# OPTIMIZACIÓN DE LA REGULACIÓN SEMAFÓRICA EN LA ZONA DEL 22@ DE BARCELONA

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## ABSTRACT

Barcelona SUMP (Sustainable Urban Mobility Plan) for the 2013-2018 period included a set of measures to stimulate the change to more sustainable transportation modes, among which traffic signal configuration based on bus frequencies can be found. This document describes the pilot case implemented in the 22@ area of the city.

The approach consists of the development of a mobility simulation model including different transportation modes, relying on the commercial software Aimsun and integrating *ad-hoc* components, having a tool supporting decision-making as a result.

During the first stage of the project, a microscopic simulation model was built, including all details of the infrastructure concerning the road network (lane configuration, traffic signaling, driving constraints…), traffic light configuration and interface with input data from the City Council, public transport surface network and private vehicle demand.

Together with the model, an optimizer component implementing specific constraints to ensure a safety, efficient, sustainable mobility was developed. In this way, the resulting tool generates an optimal configuration for traffic lights that can be used for traffic management purposes, giving priority to the bus network with no relevant penalties for the private vehicle and, of course, guaranteeing safety for pedestrians.

A relevant improvement of the bus service has been obtained for the three considered scenarios, achieving an increase of the speed between 13% and 25% (average for all lines).

As expected, both travel time and the number of stops have been reduced, which results on a better level of service as the users directly perceive these two factors.

## 1. BACKGROUND

The Barcelona City Council continuously performs adjustments in the traffic lights configuration at local level, either because modifications of the civil infrastructure or for adapting them to new traffic conditions.

However, measures that may have an impact beyond a specific location or on more than one transportation mode require certain mechanisms for a previous assessment from the mobility point of view.

Barcelona SUMP (Sustainable Urban Mobility Plan) for the 2013-2018 period fosters the use of advanced tools in order to improve the implementation of proposed measures, from the inception and design to the deployment and maintenance, if necessary.

In that context, local authorities identified the necessity of having a flexible enough software allowing both assessment about the real impact in the whole city but also having means to test innovative mobility measures such as the ones this paper focuses on, increase of the bus network performance while preserving safety for the people in the pedestrian's crosses.

Optimizing traffic lights settings is a well-known problem in traffic engineering and minimizing the sum of delays the most common objective. For example, for the particular case of a two-stage traffic signal, the first analytical solution can be found in Webster (1958) but many other approaches appeared from these years on, addressing both fixed-time and adaptive control.

Adaptive models are based on dynamic phase changing defined by traffic flow fluctuations detected by means of real-time sensors, forecasted from historical data or combining both as shown in Mirchandani (2001).

These models can also add stochastic parameters in terms of uncertainty for inflow or outflow at intersections as described in Tong (2015).

On the other hand, fixed-time systems are based on deterministic values for the cycle and green times that have been previously calculated for specific time intervals and day types, which is the operating mode in the case of the city of Barcelona since regular patterns exist.

In these situations, dealing with signal coordination (offsets) is a key factor to provide required performance for a certain transportation mode, such as buses.

How the concept of the offset can provide support to coordinate and synchronize a network can be found in Gartner (1975) and later evolved by Möhring (2006) where non-uniform cycle lengths are also introduced.

Next sections describe the mathematical approach to tackle the problem of prioritizing public transport against private vehicle in the study area, where the bus network is composed of horizontal and vertical lines creating a grid with shared intersections which add a degree of complexity.

## 2. MATHEMATICAL APPROACH

### 2.1 Delay at signalized intersections

Over the last decades, several models have been developed to estimate vehicle delay at signalized intersections. One of the first expressions was made by Wardrop (1952) assuming that the arrival flow rate was uniform, leading to a very simple formula (1):

$$d = \frac{\left(r - \frac{1}{2s}\right)^2}{2c(1-f)} \tag{1}$$

Where,

$d$ = average delay per vehicle
$r$ = effective red time
$s$ = saturation flow
$c$ = cycle length
$f$ = traffic flow

Afterwards, a few models appeared by Newell (1956), Webster (1958) or Miller (1968), who developed new expressions where the uniform arrival hypothesis were no longer used.

The model proposed by Webster assumes that arrivals are random but with a uniform departure flow. It offers a better approach on the delay calculation for low traffic intersections (intersections with high intensity usually tend to an exponential behavior when it comes to arrivals). Webster expression (2) is as follows:

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda X)} + \frac{X^2}{2f(1-X)} - 0.65\left(\frac{c}{f^2}\right)^{1/3} X^{2+5X} \tag{2}$$

Where,

$d$ = average delay per vehicle
$\lambda$ = green ratio

$X$ = degree of saturation
$c$ = cycle length
$f$ = traffic flow

The first term corresponds to the delay due to uniform arrival flow, which is equivalent to Wardrop expression (1). The second term is the delay caused by the random arrival assumption. Finally, Webster added a third empirical term as a tuning to the formulation.

Miller solved the delay calculation with a different approach; in this case, he focused on the overflow delay. In most cases, the excessive delay at intersections are due to a peak in the arrival flow. Miller took into account the average number of vehicles missing a traffic light cycle. The first term of the expression (3) is the delay due to a uniform flow rate. The second term express the average delay when there are vehicles left in the queue when red phase starts.

$$d = \frac{c(1-\lambda)}{2(1-\lambda X)}\left(c(1-\lambda) + \frac{(2X-1)I}{q(1-X)} + \frac{I+\lambda-1}{s}\right) \quad (3)$$

Where,

$d$ = average delay per vehicle
λ = green ratio
$X$ = degree of saturation
$c$ = cycle length
$f$ = traffic flow
$I$ = variance to mean ratio of flow per cycle

Newell, on the other hand, focused on the distribution arrival at the intersection. He studied general arrival and departure distributions for delay models at signalized intersections. He expressed (4) that the average delay experienced by a vehicles is as follows:

$$d = \frac{c(1-\lambda)^2}{2(1-y)} + \frac{IH(y)X}{2f(1-x)} \quad (4a)$$

$$y = \frac{sg-qc^{0.5}}{Isg} \quad (4b)$$

Where,

$d$ = average delay per vehicle
λ = green ratio
$X$ = degree of saturation
$c$ = cycle length

$f$ = traffic flow
$I$ = variance to mean ratio of flow per cycle
$y$ = flow ratio

Due to the difficulty obtaining some of the variables that define the arrival flow variance, various institutions started to develop simpler expressions based on empirical experimentation. One of the best known is the High Capacity Manual, which proposed a first equation in 1985 that was improved later by Reilly (1994) with this expression (5):

$$d = 0.38 \frac{C(1-\lambda)^2}{1-\lambda[Min(X,1)]} + 173x^2 \left[(X-1) + \sqrt{(X-1) + \frac{mX}{C}}\right] \tag{5}$$

Where,

$d$ = average delay per vehicle
λ = green ratio
$X$ = degree of saturation
$c$ = cycle length
$C$ = capacity
$m$ = calibration term representing the effect of arrivals type

The utilization of a minimum term is due the fact that it is considered that oversaturated intersections have infinite delay (no estimation when $X$ > 1).

**2.2 Offset coordination**

The formulation proposed regarding offsets is based on the paper written by Estrada (2009). There, authors proposed a reduction of travel time for several bus lines by means of offset modifications. To do so, they stablishes an expression (6) in function of the offset to be minimized, including the sum of the following three terms concerning buses:

- *Travel time in links*: average time to travel from one signalized intersection to another without taking into account the time a bus spends at stops.
- *Time lost at stops*: time spent at stops due to the passengers entering or leaving. It also includes the time lost due to acceleration and deceleration during maneuver.
- *Time lost at intersections*: time spent during red phase. Same as before, the acceleration and deceleration times are included.

Since travel time and time lost at intersections will be obtained by means of a simulation model, they will not be further developed from the theoretical point of view. On the other hand, the formulation developed by Estrada will be used further as a starting point to estimate the delay in links.

The evaluation of the total amount of time that a bus is stopped at intersections is a function (6) of the cycle time, green time and signal offset. To evaluate the intersection time, it requires determining the number of signal cycles that had passed since a bus arrives, by referencing the arrival to the signal cycle.

$$n_s = [\frac{t_{av} - theta}{T_c}] \tag{6a}$$

$$s = t_{av} - n_s T_c - theta \tag{6b}$$

Where,

$s$ = arrival time referred to signal cycle
$t_{av}$ = arrival time
$theta$ = offset referred to previous intersection
$T_c$ = cycle length
$n_s$ = number of cycles

Once the arrival times is referenced, it can be then determined if the bus will pass (green phase) or stop (red phase). Therefore, the expected delay in the link will be as detailed in expression (7):

$$t_{in} = \begin{cases} T_c - s & if \quad s > g \\ -s & if \quad s < 0 \\ 0 & if \quad 0 \leq s \leq g \end{cases} \tag{7}$$

Where,

$t_{in}$ = time stop at the intersection
$s$ = arrival time refereed to signal cycle
$g$ = start of the green signal

## 3. METHODOLOGY

Proposed methodology envisages an underlying traffic simulation model since even unable to generate a solution by themselves, simulation models are useful as a tool for the analysis of a system and its behavior under certain conditions. Aimsun is used as the simulation environment.

For each simulation, inputs can be changed manually after analyzing the outputs of the previous one. Nevertheless, as the number of parameters or size of the model grow, this process becomes as inefficient as it is inappropriate. Then, the need for a custom component giving support to the optimization process raises.

This component must implement an import and export interface with the model together with analysis capabilities through an *ad-hoc* algorithm that runs in the context of a loop process until a suitable solution is found.

As shown in Figure 1, the initial step of the iterative process is the model simulation and the corresponding export of information about the behavior of private vehicles and tracking of buses to a custom database.

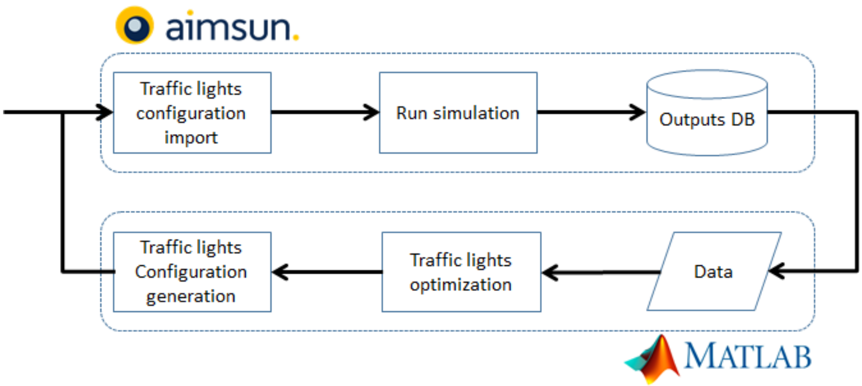


**Fig. 1 – Optimization loop process**

Then, simulation outputs are read by a component developed in Matlab, where optimization takes place in two sequential stages, deeply explained in next section:

- *Phases*: calculation of the available green time for each of the different existing phases in such a way that vehicles have the least delay possible while satisfying safety constraints for both vehicles and pedestrians as requested by the City Council.
- *Offsets:* calculation of optimal offsets between consecutive traffic lights to improve the performance of the bus network by means of generation of green waves considering stop and travel times.

## 4. OPTIMIZATION

### 4.1 Phases

This stage has two objectives: the extension of green windows for buses and the reduction of delay time for private vehicles at the rest of intersections. The following steps are taken to achieve the objectives this stage aims at:

1. A mathematical formulation gets the optimal starting time and duration of green phases for each signal group at every intersection in such a way that safety structure of the junction is preserved.

2. Definition of the optimization variable (e.g. delay time) respect to decision variables, in this case the phases. That way, it is possible to find a combination of phases that minimizes the optimized variables for each intersection.
3. Definition of the boundary conditions of the problem which are obtained from the constraints: crossing time for pedestrians, minimum duration of phases and intersection saturation.

**4.1.1 Structure of traffic lights**

In traffic lights, start and end of the green time for each signal is defined by its structure in addition to the existing phases and the definition of programs and control plans.

- *Phases*: As they are the time intervals that compose a cycle, the sum of their durations must be equal to the cycle to preserve the structure. Each phase is composed of sub phases that may have variable length (susceptible to be optimized) or fixed (for example, there are phases that, for safety reasons, are red for all signal groups, lasting 3 s or 6 s.).


**Fig. 2 – Example of phases for each signal group of an intersection**

Figure 2 shows an example in terms of a bar chart. The intersection has 3 signals (G1V, G2V and G3V) and 3 phases (A, D and H). Each phase is also divided in sub phases; for example, phase D also includes sub phases e, f and g.

- *Programs*: they define combinations of duration for each phase and the corresponding offset, which is used for synchronization with other intersection. Table 1 defines 4 programs, from P1 to P4 (values in bold face are used in Expression (8)).

| Programs | | | A | b | c | D | e | f | g | H | i | j |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | # | **3.0** | **3.0** | # | **3.0** | **3.0** | **3.0** | # | **3.0** | **3.0** |
| Plan | Cycle | Offset | | | | | | | | | | |
| P1 | 96 | 94 | **40.0** | | | **30.0** | | | | **26.0** | | |
| P2 | 96 | 53 | 41.0 | | | 27.0 | | | | 28.0 | | |
| P3 | 96 | 56 | 47.0 | | | 27.0 | | | | 22.0 | | |
| P4 | 72 | 12 | 32.0 | | | 27.0 | | | | 18.0 | | |

**Table 1 – Example of signal programs of an intersection**

- *Control plan*: hourly and daily distribution of the programs, which is used to synchronize groups of intersections into specific areas. Table 2 shows an example where P1 is the active program during the morning, P4 is reserved for some nights and both P2 and P3 are used during the rest of the time.

| Time | Mon. | Tues. | Wed. | Thurs. | Fri. | Sat. | Sun. |
|---|---|---|---|---|---|---|---|
| 2:30 | | | | | | P4 | P4 |
| 6:30 | P1 | P1 | P1 | P1 | P1 | | |
| 10:30 | P2 | P2 | P2 | P2 | P2 | | |
| 17:00 | P3 | P3 | P3 | P3 | P3 | P3 | |
| 21:30 | P2 | P2 | P2 | P2 | P2 | P2 | |
| 23:00 | | | | P4 | P4 | | P4 |

**Table 2 – Example of a control plan (some time intervals are omitted)**

Since the optimization works by changing the duration of the phases from the green perspective, it is necessary to define the existing relationship.

In expression 8, matrix A contains information about states (green or red) for each phase (columns) and, for each turn (rows). The vector $\vec{p}$ contains the total phase duration and the vector $\vec{f}$ contains the fixed part of the phase. The difference between vectors is the variable duration of the phase, which multiplied with the matrix A gives the variable green duration as a result, for each turn $\vec{g}_{var}$.

$$A \cdot \left(\vec{p} - \vec{f}\right) = \vec{g}_{var} \qquad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \cdot \left( \begin{bmatrix} 40 \\ 30 \\ 26 \end{bmatrix} - \begin{bmatrix} 6 \\ 9 \\ 6 \end{bmatrix} \right) = \begin{bmatrix} 34 \\ 21 \\ 41 \end{bmatrix} \tag{8}$$

The next step is to process the fixed sub phases, which are sub divided into small intervals supporting transition and coordination between phases. To get the green time it is necessary to add the existing green length in these intervals, $\vec{g}_{ctt}$, to the variable green duration as shown in Expression (9):

$$\vec{g} = \vec{g}_{var} + \vec{g}_{ctt} \quad \begin{bmatrix} 34 \\ 21 \\ 41 \end{bmatrix} + \begin{bmatrix} 0 \\ 6 \\ 9 \end{bmatrix} = \begin{bmatrix} 34 \\ 27 \\ 50 \end{bmatrix} \tag{9}$$

### 4.1.2 Formulation

There are three different formulations depending on the degree of saturation of the intersection. For example, since it is assumed that the delay is infinite when the intersection is saturated, the formulation aims at reducing queues in those cases.

Figure 3 shows depicts diagram showing the decisions taken during the optimization process in terms of which is the specific objective in function of the degree of saturation.

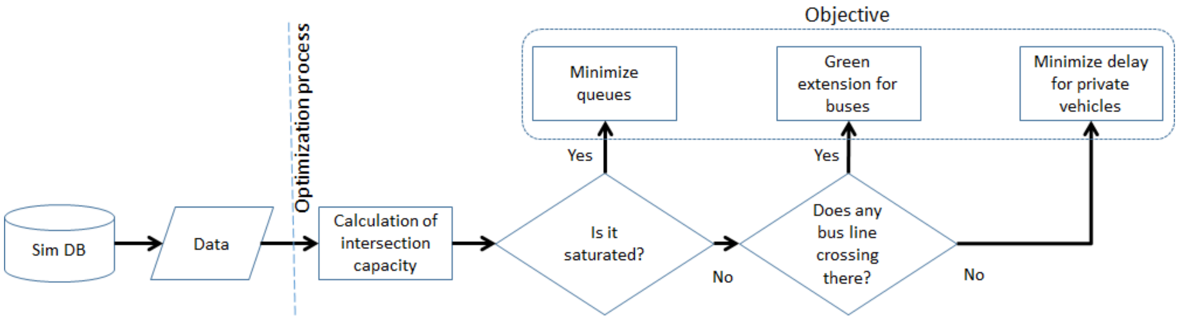


**Fig. 3 – Decision diagram during the optimization process**

- *Degree of saturation:* indicates the state of an intersection based on the capacity of the turns and the incoming flow. Given a turn, if traffic flow exceeds its specific threshold, then the intersection is not able to process all vehicles, resulting on the generation of queues. In those cases, there are two consequences: vehicles miss, at least, a cycle and queues being generated can eventually stuck adjacent intersections.

  The degree of saturation, as expressed in (10), is the ratio between number of vehicles arriving to the interaction and maximum number of vehicles that can be processed during one cycle. If the value is greater than one the intersection is oversaturated.

$$X = \frac{f \cdot c}{s \cdot g} \tag{10}$$

Where,

$X$ = degree of saturation
$f$ = traffic flow
$c$ = cycle length
$s$ = saturation flow
$g$ = effective green time

- *Delay time of non-saturated intersections:* In these cases, the High Capacity Manual formulation, as expressed in (11), is used:

$$d = \frac{f \cdot 0.5 \cdot c^2 \cdot \left(1 - \frac{g}{c}\right)^2}{1 - \left(X \cdot \frac{g}{c}\right)} \tag{11}$$

Where,

$d$ = delay time
$X$ = degree of saturation
$f$ = traffic flow
$c$ = cycle length
$g$ = effective green time

- *Over-saturated intersections:* The objective here is not to minimize the delay time but to optimize the queue distribution to reduce the impact on adjacent intersections. First, queue growth rate per cycle is obtained by calculating vehicles that miss a cycle divided by the cycle duration, as detailed in (12).

$$Q = \frac{q \cdot c - s \cdot g}{c} \tag{12}$$

Where,

$Q$ = queue growth rate
$q$ = traffic flow
$c$ = cycle length
$s$ = saturation flow
$g$ = effective green time

Since an intersection can have multiple turns, the growth rate is calculated in a per turn basis. The first turn that collapses determines the so-called obstruction time. The algorithm optimizes the obstruction time using the expression (13).

$$U_i = \frac{C_i}{Q_i} \rightarrow U_{min}(\vec{g}) = \min(U_1, \ldots, U_i) \tag{13}$$

Where,

$U$ = lane obstruction time
$Q$ = queue growth rate
$C$ = capacity

- *Green extension:* For cases where a bus line circulates, an adjustment of the green phase is used to prioritize public transport. To be more specific, the duration is increased just for signals the buses cross along (degree of saturation calculated for each signal group) using expression (14). A safety factor is added to take into account potential fluctuations in the arrival flow. Finally, the green extension is configured considering the minimum green times already calculated.

$$G = \lambda \cdot \frac{f \cdot c}{s} \quad (14)$$

Where,

$G$ = minimum green duration
$\lambda$ = safety factor
$q$ = traffic flow
$c$ = cycle length
$s$ = saturation flow

### 4.2 Offsets

The main objective when optimizing offsets is the improvement of the bus network service. This network layout was designed as a grid where users can easily transfer from vertical to horizontal lines as needed. This ease of use, however, becomes a drawback from a whole perspective because the vertical lines limit improvements in horizontal lines (and vice versa) since there are shared intersections.

In this case, the objective function does not come out of a formulation, but from the simulation model results. Input variables are the offsets of the intersections and the commercial speed is the decision variable. Therefore, the process consists of varying these variables to maximize the commercial speed.

#### 4.2.1 The problem

First, what must be taken into account is the size of the problem to solve. In the study area, there are more than 150 intersections (with their dependencies), which is a relevant number of variables. At the same time, travel times depend on the offsets, establishing an additional dependency.

Given these characteristics, the application of conventional optimization methods such as Newton's method is not feasible. Computationally speaking, the calculation time for a matrix of 150 variables is not a handicap. However, as it has so many variables, it is very likely that Newton's method ends up after finding a local optimum of the problem, which may be very far from the global optimum.

### 4.2.2 Heuristic method

As a consequence of the abovementioned, a heuristic method (a genetic algorithm, to be more specific) is used, which does not ensure finding an optimal solution but very close to and being a global optimum, which better fits with such a complex problem. An additional advantage is that heuristic methods require lower computational time, which is a very interesting feature for iterative algorithms.

### 4.2.3 Hybrid modelling

Since a large number of generations are needed for a genetic algorithm to work properly, and for each generation, to simulate many times (one per individual) a drawback arises because each simulation lasts about 40 minutes.

To tackle with that, the methodology includes a simplified mathematical model where the genetic algorithm is applied, which results on a slight loss of accuracy but also on a significant reduction of computing time.

Thus, a hybrid approach is finally used. Every time a solution is found in the mathematical model, it is simulated to get certain parameters (time at stops and speed), which will feedback again the mathematical model. This iterative process stops when a kind of convergence is reached.

### 4.2.4 Mathematical model

It models the trajectory of a bus taking into account the travel time between nodes and the time a bus is stopped (stops or traffic lights). The latter will depend on the offsets while the other parameters are static during the optimization process and only change after each iteration.

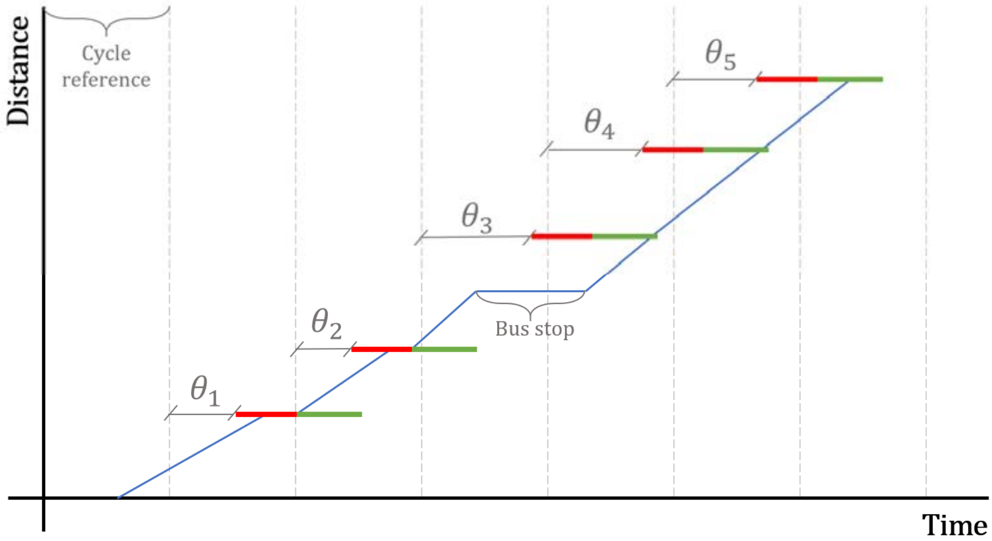


**Fig. 4 – Graphical representation of the mathematical model bus trajectory**

The model calculates the time that the bus stops (see Figure 4) for all traffic lights based on the offset configured and parameters coming from the simulation. The mathematical model could be understood again as a function to be optimized, where the input variables are the offsets and the output is the travel time as shown in expression (15):

$$t_1 = f_1(\theta_1, \ldots, \theta_n) \tag{15}$$

As previously mentioned, the bus network is composed of $m$ corridors that must optimized as a whole. As a consequence, the function to be optimized will not only minimize the travel time of a corridor but the sum of all of them as detailed in (16) where some variables are shared between components of the sum, representing the dependencies.

$$T = t_1 + \cdots + t_m = f_1(\theta_1, \theta_2, \ldots, \theta_n) + f_2(\theta_2, \theta_3, \ldots, \theta_n) + \cdots + f_m(\theta_3, \theta_4 \ldots, \theta_n) \tag{16}$$

## 5. CASE STUDY

Figure 5 highlights the area of the city of Barcelona where the study is located. There are many reasons why this area was selected, remarking the following as the most relevant:

- It represents a logical extension of an existing model to which is geographically adjacent and therefore, focusing to a future model of the whole city.
- Includes a comprehensive representation of surface transportation network, where traffic lights have an impact.
- Testing new methodologies and algorithms in a reduced scope before their application to a wide are is always a best practice.

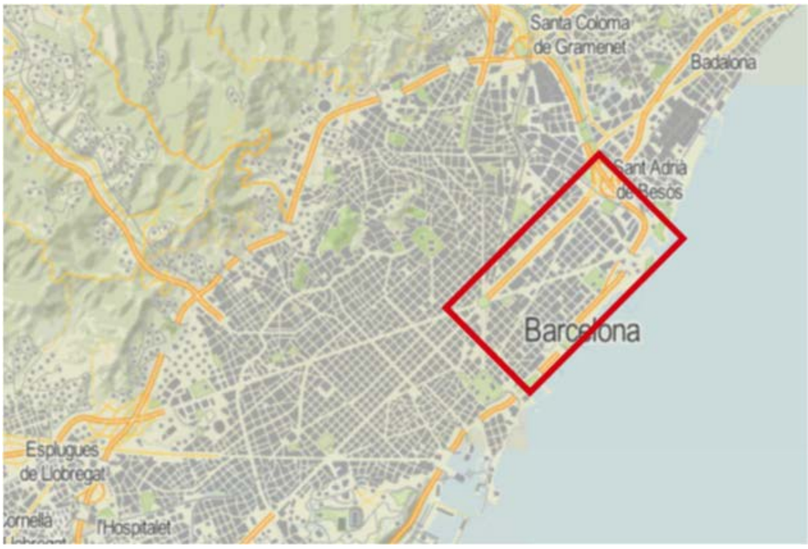


**Fig. 5 – Selected area for the case study**

### 5.1 GTFS import

Bus service is configured in the simulation model by means of real schedules included in the official GTFS-compliant files coming from the operators. *General Transit Feed Specification* defines a common format for public transportation schedules and their associated geographic information.

Aimsun has a built-in feature to import GTFS files, which unfortunately, is not totally free from some errors.

To speed up this process and to ease the detection of bugs, some mechanisms developed in python language for both pre-processing (selection of relevant services) and post-processing (completion of missing data).

### 5.1 Origin-Destination matrix calibration

Private traffic demand is configured by means of an OD matrix provided by the City Council.

To be more specific, the matrix was processed to get hourly matrices for the case study area since it was a daily matrix for all the Metropolitan Area.

Afterwards, a calibration step is needed to enhance quality by adjusting resulting trips:

- *Calibration tool:* Used together with traffic loop sensors, the software performs traffic assignments based on the OD matrix trying to match simulated flow with detected flow for each detector location (macro level).
- *Route definition:* Since traffic loops do not cover the entire study area, it is necessary to check whether the routes generated by the simulator are coherent or not in order to avoid traffic jams where they really do not exist.
- *Model parameters:* Some additional parameters need to be calibrated to ensure a valid behavior from the microscopic level perspective: aggressiveness, lane changes, the reaction time, etc.

### 5.2 Time intervals

As in most of big cities, traffic behavior in Barcelona depends on the time of day. Therefore, it is important to set the configuration for traffic lights according to the situations identified after analyzing traffic loops in the area. These time intervals define the simulation scenarios: morning and afternoon peaks, off-peak between the two previous and nightly which was finally discarded because of the low traffic and since the bus network changes a lot respect the others.

### 5.3 Other constraints and limitations

The study area and the City Council guidelines impose additional constraints that must be taken into account:

- *Pedestrians*: For each signal group, a minimum green time based on the crossing's length and the average speed of elderly population must be ensured.
- *High traffic and TRAM roads*: Roads with higher flows and included in the path of TRAM lines are already optimized and therefore, they are not included in the optimization process. However, their offsets are taken into account.

## 6. RESULTS

This section shows the main results obtained for three scenarios based on the time intervals for a typical working day. All charts have the same style: two series with values for a total of 30 iterations with bus speed (red color, left axis) and delay for private vehicles (blue color, right axis).

A relevant improvement of the bus service has been obtained for the three scenarios, achieving an increase of the speed between 13% and 25% (average for all lines). As expected, travel time is reduced as well as the number of stops, which means that green light is often found when arriving to traffic lights since commercial stops don not change between iterations.

It is important to remark that the objective was to improve the bus network as a whole not just individually lines. For that reason, although there is a global improvement, several lines can have worst indicators. There is not a fixed pattern for this behavior since it depends on some time dependent parameters resulting on having lines that improve given a scenario while they get worst in other.

### 6.1 Morning peak

In this time interval, modifications in the parameters lead to a significant change in the behavior of private vehicle as shown in Figure 6. Potential traffic jams do not have an impact on the bus because of most of the optimized lines are circulating through reserved lanes.

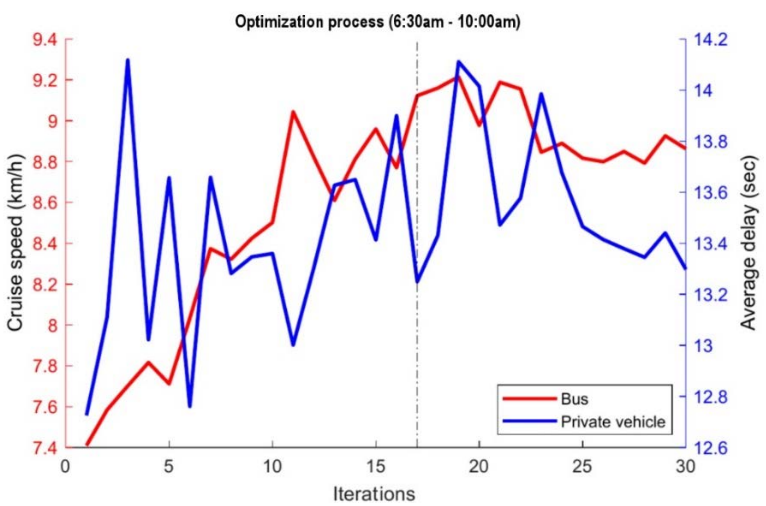


**Fig. 6 – Results obtained: morning peak**

Even private vehicle does not reach to a convergence, bus lines do until iteration 20 approximately. From this point on, bus speed is not improved anymore, thus going further in the optimization process has no sense.

Vertical dotted line remarks the iteration providing the best global performance.

Table 3 shows more details about the results of the simulation for bus lines. The average cruise speed has been increased by a 25,5 %, reducing both travel time and number of stops by 12,9 % and 6,4 % respectively.

| Line | First iteration | | | Best iteration | | | Improvement | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cruise speed (km/h) | Travel time (min) | Num. Stops (#) | Cruise speed (km/h) | Travel time (min) | Num. Stops (#) | Cruise speed (%) | Travel time (%) | Num. Stops (%) |
| H14-0 | 7,4 | 17,7 | 18,4 | 8,3 | 15,8 | 15,9 | 12,2 | -10,4 | -13,5 |
| H14-1 | 6,8 | 19,5 | 19,2 | 11,1 | 13,4 | 17,2 | 62,2 | -31,1 | -10,3 |
| H16-0 | 6,2 | 22,8 | 23,7 | 7,1 | 19,8 | 22,5 | 15,0 | -12,8 | -5,2 |
| H16-1 | 6,9 | 19,3 | 20,4 | 7,3 | 18,2 | 19,8 | 6,2 | -5,5 | -2,8 |
| V21-0 | 7,3 | 15,6 | 15,1 | 9,8 | 12,8 | 16,5 | 33,4 | -17,7 | 8,7 |
| V21-1 | 8,1 | 14,1 | 14,25 | 8 | 14,2 | 13,6 | -1,3 | 1,1 | -4,4 |
| V27-0 | 7 | 18,7 | 19,2 | 8,2 | 16 | 17,3 | 17,2 | -14,3 | -9,8 |
| V27-1 | 5,6 | 20,4 | 19,5 | 10,1 | 13,5 | 15,8 | 79,7 | -33,8 | -18,9 |
| V29-0 | 9,7 | 10,1 | 11,8 | 14,3 | 7,8 | 8,5 | 47,3 | -22,2 | -27,8 |
| V29-1 | 10,3 | 11,6 | 11,2 | 9,2 | 12,2 | 13 | -11,3 | 4,8 | 16,2 |
| H31-0 | 7,7 | 16,6 | 17,92 | 8 | 16,1 | 17,4 | 2,9 | -3,1 | -2,5 |
| H31-1 | 5,3 | 16,6 | 16,58 | 7,5 | 14,9 | 15,4 | 42,4 | -10,2 | -6,6 |
| Mean | 7,41 | 16,9 | 17,3 | 9,1 | 14,6 | 16,1 | **25,5** | **-12,9** | **-6,4** |

**Table 3 – Results obtained: morning peak**

## 6.2 Off peak

Despite its name, traffic flows are relevant for this time interval and are just slightly lower than the peaks before and after. For this scenario, both series reach a stable state simultaneously being iteration number 11 the one that offers the best configuration.

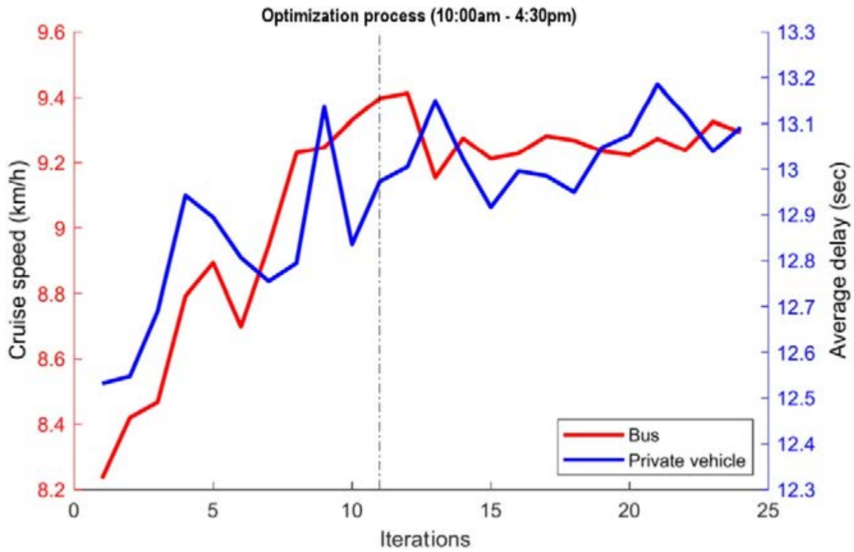


**Fig. 7 – Results obtained: off-peak peak**

Table 4 shows more details about the results of the simulation for bus lines. The average cruise speed has been increased by a 21,2 %, reducing both travel time and number of stops by 14,2 % and 10,8 % respectively.

| Line | First iteration | | | Best iteration | | | Improvement | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cruise speed (km/h) | Travel time (min) | Num. Stops (#) | Cruise speed (km/h) | Travel time (min) | Num. Stops (#) | Cruise speed (%) | Travel time (%) | Num. Stops (%) |
| H14-0 | 9,7 | 21,9 | 23,6 | 10,6 | 20,1 | 19,3 | 9,1% | -8,4 | -18,1 |
| H14-1 | 7,1 | 18,9 | 20,5 | 7,9 | 17 | 18,3 | 11,7% | -10,1 | -10,6 |
| H16-0 | 6,9 | 20,6 | 22,1 | 7,5 | 19 | 21,9 | 8,7% | -8,0 | -0,7 |
| H16-1 | 6,2 | 21,6 | 22 | 7 | 19,1 | 18,5 | 14,3% | -11,7 | -15,9 |
| V21-0 | 8,2 | 14,1 | 14,1 | 9 | 12,9 | 12,7 | 9,1% | -8,4 | -10,0 |
| V21-1 | 8,6 | 13,2 | 14 | 8,4 | 13,5 | 12,1 | -2,1% | 2,2 | -13,7 |
| V27-0 | 9,7 | 21,7 | 22,4 | 11,4 | 18,5 | 20,8 | 17,1% | -14,6 | -7,1 |
| V27-1 | 5,8 | 20,1 | 20,6 | 10,9 | 12,4 | 16,7 | 88,4% | -38,5 | -19,0 |
| V29-0 | 10,1 | 9,8 | 11,7 | 14,6 | 6,8 | 7,1 | 44,7% | -30,0 | -39,3 |
| V29-1 | 11,2 | 15,9 | 16,7 | 13 | 13,7 | 15,2 | 16,4% | -13,7 | -9,0 |
| H31-0 | 8,3 | 15,6 | 15,8 | 8,9 | 14,5 | 15,5 | 7,2% | -7,1 | -2,1 |
| H31-1 | 5,9 | 15 | 16,9 | 7,6 | 11,7 | 19,7 | 29,3% | -22,0 | 16,3 |
| Mean | 8,1 | 17,4 | 18,4 | 9,7 | 14,9 | 16,5 | **21,2%** | **-14,2** | **-10,8** |

**Table 4 – Results obtained: off-peak**

### 6.3 Afternoon peak

Behavior is similar to the peak in the morning but variation of delay for private vehicle along the iterations is not as severe. While buses reach an asymptote, private vehicle has a decreasing trend. The best configuration for traffic lights is found in iteration number 27.

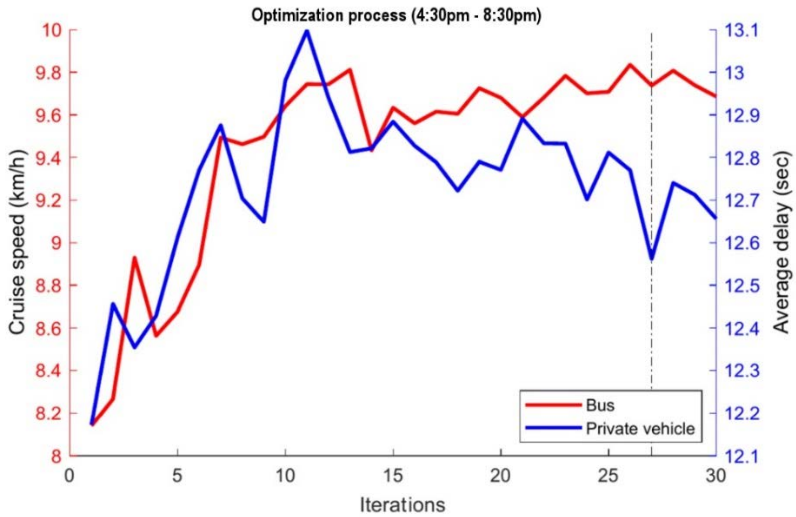


**Fig. 8 – Results obtained: afternoon peak**

Table 5 shows more details about the results of the simulation for bus lines. The average cruise speed has been increased by a 12,9 %, reducing both travel time and number of stops by 9,3 % and 11,3 % respectively.

| Line | First iteration | | | Best iteration | | | Improvement | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cruise speed (km/h) | Travel time (min) | Num. Stops (#) | Cruise speed (km/h) | Travel time (min) | Num. Stops (#) | Cruise speed (%) | Travel time (%) | Num. Stops (%) |
| H14-0 | 10,2 | 20,7 | 22 | 11,6 | 18,2 | 17,8 | 13,9 | -12,0 | -19,0 |
| H14-1 | 7,7 | 17,3 | 18,3 | 8 | 16,7 | 17,8 | 3,3 | -3,4 | -2,7 |
| H16-0 | 6,7 | 21,2 | 21,8 | 7,7 | 18,4 | 21,1 | 15,6 | -13,0 | -3,1 |
| H16-1 | 6,9 | 19,3 | 21 | 9,3 | 15,1 | 17,7 | 34,4 | -21,7 | -15,5 |
| V21-0 | 8,2 | 14 | 16 | 8 | 14,4 | 15 | -3,0 | 2,7 | -6,2 |
| V21-1 | 7,7 | 14,6 | 14,6 | 8,4 | 13,4 | 12,1 | 9,0 | -8,1 | -17,0 |
| V27-0 | 6,9 | 18,9 | 19,7 | 9,7 | 14,5 | 13,3 | 41,1 | -23,0 | -32,6 |
| V27-1 | 8,9 | 20,9 | 21 | 10,2 | 18,3 | 18,6 | 14,6 | -12,3 | -11,2 |
| V29-0 | 9,2 | 10,7 | 13 | 11,8 | 8,3 | 8,7 | 27,6 | -22,1 | -33,1 |
| V29-1 | 10,4 | 11,6 | 12,1 | 10,3 | 11,7 | 12,6 | -0,8 | 1,0 | 4,1 |
| H31-0 | 7,6 | 16,9 | 17,7 | 8 | 16,1 | 17,3 | 4,1 | -4,6 | -2,3 |
| H31-1 | 8 | 17,8 | 20 | 7,6 | 18,6 | 20,6 | -4,3 | 4,5 | 2,9 |
| Mean | 8,2 | 17 | 18,1 | 9,2 | 15,3 | 16,1 | **12,9** | **-9,3** | **-11,3** |

**Table 5 – Results obtained: afternoon peak**

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