Construction and modelling of the mobility matrix in the Metropolitan Area of Barcelona for 2015

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Barcelona, Juny 2016

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Juny 2016
Abstract

Mobility is a social aspect that must always be planned for serving society, while optimizing economic aspects and caring about other such as environmental, visual and noise impact. Then, modelling the mobility is necessary and indispensable for the society development. In the past, the data necessary to do so was obtained from surveys associated to quinquennial census. Nowadays, there are different data set sources, but all them too aggregated to model the mobility.

Autoritat del Transport Metropolità (ATM) obtained disaggregated Origin-Destination matrices per transport mode, which modeled the mobility in the Metropolitan Area of Barcelona in 2010. These matrices show the number of displacement done in a weekday in that year from each origin to each destination (the Metropolitan Area of Barcelona is divided into 582 different zones), and the transport mode used.

From here on, this project has two main purposes, both focused on the mobility in the Metropolitan Area of Barcelona.

First, determining the mobility in the Metropolitan Area of Barcelona in 2015 by updating the ATM matrices. This is done using different data sources like surveys and traffic counts, and so different methodologies.

Second, modelling the mobility. This model is expected to be capable of predicting how mobility will evolve in the near future, in order to serve as a predictor of the consequences that any implementation or change done on the infrastructures or transportation prices could have in the mobility.
Acknowledgements

I would like to put into word my sincere thanks to professors María Isabel Ortego Martínez and Francesc Robusté Antón, my two tutors in this project. They have been really helpful, sharing expertise and valuable guidance, encouraging me all along this work and helping me whenever I needed. Especially remarkable is the patience and time that they have invested on me and this project. Thank you very much for everything.

I also wish to express my sincere thanks to ATM, for trusting me to update their Origin-Destination matrices to 2015. Especially, I would like to thank Francesc Calvet, head of the Planning Service in ATM, for not only trusting me but also for helping me when I needed, providing relevant data, even if it was required for other parts that did not include their matrices updating requirement.

Special thanks to Mcrit, who performed a simulation impossible to be carried out by me and, without which, one part of the project would have not been possible to be performed.

Finally, my deepest thanks to my family and friends, who have been encouraging and supportive, helping and giving me advice when I needed it. And also my more lovely thanks to you, Diana, for always being next to me, even when I had this work in my head all the time and I was in no mood.

Thank you all for making it possible.
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Chapter 1

Introduction

Modelling the mobility, how it has changed and predicting how transportation needs can evolve is necessary and indispensable for the society development. When modelling the mobility, the classical urban transportation planning system model divides it into four steps. These steps are trip generation, trip distribution, modal choice and, finally, route assignment (Garrison, 1960).

It is also commonly accepted that there are two main displacement reasons: occupational and personal. The first one refers to the mobility done due to work or studies, while the second one includes the rest: shopping, leisure, accompaniment... Mobility is a social aspect that must always be planned for serving society, while optimizing economic aspects and caring about other such as environmental, visual and noise impact.

However, the most important aspect is the economic one; each construction done has a cost that goes from millions to billions of euros. Moreover, once these infrastructures are built, it is not possible to either relocate them or recycle the materials used, so they are definitive at least till the end of their service life, which means 100 years. In the last years, it has become usual the number of roadways oversized in capacity that end empty; in train cases, some lines are doing diary trips almost empty. All these cases mean high amounts of money spent with no benefit, that have negative consequences not only in the economic but also in the social aspect.

Society is in constant change, and so does mobility. Then, it is necessary to build new infra-
structures, or change public transport prices, according to all these changes. When planning future changes, like the ones presented, it is all based in, and though for, estimations done previously; in case the predictions done were correct, the economic and/or social benefits of building such expensive infrastructures would make them worth enough to get them ahead. So, the better we become predicting how transportation can evolve, the better and more accurate improvements in infrastructures or changes in some aspects such the public transport prices can be done.

In accordance with these aspects, Autoritat del Transport Metropolità (Metropolitan Transport Authority), abbreviated as ATM, was created in 1997. The purpose of this institution is to articulate the cooperation between the public administrations owners of the public transportation services and infrastructures in the Metropolitan Area of Barcelona (RMB), shown in figure 1.1. ATM is formed 51% by Generalitat de Catalunya and 49% by local governments such as Barcelona council and Àrea Metropolitana de Barcelona (AMB).

![Figure 1.1: Metropolitan Region of Barcelona. Source: www.iermb.uab.es](image-url)
In order to model the mobility in the RMB, ATM has divided it into 582 different zones (ATM zones), which are shown in figure 1.2; it can be appreciated in the figure that some of them fit with town or city areas, while others divide the city into smaller parts (in the case of Barcelona, the city is divided into a bit over 200 zones). In all these zones, the aim is to know the number of generated and attracted trips.

![Metropolitan Region of Barcelona division into 582 ATM zones. Source: author.](image)

To do so, every 5 years ATM models the mobility in a weekday in the Metropolitan Area of Barcelona using disaggregated Origin-Destination matrices, which from now on will be referred as ATM OD matrices. These disaggregated ATM OD matrices consist in three $582 \times 582$ matrices that show the number of trips originated in each ATM zone (rows) and the destination each trip has (columns, one of the 582 ATM zones too), and also the transport mode used. These modes are non-motorized mobility (walking or by bike), public transport mobility (bus and rail, including Metro, FFCC and Renfe) and private vehicle mobility (taxi is included in this category). Then, there are three different disaggregated ATM OD matrices per transport mode, and all them together become the aggregated ATM OD matrix.
Modelling is performed using different sources of information, which include surveys (from the most exhaustive one such the EMO survey till the less ones like the EMEF) and real time data (Management System Integration Fare (SGIT) for rail and traffic counts for road vehicles):

- **EMO survey**: Population is asked about the first occupational displacement done and the transport mode used. Modelling RMB mobility is done assuming occupational displacements as a base in all transportation modes. From this data the disaggregated EMO OD matrices are obtained.

  A few years ago they were answered together with quinquennial census, and that is the reason why they are called EMO (aka Enquesta Mobilitat Obligada). As a consequence, this survey was highly reliable.

  Nowadays, being the EMO survey asked to just a population sample, due to confidentiality, there is the need to group the 582 ATM zones into bigger groups, and so does the EMO matrices, which will be referred as EMO zones and EMO OD matrices respectively. Two different amalgamations are used: 69 EMO zones with at least 20,000 inhabitants each of them (figure 1.3a), and 40 EMO zones with at least 50,000 (figure 1.3b). Then, EMO OD matrices are built, the dimensions of which are $69 \times 69$ and $40 \times 40$ respectively.

- **EMEF survey**: Mobility survey on working day done annually to 5,700 RMB inhabitants that represent the total population. The surveyed one is asked about all travels done the day before, the origins and destinations, the transportation mode,... Finally, all collected data is treated statistically so it represents the total RMB population. It can not model the mobility because data is too aggregated, but it shows the mobility tendency through the years and represents a good complement to the EMO surveys.

- **EMQ survey**: Conceived as a complement of the EMO, it has the objective to know about all the displacements done by the surveyed person on a full day. The survey is done to a member of random families, which must enumerate all the displacements done the day before (origin and destination, reason of displacement and transport mode).
In 2006, the lastest EMQ carried through, was done to a 106,000 people sample.

- **SGIT**: The Management System Integration Fare compiles all public transport tickets
validations in the RMB. Although it can not be known the check out station (except some RENFE stations, public transportation does not required it), it can be assumed the mobility continuity, which means that the second check in station in a day coincides with the first check out; it can be also used in triangular displacements (only if all them are done by rail).

Although being an approximation, it is the most reliable data source (approximately 95%), so the ATM OD rail matrix can be obtained directly from it.

- **Traffic counts**: They are distributed in all RMB highways and roads, and they count the number of vehicle going through the PK point of the road they are located on. Depending on the amount of time they are functioning (and so their reliability), they are classified into permanent, primary, secondary and coverage stations. The recollected data from all the traffic counts in Catalonia is annually compiled in *Pla d’aforaments* by Department of Territory and Sustainability.

- **TransMet Xifres**: General balance of the different public transportation operators working in the Metropolitan Area of Barcelona, such as annual travelers or benefits. Being an overview, it does not dissect the operator per bus or rail lines.

- **Observatori de la mobilitat**: It has the objective of analysing people mobility and goods transportation in the RMB using the most relevant data. The information is completely aggregated.

As an overview of the actual RMB mobility panorama, the latest EMEF survey shows that in 2014 there were almost 4.7 million people living in the RMB. The average number of displacements in a weekday were 17.4 millions, which meant 3.7 displacement per person in a weekday.

The 17.4% of the displacements were occupational, while the 38.3% were personal; the rest 44.3% were home return. Depending on the displacement reason, the percentages of transport mode use differ (figure 1.4). As it was presented at the beginning of the introduction, a good
mobility modelling is mandatory, so a good mobility planning can be done in order to improve the 17.4 millions displacements done every weekday in time and quality.

1.1 Research objectives

After considering all the previous aspects, this work has focused on two objectives: the first, defining the mobility in the Metropolitan Area of Barcelona in 2015 and obtaining the bus and private vehicle ATM OD matrices (this is part of the research contribution of the author to ATM); the second objective, and more ambitious, has been trying to model the mobility in the Metropolitan Area of Barcelona.

The first objective, that is defining the mobility in the Metropolitan Area of Barcelona in 2015 and in which is centered chapter 2, has been done using the disaggregated ATM OD 2010 matrices as base. First, all transport modes ATM 2010 OD matrices have been updated to 2011 using the EMO 2011 OD matrices. Later, only bus and private have been updated from 2011 to 2015 using different methodologies according to their nature: for public transport TransMet Xifres has been used, while for private vehicle the updating has been done using data from selected traffic counts, together with a traffic assignation simulation done by Mcrit and the Spiess method (Spiess, 1990).

The second half of the work, presented in chapter 3, has had the objective of modelling the
Construction and modelling of the mobility matrix in the RMB
Author: Xavier Tomàs i Rodríguez

mobility in the RMB by creating a cost time distribution where the different rents and displacement reasons (in which the cost time depends on) are taken into account. This cost time model has assumed modal choice depends on its price (out-of-pocket) and time. This model is expected to predict how mobility may be in 2020 according to the predicted evolution of trip prices or time and, more importantly, to build a tool or calculator.

The aim of this calculator is to being able to update or correct this 2020 prediction, which may vary due to unpredictability in the estimations on uncertain values evolution such as combustible prices. Along the same lines, this tool could be used by authorities like ATM to assess the consequences that any implementation or change done on the infrastructures or transportation prices could have in the mobility.
Chapter 2

Modelling the transport demand in 2015

When modelling the transport demand, it is common to use old Origin-Destination matrices (OD) that model the disaggregated transportation demand to update them and obtain the new mobility. In the present work these matrices have been the ATM 2010 OD matrices (figure 2.1). The origins are all rows, while the destinations are the columns. For example, the big coloured part that can be appreciated in all modes OD matrices are the trips initiated and ended in Barcelona.

From ATM 2010 OD matrices, using different sources of data, the disaggregated ATM 2015 OD matrices for bus and private vehicle have been obtained. The rail matrix has not been updated due to the optimal and easy way of obtaining data using SGIT (Sistema de Gestió de la Integració Tarifària) as a main data source, which compile all tickets validations from all the different public transportation operators inside the RMB.

As it can be appreciated in figure 2.2, there are two main updating parts: from 2010 to 2011 and from this last one to 2015, the desired one. This division is due to the available data in each period and transport mode.

The first step, which consists in updating the matrices to 2011, is done using the 2011 EMO
(a) Private vehicle trips distribution on 2010 OD matrix.

(b) Bus trips distribution on 2010 OD matrix.

(c) Rail trips distribution on 2010 OD matrix.

(d) Non-motorized mobility trips distribution on 2010 OD matrix.

Figure 2.1: ATM 2010 OD matrices. Source: author.

Figure 2.2: Diagram of the updating process. Source: author.
It has been presented in the introduction that EMO results were organized in two disaggregated OD matrices groups, the dimension of which were 69 × 69 and 40 × 40. As they only contained the first occupational trip, they have been modified by adding the returning displacement, the recurrence factor and the personal trips using EMEF statistical data, being the final matrix symmetric. Once it has been done, it has been possible to obtain the ATM OD matrices 2011.

Once the matrices have been updated to 2011, it has been possible to proceed with the actualization to 2015. Since it does not exist any EMO matrix to this year, a different approximation has been done, using generalized data such as EMEF evolution or more specific like individual buses operators demand variation for bus or traffic counts for private vehicle.

### 2.1 Updating to 2011

The first update, which goes from 2010 to 2011, has been performed using the EMO 2011 OD matrices. In the case of bus transportation, since there is no bus EMO 2011 OD matrix, it has been assumed that the bus growth factor in each zone is equivalent to the public transportation one, which can be calculated using the EMO matrices. Having two different zone amalgamations, which unify the ATM 582 zones into 40 or 69, it has been decided to calculate the growth factors separately and, at the end, weighting the results, obtaining the definitive growth factors.

The first step is to obtain the occupational displacements \((OD_{obl})\) in 2011 from the EMO matrices as done in equation (2.1.1), where \(EMO^{mode}\) is the EMO matrix and \(f_{rec}\) the recurrence factors per origin, the average of which is 1.2, obtained from the EMEF.

\[
OD_{obl}^{mode} = EMO^{mode} \cdot f_{rec}. \tag{2.1.1}
\]

The personal trips are obtained \((OD_{pers})\) using equation (2.1.2) but instead of using \(f_{rec}\) using \(f_{rec,pers}\), which are the recurrence factors of personal trips (again obtained from the EMEF).
Two assumptions have been made: on one hand, the personal trips are assumed to have a relation with the mandatory ones, which may not be an accurate assumption. On the other hand, the personal displacements are assumed to be done inside each EMO zone (due to the fact that people do not do personal trips depending on where they work or study; i.e. $OD_{\text{total \ pers}}$ results in a diagonal matrix.

$$OD_{\text{total \ pers}} = \left( \sum_j EMO_{ij}^{\text{total}} \cdot f_{\text{rec.pers}} \right). \quad (2.1.2)$$

Another difference is the fact that while the individual transportation mode matrices are used for obtaining the obligatory trips in each mode, in the case of personal trips just the EMO matrix that represents the total number of trips has been used. Finally, the occupational displacements in each transportation mode are calculate using the percentages of the different transportation mode use in personal trips ($P(\text{mode})$), again obtained from the EMEF.

$$OD_{\text{pers}}^{\text{mode}} = OD_{\text{total \ pers}} \cdot P(\text{mode}). \quad (2.1.3)$$

Finally, both occupational and personal are added together and the final matrix is symmetrized, as shown in equation (2.1.4).

$$OD_{\text{mode, 2011}} = OD_{\text{obl}}^{\text{mode}} + OD_{\text{obl}}^{\text{mode}}T + 2 \cdot OD_{\text{pers}}^{\text{mode}}. \quad (2.1.4)$$

After adding the occupational displacements and the personal ones, and modifying them so they matched with reality, the growth factors have been determined. The original matrices have been updated with the determined growth factors using the Furness method (Ortúzar and Robusté, 2015); it concludes the updating that goes from 2010 to 2011 using the EMO matrices\(^1\).

In figures 2.3 and 2.4, the growth factor distribution on the OD matrix and the number of trips distribution in 2011 are shown respectively for bus and private vehicle.

\(^1\)All the process is shown accurately in annex A.
2.2 Updating to 2015

As presented at the beginning of the chapter, in order to update the OD matrices from 2011 to 2015 alternative methods needed to be used. There are no more EMO matrices and the EMEF surveys, although being a good complement, are far away from being capable of defining how bus and private vehicle transportation has evolved from 2011 to 2015. In this section, two different approaches have been done for both transportation updates, according to the available data of each transportation mode and its nature.
2.2.1 Bus transportation

After some research in all data available, it was concluded that TransMet Xifres is the only available data set reliable enough to have this function. However, the problem of this information is its simplicity, considering that it only gives the total number of annual trips in the RMB per bus operator, together with irrelevant information for the updating process.

Being not possible to know the internal growth factors in each bus operator (i.e. growth factor per OD pair the bus operator works at), it has been assumed it occurs uniformly in all the bus operator net. Although being an approximation, the fact that bus operators are mainly distributed per zones makes the approximation being not as far from reality as it could be thought.

A previous step has been creating one binary OD matrix for each bus operator \( (c^b) \), with the same zones than the ATM matrix that shows the different OD connections each operator has.

\[
c^b_{ij} = \begin{cases} 
1, & \text{if operator } b \text{ has a bus a connecting zones } i \text{ and } j \\
0, & \text{if operator } b \text{ does not}
\end{cases} \quad (2.2.1)
\]

For doing so, it had to be checked at which ATM zones each bus operator line passed through, and whether there was an stop there or not. With that it has been possible to know the ATM zones that each line connected and, grouping all together per bus operator they were operated by, the binary OD matrices were created. This last step concludes the previous work and the actualization can began.

Some OD pairs present multiple bus operation working simultaneously on them. In these cases, the growth factor was calculated using equation (2.2.2), where the different bus operators growth factor were weighted according to the number of total trips each operator had performed.

\[
C_{bus}^{ij} = \sum_i \sum_j \frac{\sum_b c^b_{ij} \cdot v^'_b}{\sum_b v_b} + \bar{1}, \quad (2.2.2)
\]

where \( c^b \) is the binary matrix of the bus operator \( b \), \( v_b \) the number of trips done by the bus.
operator $b$ in 2011, $v_b'$ the number of trips done by the bus operator $b$ in 2015 and $I$ a $582 \times 582$ matrix of ones.

Finally, the resulting matrix $C_{bus}$ shows the bus use growth factors for each OD pair. By multiplying the number of trips occurred in 2011 per OD pair by their growth factor (2.2.3) the definitive ATM OD matrix for bus has been obtained.

$$\text{ATM}_{2015}^{bus_{ij}} = \sum_i \sum_j C_{bus}^{ij} \cdot \text{ATM}_{2011}^{bus_{ij}}, \quad (2.2.3)$$

In figures 2.5a and 2.5b the growth factor distribution on the OD matrix between 2010 and 2015 and the number of trips distribution in 2015 are shown.

2.2.2 Private vehicle

The private vehicles case differs from the bus case in the fact that there is no direct data source like Transmet Xifres or survey that could be used for updating the private vehicle 2011 ATM OD matrix to 2015. Also, there was the interest of using some source capable of explaining the evolution of such complex transport mode to model. So it has been decided using traffic data to do this function.

The number of private vehicles on roadways is not constant; it oscillates depending on the
mobility in the area, and it follows daily, weekly, monthly and annual cycles. That is the reason why the punctual measurement on a weekday of the traffic going through one roadway can not be assumed to be the Average Annual Daily Traffic (AADT). In order to calculate the AADT, the Departament de Sostenibilitat i Territori, which is the department in charge of its control, has set up traffic counts at specific points, and annually they compile the resulting information from the measurements in Pla d’Aforaments.

There are different types of traffic counts depending on the amount of time they are in function, that are:

- **Permanent station**: It operates 24h per day every day with an automatic hour register. These are the most representative data of the network.

- **Primary station**: It works 24 hours per day during one week in alternated months (which must vary every year); i.e. six weeks per year.

- **Secondary station**: It does operate 24h for two days in alternated months (which must vary every year); i.e. 12 days per year.

- **Coverage station**: It operates a minimum of 24 hours of a weekly day every four years as maximum.

The upper the station gets at the previous list the most reliable data the traffic count has. The traffic count type used in each point is selected according to the reliability required in each highway, that normally depends on the significance of the highway and its use.

Since there is not the 2015 traffic counts data yet, the private vehicle matrix has been updated to 2014 using this method. The updating methodology consists in, by comparing the number of cars going through some of this counted points in both 2011 and 2014, and knowing where these cars came from and where they were going to in 2011 weekdays, to define the variation in OD pair fluxes.

According to it, and due to their different reliability, all permanent and primary traffic counts have been used, and only some secondary and coverage stations have been selected depending
on their location, in order to fill non-covered parts of the highway net by the permanent or primary stations. Finally, 28 permanent stations, 20 primary stations, 7 secondary stations and 14 coverage stations have been used\(^2\); all of them and their counted road can be seen in figure 2.6.

![Figure 2.6: Roads with the used traffic counts. Although the traffic counts only measure in a transversal section (PK), a longer stretch is marked in the figure to make it more visible. As a note, the longest stretches represent multiple traffic counts in a row. Source: author.](image)

**Spiess Method**

There are a few methods for OD matrix estimation using Traffic Data. It is not the goal of this project to explain all the different existent methods; other researches such (Bullejos, 2013) or (Moya, 2013) have already done this part, and the method used in this project has been selected according to their findings. Due to the complexity and size of the highway net, together with the fact that only simple data such the AADT of the selected points is available, it has been decided to use the popular Spiess method (Spiess, 1990).

\(^2\)All traffic counts data used is available in annex B
Spiess method tries to solve the OD matrix estimation problem heuristically using least squared, i.e. minimizing (2.2.4) using the gradient method.

\[ \text{MIN } F(g) = \frac{1}{2} \sum_{a \in \hat{A}} (v(g)_a - \hat{v}_a)^2, \]  

\[ \text{s.t. : } v = \text{assign}(g), \]

\[ \nabla_g F(g) = \sum_{a \in \hat{A}} \frac{\partial v}{\partial g}(g) \cdot (v(g)_a - \hat{v}_a)^2, \]  

where \( g_i \) is the estimated flux for OD pair \( i \), \( v(g)_a \) the estimated AADT at traffic station \( a \) depending on \( g \) and \( \hat{v}_a \) the observed AADT at the same traffic station (in this case in 2014).

In order to solve the Jacobian in equation 2.2.5, Spiess propose supposing it locally constant. Then:

\[ \frac{\partial v_a}{\partial g_i} = \sum_{k \in K_i} p_k \delta_{ak}, \quad i \in I, \]

so,

\[ \nabla_{g_i} F(g) = \sum_{k \in K_i} p_k \sum_{a \in \hat{A}} \delta_{ak} (v(g)_a - \hat{v}_a). \]  

Using equation (2.2.6), the iterative update of \( g \) is done as equation (2.2.7) shows:

\[ g_i^{l+1} = \begin{cases} \hat{g}_i & \text{for } l = 0 \\ g_i^l (1 - \alpha \nabla_{g_i} F(g^l)) & \text{for } l = 1, 2, 3... \end{cases} \]  

where \( \hat{g}_i \) is the seed matrix and \( \alpha \) is the optimal step length, defined in (2.2.8).

\[ \alpha^{opt} = \frac{\sum_{a \in \hat{A}} v'_a (\hat{v}_a - v_a(g))}{\sum_{a \in \hat{A}} (v'_a)^2} \]  

\[ v'_a = -\sum_{i \in I} g_i \left( \sum_{k \in K_i} p_k \sum_{a \in \hat{A}} \delta_{ak} (v(g)_a - \hat{v}_a) \right) \cdot \sum_{k \in K_i} p_k \delta_{ak}, \]
and since the flux is never wanted to be negative, one condition must be applied, which is:

\[ \alpha \nabla g_i F(g) \leq 1, \forall i \in I \text{ amb } g_i > 0 \]

This algorithm presents some issues, that are:

- Being an approximation, more iterations may be needed, and so more traffic assignations need to be done.
- It could deform the original OD matrix too much, making it unreliable.

In spite of the disadvantages, Spiess method has presented as the best option, so the update has been done applying it.

**Applying Spiess in the Metropolitan Area of Barcelona case**

Most of the variables are already defined: the seed matrix \( \hat{g}_i \) is the ATM OD 2011 matrix for private vehicle, and \( \hat{v}_a \) are the observed AADT in 2014 at the selected traffic stations. The only variables not defined yet are \( v(g)_a \), that depend on the traffic assignation, which must be obtained using a traffic simulation.

The only way of doing this simulation is by having already built a software capable of doing so. Since it was not possible to achieve such a thing, it was asked to ATM to hire a third part to do that; finally, the consultant enterprise called Mcrit carried out the simulation\(^3\).

The optimal process would have required to modify the assignment function at each iteration, due to the changes in the assignation produced by the variation in fluxes occurring at each iteration. The problem was that to do so, a constant interaction with the M-crit simulation would have been needed, increasing the time and the price of the operation; ATM preferred a simpler, and more economical, way to obtain an approximate matrix, so it has been done the simplest and most accurate possible way according to ATM specifications.

---

\(^3\)In Annex C there is the methodic note by Merit.
Then, instead of doing one traffic assignation per iteration, just one has been done: the simulation was done by using the known fluxes in 2011 (from the updated ATM 2011 OD matrix for private vehicle, performed in section 2.1, and including external traffic too) on the highway net in 2014, obtaining the hypothetical assignation that would take place if fluxes had kept constant. This traffic assignation has been assumed to be constant, independently of the variation in number of private cars going through each highway (and the new congestion that could be generated).

Finally, once the traffic assignation has been defined it has been possible to apply the Spiess method to update the ATM OD 2011 matrix to 2014.

It must be said that since most of the traffic counts are located outside cities (except three of them, that are located in the main entrances of Barcelona), only interurban trips were updated. The ones occurred inside cities were updated using the growth factors known by comparing EMEF surveys 2011 and 2014 (in the particular case of Barcelona, Dades Básiques de Mobilitat was also used).

The goal was to obtain ATM OD 2015 for private vehicle, but instead it has been obtained the 2014 matrix. For this reason, ATM provided their estimated private vehicle use growth factors from 2014 to 2015, data they had from other projects they were involved on. By applying this particular growth factor to each OD pair, the definitive ATM OD 2015 matrix for private vehicle was obtained.

In figures 2.7a and 2.7b the growth factor distribution on the OD matrix between 2010 and 2015 and the number of trips distribution in 2015 are shown.

### 2.3 Results

Once both bus and private vehicle OD matrices have been updated to 2015 and the results analysed, some interesting facts can be extracted. In order to do the comparison more visible, all transport mode results have been compiled into two tables per mode: two tables showing
the mobility between regions (tables 2.1 for bus and 2.3 for private vehicle) and two tables that show the mobility between Barcelona, the rest of the region of Barcelonès and the rest of the Metropolitan Area of Barcelona (tables 2.2 for bus and 2.4 for private vehicle).

On one hand, the use of bus for mobility in the RMB has grown 2.6% from 2010 to 2015. This increase in the bus use has been general in all the Metropolitan Area of Barcelona, except for its capital: Barcelona.

In Barcelona the number of trips by bus has decreased 3.38% since 2010. This fact could be a consequence of the new orthogonal buses net, which although being more efficient than the old one it has not had the expected users acceptance yet.

On the other hand, the private vehicle use has increased in 0.6%. In the case of private vehicle, its use as decreased in 0.1% in Barcelona and in 4.5% in the rest of the Barcelonès.

It must be said that between 2010 and 2011, the private vehicle use decreased in 5.7%, and since then it has increased again.

In annex F the complete results of all transport modes are shown, including rail (from SGIT) and non-motorized mobility (determined in chapter 3).
Table 2.1: Number of bus trips between regions in 2015, and growth factor from 2010 to 2015.

<table>
<thead>
<tr>
<th>Region</th>
<th>Alt Penedès</th>
<th>Baix Llobregat</th>
<th>Barcelona</th>
<th>Garraf</th>
<th>Maresme</th>
<th>Vallès Occ.</th>
<th>Vallès Or.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt Penedès</td>
<td>25,270</td>
<td>5,184</td>
<td>24,714</td>
<td>703</td>
<td>3,415</td>
<td>5,047</td>
<td>2,517</td>
<td>66,850</td>
</tr>
<tr>
<td></td>
<td>13.8%</td>
<td>9.4%</td>
<td>3.7%</td>
<td>2.8%</td>
<td>10.6%</td>
<td>12.0%</td>
<td>12.0%</td>
<td>9.0%</td>
</tr>
<tr>
<td>Baix Llobregat</td>
<td>5,182</td>
<td>90,172</td>
<td>38,647</td>
<td>483</td>
<td>6,074</td>
<td>1,556</td>
<td>1,393</td>
<td>143,507</td>
</tr>
<tr>
<td></td>
<td>9.4%</td>
<td>12.9%</td>
<td>6.3%</td>
<td>11.5%</td>
<td>15.3%</td>
<td>8.7%</td>
<td>13.1%</td>
<td>11.0%</td>
</tr>
<tr>
<td>Barcelona</td>
<td>24,713</td>
<td>38,647</td>
<td>590,879</td>
<td>1,247</td>
<td>11,117</td>
<td>13,632</td>
<td>8,368</td>
<td>688,604</td>
</tr>
<tr>
<td></td>
<td>3.7%</td>
<td>6.3%</td>
<td>2.7%</td>
<td>6.6%</td>
<td>5.5%</td>
<td>6.3%</td>
<td>7.8%</td>
<td>11.0%</td>
</tr>
<tr>
<td>Garraf</td>
<td>703</td>
<td>483</td>
<td>1,247</td>
<td>7,211</td>
<td>151</td>
<td>12</td>
<td>388</td>
<td>10,196</td>
</tr>
<tr>
<td></td>
<td>2.8%</td>
<td>11.5%</td>
<td>6.7%</td>
<td>3.8%</td>
<td>14.4%</td>
<td>11.9%</td>
<td>2.8%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Maresme</td>
<td>3,418</td>
<td>6,072</td>
<td>11,117</td>
<td>151</td>
<td>48,524</td>
<td>3,877</td>
<td>2,431</td>
<td>75,591</td>
</tr>
<tr>
<td></td>
<td>10.6%</td>
<td>15.2%</td>
<td>6.2%</td>
<td>11.9%</td>
<td>11.5%</td>
<td>11.5%</td>
<td>13.4%</td>
<td>8.8%</td>
</tr>
<tr>
<td>Vallès Occ.</td>
<td>5,047</td>
<td>1,557</td>
<td>13,633</td>
<td>12</td>
<td>3,877</td>
<td>129,816</td>
<td>9,314</td>
<td>163,255</td>
</tr>
<tr>
<td></td>
<td>12.0%</td>
<td>8.7%</td>
<td>6.2%</td>
<td>11.9%</td>
<td>11.5%</td>
<td>11.5%</td>
<td>11.1%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Vallès Or.</td>
<td>2,518</td>
<td>1,392</td>
<td>8,365</td>
<td>388</td>
<td>2,433</td>
<td>9,314</td>
<td>28,964</td>
<td>53,314</td>
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<td>13.0%</td>
<td>7.8%</td>
<td>2.8%</td>
<td>12.7%</td>
<td>11.1%</td>
<td>13.3%</td>
<td>11.8%</td>
</tr>
<tr>
<td>Total</td>
<td>66,850</td>
<td>143,507</td>
<td>688,603</td>
<td>10,196</td>
<td>75,591</td>
<td>163,255</td>
<td>53,314</td>
<td>1,201,318</td>
</tr>
<tr>
<td></td>
<td>9.0%</td>
<td>11.0%</td>
<td>-1.6%</td>
<td>4.6%</td>
<td>8.8%</td>
<td>6.5%</td>
<td>11.9%</td>
<td>2.6%</td>
</tr>
</tbody>
</table>

Table 2.2: Number of bus trips between Barcelona, the rest of Barcelonès and the rest of the RMB in 2015, and growth factor from 2010 to 2015.

<table>
<thead>
<tr>
<th>Region</th>
<th>Barcelona</th>
<th>Barcelonès</th>
<th>Rest of RMB</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barcelona</td>
<td>477,007</td>
<td>16,569</td>
<td>72,443</td>
<td>566,018</td>
</tr>
<tr>
<td></td>
<td>-3.8%</td>
<td>0.1%</td>
<td>5.8%</td>
<td>-2.6%</td>
</tr>
<tr>
<td>Barcelonès</td>
<td>16,565</td>
<td>80,739</td>
<td>25,282</td>
<td>122,585</td>
</tr>
<tr>
<td></td>
<td>0.2%</td>
<td>2.8%</td>
<td>5.3%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Rest of RMB</td>
<td>72,447</td>
<td>25,278</td>
<td>414,990</td>
<td>512,714</td>
</tr>
<tr>
<td></td>
<td>5.8%</td>
<td>5.3%</td>
<td>9.7%</td>
<td>8.9%</td>
</tr>
<tr>
<td>Total</td>
<td>566,018</td>
<td>122,585</td>
<td>512,714</td>
<td>1,201,318</td>
</tr>
<tr>
<td></td>
<td>-2.6%</td>
<td>2.9%</td>
<td>8.9%</td>
<td>2.6%</td>
</tr>
</tbody>
</table>
Table 2.3: Number of private vehicle trips between regions in 2015, and growth factor from 2010 to 2015.

<table>
<thead>
<tr>
<th></th>
<th>Alt Penedès</th>
<th>Baix Llobregat</th>
<th>Barcelonès</th>
<th>Garraf</th>
<th>Maresme</th>
<th>Vallès Occ.</th>
<th>Vallès Or.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt Penedès</td>
<td>222,697</td>
<td>48,597</td>
<td>96,659</td>
<td>15,347</td>
<td>40,735</td>
<td>35,263</td>
<td>35,263</td>
<td>508,558</td>
</tr>
<tr>
<td></td>
<td>1.7%</td>
<td>7.0%</td>
<td>4.7%</td>
<td>−3.3%</td>
<td>−2.0%</td>
<td>−1.6%</td>
<td>−2.6%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Baix Llobregat</td>
<td>48,597</td>
<td>545,817</td>
<td>169,300</td>
<td>8,424</td>
<td>60,797</td>
<td>108,531</td>
<td>46,608</td>
<td>883,940</td>
</tr>
<tr>
<td></td>
<td>7.0%</td>
<td>5.8%</td>
<td>5.4%</td>
<td>4.7%</td>
<td>−3.3%</td>
<td>−3.3%</td>
<td>−2.6%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Barcelonès</td>
<td>96,659</td>
<td>169,300</td>
<td>1,251,164</td>
<td>7,230</td>
<td>81,355</td>
<td>1,760,847</td>
<td>46,608</td>
<td>1,760,847</td>
</tr>
<tr>
<td></td>
<td>4.7%</td>
<td>5.4%</td>
<td>0.5%</td>
<td>2.3%</td>
<td>1.1%</td>
<td>0.5%</td>
<td>5.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Garraf</td>
<td>15,347</td>
<td>8,424</td>
<td>114,601</td>
<td>951</td>
<td>1,168</td>
<td>7,161</td>
<td>154,881</td>
<td>154,881</td>
</tr>
<tr>
<td></td>
<td>−3.3%</td>
<td>3.4%</td>
<td>−5.5%</td>
<td>3.1%</td>
<td>−3.1%</td>
<td>−4.5%</td>
<td>−3.3%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Maresme</td>
<td>40,735</td>
<td>60,797</td>
<td>498,096</td>
<td>951</td>
<td>39,962</td>
<td>769,533</td>
<td>525,560</td>
<td>769,533</td>
</tr>
<tr>
<td></td>
<td>−2.0%</td>
<td>2.3%</td>
<td>2.4%</td>
<td>3.1%</td>
<td>3.4%</td>
<td>−3.6%</td>
<td>−1.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Vallès Occ.</td>
<td>49,259</td>
<td>32,081</td>
<td>108,531</td>
<td>1,168</td>
<td>47,636</td>
<td>770,430</td>
<td>89,945</td>
<td>1,099,050</td>
</tr>
<tr>
<td></td>
<td>−1.6%</td>
<td>1.8%</td>
<td>1.0%</td>
<td>3.0%</td>
<td>3.4%</td>
<td>−1.9%</td>
<td>−0.9%</td>
<td>−1.2%</td>
</tr>
<tr>
<td>Vallès Or.</td>
<td>35,263</td>
<td>18,924</td>
<td>46,608</td>
<td>7,161</td>
<td>89,945</td>
<td>287,698</td>
<td>525,560</td>
<td>525,560</td>
</tr>
<tr>
<td></td>
<td>−2.6%</td>
<td>−0.3%</td>
<td>−2.5%</td>
<td>−4.5%</td>
<td>−3.6%</td>
<td>−0.9%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Total</td>
<td>508,558</td>
<td>883,940</td>
<td>1,760,847</td>
<td>154,881</td>
<td>769,533</td>
<td>1,099,050</td>
<td>525,560</td>
<td>5,702,368</td>
</tr>
<tr>
<td></td>
<td>1.6%</td>
<td>5.2%</td>
<td>5.5%</td>
<td>−3.3%</td>
<td>−1.2%</td>
<td>0.4%</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

Table 2.4: Number of private vehicle trips between Barcelona, the rest of Barcelonès and the rest of the RMB in 2015, and growth factor from 2010 to 2015.
Chapter 3

Transportation model of the Metropolitan Area of Barcelona

In the previous chapter it has been shown how OD matrices updating is usually performed. Not being difficult to understand, this process presents some negative aspects, such as the difficulty obtaining essential data and the significant amount of time and money needed in order to obtain it. But the most negative aspect it does have is the prediction incapability of the method; this updating process can be used for modelling the present transportation situation, but it is not able to predict the future due to the fact that the input data can only be obtained once it has become a reality.

Predicting how transportation needs can evolve is necessary and indispensable for the society development. Transportation is a social aspect that must always be planned for serving society, while optimizing economic aspects and caring about other such as environmental, visual and noise impact. However, the most important aspect is the economic one, with costs that can be of billions of euros.

Society is in constant change, and so does mobility. Then, it is necessary to build new infrastructures, or change public transport prices, according to all these changes. When planning future changes like the ones presented, it is all based in, and though for, estimations done
previously. So, the better we become predicting how transportation can evolve the better and more accurate improvements in infrastructures or changes in some aspects such the public transportation prices can be done.

The second objective of this research work, together with updating the ATM OD matrices to 2015, has been to propose a model capable of predicting how RMB transportation might evolve depending on predictable parameters (or designable ones) like combustible or parking prices, public transportation and toll prices or the estimate travel time of each transportation mode.

3.1 Modeling the mobility in the Metropolitan Area of Barcelona and predicting the future disaggregated Origin-Destination matrices

The model has been built following the basic four steps transportation model (Garrison, 1960), that as it has been presented in the introduction are trip generation, trip distribution, modal choice and, finally, route assignment; the proposed model to predict the future ATM OD matrices includes the first three steps.

Of these three steps, completing the first two means predicting the aggregated ATM OD matrix in the desired year, while the third one is defining the modal choice, i.e. separating the aggregated ATM OD matrix into the disaggregated ATM OD matrices (per transport mode).

In accordance to the explained above, figure 3.1 shows the proposed model to predict the future OD matrices (2015, as shown in figure, and analogously 2020). Although the model objective is to predict future mobility, by modelling the ATM OD matrix 2015 it has been wanted to check the reliability of the method by checking the similarity between the predicted private vehicle ATM OD matrix in 2015 and the determined one for the same year (done in section 2.2.2). In addition, since the non-motorized ATM OD matrix in 2015 is unknown, by modelling mobility in 2015 it have been defined.
3.2 Modeling aggregated Origin-Destination matrices in 2015 and 2020

Predicting the future aggregated OD matrices is done by predicting the future EMO OD matrices first. That is due to the fact that EMO is an OD matrix that shows just the first occupational trip (they are not only disaggregated per modes, but also per work and studies), being easier to predict the evolution of both work and studies independently and finally mixing them and adding home return displacement, recurrence factor and the personal displacement later, again obtained from the EMEF. Finally, as it has been done while updating from 2010 to 2011, the Furness method (Ortúzar and Robusté, 2015) has been applied.

3.2.1 Aggregated Origin-Destination matrix in 2015

For updating the aggregated EMO matrices to 2015 (both EMO OD matrix 69 zones and EMO OD matrix 40 zones), the same process for displacements due to work or studies has been followed. The total number of jobs in each city or town is known, and also the number of workers in each city/town that do not work in the city/town where they live; in studies case, the number of people studying in each city/town and the number of students in each city/town (distinguishing between the students that study where they live and the ones who do not) (Idescat, 2016).
There is no differentiation between works or studies done in weekdays and weekends, so the number of displacements in EMO matrices do not coincide with Idescat data. Then, instead of making the total first displacements with origin or destination to each city/town be equal to the ones shown in Idescat data, the same municipal growth factors from 2011 to 2015 in Idescat data have been applied on the EMO displacements.

Once the first occupational displacements originated in or destined to each EMO zone have been determined, the Furness method (Ortúzar and Robusté, 2015) has been applied in both work and studies matrices. Finally, adding them the aggregated EMO 2015 OD matrix 69 zones and aggregated EMO 2015 OD matrix 40 zones have been obtained.

From this point, the same process than the one done when updating the bus and private vehicle ATM OD matrices to 2011 has been applied, resulting on the predicted aggregated ATM OD matrix 2015 (figure 3.2).

![Predicted growth factors OD matrix from 2010 to 2015](image1.png) ![Predicted total trips distribution on 2015 OD matrix](image2.png)

**Figure 3.2: Predicted aggregated ATM 2015 OD matrix. Source: author.**

### 3.2.2 Aggregated Origin-Destination matrix in 2020

When building the aggregated EMO matrices in 2020, the process is exactly the same than the one done in section 3.2.1. The only difference is that while in 2015 the number of works (and workers) and the number of students living and studying in each EMO zone were already known, in 2020 they must be predicted. Due to their different nature, the predictions have
been done separately.

**Occupational displacements due to work in 2020**

The prediction of job evolution in the Metropolitan Area of Barcelona has been obtained from the previous research *Prospectiva de necessitats d’ocupació i formació a la RMB* (Homs et al., 2014), the results of which are shown in figure 3.3. Knowing the different number of works per sector in each EMO zone (Idescat, 2016), and applying to each sector its growth factor, it has been possible to estimate the number of works in each EMO zone, and in consequence the number of occupational displacements in each destination.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Number of jobs (thousand)</th>
<th>Annual variation (%)</th>
<th>Absolute variation (thousand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>15,8</td>
<td>10,4</td>
<td>8,9</td>
</tr>
<tr>
<td>Industry</td>
<td>522,3</td>
<td>400,9</td>
<td>384,8</td>
</tr>
<tr>
<td>Construction</td>
<td>202,8</td>
<td>174,0</td>
<td>135,0</td>
</tr>
<tr>
<td>Services</td>
<td>1,554,7</td>
<td>1,602,1</td>
<td>1,661,2</td>
</tr>
<tr>
<td>Total</td>
<td>2,295,5</td>
<td>2,187,3</td>
<td>2,189,9</td>
</tr>
</tbody>
</table>

*Figure 3.3: Job evolution in the Metropolitan Area of Barcelona (2015-2020). Source: (Homs et al., 2014).*

Once the number of occupational displacements due to work in 2020 in each destination is known, it is necessary to obtain where they are originated. To do so, it has been proposed to use the Spiess method (Spiess, 1990), by assuming:

- Destinations as traffic counts, that means assuming the number of occupational displacements in 2020 in each destination $a$ as $\hat{v}_a$.

- The number of occupational displacements in each origin in 2015 as $g_0$, and the number of occupational displacements in each origin in 2020 as $g_l$ that satisfies $v(g)_a = \hat{v}_a$ for all destinations.

- The assignation to be the same than in 2015.
Using the proposed method, it has been possible to know the number of occupational displacements due to work in 2020 in each origin, and finally the Furness method (Ortúzar and Robusté, 2015) has been applied, obtaining the aggregated EMO matrices due to work in 2020 (both EMO OD matrix 69 zones and EMO OD matrix 40 zones).

**Occupational displacements due to studies in 2020**

Exactly the same process than in jobs case has been followed in studies case, but instead of predicting how the number of study offers will evolve in 2020, it has been tried to predict the variation in the number of students in each EMO zone.

To do so, the medium projection of population done by Idescat has been used, obtaining the growth factor per range of age. Since it is known the number of students in each EMO zone per ages (and so the percentage of the total students each range of age represents), it has been possible to calculate the growth factor of the occupational displacements due to studies in each EMO zone by using equation (3.2.1).

$$\frac{d'_a}{d_a} = \sum_i \rho_{ia} \cdot p_{ia},$$  \hspace{1cm} (3.2.1)

where $d_a$ and $d'_a$ are the number of occupational displacements due to studies originated in the EMO zone $a$ in 2015 and 2020 respectively, $i$ are the different ranges of age, $\rho_{ia}$ the growth factor per range of age in the EMO zone and $p_{ia}$ the percentage of the total students each range of age represents in the EMO zone.

Again, the Spiess method has been used but now assuming:

- Origins as traffic counts, that means assuming the number of occupational displacements in 2020 in each origin $a$ as $\hat{v}_a$.
- The number of occupational displacements in each destination in 2015 as $g_0$, and the number of occupational displacements in each destination in 2020 as $g_1$ that satisfies $v(g)_a = \hat{v}_a$ for all origins.
• The assignation to be the same than in 2015.

As done in jobs case, once it has been known the number of occupational displacements due to studies in 2020 in each destination, the Furness method has been applied, obtaining the aggregated EMO OD matrices due to studies in 2020 (both EMO OD matrix 69 zones and EMO OD matrix 40 zones).

Aggregated ATM 2020 OD matrix

The definitive aggregated EMO matrices in 2020 are made by adding the EMO matrices due to work and studies. From this point, the same process than the one done when updating the ATM OD matrices to 2015 has been applied, resulting on the predicted aggregated ATM OD matrix 2020 (figure 3.4).

The predicted total number of displacements is 16,976,987 in 2020, which represents an increment of 3.8% from the 16,347,213 of displacements determined in 2015 (once all disaggregated matrices were already determined, including the rail mode matrix from SGIT).
3.3 Decision cost-time model

Once the first two steps of the basic transport model have been completed (trip generation and distribution), it is the time for the modal choice. When deciding which transport mode to use, people have different parameters that take into account, like the price or the travel time of the mode, together with others like for example not using metro due to the high agglomeration or being underground instead of outside. Excluding the last reason, the other ones can be modeled by monetizing them; this virtual costs are known as generalized costs.

The excluded reason may be a parameter, for example, for deciding whether to go by bus or metro once it has already been decided to go by public transport. That is why it is usual when modelling the mobility to separate the modal choice into a tree modal choice, as it is shown in figure 3.5. The model of this project has been centered on the first election, which is the one that determines the disaggregated ATM OD matrices.

![Diagram of the tree modal choice](source: author)

Then, the proposed method assumes that the modal choice depends only in the generalized cost, so people select the transport mode with the minor generalized cost. The model is deterministic, and assumes that people will always select accurately the best mode in generalized cost and that includes all three modes, although some people can not use some of them (in those cases the election would be between two).

The generalized cost per transport mode (non-motorized, public transport and private vehicle) has been defined according to equation (3.3.1a), being $k$ the transport mode, $t_k$ the travel time.
and $C_k$ the *out-of-pocket* cost\(^1\). So the generalized cost time for non-motorized mode (NM), public transport (PT) and private vehicle (PV) will be represented by equations (3.3.1b)-(3.3.1d) respectively.

\[
GC_k = V_o T \cdot t_k + C_k
\]

\[
GC_{NM} = V_o T \cdot t_{NM}
\]

\[
GC_{PT} = V_o T \cdot t_{PT} + C_{ticket}
\]

\[
GC_{PV} = V_o T \cdot t_{PV} + C_{toll} + C_{combustible} + C_{parking}
\]

Being the travel times\(^2\) and the rest of costs already determined\(^3\), the only parameter to determine, and that defines the personal modal choice, is the value of time people take into account when deciding the transport mode (consciously or not). The value of time depends on mainly two reasons:

- The purpose of the trip.
- The income (how much people is ready to pay in order to save some time).

### 3.3.1 Theoretical application of the method

The model has been based on building a cost time distribution per ATM zone, city or the total RMB, depending on whether the results showed a general modal choice behavior or particular ones.

In all OD pairs where $t_{NM} > t_{PT} > t_{PV}$ and, at the same time, $C_{PT} < C_{PV}$ (in 93.3% of the OD pairs this condition is fulfilled), the non-motorized critical cost time (3.3.2) and the public transport critical cost time (3.3.3) can be defined.

---

\(^1\) *Out-of-pocket* cost: direct cost the transport mode has. Tickets for public transport, and tolls, spent combustible (in euros) and parking for private vehicle are an example of it.

\(^2\) Provided by ATM

\(^3\) In Annex E the calculations of out-of-pocket prices are shown.
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\[ GC_{NM} = GC_{PT} \Rightarrow \]

\[ VoT \cdot t_{NM} = VoT \cdot t_{PT} + C_{ticket} \]

\[ VoT_{NM_{cr}} = \frac{C_{ticket}}{t_{NM} - t_{PT}} \] (3.3.2)

\[ GC_{PT} = GC_{VT} \Rightarrow \]

\[ VoT \cdot t_{PT} + C_{ticket} = VoT \cdot t_{PV} + C_{toll} + C_{combustible} + C_{parking} \]

\[ VoT_{PT_{cr}} = \frac{C_{toll} + C_{combustible} + C_{parking} - C_{ticket}}{t_{PT} - t_{PV}} \] (3.3.3)

If it is also fulfilled that \( VoT_{NM_{cr}} < VoT_{PT_{cr}} \) (87.7% of the OD pairs): when \( VoT \leq VoT_{NM_{cr}} \) the selected mode would be the non-motorized mode; when \( VoT_{NM_{cr}} < VoT \leq VoT_{PT_{cr}} \), the selected mode would be public transport; finally, when \( VoT > VoT_{PT_{cr}} \) the selected mode would be private vehicle. For example, if the value of time were 0, people would select going by non-motorized mode, which is free; on the other side, a value of time too high means going by private vehicle, the fastest one.

The cost time distribution is built following the next steps, only using the exposed case, which is the one that fits with the model:

1. In each OD pair, finding the critical cost time for non-motorized mobility and assuming that the percentage of people that use a non-motorized mode have a value of time fewer than the critical cost time for non-motorized mobility.

2. Again in each OD pair, finding the critical cost time for public transport and assuming that the percentage of people that use a non-motorized mode or public transport have a value of time smaller than the critical cost time for public transport.

3. By plotting 1 and 2 in a \( VoT - Percentage \) and doing a regression it is expected to obtain a cost time distribution (which depending on the results could be per ATM
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zone, city, region...).

Once the cost time distribution/s has/ve been built, the model will have been set up. With future price or time of each mode variations, and in consequence variation in the critical cost times, by plotting them in the cost time distribution of the OD pair the new percentages of usage of each transport mode will be obtained.

3.3.2 Exceptions in which the model does not fit

As it has already been exposed, there are cases in which people do not select a transport mode according to the model assumptions. In order to make all these cases fit with the cost-time mode, some extra assumptions must be done.

<table>
<thead>
<tr>
<th>Out-of-pocket cost</th>
<th>Trip time</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NM &gt; PT &gt; PV</td>
<td>PT &gt; NM &gt; PV</td>
<td>PT &gt; PV &gt; NM</td>
</tr>
<tr>
<td>$C_{PT} &lt; C_{PV}$</td>
<td>316100</td>
<td>10157</td>
<td>109</td>
</tr>
<tr>
<td>$C_{PV} &lt; C_{PT}$</td>
<td>9494</td>
<td>1037</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>NM &gt; PV &gt; PT</td>
<td>PV &gt; NM &gt; PT</td>
<td>PV &gt; PT &gt; NM</td>
</tr>
<tr>
<td>$C_{PT} &lt; C_{PV}$</td>
<td>1731</td>
<td>1</td>
<td>67</td>
</tr>
<tr>
<td>$C_{PV} &lt; C_{PT}$</td>
<td>10</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

*Table 3.1: Number of OD pairs per types*

In table 3.1 all possible cases are shown. It can be seen that in most of the OD pairs (93.3%) $t_{NM} > t_{PT} > t_{PV}$ and, at the same time, $C_{PT} < C_{PV}$. Of these, only those where $V\circ T_{NMcr} < V\circ T_{PTcr}$ (87.7% of the total) do adjust to the model assumptions.

However, in cases where $t_{NM} > t_{PT} > t_{PV}$ and $C_{PT} < C_{PV}$, but $V\circ T_{NMcr} > V\circ T_{PTcr}$, the model would determine that people go by either non-motorized modes or by private vehicle. That is because once the value of time is large enough to make public transport more attractive in generalized cost than the non-motorized mode, it is already better to use private vehicle. In these cases, population travelling between the OD pair must be separated into the two parts:

- The ones that can not, or do not want to, go by private vehicle, so they change from non-motorized mobility to public transport once their value of time is larger than $V\circ T_{NMcr}$. 


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The ones that change from non-motorized mobility to private vehicle once their value of time is larger than the critical cost time between non-motorized mobility and private vehicle.

For the rest of the cases the proposed methodology is exposed in table 3.2:

<table>
<thead>
<tr>
<th>Trip time</th>
<th>Out-of-pocket cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$NM &gt; PT &gt; PV$</td>
<td>$PT &gt; NM &gt; PV$</td>
</tr>
<tr>
<td>$C_{PT} &lt; C_{PV}$</td>
<td>Already explained.</td>
</tr>
<tr>
<td>$C_{PV} &lt; C_{PT}$</td>
<td>It is always better to use PV than PT, so population must be divided into the ones that use PV and the ones that do never use it.</td>
</tr>
<tr>
<td>$C_{PT} &lt; C_{PV}$</td>
<td>$NM &gt; PV &gt; PT$</td>
</tr>
<tr>
<td>$C_{PV} &lt; C_{PT}$</td>
<td>It follows the proposed model assumptions, except for the fact that PT is the most expensive but fastest mode.</td>
</tr>
</tbody>
</table>

Table 3.2: Proposed methodology for each OD pairs per type
3.3.3 Applying the method to the Metropolitan Area of Barcelona

Unfortunately, when applying the method to the Metropolitan Area of Barcelona using the ATM 2010 OD matrices (or 2011), no representative modal choice behavior has been observed. Obtaining results as the ones shown in figure 3.6, no cost time distribution has been modelled.

![Figure 3.6: Example of cost time distribution in an ATM zone. Source: author.](image)

Since the model has been proved to be incapable of explaining the mobility in the RMB, some possible reasons why it happens are exposed:

1. The reliability of the data, so mobility may not be exactly the one that ATM 2010 OD matrices show. Along the same lines is the lack of information about the incapability of using any of the transport modes, especially the non-motorized ones (due to health or the lack of bike) and the private vehicle.

2. Existence of other parameters, apart from the generalized modal cost, that may appear depending on the reason of the displacement. For example, commodity or the need of
transporting the purchase. Due to their different nature, separating the occupational and personal displacements could resolve this reason, especially in the first ones where the transport mode cost may be the only existent parameter in the modal choice.

3. Probably a common reason that may have affected to most of the modal choices is the fact that people do not calculate so accurately the cost of each mode, so the probable miscalculation or misinformation could be the reason why people modal choices are not the ones they would select in case they knew it exactly.

For these reasons, stochastic models such logit are the ones used when modelling mobility instead of deterministic ones, even if they are conceived to consider different patrons like the one built in this research. The stochastic factor could be added to the proposed model by applying a probability density function around the expected cost time distribution. However, all these options require the available data to be much more accurate than it is, so all these options have been discarded.

3.4 Generalized cost gradient method

Since the model presented in section 3.3 is not capable of modelling the mobility in the RMB, a new model is proposed by the author. Although the negative aspects due to its simplicity, it is a model easy to apply, and capable of predicting how the attractiveness of each transport mode in comparison with the other modes will vary, and in consequence the new demand proportions.

3.4.1 Assumptions

This model is based on equation 3.4.1, used in (Calvet and Roselló, 2007) for predicting the induced demand when a new infrastructure modifies the generalized cost of any transport mode between OD pairs.

\[
\frac{\Delta D_k}{D_k} = -c_k CG'',
\]  

(3.4.1)
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\[
CG'' = \begin{cases} 
\frac{GC'_k - GC_k}{GC_k}, & \text{the one used by ATM}, \\
\log\left(\frac{GC'_k}{CG''_k}\right), & \text{proposed by the author}, 
\end{cases}
\]

where \(D_k\) is the actual transport mode \(k\) demand, \(\Delta D_k\) the generated/lost demand after generalized cost in mode \(k\) change, \(GC'_k\) the new transport mode \(k\) generalized cost and \(GC_k\) the old one. Finally, \(e_k\) is an elasticity value, which will be defined per OD pair and transport mode in order to calibrate the model with reality.

The new generalized cost comparison \(CG''\) has been proposed because in the proposed one the proportional increments have more weight rather than in the ATM \(CG''\) formula.

The generalized costs are assumed to be the same than in section 3.3, but this time the value of time has been predefined. In 2000 the value of time in Barcelona was defined to be \(VoT_{2000} = 4.87 \text{ €/h} \) (Robusté, 2000), and in 2007 it was defined as \(VoT_{2007} = 8.70 \text{ €/h} \) (Calvet and Roselló, 2007). So, the value of time has been updated to 2010, 2011, 2015 and 2020 according to the equation \(VoT_{i+1} = \frac{CPI_{i+1}}{CPI_i} \cdot VoT_i\), being \(i\) the year (it can be assumed 2007 as \(i = 0\)) and CPI the Consumer Price Index (INE, 2016).

Finally, being the new demand \(D' = D + \Delta D\), it is easy to define the new percentage of the transport mode demand in each OD pair as done in equation (3.4.2).

\[
P_{\text{pred}} = \frac{D'_k}{\sum_{k \in K} D'_k} = \frac{D_k + \Delta D_k}{\sum_{k \in K} D_k + \Delta D_k} = \frac{D_k \cdot (1 - e_k CG'')}{\sum_{k \in K} D_k \cdot (1 - e_k CG'')}.
\] (3.4.2)

Although value \(e\) can be considered to be equal to one (or \(e \leq \frac{1}{CG''}\) if \(CG'' > 1\)), a calibration can be made, the objective of which is to obtain the optimal \(e\) values per each transport mode on each OD pair. To do so, both 2010 and 2011 ATM OD matrices (per transport mode and aggregated ones) have been used: knowing the percentages and generalized costs of each transport mode in 2010 and 2011, the values of \(e_k\) are modified using the gradient method so the global calculated error in the OD pair is minimized. Two different objective functions are proposed in the following sections, being the first one more accurate but complex to compute, and the second one an approximation (less precise) but much more simple. It is assumed that
elasticiy value must always be \( e_k \geq 0 \), due to the fact that an increment of the generalized cost can not reduce the individual attractiveness for the mode, and taking into account that it must always be satisfied that the demand is not negative, so \( e \leq \frac{1}{\text{CGG}} \).

### 3.4.2 Objective function using Aitchison distance

As a distance between probabilities is computed, the Aitchison distance is a good option (Pawlowsky-Glahn et al., 2015). The Aitchison distance is defined as 3.4.3, which is converted into 3.4.4 in order to simplify the objective function, having this last one the same minimisation but simplified (when the second one is simplified, the first will be simplified too).

\[
d_{d}(P_{\text{pred}_k}, P_{\text{meas}_k}) = \sqrt{\frac{1}{4} \sum \left( \log\left( \frac{P_{\text{pred}_k}}{1 - P_{\text{pred}_k}} \right) - \log\left( \frac{P_{\text{meas}_k}}{1 - P_{\text{meas}_k}} \right) \right)^2}, \tag{3.4.3}
\]

\[
\min F(e_k) = \frac{1}{2} \sum \gamma_k \cdot \left( \log\left( \frac{P_{\text{pred}_k}}{1 - P_{\text{pred}_k}} \right) - \log\left( \frac{P_{\text{meas}_k}}{1 - P_{\text{meas}_k}} \right) \right)^2, \tag{3.4.4}
\]

where \( \gamma_k \) is the weighting value per each transport mode and \( P_{\text{meas}_k} \) the measured new proportion of the mode. The gradient of the objective equation (3.4.4) is defined in equation 3.4.5.

\[
\nabla e_k F(e_k) = -\sum_{k \in K} \gamma_k \cdot \left( \log\left( \frac{P_{\text{pred}_k}}{1 - P_{\text{pred}_k}} \right) - \log\left( \frac{P_{\text{meas}_k}}{1 - P_{\text{meas}_k}} \right) \right) \cdot \frac{\sum_{k' \neq k} D'_{k'} \cdot GC''_k}{(1 - e_k \text{CGG}) \cdot GC''_k}. \tag{3.4.5}
\]

Once the gradient is known, the iteration process will update \( e_k \) values in each OD pair as equation (3.4.6) shows.

\[
e^{l+1}_k = e^l_k \cdot (1 - \alpha^l \nabla e_k F(e^l_k)), \tag{3.4.6}
\]

where \( l = 0, 1, 2, ..., e^0_k = 1 \) and \( \alpha \) is the optimal step length, defined in (3.4.7a)\(^4\). It can be seen it is not possible to achieve an equation that express the \( \alpha \) value, but an iterative method can be used to find out which is the \( \alpha \) value that accomplishes both conditions.

\[
\sum_{k \in K} \left( \log\left( \frac{D'_k + \alpha r_k}{\sum_{k' \neq k} D'_{k'} + \alpha r_{k'}} \right) - \log\left( \frac{P_{\text{meas}_k}}{1 - P_{\text{meas}_k}} \right) \right) \cdot \frac{r_k}{D'_k + \alpha r_k} - \sum_{k' \neq k} \frac{r_{k'}}{D'_{k'} + \alpha r_{k'}} = 0, \tag{3.4.7a}
\]

\(^4\)In annex D shows the process followed to obtain it.
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\[ \sum_{k \in K} \left[ \left( \frac{r_k}{D_k'} + \alpha r_k \right) - \sum_{k' \notin k} \frac{r_{k'}}{D_{k'}'} \right]^2 + (\log(\frac{r_k}{D_k'} + \alpha r_k) - \log(\frac{P_{\text{meas}_k}}{1 - P_{\text{meas}_k}})) \cdot \left( \sum_{k' \notin k} \left( \frac{r_{k'}}{D_{k'}'} \right)^2 - \left( \frac{r_k}{D_k'} + \alpha r_k \right)^2 \right) = 0 > 0, \]

(3.4.7b)

where \( r_k = D_k \cdot e_k \cdot \frac{\partial F}{\partial e_k} \cdot CG_k'' \). Due to initial assumption that \( e_k \geq 0 \) for \( \forall k \in K \), it must also be verified that \( \alpha \nabla e_k F(e_k) \leq 1, \forall k \in K \).

Complete method process

As presented in the previous section, the first step of the method is the iterative process, which obtains the flexibility value \( e_k \) in each OD pair for \( \forall k \in K \) will be as it follows:

1. If \( GC'' > 1 \) \( \Rightarrow e_k^l = e_k^0 = \frac{1}{CG''} \); if not \( \Rightarrow e_k^l = e_k^0 = 1 \).

2. \( \Delta D_k = -e_k^l \cdot D_k CG'' \).

3. \( P_{\text{pred}_k} = \frac{D_k + \Delta D_k}{\sum_{k \in K} D_k + \Delta D_k} = \frac{D_k \cdot (1 - e_k^l CG'')}{\sum_{k \in K} D_k (1 - e_k^l CG'')} \).

4. If it is the optimal solution, it converges or the maximum number of iterations have been achieved, \textit{STOP} iteration. If not, go to step 5.

5. \( \nabla e_k F(e_k) = -\sum_{k \in K} \gamma_k \cdot (\log(\frac{P_{\text{pred}_k}}{P_{\text{meas}_k}}) - \log(\frac{P_{\text{meas}_k}}{1 - P_{\text{meas}_k}})) \cdot \frac{\sum_{k' \notin k} D_{k'}'}{(1 - e_k CG_k'')} \cdot CG_k'' \).

6. Find \( \alpha \) that satisfies (3.4.7a) and (3.4.7b).

7. \( e_k^{l+1} = e_k^l \cdot (1 - \alpha l \nabla e_k F(e_k^l)). \)

8. Return to step 2.

The definitive value of \( e_k \) will be the one used from this point to predict the future attractiveness and, in consequence, the proportion of each transport mode depending on their generalized cost evolution.

The prediction is performed by using the steps 2 and 3 of the iteration process, being \( e_k \) the one defined before. It is easy to see that the prediction can be done by comparing the generalized costs and percentages of each transport mode in the desired year with the ones in any of the
years above. It is assumable that all predictions may differ, so there are different ways to obtain the assumable optimal solution; some of them are exposed here:

1. Using just one of the years data, such as the most proximate to the desired year, or the one with the most reliable data.

2. Doing the prediction using all years data and weighting them (3.4.8) differently according to its proximity to the desired year or the reliability the data of each year has.

\[ P_{pred_k} = \sum_{i \in I} \gamma_i \cdot P_{pred_i}, \]  
\[ (3.4.8) \]

being \( i \) the years that have available data. In order to make sure that \( \sum_{k \in K} P_{pred_k} = 1 \), it must always be satisfied that \( \sum_{i \in I} \gamma_i = 1 \);

**Case with only two transport modes**

In cases with only two categories, it is possible to obtain an equation that defines the optimal step length (3.4.9). It is possible to define it due to the fact that with only two categories, the complementary percentage of one mode is the percentage of the second one, simplifying equation (3.4.7a).

\[ \alpha = \frac{P_{meas_i} D_2' - (1 - P_{meas_i}) D_1'}{(1 - P_{meas_i}) r_2 - P_{meas_i} r_1}, \]  
\[ (3.4.9) \]

being indifferent which transport mode is assigned as 1 or 2.

It can not only be used when there are two transport modes, but when the election using the generalized costs as the parameter is between two. In figure 3.7 an example of the second case is shown, where the first election, which is choosing between going by a motorized mode or a non-motorized one, is done taking into account other parameters such as the distance between the OD pair, and then it is in the second election that users election depends on the generalized costs.

When it is satisfied, the use of the Aitchison distance is situable, being the most proximate method and, at the same time, easy to use.
3.4.3 Objective function using Euclidean distance

As presented in the previous section, the suitable distance is the Aitchison, although for more than two categories, the application has some complication. The Euclidean distance (Pawlowsky-Glahn et al., 2015) is defined as in equation 3.4.10. As done in the Aitchison case and in order to simplify the objective function, is converted into 3.4.11, having this last one the same minimisation but simplified.

\[ d_e(P_{predk}, P_{meas}) = \sqrt{\sum_{k \in K} \gamma_k \cdot (P_{predk} - P_{meas})^2}, \]  
\[ \text{min} F(e_k) = \frac{1}{2} \sum_{k \in K} \gamma_k \cdot (P_{predk}(e_k) - P_{meas})^2, \]  

where \( \gamma_k \) is the weighting value per each transport mode and \( P_{meas} \) the measured new proportion of the mode (in this case in 2011). The gradient of the objective equation (3.4.11) is defined in equation 3.4.12.

\[ \nabla_{e_k} F(e_k) = -\sum_{k \in K} \gamma_k \cdot (P_{predk}(e_k) - P_{meas}) \cdot \frac{\partial P_{predk}(e_k)}{\partial e_k}. \]  

This model proposes assuming that variation caused in \( P_{predk} \) by \( e_k \) is locally constant, i.e. it only modifies the proportion of the \( k \) transport mode. It means that when calculating the Jacobian of the predicted proportion, it will be the one shown in (3.4.13).

\[ \frac{\partial P_{predk}(e_k)}{\partial e_k} = -c \cdot D_k \cdot CG'', \]
where \( c = \sum_{k \in K} D_k \cdot (1 - e_k \cdot CG'') \) and assumed to be constant \( (c \simeq ct) \).

Taking into account this assumption, the gradient of the objective equation can be rewritten as done in equation (3.4.14).

\[
\nabla_{e_k} F(e_k) = \sum_{k \in K} \gamma_k \cdot (P_{pred_k}(e_k) - P_{meas_k}) \cdot c \cdot D_k \cdot CG''.
\] (3.4.14)

As it happened in Spiess method (Spiess, 1990), the simplicity of the Jacobian estimation has some limitations. For example, the step length must be as small as possible, and the gradient could not be the maximum descent direction, so some more iterations may need to be made.

Once the gradient is known, the iteration process will update \( e_k \) values in each OD pair as equation (3.4.15) shows.

\[
e_{k}^{l+1} = e_{k}^{l} \cdot (1 - \alpha_{l} \nabla_{e_k} F(e_k^{l})),
\] (3.4.15)

where \( l = 0, 1, 2, ..., e_{k}^{0} = 1 \) and \( \alpha \) is the optimal step length, defined in (3.4.16) \(^5\).

\[
\alpha_{l} = \frac{\sum_{k \in K} \gamma_k \cdot (P_{pred_k}(e_k^{l}) - P_{meas_k}) \cdot \tilde{P}_k}{\sum_{k \in K} \gamma_k \cdot P_k^2}
\] (3.4.16)

\[
\tilde{P}_k = -c \cdot D_k \cdot \nabla_{e_k} F_k \cdot e_k \cdot CG''.
\]

Again, due to initial assumption that \( e_k \geq 0 \) for \( \forall k \in K \), it must also be verified that

\[
\alpha \nabla_{e_k} F(e_k) \leq 1, \ \forall k \in K.
\]

**Complete method process**

The algorithm is the same than in the Aitchison alternative shown in the last section, differing in the equations that must be used. The complete method follows:

1. If \( GC'' > 1 \Rightarrow e_k^{l} = e_k^{0} = \frac{1}{CG''} \); if not \( \Rightarrow e_k^{l} = e_k^{0} = 1 \).

\(^5\)In Annex D it is shown how the equation has been obtained.
2. \[ \Delta D_k = -e_k \cdot D_k CG'' \].

3. \[ P_{\text{pred}} = \frac{D_k + \Delta D_k}{\sum_{k \in K} D_k + \Delta D_k} = \frac{D_k^* (1 - e_k CG'')}{\sum_{k \in K} D_k^* (1 - e_k CG'')} \].

4. If it is the optimal solution, it converges or the maximum number of iterations have been done, STOP iteration. If not, go to step 5.

5. \[ c = \sum_{k \in K} (D_k + \Delta D_k) \).

6. \[ \nabla e_k^l F(e_k^l) = -\sum_{k \in K} \gamma_k \cdot (P_{\text{pred}}(e_k^l) - P_{\text{meas}}) \cdot c \cdot D_k \cdot CG'' \].

7. \[ \tilde{P}_k = -c \cdot D_k \cdot \nabla e_k^l F_k \cdot e_k \cdot CG'' \).

8. \[ \alpha = \frac{\sum_{k \in K} \gamma_k \cdot (P_{\text{pred}}(e_k^l) - P_{\text{meas}}) \cdot \tilde{P}_k}{\sum_{k \in K} \gamma_k \cdot \tilde{P}_k^2} \).

9. \[ e_k^{l+1} = e_k^l \cdot (1 - \alpha \nabla e_k F(e_k^l)) \).

10. Return to step 2.

The definitive \( e_k \) will be the ones used from this point to predict the future attractiveness and, in consequences, the proportion of each transport mode depending on their generalized cost evolution.

As happened in section 3.4.2, the prediction can be done by comparing the generalized costs and percentages of each transport mode in the desired year with the ones in any of the years above. The same ways explained there work in this alternative method.

### 3.4.4 Applying the method to predict the disaggregated ATM Origin-Destination matrices in 2015

The exposed method above has been applied for predicting the mobility in 2015, using the Euclidean distance due to the fact that the election is between three modes.

First of all, all disaggregated ATM OD matrices have been updated to 2011 using the EMO surveys, following exactly the same pattern than when updating the bus or private vehicle in section 2.1. The generalized costs for both years have been calculated using equations 3.3.1,
together with trip time per mode provided by ATM and the out-of-pocket costs obtained as it is explained in annex E. Once all these have been obtained, it has been possible to calculate the estimated flexibility of each mode in each OD pair using the generalized cost gradient method.

Using the predicted aggregated ATM OD matrix in 2015, the modal choice has been estimated using the obtained flexibility values together with the generalized cost per mode in 2015. It must be mentioned that due to their proximity and supposed similar accuracies, the prediction has been done by comparing the generalized costs and percentages of each transport mode in 2015 with the ones in both 2010 and 2011 (weighting equally, i.e. $\gamma_{2010} = \gamma_{2011} = 0.5$).

**Comparison between the determined and the predicted ATM 2015 OD matrices for private vehicle**

Once the ATM 2015 OD matrix for private vehicle has been predicted, both predicted and determined have been compared, as it is shown in figure 3.8.

![Comparison between the determined and the predicted ATM 2015 OD matrices for private vehicle](image)

*(a) Determined-Predicted private vehicle comparison factors OD matrix. (b) Determined-Predicted private vehicle trips plot.*

*Figure 3.8: Comparison between the determined and the predicted ATM 2015 OD matrices for private vehicle. Source: author.*

It can be appreciated in both figures that there is a clear similarity between both OD matrices. If instead of using figures the predicted results are shown in tables 3.3 and 3.4, it can be
Construction and modelling of the mobility matrix in the RMB

Author: Xavier Tomàs i Rodríguez

It can be concluded that the proposed method works. The accuracy of the predictions do not only depend on the proposed predicting method itself but also on other important parameters. In section 3.5 is gone in depth about it.

**ATM OD matrix in 2015 for non-motorized mode**

Since the method has been proved to work quite well, the predicted ATM OD matrix in 2015 for non-motorized mode has been delivered to ATM together with the bus and private vehicle ATM OD matrices in chapter 2.
As it has been performed for both bus and private vehicle OD matrices, the non-motorized results have been analysed in tables 3.5 and 3.6, in which, following the tendency in the last years, the general decrease in non-motorized mobility in all the Metropolitan Area of Barcelona can be noted.

<table>
<thead>
<tr>
<th></th>
<th>Barcelona</th>
<th>Barcelonès</th>
<th>Rest of RMB</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barcelona</td>
<td>2,670,223</td>
<td>32,346</td>
<td>17,331</td>
<td>2,719,900</td>
</tr>
<tr>
<td></td>
<td>−1.0%</td>
<td>−4.9%</td>
<td>−6.8%</td>
<td>−1.1%</td>
</tr>
<tr>
<td>Barcelonès</td>
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<td>867,035</td>
<td>56,381</td>
<td>955,763</td>
</tr>
<tr>
<td></td>
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<td>−10.4%</td>
<td>−13.2%</td>
<td>−10.4%</td>
</tr>
<tr>
<td>Rest of RMB</td>
<td>17,331</td>
<td>56,389</td>
<td>3,676,445</td>
<td>3,750,164</td>
</tr>
<tr>
<td></td>
<td>−6.8%</td>
<td>−13.2%</td>
<td>−8.2%</td>
<td>−8.3%</td>
</tr>
<tr>
<td>Total</td>
<td>2,719,901</td>
<td>955,770</td>
<td>3,750,156</td>
<td>7,425,827</td>
</tr>
<tr>
<td></td>
<td>−1.1%</td>
<td>−10.4%</td>
<td>−8.3%</td>
<td>−6.1%</td>
</tr>
</tbody>
</table>

Table 3.5: Number of non-motorized trips between Barcelona, the rest of Barcelonès and the rest of the RMB in 2015, and growth factor from 2010 to 2015.

<table>
<thead>
<tr>
<th></th>
<th>Alt Penedès</th>
<th>Baix Llobregat</th>
<th>Barcelonès</th>
<th>Garraf</th>
<th>Maresme</th>
<th>Vallès Occ.</th>
<th>Vallès Or.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt Penedès</td>
<td>431,791</td>
<td>1,852</td>
<td>50,148</td>
<td>5,444</td>
<td>19,892</td>
<td>4,353</td>
<td>10,754</td>
<td>524,233</td>
</tr>
<tr>
<td></td>
<td>−7.5%</td>
<td>−12.8%</td>
<td>−13.1%</td>
<td>−13.4%</td>
<td>−10.4%</td>
<td>−12.9%</td>
<td>−9.7%</td>
<td>−8.4%</td>
</tr>
<tr>
<td>Baix Llobregat</td>
<td>1,851</td>
<td>900,786</td>
<td>15,548</td>
<td>99</td>
<td>6,261</td>
<td>383</td>
<td>6,917</td>
<td>931,843</td>
</tr>
<tr>
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<td>−7.7%</td>
<td>−8.6%</td>
<td>−1.0%</td>
<td>−18.2%</td>
<td>−1.1%</td>
<td>−2.2%</td>
<td>−7.8%</td>
</tr>
<tr>
<td>Barcelonès</td>
<td>50,139</td>
<td>15,548</td>
<td>3,601,951</td>
<td>405</td>
<td>1,865</td>
<td>4,650</td>
<td>1,096</td>
<td>3,675,663</td>
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<tr>
<td></td>
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<td>−8.6%</td>
<td>−3.5%</td>
<td>−3.5%</td>
<td>−13.5%</td>
<td>−8.6%</td>
<td>−5.8%</td>
<td>−3.7%</td>
</tr>
<tr>
<td>Garraf</td>
<td>5,444</td>
<td>99</td>
<td>405</td>
<td>134,386</td>
<td>18</td>
<td>4</td>
<td>12,888</td>
<td>153,243</td>
</tr>
<tr>
<td></td>
<td>−13.4%</td>
<td>−1.0%</td>
<td>−3.6%</td>
<td>−8.6%</td>
<td>−15.5%</td>
<td>−4.4%</td>
<td>−5.3%</td>
<td>−8.5%</td>
</tr>
<tr>
<td>Maresme</td>
<td>19,891</td>
<td>6,258</td>
<td>1,865</td>
<td>18</td>
<td>766,253</td>
<td>3,181</td>
<td>5,345</td>
<td>802,811</td>
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<td></td>
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<td>−13.5%</td>
<td>−15.7%</td>
<td>−9.8%</td>
<td>−15.4%</td>
<td>−8.5%</td>
<td>−9.9%</td>
</tr>
<tr>
<td>Vallès Occ.</td>
<td>4,350</td>
<td>383</td>
<td>4,657</td>
<td>4</td>
<td>3,182</td>
<td>897,569</td>
<td>32,364</td>
<td>942,508</td>
</tr>
<tr>
<td></td>
<td>−13.0%</td>
<td>−1.1%</td>
<td>−8.6%</td>
<td>−4.4%</td>
<td>−15.4%</td>
<td>−7.6%</td>
<td>−15.1%</td>
<td>−7.9%</td>
</tr>
<tr>
<td>Vallès Or.</td>
<td>10,751</td>
<td>6,917</td>
<td>1,096</td>
<td>12,888</td>
<td>5,345</td>
<td>32,365</td>
<td>326,165</td>
<td>395,526</td>
</tr>
<tr>
<td></td>
<td>−9.7%</td>
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<td>−5.8%</td>
<td>−5.3%</td>
<td>−8.5%</td>
<td>−15.1%</td>
<td>−6.3%</td>
<td>−7.1%</td>
</tr>
<tr>
<td>Total</td>
<td>524,216</td>
<td>931,842</td>
<td>3,675,671</td>
<td>153,243</td>
<td>802,814</td>
<td>942,513</td>
<td>395,528</td>
<td>7,425,827</td>
</tr>
<tr>
<td></td>
<td>−8.4%</td>
<td>−7.8%</td>
<td>−3.7%</td>
<td>−8.5%</td>
<td>−9.9%</td>
<td>−7.9%</td>
<td>−7.1%</td>
<td>−6.1%</td>
</tr>
</tbody>
</table>

Table 3.6: Number of non-motorized trips between regions in 2015, and growth factor from 2010 to 2015.

3.4.5 Applying the method to predict the disaggregated ATM Origin-Destination matrices in 2020

Proved the method to work, predicting the mobility in 2015 and checked with the real one, in this section the goal has been predicting how the mobility in the Metropolitan Area of Barcelona will be in 2020 if the conditions in 2020 were the same than now, but updated to that year.
It means that in 2020 it has been assumed the travel time to be the same and the costs too but updated according to CPI prediction, which means increased in 5%. The only cost that has been defined differently has been the combustible price\(^6\), which varies according to crude oil price. It must be said that this parameter represents a high uncertainty, and so does the predicted mobility in 2020.

As performed when applying the generalized cost gradient method to predict the disaggregated ATM OD matrices in 2015, the Euclidean distance has been the one used. In this case, years 2010 and 2015 have been used as a base to determine the flexibility values in each OD pair: the generalized costs for both years have been calculated using equations 3.3.1, together with trip time per mode provided by ATM and the out-of-pocket costs obtained as it is explained in annex E. Once all these have been obtained, it has been possible to calculate the estimated flexibility of each mode in each OD pair using the generalized cost gradient method.

Finally, using the predicted aggregated ATM OD matrix in 2020 (section 3.2.2), the modal choice has been estimated using the obtained flexibility values together with the estimated generalized cost per mode in 2020. In figure 3.9 the growth factor distribution on the disaggregated OD matrices between 2015 and 2020 are shown\(^7\).

### 3.4.6 Calculator tool

Using the model as base, a calculation tool has been created. The aim of this calculator is to be capable of:

- Predicting how the mobility may evolve according to updated 2020 predictions based on the real evolution of the different parameters (it has already been said how unpredictable is the evolution of the combustible price).
- As a predictor for authorities like ATM to know the consequences that any implementation or change done on the infrastructures or transportation prices could have in the mobility.

\(^6\)Combustible price prediction has been done in annex E  
\(^7\)In annex G the complete results are shown.
Being the mobility in the Metropolitan Area of Barcelona in 2010 and 2015 already defined, the only parameters to be defined are the generalized costs. Although in this project the generalized costs have been defined (and predicted in 2020 case) according to some assumptions, it is possible that authorities prefer using other assumptions, so generalized costs may differ. Moreover, the predicted generalized costs in 2020 only assumed changes in combustible prices, being the rest constant (but update according to CPI).

As an indicator, one of the mobility objectives in Barcelona is to reduce in 21% the number of stages done by private vehicle from 2013 to 2018 (Ajuntament de Barcelona, 2014). In the prediction done in this project, when assuming everything to be constant, the private vehicle usage decreases in percentage of use $-0.08\%$, but due to the expected increment in total number
of displacements, the number of trips done by private car is expected to increase in 4% respect from 2015.

Some scenarios have been proposed by authorities in order to achieve the exposed objective of reducing private vehicle usage. The unified tramvia operating the whole Diagonal and the Superilles (superblocks) are some examples of them. Knowing the direct effects all these changes may have on mobility (trip time reduction in non-motorized mobility and public transport, and working against private vehicle), and introducing them to the calculator as generalized costs variations, it is expected to know how they may affect in the mobility in the Metropolitan Area of Barcelona.

With it, this calculator is expected to help authorities when deciding which decision may represent a better benefit for society, and if the benefits are worth enough to do the inversion.

**Calculator functioning**

For using the calculator, only the following steps will have to be done:

1. Defining both aggregated and disaggregated ATM 2010 OD matrices (default or new).

2. Defining both aggregated and disaggregated ATM 2015 OD matrices (default or new).

3. Defining aggregated ATM 2020 OD matrix (default or new).

4. Defining generalized costs in 2010, 2015 and 2020 (following equation (3.3.1a) or not).

   (a) If using equation (3.3.1a), defining time in 2020, the value of time and out-of-pocket costs.

   (b) If not, introduce the new generalized costs values.

By using all the default data, the same results than in section 3.4.5 would be obtained.

The calculator could also be used for predicting the mobility in other regions. In that case, the OD matrices should be changed to OD matrices from the desired area, and so do the rest of parameters.
3.5 Method strengths, and possible improvements

The model presents some strong points, already exposed, which are pointed here:

- Its simple application, especially when using Euclidean distance. In case the election were between two modes, using Aitchison distance is as simple as Euclidean, and more exact.

- The flexibility the method presents, being easy to change the number of modes present in the modal choice, or divide it into occupational and personal displacements. It can also include variations inside the same mode, i.e. bus and rail for public transport, car and motorbike for private vehicle or bike and walking for non-motorized mobility.

- Being the method so disaggregated as it is, presenting two very differentiate parts which are updating first the aggregated OD matrix (steps 1 and 2 in the four steps transport model) and the modal choice (step 3), it is easier to solve any detected inaccuracy.

While all the exposed points above are strengths, the model presents some weaknesses that must be taken into account:

- The model is deterministic, not stochastic. As all models involving decisions, although the decisions are done taking into account some parameters (the ones that generalized costs try to represent), there is always a stochastic aspect in the decision. Other models like logit are better in this aspect.

- The flexibility values \((\epsilon_k)\) are defined as constant, which may not be true. Depending on the value of the generalized cost or the variation on it, it is possible that the flexibility values become variant.

- There is no variation between the trip time and the waiting time (for example when waiting for the bus), which are perceived differently (being the second one more negative than the first).
As the model is based on the four steps transport model, it does not contemplate the generated trips due to the new infrastructures or costs; it only considers how the old demand is distributed into the different transport modes under the new conditions.

An usual problem when modelling the mobility, especially in areas as big as the Metropolitan Area of Barcelona, is the poor data available. Being the data not as reliable as it should, it is not possible to achieve complex and accurate models.

However, in the near future it is going to change. The appearance of mobiles and GPS, the intelligent cards such the T-mobilitat\textsuperscript{8} and the Big Data, together with the use of surveys such the EMO, EMEF and EMQ, will change the actual panorama. With it, it will be possible and interesting to do some improvement to what it has been proposed in this work. Moreover, much more accurate models may be achieved.

\textsuperscript{8}In annex E.1.1 it is explained deeper.
Chapter 4

Conclusions

The first objective of the work has been defining the mobility in the Metropolitan Area of Barcelona in 2015 and obtaining the bus and private vehicle ATM OD matrices, and it has been completed successfully. The matrices were provided to ATM, becoming a tool for them for future mobility planning, and some interesting conclusions have been obtained after the 2015 mobility has been analysed.

The number of displacements occurred in a weekday has decreased since 2010, especially due to the minor number of trips done by non-motorized mobility (walking or by bike) that, representing almost 50% of total, has decreased from almost 8 millions diary to 7.5. It has affected in urban mobility particularly, where most of the non-motorized trips are present. Meanwhile, the rest of the transport modes has increased their usage.

Rail and bus transportation, although together conform public transport mobility, present different evolutions. On one hand, in the rail case the number of trips with origin or destination Barcelona has increased, while the rest (except for Baix Llobregat internal mobility) has decreased. On the other hand, bus use has increased from 2010 is all the RMB except for Barcelona, where it has decreased 3.8%. It could be caused by the bus net variation that has changed most of the old lines in Barcelona by new ones. Maybe these are changes that people are not still used to. Moreover, the increase in rail transportation in Barcelona (in which Metro
is included) may be a result of it.

The second objective has not been achieved completely. When trying to model the mobility in the Metropolitan Area of Barcelona one conclusion can be extracted: people do not select transport mode according to trip costs parameters exclusively, including cost time. Although it can be assumed as true that it is a parameter when selecting the transport mode, it has been demonstrated that people do not follow a deterministic patron in the election. There are several reasons why it happens, and probably the cause that makes the cost time model not being able to model the modal choice is the combination of some of them.

The first reason is the reliability of the data. Along the same lines is the lack of information about the incapability of using any of the transport modes, especially the non-motorized ones (due to health or the lack of bike) and the private vehicle.

The second reason is the existence of other parameters, apart from the generalized modal cost, that may appear depending on the motive of the displacement. For example, when shopping people may prefer going by car due to the need to transport the purchase, although being the most expensive mode in cost and time. Due to their different nature, separating the occupational and personal displacements could resolve this reason, especially in the first ones where the generalized modal costs may be the only existent parameter in the modal choice.

Finally, the last reason and, probably, a common one that may have affected to most of the modal choices is the fact that people do not calculate so accurately the cost of each mode, so the probable miscalculation or misinformation could be the reason why people modal choices are not the ones they would select in case they knew it exactly.

For these reasons, stochastic models such logit are the ones used when modelling mobility instead of deterministic ones, even if they are conceived to consider different patrons like the one built in this research. Uncertainty could be added to the proposed model, but to do so the data should be much more reliable than it is nowadays. In the near future, the appearance of new technologies as GPS, T-mobilitat and Big Data is going to make it possible.
In spite of not being possible to define the modal choice using the cost time model, an alternative method has been proposed and proved to work. This method assumes that the variation in the generalized costs of each transport mode affects to modal choice the same way the changes in the past have affected it. The method proved to work predicting the mobility in 2015 and checked with the real one.

After that, it has been used to predict the mobility in the Metropolitan Area of Barcelona in 2020 according to actual predictions and, more importantly, a calculation tool has been built. The calculator is expected to be able to update the 2020 prediction according to the real evolution of the parameters instead of their prediction, and as a predictor for authorities like ATM to know the consequences that any implementation or change done on the infrastructures or transportation prices could have in the mobility.

In conclusion, the direct products of this research have been the disaggregated ATM OD matrices 2015 and the predicted 2020, the updating method itself (including both aggregated ATM OD matrices update and the modal choice modelling, in which the calculator is based on) and the predictor tool.
Chapter 5

Bibliography

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