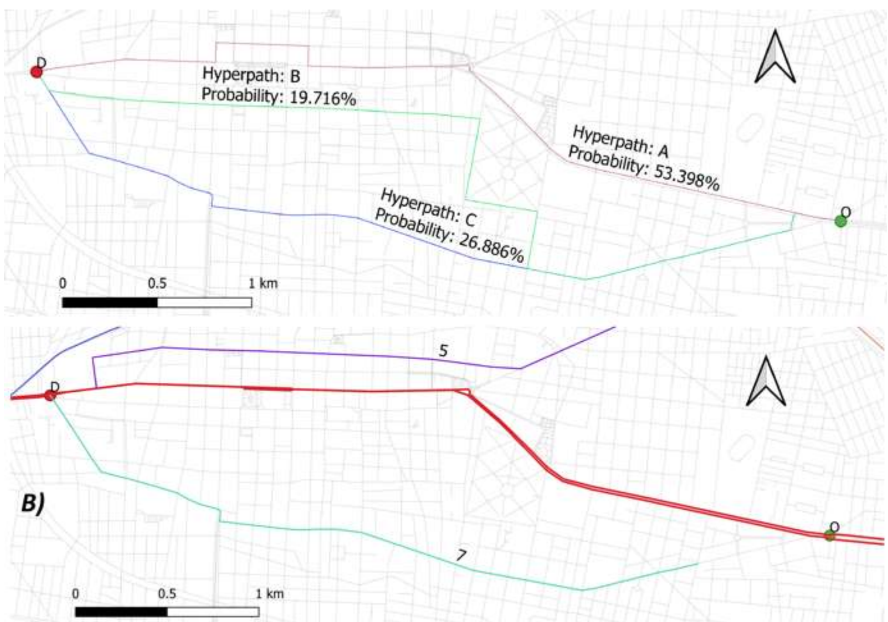

Figure 4.11: Comparison Unified CPCT system with hyperpaths

4.3.5 Proposal for the CPCT unification

Towards to improve the efficiency of the CPCT of Morelia, a unification scheme is proposed. This scheme is based on the backbone and the feeder systems, depicted in the previous sections.

The proposed backbone connects two endpoints of the city, through the main road axle having a length of 22.353km. In addition, this system unifies up to 48 routes that share their trajectories in a determined segment of them, becoming it into the route with the highest level of supply. A general view of the backbone and feeder system is depicted trough the GIS layer that is shown in figure 4.12

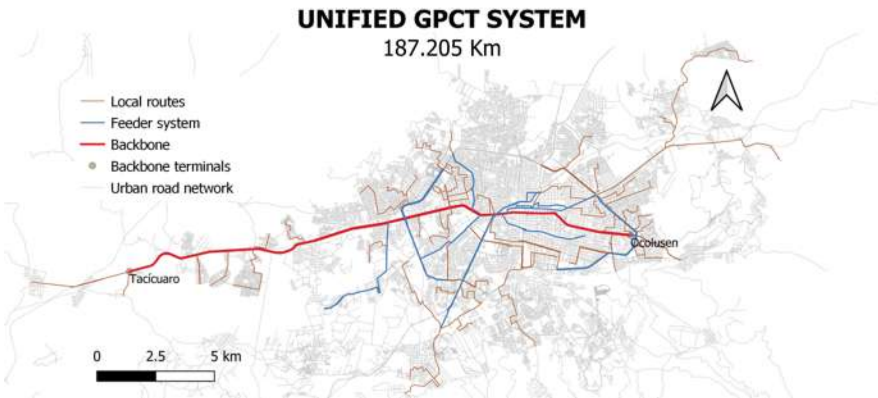

Figure 4.12: Unified system

Complementing the backbone deployment, it was determined the routes deployment which fits as a feeder system. The feeder system comprises 9 trajectories that unify up to 17 CPCT routes. These trajectories have lengths from 2.66km until 7.77 km, which significantly reduces the average length of the current CPCT routes. The feeder routes are depicted in figure 4.13 and their characteristics are summarized in table 4.4.

Finally, the unified CPCT system is enriched by trajectories that could operate as local routes. These potential routes have been composed of the edges that were discarded in the backbone construction process. So, the local system comprises 60 trajectories with lengths from 0.125km to 6.77km. However, there are 12 routes that could be omitted due to their length is of up to 1 kilometer, which is considered unproductive [CBL+18]. Based on the last assumption, the system of local routes is composed by 48 potential routes that are depicted in figure 4.14.

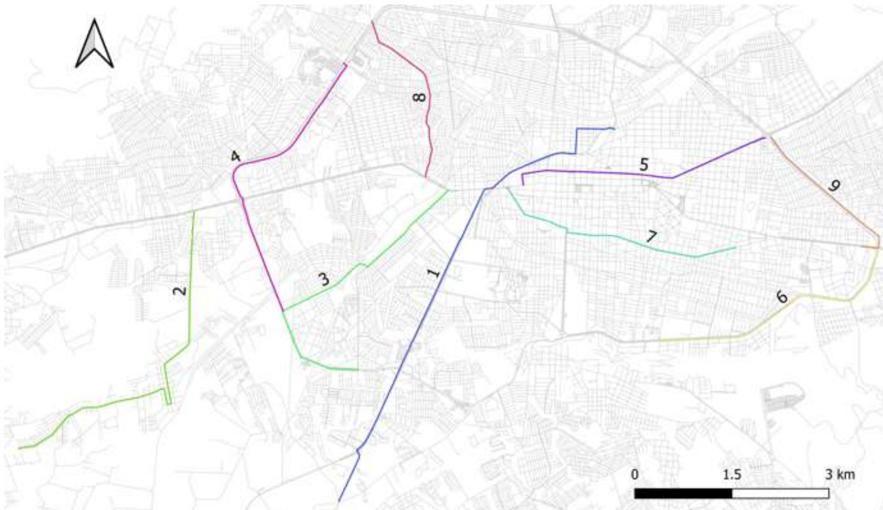

Figure 4.13: Feeder routes

Feeder route	Length (km)	CPCT routes unified
1	7.77	17
2	5.99	3
3	4.93	6
4	4.86	5
5	4.35	10
6	4.27	8
7	3.92	16
8	2.83	13
9	2.66	3

Table 4.4: Summary of the feeder system

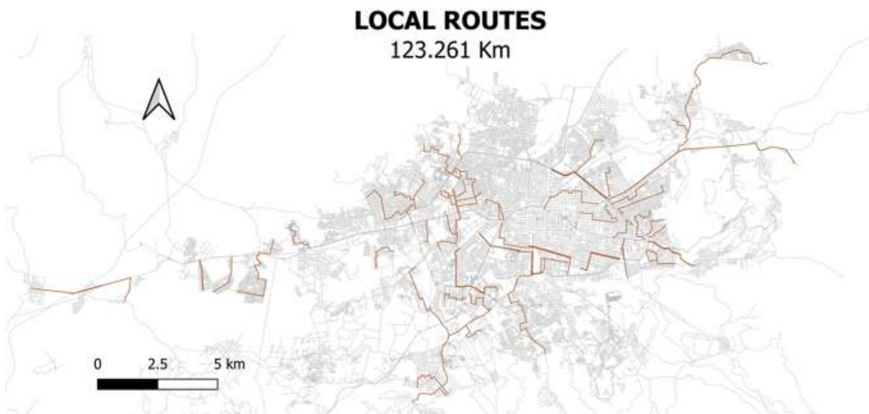

Figure 4.14: Potential trajectories to be operated as local routes

4.4 Microscopic traffic model of the case study

To show the feasibility of the proposed solution, a microscopic simulation of the case study was developed. A SUMO-based simulation [KEBB12] was developed to recreate the behavior of the traffic flow, under the various fluctuations that are experimented during a whole day. The microscopic simulation has two main objectives: a) to characterize the case study through the traffic flow and density, according to the current situation, and b) to obtain a preliminary analysis of the impact of the unification scheme application.

The system model which has been used for the microscopic model is composed by the following elements:

- Two dual arterial roads with west-east, east west, north-south and south-north traffic respectively.
- A roundabout with three pre-fixed traffic lights where the arterial roads converge.
- Three collector roads with dual flows.
- Eighteen local roads with single traffic orientation.

Road type	Maximum speed (km/h)
Arterial	50
Collector	40
Local	30

Table 4.5: Summary of the feeder system

4.4.1 Digital map

The simulated road network is based on Open Street Maps (OSM), however, some configurations are needed to fit it on the simulator. The supply transportation is represented by the real conditions of the static elements in the case study, considering number of lanes, road orientation, speed limit, and allowed movements. Nevertheless, there are segments where their capacity is reduced because of the non-regular parking and the informal commerce that is occupying space of the road. In this way, the digital map was constructed just considering the useful lanes, ignoring the remaining of them (see figure 4.15). Moreover, the local traffic signs rule the maximum speed on the different kind of roads, such as depicted in table 4.5.

The road network of the case study is regulated by 12 synchronized pre-timed traffic lights, whose signaling are adjusted within cycle times from 90 until 110 seconds. The offset times are different between each other, due to the different cycle times. The traffic lights properties are summarized in table 4.6.

4.4.2 Traffic information retrieval

To collect the current traffic volumes, video-camera records and pneumatic-tube sensors were deployed on the involved roads. To improve the accuracy in travel distributions, the video recordings were used at intersections to retrieve the directional traffic distribution. In such roads where only through movements are present, the counting was performed by deploying pneumatic-tube sensors. There

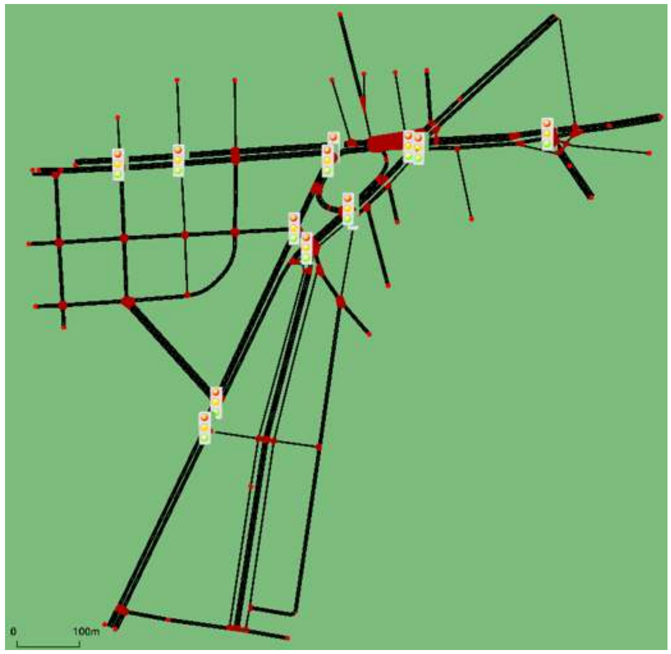

Figure 4.15: Digital map of the case study

Traffic Light	Cycle time (seconds)	Intersection	Signalled turn
1	110	Huerta and Pantoja (Streets)	-
2	110	Huerta and Justicia	Left to Justicia
3	100	Madero and Huerta	-
4	100	Nocupetaro and Huerta	Right to Madero
5	100	Obelisk and Gardenia	-
6	100	Madero and Lazarín	-
7	100	Madero and Dávalos	-
8	100	Madero and Mintzita	-
9	90	Obelisk and Solidaridad	-
10	90	Huerta and Panteón	-
11	90	Obelisk and Romano	Left to Panteón
12	90	Madero and Michelena	Left to Michelena

Table 4.6: Properties of traffic lights

Road segment	Lanes	Orientation	Method
Huerta avenue (1)	2	South-North	Rubber tubes
Huerta avenue (2)	2	North-South	Rubber tubes
Madero avenue (1)	2	West-East	Rubber tubes
Madero avenue (2)	4	East-West	Rubber tubes
Madero avenue (3)	3	West-East	Video recordings
Madero avenue (4)	3	East-West	Video recordings
Nocupetaro avenue (1)	2	South-North	Rubber tubes
Nocupetaro avenue (2)	2	North-South	Rubber tubes
Panteon avenue (1)	3	South-North	Video recordings
Panteon avenue (2)	2	North-South	Video recordings

Table 4.7: Characteristics of the traffic counting points

are some roads that have not favorable conditions for sensors deployment, therefore, for such cases, the counting was manually performed. Table 4.7 describes some characteristics of the roads selected to establish the 10 counting points.

The vehicle counting was performed to get the hourly traffic, daily traffic and weekly traffic volumes. The hourly traffic volume was retrieved in intervals of fifteen minutes. A summary of the hourly traffic volume of the most loaded segment is depicted in table 4.8, which corresponds to the section on *Madero* Avenue with 4 lanes. As can be depicted, the total weekly traffic volume is of 162,908 vehicles.

From the weekly traffic volume, the most representative time intervals were identified. Therefore, it was established the day of the week which consists of the day with the highest traffic volume, along a full operative week.

Based on the daily traffic volume and in the day with the greatest demand, it was identified the most representative time of days (TODs) by analyzing samples of fifteen minutes. These time of days are the time intervals in which the most

Day/Time	Mon	Tu	We	Th	Fr	Sa	Su	Avg
0-1	338	266	289	394	409	573	768	434
1-2	198	137	183	250	267	398	643	297
2-3	123	101	103	170	253	355	525	233
3-4	107	58	97	157	196	307	442	195
4-5	91	76	82	129	139	217	263	142
5-6	211	181	205	211	228	204	233	210
6-7	662	605	643	638	603	371	354	554
7-8	1333	1281	1346	1442	1325	687	532	1135
8-9	1389	1329	1425	1408	1376	1036	611	1225
9-10	1315	1267	1358	1302	1300	1069	789	1200
10-11	1102	1259	1334	1318	1320	1217	849	1200
11-12	1093	1383	1222	1263	1365	1143	954	1203
12-13	1293	1396	1035	1345	1430	1370	1070	1277
13-14	1343	1444	1593	1331	1553	1516	1251	1433
14-15	1499	1390	1512	1628	1598	1565	1460	1522
15-16	1478	1526	1507	1582	1798	1641	1438	1567
16-17	1393	1385	1339	1504	1592	1337	1384	1419
17-18	1333	1358	1411	1547	1507	1267	1258	1383
18-19	1444	1489	1368	1523	1472	1050	1220	1367
19-20	1565	1630	953	1546	1464	1109	1446	1388
20-21	1293	1477	1181	1242	1306	1161	1294	1279
21-22	1169	1212	1178	1077	1355	1085	968	1149
22-23	756	771	817	850	1015	1123	661	856
23-24	442	503	528	546	756	964	497	605
Totals	22970	23524	22709	24403	25627	22765	20910	162,908
Percent	14.10%	14.44%	13.94%	14.98%	15.73%	13.97%	12.84%	100%

Table 4.8: Traffic volume study summary

representative traffic conditions take place, i.e., the greatest and lowest demand along an operative day.

By considering the TODs, identified from the weekly traffic volume, the most traffic demand hour is reproduced through a sequence of 54000 simulation steps, being 1800 simulation steps used to feed the digital map, and then to analyze the concerned TOD with the greatest demand. The hour and half considered for the microscopic simulation is the following:

- From 07:30 to 08:00, the increasing period that depicts the beginning of the human activities.

- From 08:00 to 09:00, the greatest traffic demand was identified in this period on the whole digital map.

To reproduce a behavior with a maximum similitude to the real scenario of the case study, the trip distribution was computed by considering the TODs and the directional distribution at each intersection. This latter under the premise of the input vehicles are equal to the output vehicles from/to each intersection. The assumed premise represents the real behavior, due to the fact that the vehicles can not stop at the middle of the intersections. In this way, the outgoing volume of each intersection may be the incoming volume of the next intersection.

For instance, in the figure 4.16 the green cells represent the total outgoing/incoming traffic volume of the intersection. Thus, the orange cells represent the traffic volume for each movement; if there are three orange cells surrounding the green one, the allowed movements incoming to the intersection are three.

The directional distribution was retrieved by several video recordings, determining the turns percentage at the intersections. The computing distribution as can be seen in figure 4.16 was recursively applied at each intersection of the digital map.

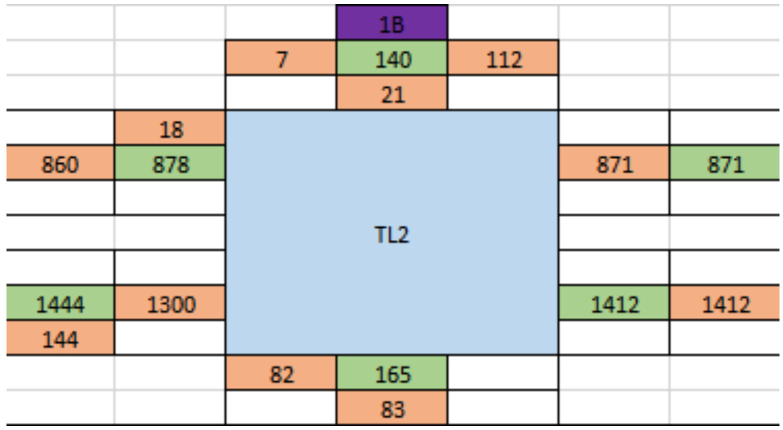

Figure 4.16: Traffic flow distribution at intersections

4.4.3 Dynamic microscopic model

The calibration of the SUMO model was carried out by satisfying the parameters required by the lane change model [SWXL15] and the car-following model of Krauss [SWXL14], which is a model derived from Gipp's model. The mobility patterns were obtained through the registered flows and the queue length observed. The mean speed of the vehicles was computed from the corresponding reports at the 85th percentile of the entire sample. Based on the trip distribution, several origin-destination routes were defined. By using the SUMO simulator, every route is defined from a certain type vehicle, denotes as Vtype. In this sense, four Vtypes were defined: Car, Combi, Urbano and Moto. The *Vtype Car* represents the private vehicles characterized with a length of 4.50m from frontal-bumper to tail-bumper, 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 characteristics of the whole Vtypes are depicted in table 4.9. In addition, for the four Vtypes was considered a standard deviation of 20% up and down of the maximum speed, to reproduce the fluctuations of the real world, as well as a sigma value of 0.5 and 0.9 (for motorcycles) to describe the driver imperfection.

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

Vtype	Accel (m/s^2)	Deccel (m/s^2)	Length (m)	Max Speed (m/s)	Sigma	Speed Factor	Speed Dev
Car	2.6	4.5	4.5	30	0.5	1.2	0.3
Combi	2.2	4.5	5.4	22	0.5	1.2	0.3
Urbano	1.8	5.0	8.6	22	0.5	1.2	0.3
Moto	4.0	4.5	2.0	30	0.9	1.2	0.3

Table 4.9: Definition of the Vtypes in the dynamic model

The definition of the CPCT routes was carried out according to the retrieved data about their trajectories, considering frequencies and transportation mode (see tables 4.2 and 4.1).

Once having the routes defined, the dynamic model was developed considering 90 minutes of simulation according to the greatest TOD. In this sense, the simulation was limited up to the simulation step 5400, which represent the feeding process of the digital map and the operational characteristics in the period 08:00-09:00 hrs of the day of the week ($Thursday$).

4.4.3.1 Calibration of the simulation model

Even though the microscopic model was fed with *in situ*statistically aggregated retrieved data, the simulation environment was calibrated by applying the GEH statistic [Fel12]. By contrasting the simulated flow M against the measured traffic flow C, the GEH statistic warranties the accomplishment of the real-world behavior within a confidence level of 95%.

In order to calibrate the traffic flows through GEH, it was selected a TOD with steady traffic condition, since the outliers flows happen when the vehicle's behavior overcame the model. The selected TOD corresponds to the period from 04:15-05:15 on Monday, since the flow depicts consistency along the 3600 simulation steps (see figure 4.17).

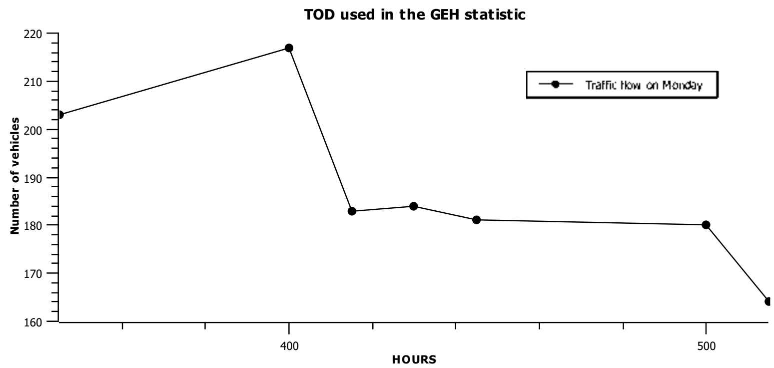

Figure 4.17: Time of day used in GEH statistic

Road segment	Traffic flow M	Traffic flow C	GEH
Huerta avenue (1)	142	145	0.25
Huerta avenue (2)	119	154	3.00
Madero avenue (1)	191	191	0.00
Madero avenue (2)	178	191	0.96
Madero avenue (3)	80	114	3.45
Madero avenue (4)	98	114	1.55
Nocupetaro avenue (1)	173	205	2.33
Nocupetaro avenue (2)	180	250	4.77

Table 4.10: Results by computing the GEH

In this way, for the GEH statistic, eighth different flow conditions were considered from the traffic counts. These traffic conditions were modeled in order to get the new traffic flow M computed by the micro-simulation. The traffic flow M was measured by simulating on-road induction loops, deployed within each segment. The induction loops allow to simulate a virtual traffic counting point, trying to reproduce the same way as the real traffic flow C was measured. Once the flow M was obtained, the GEH was computed in every based point, respective results are depicted in table 4.10.

As can be noted in table 4.10, the computed GEH shows an adequate virtual stage to reproduce the real conditions of the case study, due to the whole GEH values are lower than 5. This latter is supported by the premise that the 85% of the GEH values must be lower than 5 to guarantee an adequate representation of the real traffic flow behavior in the model [DEE+13].

4.4.4 Effects of the current CPCT scheme on the network performance

The simulations were executed by considering the current conditions of both the static and the dynamic elements of the model. In this way, the first simulation was developed with the real CPCT flows without changes. The latter in order to get the density, speed and the mean speed of the current conditions. The output reports yielded the mean density and the mean speed per lane every 15 minutes. Moreover, the simulator computed the mean speed of the whole vehicles in the network per each simulation step.

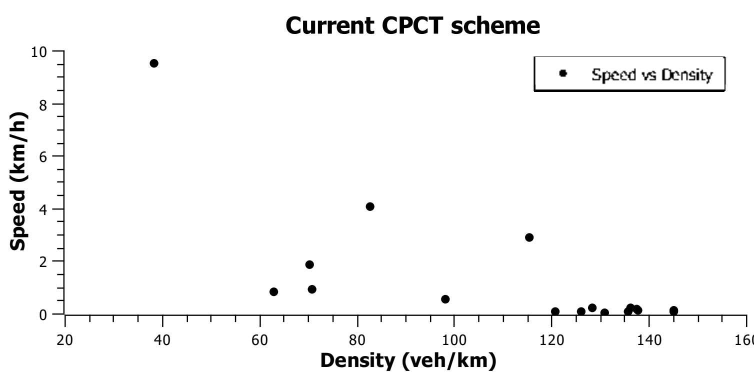

Figure 4.18: Density and speed in the virtual stage with the current conditions.

As can be seen in figure 4.18, the major simulation steps were with high densities and low speeds. This with an average density of 111.50 vehicles/km/lane and an average speed of 1.24 km/h/lane. In this sense, the theoretic traffic flow per lane can be calculated, resulting in 137.82 veh/h/lane.

The results of the first simulation depicts the collapsed road network because of the low speed and the high densities. Thus, the mean speed in the whole simulation is 2.50 km/h (see figure 4.19).

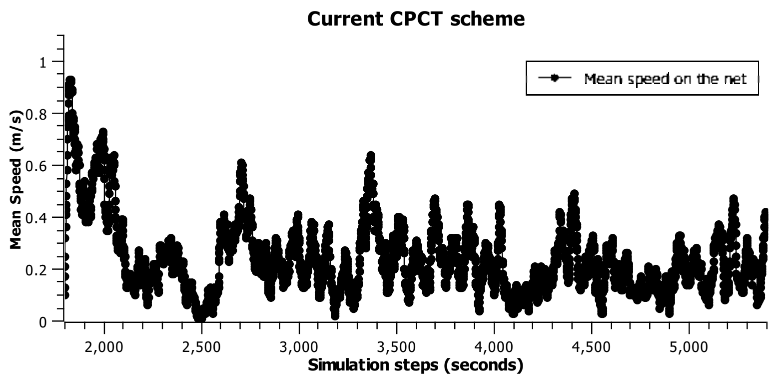

Figure 4.19: Mean speed in the whole digital map

Based on the calibrated simulation model, five different scenarios were carried out by reproducing five different CPCT vehicles population. These five tests are aimed to show how mobility conditions are improved as more routes are unified within the MST-based trajectories. The resulting parameters and characteristics are depicted in the following sections.

4.4.4.1 Test 1: reduction of the 10% of the CPCT flow

The CPCT unification must be in order to decrease the vehicular density and to increase the speed, which means an increasing traffic flow. In this test, the digital map was simulated considering a reduction of the CPCT frequencies up to an equitable 10%. This simulation computed the density and the speed under the assumed conditions. The results were clearly different, especially in the density decreasing and the increment of the speed, figure 4.20. The resultant average density was equal to 110.58veh/km/lane; and the average speed is equal to 3.21 km/h/lane.

In this way the mean speed in the net was increased (see figure 4.21), showing the improvement of the traffic flow in the case study with an average of 3.88km/h.

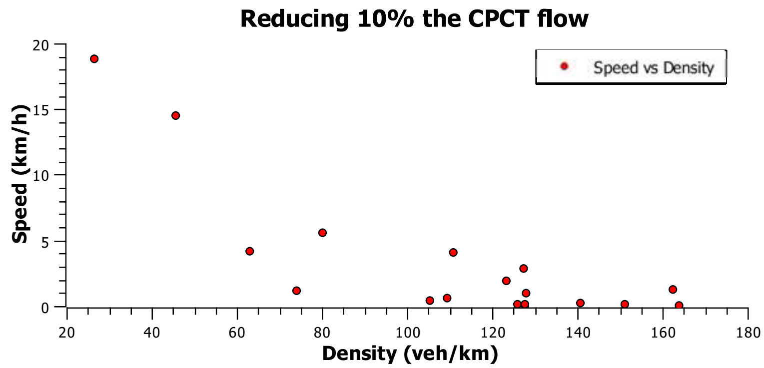

Figure 4.20: Density and speed when the CPCT was reduced 10%

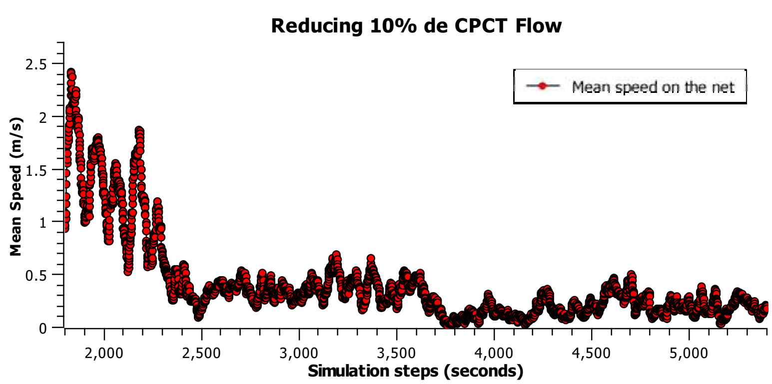

Figure 4.21: Mean speed when the CPCT was reduced 10%

4.4.4.2 Test 2: reduction of the 20% of the CPCT flow

In this test, the digital map was simulated considering a reduction of 20% of the CPCT, yielding an average density of 106 veh/km/lane and an average speed of 2.24 km/h/lane (figure 4.22). These above results represent the case when the management actions do not impact in favor for both variables, because of the speed is also reducing.

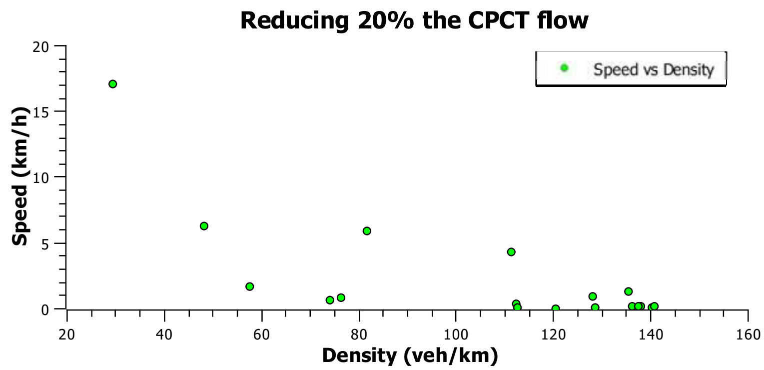

Figure 4.22: Density and speed when the CPCT was reduced 20%

In this way the mean speed in the net was decreased respect to the conditions in *Test* 1 (see figure 4.23), showing the lack of enhancing of the traffic flow in the case study. The mean speed in the network by this conditions was of 3.32km/h.

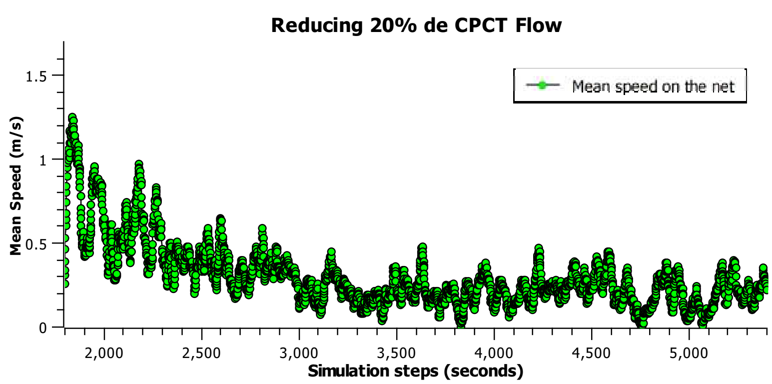

Figure 4.23: Mean speed when the CPCT was reduced 20%

4.4.4.3 Test 3: reduction of the 30% of the CPCT flow

The simulations results for a reduction of the CPCT frequencies up to an equitable 30%, are the following: average density was of 111.61 veh/km/lane and the speed was of 3.06 km/h. This simulation computed the density and the speed under the assumed conditions. The results of this simulation show a premise to improve again the mobility patterns (figure 4.24), since the density increased but the speed too.

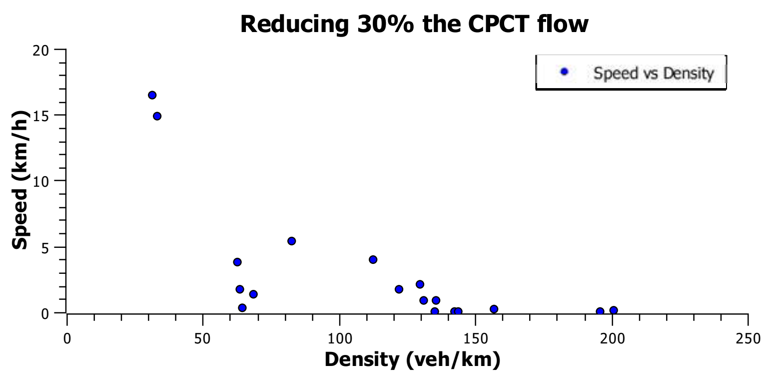

Figure 4.24: Density and speed when the CPCT was reduced 30%

In this way the mean speed in the net was increased (see figure 4.25), showing the improvement of the traffic flow in the case study with an average of 3.77km/h.

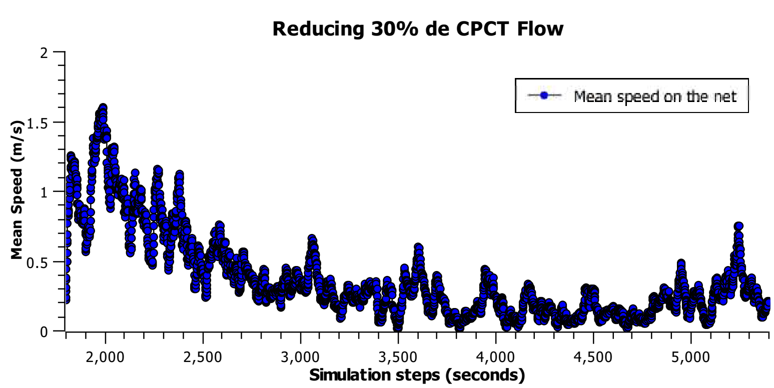

Figure 4.25: Mean speed when the CPCT was reduced 30%

4.4.4.4 Test 4: reduction of the 40% of the CPCT flow

At this point, the simulation results were significant due to the difference between the condition of this test with the real conditions. Regarding the simulation results, te average density was equal to 111.54veh/km/lane and the average speed was 3.84km/h/lane (figure 4.26). These results show an increment of the speed, depicting an improvment of the traffic flow.

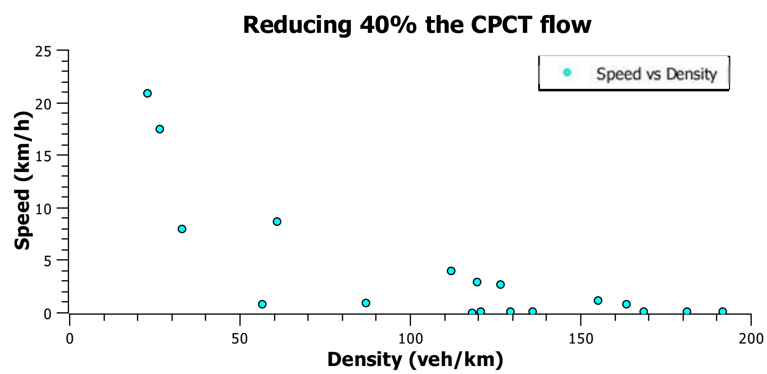

Figure 4.26: Density and speed when the CPCT was reduced 40%

In this way the mean speed in the net was radically increased up to 4.08 km/h(see figure 4.27).

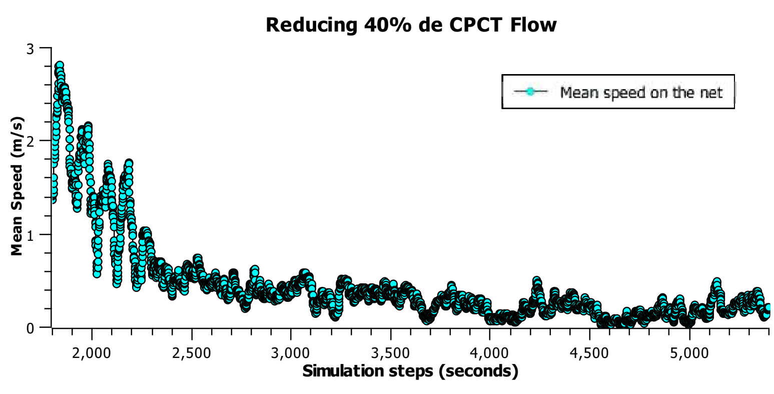

Figure 4.27: Mean speed when the CPCT was reduced 40%

4.4.4.5 Test 5: reduction of the 50% of the CPCT flow

This last test was the siulation whose results were very radical, since the density decreased until 102.40 veh/km/lane and the speed increased until 4.17 km/h/lane. This latter allows traffic flows up to 427 veh/h, which means an increment of the traffic flow until 3.17 times more than the current conditions of the CPCT (figure 4.28).

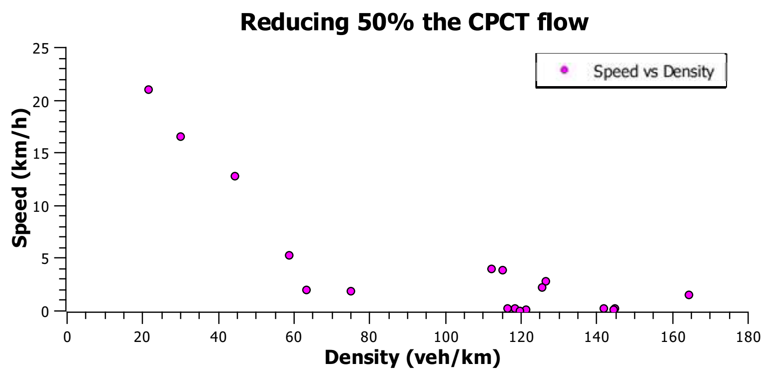

Figure 4.28: Density and speed when the CPCT was reduced 50%

Regarding the mean speed in the net, it was increased almost twice more than the one with the CPCT scheme that currently operates; being this mean speed of 4.48km/h in the entire network (see figure 4.29).

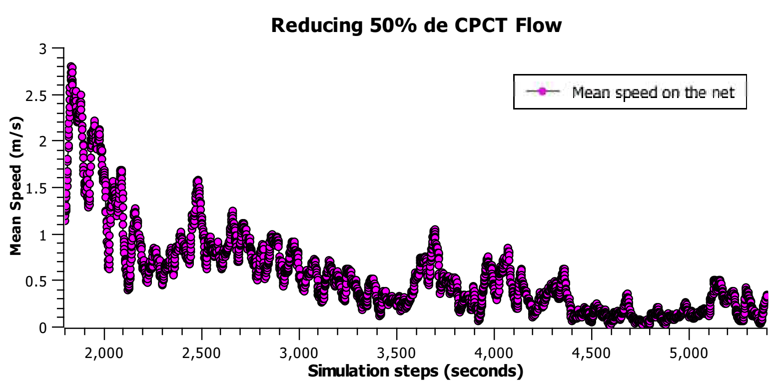

Figure 4.29: Mean speed when the CPCT was reduced 50%

4.4.4.6 Improvement of the urban mobility by reducing the CPCT vehicles redundancy

The above tests depict the relation between the high CPCT routes redundancy with the low value of mobility patterns. The density tended to reduce when the CPCT frequency was limited (see figure 4.30), in this sense, the speed tended to increment every test where the CPCT flows were reduced (see figure 4.31).

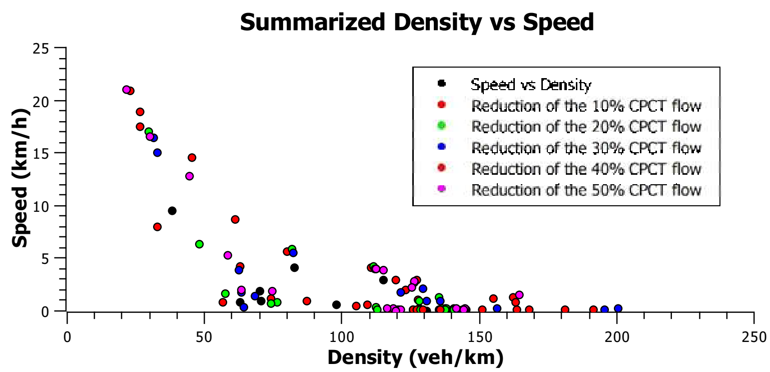

Figure 4.30: Density variation based on the tests

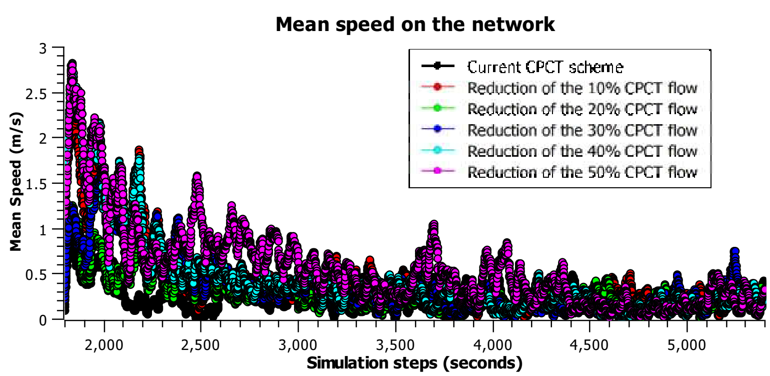

Figure 4.31: Mean speed variation during the tests

Chapter 5

Conclusions and future work

5.1 Summary

This work has formally presented a methodology to identify the trajectories that would be used to unify the collective transit supply, deployed in some Mexican cities under the concept of Concessioned Public Collective Transport (CPCT). Since the CPCT was supported by weak regulations, this pubic transport supply mode has a disorganized deployment which directly impacts the mobility efficiency of the cities since it induces a vehicular load that in many cases exceeds the road infrastructure capacity.

In this work, it is claimed that the impact that the CPCT has on urban mobility is due to the service oversupply, resulting from the high redundancy of routes which can be traduced in an excessive overlap among the trajectories used by different transport lines. A special case of this phenomenon takes place in the city of Morelia, Michoacán, where on a one-kilometer segment of an arterial road coexist 36 routes, which means up to 374 CPCT vehicles per km/h.

This work took as a case study, an on-level interchange located in the city of Morelia, which acts as the main traffic distributor of the road network and has severe mobility problems due to the high population of CPCT. By considering such a system, a public transport re-organization scheme was proposed. The proposal consists of determining the minimum spanning the tree (MST) of the directed graph, constructed by the trajectories that currently use the different lines of CPCT to provide the service from certain origins and destinations.

Supported by a geographical information system, the MST was trimmed and with the resulting subgraphs, there were defined three systems in which the CPCT can be unified: the backbone, feeder and local, respectively.

Analytically was proved that the obtained systems, in which the unification scheme is based, accomplishes with the theoretical concept of hyperpath, which determines a profitable trajectory for public transport by considering the probability of users' choosing.

In addition, a preliminary MST-based re-organization was tested through a microscopic simulation of the studied zone. By comparing the current traffic conditions against the resulting from the scheme application, it was noted that the vehicular density is reduced up to 19%, while the flow and speed are increased up to 209% and 79%, respectively.

5.2 Future work

This public transport reorganization proposal was exclusively focused on to the rational management of the territory. Hence, only the space-time variables such as density and trip trajectories were considered. Although the proposed approach matches with the theoretical model of hyperpaths, that considers the user travel desires, the exclusion of the social variables limits the proposal scope.

In order to achieve a more integral solution, new extensions of the work will be focused on incorporating additional variables, such as the social and the economical.

Another extension of this work, must be focused on modeling the road network from the macroscopic perspective, involving socioeconomic and demographic characteristics in combination with multi-objective optimization techniques.

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