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Tesis Doctoral

OPTIMIZACIÓN DEL DISEÑO DE LA OPERACIÓN DE LOS SERVICIOS DE TRANSPORTE PÚBLICO EN EL ÁREA URBANA

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RESUMEN

Llevar a cabo un uso racional de los recursos en los últimos 30 años se ha convertido en el objetivo tanto de empresas como instituciones gubernamentales de cualquier ámbito. El campo del transporte no ha sido una excepción a esta tendencia y acompañado del auge de las nuevas tecnologías se ha logrado avanzar de una manera muy exitosa en el campo de la optimización de los sistemas de transporte.

Para resolver los problemas de optimización de los servicios de transporte han aparecido numerosas herramientas de simulación tanto en los ámbitos de la macrosimulación como de la microsimulación. Estas herramientas no solo permiten al planificador tomar decisiones con una base mucho más fundada, sino también le permite analizar un mayor número de escenarios posibles de una manera rápida y sencilla. Todo esto hace que aparezcan nuevas posibilidades en la manera de afrontar las decisiones de actuación y planificación sobre los sistemas de transporte urbanos.

El trabajo que se presenta a continuación reúne un conjunto de modelos, herramientas y algoritmos que basándose en las herramientas de simulación que nos brindan las nuevas tecnologías, llevan a cabo una racionalización tanto de aspectos operativos, como son las frecuencias y el tamaño de la flota del sistema, como de aspectos de la red como es la localización de las paradas y su topología.

En todos los trabajos se ha usado como modelo de estudio la Ciudad de Santander, esta es una ciudad de tamaño medio situada en el norte de España y que desde el punto de vista de su topología urbana hace que el sistema de transporte tenga una característica bastante lineal siendo proclive al uso de corredores de transporte.

A lo largo del trabajo se usarán un conjunto de algoritmos heurísticos más usados en el mundo de la optimización matemática pero que han sido aplicados de una manera muy exitosa para la resolución de los problemas planteados en esta Tesis Doctoral.

Los resultados obtenidos en cada uno de los trabajos presentados en esta Tesis refrendan altos beneficios, no solo para el usuario del transporte sino para el organismo que explota el sistema. De esta manera se verá que con los métodos aquí presentados se puede actuar de una manera positiva sobre diferentes parámetros que sirven de indicativo de la correcta racionalización del sistema de transporte como son el aumento de las demandas, descenso de tiempos de viaje, ajustes de los costes de operación y de los costes de usuario

Hay que resaltar que esta investigación se basa en la compilación de cuatro artículos revisados por pares y publicados en revistas indexadas (JCR), lo cual respalda los resultados obtenidos en la misma.

ABSTRACT

Over the last 30 years the rational use of resources has become the goal of both private companies and governments of all persuasions. The field of transport has not been an exception to this trend and, accompanied by the rise of new technologies, many successful advances have been made in the optimisation of transport systems.

Many of both macro simulation and micro simulation tools have appeared for solving the problems associated with optimising transport services. These tools not only allow the planner to take decisions on a much firmer base, but also they allow them to analyse a much greater number of possible scenarios, quickly and simply. All of which means new possibilities appear for facing up to policy and planning decisions for the future of urban transport systems.

The work presented below brings together a group of models, tools and algorithms which, based on the simulation tools made possible through new technologies, rationalise both the operational aspects like frequencies and fleet size as well as network factors like the location and topology of the stops.

The study model for all the work has been the city of Santander, a medium sized city located in the north of Spain with a particular urban topology which makes the transport system have such a linear nature that the use of transport corridors is the norm.

The more common heuristic algorithms found in the field of mathematical optimisation will be used throughout the work and successfully applied for the solution of the problems addressed in this Doctoral Thesis.

The works presented in this Thesis achieve results which provide benefits not only for the transport users but also for the organisations running the systems. It will be shown that by applying the methods presented here it is possible to positively act on the different parameters indicating the proper rationalisation of the transport system, parameters like increased demand, reduced journey times, leaner operating costs and user costs.

Note that this research is based on the compilation of four peer reviewed articles published in indexed journals (JCR), which support the results obtained.

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Capítulo 1

INTRODUCCIÓN Y OBJETIVOS

1. INTRODUCCIÓN Y OBJETIVOS

1.1. Motivación

La racionalización de los recursos se ha convertido en una tendencia imparable en los últimos años, la correcta utilización de los recursos es sin duda uno de los aspectos que más valoran tanto entidades públicas como empresas privadas, pero esta racionalización no puede darse a expensas de penalizar los servicios ofrecidos a los clientes.

No es necesario recalcar que en los últimos 30 años las ciudades han sufrido un cambio dramático en cuanto al nivel de tráfico existente se refiere, esto ha llevado a los gobernantes a tomar decisiones en favor del uso de sistemas de transporte colectivos, ciudades como Madrid y Barcelona están valorando la posibilidad de cerrar sus centros al tráfico rodado debido a la insostenibilidad que supone.

Pero estas actuaciones requieren por parte de los dirigentes y los técnicos el ofrecer a los ciudadanos formas de transporte alternativas al vehículo privado y que sean lo suficientemente atractivas para él. Es decir se ha de cumplir que el ratio entre el coste del uso del vehículo privado y el coste del uso de los servicios de transporte público no se incline del lado del primero.

Para llevar a cabo estas tareas de racionalización de los sistemas de transportes y gracias al desarrollo de las nuevas tecnologías se han abierto un sinfín de posibilidades ante los técnicos que se encargan tanto de estructurar las redes como las políticas de transporte en las áreas urbanas, permitiéndoles tomar decisiones basándose en modelos matemáticos y de simulación cada vez más fiables.

De esta idea de optimizar y racionalizar los servicios ofrecidos al ciudadano en el ámbito de los sistemas de transporte urbano nace el trabajo que se presenta a continuación.

1.2. Objetivos

De todos los problemas que se pueden dar en el diseño de un sistema de transporte este trabajo se centrará principalmente en la relación existente entre frecuencias y tamaños de flota que deben existir dentro de un sistema de transporte. Para este propósito se presentarán un conjunto de trabajos los cuales describen métodos y algoritmos que permiten optimizar el tamaño de los autobuses que se usan en las diferentes líneas así como la frecuencia necesaria para que el sistema sea óptimo para todos los agentes involucrados.

También se presentarán varios trabajos relacionados con la manera de ubicar las paradas a lo largo de las redes de transporte y demostrando que una correcta localización hace descender los valores de tiempos de viaje, aumentado de esta manera las velocidades comerciales del sistema, revirtiéndose todo esto un mejor servicio para los usuarios del sistema de transporte.

En particular, los objetivos se detallan en los siguientes puntos.

- Plantear un algoritmo y el desarrollo de una herramienta para obtener una asignación de frecuencias y tamaños de flota óptimas para todo el conjunto de las líneas de un sistema de transporte.
- Plantear diversos algoritmos de resolución al problema de asignación de tamaños y frecuencias y realizar un análisis comparativo entre ellos.
- aportar un modelo para asignar el uso de dobles paradas dentro de una red de transporte, intentando minimizar el problema de la congestión.
- Proponer una serie de herramientas para una correcta localización de las paradas de una red de transporte para reducir los tiempos de viaje.
- Comparar la efectividad del uso de diferentes algoritmos para resolver los problemas propuestos.

1.3. Estructura de la tesis

La presente tesis se estructura en cuatro capítulos a lo largo de los cuales se presentan una serie de modelos y algoritmos que permiten llevar a cabo de una manera más eficiente el diseño e implantación de un sistema de transporte urbano.

Los dos primeros hacen referencia al estudio y la solución del problema de la relación que ha de existir entre la frecuencia y el tamaño de la flota en un sistema de transporte.

Los capítulos 4 y 5 presentaran sendas investigaciones relacionadas con la localización de las paradas dentro de las redes de transporte.

En el capítulo 6 se recoge las conclusiones finales del trabajo y la investigación realizada y se proponen las futuras líneas de investigación que complementarán los resultados obtenidos hasta el momento.

1.4. Aportaciones

A lo largo de esta tesis se presentan un conjunto de modelos y herramientas que abordan las problemáticas que encuentran los planificadores de transporte urbano cuando se enfrentan ante el reto de planificar un sistema que arroje unos resultados optimizados tanto para los usuarios del sistema como para los operadores que se encargan de prestar el servicio.

En la literatura internacional se han presentado una gran cantidad de trabajos que aportan varios métodos que llevasen a cabo una optimización del transporte, pero los diferentes trabajos recogidos en esta tesis presentan un conjunto de modelos y herramientas que actúan sobre variables típicas de la planificación operacional del sistema de transporte, como son la frecuencia y las tipologías que se han de usar en las distintas líneas del sistema, así como sobre variables que se han de tener en cuenta a la hora de diseñar la infraestructura de la red de transporte, tal como la posición y el tipo de paradas que se han de usar en la red de transporte.

Para lograr estos hitos, en la siguiente tesis se proponen avances en los siguientes aspectos.

a) Se propone un modelo que optimiza conjuntamente el tamaño de los autobuses y la frecuencia para las diferentes líneas de un sistema completo de transporte en condición de demanda fija, integrando el modelo de asignación a transporte público con restricción de capacidad propuesto por de Cea y Fernández (1993) con un algoritmo de resolución programado en MATLAB.

b) Se diseña un algoritmo de tipo TABU SEARCH que permite resolver el problema mencionado anteriormente de una manera mucho más rápida, posibilitando su uso sobre redes de transporte más grandes.

c) Se presenta un modelo que permite analizar el uso de paradas dobles a lo largo de un corredor de transporte, para este efecto se diseña un algoritmo genético que se combina con un modelo de asignación a transporte público con restricción de capacidad.

d) Se desarrolla un modelo de dos etapas que permite optimiza la localización de las paradas en un corredor de transporte urbano, en este método se presenta una primera etapa de carácter macroscópico la cual ubica las paradas a lo largo de la red y una segunda etapa de carácter microscópico que sirve para afinar la posición de la paradas dentro de la zona obtenida por la primera etapa del modelo.

e) Por otro lado todos los trabajos se han aplicado sobre un sistema de transporte real, el cual pertenece a la ciudad de Santander, esto hace que los resultados tengan un valor especial ya que se han podido comparar los resultados aportados por este trabajo con la situación actual del transporte de la ciudad.

f) Es importante mencionar que esta tesis es producto del compendio de cuatro artículos publicados en revistas internacionales (JCR), los cuales validan el aporte de las investigaciones desarrolladas al estado del arte. Las referencias de los tres artículos mencionados son las siguientes:

I. Dell'Olio L., Ibeas A., Ruisanchez .F (2012) Optimizing bus-size and headway in transit networks. *Transportation* 39, 449-464. http://dx.doi.org/10.1007/s11116-011-9332-2

II. Ruisanchez F., dell'Olio L., Ibeas A. (2012) Design of a tabu search algorithm for assigning optimal bus sizes and frequencies in urban transport services. *Journal of Advanced Transportation* 46, 366-377. http://dx.doi.org/10.1002/atr.1195

III. Alonso, B., Moura, J., Ibeas, A., and Ruisánchez, F. (2011). Public Transport Line Assignment Model to Dual-Berth Bus Stops. *J. Transp. Eng* 137, 12, 953-961.

http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000260

IV. Moura J. L., Alonso B., Ibeas A., Ruisanchez F. (2012) A Two-Stage Urban Bus Stop Location Model. *Networks and Spatial Economics* 12, 3, 403-420.

http://dx.doi.org/:10.1007/s11067-011-9161-z

Capítulo 2

OPTIMIZING BUS-SIZE AND HEADWAY IN TRANSIT NETWORKS

2. OPTIMIZING BUS-SIZE AND HEADWAY IN TRANSIT NETWORKS [1]

2.1. Resumen

El problema de la optimización del tamaño de los autobuses es un tema que se trató con profundidad en la década de los ochenta. Dicho problema ha ido perdiendo relevancia con el paso del tiempo hasta volver a renacer en la actualidad. En los últimos veinte años los avances tecnológicos de los vehículos de transporte han ido dirigidos principalmente, por un lado a la reducción de los costes de operación y por otro hacia las tecnologías respetuosas con el medio ambiente. Todo ello ha dado lugar a que las empresas de transporte público se replanteen la tipología de autobús a utilizar para rentabilizar los servicios teniendo en cuenta la variabilidad de la demanda así como las variables operacionales.

Para conseguir dicho objetivo, se propone y resuelve un problema de minimización del coste social total involucrado en la operación del sistema de transporte, que incluirá los costes empresariales y los costes de los usuarios. Este Problema de Optimización se plantea como un problema de programación matemática de tipo bi-nivel. En el nivel superior, se define una función de coste social total del sistema que debe ser minimizada, y que ha de estar sometida a restricciones tecnológicas. En el nivel inferior se define asimismo, un modelo de comportamiento para los usuarios del sistema en función del diseño físico y operacional del sistema de transporte público, previamente definido.

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[1] Dell'Olio L., Ibeas A., Ruisanchez .F (2012) Optimizing bus-size and headway in transit networks. *Transportation* 39, 449-464.

http://dx.doi.org/10.1007/s11116-011-9332-2

Claramente las variables de decisión del problema son, el tamaño o tipología óptima de los buses y su frecuencia en cada línea. Dicho problema se resuelve considerando varios escenarios de demanda a partir de los cuales se procede a comparar los resultados.

Por último se usaran los datos obtenidos de nuestro problema de optimización para generar una superficie teórica en tres dimensiones en la que la demanda sea función del tamaño de bus y del intervalo, la superficie contiene los puntos que optimizan el sistema para las tres variables estudiadas, (Demanda, Intervalo, Tamaño de bus).

2.2. Introduction

The problem of achieving an efficient urban public bus service depends on different factors. Some of these factors are related to the structure of the network, others with the distances between stops and routes, with fare policies, with operating headways and, finally, with the size and type of buses.

These last two variables can be the most flexible to change, given that the first are difficult to change, are usually already well optimized and follow criteria of satisfying demand. With reference to the charging policy, it has been well demonstrated that the demand elasticity of the fare on public transport bus services is practically rigid (De Rus, 2003).

Therefore, this article concentrates on optimizing the headways on routes and bus size, considering that the rest of the relevant variables that intervene in the operation of a public transport urban bus service are fixed.

From the calculations of demand, headway and bus size obtained from the model a graphic tool will be built to obtain any one of these variables (demand, headway, bus size) once the other two are known.

The international literature gives examples of the advantages of small buses over more conventional medium sized or even high capacity buses. The model proposed here evaluates the advantages and disadvantages of each of the different types of buses and, depending on the different conditioning factors, determines which is most suitable according to the social and operating costs of the system. Another important advantage of this type of study is that to obtain a systems' optimum operating level the whole network and all its routes have to be included. This method takes into account all the interactions between routes as well as the different states of congestion that are normally found on the links and even on the buses.

The work of Spiess and Florian (1977) and that of De Cea and Fernández (1993) are references for the public transport assignment model used here. This is a model that introduces capacity constraints on the buses, it takes into account the fact that users who do not manage to get on a bus due to capacity problems suffer longer waiting times, thereby considerably increasing the system's social cost. This is of great importance as the goal of the proposed model is to choose bus sizes for each route on the network by optimizing the system's social costs.

Evidently, apart from the size of the buses, frequency of service plays an important role throughout the study and a point of equilibrium must be determined which minimizes the social and operational costs of the service.

This article is structured in the following way: firstly, the state of the art is presented. Later, the proposed model and solution algorithm are determined, and finally, an analytical solution of the proposed model is presented along with an analysis of the results. At the end of the paper the final conclusions are presented.

2.3. State of Art

The study of the optimum size and type of buses was dealt with in depth in the 1980s when a whole series of policies were developed to give priority to public transport and thereby deal with traffic congestion in large urban areas.

Work of note at that time was done by: Jansson (1980), Walters (1982), Vijakamur (1986), Glaiser (1986), Oldfield and Bly (1988),

Most of these studies concentrate not only on obtaining the optimum bus size but also on optimizing the frequencies of the buses (headway).

A starting point in this type of study can be seen in the work of Webster (1968) who looked at the effects of transferring travellers from the car to differently sized surface public transport vehicles in London. Later, Webster and Oldfield (1972) continued on a similar line proposing modal distribution models based on minimizing the overall total cost for the private and public modes. Vickrey (1955) and Mohring (1972, 1976) publish recognised works establishing that the route's headway should be proportional to the square route of the demand.

On the other hand, Jansson (1980) demonstrates in his work that headway outside rush hour should not differ much from headway at rush hour because the operators underestimate the costs of the users in their analysis.

The same author considers that headway is not very sensitive to changes in bus size and therefore thinks it unnecessary to use very large buses.

Jara-Díaz, S.R. and Gschwender (2003a, 2003b, 2008) also propose a bus size optimization model but making use of budget constraints.

Similarly, Walters (1982) points out the benefits of using small buses on public transport networks.

Glaiser (1986) notes, for the first time, the importance of the cost per seat according to bus size indicating that the greater the number of seats, the lower the cost per seat has to be (because of the existing relationship: operating cost / number of seats). This author's study in Aberdeen concluded that there it was more efficient to use smaller buses with lower capacities.

Oldfield and Bly (1988) give an in-depth analysis of the advantages and disadvantages of using smaller buses, concentrating on the effects that these buses have on demand and headway.

More recent years have seen local authorities more preoccupied with the social character of the service and they are once again looking at minibuses as an attractive possibility with corresponding higher headways and reductions in waiting times.

2.4. The Model

A bi-level mathematical optimization model is proposed to solve the problem of finding the optimal bus size on each route. At the upper level is the function of social wellbeing which considers the user costs and the operator costs, subject to technological constraints and satisfying the demand, and at the lower level a public transport trip assignment model (dell'Olio et al., 2006).

The international bibliography reveals a series of studies on the design of transport networks using bi-level programming techniques (Yang and Michael, 1998; Yang, 1997; Wong and Yang, 1997; Yang and Bell, 1997).

The decision variables of the model will be the frequency of each route $f_i \quad \forall \quad i = 1,2,\ldots n$, where n is the number of routes on the network being considered, taking into account, as a discrete dummy variable (0, 1) $\delta_{k,i}$, the optimal size of the buses, assigning the value "1" if bus type A is used to service route i ($A_{k,i}$) and "0" in other cases.

The cost structure used in this investigation considers the user costs (UC) and the operator costs (OC). The user costs are obtained by simulation and are affected by the decision variables and follow the following formation:

$$UC = \varphi_a TAT + \varphi_w TWT + \varphi_v TIVT + \varphi_t TTT \tag{2.1}$$

Where:

TAT = Total Access Time.

TWT = Total Waiting Time.

TIVT = Total In-Vehicle Time.

TTT = Total Transfer Time.

ϕ_a = Value of Access time.

ϕ_w = Value of waiting time.

ϕ_v = Value of in-vehicle time.

ϕ_t = Value of transfer time.

The operator costs are considered to be the sum of the direct costs plus the indirect costs (Ibeas et al., 2006). The Direct Costs are made up of three factors: rolling costs (km covered) (CK), hourly costs (CR) due to engine ticking over, personnel costs (CP), and fixed costs (CF). The Indirect Costs (CI) have been found in other studies to be around 12% of the Direct Costs (Ibeas et al., 2006).

The total cost of the kilometres covered is equal to:

$$CK = \sum_i \sum_k L_i f_i CK_k \delta_{k,i} \tag{2.2}$$

Where:

L_i = Length of route i (km per bus).

f_i = Frequency of route i (buses per hour).

CK_k = unit cost per kilometre covered by bus type k (€ per km).

$\delta_{k,i}$ = mute variable worth 1 if bus type k is assigned to route i and 0 if not.

The cost of the buses standing still with the engine running is:

$$CR = t_{sb} \sum_{i} \sum_{k} CR_k \delta_{k,i} Y_i \tag{2.3}$$

Where:

t_{sb} = average time for passengers getting on and off the bus (min per passenger).

CR_k = unit cost per hour of bus type k standing still with engine running (€ per hour).

Y_i = journey demand on route i obtained by simulation (passengers per hour).

The personnel cost is considered as the cost of personnel who are working or, effectively, employed:

$$CP = C_p \sum_{i} \left(tc_i / H_i \right) \tag{2.4}$$

Where:

C_p = is the hourly cost of personnel (€ per hour).

tc_i = is the time of a round trip (min).

H_i = is the headway of route i (min).

The fixed costs are calculated with the following formula considering the buses that are actually circulating:

$$CF = \sum_{i} \sum_{k} \left(\left(tc_i / H_i \right) \cdot CF_k \cdot \delta_{k,i} \right) \tag{2.5}$$

Where:

CF_k = unit fixed cost per hour of bus type k (€ per hour).

Based on this cost structure the optimization problem at the upper level is defined as:

$$\begin{aligned} \min \quad & Z = \phi_a TAT + \phi_w TWT + \phi_v TIVT + \phi_t TTT \\ & + \sum_i \sum_k L_i f_i CK_k \delta_{k,i} + t_{sb} \sum_i \sum_k CR_k \cdot 60 \cdot \delta_{k,i} Y_i + C_p \sum_i \left(tc_i / H_i \right) + \\ & + \sum_i \sum_k \left(\left(tc_i / H_i \right) \cdot CF_k \cdot \delta_{k,i} \right) \end{aligned} \tag{2.6}$$

s.t.

$$\begin{aligned} & \delta_{k,i} \in (0,1) \\ & \sum_k \delta_{k,i} = 1 \quad \forall i \\ & \sum_i f_i = \sum_i \sum_k \frac{Y_i \delta_{k,i}}{K_k} \end{aligned} \tag{2.7}$$

The first constraint defines the characteristics of the binary variables $\delta_{k,i}$. The second constraint indicates that each route can only be assigned one type of bus, and the third is a demand satisfaction constraint as a function of the different capacities of the different buses, where K_k is the capacity of bus type k.

The lower level is modelled using a public transport assignment model.

The above mentioned equilibrium conditions can be formulated for the considered problem using a variational inequality of the following type:

$$c(V^*) \cdot (V^* - V) \leq 0, \qquad \forall V \in \Omega \tag{2.8}$$

Where c is the cost vector in sections of route, V is any workable flow vector in sections of route $\{V_s\}$ and V* represents the equilibrium solution in terms of flows in sections of route.

A commonly used solution method in these cases is the diagonalization algorithm (Florian (1977)); (Abdulaal y LeBlanc (1979)), which allows separable cost functions to be obtained at each iteration and, therefore, poses an equivalent optimization problem. Alternatively, a method can be used that directly solves the problem of equilibrium assignment such as the cutting-plane algorithm (Nguyen and Dupuis (1984)).

Therefore, the equilibrium assignment model on public transport networks used in the formulation requires the definition of a more complex network, represented by a graph $G' = (\overline{N}, S)$, where S is the whole of the links on the network, composed of sections of route and access links. One route section is a portion of a route between two consecutive transfer nodes with an associated group of routes of equal attractiveness for the users (De Cea and Fernández (1993)). The optimization problem equivalent to the variational inequality $c(V^*)\cdot(V^*-V)\leq 0,$ is as follows:

$$Min \quad \sum_{s\in S}\int_0^{V_s} c_s(x)dx \tag{2.9}$$

s.t.

$$\begin{aligned}
&\sum_{r\in R_w} h_r = T_w && \forall w\in W \\
&\sum_{r\in R} \delta_{sr} h_r = V_s && \forall s\in S \\
&v_l^s = \frac{f_l\cdot V_s}{f_s} && \forall l\in B_s, \forall s\in S \\
&h_r \geq 0 && \forall r\in R
\end{aligned} \tag{2.10}$$

Where:

w: Element of group W, in which $w=(i,j)$, with i, j centroids.

Tw: Total number of journeys between the pair O-D w for users of public transport.

l: Index to designate a public transport route.

R: Group of routes available to users of public transport.

r: Index to designate a public transport route.

Rw: Group of public transport routes associated to the pair O-D w.

$\bar{h}_r$: Flow of public transport passengers on route r.

s: Index to designate a section of route on public transport

S: Group of route sections available to users of public transport.

cs : Cost of journey for users of public transport on route section s.

δsr : Element of the incidence matrix section of route to route: takes value 1 if route r passes by s and 0 in other cases.

Vs: Passenger flow on route section s.

vls: Passenger flow on route section s that uses route l.

fl: Headway on route l.

fs: Total headway on route section s.

The model assumes that the users choose from all the possible routes that connect a certain pair of nodes on a public transport network, the route that minimizes their total journey time (cost) (fare + journey time in vehicle + waiting time + access time).

On the other hand, the system is assumed to have a limited capacity and with increased numbers of users on the system come increased journey times. There is assumed to be congestion at the bus stops, given that passengers experience waiting times which depend on the total capacity of the group of routes and the number of passengers that wish to use those routes for their journeys.

Once a passenger gets on a vehicle at a bus stop, the journey time on this vehicle will only be determined by the current level of congestion on the road network (flows of both private and public transport vehicles).

In relation to the group of routes available for a journey, the model assumes that there is a group of “common routes” between each pair of nodes on a public transport network which are equally attractive to the user. So at each bus stop the passengers will consider the group of common routes to make their journey and will get on the first vehicle belonging to this group that has available capacity.

Depending on the system's actual level of congestion, distinct groups of common routes can be defined for a user travelling between a given pair of nodes. The more general consideration is that all the routes connecting a pair of nodes are "potentially" attractive. It therefore becomes possible to define an initial group which contains the "fastest" routes and which corresponds to the group of common routes determined in accordance with the Chriqui algorithm (see Chriqui, 1974, and Chriqui and Robillard, 1975).

This group of common routes will be used by customers when there is no congestion on the system. Otherwise, as these routes become congested, the "slower" routes start to become more attractive because the waiting times on the "faster" routes increase.

2.5. Solution Algorithm

The algorithm (see figure 2-1) developed to solve the headway and bus size optimization problem, with constraints on demand fulfilment, is made up of four simple steps:

Generate an initial feasible frequency solution of ($f_1, f_2, \ldots, f_n$) and $\delta_{k,i}$ which is generally the current situation on the network.

The optimization problem is solved at the upper level (assigning equilibrium to public transport)

New values of ($f_1^1, f_2^1, \ldots, f_n^1$) are generated with, for example, the Hooke-Jeeves algorithm (Hooke and Jeeves, 1961) and the entire optimization problem is solved at the upper level subject to the demand satisfaction constraint, to determine $\delta_{k,i}$.

If $Z^{i+1} - Z^i > \tau$ we return to step 2 if $Z^{i+1} - Z^i \leq \tau$ the algorithm is stopped.

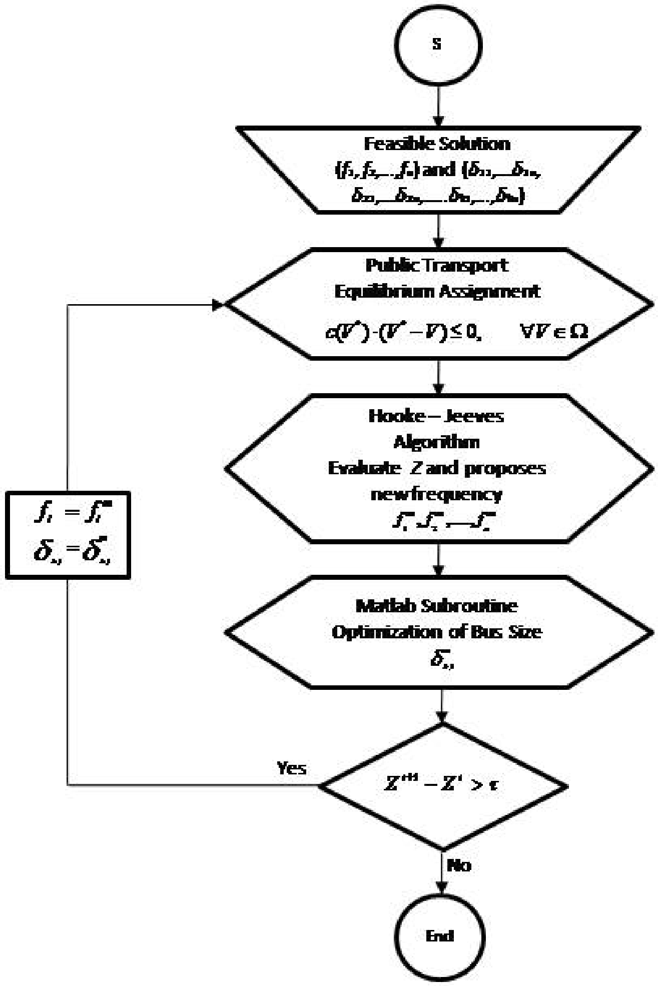

Figure 2-1 Flow diagram of the proposed model.

2.6. Study case and preliminary analysis of results

The model is applied to the public transport bus service in the city of Santander. The city has a population of 180,000 and the current demand is for around 20 million journeys a year distributed between 11 lineal routes (return trips) and 4 circular routes. The model is loaded with data from the morning rush hour with a demand of around 5,000 journeys. There are 6 different types of bus used in the model, the sizes chosen were for 30, 60, 90, 120, 150, 180 passengers/vehicle.

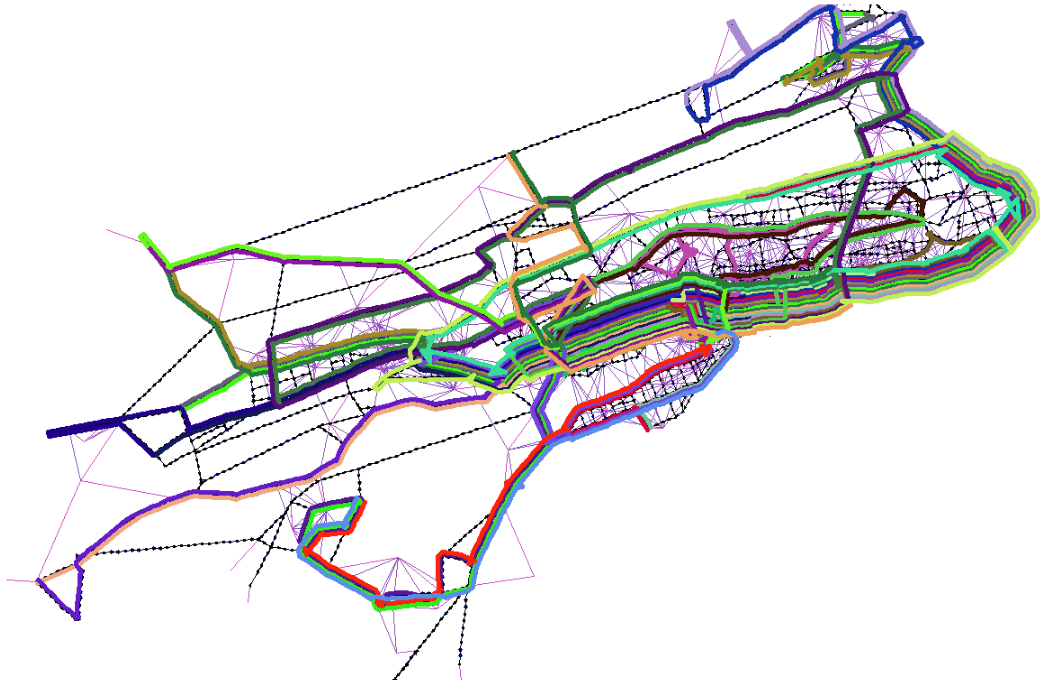

Figure 2-2 shows the network of bus routes in Santander to which the model has been applied.

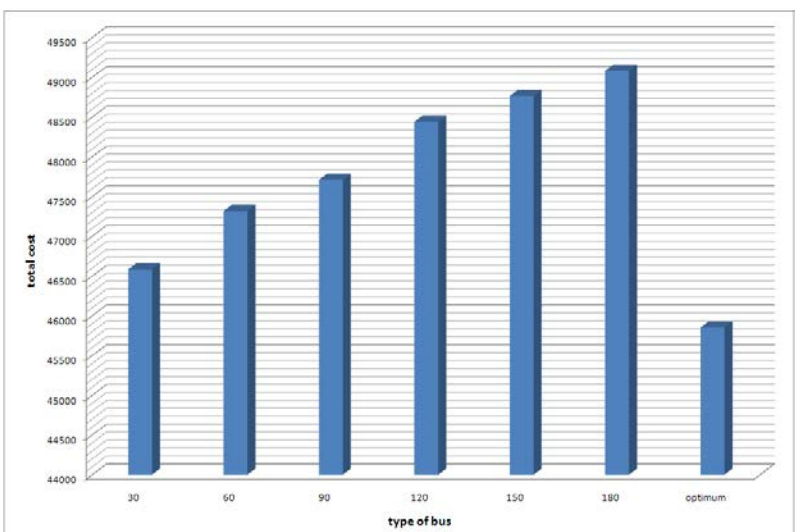

Figure 2-3 Relationship between total cost and type of bus.

The depth of analysis performed has needed an ample supply of results, obtained by studying different cases using various tests on different fleet configurations. Homogenous fleets were used in which all the buses were of the same size, and then heterogeneous fleets were used which could be made up of different bus types.

Figure 2-3 shows the results of the total system cost for the different homogenous configurations and their comparison with the optimal obtained using the model, which corresponds to a heterogeneous fleet configuration. This result contradicts those found by some authors such as (Walters (1982)), who concluded that using smaller buses was better for the system. The results obtained in this study indicate that a better service is provided by using heterogeneous fleets.

Table 2-1 shows the results of the optimization contrasted with the real situation of public transport planning in Santander (the decision variables are bus size and headway). Currently, the city's transport system only uses buses with a capacity of 90 passengers/vehicle

Route	Headway	Bus Size	Demand
'1001I'	12.5	90	276
'1001R'	13.0	60	256
'1002I'	11.5	90	334
'1002R'	11.0	90	362
'1003I'	18.5	60	119
'1003R'	17.5	60	136
'1004I'	16.5	120	140
'1004R'	11.5	150	317
'1008I'	34.0	60	24

'1008R'	31.5	30	30
'1009I'	24.5	30	61
'1009R'	27.9	30	42
'1010I'	26.5	150	47
'1010R'	36.5	180	10
'1011I'	26.0	150	65
'1011R'	41.0	180	3
'1012I'	19.5	90	122
'1012R'	18.5	120	133
'1014I'	15.5	150	174
'1014R'	22.0	150	68
'1016I'	22.0	120	59
'1051I'	9.0	180	506
'1052I'	7.5	180	740
'1061I'	19.5	30	119
'1062I'	21.5	30	96
'1071I'	11.5	120	329
'1072I'	11.5	90	341
Average	20	103	4909

Table 2-1 Results of the model.

The results obtained from the optimization provide a saving of 4% compared with the current situation in the total system costs at rush hour, as well as getting better use out of the buses because they make better use of their size in most cases.

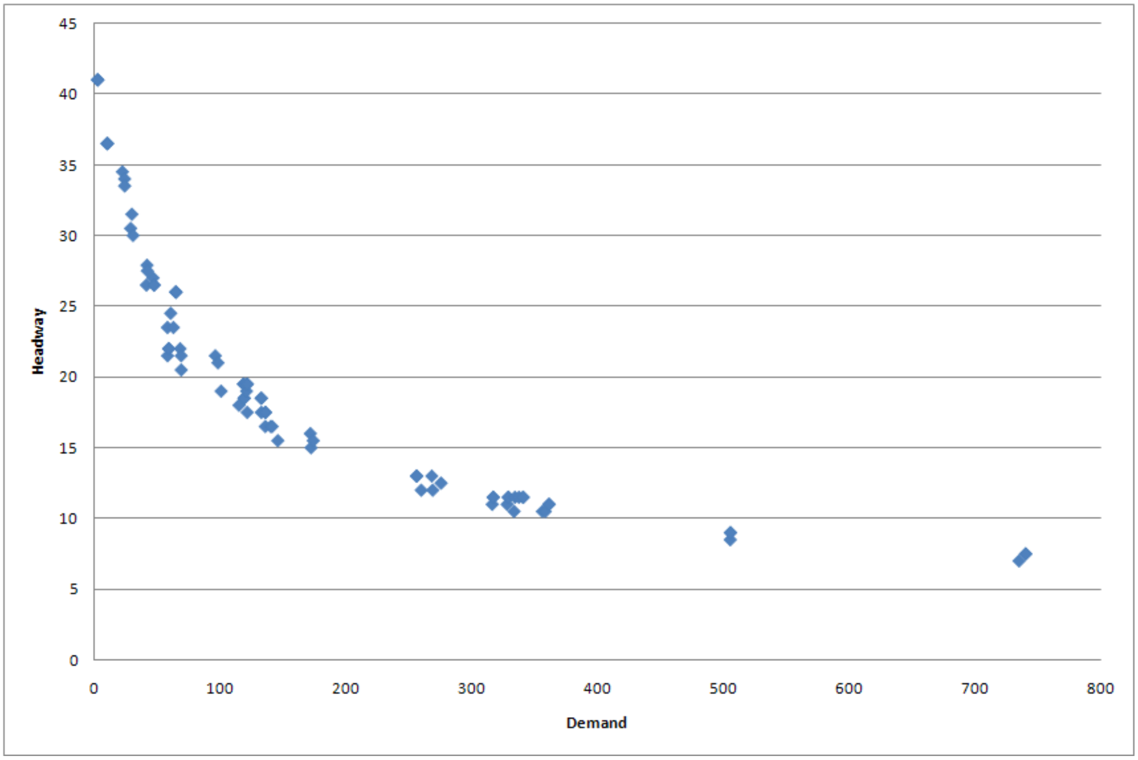

Figure 2-4 headway with demand.

Figure 2-4 shows the existing relationship between demand and headway obtained using the model, clearly demonstrating that there is an exponential relationship between both variables. The fit corresponds to the following expression:

$$H_i = 88,69 \cdot D_i^{-0,34} \tag{2.11}$$

Where H_i and D_i are the headway and demand on each route i.

Running the model provides the following expression for headway

$$\left(f_i = \frac{1}{H_i} \right) \tag{2.12}$$

$$f_i = 0,3 \cdot \sqrt{D_i} \tag{2.13}$$

This formula is consistent with that proposed by Mohring, (Mohring, 1972) stating that headway is proportional to the square root of the demand D on each route i. Headway is clearly seen to be greater for low demands.

It is also worth pointing out that the value of the headway between buses oscillates between 40 minutes maximum and 5 minutes minimum. This fact should be taken into account in the process of optimizing the user and operating costs.

2.7. Analysis and discussion

An equation which provides values on bus size and headway for given demands could be a useful tool for the transport planner. Obtaining this is by no means an easy task because of the distribution of the data obtained. The application of a mathematical interpolation method was chosen in this case because it could generate a group of graphs from the experimental data which facilitate choosing the values of the three variables (demand, headway, bus size) so that the situation of the system would be optimal for the cost function.

Table 2-1 shows the results of the model when applied to the proposed study case on bus routes in Santander. Firstly, the demand (D) is represented against bus size (BS) and headway (H) obtaining a spatial distribution of discrete points (figure 2-5).

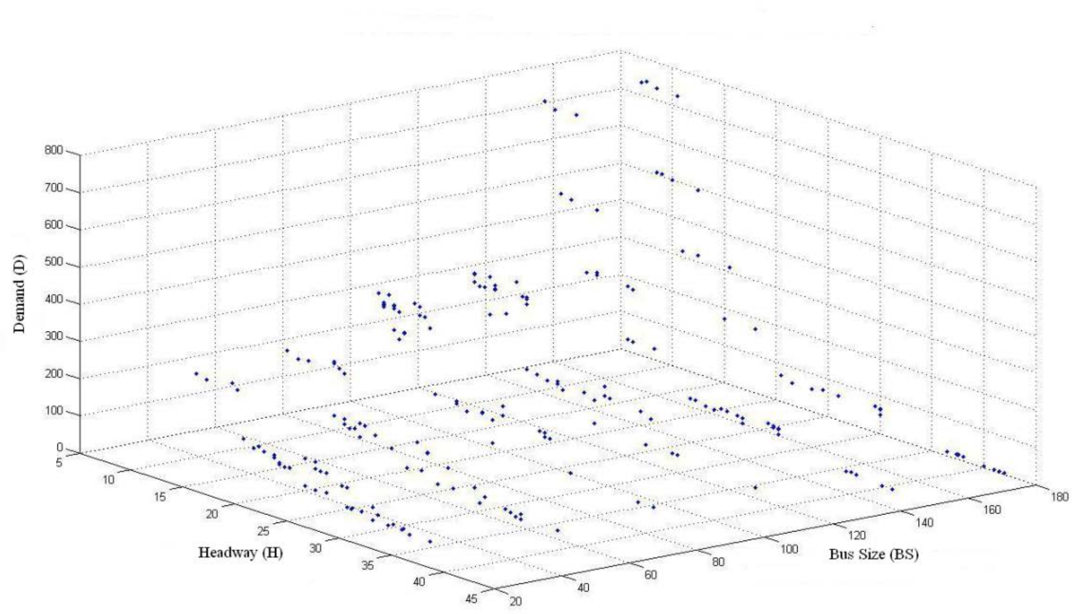

Figure 2-5 Demand vs headway vs bus size

Using the bilinear interpolation method (Nakamura ,1997) (see appendix A) generated a surface from a group of discrete points in a space R3, in our case this space will be formed by the variables (D, H, BS). The surface generated can be seen in Figure 2-6. The coordinates of each point on the surface are the values of demand, headway and bus size which manage to make the system costs minimum.

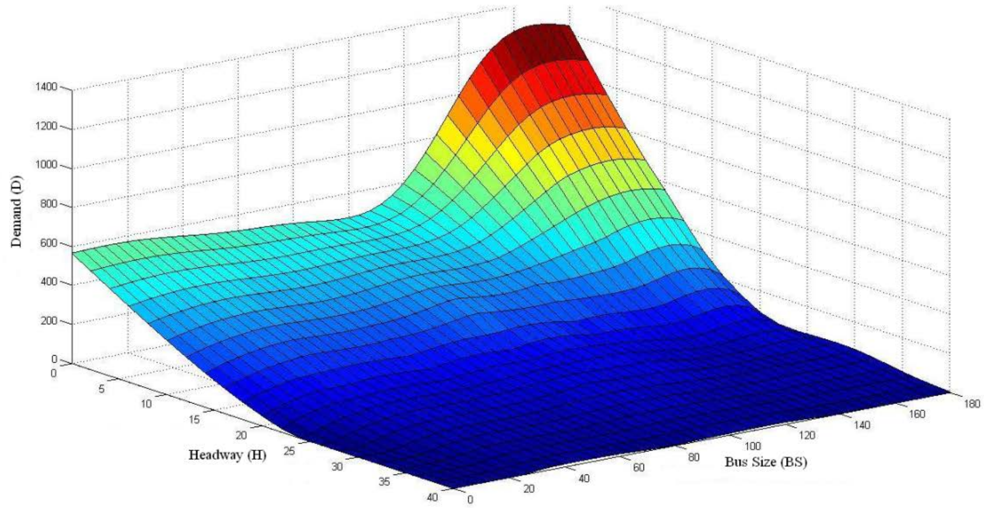

Figure 2-6 Surface generated from the experimental points

As is known, all surfaces respond to a function which defines them, in this case, working on a space defined by the variables (D, H, BS) the function is as follows:

f(D,H,BS) = 0

As stated earlier the ideal situation would be to obtain the mathematical expression as a function of the variables mentioned, so, knowing two of them, it is possible to get the value of the third and guarantee a minimum for the system, but, because of the complexity of the surface, the function does not have a trivial form, therefore, it was decided to propose a series of analytical solutions.

Analytical solutions for the function f(D,H,BS) = 0

The analytical solution is no more than a group of graphs which provide the value of the points (D, H, BS) that satisfy the equation, for which we can represent the corresponding cuts through the surface obtained for the planes (D, BS) (D, H) and (H, BS) for different fixed values of H (headway) for the first plane, of BS (bus size) on the second plane and of

D (demand) on the last plane. These graphs represent an analytical solution for the function f(D, H, BS) = 0.

Figure 2-7 represents the value of the demand (D) as a function of headway (H) for different values of bus capacities (BS).

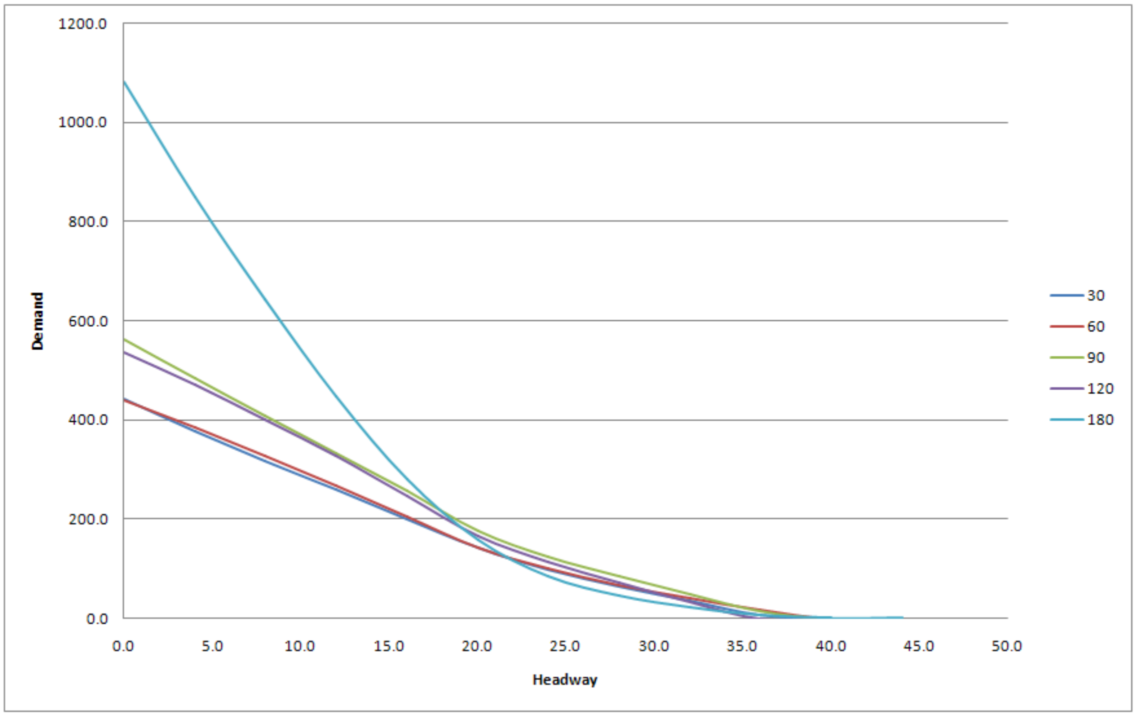

Figure 2-7 Demand vs Headway for different bus sizes.

An analysis of figure 2-7 shows that buses with sizes of 30 and 60 passengers/bus are optimal for the same values of demand and headway. The same happens with buses of 90 and 120 passengers/bus. On the other hand, buses of 180 passengers/bus would be needed to best satisfy demands of over 600 passengers/hour and at headways under 10 minutes. It also works out that for demands of fewer than 200 passengers/hour and headways over 20 minutes any type of bus is equally attractive for obtaining the optimal cost function.

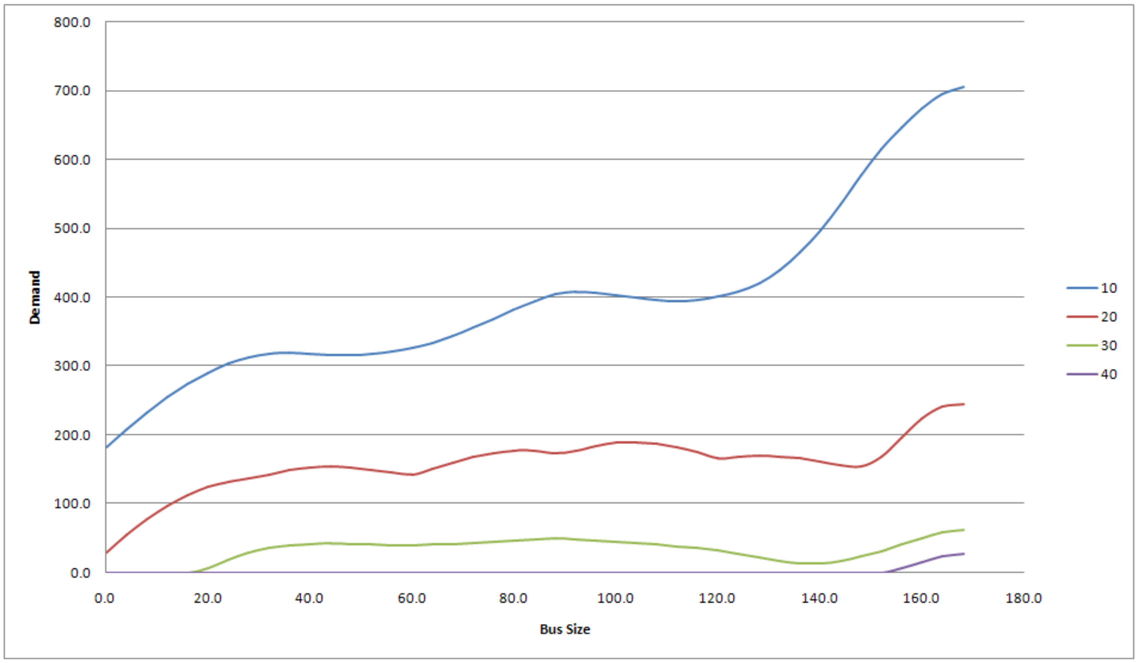

Figure 2-8 Demand vs. Capacity for different headway values

Figure 2-8 represents demand against bus size for different headway values. The most striking point that appears is that demands of over 400 passengers/hour can only be satisfied at headways of 10 minutes or less with bus sizes of at least 140 passengers/bus. This idea contradicts the proposals of other works which defend the use of smaller rather than large buses in most cases. Another interesting result is that size constraints start to appear at headways of over 30 minutes, in other words, as headway increases, smaller buses lose their efficiency to best satisfy demand.

Finally, figure 2-9 represents the cut at plane (H, BS) for certain fixed values of demand (D).

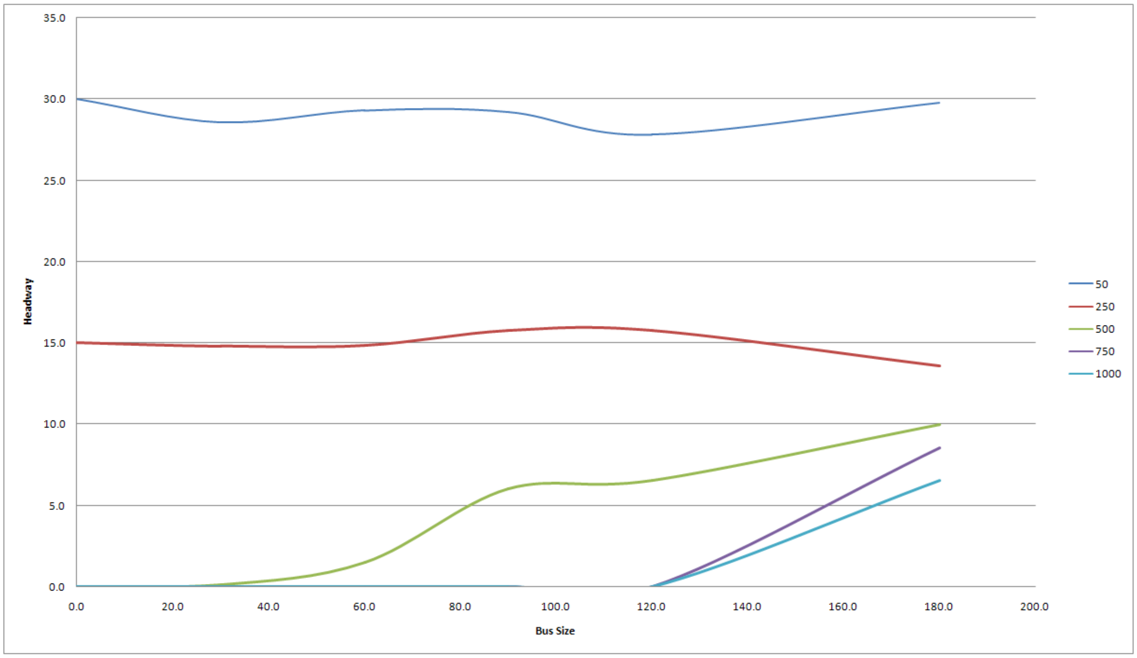

Figure 2-9 Headway vs bus size for different levels of demand.

It is worth pointing out that for demands of fewer than 250 passengers/hour, the graphs obtained are basically straight and run parallel to each other; this indicates that all bus types are equally attractive with the same headway from the perspective of a system optimal. This result had already been seen in figure 2-5. The use of certain buses ceases to be attractive at demands of over 500 passengers/hour, for example, buses with a capacity of 30, and those of between 40 and 80 passengers/bus would have to be at headways of under 5 minutes. If the demand were even higher (750 and 1000 passengers/hour) then only the buses of over 200 passengers/bus are attractive and if headways of over 5 minutes are required then the buses must hold over 160 passengers/bus.

2.8. Conclusions

The model proposed solves the optimization problem for headways and bus sizes on each route. Thanks to its formulation this model can be considered as an assignment model for bus types to different routes.

This model differs from other commonly used models in that it simulates a complete public transport network, taking into account the interactions between private transport and the bus network, as well as how the different bus routes influence each other. Therefore, it not only optimizes the headway and bus size per route but it also optimizes these variables taking into account the "network effect".

The model also provides results which are consistent with Mohring. However, it contradicts the idea that small buses are more profitable in most cases, this paper has shown that the optimal situation when planning a public transport network is obtained with a configuration of mixed bus sizes.

Another important aspect of the work done is obtaining a series of theoretical curves, which provide an analytical solution to a function including variables like: demand, headway and bus size. When the values of two of the variables are known the value of the third can be found under optimal system conditions. These graphs can be a very useful tool for optimal and rational planning of any public transport system in congested urban areas.

The results show that demands greater than 600 passengers/hour can only be satisfied by using buses that can carry more than 120 passengers/bus using headways of under 10 minutes. Furthermore, for low levels of demand (less than 200 passengers per hour) and at headways of over 20 minutes, all types of buses are equally attractive from the point of view of obtaining an optimal system. As headway increases, the smaller buses become less attractive and are only useful for satisfying very low demand levels at high intervals or greater demands but at the cost of reducing headway, meaning more buses and therefore, higher operating costs.

Capítulo 3

DESIGN OF A TABU SEARCH ALGORITHM FOR ASSIGNING OPTIMAL BUS SIZES AND FREQUENCIES IN URBAN TRANSPORT SERVICES

3. DESIGN OF A TABU SEARCH ALGORITHM FOR ASSIGNING OPTIMAL BUS SIZES AND FREQUENCIES IN URBAN TRANSPORT SERVICES[2]

3.1. Resumen

En este capítulo se presenta un modelo de optimización de tipo bi-nivel para optimizar frecuencias y asignar autobuses de diferente tamaño a líneas de transporte público. El modelo propuesto considera en el nivel superior una función a minimizar que considera costes de los usuarios y costes del operador y en el nivel inferior un modelo de asignación al transporte público con restricción de capacidad. En el artículo se discute la conveniencia utilizar como algoritmo de solución del modelo bi-nivel el algoritmo de Hooke-Jeeves o un Tabu-Search. Tras una aplicación práctica al caso de la ciudad de Santander (España), se concluye que los dos algoritmos conducen soluciones muy cercanas. Además se ha comprobado que partiendo ambos algoritmos de una misma solución homogénea, la velocidad de convergencia del Tabu-Search es casi un 50% más alta que la del Hooke-Jeeves, lo que hace que este algoritmo sea más atractivo si existe la necesidad de resolver el problema un número alto de veces y para redes de gran tamaño.

[2] Ruisanchez F., dell'Olio L., Ibeas A. (2012) Design of a tabu search algorithm for assigning optimal bus sizes and frequencies in urban transport services. Journal of Advanced Transportation 46, 366-377.

http://dx.doi.org/10.1002/atr.1195

3.2. Introduction

The efficient use of resources by both service providers and users has made the creation of optimization algorithms one of today's main fields of study in engineering and mathematical science. They can improve efficiency by solving common problems like calculating headways and bus sizes for each route on a network. These problems have been solved by many techniques such as genetic algorithms (Holland, 1975), probabilistic and neural networks (Minsky, 1954), multiobjective, combinatorial optimization (Zac et al., 2009) and intelligent search algorithms (Glover et al, 1989) among others. Public transport services are no exception. The optimization of these services requires efficient and rational planning which will substantially improve society's investment costs in the overall system. This work presents the methodology for calculating the optimal bus sizes and headways for each route in an urban public transport system.

One of the ways of solving this dilemma is by designing and solving a bi-level problem. An optimization function is established at the upper level for the overall system costs (user costs and transport company costs). A transport network assignment problem is solved at the lower level using ESTRAUSTM (SECTU, 1989) software. The solution of this type of heuristic procedure generally requires a large number of iterations implying heavy use of computing resources making it difficult to find an ideal and efficient way of moving forward.

This research compares the efficiency of different methods by using them to solve the same problem. One of the more common methods for solving this type of problem uses the Hooke Jeeves (HJ) algorithm (Hooke and Jeeves, 1961) which is applied here alongside a Tabu Search (TS) Algorithm (Glover et al, 1989) specially designed in this work.

After applying both solution algorithms to the real case of the city of Santander (Northern Spain, 180,000 inhabitants), it was found that both algorithms provided similar results but the TS solved the problem around 50% more quickly than HJ.

The purpose behind this research is to demonstrate that, after deciding on a bi-level optimization problem, it is important to find the most time and resource efficient algorithm which gives valid policy solutions for providers of urban public transport services.

The paper is structured in the following way: a brief description about the state of the art in the field of bus size optimization and route assignment is followed by a presentation of the methodology used for optimizing bus frequencies and assigning them to their respective routes. The two alternative algorithms are presented and the study case is explained along with the results of the model and the pertinent conclusions are drawn.

3.3. State of art

The study of the optimum size and type of buses was dealt with in depth in the 1980s when a whole series of policies were developed to give priority to public transport and thereby deal with traffic congestion in large urban areas (dell'Olio et al., 2011).

Work of note at that time was done by: Jansson (1980), Walters (1982), Vijakamur (1986), Glaister (1986), Oldfield and Bly (1988), Zac et al. (2009). Most of these studies concentrate not only on obtaining the optimum bus size but also on optimizing the frequencies of the buses (headway). A starting point in this type of study can be seen in the work of Webster (1968) who looked at the effects of transferring travellers from the car to differently sized surface public transport vehicles in London. Later, Webster and Oldfield (1972) continued on a similar line proposing modal distribution models based on minimizing the overall total cost for the private and public modes. Vickrey (1955) and Mohring (1972, 1976) publish recognised works establishing that route headways should be inversely proportional to the square root of the demand.

On the other hand, Jansson (1980) demonstrates in his work that headway outside rush hour should not differ much from headway at rush hour because the operators underestimate the costs of the users (this cost includes journey time and waiting time multiplied by their respective values of time) in their analysis. The same author considers that headway is not very sensitive to changes in bus size and therefore thinks it unnecessary to use very large buses.

Jara-Díaz, S.R. and Gschwender (2003a, 2003b, 2009) also propose a bus size optimization model but make use of budget constraints.

Similarly, Walters (1982) points out the benefits of using small buses on public transport networks. Glaister (1986) notes, for the first time, the importance of the cost per seat according to bus size indicating that the greater the number of seats, the lower the cost per seat has to be (because of the existing relationship: operating cost / number of seats). This author's study in Aberdeen concluded that there it was more efficient to use smaller buses with lower capacities.

Oldfield and Bly (1988) give an in-depth analysis of the advantages and disadvantages of using smaller buses, concentrating on the effects that these buses have on demand and headway.

Zac et al. (2009) propose a vehicle assignment problem in a long-haul, road passenger transport company with a heterogeneous fleet of buses.

More recent years have seen local authorities more worried about the social character of the service and they are once again looking at minibuses as an attractive possibility with corresponding lower headways and reductions in waiting times.

3.4. Methodology

The methodology followed in this work is made up of four clearly differentiated parts.

Proposal of the bi-level problem involving optimizing the overall system costs and the problem of vehicle assignment to the network.

Solution of the problem for calculating the optimal bus sizes and frequencies per route using the Hooke Jeeves algorithm and design of a tabu search algorithm for calculating the optimal bus sizes and frequencies per route.

Comparison of the results from each method.

A bi-level mathematical optimization problem is proposed for finding the optimal bus size to use on each route. At the upper level is a social wellbeing function which takes into account the user costs and operating company costs, subject to technological constraints and demand satisfaction. At the lower level is a public transport trip assignment model (dell'Olio et al., 2006 and Ibeas et al. 2010).

The international bibliography reveals a series of studies on the design of transport networks using bi-level programming techniques (Yang and Michael, 1998; Yang, 1997; Wong and Yang, 1997; Yang and Bell, 1997).

The nomenclature used for the problem is as follows:

TAT = Total Access time.

TWT = Total waiting time.

TIVT = Total in-vehicle time.

TTT = Total transfer time.

ϕ_a = Value of Access time.

ϕ_w = Value of waiting time.

ϕ_v = Value of in-vehicle time.

$\phi_v^{'}$ = Value of car journey time

L_i = length of route i (km per bus).

f_i = Frequency of route i (bus per hour).

CK_k = Unit cost per km for bus type k (€ per km).

$\delta_{k,i}$ = Mute variable, 1 if bus type k is assigned to route i and 0 in other cases.

t_{sb} = Time taken by passengers to get on and off the bus (minutes per passenger).

CR_k = Unit cost per hour for bus type k with engine ticking over (€ per hour).

Y_i = Demand for route i obtained by simulation (passengers per hour).

C_p = Hourly cost of personnel (€ per hour).

tc_i = turnaround time for route i (min).

H_i = headway in route i (min).

CF_k = fixed unit cost per hour of bus type k (€ per hour).

W: Group of origen-destination O-D pairs.

w: Element of group W, in which $w=(i, j)$, with i, j centroids.

Tw: Total number of journeys between O-D pair w for public transport users.

l: Index for designating a public transport line.

R: Group of available routes for public transport users.

r: Index for designating a public transport route section.

Rw: Group of public transport routes associated with the O-D pair w.

$\overline{h}_r$: Passenger flow on route r.

s: Index for designating a section of route

S: Group of available route sections for users of public transport.

cs : Cost of journey for passengers on route section s.

δsr : Element of the route-route section incidence matrix: value 1 if route r crosses s and 0 in other cases.

Vs: Passenger flow in route section s.

vls: Passenger flow in route section s using route l.

fl: Service headway on route l.

fs: Total headway in route section s.

The decision variables of the model will be the frequencies of each route $f_i \quad \forall \quad i = 1,2,...n$, where n is the number of routes on the network being considered, taking into account, as a discrete dummy variable (0, 1) $\delta_{k,i}$, the optimal bus size, assigning a value of "1" if bus type A is used to provide a service on route i ($\delta_{k,i}$) and "0" in other cases.

The cost structure used in this investigation considers the user costs (UC) and the operating company costs (OC). The user costs are obtained by simulation and are affected by the decision variables in the following way:

$$UC = \phi_a TAT + \phi_w TWT + \phi_v TIVT + \phi_t TTT \tag{3.1}$$

The operating company costs are considered to be the sum of the direct costs and the indirect costs (Ibeas et al., 2006). The Direct Costs are made up of three factors: Running costs (km covered) (CK), hourly costs (CR) with engine ticking over, personnel cost (CP), and fixed costs (CF). The Indirect Costs (CI) were estimated to be around 12% of the Direct Costs (Ibeas et al., 2006).

The total cost of the kilometres covered is equal to:

$$CK = \sum_i \sum_k L_i f_i CK_k \delta_{k,i} \tag{3.2}$$

The cost of stationary buses ticking over is:

$$CR = t_{sb} \sum_i \sum_k \; CR_k \delta_{k,i} Y_i \tag{3.3}$$

The personnel cost is taken as the cost of employees actually working on the service:

$$CP = C_p \sum_i \left(tc_i / H_i \right) \tag{3.4}$$

The fixed costs are calculated with the following formula considering the buses which are actually circulating:

$$CF = \sum_i \sum_k \left(\left(tc_i / H_i \right) \cdot CF_k \cdot \delta_{k,i} \right) \tag{3.5}$$

The upper level optimization problem is defined based on this cost structure:

$$\begin{aligned} \min \quad & Z = \phi_a TAT + \phi_w TWT + \phi_v TIVT + \phi_t TTT \\ & + \sum_i \sum_k L_i f_i CK_k \delta_{k,i} + t_{sb} \sum_i \sum_k CR_k \cdot 60 \cdot \delta_{k,i} Y_i + C_p \sum_i \left(tc_i / H_i \right) + \\ & + \sum_i \sum_k \left(\left(tc_i / H_i \right) \cdot CF_k \cdot \delta_{k,i} \right) \end{aligned} \tag{3.6}$$

s.t.

$$\begin{aligned} & \delta_{a,i} \in (0,1) \\ & \sum_a \delta_{a,i} = 1 \quad \forall i \\ & \sum_i \delta_{a,i} = n_a \quad \forall a \in A \\ & f_i \geq round^+ \left(\frac{Y_{t,i}}{\sum_a K_a \delta_{a,i}} \right) \quad \forall i \ (10) \end{aligned} \tag{3.7}$$

The first constraint defines the characteristics of the binary variables $\delta_{a,i}$. The second constraint indicates that each route can only be assigned one bus size, the third constraint indicates there is a restriction on fleet size, being na the number of routes that a bus of size a can cover, and the fourth is a demand satisfaction constraint as a function of the different capacities of the different buses, where K_a is the capacity of bus size a and Yt,i is the demand in the busiest section of route i.

The lower level is modelled using a public transport assignment model used in the public transport and traffic simulator ESTRAUSTM (SECTU, 1989).

Equilibrium conditions considered for the problem can be formulated using a variational disequality of the following type:

$$c(V^*)\cdot(V^*-V)\leq 0, \qquad \forall V\in\Omega \tag{3.8}$$

Where c is the cost vector in the route sections, V is any feasible flow vector in route sections $\{V_s\}$ and V* represents the equilibrium solution in terms of flows within route sections.

Consequently, the public transport equilibrium assignment model used in the formulation requires the definition of a more complex network, represented by a $G'=(\bar{N},S)$ graph where S is the group of links on the network, composed of route sections and access links. A route section is a portion of a route between two consecutive transfer nodes, and is associated with a group of routes which are equally attractive for the users (De Cea and Fernández, 1993). The optimization problem equivalent to the variational disequality, $c(V^*)\cdot(V^*-V)\leq 0,$ will be as follows:

$$Min \quad \sum_{s\in S}\int_0^{V_s} c_s(x)dx \tag{3.9}$$

s.t.

$$\begin{aligned}
&\sum_{r\in R_w} h_r = T_w && \forall w\in W\\
&\sum_{r\in R}\delta_{sr}h_r = V_s && \forall s\in S\\
&v_l^s = \frac{f_l\cdot V_s}{f_s} && \forall l\in B_s, \forall s\in S\\
&h_r\geq 0 && \forall r\in R
\end{aligned} \tag{3.10}$$

The model assumes the users choose the route that minimizes their total journey costs (fare + in-vehicle time + waiting time + access time). The system is assumed to have a limited capacity and, therefore, as the numbers using the system increase so does their journey time. It is assumed there is congestion at the bus stops.

3.5. Algorithm used: TABU-SEARCH vs HOOKE-JEEVES

The proposed problem will be solved using the real case of the city of Santander in Northern Spain. The Hooke Jeeves method was used first, followed by a Tabu Search method specially designed for solving the proposed problem (Appendix B). The roll of these algorithms is to generate a new frequency vector to solve the bus size optimization problem. The TS method is shown to be more efficient in the use of computing resources for finding the overall optimal situation for the system.

The Tabu Search algorithm was designed by Glover in 1989, it is a Heuristic iterative algorithm generally used for solving combined optimization problems. Tabu search belongs to the general field of local search algorithms. The neighbours within the current solution are investigated at each iteration, the best solution is chosen from that neighbourhood making it the start solution for the following iteration in the algorithm. However, if the local search algorithm stops because it does not find a better solution in the neighbourhood, the Tabu Search algorithm continues searching even if the starting solution is worse than before. To avoid the recycling of already explored results they are included in a Tabu List, also called the memory, this can be permanent throughout the entire process or can be cleaned out after a certain number of iterations. A detailed discussion around the architecture of the Tabu Search algorithm can be found in Glover et al (1998) and in Sait and Youssef (1999). The efficiency of Tabu Search can be improved by adding new characteristics like intensive searches in specific areas of the solution space or, contrarily, perform diversified searches in the solution space depending on the type of problem being solved with the algorithm (Glover et al (1998) Ben-daya and Al-Fawzan (1998).

Like Tabu Search, the Hooke-Jeeves algorithm is a heuristic iterative method, meaning that the obtained minimum is not guaranteed to be the overall minimum of the problem. This algorithm is quite often used in problems relating to the design of public transport networks because it can be implemented whatever the objective function (no type of restriction exists). The Hooke-Jeeves algorithm basically consists of the repetition of two stages:

Exploratory Search through each of the coordinates in the solution space, in order to find a sound local descent (reduction in the value of the objective function).

During this stage, the algorithm searches for a point highlighting a good local direction of movement. This is done by increasing or decreasing the value of one of the variables by a predetermined amount ("delta") and evaluating the objective function at this new point.

Movement pattern consists of an advance in the direction determined in the first stage.

If the first stage of the method produces a sound result, or, a point has been found where the value of the objective function is lower than at the best base point, an advance is made in the direction indicated and the new point is found. The length of this advance is determined by the difference between these two points multiplied by a pre-established value ("alpha").

Once an advance has been made in the direction determined during the first phase, another exploratory search is made from the new point, corresponding to a new iteration in the Hooke-Jeeves algorithm. A broader definition of this method can be found in Hooke-Jeeves (1961).

The steps taken are presented below along with the general flow diagram valid for the two algorithms being compared.

Algorithm used:

An initial feasible solution for frequencies is generated ($f_1, f_2, \ldots, f_n$) as well as for $\delta_{k,i}$ which is generally the current situation on the network.

The optimization problem is solved at the lower level (assigning equilibrium to public transport)

New frequency values ($f_1^1, f_2^1, \ldots, f_n^1$) are generated using, for example, the Hooke-Jeeves algorithm and the entire optimization problem is solved at the upper level, subject to the demand satisfaction constraint, to determine the values of $\delta_{k,i}$.

If $Z^{i+1} - Z^i > \tau$ then return to step 2, if $Z^{i+1} - Z^i \leq \tau$ the algorithm is stopped.

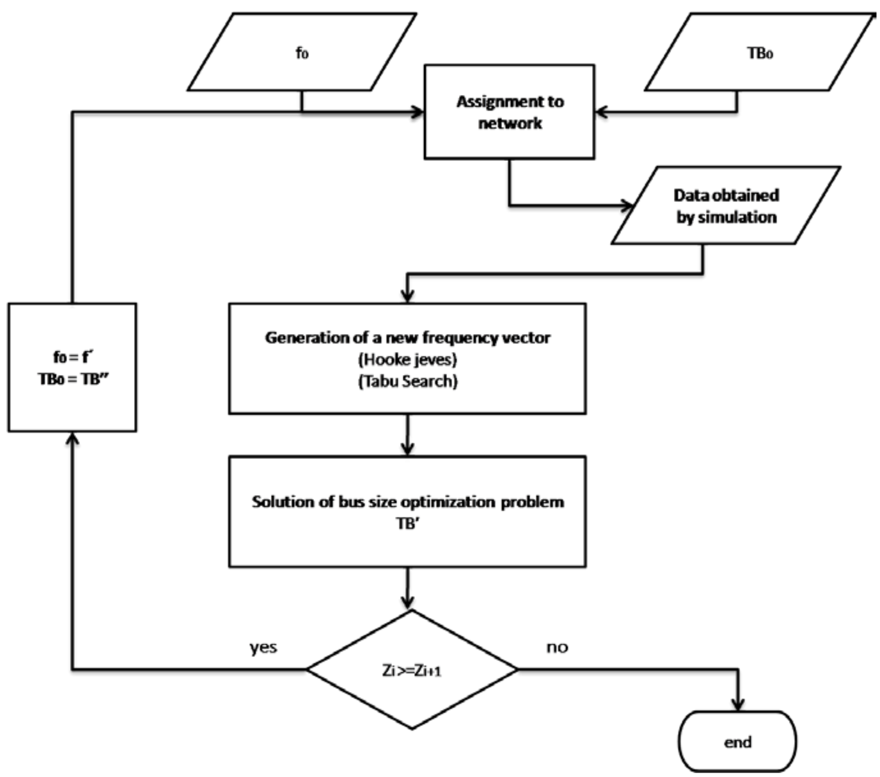

Figure 3-1 Flow diagram of solution algorithm.

The flow diagram in figure 3-1 shows a process defined as generation of a new frequency vector. This is where either the HJ or the TS algorithm is used, allowing comparisons to be made showing how the overall solution algorithm of the bi-level problem is affected by using either of the options.

3.6. Studied case: Comparison of models

The model is applied to the public transport bus service in the city of Santander. The city has a population of 180,000 and the current demand is for around 20 million journeys per year distributed between 11 lineal routes (return trips) and 4 circular routes. The model is loaded with data from the evening rush hour with a demand of around 4,000 journeys. The size of the buses currently operating in the city is 90 passengers/bus and the average headway is 20 minutes. There are 6 different bus sizes used in the model, the sizes chosen were for 30, 60, 90, 120, 150, 180 passengers/vehicle.

This study considered a value of in-vehicle journey time of 6 €/hour. The personnel cost, which did not change with bus size, was assumed to be 14 €/bus/hour. Both the fixed costs (CFa), and the running costs (CKa) varied according to the bus size (See Table 3-1)

Bus Size (a)	CK_a (€/km)	CF_a (€/bus/h)
30 pax	0.30 €/Km	14 €/bus/h
60 pax	0.50 €/Km	23 €/bus/h
90 pax	0.70 €/Km	32 €/bus/h
120 pax	0.80 €/Km	35 €/bus/h
150 pax	0.85 €/Km	37 €/bus/h
180 pax	0.90 €/Km	41 €/bus/h

Table 3-1 Unit costs depending on bus size

The results of applying the model to the real case study using the two methods being compared (HJ and TS) are presented below. The Tabu Search algorithm was run starting from a vector of headways of the 28 lines (counting out and return journeys separately) and each one was varied by a delta of ±0.5, making 56 the size of the neighbourhood being considered.

Various penalties were tested for the short-term memory, in the end it was decided to use a penalty of 7 iterations. In a previous study different values of delta and alpha were tested for the Hooke-Jeeves algorithm and it was concluded that the combination of delta=0.5 and alpha=1 produced the best results. To perform a sufficiently extensive comparison both algorithms were applied using various initial solutions. This allowed the behaviour of both algorithms to be observed for the appearance of any possible local minimums throughout the process of looking for the optimal solution. Three initial solutions called Case A, Case B, and Case C are proposed. Case A (the headways on all the lines equal 60 minutes) uses very different bus frequencies and capacities from those currently in operation on the case study transport network; Case B (the headways on all the lines equal 20 minutes) is the opposite, a solution very similar to the current situation and Case C (the headways on all the lines equal 40 minutes) is used as an intermediate solution between the two and serves as a control, because, at the end of the study the three cases should reach similar minimum values, demonstrating that the method is independent of the initial solution proposed by the researcher.

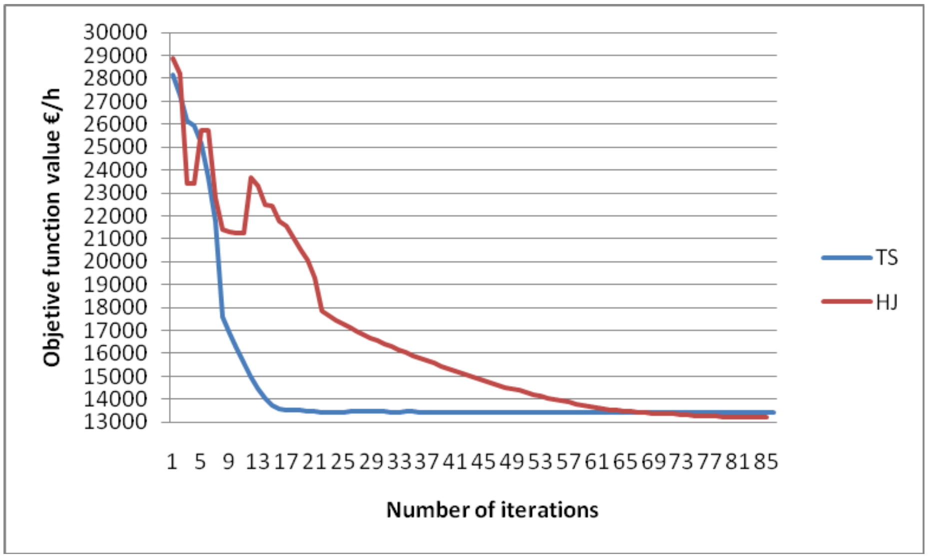

Figure 3-2 Evolution of objective function for Case A.

Figure 3-2 shows how the objective function evolves using the two methods on Case A, HJ is seen to be more sensitive to local minimums which could imply that this method gets trapped at a minimum if the algorithm's parameters have not been carefully chosen. Another observation is the greater convergence speed of the TS algorithm over HJ, however, the value of the objective function for HJ is a little lower than for TS, all these results are analysed in greater detail at the end of this section.

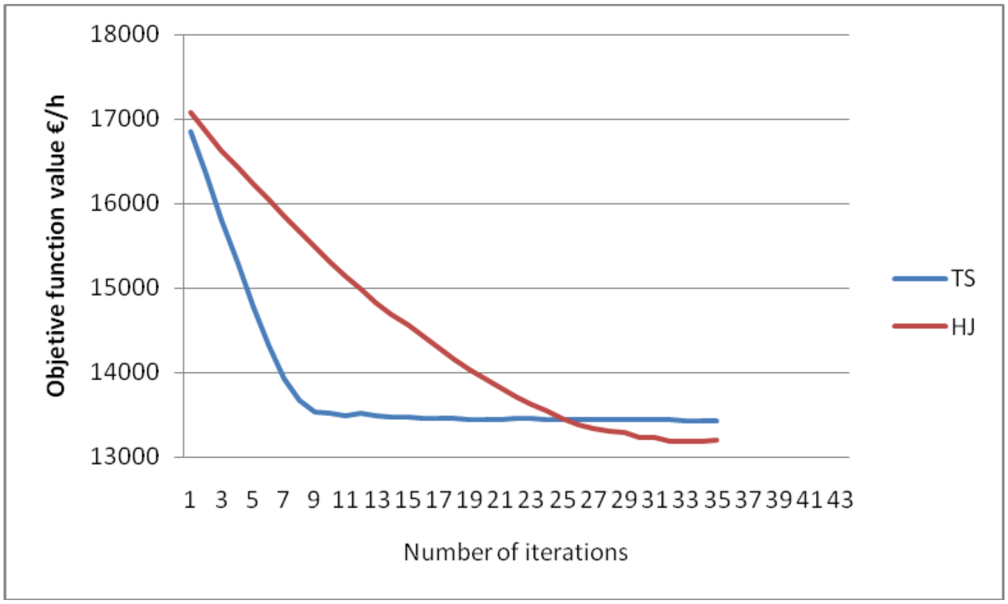

Figure 3-3 Evolution of objective function for Case B.

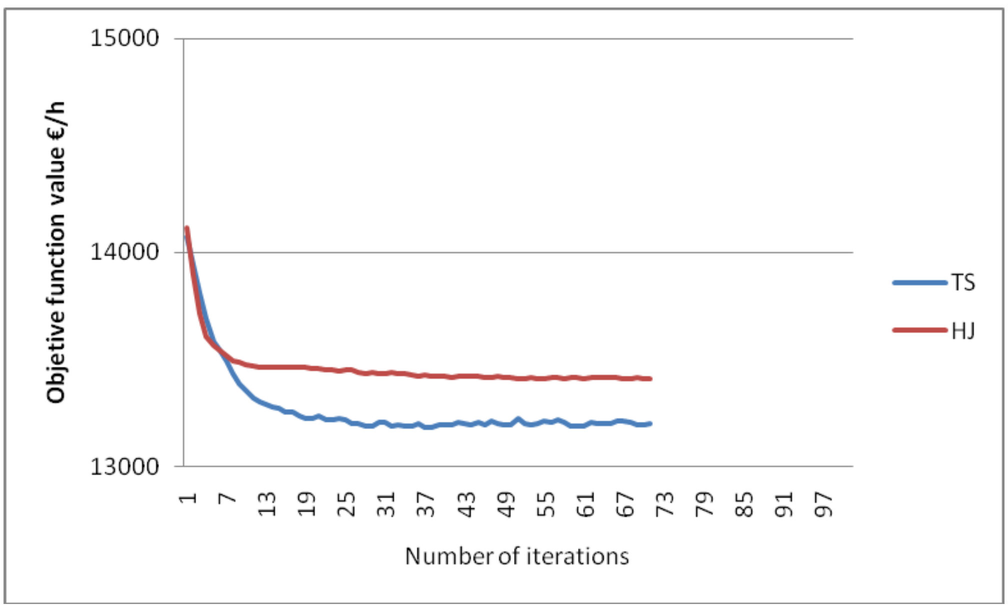

Figure 3-4 Evolution of objective function for Case C.

Figures 3-3 and 3-4 show how the objective functions evolve for Cases B and C, respectively. The difference in convergence speed between HJ and TS can also be seen in Figure 3-2, TS reaching near minimum values in half the time it takes HJ. For Case C we can see that the behaviour of both methods is practically analogous. An additional reading can also be seen in the figure showing the correct optimization of frequencies and capacities in the current case study as the initial value of the objective function is found to be very close to the final solution provided by the algorithms.

	Cost (€/h)	
Initial Solution	Using TS	Using HJ
CASE A	13410	13183.65
CASE B	13438	13200.32
CASE C	13423	13185.68
Variance	196.33	82.72
Deviation	14.01	9.10

Table 3-2 Final values for the three cases studied

The results found in the group of 3 figures will now be analysed. Table 3-2 shows the final values of the objective function for the 3 cases along with the two proposed methods and their variances and deviations. A small difference can be seen in the higher final value for the objective function found using TS than obtained with HJ, this is only a difference of 1.7% and can be put down to the greater flexibility of HJ for assigning values to the different variables in the problem. Turning to the deviations found in the 3 proposed cases we can see that HJ and TS are 14 and 9 €/h, respectively meaning that both methods are independent of the initial solution taken as the starting point.

Table 3-3 shows the results obtained for Case B and allows more detailed comparison to be made between the results of the two methods used for optimizing bus capacities and frequencies

line	H HJ	TB HJ	H TS	TB TS	diff H	diff TB
1I	13.64	30	14.5	30	0.86	0
1R	13.34	30	14	30	0.66	0
2I	14.16	30	14	30	0.16	0
2R	12.24	30	13	30	0.76	0
3I	25.34	90	24	90	1.34	0
3R	27.86	90	25.5	90	2.36	0
4I	15.16	90	14	90	1.16	0
4R	15.56	90	14.5	90	1.06	0
11I	56.06	180	51	180	5.06	0
11R	23.06	180	24.5	180	1.44	0
12I	31.34	120	33.5	120	2.16	0
12R	21.24	90	23.5	90	2.26	0
13I	24.34	90	27	90	2.66	0
13R	27.56	90	27	90	0.56	0
14I	12.44	90	13	90	0.56	0
16I	29.36	120	30	120	0.64	0
17I	30.74	120	32	120	1.26	0
17R	42.46	120	47	120	4.54	0

18I	28.74	120	32	120	3.26	0
18R	57.06	180	60	180	2.94	0
19I	51.06	180	59.5	180	8.44	0
19R	51.14	180	59	180	7.86	0
51I	9	60	10	60	1	0
52I	10.66	60	10	60	0.66	0
61I	23.26	90	23	90	0.26	0
62I	22.14	90	23.5	90	1.36	0
71I	16.96	60	16.5	60	0.46	0
72I	16	60	15.5	60	0.5	0

Table 3-3 Results of the model for Case B.

The first column identifies the bus line, where I and R indicate if they are out routes or return routes, respectively, the second (H HJ) and third (TB HJ) columns give the optimum headway and bus size, respectively, found using HJ, the fourth (H TS) and fifth (TB TS) columns present the optimum headway and bus size found using TS and the two final columns represent the differences both in optimal headway (H) and bus size (TB) obtained by both methods.

The difference between the solutions offered by TS and HJ are seen to be very close at almost all frequencies and are only over 3 minutes in 5 of them. The assignment of bus sizes to the network was the same using both algorithms. With respect to the current situation which includes vehicles of 90 passengers/bus, the optimized solution uses various bus sizes on the different lines to better cater for the demand for each service frequency used in the optimization process.

A figure follows showing the evolution of the objective function value against the number of iterations of the algorithm (Z vs time) (This article uses I iteration as a unit of time equivalent to about 30 seconds).

Figure 3-2 shows that almost minimum values are obtained after iteration 13 when using TS, while HJ does not reach a similar value until iteration 26, meaning that the TS algorithm when applied to this specific problem is 50% quicker than HJ.

It can also be seen that HJ obtains lower values for the objective function; this is because its architecture allows it to be more precise in looking for the minimum value, although the final values in both cases only differ by 1.7%, which could be acceptable with the 50% reduction in computing time offered by the TS algorithm.

An analysis of the results presented in table 3-3 provides a wide range of headway values (from 10 - 59 minutes). The lines with the shortest headways (such as lines 51I, 52I, 4I and 4R) are the most frequently used during the studied time period and pass through the city centre. The lines with the longest headways, such as 19I and 19R, are lines serving peripheral neighbourhoods (in practice they work more to a time table than on headways: the public know the times when the buses pass by).

As the proposed model optimizes the sum of the user and operating costs, the model was expected to compensate the headways in this way.

3.7. Conclusions

The model proposed in this paper solves the optimization problem for headways and bus sizes on each route. Thanks to its formulation this model can be considered as an assignment model for matching bus sizes to different routes.

This research has used two heuristic methods for solving a bus size assignment and frequency optimization problem for an urban bus network.

Both the computational results and the final result of the problem reveal that the TS algorithm is the faster of the two algorithms used, but the final solution values for bus sizes and frequencies differ only a little from that offered by HJ.

It has also been shown that when both algorithms start from the same homogenous solution, the convergence speed of Tabu Search is almost 50% quicker than Hooke-Jeeves, making Tabu Search more attractive if there is a need to solve a problem many times and for large networks. The similarity in the solutions offered by both algorithms show they provide very similar values for the variables under study, although there are certain localised differences, which could be down to their singularity, as they experience abnormally low demand values.

It is also worth noting that the method used with either algorithm is independent of the initial solution used to initiate the optimization process looking at the variances obtained over the three initial situations proposed in our study.

The final value of the minimized objective function was seen to be lower using HJ because of its more flexible characteristics when generating new possible solutions to the problem, even so the difference with TS is only 1.7 % making the TS method much more attractive for solving the problem because it reaches almost optimal solutions in half the time.

The results of the bus size optimization process show that the type of bus assigned to each line changes notably (currently only vehicles of 90 passengers/bus are running), indicating that the use of heterogeneous fleets could only be advantageous if the bus size is optimized taking into account service frequency and journey demand.

Capítulo 4

PUBLIC TRANSPORT LINE ASSIGNMENT MODEL TO DUAL-BERTH BUS STOPS

4. PUBLIC TRANSPORT LINE ASSIGNMENT MODEL DUAL-BERTH BUS STOP[3]

4.1. Resumen

En esta capítulo se trata la problemática de la congestión en las paradas de transporte público, proponiendo como solución la diversificación de las paradas de bus con un modelo de distribución de líneas de transporte público en el que se minimiza el coste del usuario teniendo en cuenta la interacción con el tráfico privado y la congestión en el sistema de transporte público.

Finalmente, se muestra su aplicación a un caso real en la ciudad de Santander (España), comparando la situación actual con la optimizada, comprobando los beneficios reales del modelo.

4.2. Introduction and objectives

Congestion in public transport (Spiess 1984, Gibson et al. 1989 and De Cea and Fernández 1993) does not only occur due to insufficient in-vehicle capacity (Larrain and Muñoz 2008) it can also be caused by vehicle interaction when high flow causes bunching at bus stops.

Bus stops are critical locations in the overall public transport system where only a maximum number of buses can use a stop at any one time (Gibson et al. 1989). When a bus arrives at a stop certain stages can be defined (Tyler 2002): approach, deceleration,

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[3] Alonso, B., Moura, J., Ibeas, A., and Ruisánchez, F. (2011). Public Transport Line Assignment Model to Dual-Berth Bus Stops. J. Transp. Eng 137, 12, 953-961.

http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000260 stopping at the bus stop, dwell time (opening doors, boarding and alighting, closing doors), and clearance time (waiting for a gap to get back into the

traffic flow, acceleration and leaving the bus stop area). Other buses can arrive during any of these stages and create a queue while they wait for the first bus to clear the stop and allow them to enter and complete the rest of the stages described above.

The time spent during each these stages is significant (Fernandez and Tyler 2005) and their optimization would undoubtedly improve the average bus speed. However, the most important of them is definitely the time lost queuing and that depends on the distribution of bus arrivals at the stops.

Greater demand for buses and increased flows will eventually saturate bus stops so certain solutions have to be found to increase their capacities. The instinctive option is to locate two or more stopping areas in a line, however, while the first area will be fully efficient, the capacity of the rest will drop, reaching reductions of up to 95% for the stop located in fifth place (TRB 2000, 2003). This leads to the concept of divided (dual berth) bus stops (Gibson and Fernandez 1995), where capacity can be increased by dividing stop n into smaller, more efficient stops m to deal with increased passenger and bus demands (Figure 4-1).

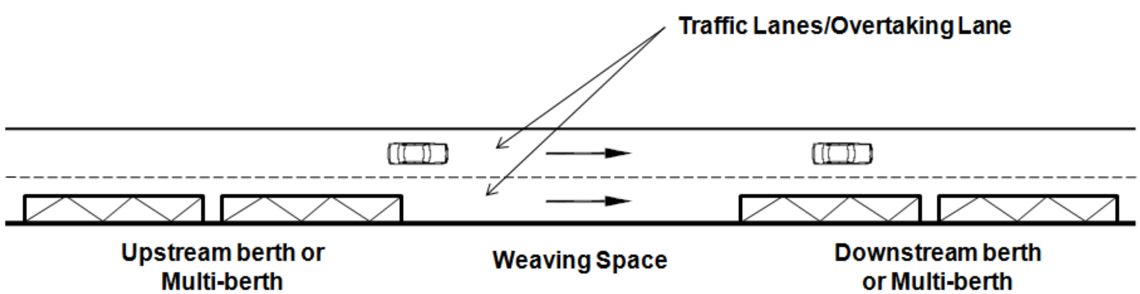

Figure 4-1 Divided bus stop/Dual berth bus stop

Traditionally, buses have been assigned to these multi-berth stops according to their routes or common destinations; however, these groupings cannot always be made efficiently in a public transport system. The model presented in this study addresses this problem by proposing a method which efficiently assigns buses to individual berths within dual-berth bus stops.

The main objective of the research proposed here is to develop a model which can distribute bus lines among the berths of a divided bus stop and thereby minimize the costs of public transport users.

The section below evaluates current and past research on the problem and is followed by a description of the proposed model and the proposed solution algorithm. The model is tested on a small study case and a sensitivity analysis is performed before its final application to the real case in the city of Santander (Spain).

4.3. Literature review

The bibliographic review found recent research which studied the influence and operation of a bus stop (Saka 2001, Fernandez 2001, 2003) in greater and more specific detail with applications for micro simulation models like PASSION (Fernandez 1993 and Fernandez and Planzer, 2002), IRENE (Gibson et al. 1989), MISTRANSIT (Burgos et al. 2005 and Cortés et al. 2007) or BusSIGSIM (Silva 2001 and Tyler et al. 2003).

Other research studies have analysed the influence of bus stops on traffic flow and have established parameters for changing the typology of the stop (Koshy and Arasan 2005) or how to determine the typology and number of locations for a bus stop based on the number of effective areas of each type and the demands of buses and users (Shi et al. 2007).

More specific research has analysed divided bus stops and made recommendations on their design criteria (Gibson and Fernandez 1995, Fernandez 1998 and Fernandez and Tyler 1999). Work done by Fernandez et al. (2007) studied bus stop capacity and the mutual influence of stopping areas, showing that for high bus flows the capacity of the stop located upstream is affected by the flow of buses going to the stop located downstream.

However, no work has been found on how to distribute all the lines operating at a bus stop to each of the berths. Divided bus stops of this kind already exist in cities such as Edinburgh, London, Santiago de Chile, or Santander (Spain), where the lines are pre-assigned to one of the berths (generally by a common destination). The main reason for pre-assigning the lines to each berth is to avoid passenger discomfort when faced with the dilemma of where to stand without having to rush from one berth to another when their bus arrives. This research provides the solution of how to pre-assign lines to berths efficiently and at a minimal cost to the user.

4.4. Proposed optimization model

The model proposed here assigns bus routes to multi-berth bus stops taking into account congestion both on-board the buses and at the stops and does so at a minimum cost to the public transport user.

Assumptions

It is assumed that the arrival of the buses at the stops adheres to a determined distribution (Cowan 1975; Danas 1980 and Law and Kelton 1991). Therefore, the probability that two consecutive buses arrive at the same stop at an interval (headway *h*) lower than *t* is given by:

$$\Pr(h < t) = 1 - \Pr(h \geq t) \tag{4.1}$$

A fixed and known demand for journeys will be considered, defined by the respective O-D trip matrices for each mode of transport.

It is assumed that the users will choose from a sub-group of common lines (Chriqui and Robillard 1975) called attractive lines which minimize their total expected journey time (waiting time plus in-vehicle time) between a given O-D pair. When journeys include transfers it is not possible to assume that all travellers moving between an O-D (T_p) pair would choose a particular group of attractive lines to make their journey, instead they would do it in stages. These stages are modelled using route sections (De Cea and Fernandez 1993) defined by stage origin and destination nodes and by a group of possible attractive lines.

Logically, the vector assigning lines to stops will condition the probability of arrival as well as the group of attractive lines (and, therefore, the route sections), which in turn will influence the journey, waiting and transfer times.

Proposed Model

A Bi-Level mathematical optimization model is proposed for solving the problem of assigning bus lines to bus stops. The upper level of the model minimizes a cost function for the user of public transport, while the lower level public transport assignment model takes into account the influence of private traffic and congestion among public transport vehicles. The general layout of the proposed model is shown in figure 4-2.

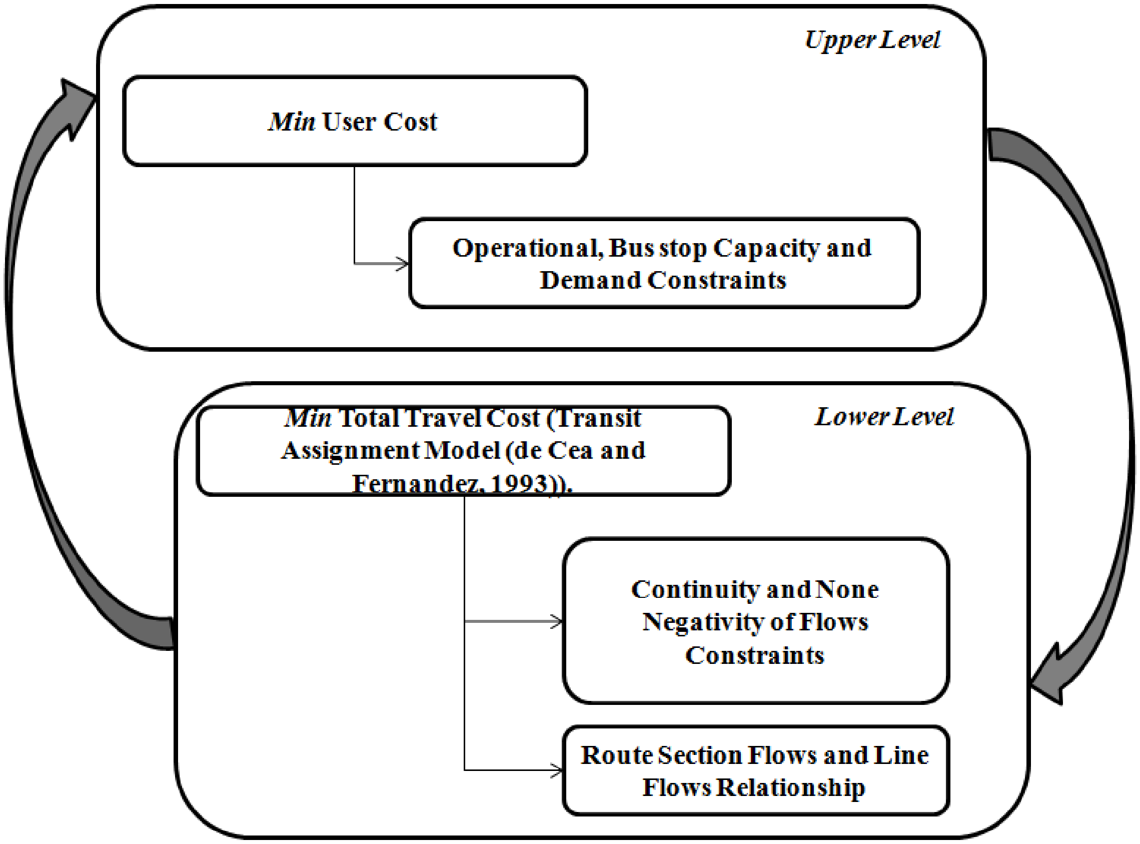

Figure 4-2 General layout of the proposed model.

Lower Level

The lower level optimization function is modelled using a public transport equilibrium assignment model restricted by a bus capacity constraint (De Cea and Fernandez 1993) and can be formulated with a variational disequality of the following type:

$$\overline{C}(\overline{V}^*)\cdot(\overline{V}^* - \overline{V}) \leq 0, \qquad \forall \overline{V} \in \Omega \tag{4.2}$$

where $\overline{V}$ is any feasible flow vector in route sections $\{V_s\}$, $\overline{V}$ * represents the equilibrium flow solution in the route sections, Ω is the group of feasible flow vectors in the route sections and $\overline{C}$ is the diagonalized route section cost vector c_s. The authors demonstrate that an equivalent optimization problem of (4.1) can be formulated as:

$$\min \quad \sum_{s \in S} \int_0^{V_s} c_s(x_s) dx_s \tag{4.3}$$

$$\begin{aligned} & s.t.: \\ & T_w = \sum_{r \in P_w^m} h_p, \quad \forall w \\ & V_s = \sum_{p,w} h_p \cdot \beta_{sp}, \quad \forall s \\ & h_p, V_s \geq 0, \quad \forall p, s \end{aligned} \tag{4.4}$$

Where T_w is the demand for O-D pair *w*, *hp* is the flow on route *p*, V_s is the flow on route section *s* and β_{sp} is an element taking a value of 1 if route section *s* belongs to *p* and 0 in other cases. The group of constraints (4.4) refer to continuity and none negativity of flows as well as the flow distribution restrictions on public transport links to route sections.

Upper Level

The user's costs (UC) are divided into 4 components associated with access, waiting, in-vehicle and transfer times (dell'Olio et al. 2006):

$$UC = \phi_a TAT + \phi_w TWT + \phi_v TIVT + \phi_T TTT \tag{4.5}$$

where:

TAT = Total Access Time from/to the origin/destination.

TWT = Total Waiting Time.

TIVT = Total in-vehicle Journey Time.

TTT = Total Transfer Time.

ϕ_a = Value of access time.

ϕ_w = Value of waiting time.

ϕ_v = Value of in-vehicle journey time.

ϕ_t = Value of transfer time.

In equation (4.5), the waiting, journey and transfer times will be given by the lower level (public transport assignment model (De Cea and Fernandez 1993)) and will be functions of bus line assignment to stops. Access time is assumed to be constant because the different stopping areas are so close to each other.

So, the total waiting time will be, using an initial approximation (Chriqui 1974, Chriqui and Robillard 1975 and Leiva et al. 2010):

$$TWT = \sum_{w}\sum_{s}\left[V_s^w \cdot \left(k \Big/ \sum_{l \in L} f_l \cdot x_l^s\right)\right] \Rightarrow \sum_{w}\sum_{s}\left[\left(k/f_s\right) \cdot V_s^w\right] \tag{4.6}$$

where:

k= parameter value depending on the time distribution of buses arriving at the stops.

L= group of lines.

f_l= frequency of line l.

x_l^s= binary variable taking a value of 1 if line l is attractive for route section s, and it takes 0 if not.

V_s^w= passenger flow over route section s for O-D pair w, obtained at the lower level.

f_s= frequency over route section s.

Once a passenger boards a vehicle at a stop, the journey time on board that vehicle is determined by: (Fernandez and Tyler 1999) the level of congestion existing on the network (flows of private and public transport vehicles) (*Tv*), delays due to traffic lights (*Tc*) found on the route and dwelling time at bus stops (*TBS*) (Larrain and Muñoz 2008) which also includes the effect of bunching (bus congestion) at stops. Therefore, the in-vehicle journey time will be:

$$TV = \sum_{\kappa} Tv_{\kappa} + \sum_{c} Tc_{c} + \sum_{n} TBS_{n} \tag{4.7}$$

Where:

κ, c and *n* represent the number of links, traffic light controlled intersections and stops, respectively.

Tv_{κ} can be obtained from a flow-delay function.

Tc can be found using the formula (Saka 2001):

$$Tc_{l} = \sum_{c=1}^{CT} \left(\left(C_{c} - g_{c} \right) / C_{c} \right) \cdot \left[0.50 \left(C_{c} - g_{c} \right) \right] / 60 \tag{4.8}$$

where:

C_c = cycle duration of traffic light *c* (min).

g_c = duration of green at traffic light *c* (min).

CT = Number of traffic lights on the bus route.

$TBS_{l,n}$ will be its own operating time plus the queuing time, which will depend on the operating times of the buses already at the stop or waiting ahead in the queue expressed as:

$$TBS_{l,n} = \left(\max \left(Y_{l,n} \cdot t_{s} ; X_{l,n} \cdot t_{b} \right) + \left(t_{o,c} / 60 \right) \cdot f_{l} \right) + \left(OT_{L,n} \cdot \phi \cdot \left(\varsigma_{n} \right)^{\vartheta} \right) \tag{4.9}$$

where:

t_s = average passenger boarding time (h).

t_b = average passenger alighting time (h).

$Y_{l,n}$ = actual demand for trips on line *l* originating at stop *n* (pax/h).

$X_{l,n}$ = actual demand for trips on line *l* and destination at stop *n* (pax/h).

$t_{o,c}$ = average time spent opening and closing doors and in entering and leaving the bus bay for each bus (min).

ς_n is the probability of consecutive buses arriving, or the probability that stop *n* is already occupied → $\Pr(h < t)$ and ϕ and θ are calibration parameters.

$OT_{L,n}$ is the average operating time for all the lines stopping at bus stop *L*

obtained by:

$$OT_{L,n} = (1/L)\sum_{l}\left[\max\left(Y_{l,n}\cdot t_s ; X_{l,n}\cdot t_b\right)+\left(t_{o,c}/60\right)\cdot f_l\right] \quad (4.10)$$

Assuming there is an available sub-group of attractive lines for a determined trip, the total journey time is considered as (Chriqui 1974, Chriqui and Robillard 1975 and Leiva et al. 2010):

$$TIVT = \sum_{w}\sum_{s}\left[\left(\frac{\sum_{l\in L} TV_l\cdot f_l\cdot x_l}{\sum_{l\in L} f_l\cdot x_l}\right)\cdot V_s^w\right] \Rightarrow \sum_{w}\sum_{s}\left[\left(\frac{\sum_{l\in L} TV_l\cdot f_l\cdot x_l^s}{f_s}\right)\cdot V_s^w\right] \quad (4.11)$$

where:

TV_l = is the journey time defined in (A.2).

Finally, the total transfer time will depend on the number of transfers to be made, given by (Leiva et al. 2010):

$$TT = \theta\cdot\left(\sum_{s,w} V_s^w - \sum_{w} T_w\right) \quad (4.12)$$

where:

T_w = journeys between O-D pair *w*.

ϑ = average time to move between bus stop areas.

The cost structure and the times described above mean the proposed upper level optimization problem can be defined as:

$$\min \ \phi_w \sum_w \sum_s \left[\left(\frac{k}{f_s} \right) \cdot V_s^w \right] + \phi_v \sum_w \sum_s \left[\left(\frac{\sum_{l \in L} TV_l \cdot f_l \cdot x_l^s}{f_s} \right) \cdot V_s^w \right] + \phi_T \cdot \theta \cdot \left(\sum_{s,w} V_s^w - \sum_w T_w \right) \quad (4.13)$$

s.t.:

$$\sum_l f_l \cdot \delta_{l,m} \leq N_{eb} \frac{3600 \cdot \left({}^{g}\!/\!{}_{C} \right)}{t_c + \left(\max(X_n \cdot t_s, Y_n \cdot t_b) + t_{o,c} \right) \cdot \left(\left({}^{g}\!/\!{}_{C} \right) + Z_a \cdot c_v \right)}, \quad \forall \ m \quad (4.14)$$

$$\sum_l f_l \cdot \delta_{l,m} \geq \sum_l \frac{Y_l \cdot \delta_{l,m}}{K_l} \quad , \forall l \in L \quad (4.15)$$

where:

N_{eb}= effective shelters per stop.

g/C = time on green at traffic light influencing bus stop (if present).

t_c = clearance time between two consecutive buses.

Z_a = factor corresponding to the probability of a queue forming at a bus stop.

c_v = dwell time variation coefficient.

$\delta_{l,m}$ = binary variable taking a value of 1 if line *l* stops at sub-stop *m* and 0 if not.

Constraints (4.14) and (4.15) were calculated following the TCQS Manual (TRB 2003) guidelines to guarantee that the solution satisfies the restrictions on bus stop capacity and demand, respectively.

4.5. Solution methodology

The methodology followed for solving the proposed problem is based on a heuristic which finds the optimal assignment of lines to bus stops whilst minimizing the public transport user's costs.

A genetic algorithm has been developed to find an optimal solution. These algorithms imitate the genetic process of living organisms tending towards the survival of the best adapted specimens of a species. In the case of a mathematical problem the species is the different number of possible solutions and the best adaptation will depend on the specific characteristics of the proposed problem. In this case, the best adapted will be the solutions that minimize the value of the objective function.

The basic principles of Genetic Algorithms were established by Holland (1975) and have been well described in many texts, Goldberg and Richardson (1989), Davis (1991), Michalewicz (1992), and Reeves (1993). This research uses the Simple or Canonic Genetic Algorithm (AGS) which uses the basic components of *Generation, Selection, Crossover, and Mutation*.

The heuristic algorithm used in this research can be described in the following stages which are also shown schematically in figure 4-3, the code is saw in (Appendix C)

Stage 1: The first phase distributes an initial feasible assignment of lines to stops, forming the vector $[d^n]$, where each component represents each bus line and takes a value of 1 if the upstream berth is assigned, or 0 if the downstream berth is assigned. The lower level public transport assignment model is applied using this configuration of bus lines at the stops.

Stage 2: The data on journey, waiting and transfer times from Stage 1 is then used to calculate the upper level cost function value UC^n

Stage 3: The AGS genetic algorithm mutates the vector $[d^n] \rightarrow [d^{n+1}]$, returning to Stages 1 and 2. An example of the pseudo-coding of the AGS follows below.

```
BEGIN
    Generation: the start-up population is generated.
    Compute the objective function to be minimized
    WHILE terminated ≠ TRUE
        FOR population size/2
            BEGIN
                Selection: select two individuals from the population
                for breeding (this choice is proportional to
                the individual's evaluation function).
                Crossover: the two individuals breed with certain probability
                and produce descendents.
                Mutation: the descendents mutate with a certain probability.
                The value of the objective function is computed for the
            descendents
                These two descendents now form part of the new generation.
            END
            IF population has converged THEN
                Terminated = TRUE.
        END
    END
```

Stage 4: Once the genetic algorithm has converged, the vector $[d^n]$ with the minimum UC^n is obtained.

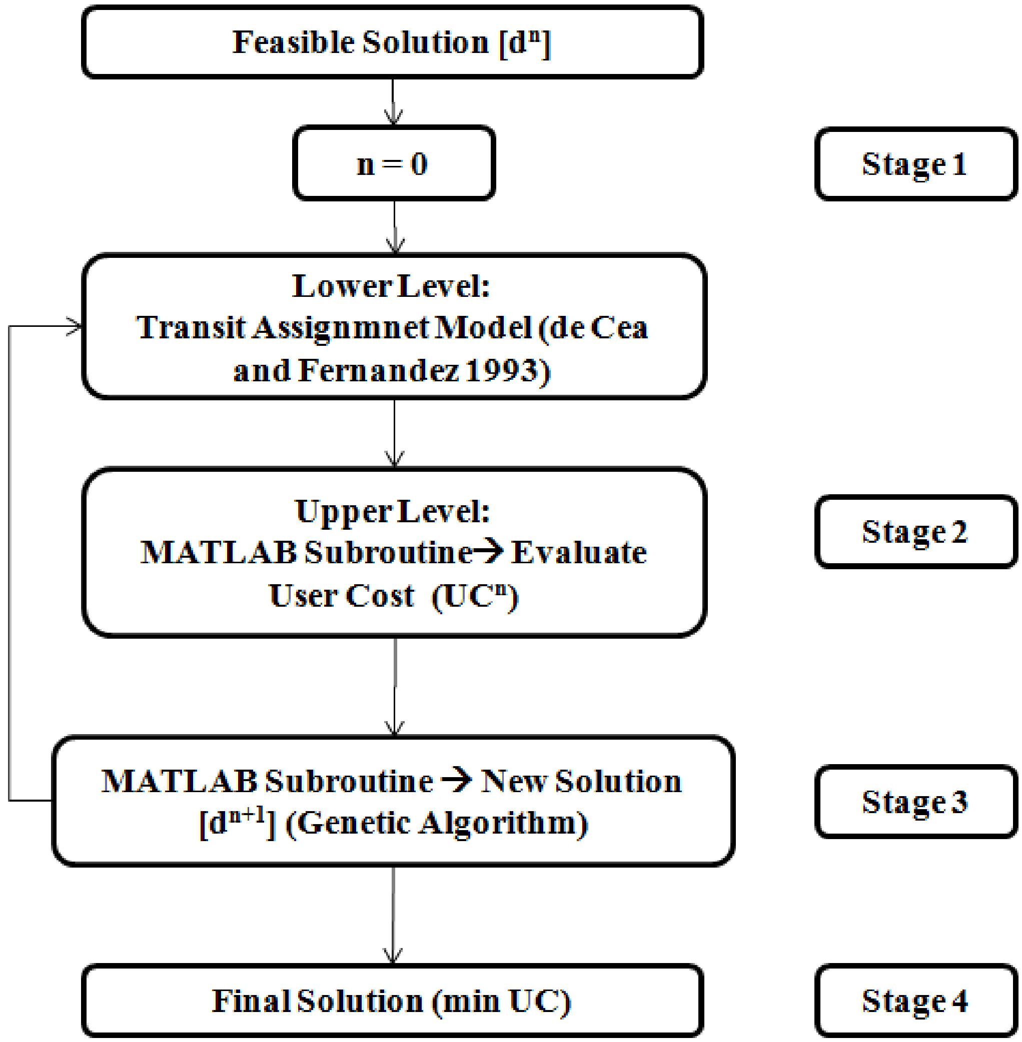

Figure 4-3 Flow diagram of the solution algorithm.

The software package ESTRAUS™ (De Cea et al. 2003) is used for the lower level (Transit Assignment Model), while MATLAB™ (www.mathworks.com) is used for calculating the upper level cost function and for running the solution algorithm.

4.6. Case study

The validity of the proposed model has been checked by designing a unidirectional experimental network as shown in figure 4-4. This network is made up of 15 nodes or bus stops and 7 public transport lines with the characteristics detailed in table 4-1. Nodes 1, 2 and 3 are exclusively trip generators, nodes 13, 14 and 15 are exclusively trip attractors, while nodes 4 to 12 are both trip generators and attractors.

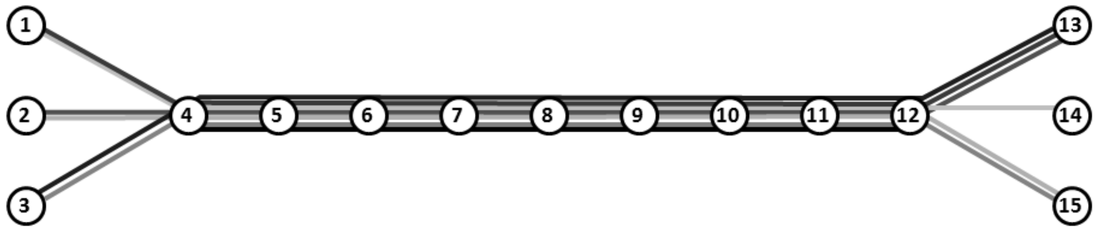

Figure 4-4 Case Study network.

Line	Headway (min)	Frequency (bph)	Origin-Destination
1	6	10	1-13
2	8	7.5	2-13
3	6	10	2-14
4	8	7.5	3-15
5	10	6	3-13
6	8	7.5	3-14
7	4	15	4-12

Table 4-1 Characteristics of public transport lines.

All the transport lines in this network converge on a central common corridor which is 4 km long and made up of stops 4-5-6-7-8-9-10-11-12. The bus journey matrix shown in table 4-2 is assumed to be fixed and known. The public transport system lacks any segregated infrastructure, in other words there are no bus lanes and it shares the road with the car so the arrival of buses at stops is assumed to distribute Poisson, it adjusts to a negative exponential distribution.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Σ**
2	0	0	0	78	61	67	62	82	99	40	68	57	45	57	50	767
1	0	0	0	40	0	123	32	60	111	0	101	0	99	50	69	685
3	0	0	0	130	49	71	28	110	0	115	72	109	98	50	72	903
4	0	0	0	0	55	49	0	143	0	127	50	79	90	76	94	763
5	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	32
6	0	0	0	0	0	0	136	75	28	46	23	105	76	85	24	599
7	0	0	0	0	0	0	0	0	63	28	101	27	101	72	84	475
8	0	0	0	0	0	0	0	0	142	118	0	0	41	79	0	381
9	0	0	0	0	0	0	0	0	0	150	39	81	57	50	74	451
10	0	0	0	0	0	0	0	0	0	0	54	74	132	78	80	418
11	0	0	0	0	0	0	0	0	0	0	0	144	0	35	32	210
12	0	0	0	0	0	0	0	0	0	0	0	0	88	48	0	136
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Σ	0	0	0	248	165	310	258	471	444	626	507	676	827	711	578	5821

Table 4-2 Public transport O-D matrix.

The characteristics of each line show that 63.5 buses/hour should be served by stops 4 to 12. According to TCQS (TRB 2003), this value can well exceed the capacity of a single bus stop, depending on control conditions, traffic and demand. More specifically, assuming that the traffic along stretch 4-12 is 900 veh/h, there is no segregated bus lane, there is a traffic light with a 90 second cycle with a proportion of 0.71 on green, taking dwell time based on passenger demand as 44s, a dwell time variation of 0.6 and a design failure rate of 15% (Z = 1.040), then the capacity of a single bus stop is 40 buses/h. If they are not located near a traffic light their capacity increases to up to 46 buses/h. Both values are clearly lower than the number of buses operating on corridor 4-12, so, the division of each of the stops in section 4-12 into dual berth stops: made up of an upstream stop and a downstream stop, as shown in figure 4-5, will allow all the buses that should use the stop to be served. The problem becomes one of assigning the lines to each stop so as to minimize the cost to the user. This assignment will stay constant at all the stops along the axis.

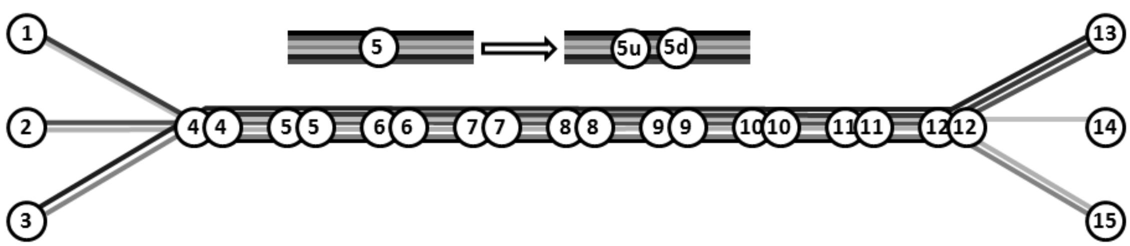

Figure 4-5 Representation of the division of a bus stop on the example network.

The division of the bus stops now means that the sub-group of attractive lines for a determined O-D pair could change, in some cases increasing waiting times but reducing in-vehicle journey times given that the time lost at each stop is lower.

The model was run using different values for the capacity constraints on the new dual berth bus stops, depending on the proximity of a traffic light and the influence between the dual berth stops themselves (Cortés et al. 2007). The values of journey time, waiting time, access time and transfer time are shown in table 4-3. These values have been taken from previous research (Ibeas et al. 2010).

Variable	Value
Journey time (BUS)	26.43 €/h
Waiting time (BUS)	51.29 €/h
Access time (BUS)	31.01 €/h
Transfer time (BUS)	79.77 €/h
Journey time (CAR)	28.90 €/h
φ	1.5
ϑ	1.5

Table 4-3 Values of the variables used in the model.

4.7. Analysis and discussion

Two search methods have been checked to minimize the proposed problem. Firstly, an exhaustive search algorithm (full search algorithm) was used to explore all possible solution spacings and then a specially designed genetic algorithm was used to solve the proposed problem, as described in section 4.3. A cross probability of 0.8 was adopted along with a 0.2 probability of mutation. A single crossover point was used and the initial population was established as twice the number of variables following Alander's recommendation (Alander 1992) that an initial population should be between l and 2 times the number of the problem's variables.

Figure 4-6 shows the results from the two algorithms, the fact that both start at and arrive at identical values is a good test for the new algorithm. It should not be forgotten that the extensive search provides an absolute minimum for the system and the coincidence between the minimum from both methods only elevates the trustworthiness of the new genetic algorithm for solving the problem presented in this article.

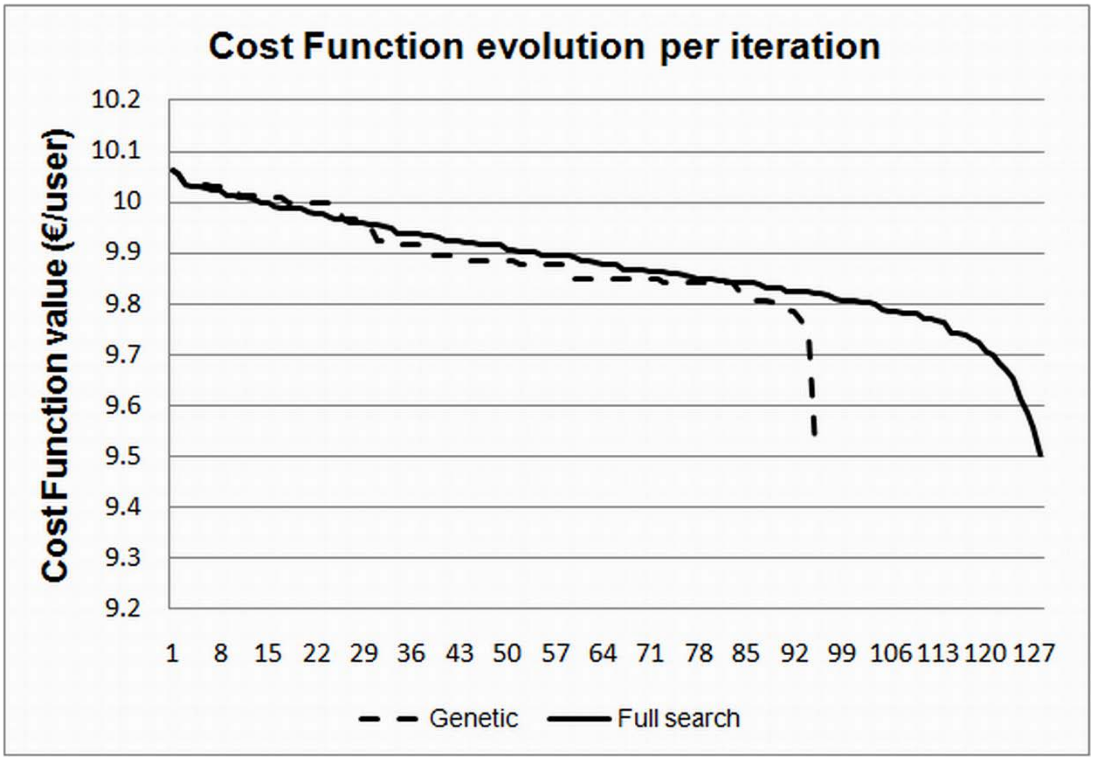

Figure 4-6 Evolution of the objective function with number of iterations.

Even though the number of variables in the proposed problem does not sufficiently exploit the computing speed of the genetic algorithm the network's characteristics mean it still used 20% fewer iterations. In the sensitivity analysis the model was applied varying the number of lines (and therefore, the number of variables) from 1 to 12 and showed that the efficiency of the genetic algorithm increased as the number of lines increased. For a small number of lines the full search algorithm required fewer iterations than the genetic algorithm. This comparison is shown in figure 4-7.

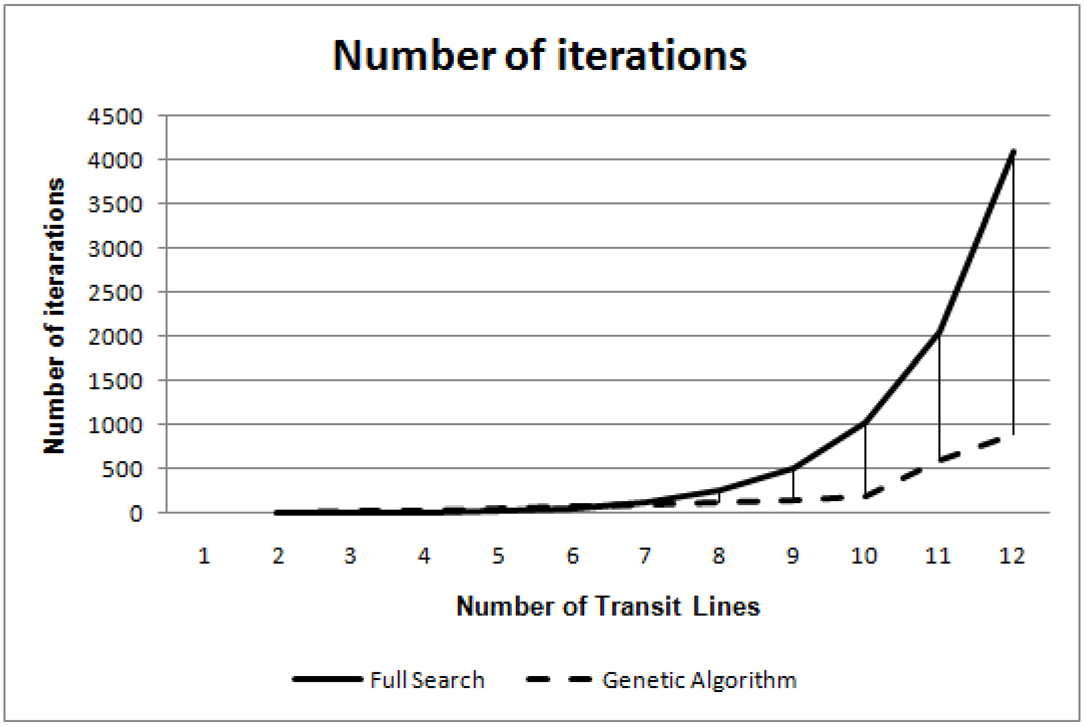

Figure 4-7 Full Search vs. Genetic Algorithm number of iterations.

Table 4-4 shows the results obtained for each of the alternatives analysed. The distribution of lines varies slightly depending on the capacity constraints at each stop, always tending to assign more lines to the stops with more space so that the number of buses/hour gets closer to capacity. In fact, the assumption of high capacity stops implies grouping most of the lines at the same stop in such a way that it minimizes waiting times for the attractive lines. Common patterns can be seen from all the results. Lines L1, L2 and L5 always appear at the same stops. These lines all share the same destination at node 13; this is relevant given that according to the O-D matrix (table 2) this node has the greatest trip demand. The same thing happens with L3 and L6, with destination at node 14. The fact that most buses tend to group at the stop with the highest capacity manages to increase the effective frequency in section 4-6-7, which is a high demand zone.

Capacity		**Lines**		**Buses/hour**		**Vel. Commercial**	**User Cost**
Stop U	**Stop D**	**Stop U**	**Stop D**	**Stop U**	**Stop D**	**(kmph)**	**(€/pax)**
40	40	L1,L2,L5	L3,L4,L6,L7	23.5	40	11.82	9.58
35	35	L1,L2,L4,L5	L3,L6,L7	31	32.5	11.82	9.71
30	40	L1,L2,L5	L3,L4,L6,L7	23.5	40	11.82	9.58
25	40	L1,L2,L5	L3,L4,L6,L7	23.5	40	11.82	9.58

Table 4-4 Final model solutions.

An example of the importance of correctly assigning lines to stops is shown in table 5. Different assignments produce important variations in average bus speed and user cost. The optima and the worst produced by the model have been presented. A 10% increase in average bus speed can be seen, representing a saving of 2 minutes on the corridor used here, or, 2 minutes in a total journey time of 21 minutes. The cost to the user drops by 5% in most of the tests performed.

Solution	Capacity Stop U	Capacity Stop D	Lines Stop A	Lines Stop B	Buses/hour Stop U	Buses/hour Stop D	Commercial Vel. (kmph)	User cost (€/pax)
Optimal	40	40	L1, L2, L5	L3, L4, L6, L7	23.5	40	11.82	9.58
Worst	40	40	L2, L4, L6, L7	L1, L3, L5	37.5	26	11.07	9.88
Optimal	35	35	L1, L2, L4,L5	L3, L6, L7	31	32.5	11.82	9.71
Worst	35	35	L4, L5, L7	L1, L2, L3, L6	28.5	35	10.98	9.95
Optimal	30	40	L1, L2, L5	L3,L4,L6,L7	23.5	40	11.82	9.58
Worst	30	40	L1, L2, L4, L5	L3, L6, L7, L8	25	39	11.25	10.06
Optimal	25	40	L1, L2, L5	L3,L4,L6,L7	23.5	40	11.82	9.58
Worst	25	40	L2, L3, L4	L1, L5, L6, L7	25	38.5	11.25	10.06

Table 4-5 Comparison between different distributions of lines to bus stops.

4.8. Application to a real case

After the model had been tested on the example network its validity was checked by applying it to Santander which is a medium sized town (c180,000 inhabitants) with a well established urban bus service located on the north coast of Spain,.

The urban bus network is made up of 15 lines as shown in table 4-6, three of the lines are circular and run in both directions.

	Line	Headway (minutes)
1	Alisal-Valdenoja	16
2	Corbán-Valdenoja	16
3	Peñacastillo-UC (tunnel)	20
4	Bº Pesquero-Piquío-UC	16
5c2	Miranda-Gral. Dávila	11
6c2	Complejo-Puertochico (tunnel)	30
7c2	Joaquín Bustamante-Puertochico	16
11	Valdecilla-C/Alta	30
12	Carrefour-Canaleja	30
13	Lluja-Cueto	30
17	Estaciones-Corbán	30
18	Monte-Puertochico	30

Table 4-6 Public transport lines of Santander.

Most of the lines run East to West and connect the residential areas with the city's economic and commercial centre which also has a high number of residents. Most of the lines run along the city's main central axis which has 6 stops in each direction: "Cuatro Caminos" (P1), "San Fernando" (P2), "Ayuntamiento" (P3), "Catedral" (P4), "Jardines de Pereda" (P5) and "Puertochico" (P6). These lines, 1, 2, 3, 4, 5c2, 6c2, 7c2, 12, 13, 17 and 18 are shown in figure 8 (and schematically in figure 9) and on average mean 38 buses per hour run along this axis. Although this flow appears too small to cause congestion problems, the excessive demand for certain lines at these stops causes high operating times and excessive delays, so it is suggested that the capacity of stops P1 to P6 is increased by dividing them in accordance with the design shown in figure 4-1.

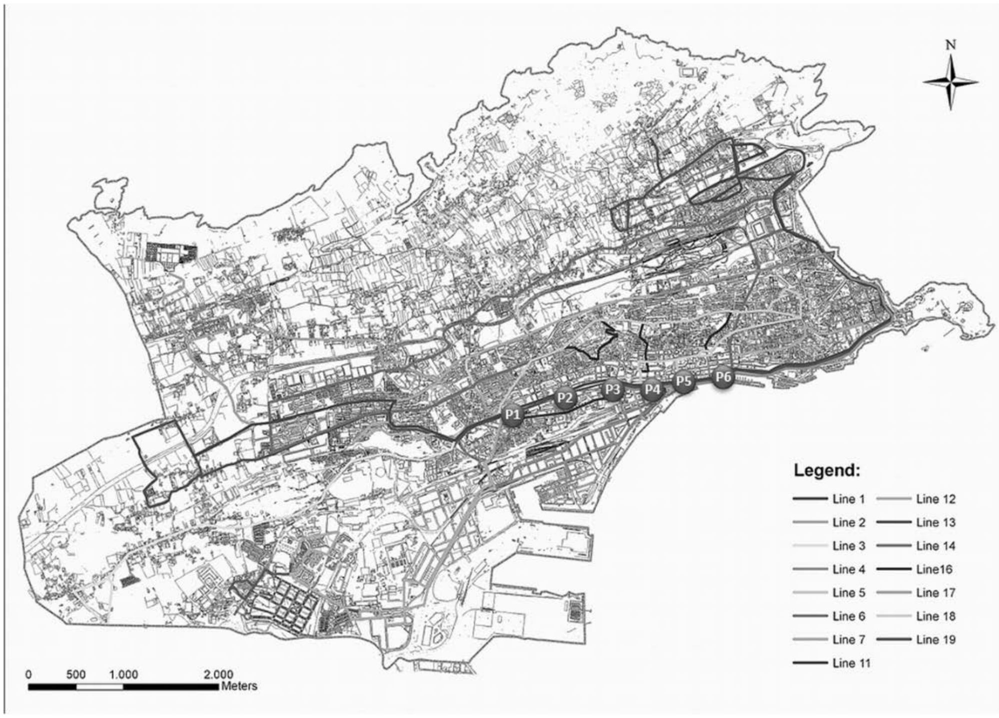

Figure 4-8 Application to a real case: Bus lines and bus stops (background source: National Geographic Institute. Spanish Government).

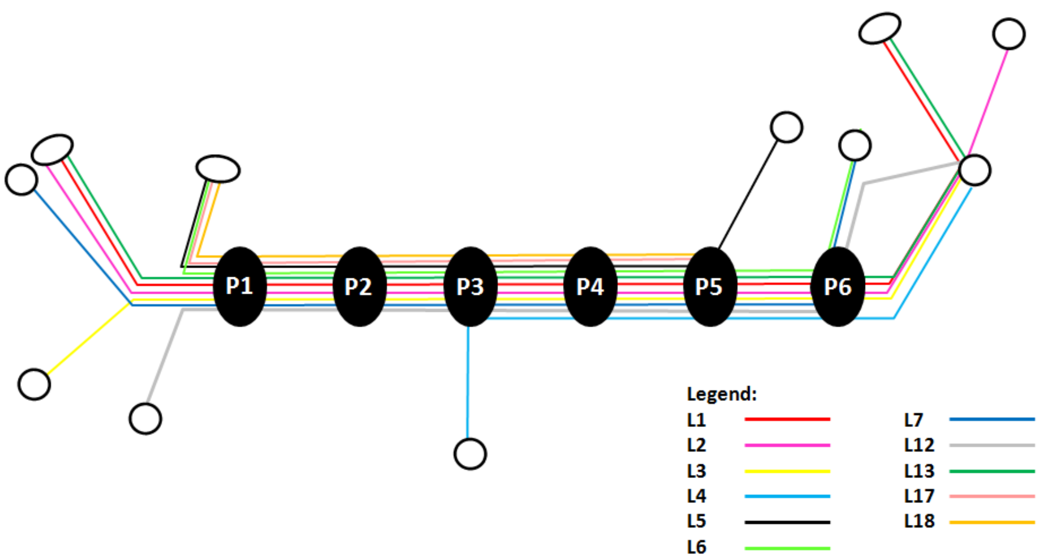

Figure 4-9 Schematic representation of the Santander Bus network.

The lines will be assigned to operate at specific berths at each stop and to keep to their assignments through all the stops along the corridor, thereby avoiding any uncertainty for passengers about where to wait.

The solution provided by the model came after 752 iterations, requiring a total of 4 hours and 32 minutes. The full search algorithm covered all the 2,048 possible iterations after 18 hours computing time and came to the same distribution of lines.

The final solution can be seen in table 4-7 which shows a coherent grouping of the common destinations of the bus lines.

Bus Stop	**Lines**		**Buses/hour**	
	Stop U	**Stop D**	**Stop U**	**Stop D**
P1	L3,L5,L6,L12, L17,L18	L1,L2,L7,L13	17	16
P2	L3,L5,L6,L12, L17,L18	L1,L2,L7,L13	17	16
P3	L3,L5,L6,L11,L12, L17,L18	L1,L2,L4,L7,L13	19	20
P4	L3,L5,L6,L11,L12, L17,L18	L1,L2,L4,L7,L13	19	20
P5	L3,L5,L6,L12,L18	L1,L2,L4,L7,L13	17	20
P6	L3,L6,L12,L18	L1,L2,L4,L7,L13	13	20

Table 4-7 Application results (1).

Table 4-8 shows not only an improvement of 11.7% in the average bus speed along that corridor (and therefore journey times) but also an increase of almost 4% in the overall average bus speed throughout the network. Furthermore, the users benefit by a reduction of 2.3% in their costs.

	Commercial Speed. (kmph)		
Solution	**Corridor**	**Overall Transit System**	**User cost (€/pax)**
Actual	10.76	11.88	15.81
Proposed	12.02	12.34	15.44

Table 4-8 Application results (2).

4.9. Conclusions

A methodology has been proposed to assign bus lines to divided stops which minimizes the costs of the user and takes into account the interaction with private traffic and congestion on the public transport system.

The assignment obtained from the proposed model follows expected coherent patterns, grouping lines with the same destination at the same stop and giving preference to destinations with the highest demand.

Furthermore, the results of this research show the importance of a sound assignment of lines to berths demonstrating that differences of up to 10% in average bus speed can be obtained along with 5% in social cost.

When the technique was applied to a real case it provided increases of 11.7% in average bus speed along the city’s busy main corridor, along with an improvement of almost 4% in the average bus speed of the entire urban network.

Capítulo 5

A TWO-STAGE URBAN BUS STOP LOCATION MODEL

5. A TWO-STAGE URBAN BUS STOP LOCATION MODEL[4]

5.1. Resumen

En esta investigación se analiza la localización óptima de paradas de bus mediante la aplicación secuencial de un modelo de dos etapas: una primera etapa a nivel estratégico en el que se localizan las paradas de bus en todo el sistema de transporte público a escala macroscópica minimizando el Coste Social de toda la red y una segunda etapa a nivel táctico donde, a partir de la solución macroscópica obtenida, se afina la ubicación de paradas en ejes específicos de una ciudad a escala microscópica maximizando la velocidad comercial del transporte público.

El modelo propuesto se aplica a un caso real, realizándose un análisis de sensibilidad para estudiar las variaciones de localización final de las paradas para diferentes niveles de flujos de tráfico, flujo de buses de transporte público y duración de ciclos semafóricos. Los resultados obtenidos arrojan importantes diferencias en la velocidad comercial del bus en función de la localización final de las paradas para cada caso.

5.2. Introduction

From the point of view of good urban transport planning it would be beneficial to consider the influence of public transport on overall traffic flows within a city. One of the more

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[4] Moura J. L., Alonso B., Ibeas A., Ruisanchez F. (2012) A Two-Stage Urban Bus Stop Location Model. *Networks and Spatial Economics* 12, 3, 403-420.

http://dx.doi.org/:10.1007/s11067-011-9161-z specific and contentious issues is the influence of the bus stops which not only represent the places where the users access the transit system they are also a determinant factor in the average bus speed.

Urban bus stop distribution and location has been the subject of several research projects which were mainly carried out on a macroscopic level and used analytical models to look at either a particular bus line: Lesley (1976), Wrasinghe and Ghoneim (1981) or more recently Furth and Rahbee (2000), Saka (2001), Sankar et al. (2003) or Chien and Qin (2004); or at the overall network: Kuah and Perl (1988), Van Nes (2000), Van Nes and Bovy (2000), dell'Olio et al. (2006) or Ibeas et al. (2010).

Nevertheless, the importance and complexity of well operated bus stops has meant that more detailed, exclusive research has appeared over recent years (Fernandez, 2001, 2003) with the design of applications for micro simulation models like PASSION (Fernandez 1993; Fernández and Planzer 2002), IRENE (Gibson et al. 1989, Gibson 1996) MISTRANSIT (Cortes et al. 2007) or BusSIGSIM (Silva 2001).

Wong et al. (1998) evaluated the effect of a bus stop close to traffic lights with no designated area to pull over so the buses occupied a lane and interrupted traffic flow. They proposed a new expression to calculate delay based on the classic formulation of Webster and Cobbe (1966) but added terms to simulate the effect of the bus stop. More recently, Koshy and Arasan (2005) looked at the influence of bus stops on traffic flow taking into account their composition and established parameters for changing the type of bus stop. They developed the HETERO-SIM simulation model. Furth and San Clemente (2006) analysed how ramps and slopes increased delays in public transport showing that the effects become noticeable after 3% and that far-side locations were preferable. Fernandez et al. (2007) concentrated on analysing the interaction between traffic and bus stops when they are located close to a signal controlled junction, their simulation included a user behaviour model. Finally, Zhao et al. (2008) used a cellular automata model to study the effect on traffic of positioning a bus stop between two nearby intersections.

In the proposed two-stage model, all the bus stops in an urban area are macroscopically distributed over the public transport network, these positions are then microscopically adjusted along the main urban corridor. The macroscopic location of bus stops is based on a bi-level optimization model with an upper level which minimizes a cost function for the overall system (social cost) and a lower level which includes a modal split assignment model, the development and results of which can be found in Ibeas et al. (2010). The microscopic positioning of stops based on their macroscopic distribution is supported by a micro simulation model which provides the optimal bus stop locations along an urban corridor and maximizes the commercial speed of the transit buses running along it.

The proposed model is described and defined in the next section, followed by the presentation of the solution algorithm and its application to a real case (Santander city, in Spain). Sensitivity analysis studies the effect of variations in bus stop location and finally the main conclusions drawn from this investigation are presented.

5.3. Description of the proposed model

As already mentioned, the proposed model is based on the sequential application of two stages, shown in Figure 5-1. The first stage strategically locates the bus stops throughout the whole public transport system on a macroscopic scale followed by a second stage, at a tactical level, which uses the macroscopic solution to microscopically position the bus stops along specific urban roads.

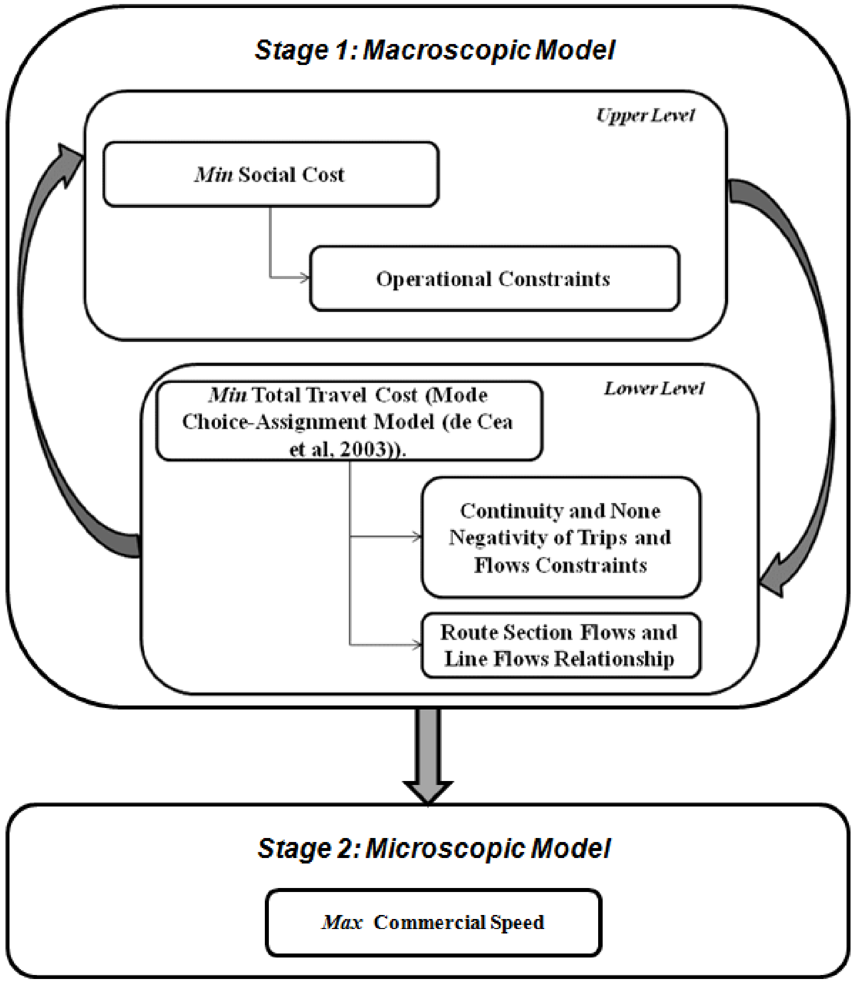


Figure 5-1 Diagram of the Proposed Model

First Stage: Macroscopic Model

A mathematical bi-level optimization model is proposed for solving the problem of macroscopically locating the bus stops (Ibeas et al. 2010). The model's upper level minimizes a cost function (Z) made up of the user costs (UC) and operator costs (OC), and the lower level includes a modal split assignment model which takes into account the influence of private cars and congestion among transit vehicles.

Upper level

On the one hand, user costs are made up of the respective access (TAT), waiting (TWT), journey, (TIVT for buses and TCTT for cars) and transfer (TTT) times weighted by their respective values (φ). On the other hand, the operator costs are made up of the sum of the direct costs (CD) and the indirect costs (CI). The direct costs, in turn, can be split into running costs (CK), personnel costs (CP), idling costs (CR) and fixed costs (CF). The indirect costs are taken to be 12% of the direct costs (Ibeas et al. 2006).

The upper level of the optimization problem has been defined by this cost structure, consisting of the minimization of the costs suggested here (5.1) subjected to any operational constraints which need to be considered. It seems self-evident that user access time to the system will reduce if the number of bus stops increases, but the cost of the operation will increase if the turnaround time increases requiring a larger fleet or different frequencies. Therefore, these operational constraints may include a maximum operating budget or maximum fleet size like those shown respectively in the following group of constraints (5.2).

$$\min \quad Z = \phi_a TAT + \phi_w TWT + \phi_v TIVT + \phi_t TTT + \phi_v^{'} TCTT + 1.12 \cdot \left(CK + CR + CP + CF \right) \tag{5.1}$$

s.t.

$$\begin{aligned} & C_o \leq C_o^{\max} \\ & \sum_l round^{+}\left(tc_l / h_l \right) \leq fls_{\max} \end{aligned} \tag{5.2}$$

Where:

C_o = the operator costs

$C_o^{\max}$ = the maximum operating budget

tc_l = the cycle time of transit line l.

h_l = the headway of line l

$fls_{\max}$ = the maximum fleet size

Lower level

The lower level is modelled using a combined mode choice – assignment model (De Cea et al. 2003). This model considers the deterministic user equilibrium (DUE) for choosing routes on different modal networks of public and private transport, and a logit type model (multinomial or hierarchical) for decisions relating to transport mode. The model performs simultaneous supply and demand equilibrium instead of using the classic four stage model, proving very useful on congested networks (De Cea et al. 2003). Equilibrium flow conditions for the problem can be formulated using a variational inequality of the following type:

$$c(X^*)^t \cdot (X - X^*) - g(T^*)^t \cdot (T - T^*) \geq 0, \qquad \forall \ feasible \ X, T \tag{5.3}$$

Where c(X) is a column-vector of a network link cost function, g(T*) is the matrix of the inverse of the demand function (depending on the modal utility vector for each O-D pair w), X is any feasible flow on links vector in the multimodal network (public and private transport), X* represents the equilibrium solution in terms of flows on the multimodal network, T is the trip vector between O-D pairs on the network and T* is the equilibrium trip vector between O-D pairs on the network (see De Cea et al. 2003; Ibeas et al. 2010).

Second Stage: Microscopic Level

The application of the macroscopic model provides a feasible proposal for bus stop location throughout the entire network, along with the associated hourly demand for each stop and each transit line as well as the traffic flow on the road network. However, due to limitations in simulation scales, this location is not exact enough to take into account any interactions with the dynamic effects of traffic and any associated phenomena (spillback, lane changes, vehicles moving back into traffic flow from bus stops, signal coordination, etc.).

This is where the proposed micro simulation model becomes useful. A GIS is used to adapt the solution of the macro simulation model into the micro simulation model. So, for each macro point, depending on the initial location, various alternative micro positions are proposed for the bus stop, in the end finding the optimal location for each one. A good example is the case of a bus stop located near a traffic light; possible alternative locations are positioned upstream and downstream of the traffic light.

Therefore, the method proposed here can be defined as a refinement of the macro simulation process which can specifically locate a bus stop in accordance with any traffic parameter which the planner wishes to use: commercial bus speed, overall delays, private traffic delays, etc.

After choosing the different possible locations for each bus stop the different scenarios generated by the combinations of these locations are simulated.

5.4. Solution algorithm

A heuristic solution algorithm was developed to solve the bi-level optimization problem (see flowchart in Figure 5-2) for the macroscopic location of stops. The data is loaded into the microscopic model to find the location along the urban corridor which provides the maximum commercial speed. Its description follows below:

Step 0. This first step could be described as "network preparation". The road network has to be discretized into quasi uniform links, thereby defining all the potential candidate locations for bus stops. The study area is then divided into a number of zones, each of which should have the same spacing between bus stops. A vector (∂) is thus formed with an equal number of components as zones. Details on the zoning criteria are described in Ibeas et al. (2010).

Step 1. The first iteration generates an initial feasible bus stop spacing solution vector (∂0). Each component of vector (∂) will be the bus stop spacing in each zone.

Step 2. Given the network bus stop configuration defined by (∂i) the lower level optimization problem of the proposed model is solved at each iteration i of the algorithm and the upper level objective cost function (Zi) is calculated.

Step 3. New values of (∂i+1) are generated using the Tabu Search algorithm (Glover 1989) and the upper level problem is solved to determine the new value of Zi+1, after which we return to Step 2.

Step 4. If $Z^{i+1} - Z^{i} > \tau$ we return to Step 3; however, if $Z^{i+1} - Z^{i} \leq \tau$ the algorithm is stopped, where τ is a reduction in the objective function established as the stop criteria.

Step 5. The solution of Step 4 is loaded into the micro simulation model for the study corridor. In the simulation scenario there is a total number of stops M on the corridor (given by the macroscopic model) a sub group of which will be susceptible to having various possible locations, while the rest, either because of the typology of the zone, or because they are mid-block, their location becomes final. Each one of these M stops constitutes an element of a vector [$\overline{M}$] whose value may vary from 1 to p, where p is the total number of possible locations for that stop. In other words, each stop alternative will have an associated label of 1 to p.

Step 6. Once the vector [$\overline{M}$] has been created, the next step is to create an initial feasible vector [$\overline{M}^{0}$] in which each stop or element i randomly takes a value between 1 and pi.

Step 6.1. New values of (Mn+1) are generated using a full search algorithm which runs the entire sequence of bus stop locations.

Step 6.2. Each initial vector [$\overline{M}^{n}$] is used to perform the microscopic simulations of the defined scenarios, finally registering the parameter which needs to be optimized, for example, the commercial speed of the bus.

Step 6.3. After completing the number of iterations of the search algorithm, a search is made to find the parameter obtained at each [$\overline{M}^n$] to obtain the vector with the minimum value. The final location of the bus stops along the corridor will be defined by that vector.

Step 7. A search is made to find the maximum value of the vector (v) and the definitive location is found.

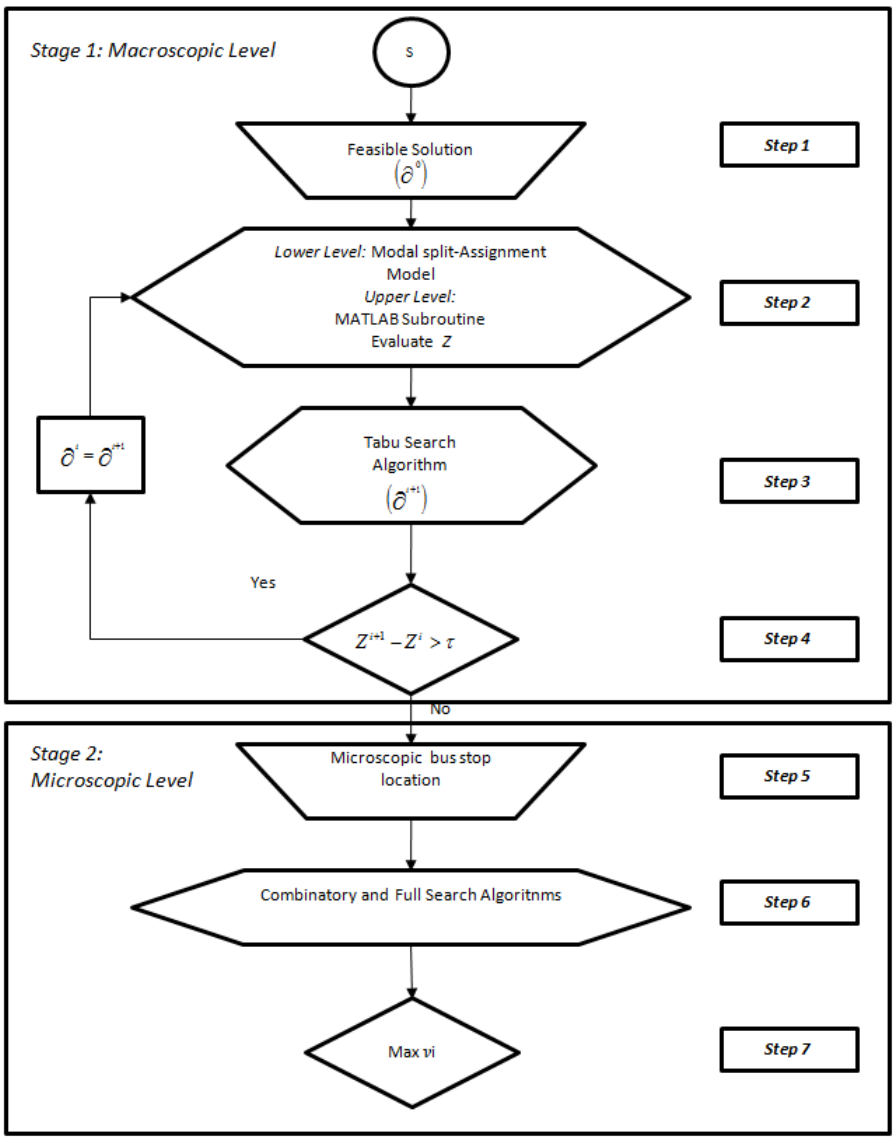


Figure 5-2 Flowchart of the solution algorithm

5.5. Application to a real network: Description and analysis results

The validity and usefulness of the model presented in this article has been checked by applying it to a real case. The area used for the application is Santander city with around 180,000 inhabitants located in the north of Spain and boasting a well-established urban bus service. The city is characterized by its linear structure, a well-developed commercial and urban Centre and several peripheral residential areas with diverse population densities (Figure 5-3).

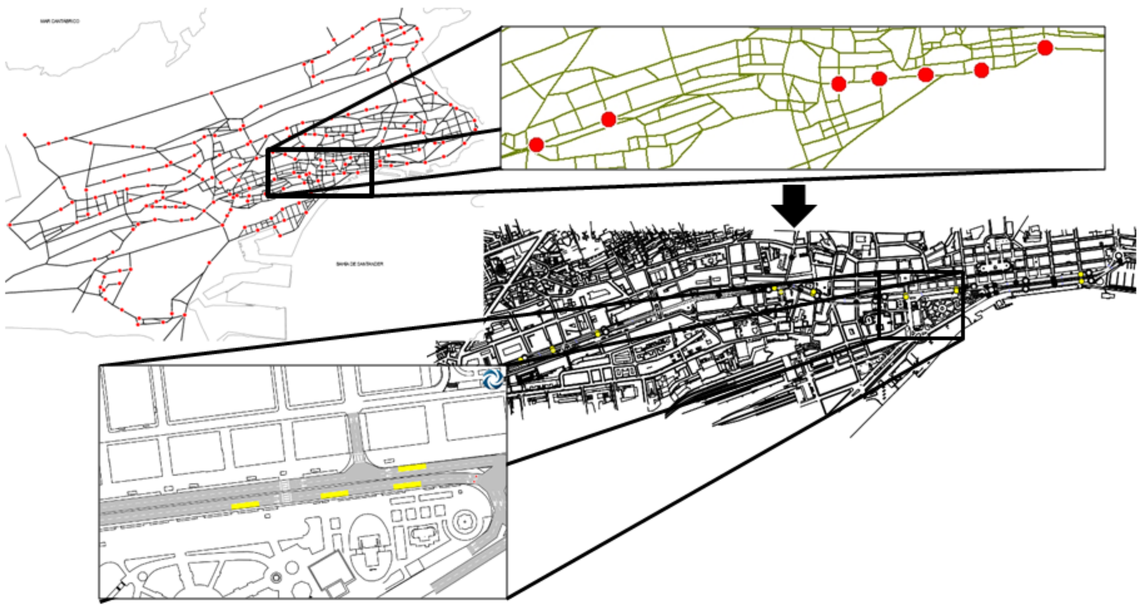


Figure 5-3 Moving from the macro model to the micro model

The first step is to estimate the optimal macroscopic spacing and location using ESTRAUS (de Cea et al. 2003) software for the modal split assignment model and MATLAB (www.mathworks.com) for programming the algorithm and calculating the social cost function.

The locations initially found for the bus stops needed to be checked especially in those parts of the city with denser traffic flows, where the presence of certain control elements may significantly alter the correct working of the bus stop. This had to be done on a much more detailed scale by applying the second step of the model. Figure 5-3 describes this process.

This microscopic application was applied along the main urban corridor of the city which is approximately 2.5 km long and used by 11 bus lines at a rate of 43 buses/hour in each direction. At rush hour there are a about 1,700 veh/hour also travelling along this corridor in each direction. The road is made up of 2 lanes averaging about 3m wide. The AIMSUN simulator (TSS 2010) was used to combine, generate, simulate and store the results of each scenario with the help of a macro programmed in Python (Appendix D) to make the process automatic.

First Stage:

Software restrictions meant the network had to be split into 60m long segments to more precisely pinpoint the location of each stop. A GIS has been developed holding the economic, social and demographic characteristics of each zone, as well as the more significant attributes for each node: typology (junction, router…), control (traffic lights) and location (on a slope or not, presence of residential areas or attraction points within a maximum distance, scheduled stop, etc.) among others. The GIS was able to ignore nodes with certain characteristics (steep slopes, location in a tunnel, etc) which made them poor candidates for bus stop locations.

The city was zoned based on population density and commercial activity and produced five groups of zones of equal distances (in metres) between stops ($\partial 0$): (240, 300, 360, 360, and 840) with each node being associated to the zone it belonged in. Starting at the terminus of each route the algorithm simulated movement along the route passing by each node and if the node in question had not already been discarded in the way described above it positioned a stop at the node when the distance covered was equal to or greater than the δ for that zone. If the route crosses from one zone to another, the value taken is the one reached first, calculated from the border of the zone, between either the δ of the previous zone, or the value of $\delta/2$ of the new zone.

The social cost function was calculated using the time values shown in table 5-1 (Ibeas et al. 2010). With this vector the solution algorithm can be run. The final result came after 32 iterations and just over 35 minutes of running time (Pentium Dual Core 2.4 Ghz, 4 Gb RAM).

Details of the results are presented in table 2, where the current situation of the public transport system, using average real spacings between stops in each of the zones, is compared with the optimized situation. It can also be seen how using this new distribution of stops we managed to reduce the total number of stops and improve their distribution throughout the city in such a way that made it possible to reduce the fleet size required to provide the service. The commercial speed has increased along with a slight increase in the number of passengers using the service. A comparison between the initial bus stop distribution and that provided by the model is shown in Figure 5-4.

Variable	Value
Journey time (BUS)	26.43 €/h
Waiting time (BUS)	51.29 €/h
Access time (BUS)	31.01 €/h
Transfer time (BUS)	79.77 €/h
Journey time (Car)	28.90 €/h
CK	0.4 €/km
CP	14 €/bus
CF	32 €/bus
CR	0.02 €/h

Table 5-1 Values of time and unit

	[D] (m)	Number of Bus stops	Passengers (pax/h)	Fleet (buses)	Commercial speed (km/h)
Initial situation	δ_1=240 δ_2=300 δ_3=360 δ_4=360 δ_5=780	295	4944	63	11.88
Optimized situation	δ_1=360 δ_2=420 δ_3=540 δ_4=420 δ_5=780	264	5109	61	13.07

Table 5-2 Results of the application in Santander- Comparison between the current situation and the optimal.

Figure 5-4 Initial distribution (top) and proposal for the Santander network

Second Stage:

The output from the macro simulation model applied to the whole city becomes the input of the micro simulation model applied to the main urban corridor. The position for the bus stop indicated by the macro model is the basis for proposing several alternative locations on a micro level (see Figure 5-3). Apart from the locations of the stops further information is imported about the private transport O/D matrix and the boarding/alighting figures for each line at each stop along the corridor.

There are 7 bus stops along the study corridor (P1 to P7), their possible locations are shown in figure 5-5 (from left to right and top to bottom) and schematically presented in table 5-3. Bus stop P1 is a mid block type with traffic light and has three proposed alternative locations: on road, up stream away from the traffic light and downstream from the traffic light. Bus stop P2 is located downstream from the traffic light and has a possible alternative location up stream from the traffic light. Bus stop P3 is a twin stop with traffic light and intersection, with several possible alternative locations proposed for each part of the stop: upstream and downstream, both downstream (2), and both upstream. Bus stop P5 is located near to a junction (roundabout) and traffic light with possible alternative locations upstream and downstream from the traffic light. Finally, bus stops P4, P6 and P7 are mid-block types without traffic lights and their location is already definitive.

Bus Stop	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**
Description (initial)	mid block*	far side	divided	mid block	near side	mid block	mid block
	initial	initial	fs-ns	none	initial	none	none
Alternatives	near side	near side	fs-ns		far side		
	far side		ns-ns				

Table 5-3 Proposal for micro locating bus stops along the main corridor

Figure 5-5 Final microscopic bus stop location

These alternatives are used to generate a vector [$\overline{M}$] with 7 components, one for each stop, where stops 4, 6 and 7 already have a definitive location. Each component of this vector will have two or three possible values, each of which is associated to a final location, taking a value of 1 to 2 or 1 to 3 following the direction of traffic flow.

The different combinations of final locations produce 72 possible vectors. The application programming interface (API) designed here takes charge of varying the vector [$\overline{M}$] and running 10 simulations for each scenario, generating the average for each one and storing it in an ACCESS data base. The 720 simulations are run in this way.

With the same equipment used for the macroscopic application the microscopic model took 3 hours and 4 minutes to cover the 72 combinations.

Once all the simulations had been finished, the final module was run to find the vector with the maximum commercial bus speed and thereby find the final optimal location of bus stops along the corridor. The representation of the specific vector chosen (2; 1; 1; 1; 1; 1; 1) along the road network is shown in figure 5-5.

This definitive location for each bus stop shows that they are always located either downstream from the signal or upstream but further away from it so that the cars queuing on red do not stretch back to the bus stop area and allow the buses to operate more freely. Furthermore, as can be seen in figure 5-6, there is a slight change in the value of the commercial speed when the positions of the stops are changed, reaching a maximum of 10.3 km/h and a minimum of 6.9 km/h.

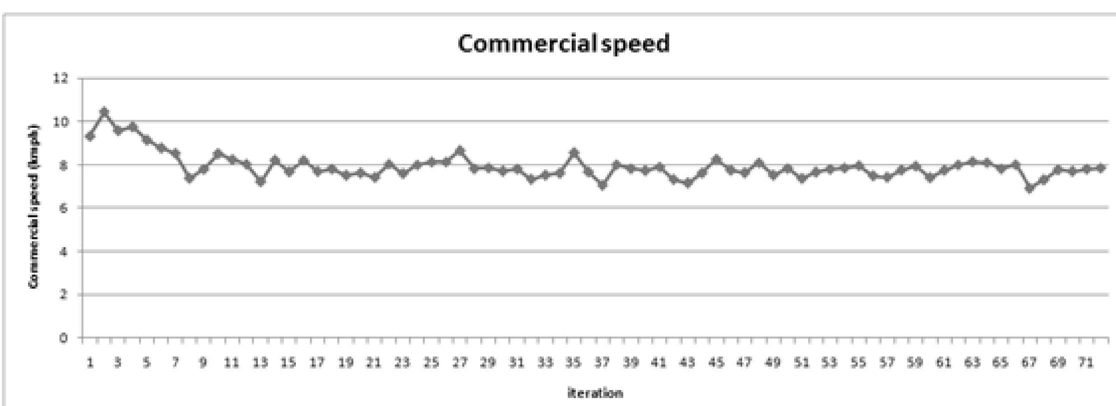


Figure 5-6 Commercial speed for different location combinations

5.6. Sensitivity analysis: Influence of traffic flow, buses and traffic light cycle

An analysis of the results after applying the model to a real case show how the final solution can change under different operational circumstances and traffic variables.

The microscopic location algorithm was next run for different combinations of bus and other traffic flows and traffic light cycles on the same urban corridor as before. The combination of the operational and traffic variables uses the following values:

Demand for buses: high (120 buses/hour), medium (60 buses/hour) and low (30 buses/hour).

Traffic demand along corridor: high (2500 veh/hour), medium (1500 veh/hour) and low (500 veh/hour).

Traffic light cycle: long (120 s.), medium (90 s.) and short (60 s.).

Proportion of time on green = 0.66.

The 72 combinations of bus stop locations were evaluated for each combination of the above demands between traffic, buses and cycle duration.

Firstly, variations were made to the demands both of traffic and buses whilst keeping the cycle on 90 s. In all cases with high traffic demand, the commercial speed drops due to the increased congestion on the network. However, these variations were very important in the case of bus demand. When there were low bus flows, the commercial speed was greater than under high bus flows where the increased congestion on the roads had to be added to the greater congestion at the stops, implying waiting time spent in queues of buses. Figure 5-7 represents the commercial speed values for each of the 72 combinations of stops as well as for high, medium and low bus flows. This figure also shows that as bus flow increases, the best locations correspond to those which position the stops in such a way that they avoid the queues at traffic lights by moving them far side. It is also worth noting how some final stop locations can be beneficial to high flows yet prejudicial for low flows and vice versa.

The location providing the best commercial speed under medium traffic demands coincides for all levels of bus demand although it is true that for low bus demands the far side location gives practically the same commercial speeds as the near side locations further away from the traffic light.

Under low traffic demand the final location becomes practically irrelevant because of the negligible influence of the private cars, meaning that the near side stops should be positioned at such a distance away from the signal that does not allow the buses to saturate the area around the stop, as these are precisely the locations which provide the best commercial speeds when bus flow is high. This is why the changes made to a commercial speed at the same demand level show a variation lower than 0.5 km/h for low and medium bus flows and a greater sensitivity to location for high flows, as shown in Figure 5-7.

Varying the timing of the traffic light cycle but keeping the same proportion of time on green produces different optimal locations. An example of this is shown in Figure 5-8. The commercial speed is shown for 3 types of bus stop location in the analysis scenario: upstream from the traffic light, but well away from it; upstream from the traffic light next to the stop line and downstream. All of these traffic flow, bus flow and cycle duration combinations that were analysed are shown in table 5-4. It can be seen that, depending on the level of demand (both traffic and buses) and the signalling, the location of the stops along the corridor varies in favour of upstream and away from, or downstream for high traffic loads. Finally, the influence of the traffic light cycle on the commercial speed was analysed for each of the locations, having seen that for the three cycles used (60, 90 and 120 s. with a proportion of 0.66 on green) it is always better to locate the stops upstream and away from, or downstream from, the traffic lights. The results in Figure 5-9 show that a short cycle is preferable in practically all cases, even when for reasons of spacing the stop has to be located near side, which agrees with other research on this topic (Wong et al. 1998, Furth and SanClemente 2006, Valencia and Fernandez 2007 or Fernandez et al. 2007).

				Bus speed (km/h)		
N	**cars**	**buses**	**cycle**	**Upstream (distant)**	**Upstream**	**Downstream**
1	500	30	60	14.96	15.25	15.46
2	500	60	60	14.8	15.18	15.35
3	500	120	60	14.63	13.19	9.86
4	1500	30	60	11.92	12.33	13.85
5	1500	60	60	10.8	11.41	13.67
6	1500	120	60	8.67	5.01	5.93
7	2500	30	60	8.6	8.33	8.42
8	2500	60	60	8.27	6.95	8.07
9	2500	120	60	7.67	4.89	7.3
10	500	30	90	12.04	12.15	12.49
11	500	60	90	12.04	12.02	12.37
12	500	120	90	11.74	7.79	9.48
13	1500	30	90	11.95	11.62	12.28
14	1500	60	90	11.69	11.38	11.79
15	1500	120	90	7.16	4.02	5.47
16	2500	30	90	9.8	9.04	9.92
17	2500	60	90	7.26	6.55	7.03
18	2500	120	90	7.29	4.83	7.06
19	500	30	120	15.01	15.02	15.19
20	500	60	120	11.93	11.95	15.24
21	500	120	120	13.08	12.8	9.41
22	1500	30	120	11.62	11.43	11.47
23	1500	60	120	9.92	10.21	13.21
24	1500	120	120	5.55	2.84	4.46
25	2500	30	120	8.14	8.94	9.99
26	2500	60	120	7.43	6.1	7.84
27	2500	120	120	7.97	4.46	7.93

Table 5-4 Commercial speed for different combinations of location, flow and traffic light cycle

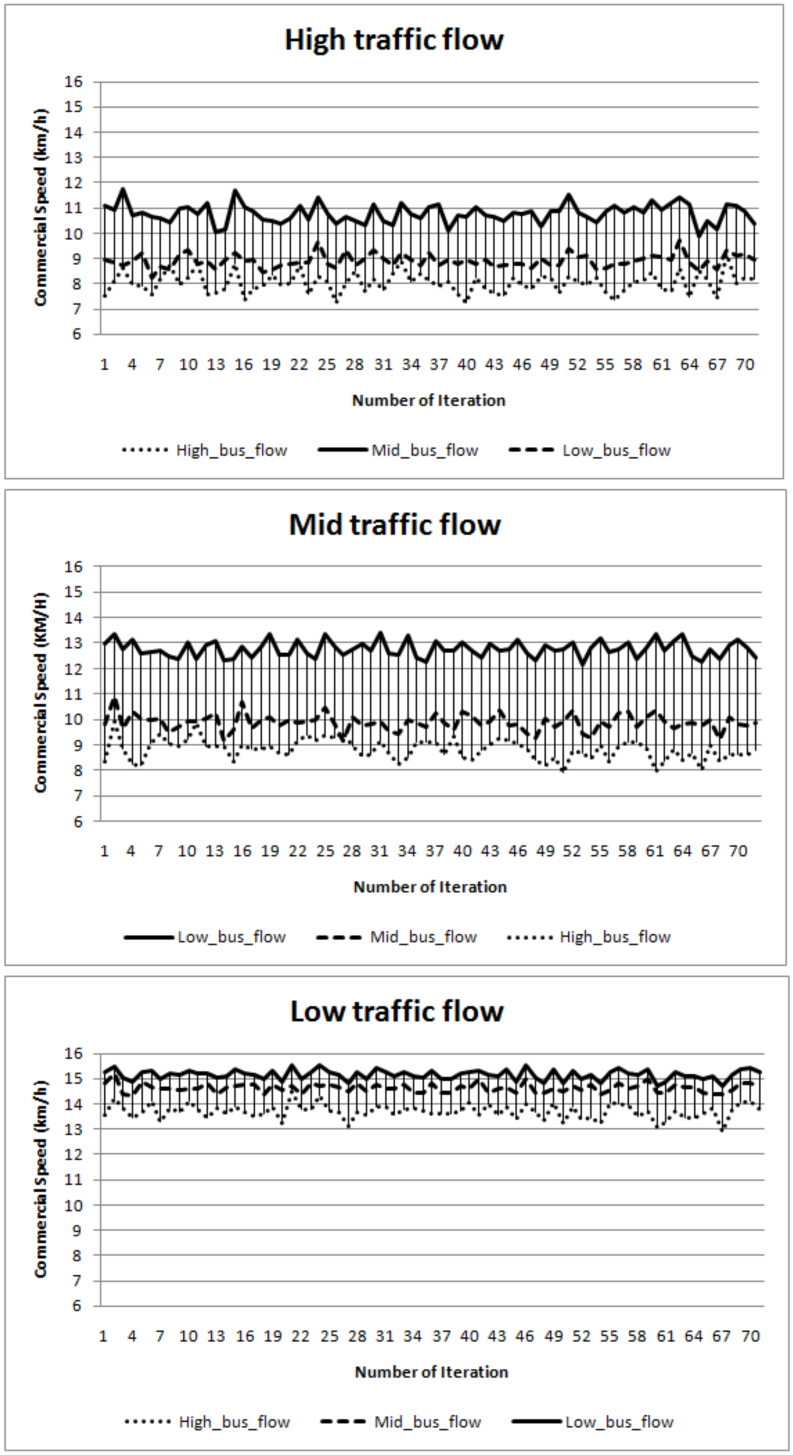


Figure 5-7 Commercial speed with high (top), medium and low (bottom) traffic flows

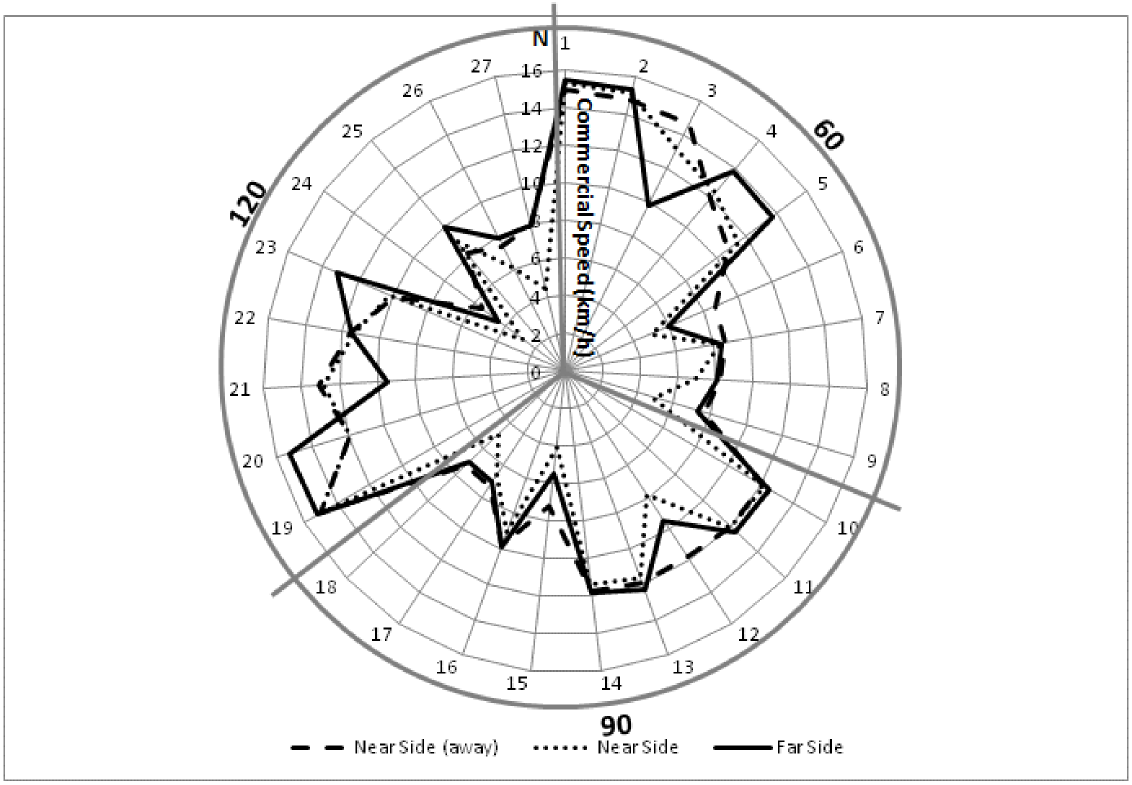
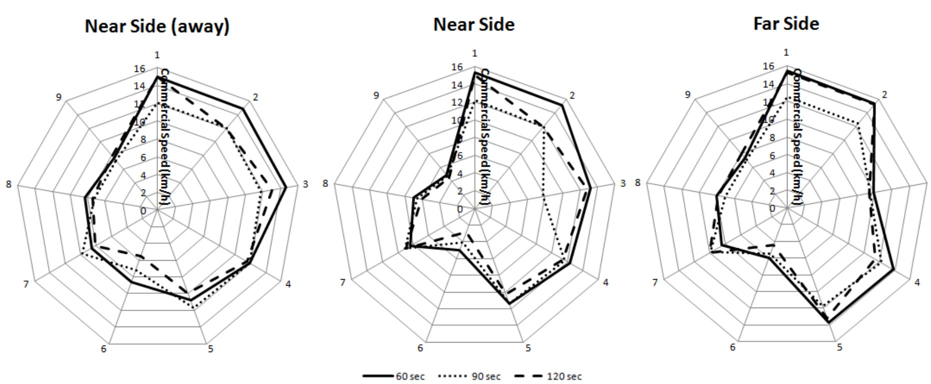


Figure 5-8 Commercial speed for each case depending on traffic light cycle



N	1	2	3	4	5	6	7	8	9
car flow (veh/h)	500	500	500	1500	1500	1500	2500	2500	2500
bus flow (bus/h)	30	60	120	30	60	120	30	60	120

Figure 5-9 Commercial speed for each case depending on traffic light cycle and type of location

5.7. Conclusions

This article has presented a model for locating bus stops using the sequential application of two stages: a first stage at a strategic level distributes the bus stops throughout the public transport system on a macroscopic scale and a second stage at a tactical level where, based on the macroscopic solution obtained beforehand, the location of the bus stops is finely tuned along specific urban roads on a microscopic scale.

The sequential application of both methods provides a greater degree of detail and better results than by applying them individually, given that each model adapts to the scale of the problem and provides a greater degree of definition in the more problematic areas.

The validity and utility of the proposed model was checked with its application to a real case, where the existing system has been optimized by improving the service using fewer resources, increasing the commercial speed by 10% and reducing the fleet needed by 3%.The results analysis shows that the location of bus stops has a strong influence on the commercial speed of the bus. The application of the microscopic model has obtained a range in the variation of this speed of between 6 and 10 km/h.

The final position of the stops along the test corridor providing the best commercial speed have been found to be either upstream but away from the traffic lights or downstream from them. Finally, sensitivity analysis established which types of bus stop locations were more suitable to certain levels of demand for buses, private traffic and traffic light cycles on the network.

Future work could be carried out on the macroscopic stage by applying different solution algorithms to work with zoning based on cluster analysis, or the incorporation of a frequency optimisation algorithm into the model. Further research into the microscopic stage would amplify the sensitivity analysis to test different cycle proportions on green, define if the bus stop is segregated from traffic or not and analyse the effects of different sequencing and other measures for prioritising traffic lights.

Capítulo 6

CONCLUSIONES FINALES Y LÍNEAS DE INVESTIGACIÓN FUTURAS

6. CONCLUSIONES FINALES Y LÍNEAS DE INVESTIGACIÓN FUTURAS

6.1. Conclusiones

A lo largo de esta tesis se han presentado una serie de métodos y modelos que hacen más eficiente el diseño y la optimización de los sistemas urbanos de transporte.

En los modelos presentados se ha optado por actuar sobre variables capitales para el funcionamiento de un sistema de transporte tales como las frecuencias los tamaños de autobuses y el posicionamiento y la morfología de las paradas en el mismo.

La finalidad de este trabajo ha sido la de platear una serie de modelos y métodos que le sirvan a los planificadores de redes de transporte para tomar decisiones más optimizadas en la implantación o reorganización de cualquier sistema de transporte urbano, las herramientas presentadas cubren tanto el espectro de la macro simulación como de la micro simulación ofreciendo un amplio abanico de posibilidades al gestor para optimizar su red de transporte urbano.

Las presentes conclusiones tratan dos temas principales.

- Beneficios de minimizar los costes en función de la frecuencia de las líneas y el tamaño de los autobuses dentro de una red completa de transporte urbano.
- El rol que juegan el correcto posicionamiento y la topología de las paradas dentro de una red de transporte.

6.1.1. Beneficios de minimizar los costes en función de la frecuencia de las líneas y el tamaño de los buses dentro de una red completa de transporte urbano.

A lo largo de los capítulos 2 y 3 de esta tesis se han planteado sendos métodos para la optimización de un sistema integro de transporte incidiendo sobre los valores de las frecuencias y los tamaños de autobús.

Los modelos presentados se diferencian de otros modelos que buscan el mismo fin en que para su resolución se hace uso de una simulación completa de transporte público, es decir se tiene en cuenta la interacción del transporte privado con el transporte público, por otro lado también se considera la interacción de unas líneas del sistema con otras. Todo esto no solo optimiza los tamaños de bus y de frecuencias para que todo el sistema sea óptimo, sino que estas variables se optimizan teniendo en cuenta el efecto red.

Todo el modelo usado presenta resultados que son consistentes con lo postulado por Mohring, pero por el contrario contradice la idea de que los buses más pequeños son los más rentables en la mayoría de los casos. A lo largo de esta tesis se ha demostrado que la solución óptima para el sistema en estudio se compone de una flota heterogénea de diferentes tamaños de autobús.

Otro aspecto fundamental de este trabajo ha sido la obtención de una relación entre las diferentes variables en estudio, en el capítulo 2 se han presentado un conjunto de graficas que presentan una solución analítica a la función que relaciona los valores de Demanda, Tamaño de bus y Frecuencia o intervalo del sistema para que el sistema de transporte se encuentre en estado óptimo tanto desde el punto de vista del operador como de los usuarios del mismo. Las gráficas presentadas en el apartado 2.7 del capítulo dos pueden ser una herramienta muy potente para llevar a cabo la planificación de un sistema de transporte público urbano de una manera óptima y racional.

Si a continuación se presta atención a los resultados presentados en el capítulo 2 de esta tesis se observa que cuando existe un alto nivel de demanda, superando los 600 pasajeros por hora, se impone el uso de autobuses de gran tamaño con intervalos inferiores a 10 minutos, sin embargo cuando nos movemos en demandas que se pueden denominar bajas unos 200 pasajeros por hora los intervalos aumentan hasta los 20 minutos y se observa que cualquier tipología de autobús es atractiva para obtener un óptimo del sistema.

El capítulo 3 de este trabajo puede ser considerado como una extensión y una búsqueda de perfeccionar lo presentado a lo largo del capítulo 2, a este efecto se diseñó un algoritmo que resultase mucho más eficaz para la resolución del modelo de optimización de frecuencias y tamaños de autobús dentro de una red de transporte urbano. A efectos de este propósito se introduce el uso del método Tabu Search que permite la resolución del problema planteado de una manera más eficiente y rápida.

Los resultados tanto computacionales como el resultado final del problema planteado revelan que el método Tabu Seach es más eficiente en velocidad de computación, por otro lado tanto los resultados de tamaños y de frecuencias como el valor final de la función de costes difiere un poco de lo obtenido mediante el método de Hooke-Jeeves usado a lo larga del capítulo 2.

Tal como se ha observado en este trabajo si se hace que ambos métodos comiencen desde una misma situación inicial el algoritmo Tabu Search posee una velocidad de convergencia que es un 50% más rápida que la del algoritmo de Hooke-Jeeves, esto hace que el algoritmo presentado en el capítulo 3 sea mucho más atractivo cuando tenemos que resolver el problema un alto número de veces o aplicarlo sobre redes de transporte de gran tamaño. Como se observó en el apartado 3.6 de esta tesis los valores de la solución final sobre las variables en estudio son muy similares, existiendo diferencias en ciertas líneas puntuales, esto puede achacarse a su singularidad ya que experimentan valores anormalmente bajos de la demanda.

Otro resultado a tener en cuenta es que el método usando uno u otro algoritmo es independiente de la solución inicial con la que se inicia el proceso de optimización a la vista de las varianzas obtenidas sobre las tres situaciones iníciales propuestas en nuestro estudio.

Atendiendo al valor final de la función objetivo que se intenta minimizar se observó que el HJ llega a un valor menor debido a las características más flexibles de este a la hora de generar las nuevas posibles soluciones del problema, aun así la diferencia con el TS es tan solo de un 1,7 % lo que hace que sea este último método mucho más atractivo para la resolución del problema ya que permitirá obtener soluciones prácticamente optimas en la mitad de tiempo.

6.1.2. El rol que juegan el correcto posicionamiento y la topología de las paradas dentro de una red de transporte.

En los capítulos 4 y 5 de este trabajo se han planteado dos métodos para actuar tanto sobre el uso como el correcto posicionamiento de las paradas a lo largo de un eje de transporte urbano.

A lo largo del capítulo 4 se han visto los beneficios del uso de dobles paradas asignadas a diferentes líneas lo consiguiendo disminuir los niveles de congestión en las paradas y aportando un incremento de la velocidad comercial del sistema de transporte. Para llevar a cabo la resolución de la problemática de que líneas han de parar en cada parada, se ha propuesto una metodología de distribución de líneas de transporte público a paradas de bus divididas en el que se minimiza el coste del usuario teniendo en cuenta la interacción con el tráfico privado y la congestión en el sistema de transporte público. Para la generación de soluciones factibles se ha utilizado un algoritmo genético, contrastado con uno de búsqueda exhaustiva, que reduce el coste computacional y de tiempo de ejecución.

La distribución obtenida con el modelo propuesto sigue pautas coherentes con lo esperado, en cuanto a que agrupa las líneas de destinos comunes en una misma parada, dando preferencia a los destinos con mayor demanda.

Los resultados obtenidos muestran la importancia de una buena distribución de líneas a paradas en cuanto a que se pueden obtener diferencias del 10% en la velocidad comercial y del 5% en el coste social.

Por otro lado en el capítulo 5 se ha visto que la correcta colocación de las paradas a lo largo de una línea de transporte arroja grandes beneficios en el funcionamiento del conjunto del servicio de transporte urbano. Para llevar a cabo este propósito.

Se ha propuesto un modelo de localización de paradas de bus mediante la aplicación secuencial de dos etapas: una primera etapa a nivel estratégico en el que se localizan las paradas de bus en todo el sistema de transporte público a escala macroscópica y una segunda etapa a nivel táctico donde, a partir de la solución macroscópica obtenida se afina la ubicación de paradas en ejes específicos de una ciudad a escala microscópica.

La aplicación secuencial de ambos enfoques permite un mayor grado de detalle y mejores resultados que con la aplicación individual de cada uno de ellos, puesto que cada modelo se adapta a la escala del problema y permite un mayor grado de definición en las áreas más problemáticas.

La validez y utilidad del modelo propuesto se ha comprobado mediante la aplicación a un caso real, donde se ha conseguido optimizar el sistema existente consiguiendo una mejora del servicio de transporte público con menos recursos, aumentando la velocidad comercial en un 10% y reduciendo la flota necesaria en un 3%.

En el análisis de resultados realizado se ha comprobado que la ubicación de las paradas influye fuertemente en la velocidad comercial del bus. Así, la aplicación del modelo microscópico ha obteniendo un arco de variación de dicha velocidad entre 6 y 10 km/h.

Analizando la posición final de las paradas sobre el escenario que proporciona la velocidad máxima se puede ver que éstas han sido situadas bien aguas arriba de los semáforos pero alejados del mismo, bien aguas abajo.

Finalmente, en el análisis de sensibilidad realizado se han establecido las tipologías de ubicación de paradas más adecuadas al nivel de demanda de buses, tráfico privado y ciclos semafóricos en la red vial.

6.2. Líneas futuras de investigación.

A partir de los trabajos realizados en esta tesis quedan abiertas diferentes líneas de investigación que se espera continuar en el futuro:

I. Aplicar el modelo de optimización de frecuencias y tamaños de bus, combinado con el de localización de paradas en un escenario de demanda variable.
II. A partir del modelo usado para la obtención de la relación optima entre demanda, frecuencia y tamaño de bus, intentar encontrar la ecuación que relaciona estas variables para el sistema de transporte en estudio.
III. Profundizar en el diseño de nuevos algoritmos de resolución para los problemas presentados.
IV. Introducir distintas morfologías de paradas en los métodos planteados.
V. Ampliar la aplicación del método de localización de paradas, intentar abarcar un número mayor de paradas del que se ha usado en esta investigación.

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ANEXOS

ANEXOS.

A. Método de interpolación Bilineal.

A continuación se describe el método de la interpolación bilineal (Nakamura, 1997). El objetivo es obtener el valor de P = f(x,y) en cualquier punto a partir de ciertos valores conocidos $Q_{11}=f(x_1,y_1)$, $Q_{12}=f(x_1,y_2)$, $Q_{21}=f(x_2,y_1)$, $Q_{22}=f(x_2,y_2)$. Para obtener el valor de P se siguen los siguientes pasos.

1º se realiza la interpolación lineal en x:

$$f(R_1)\approx\frac{x_2-x}{x_2-x_1}\cdot f(Q_{11})+\frac{x-x_1}{x_2-x_1}\cdot f(Q_{21}) \quad \text{Donde } R_1=(x,y_1) \qquad \text{(A.1)}$$

$$f(R_2)\approx\frac{x_2-x}{x_2-x_1}\cdot f(Q_{12})+\frac{x-x_1}{x_2-x_1}\cdot f(Q_{22}) \quad \text{Donde } R_2=(x,y_2) \qquad \text{(A.2)}$$

2º se realiza la interpolación en el eje y:

$$f(P)\approx\frac{y_2-y}{y_2-y_1}\cdot f(R_1)+\frac{y-y_1}{y_2-y_1}\cdot f(R_2) \qquad \text{(A.3)}$$

3º se sustituyen los valores de $f(R_1)$ y $f(R_2)$ en la expresión anterior y se obtiene la siguiente expresión.

$$\begin{aligned} f(x,y)\approx{}&\frac{f(Q_{11})}{(x_2-x_1)\cdot(y_2-y_1)}\cdot(x_2-x)\cdot(y_2-y)+\frac{f(Q_{21})}{(x_2-x_1)\cdot(y_2-y_1)}\cdot(x-x_1)\cdot(y_2-y)+\\ &+\frac{f(Q_{12})}{(x_2-x_1)\cdot(y_2-y_1)}\cdot(x_2-x)\cdot(y-y_1)+\frac{f(Q_{22})}{(x_2-x_1)\cdot(y_2-y_1)}\cdot(x-x_1)\cdot(y-y_1) \end{aligned} \qquad \text{(A.4)}$$

En la figura.A-1 se observa un ejemplo gráfico del método usado.

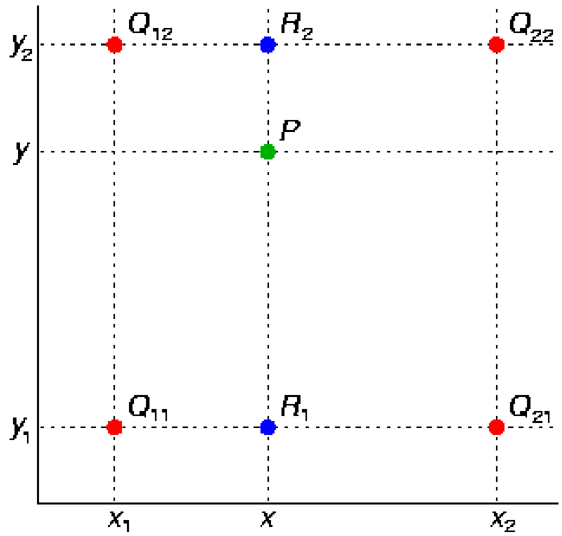

Figura 7-1 ejemplo grafico de interpolación bilineal

El método de interpolación bilineal descrito, esta implementado en numerosos paquetes de cálculo matemático, en este caso el programa elegido es el MATLAB.

B. Código del Algoritmo Genético usado para la asignación de dobles paradas.

En este anexo se nuestra el código de la función de Matlab que implementa el algoritmo TABU SEARCH usado en el capítulo 3 de esta tesis.

El código de la función usada se presenta a continuación:

```
-----------------------------------------------------------------
-----------------------------------------------------------------
function [f,z,zu,zop] =
funcion_tabu(v_tiempo_viaje,v_tiempo_acceso,v_tiempo_espera,c_cons
truccion_parada,c_rodadura,c_personal,f,t_acceso,t_viaje,nv_linea,
num_paradas,num_lineas,c_fijos,km_lineas,tc_linea,alfa_t_espera,z_
inicial)

memoria_larga = f;
memoria_posicion =[];
[fil_f,col_f] = size(f);
```

```
m_vecindario1 = zeros(col_f,col_f);
m_vecindario2 = zeros(col_f,col_f);
flota_final = [];

n = 1;
z_totales = [];
z_best = 10000000;
z_best_o = 10000000;
z_best_u = 10000000;
posicion = 1;

%creo una matriz vecindario de la actual sumando y restando un
offser d



while n <= 300
    f_ini = f;
    d = 0.2;
    cont = 1;
    for i = 1:col_f
        for j = 1:col_f
            if j == cont
                m_vecindario1(i,j) = f(j) + d;
                if m_vecindario1(i,j) <= 10
                    m_vecindario1(i,j) = 10;
                end
                if m_vecindario1(i,j) >= 40
                    m_vecindario1(i,j) = 40;
                end
            else
                m_vecindario1(i,j) = f(j);
            end
        end
        cont = cont + 1;
```

```
    end
    cont = 1;
    for i = 1:col_f
        for j = 1:col_f
            if j == cont
                m_vecindario2(i,j) = f(j) - d;
                if m_vecindario2(i,j) <= 10
                    m_vecindario2(i,j) = 10;
                end
                if m_vecindario2(i,j) >= 40
                    m_vecindario2(i,j) = 40;
                end
            else
                m_vecindario2(i,j) = f(j);
            end
        end
        cont = cont + 1;
    end
    n = n+1;

    m_vecindario = [m_vecindario1;m_vecindario2];
    [fil_vecindario,col_vecindario] = size(m_vecindario);

% busco en la memoria a largo plazo.

    [f_men,c_men] = size(memoria_larga);
    candidatos_1 = [];
    for h = 1:fil_vecindario
        replicado = 0;
        for k = 1:f_men
            if isequal(m_vecindario(h,:),memoria_larga(k,:))==1;
                replicado = 1;
            end
        end
```

```
        if replicado == 0;
            candidatos_1 = [candidatos_1;m_vecindario(h,:)];
        end
    end

% busco en la memoria de posiciones.
    if n > 1
        [f_pos,c_pos] = size(memoria_posicion);
        [f_candi,c_candi] = size(candidatos_1);
        candidatos = [];
        for p = 1:f_candi
            difer = abs(f_ini - candidatos_1(p,:));
            pos_cambia = find(difer,1);
            existe = 0;
            for q = 1:f_pos
                if pos_cambia == memoria_posicion(q,1)
                    existe = 1;
                end
            end
            if existe == 0
                candidatos = [candidatos;candidatos_1(p,:)];
            end
        end
    else
        candidatos = candidatos_1;
    end

% calculo los valores de las funciones objetivo para la matriz
vecindario.

    [fil_candidatos,col_candidatos] = size(candidatos);
    cont = 1;
    for k = 1:fil_candidatos
        f = candidatos(k,:);
```

```
        % calculo la flota y veo si cumple
        flota_total = (tc_linea./f);
        [fil_flota_total,col_flota_total] = size(flota_total);
        flota_final =[];
        for m = 1:col_flota_total
                n_buses = flota_total(1,m);
                int_buses = uint16(flota_total(1,m));
                dif = n_buses - double(int_buses);
                if dif == 0
                     flota_final = [flota_final;n_buses];
                else
                     flota_final = [flota_final;(double(int_buses)
+ 1)];
                end
        end
        flota_final1 = sum(flota_final);
        if flota_final1 <= 63
            [z1,fn,zu1,zop1] =
frecuencia_parada_capac(v_tiempo_viaje,v_tiempo_acceso,v_tiempo_es
pera,c_construccion_parada,c_rodadura,c_personal,c_fijos,km_lineas
,f,t_acceso,t_viaje,nv_linea,num_lineas,alfa_t_espera);
            %[z1,fn,zu1,zop1] =
frecuencia_parada(v_tiempo_viaje,v_tiempo_acceso,v_tiempo_espera,c
_construccion_parada,c_rodadura,c_personal,c_fijos,km_lineas,f,t_a
cceso,t_viaje,nv_linea,num_paradas,alfa_t_espera);
            z_vecindario(cont,:) = z1;
            z_vecindarioU(cont,:) = zu1;
            z_vecindarioOp(cont,:) = zop1;
            candidatos1(cont,:) = f;
            cont = cont + 1;
        end

    end

% evaluo las soluciones para ver cual es la mejor solucion del
vecindario.
```

```
    matriz = z_vecindario;
    v_anterior = z_vecindario(1,:);
    valor = v_anterior;
    [fil,col] = size(matriz);

    for i = 1:fil
        %for j = 1:col
            if matriz(i,1) <= v_anterior
                z = matriz(i,:);
                v_anterior = z;
                solucion = candidatos1(i,:);
                posicion = i;
            end
        %end
    end

% incluyo este valor en la memoria TABU
    memoria_larga =[memoria_larga;solucion];

% almaceno la posicion que se ha movido y le asigmo una
penalizacion.
%     vector_diferencia = abs(f_ini - solucion);
%
%     posicion = find(vector_diferencia,1);
%     if posicion > 0
%         posicion_contador = [posicion 28];
%         memoria_posicion = [memoria_posicion;posicion_contador];
%
%         if n >= 1
%             b = (memoria_posicion(:,2) - 1);
%             memoria_posicion(:,2) = b;
%             [fmp,cmp] = size(memoria_posicion);
%             elimina = 0;
```

```
%              for h = 1:fmp
%                  if memoria_posicion(h,2) == 0
%
%                      elimina = h;
%                  end
%              end
%          end
%
%          if elimina > 0
%              memoria_posicion(elimina,:) = [];
%          end
%      end

% cambio el valor de las frecuencias por el nuevo resultado.
    f = solucion;
    z_vecindario = [];
    z_totales = [z_totales;v_anterior];
    z = v_anterior;
    zu = z_vecindarioU(posicion,:);
    zop = z_vecindarioOp(posicion,:);
%      if z <= z_best
%          z_best = z;
%          posicion_best = posicion;
%          f_best = f;
%      end
   n = n+1;
end
% z = z_best;
% f = f_best;
clear memoria_larga
```

C. Codigo del Algoritmo Genetico usado para la asignación de dobles paradas.

En este anexo se muestra el código en Matlab que implementa el algoritmo diseñado para resolver el problema de la asignación de líneas a paradas dobles presentado en el capítulo 4 de esta tesis.

El código para el algoritmo usado es el siguiente:

```
-------------------------------------------------------------------
-------------------------------------------------------------------
%clear all

% datos del algoritmo genetico.
% evaluacion decimal de la poblacion inicial.
cont = 0;
%f_bin = [f1;f2;f3;f4];
%f_dec = bin2dec(f_bin);
clear z
[f_poblacion,c_poblacion] = size(poblacion);
for i = 1:f_poblacion
    vector = poblacion(i,:);
    [z(i,:),t_a(i,:),t_e(i,:),t_v(i,:),v_c(i,:)] =
mainDoblesMod(vector,ruta_detencion,ruta_auto,ruta_bus,ruta_actual
,ruta_informe5,v_t_viaje,v_t_espera,archivo_caract);
    cont = 1 + cont
end

% funcion de evaluacion.

%z = f_dec.^2;

% probabilidad de eleccion de cada f

sum_f = sum(z);
[fil_z,col_z] = size(z);
p1 = 0;
```

```
for i = 1:fil_z
    p(i) = z(i)/sum_f;
    p1 = p1 + p(i);
    p_sum(i) = p1;
end

clear i

p1 = p';
p_sum1 = p_sum' ;

% resultado para la primera poblacion.

%r_ini = [poblacion,z,perd];
r_ini = [poblacion,z,t_a,t_e,t_v,v_c];

% generamos vectores de probabilidad uniformes

for j = 1:fil_z
    R = unifrnd(0,1);
    prob1(j) = R;
end

clear j

% emparejamientos usando las prob1

[fil_prob1,col_prob1] = size(prob1);
[fil_r_ini,col_r_ini] = size(r_ini);

for k = 1:col_prob1
    for m = 1:fil_r_ini
        g1 = p_sum1(m,1);
        g2 = prob1(1,k);
```

```
        matriz_dif(k,m) =p_sum1(m,1) - prob1(1,k);
    end
end

clear k
clear m

% transformo los valores negativos en 1s

[fil_matriz_dif,col_matriz_dif] = size(matriz_dif);

for k = 1:fil_matriz_dif
    for m = 1:col_matriz_dif
        if matriz_dif(k,m) < 0
            matriz_1s(k,m) = 1;
        else
            matriz_1s(k,m) = matriz_dif(k,m);
        end
    end
end

% busco el menor valor de cada fila

[fil_matriz_1s,col_matriz_1s] = size(matriz_1s);

for i = 1:fil_matriz_1s
    minimo = min(matriz_1s(i,:));
    posicion = find(matriz_1s(i,:)==minimo);
    pos_min(i) = posicion;
end

clear i

pos_min1 = pos_min';
```

```
% matiz de padres

[fil_pos_min,col_pos_min] = size(pos_min1);

for i = 1:fil_pos_min
    indice = pos_min(i);
    padres(i,:) = poblacion(indice,:);
end

clear i

% calculo de la probabilidad de cruce (idica si se produce el
cruce 2 a 2)

[fil_padres,col_padres] = size(padres);

num_prob2 = (fil_padres/2);

for j = 1:num_prob2
    R = unifrnd(0,1);
    prob2(j) = R;
end
prob21 = prob2';
clear j

% calculo el punto en el que se pruduce la interseccion entre los
fenotipos

[fil_prob21,col_prob21] = size(prob21);

cont1 = 0;
cont2 = 1;
cont3 = 1;
```

```
for i = 1:fil_prob21

    if prob21(i,:) < p_cruce
        corte = unifrnd(1,longitud);
        corte = uint16(corte);
        padre1 = padres(i+cont1,:);
        padre2 = padres(i+cont2,:);
        pd11 = padre1(1:corte-1);
        pd22 = padre2((corte):uint16(col_padres));
        pd21 = padre2(1:corte);
        pd12 = padre1((corte+1):uint16(col_padres));
        hijo1 = [pd11,pd22];
        hijo2 = [pd21,pd12];
        hijos(cont3,:) = hijo1;
        cont3 = cont3 + 1;
        hijos(cont3,:) = hijo2;
        cont1 = cont1 + 1;
        cont2 = cont2 + 1;
        cont3 = cont3 + 1;
    else
        cont1 = cont1 + 1;
        cont2 = cont2 + 1;
    end
end

% introduzco la mutacion de los hijos

[fil_hijos,col_hijos] = size(hijos);



for i = 1:fil_hijos
    for j = 1:col_hijos
        prob3 = unifrnd(0,1);
        if prob3 < p_mutacion
```

```
            if hijos(i,j) == 0
                hijos(i,j) = 1;
            else
                hijos(i,j) = 0;
            end
        end
    end
end

clear i j

hijos1 = [padres;hijos];

% hijos_dec = bin2dec(hijos);

[fil_hijos,col_hijos] = size(hijos);

for i = 1:fil_hijos

[z_hijos(i,:),t_a_hijos(i,:),t_e_hijos(i,:),t_v_hijos(i,:),v_c_hij
os(i,:)] =
mainDoblesMod(hijos(i,:),ruta_detencion,ruta_auto,ruta_bus,ruta_ac
tual,ruta_informe5,v_t_viaje,v_t_espera,archivo_caract);
    cont = 1 + cont;
end
clear i

%r_hijos = [hijos,z_hijos,perd_hijos];
r_hijos = [hijos,z_hijos,t_a_hijos,t_e_hijos,t_v_hijos,v_c_hijos];
r_total = [r_ini;r_hijos];

% guardo las soluciones probadas.
[f_r_total,c_r_total] = size(r_total);
fid2 = fopen('soluciones_visitadas.out','a');
for i = 1:f_r_total
```

```
   % fprintf(fid2,'%s %5.4f %5.4 %5.4 %5.4 %5.3
\n',num2str(r_total(i,1:8)),r_total(i,9),r_total(i,10),r_total(i,1
1),r_total(i,12),r_total(i,13))
    fprintf(fid2,'%s %5.4f %5.4f %5.4f %5.4f
%5.3f\n',num2str(r_total(i,1:longitud)),r_total(i,longitud+1),r_to
tal(i,longitud+2),r_total(i,longitud+3),r_total(i,longitud+4),r_to
tal(i,longitud+5));
end
plot(r_total(:,longitud+1));
fclose(fid2);

% funcion de evaluacion de los hijos.
%z_hijos = hijos_dec.^2;
sum_f_hijos = sum(z_hijos);
[fil_z_hijos,col_z_hijos] = size(z_hijos);

% seleccion de los cuatro miembros mas competentes

r_total_aux = r_total;

for i = 1:f_poblacion
    indice = r_total_aux(:,c_r_total);
    [valor_min,indice_min] = min(indice);
    nueva_poblacion(i,:) = r_total_aux(indice_min,:);
    r_total_aux(indice_min,:)= [];
end

poblacion1 = nueva_poblacion(:,1:longitud);
poblacion2 = nueva_poblacion(:,:);

%-----------Compruebo si cumple la restriccion--------------------
---------
% paradas que se desean probar
% matriz_paradas = [1041,1042;1061,1062;1071,1072];

% matriz de lineas....
```

```
% matriz_lineas = [1 2 3 4 5 6 7 8];
[fil_matriz_lineas,col_matriz_lineas] = size(matriz_lineas);
% [fil_matriz_lineas,col_matriz_lineas] = size(matriz_lineas);
% matriz_frecuencias = [10 12 10 8 10 4 8 6];
matriz_frecuencias = LeoFrecuencia(archivo_caract);
% buses_hora = 60./matriz_frecuencias;
 sum_buses_hora = sum(buses_hora);
 [f_poblacion1,col_poblacion1] = size(poblacion1);
cont = 1;
for i = 1:f_poblacion1
    m_buses_parada = poblacion1(i,:).*buses_hora;
    buses_parada1 = sum(m_buses_parada);
    buses_parada2 = sum_buses_hora - buses_parada1;
    fid3 = fopen('resultados_filtrados.out','a');
    if buses_parada1 <= busesA && buses_parada2 <= busesB
        poblacion(cont,:) = poblacion1(i,:);
        resultadoParcial = poblacion2(i,:);
        fprintf(fid2,'%s %5.4f %5.4f %5.4f %5.4f
%5.3f\n',num2str(resultadoParcial(1:longitud)),resultadoParcial(lo
ngitud+1),resultadoParcial(longitud+2),resultadoParcial(longitud+3
),resultadoParcial(longitud+4),resultadoParcial(longitud+5));
        cont = cont + 1;
    end
    fclose(fid3);
end
%-----------------------------------------------------------------
---------
```

D. Código de Python usado para la localización de paradas en AINSUM.

A continuación se muestra el código usado para la automatización del proceso para la localización de las paradas a lo largo del corredor definido en el capítulo 5 de esta Tesis. Para llevar a cabo esta automatización se ha usado una macro diseñada usando la API de

Python que incorpora el programa AINSUM y que permite analizar un amplio número de escenarios de forma automática.

El código usado es el siguiente:

```
def AlmacenaLineas( model ):
	LineasItem = list()
	lineaType = model.getType( "GKPublicLine" )
	for lineas in model.getCatalog().getObjectsByType( lineaType
).itervalues():
		print "Id: %i" % (lineas.getId())
		LineasItem = LineasItem + [lineas.getId()]
	return LineasItem

def TransformoHoras( Tiempo ):

	min_t = Tiempo//60
	min = Tiempo/60
	seg_t = (min_t -min)*60

	print min
	print min_t
	print seg_t

	return min_t
	return seg_t

def AlmacenaReplicaciones( model ):
	replicacionesItem = list()
	replicationType = model.getType( "GKReplication" )
	for replicaciones in model.getCatalog().getObjectsByType(
replicationType ).itervalues():
		print "Id: %i" % (replicaciones.getId())
```

```
            replicacionesItem = replicacionesItem +
[replicaciones.getId()]
      return replicacionesItem


def simula(model,replication_id):
      replication1 = model.getCatalog().find(replication_id)
      plugin = GKSystem.getSystem().getPlugin( "GGetram" )
      simulator = plugin.getCreateSimulator( model )
      simulator.addSimulationTask( replication1,
GKReplication.eBatch )
      simulator.simulate()


def crea_media(replicaciones,model,experimento_id):
      model = GKSystem.getSystem().getActiveModel()
      average = GKSystem.getSystem().newObject(
"GKExperimentResult",model)
      num_replicaciones = len(replicaciones)
      vector_num_replicaciones = range(num_replicaciones)
      for r in vector_num_replicaciones:
            repl = model.getCatalog().find(replicaciones[r])
            average.addReplication( repl )
      experiment = model.getCatalog().find( experimento_id )
      experiment.addReplication( average )
      # take and calculate the average
      if average != None and average.isA( "GKExperimentResult" ):
            #Calculate and store in the database the average of all
the simulated
            #replications in a given experiment result.
            GAimsunAvgCalculator().calculateAverage( average )
            GAimsunReplicationRetriever().retrieve( average )
# Be sure that we reset the UNDO buffer after a non undoable
modification
model.getCommander().addCommand( None )
```

```
#def
CambiaValores(linea,media_h,media_min,media_sec,desv_h,desv_min,de
sv_sec,t_stop,d_stop)
#    timeTable = linea.getTimeTables();
#    tTid = timeTable[0].getId()
#    timeT1 = model.getCatalog().find(tTid)
#    timeT1.removeSchedules()
#    schedule = timeT1.createNewSchedule()
#    departure = GKPublicLineTimeTableDeparture()
#    schedule.setDepartureType(
GKPublicLineTimeTableSchedule.eInterval )
#    departure.setMeanTime( GKTimeDuration( media_h, media_min,
media_sec ) )
#    departure.setDeviationTime( GKTimeDuration( desv_h, desv_min
, desv_sec ))
#    vehiculo = model.getCatalog().find(64)
#    departure.setVehicle(vehiculo)
#    schedule.addDepartureTime(departure)
#    stopTime = GKPublicLineTimeTableScheduleStopTime()
#    stopTime.mean = t_stop
#    stopTime.deviation = d_stop
#    parada = model.getCatalog().find(206)
#    schedule.setStopTime( parada,stopTime )
#    timeT1.addSchedule( schedule )
#    linea.addTimeTable( timeT1 )




#------------------------PROGRAMAPRNCIPAL-------------------------
-------------------------------------------------------------
model = GKSystem.getSystem().getActiveModel()
print model
ptType = model.getType( "GKPublicLine")
```

```
print ptType
l = AlmacenaLineas( model )
print l

# Vector de medias de detencion

matriz1 = [218,228,232,236,264,265,266]
matriz2 = [40,40,30,20,30,25,30]
matriz3 = [60.0,120.0,180.0,240.0,300.0,360.0,420.0]
replicaciones = AlmacenaReplicaciones( model )
pos = 0
cont1 = 0
while (cont1<=4)
     for lineaId in l:

          media_h = 0
          desv_h = 0

          cont = 0
          for  m in matriz1:
               if m == lineaId:
                    t_stop = matriz2[cont]
                    d_stop = 0
                    Tiempo = matriz3[cont]
                    Tiempo2 = Tiempo/2
                    media_min = Tiempo//60
                    min_t = Tiempo/60
                    media_sec = (min_t -media_min)*60
                    desv_min = Tiempo2//60
                    min_dt = Tiempo2/60
                    desv_sec= (min_dt -desv_min)*60

               cont = cont + 1
          linea = model.getCatalog().find(lineaId)
```

```
            timeTable = linea.getTimeTables();
            tTid = timeTable[0].getId()
            timeT1 = model.getCatalog().find(tTid)
            timeT1.removeSchedules()
            schedule = timeT1.createNewSchedule()
            departure = GKPublicLineTimeTableDeparture()
            schedule.setDepartureType(
GKPublicLineTimeTableSchedule.eInterval )
            departure.setMeanTime( GKTimeDuration( media_h,
media_min, media_sec ) )
            departure.setDeviationTime( GKTimeDuration( desv_h,
desv_min , desv_sec ))
            vehiculo = model.getCatalog().find(64)
            departure.setVehicle(vehiculo)
            schedule.addDepartureTime(departure)
            stopTime = GKPublicLineTimeTableScheduleStopTime()
            stopTime.mean = t_stop
            stopTime.deviation = d_stop
            parada = model.getCatalog().find(206)
            schedule.setStopTime( parada,stopTime )
            timeT1.addSchedule( schedule )
            linea.addTimeTable( timeT1 )
            simula(model,replicaciones[pos])
            cont1 = cont1 + 1
            lista_replicaciones = lista_replicaciones +
[replicaciones[pos]]
            pos = pos + 1
            crea_media(lista_replicaciones,model,246)

#for t in timeTable:
#           print "IdTT: %i" % (t.getId())
#timeT1 = model.getCatalog().find(227)
#timeT1.removeSchedules()
#schedule = timeT1.createNewSchedule()
#departure = GKPublicLineTimeTableDeparture()
```

```
#schedule.setDepartureType(
GKPublicLineTimeTableSchedule.eInterval )
#departure.setMeanTime( GKTimeDuration( 0, 5, 0 ) )
#departure.setDeviationTime( GKTimeDuration( 0, 2 , 30 ))
#vehiculo = model.getCatalog().find(64)
#departure.setVehicle(vehiculo)
#schedule.addDepartureTime(departure)
#stopTime = GKPublicLineTimeTableScheduleStopTime()
#stopTime.mean = 10.0
#stopTime.deviation = 2.0
#parada = model.getCatalog().find(206)
#schedule.setStopTime( parada,stopTime )



#timeT1.addSchedule( schedule )
#lineas.addTimeTable( timeT1 )
```