8. APPLICATION OF THE ANALYTICAL MODEL TO CHICAGO AND BARCELONA

As discussed in Chapter 4, the analytical model that will be used in this study will be the one presented by van Nes (1999). The main characteristic of this model is that its analytical formulation is based on the objectives of the parties involved in a transit network: users, operator, and authority.

After presenting these different objectives and discussing them, the conclusions of van Nes' study are that the operator's objective of maximizing profit (O4) and the authority's objective of minimizing total costs (O5) are the most realistic formulations. The user's objective of minimizing total travel time (O2) is also a good formulation to improve the results obtained by either of the previous mentioned objectives.

For this study, objective O5, minimizing total costs, is chosen to optimize the bus networks depending on the variables stop distance and line distance. Objective O5 is chosen over objective O4 for the simple reason that it allows a fixed demand variable on the formulation, whereas objective O4 is more sensitive to demand changes. And in this study the demand will be a fixed level, given the actual demand that the network operators in Chicago and Barcelona provide us. Therefore, objective O5 is chosen for the first approach to the network optimization. On the second optimization step, objective O2, minimizing total travel time, is then used to improve the results by including the vehicle frequency under the design variables.

This chapter comprises an explanation of the data used for the model, including its origin and sources, and the results obtained by the application of the mathematical model to the two cities. Additionally, a validation of the model is also included. This validation is elaborated by means of a simulation of one of the bus routes. That is to say, a specific bus route is entered in the model adopting the values described in this chapter, and the results are compared with the real values available for the bus route. The route that was chosen is route number 9, of the city of Barcelona.

8.1. Data gathering

The data gathering process involved researching particular values for the variables needed as well as adopting standard values, and collecting some values specifically for the cities of Chicago and Barcelona by means of a survey. The justification for the values of the parameters is described in this chapter.

8.1.1. Adopted standard values

Among the variables that can be considered standard there is the user's access speed (v_a): the walking speed is taken as 4km/h. Although there are other possibilities for accessing the network with different speed, such as cycling, they are not considered in this model. It is assumed that the users access the network by foot.

The access distance factor (f_a) is also considered standard and it is supposed that the user will access the network from the mid point in between two different bus routes and two different bus stops. Consequently, considering that the assumption for this study is that the network is a square grid, this factor will be 0,25.

The factor waiting time (f_w) is considered to be 0,5, which means that the waiting time is supposed to be an average of half the headway.

The time lost at stops (T_s) is taken from the *Transit Capacity and Quality of Service Manual*, an edition of the *Transit Cooperative Research Program – Report 100* (2003). This manual states that the average time lost at stops is 20s. However, this value is approximate since it's the result of adopting certain assumptions. Therefore, further research on increasing the accuracy of the value would be of great importance. The mentioned manual is also the source for the egress time (T_e), which is said to be from 15s to 60s per stop. A middle value of 30s per stop is taken, and the total average egress time per passenger is therefore 30s multiplied by the average number of bus stops served within the passenger travel distance.

The last of the standard values is the Value of Time for travelers (c_t). This value is assumed to be $15 for the city of Chicago, considering the average hourly salary. For the city of Barcelona the value of time is taken from the suggested value in Robusté (1994), which rates it as 10€ per hour. It is interesting to notice that these values are subject to change throughout the day, since the time consumed on the transit network is valued differently depending on the time of the day: peak hour in the morning, peak hour in the afternoon, or non-peak hour. A more accurate model could take under consideration this variability; however, for this study, the average value meets the precision requirements and it is therefore used.

8.1.2. Data from network operators

The original values for the three basic variables (stop spacing, line spacing and vehicle frequency) were taken from the operator's available data in both cities, CTA and TMB.

In the case of Barcelona, only the bus routes comprehended within the neighborhood of the *Eixample* were taken into consideration. The bus stop spacing adopted was then the average value of all the bus stop spacing along a single route and among all the bus routes considered: 350m. The vehicle frequency was taken in a similar way, adopting the average value, in rush hour period, of all the bus routes considered.

The line spacing in Barcelona is slightly variable from route to route, due to the one way character of the streets in the *Eixample*. However, it is close to the same value in all cases: 7 blocks, or 700m approximately.

In the case of Chicago, the parameters of stop spacing and line spacing are robustly defined. The CTA policy on bus stops is to place one at every intersection, or 1/8 of a mile (about 200 m). Lines are found at every main street, which makes it an almost homogeneous one mile line spacing distance. Some exceptions can be found within the *Loop* and along the *Lakeshore*, where more than one bus route can be found in the same street.

Regarding the vehicle frequency, the same procedure as in Barcelona was followed in order to adopt a standard value for the model: it is the average value in rush hour period of the frequencies of a set of bus routes that delimited a square area and complied with a one-mile line spacing distance (the Loop and the Lakeshore where excluded).

The vehicle commercial speed was also taken from data made available by the operators. The CTA provided and average vehicle speed throughout the network in Chicago, whereas TMB provided more detailed information: the speed is defined for different sub-categories such as single routes, transversal and S-M routes, and overall average speed.

Regarding the demand value taken for the model, in terms of passengers per square kilometer, ridership reports in both networks were used. In the case of Chicago, it was the 2004 annual ridership for the bus routes considered (delimiting a square area excluding the *Loop* and the *Lakeshore*). This set of routes was selected after a sensitivity test was applied to the whole network, with the concluding remarks that at a 95% confidence level, bus ridership was indifferent between Chicago's Business District (the *Loop*) and the rest of the network. TMB offered annual patronage data as well for all their routes and as an overall value.

One of the most important values for the model is the operating costs per vehicle for the operator. It is essential to clarify which costs they include and which ones they exclude.

The CTA provides the operational cost per vehicle in terms of total expenses per vehicle-revenue mile. This dollar amount comes from the total expenses of the service divided by the total revenue miles of the bus fleet. The total expenses include operational expenses and other expenses.

Among operating expenses, the costs for labor and material are considered. The fuel, electric power, and provision for Injuries and Damages, as well as purchase of Security Services are also classified as operating expenses.

Other expenses are defined as costs related with utilities, maintenance and repair, advertising and promotion, contractual services, provision for passenger security, leases and rentals, warranty and other credits, travel, training, and seminars and dues.

CTA's operating expenses are illustrated in *Figure 13*.

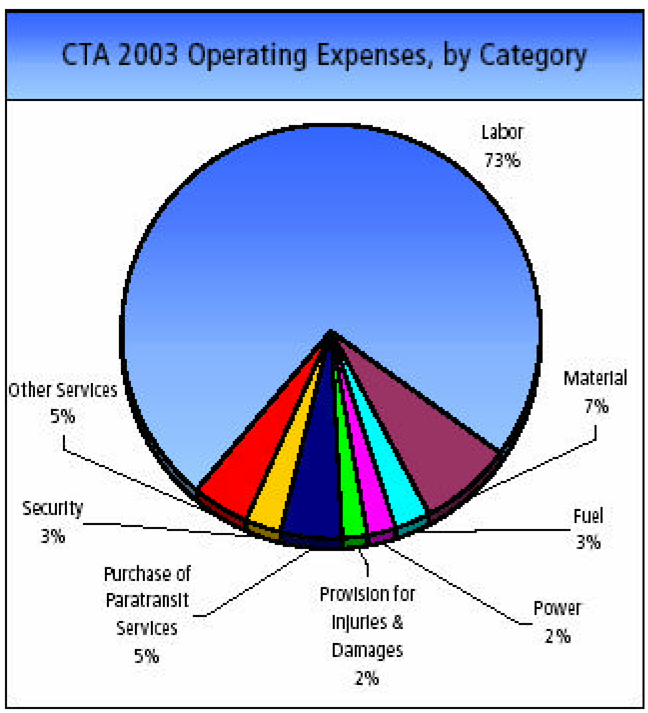

Figure 13. CTA's operating expenses, by category.
Source: CTA Annual Budget 2003.

For the city of Barcelona, the operating expenses per vehicle and kilometer include costs for provisions, fuel, labor, purchase of Security Services and Insurance, and other expenses. Other expenses include passenger security, maintenance, repair, cleaning services, and such. *Figure 14* illustrates TMB's operating expenses by category.

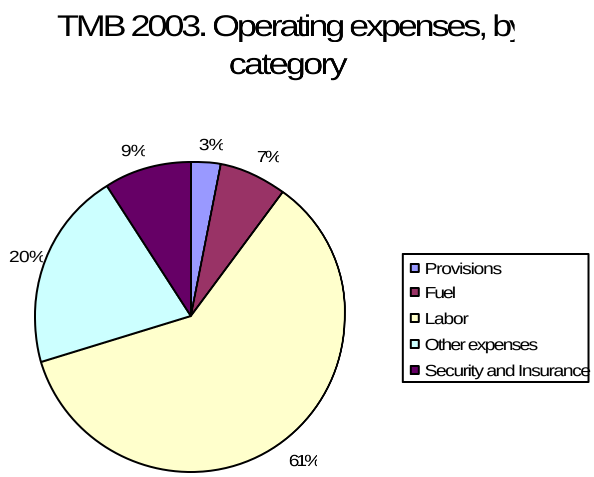

Figure 14. TMB's operating expenses, by category.
Source: TMB Financial Data.

The operating costs for both cities are comparable since they include the same categories. Unfortunately, neither of the operators regards environmental costs or social costs in their definition of operational costs. This is of great importance, since the analytical model used in this study aims to improve the bus network under the concept of social welfare. Besides, environmental and social costs cannot be disregarded in the evaluation of a transit system anymore, if society is aiming to reach sustainable urban transport systems.

It is therefore strongly recommended to further research the environmental costs, such as air pollution or sound contamination, and social costs, such as costs derived from collisions and accidents, and include them in the analytical model.

8.1.3.Data collected by means of a survey

Although bus network operators, *Chicago Transit Authority* and *Transports Metropolitans de Barcelona*, provided several basic data, the analytical model required some specific values that were needed for the user's cost evaluation, but couldn't be found in their databases.

These parameters are the weights for the different times (access time, egress time and waiting time) as well as the average traveled distance by system users. The values were collected by means of a survey. A sample survey form is shown in *Figure 15*.

<table>
<tr><td colspan="2">Bus Stop</td><td colspan="2">Destination</td><td colspan="3">Value the times</td></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="2"></td><td>access time</td><td>waiting time</td><td>egress time</td></tr>
<tr><td>1
2
3</td><td>1
2
3</td><td>1
2
3</td></tr>
<tr><td rowspan="3">Male</td><td rowspan="3">female</td><td colspan="2">Age range</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>15-25</td><td>35-55</td></tr>
<tr><td>25-35</td><td>more than 55</td></tr>
</table>

Figure 15. Sample survey form.

As shown in the sample, the information collected comprised the origin and destination bus stops, gender and age range of the user, and the weights for the different times. The same survey was conducted in both cities.

Gender and age were collected only to ensure a representative sampling of the population. The different types of times were valued on a scale from 1 to 3, being 1 the less valuable and 3 the most valuable.

The survey was conducted during peak-hour in the morning and in the evening on three different days (to avoid weather derived behavior incidents). A total of 66 bus customers in Chicago and 62 in Barcelona completed the survey satisfactorily. 50% of the customers in Chicago were female, whereas in Barcelona female customers were almost the 65%.

The results of this survey showed that customers in Chicago travel for an average of 4 km, while customers in Barcelona do it for an average travel distance of 2,7 km. This latest result can be validated comparing it with the data provided by TMB: according to their website information, the average passenger in Barcelona's bus network travels for about 3.3 km. Therefore, the results obtained by this survey can be considered as applicable average values for the model. In the case of Barcelona, however, the average travel distance used in the model will be the value given by the local bus operator, since it is available for its use.

Regarding the time weights, it is interesting to notice that the values for access time and egress time are between 20% and 30% higher in Chicago than in Barcelona. The precise values for all the parameters used in the analytical model and their sources and justification are summarized in *Tables 8* and 9.

Table 8. Value of the parameters

Parameter	Symbol	Chicago	Barcelona	Units
Travel distance	D_c	4,000	3,300	m
Access speed	v_a	1.1	1.1	m/s
Factor access distance	f_a	0.25	0.25	
Maximum speed transit	v	5.8	4	m/s
Time lost at stops	T_s	20	20	s/stop
Factor waiting time	f_w	0.5	0.5	
Egress time	T_e	10	4.72	min
Weight Access time	w_a	2.15	1.61	
Weight Waiting time	w_w	2.65	2.55	
Weight Egress time	w_e	1.92	1.58	
Frequency	F	8	8.5	veh/h
Travel demand per square kilometer	P	213	500	pax/km^2
Value of Time for travelers	c_t	\$15	10€	/h
Operating costs per vehicle	c_o	\$9.27 /veh-mile	4.5€ /veh-km	

Table 9. Source and justification of the values.

Parameter	Symbol	Chicago	Barcelona
Travel distance	D_c	survey	TMB data
Access speed	v_a	Assumed to be 4km/h	Assumed to be 4km/h
Factor access distance	f_a	Assumed to be the average of $D_S/2$ and $D_l/2$	Assumed to be the average of $D_S/2$ and $D_l/2$
Maximum speed transit	v	CTA data	TMB data
Time lost at stops	T_s	TCRP Report	TCRP - Report 100
Factor waiting time	f_w	Average half headway	Average half headway
Egress time	T_e	15s -60s per stop TCRP Report	15s -60s per stop TCRP – Report 100
Weight Access time	w_a	survey	survey
Weight Waiting time	w_w	survey	survey
Weight Egress time	w_e	survey	survey
Frequency	F	CTA data	TMB data
Travel demand per square kilometer	P	CTA data	TMB data
Value of Time for travelers	c_t	Assumed	Robusté, 1994
Operating costs per vehicle	c_o	CTA data	TMB data

8.2. Results

The optimization of the model was done by the adoption of certain constraints for each design variable. These constraints include the maximum allowable stop spacing distance, the minimum vehicle frequency required, and the maximum and minimum allowable line spacing distance.

According to different transportation studies, such as Saka (2001), the maximum distance that people are willing to walk to access the bus network is 800m. Therefore, the maximum stop distance allowed within the network would be 1.600 m. This constraint was adopted for the city of Barcelona, although for the city of Chicago it was thought to be an excessive constraint, given that the current stop spacing is 1/8 of a mile (about 200 m). Consequently, the constraint adopted was a maximum stop spacing of 2/3 of a mile, or 1.000 m.

The minimum vehicle frequency adopted in both cities was 5 vehicles per hour, or an average headway of 12 minutes.

The constraints regarding the line spacing were as follows:

- For the city of Chicago, a maximum line spacing of 1 mile (current line spacing) and a minimum line spacing of ½ of the current spacing, or ½ miles.
- For the city of Barcelona a maximum line spacing of 1100 m (1.5 times the current line spacing) and a minimum line spacing of 400 m (1/2 of the current line spacing).

The results of the application of this model are shown in *Tables 10* and *11*, including some of the network characteristics. On the first place, line spacing was included as a design variable in the analytical model (Scenario 1). Afterwards, it was removed from the design variables set, leaving only bus stop spacing and vehicle frequency as variables to optimize (Scenario 2).

The reason for this double scenario was to analyze the possibility of optimizing only two of the three key design variables, given that line spacing is the most difficult variable where the improvements could be implemented. Therefore, Scenario 2 was created in order to evaluate which improvement could be done in the bus networks if only stop spacing and vehicle frequency were subject to the implementation of variations.

Table 10. Results of the objectives for Chicago. All distances are in meters and time is in minutes.

	Original Values	Scenario 1		Scenario 2	
		O5	O2	O5	O2
Stop Distance	200	511	511	475	475
Line Distance	1.609	1.031	1.031	1.609	1.609
Stop density /km^2	3,1	1,9	1,9	1,3	1,3
Frequency	8	8 (fixed)	9,4	8 (fixed)	14
Travel Time	29	23	23	24	24
Weighted travel time	62	56	54	60,5	55,9
Operator costs	$369	$447	$526	$456	$528
Total Costs	$3.672	$3.418	$3.418	$3.507	$3.507
Patronage (pax/km^2)	213	213	213	213	213
Operational costs per traveler	$1,7	$2	$2,5	$2,1	$2,5
Total costs per traveler	$17,2	$16	$16	$16,5	$16,5

Table 11. Results of the objectives for Barcelona. All distances are in meters and time is in minutes.

	Original Values	Scenario 1		Scenario 2	
		O5	O2	O5	O2
Stop Distance	350	489	489	502	502
Line Distance	700	854	854	700	700
Stop density /km^2	4	2,4	2,4	2,8	2,8
Frequency	8,5	8,5 (fixed)	14,5	8,5 (fixed)	12
Travel Time	25	24,5	23	24	23
Weighted travel time	40	40	37	40	37
Operator costs	559€	433€	750€	527€	750€
Total Costs	3.871€	3.821€	3.821€	3.838€	3.838€
Patronage (pax/km^2)	500	500	500	500	500
Operational costs per traveler	1,1€	0,86€	1,5€	1€	1,5€
Total costs per traveler	7,7€	7,5€	7,5€	7,5€	7,5€

8.3. Model validation

This section intends to validate the results obtained by the analytical model used to evaluate and optimize the bus networks in Chicago as well as Barcelona. This validation is of great importance since it is the evidence that allows a network designer to consider the model as a useful tool available for its use or as a mere academic research study with no specific applications.

An analytical model is a representation of reality through a set of hypothesis and assumptions considered to be reasonable and justifiable. The validation process can be seen as a way of testing the accuracy of this set of assumptions. In this study, the analytical model used was originally created to represent bus networks in cities of the Netherlands. It has been adapted to the cities of Chicago and Barcelona, and the assumptions and hypothesis have been slightly modified in order to better represent these new circumstances. This validation process is therefore meant to test whether the adaptation has been successful or still remains inaccurate.

The validation process will be focused on the application of the model to a single bus route. The model has been built with the purpose of representing the whole bus network system in both cities, and in order to do so the values for the characteristic parameters have been chosen as the average values that best represented the system.

This is the reason why the validation will aim to prove that, if the model represents a single and specific bus route at a certain degree of accuracy, the whole model should be considered as valid for its purposes.

The route selected to be used in the validation process is bus route number 9, in the city of Barcelona. This bus route is classified as a transversal route, and runs about half its length across the district of the *Eixample*.

The validation process will start with a detailed description of the route selected, including characteristics such as its path, daily ridership, commercial speed, and time invested on the completion of a run.

The values adopted for the analytical model will be used to obtain the same information about the route, and then a comparison between the real values and the obtained values will take place.

Not only the actual values can be tested in the model, but an optimization for this single route can also be conducted and analyzed, leading to the evaluation of the efficiency of the actual route parameters as well as the improvements achieved after the optimization process takes place.

Bus route number 9 in Barcelona runs from the city center towards one of the city borders on the south, along a 5.800 m path. It has an average weekday ridership of 14.000 passengers, which makes it the twenty-third most demanded bus route over a total of seventy five routes. *Figure 16* shows the sketch of the bus route.

Figure 16. Route number 9.
Source: Transports Metropolitans de Barcelona, 2005.

Route number 9 starts the service at 5:00am and the last vehicle is scheduled to finish the service at 23:00, which is a total of 18 hours of service. During the service schedule, there is a peak passenger volume at 8:00am and a second peak passenger volume at 5:00pm. Peak-hour volume in the afternoon is lower, but it is distributed over a wider range of time (from 5pm to 8pm). Passengers on peak-hour period represent almost 40% of the route's ridership.

Figure 17 shows the passenger flow over the day for route number 9.

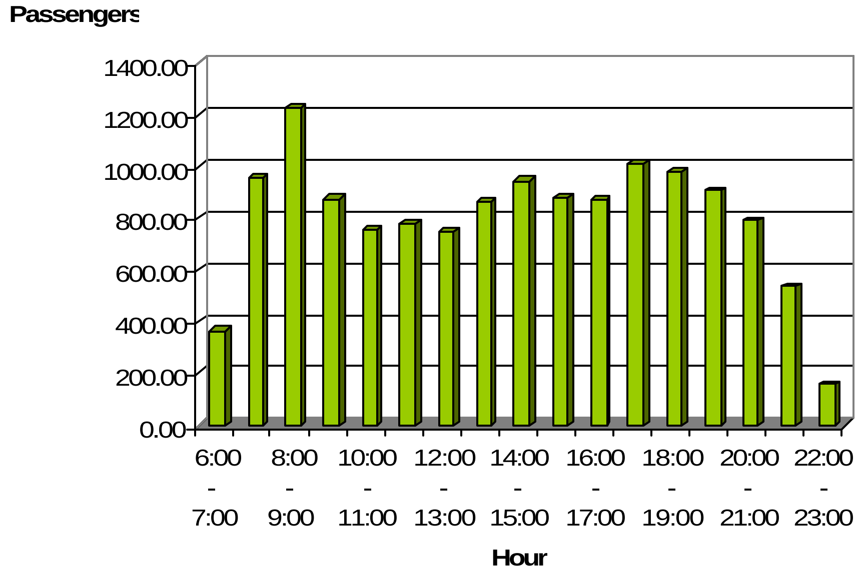

Figure 17. Passenger hourly flow for route 9.
Source: Llorca Martín, 2004.

The commercial vehicle speed of the service is defined as 12 km/h on average, a little under the overall system average speed. This may be due to the specific characteristics of its course as of road infrastructures: the route crosses two of the city's major street-crossings (*Plaça Espanya* and *Plaça Cerdà*). They are therefore two conflictive centers regarding traffic signals as well as vehicle density. This makes the route's commercial speed very sensitive to hour variations, to the point that during peak-hour in the morning the average speed is reduced by more than 40%, compared to the first hour of service.

This sensitivity is clearly illustrated in *Figure 18*, which shows the speed's variations over a day.

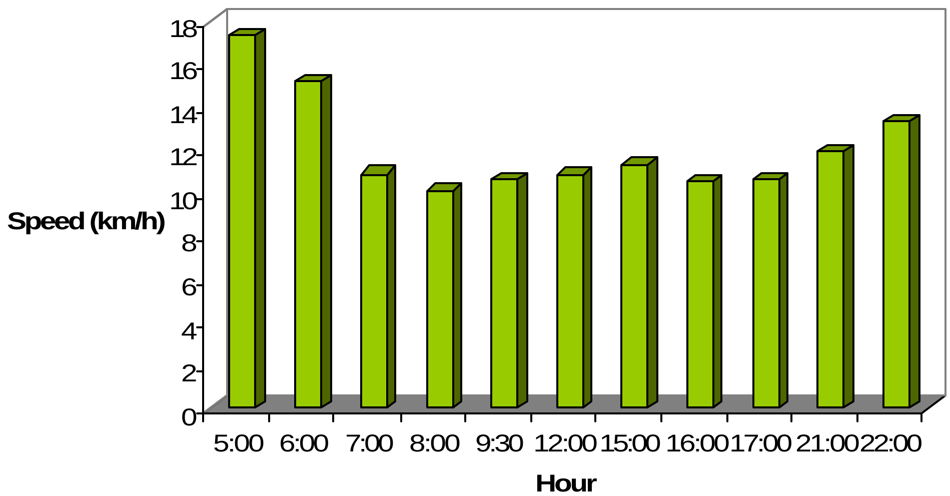

Figure 18. Speed flow over the day.
Source: TMB 2004.

The last bit of information about route number 9 concerns the path that the route follows through the city. This path will be the base for the validation procedure, and it is therefore essential to classify the current situation.

The path is subdivided in two different sets, depending on the direction of the vehicle. The first set is the path that has the city center as the origin and the south border of the city as the destination. The second set is the opposite direction. This division is needed because of the one-way character of most of the streets in Barcelona. This characteristic forces the vehicle to turn at different spots depending on the direction that it's following.

For validation purposes, only the path followed from the city center towards the city border will be considered. This path has currently 17 stops throughout a 5,8km length.

The current average total time to travel from the origin (*Plaça Catalunya*) to the destination (*Plaça del Nou*) is 31,6 minutes, although this value is modified during the day, along with the vehicle speed. *Figure 19* shows this time flow over the day.

The validation process will focus on the time spent to travel from the origin to the destination. The parameters used for the model will be applied and an average total traveling time will be found and compared to the real one.

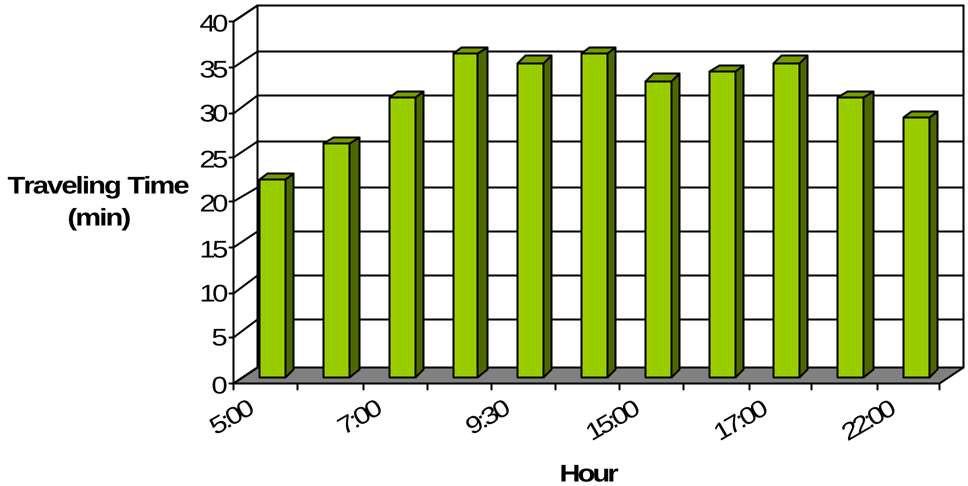

Figure 19. Traveling Time over the day.
Source: TMB 2004.

The total traveling time was estimated by building the different time consuming parts of a trip: in-vehicle time, dwell time and traffic signal delays.

The in-vehicle time was calculated as a composition of the time spent from stop to stop. This was done in order to take into consideration the time spent for accelerating and decelerating the vehicle. The vehicle acceleration was assumed to be 1,2 m/s^2, for both acceleration and deceleration. For every pair of stops, it was needed to calculate the time spent to accelerate from 0 km/h to 50 km/h, the time spent at cruise speed (assumed 50 km/h), and the time spent to decelerate from 50 km/h to 0. Some stops were too close to even reach the top speed, and so the time needed to go from one to the other was completely spent on acceleration and deceleration. An average delay of 7s, or clearance time, was added to the in-vehicle time for each pair of stops on account of the delays caused by resetting the vehicle ready to move and re-entering the street.

Dwell time comprises the time needed for passengers to board and alight the vehicle. As listed in the *Transit Capacity and Quality of Service Manual*, there are several approximations for quantifying the time spent for each boarding or alighting passenger, depending on factors such as the fare card type or the number of available doors on the vehicle. Taking the most adequate values for the specific characteristics in route number 9, the average time spent per passenger on dwell time would be 3,2 seconds. It is important to remember that it is an approximate value, and that it can vary within the range of 2,0 and 3,6 seconds. For instance, Robusté (1994) estimates it as 2,0 seconds for alighting passengers, and 2,4 seconds for boarding passengers.

To calculate the number of passengers per bus stop that would board or alight the vehicle, an estimate of the passenger distribution over the stops was made. The route's path was subdivided in three parts and it was assumed that 50% would board on the first part, 40% would board on the second, and the remaining 10% would board on the final part of the path. Similarly, the first part of the path would concentrate the 20% of alighting passengers, the mid part would have 50%, and the final part would have the remaining 30% of the passengers. These volumes of passengers were evenly distributed between the bus stops that formed the three parts of the path, and so every bus stop was assigned a certain number of boarding and alighting passengers, given the demand in terms of passengers per hour and the vehicle frequency.

To calculate the time lost at traffic signals there are different approaches and recommendations. For instance, the TCRP – Report 100 (2003) recommends a value of about 2 minutes per kilometer of route. Since route number 9 has about 5,8 km of length, the time lost at traffic signals would sum up to about 11,6 minutes. Another approach is the one suggested by Saka (2001), who determines the delay attributed to traffic signals as

$$T_{tl} = \left\{ \left(\frac{T_v}{C} \right) \cdot T_v \right\} \cdot n \qquad \text{(a)}$$

Where:

T_{tl}= Time lost at traffic lights

C= average traffic light cycle time

T_v= average red light time

n= number of intersections

In this case, the delay caused to route number 9 would be a 12 minute delay, which will be the one used for this simulation.

The values for the traffic lights cycle times were collected on the field, as well as the number of intersections. The estimate of alighting and boarding passengers over the stops is also a variable based in values collected from the field.

The values for the vehicle frequency and the demand were taken from the adopted values for the model. That is to say, a vehicle frequency of 8.5 vehicles/hour and a demand value of 500 passengers/km^2 (or 400 passengers/hour).

Entering all these data, the average total travel time results in almost 28 minutes, which is practically the same as what the real bus route takes to cover the run (31,6 minutes on average). Therefore, the model can be validated and can be considered accurate enough to represent the bus network.

The next step is to introduce the values for the parameters that were obtained by the model after the optimization was completed. In this case, we will use the results obtained in Scenario 2, where the line spacing is fixed so that bus routes are not redesigned.

The new values to input in the bus route start with stop distance: a new set of bus stops is created over the length of the route, with a standard spacing distance of 500m. In this case, only 10 bus stops are needed (the stop spacing for the last two stops will not be 500m but the difference between the route's total length and the length covered by the previous stops). The demand level remains the same, so as to follow the same assumption than in the analytical model, but the vehicle frequency changes to the new value, 12 vehicles per hour.

With these new values, the total traveling time is reduced to 23,6 minutes, or a reduction of over 3 minutes of time. *Figure 20* thru *Figure 23* illustrate the comparison between the original values and the optimized values.

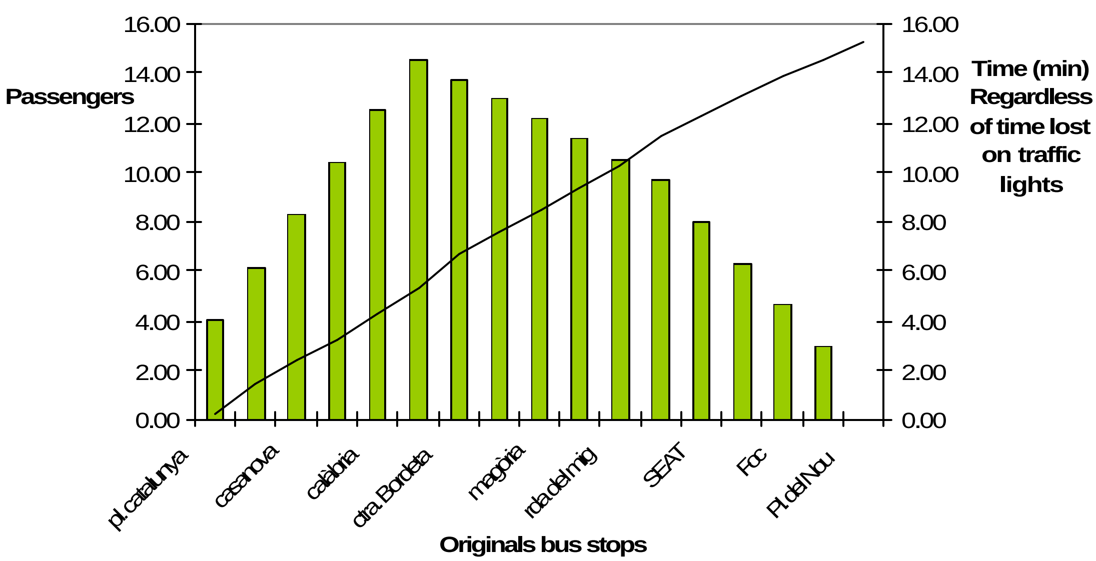

Figure 20. Original configuration of bus stops, passenger occupation and total time.

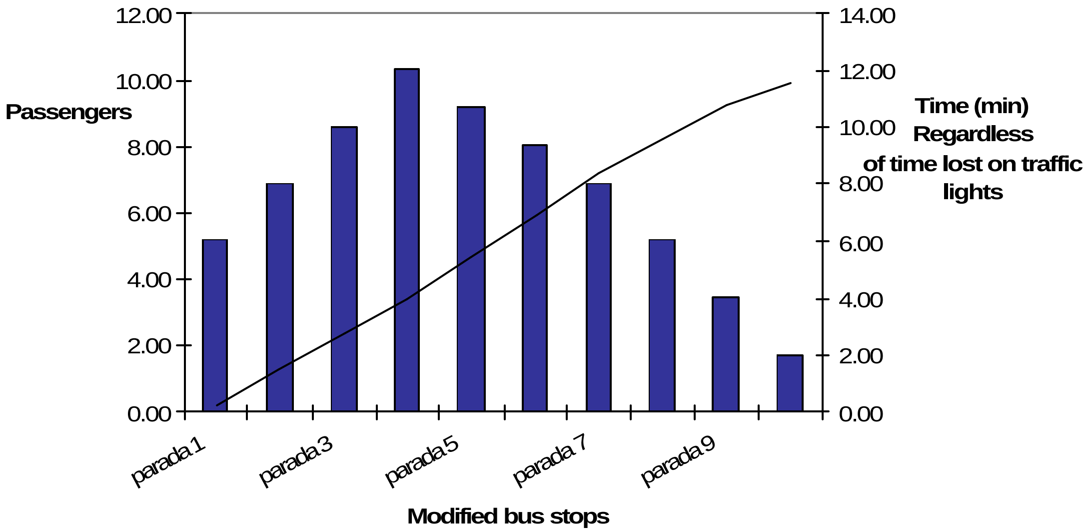

Figure 21. Modified bus stops, passenger occupation and total travel time.

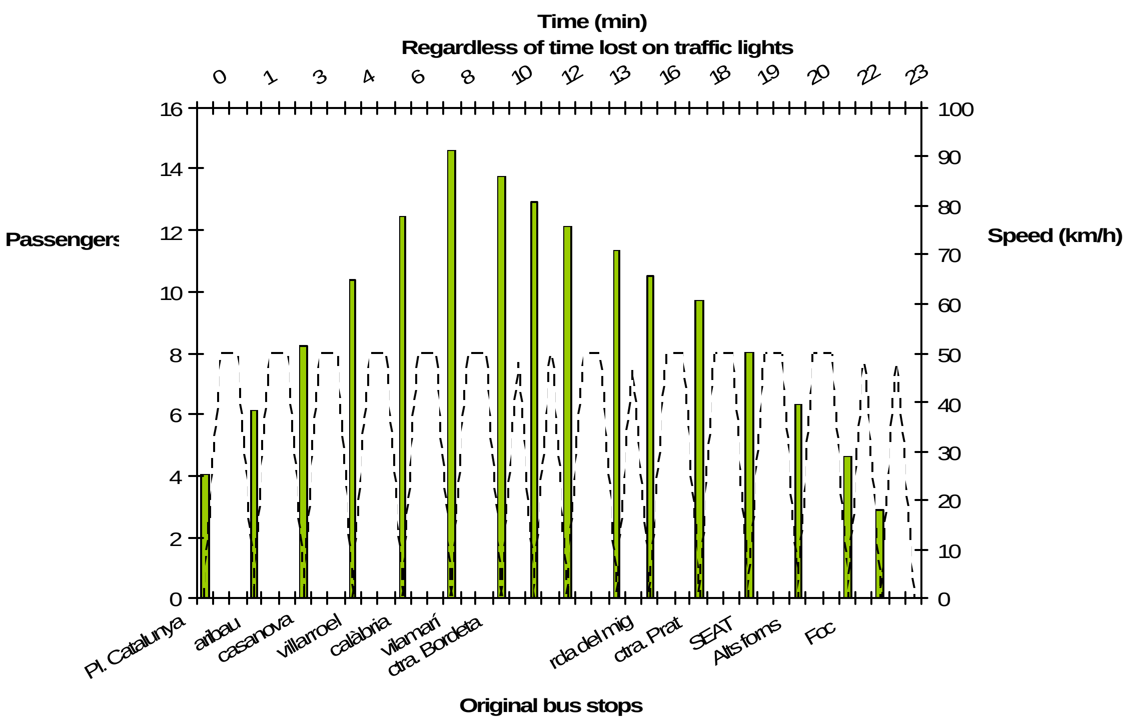

Figure 22. Original bus stops, passenger occupation and vehicle speed.

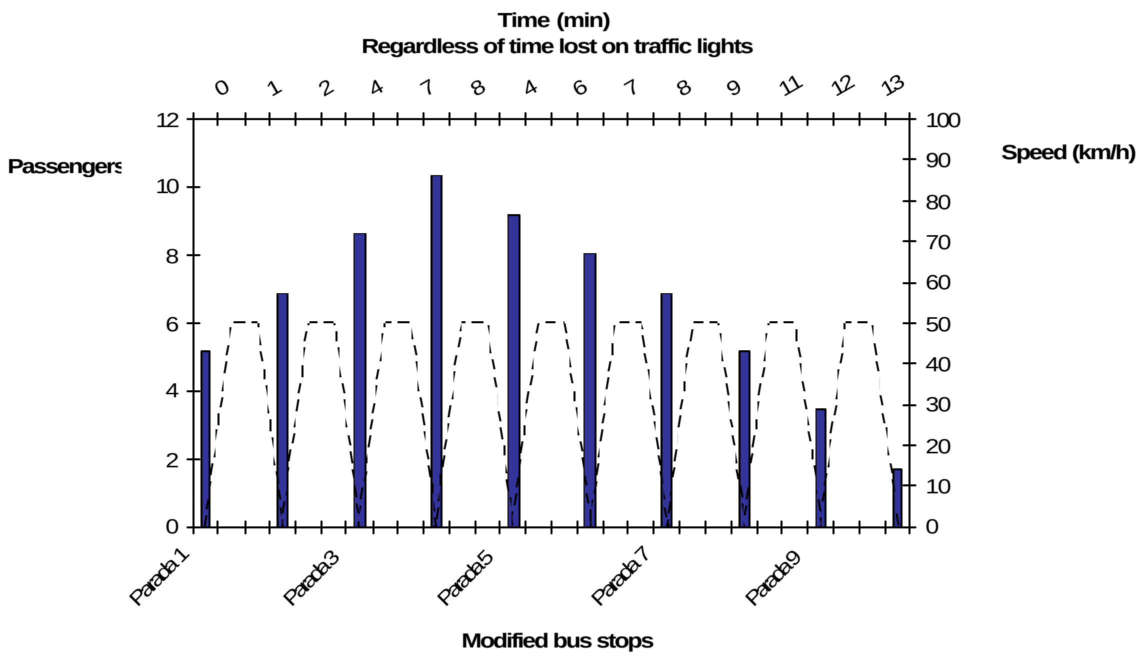

Figure 23. Modified bus stops, passenger occupation and vehicle speed.

This analysis shows that by implementing the optimized values in route number 9's configuration, there would be a total time saving of over 3 minutes. These 3 minutes can be valued in terms of currency, and they would suppose 0,61€ for each run. Considering that there would be 12 runs in an hour and that the demand would still be 400 passengers per hour, the total savings would sum up to over 3.000 €/h, or over 50.000 €/day. However, the savings would not be as high as it seems if we took into consideration the extra access time cost for the users that the new stop spacing would imply.

Nevertheless, it is an interesting improvement to consider, although there are also several remarks that need to be mentioned before deciding weather this improvement is worth it or not. In the following chapters some measures for implementing this new configuration will be proposed and analyzed in terms of viability. The concluding remarks and recommendations will give a final overview on the applicability of the model.