Final Degree Project
Master in Logistics, Transport and Mobility

Evaluation of the spatial impacts of improved connectivity from urban transport investments.

A GIS (Geographic Information System) application of the ICON indicator.

Author: Hector Tapia
Director: Mateu Turró
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Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports de Barcelona
Escola Tècnica Superior d'Enginyeria Industrial de Barcelona

Abstract

A well-designed urban public transport policy provides significant benefits: ensures a more efficient transport system that reduces costs, congestion and environmental impacts. Accessibility indicators are used by planners to assess the spatial effects of their proposals and to identify those areas requiring actions to ensure minimum conditions of service. They are also used in decision making on the implementation of new infrastructure projects or improvement of the existing ones.

This research will first review the ICON indicator, which evaluates the connectivity of a location to the transport networks as a function of the minimum time required to reach the connection nodes of each network and the utility provided in these nodes. In the interurban ICON these networks include roads, railways, but also, ports and airports.

ICON is being used in planning and in project appraisal to quantify in an understandable way the relationship between transport infrastructure and services endowment and variables that are spatially defined. But it has been seldom used in the urban environment context because its particularities introduce important methodological difficulties. Therefore the proposed research presents the adaptation of the ICON indicator to the public transport endowment of urban areas.

The main objectives of the research are: the definition of a suitable URBan Indicator of CONnectivity (URBICON) providing a quantified spatial measure of connectivity to the transport networks, to integrate this indicator with other information (population, economical activity) and GIS tools in order to generate complex spatial indicators and to analyse the potential of these indicators in the planning process and in project appraisal. Implementing this ICON indicator in GIS tools allows, for instance, to produce a visual reference, on a map of the territory, of the most disadvantaged areas from the standpoint of its connectivity to the networks and, of the impact that the new transport projects would have on them.

An application to the case of the city of Barcelona is presented, based on its public transport endowment in the year 2004. The URBICON indicator has been used to detect the areas that were poorly covered by the public transport system in 2004. Some of these areas are already covered by new or improved infrastructures and services and others should be served by 2014. This indicates that the areas identified with the URBICON correspond to those where planners have somehow decided to improve public transport services. URBICON thus appears as a powerful quantitative indicator to support urban planning.

This TFM presents the first part of the research, including the following points: research context and main objectives, review of the ICON concept, definition of the URBICON, its application to the case of the city of Barcelona, conclusions derived and further research.

Index

1 Introduction

This project will take place in the context of a research line that has been developed at the Civil Engineering School of the Polytechnic University of Catalonia (UPC, Barcelona) over a long period of time.

The main purpose is to go one step forward in the research about indicators of accessibility to the transport networks (or connectivity) and particularly about using the ICON indicator in urban areas. ICON allows quantifying the connectivity of a determined place to the transport networks as a function of the minimum time required to reach the connection nodes of each network and the utility provided in these nodes. In the interurban ICON these networks include roads, railways, but also, ports and airports.

The ICON development originated in the study "Analysis of the Isolated Zones in the Mediterranean Regions", made by the CITRAME (Interregional Transport Commission for the Mediterranean) between 1987 and 1989. Its main purpose was to evaluate the transport infrastructure endowment in the European part of the Mediterranean Basin, especially to detect the most isolated areas in each region and to assess the accessibility improvement that could be obtained through the suppression of network discontinuities, especially found in the borders between regions. A first connectivity map for the European Mediterranean Regions based on ICON was produced. A deeper theoretical development of this indicator was carried out by Turró (1989) and Ulied (1995).

Since then, ICON has been used at European level (for instance, in an atlas published by ESPON (2004)) and also for project appraisal (Mcrit (1996) and European Investment Bank - EIB- with the support of Mcrit (1999)).

The proposed research aims at further developing this line of research in the very complex urban set up, notably through a technical component and an evaluation component. The technical part aims at the improvement of the theoretical model to better reflect "public transport endowment" and through the use of new information tools, especially those linked to geographic information systems (GIS) which have had a strong development in the past few years. The evaluation component seeks to find ways of incorporation the spatial effects identified by the ICON indicator into plans and projects appraisal.

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2 Research context and objectives

2.1 Urban Transport

Activity concentration in cities has many positive aspects. Economies of scale and scope enabled by this concentration contribute to the economic growth in the area, with the consequent increase in jobs and wealth, in a revolving process of attraction that explains the increasing urbanization worldwide. On the other hand, it entails negative aspects, such as congestion and environmental impacts. To enable the smooth functioning and development of the city, we must therefore ensure good and sustainable mobility. The existence of an efficient urban transport system with few externalities is a critical factor for this and therefore for the city's economic competitiveness and for the quality of life of its inhabitants.

The traffic situation in most medium and large cities is burdened with serious congestion problems. As demand expands and urban roads construction is extremely difficult and expensive, acceptable mobility conditions can eventually be provided only by a good public transport system. Social cohesion requires that adequate public transport services be available to all (or most) inhabitants of the city, which implies a good geographic coverage, adapted services at reasonable fares and proper physical accessibility (particularly for the elderly and people with reduced mobility).

The proposed research concentrates on geographic coverage on the premise that availability of public transport services, including for those who do not own a car, low-income groups and young people which need access to economic and social activities, is an essential social cohesion factor but also on the principle that all inhabitants must have access to sustainable mobility options.

The existence of a well-designed urban public transport policy provides significant benefits: ensures a more efficient transport system that reduces costs, congestion, accidents and environmental impacts. Moreover, such a policy should aim to mitigate one of the main problems of suburban areas, which is the poor connectivity between them, particularly by public transport, as this usually only connects them with the centre of the community. To properly develop such policy, it is essential to create tools allowing the quantification of the accessibility provided by the public transport system. Accessibility indicators allow planners to assess which areas require the most urgent actions in order to give them the minimum conditions of service.

2.2 Mobility demand on urban regions

Krupnick (1992) has observed that in the US people have more cars, drive them futher each year, and use them on more trips (particularly from non-work and off-peak trips). These trips occur in progressively more congested conditions, with lower occupancy rates. This statement could be universally accepted nowadays.

The time that most people only made daily trips home-to-work or home-to-school is over. "Traffic problems such as congestion and massive energy consumption by private vehicles can no longer be considered merely as a rush-hour problem, and they therefore become less controllable. This situation is caused by the increasing diversification of transport needs, generated by more diverse population groups."(Portal, 2003)

This statement is confirmed in Table 1, which shows the results of a study on the reasons for travel in the city of Flanders (Belgium), which could be representative of other European cities. It may be noted that trips with purposes of going from home to work or school are starting to be less important, being in this case lower than shopping or entertainment.

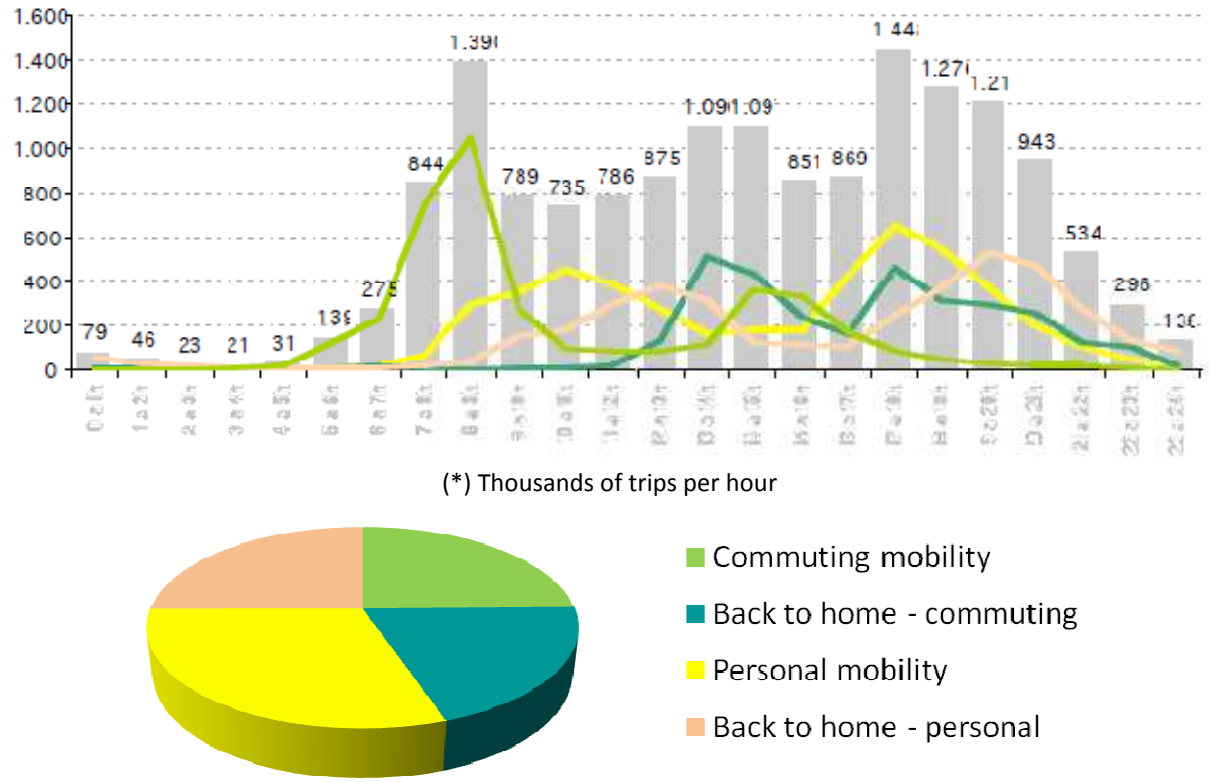
Trip purposes	Share
Services	3.2%
Business traffic	5.0%
Home to school	9.1%
Home to work	18.6%
Shopping	21.9%
Leisure	33.0%
Others	9.2%

Table 1. Importance of the different trip purposes,
(% of average number of trips per day, Flanders, Belgium, 1996)

This diversification leads to greater mobility between different parts of the urban landscape. Since trips are no longer produced mostly between residential areas and work (CBD) or education (schools, universities), they are now much more widely scattered. This dispersion in the origins and destinations of the trips makes the demand of transportation much more unpredictable in the short-term. Furthermore, it leads to more complex public transport networks, requiring exchange points between different lines or ways to meet the mobility needs of users.

The major number of personal purpose trips in front of the commuting trips is observed in a biggest environment as is the Metropolitan Region of Barcelona. The 2006 Daily Mobility Survey (EMQ06) shows again that the personal mobility represents more than 55% of the total trips on a weekday (see Figure 1).

In the next decades with new technologies, more free time and possible growing GDP, these trends may be accentuated.



(*) Thousands of trips per hour

Figure 1. Weekday travel demand in Metropolitan Region of Barcelona (RMB)
Source: Daily mobility survey 2006 (EMQ 2006)

2.3 Transport and spatial development

The exact role that transportation plays in urban and regional development has been discussed for a long time. Long-term studies in various parts of the world have demonstrated that the demand for transport of goods and passengers has usually increased more quickly than the GDP per capita. In development countries, transport demand has grown annually on average some 20-25% more than GDP and, in developing countries, this percentage is around 50% (Batten & Thord, 1989).

The social or economic distance between the places not depend on the physical geography but rather in the conditions of their connection to the transport and communications networks. The development of transportation systems in economic development countries implies that, in these areas, the absence of one kind of connection is more relevant to hinder regional development than the presence of an optimum connection is to stimulate development.

The clear distinction that once existed between largely homogeneous areas like “city”, “suburbs” and “country side” have now diminished to be replaced by the subtler boundaries between different urban realms with specific functional and social identities (Rowe,1991).

In American cities, the traditional intensive tertiary downtown and low residential suburbs model is broken by the emergency of intensive developments nodes in the periphery. *The structure of the metropolitan regions spontaneously tends to become polycentric* and in some cases transit improvements (light railways, for instance) and other projects begin to improve the public spaces in old centres as well as increase the urban quality of new suburbs.

Plassard (1992), Vickerman (1993) and other European experts have observed the impact that transportation networks will induce in the larger context of the European spatial development:

- Extension of links: increased speed requires longer distances between stops. In France in 1930 every sub-prefecture had a railway station; nowadays not all regional capitals have high speed railway stations.
- Polarization in the nodes and spatial discontinuities in the spaces between the nodes. Some authors have pointed out that transport infrastructures increase the utility of the places connected to the nodes (in terms of development opportunities) and decrease the utility of the places along the infrastructure.
- Creation of corridors. While the advantages are only felt in the surrounding spaces of the nodes in the network, environmental costs are felt throughout the length of the infrastructure.
- Increasing conflicts in the interconnection between modes, especially between interregional and urban transit systems.

All these effects proposed by Plassard and Vickerman can be observed in the deployment of the new high speed lines in Spain. With this high speed services linking big cities and regional capitals, most of the regional services have been eliminated, leaving the towns between them with less than the half of services they had before. This is clearly seen in the case of the high speed line Madrid – Barcelona. Before the HST implementation, medium speed and regional services stop at the main cities and villages 8 or 10 times per day. Now due to the fact that HST services don’t stop there and most of the regional services are closed because of the decreasing demand, these towns have only 2 or 3 trains per day.

These changes in transport accessibility can induce that the population of towns located in the middle of a link between two HST stations decreases rapidly in favour of the population of cities with HST. Thus, big cities will trend to grow to the peripheral area in detriment of other cities located far away from HST stations. This can be the case of the city of Girona, located at 100 km north of Barcelona, which will be linked together in 2014. Travel time to Girona will be then about 30 minutes, less than the one needed to reach most of the towns between them by car or regional train.

As Ulied (1995) suggests: *The distance between two places depends on the kind of networks that are linking them rather than on the geographical distance. The spatial periphery is*

defined rather by the "connectedness" to the network than by the geographical "remoteness".

In the future integrated world economic system, the currently expanding metropolitan areas will become nodes connected to international networks of relations rather than centres of their traditional surrounding territories (Vikerman, 1992; Plassard, 1992).

The connectivity to the networks (measured as the facility to reach the connection node and the utility of the available services there) provides the best way to analyze the contribution of transport and communication networks to the creation of spatial centrality and to the induction of urbanization patterns (Turro & Ulied, 1990).

2.4 Evaluation of actions in urban transport

The development of the city requires continuous improvement of existing transport infrastructures and the creation of new capacity and new and better services. Decision making about implementation of these projects needs to estimate their financial and technical feasibility, as well as their socio-economic profitability to ensure good use of society's resources. The methodology for assessing this profitability is complex (see, for example, URBPAG, Urban Project Appraisal Guidelines, the method used by the EIB) and has some particular difficulties. One of them is how to incorporate in the appraisal the value of providing an adequate geographical coverage of public transport services. The strong connection between transport and land use and consequently the impact of transport investment on real estate values, requires that decision makers take into account the spatial effects of infrastructure and transport services.

The urban connectivity indicator (URBICON) developed here can provide the needed quantification of such coverage and improve the efficiency of the decision-making process presenting, in a clear fashion, both the different conflicts and opportunities created by the investment alternatives. The indicator may also be used to quantify the relationship between public transport endowment and variables that are similarly spatially defined in the urban area.

The ICON has been used effectively in the past for these purposes, but the particularities of the urban environment make very difficult to apply the same methodology created for the interurban context. URBICON is an adaptation of ICON to urban public transport, which tries to reflect, also through a pure time value, both the ability to reach, from a certain location in the urban area, the nodes of the public transport networks, and the quality of service provided in these nodes.

2.5 Geographic tools

GIS are tools that allow geographic information data storage associated with specific points of the territory. You can associate them to different databases and thereby integrate demographic, economic and indeed data on the transport system.

The opportunity to use these tools in the evaluation of transport infrastructure projects has been raised, but the reality is that GIS are seldom used in project appraisal. There is a thus a major challenge to include in the socio-economic analysis the characteristics of the territory affected by the project and to show in a comprehensible way the spatial effects it would entail (improved accessibility, changes in land value, etc.).

GIS indicators, including ICON, will allow, for instance, producing a visual reference, on a map of the territory, of the most disadvantaged areas from the standpoint of its connectivity to the networks and, of the impact that new transport projects would have on them. These indicators can help decision-makers and provide government agents with a type of information, understandable by most citizens, about the need for new projects.

2.6 Research objectives

The objectives of the research are:

- To define a suitable URBan Indicator of CONnectivity (URBICON) providing a quantified spatial measure of connectivity to the transport networks (public transport networks and major intermodal centres such as stations, port and airport) in the urban context/area.
- To analyse the weight to be given to the transport services provided in the public transport nodes (bus and tram stops, underground stations and intermodal key points) in order to achieve a reasonable measure of connectivity to the networks. The services provided at these connection points (frequencies, quality of service, commercial speed...) will be the most relevant factor to define the nodes' utility.
- To carry out a practical application, using information available (existing graphs of the road network and the public transport network), to detect the difficulties of obtaining the information required by URBICON.
- To integrate this indicator with other GIS information (i.e. population, economical activity and so on) and tools in order to generate complex spatial indicators adapted to planning and evaluation requirements.
- To analyse the potential of the previous indicators in the planning process and in project appraisal (particularly in assessing the impact on the most disadvantaged urban areas), initially in multicriteria analysis and eventually in CBA through its adequate monetisation.

The practical application of URBICON to the Metropolitan Area of Barcelona, an urban area having the necessary GIS and sufficient transport and spatial information, will be essential to ensure the usefulness of the indicator.

2.7 Work program

The research has an estimated duration of one year and includes a series of tasks described below:

1) Definition of accessibility measures. Comparison between the different accessibility measures to choose the ones that can fit our purposes, following the studies made by, amongst others, Pirie (1979), Turró (1989), Ulied (1995), Geurs and Ritsema van Eck (2001) and Geurs and van Wee (2004).

2) Based on the selected measures, define the parameters to be included in the urban ICON, such as frequency, commercial speed, service quality, etc, and study their viability as policy indicators. Identify the relative importance that should be given to each parameter. Evaluate the need to introduce factors indicating the variability of service conditions during the day.

3) As all these measures are time dependent, it is necessary to define how travel time is measured. Then, taking into account that the user has many public transport alternatives, a transit assignment algorithm must be selected, like the ones proposed by Dial (1967) or Spiess and Florian (1989).

4) Define the initial urban ICON indicator (URBICON) so it gives a comprehensive measure of the accessibility to the public transport network.

5) Analyse the state-of-the-art GIS applications that currently can measure accessibility and assess if they can be used to calculate the Urban ICON. Liu and Zhu (2004) developed an application called Accessibility Analyst for the ArcView 3.2 which is no longer supported by the development company. Some current candidates are TransCAD, ArcGIS or the SIMCAT system, developed by Mcrit (www.mcrit.com, Barcelona, Spain) for DPTOP (the regional Ministry of Public Works).

6) Once the model to calculate the Urban ICON indicator is well defined and the best GIS application has been adapted to map it, determine the process to apply it to the case of Barcelona Metropolitan Region (RMB).

7) Collect all the data necessary to perform the calculations, like the graphs of the road network and the public transport network, transit lines specifications (stops, headways and commercial speeds), access and egress links characteristics, etc.

8) The use of SIMCAT will require signing agreements with DPTOP and Intergraph (owner of the GIS-based software) to have access to the system and an agreement with Mcrit (SIMCAT system developer) to get training and installation support.

9) Training on the current content and use of the SIMCAT system or other GIS used.

10) Basic analysis of the ICON results in the urban areas of the RMB and redefinition of the indicator if it is necessary. Depending on this first analysis, it would be useful to add parameters to the model that could refine the results or remove the ones that don't provide realistic results.

11) Overlay ICON on a map of the RMB to detect those areas that are poorly served and analyse whether this information may be of interest to the decision-maker.

That is, evaluate the possibility of incorporating this indicator in the planning of new or improved transport infrastructures and in the analysis of the profitability of these investments.

3 Definition and measurement of accessibility

3.1 Definition

Accessibility is a frequently-used concept but there is no consensus about its definition and formulation. It is commonly defined as the ease with which activities can be reached from a certain place and with a certain system of transport (Morris et al., 1979; Johnston et al., 2000). The concept generally takes the combination of two elements into account: the location on a surface relative to suitable destinations and the characteristics of the transport network (Vickerman, 1974). Handy and Niemeier (1997) suggested that accessibility is determined by the spatial distribution of potential destinations, the ease of reaching each destination, as well as the magnitude, quality and character of the activities found there.

Geurs and Ritsema van Eck (2001) formulated a very complete definition of the concept: according to them, accessibility reflects *''the extent to which the land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)"* (p. 36). This implies that the concept of accessibility is determined by four interdependent components: a transport component (transport system), a land-use component (the magnitude, quality and characteristics of activities found at each destination), a temporal component (availability of activities) and an individual component (needs, abilities and opportunities of individuals).

Bhat et al. (2001) classified the accessibility measures in five types: spatial separation, cumulative opportunities, gravity, utility, and time-space. Spatial separation measures use the distance between a location and every other location in the study area as the value of accessibility. Cumulative opportunities measures consider the attractiveness of a journey by the summation of these attractions or opportunities within a specified travel time or distance. The gravity measure type is a continuous measure that sum attractions in a study area but decreasing their value with increasing time or distance from the origin. Utility measures are based on an individual's perceived utility for different travel choices. These measures take the form of the natural log of the sum of the travel choices. Time-space measures take into account the time constraints of the individuals being considered.

Another classification was established by Geurs and Ritsema van Eck (2001), who suggested four basic perspectives: infrastructure-based measures, activity-based measures, person-based measures and utility-based measures.

3.2 Review of accessibility measures

3.2.1 Topological measures

Graph Theory allows accessibility to be defined solely in relation to the transportation network's configuration, independently of the social or economic interest of the existing relations.

The Shimbel Index measures the minimum number of links necessary to connect one node with all other nodes in a defined graph. The Shimbel index of each node is obtained by adding the number of links which separate this particular node from each of the others by the shortest path and may be expressed as:

$$S_i = \sum_{j=1}^{N} d_{ij} \qquad \text{(Eq. 3.1)}$$

where S_i is the Shimbel index of the node i in a network with N nodes and d_{ij} is the number of edges corresponding to the shortest path between nodes i and j.

This formulation can be modified to give a measure of accessibility:

$$A_i = \sum_{j=1}^{N} t_{ij} \qquad \text{(Eq. 3.2)}$$

where Ai is the accessibility in node i and t is the travel time from node i to node j. Then, the formal structure and characteristics of the transportation network is what defines the relative accessibility of each node in relation to the others.

3.2.2 Infrastructure-based measures

These measures are used to describe the functioning of the transport system. They analyse the performance or service level of transport infrastructures, such as travel times, level of congestion and average travel speed on the road network. This measure type is typically used in transport planning.

The UK Transport 2010 policy plan (DETR, 2000) was evaluated using congestion and total time lost in congestion as accessibility measures.
The drawback of this measure is that do not incorporate the land-use component, temporal constraints or individual characteristics. For example, Linneker and Spence (1992) illustrated that inner London has the highest access costs (in terms of time and vehicle operation costs) in the UK, but the highest level of potential accessibility to jobs, despite the high travel cost. (Geurs and van Wee 2004, p. 131)

3.2.3 Location-based or Activity-based measures

These measures describe the level of accessibility to spatially distributed activities, such as “the number of jobs within 30 min travel time form origin locations”. These measures are typically used in urban planning and geographical studies. Location-based measures can be also classified in different types.

A *contour measure*, also known as *isochronic measure* or *cumulative opportunities*, counts the number of opportunities which can be reached within a given travel time, distance or cost. This measure can be expressed as follows:

$$A_i = \begin{cases} \sum_j O_j, & \text{if } t_{ij} \leq T \\ 0, & \text{if } t_{ij} > T \end{cases} \qquad \text{(Eq. 3.3)}$$

This measure indicates that accessibility increases if more opportunities can be reached within a given travel time or distance. This increase can be the result of a shortening in travel times due to infrastructure improvements and/or land-use changes that lead in a growth of opportunities.

Contour measures are relatively undemanding of data an easy to interpret for policy makers, as no assumptions are made on a person's perception of transport. But this measure presents several drawbacks:

- As measures do not take individuals perceptions and preferences into account, it implies that all opportunities are equally desirable, regardless of the time spent on travelling or the type of opportunity.
- The arbitrary selection of the isochrone (or isodistance) of interest. If the maximum time or distance chosen increases, the level of accessibility in the origin increases too.
- The lack of differentiation between opportunities adjacent to the origin and those just within the isochrone of interest.

To avoid introducing subjective or arbitrary spatial boundary, potential measures can be used.

Potential or gravity-based measures allow accessibility to decrease gradually as the travel time to destinations increases. They estimate the accessibility of opportunities in a given zone i to all other n zones in which more distance opportunities provide diminishing influences. The measure has the following form:

$$A_i = \sum_{j=1}^{n} O_j F(c_{ij}) \qquad \text{(Eq. 3.4)}$$

Where A_i is a measure of accessibility in zone i to all opportunities O in zone j, c_{ij} the costs of travel between i and j and F(cij) the impedance function. Hansen (1959) used a power function adopted from Newton's law of gravity:

$$A_i = \sum_{j=1}^{n} O_j d_{ij}^{-\alpha} \qquad \text{(Eq. 3.5)}$$

Where d_{ij} is the distance between i and j and α is a parameter reflecting distance deterrence. Alternative distance decay functions can also be used such as Gaussian, logistic or negative exponential functions:

$$A_i = \sum_{j=1}^{n} O_j e^{-\beta c_{ij}} \qquad \text{(Eq. 3.6)}$$

Potential measures have some drawbacks:

- The self-potential (the number of opportunities within origin zone i weighted by the average travel time within that zone) may have an important influence on the calculation of the accessibility. For instance, the contribution of a city to its own accessibility may be considerable for large cities. The use of small zones or areas leads to less dependence on the self-potential, being a good way to avoid this problem.
- These measures show the spatial distribution of destinations (e.g. jobs, shops), but do not account for the spatial distribution of the demand for those opportunities (e.g. inhabitants). Thus, it is assumed that the distribution of the demand does not affect the accessibility level of opportunities.
- The distance decay function used has a significant influence on the accessibility measure. For plausible results, the form of the function should be carefully chosen and its parameters estimated using recent empirical data. For instance, with a distance decay parameter of α=2, 100 jobs at a distance of 100 m have the same effect on the score as 1,000,000 jobs at a distance of 10 kilometres, so potential values seem to overstress the very short distances.

3.2.4 Person-based or space-time measures

Person-based measures analyse accessibility at the individual level, such as “the activities in which an individual can participate at a given time”. They are founded in the space-time geography of Hägerstrand (1970) that measures limitations on an individual’s freedom of action in the environment, i.e., the location and duration of mandatory activities, the time budgets for flexible activities and travel speeds allowed by the transport system.

The strongest disadvantages are related to operational matters and communicability. Some difficulties are the detailed individual activity-travel data required (individual’s time budgets are often not available from standard travel surveys), their computational intensity and the lack of feasible operational algorithms (Kwan, 1998).

The applications are often restricted to a relatively small region or subset of the population because of the large data requirements. Accordingly, the results are difficult to aggregate to the entire population or to a higher geographical scale.

3.2.5 Utility-based measures

These measures are founded in economic theory and analyse the (economic) benefits that people derive from access to spatially distributed activities.

Utility theory addresses the decision to purchase one discrete item from a set of potential choices, all of which satisfy essentially the same need, and can be used to model travel behaviour and the net benefits of different users of a transport system.

If it is assumed that an individual assigns a utility to each destination choice in a choice set and selects the alternative which maximises his or her utility, accessibility can then be defined as the denominator of the multinomial logit model, also known as the logsum. The logsum serves as a summary measure indicating the desirability of the full choice set (Ben-Akiva and Lerman, 1985):

$$A_i = \ln\left(\sum_{m=1}^{M} e^{V_k}\right) \qquad \text{(Eq. 3.7)}$$

Where Ai is a measure of accessibility, Vk is the indirect or observed utility portion of the choice k (i.e. a combined mode-destination choice) for a person n.

The measure has a better behavioural basis than the basic potential accessibility measure, i.e. utility-based measures represent accessibility of individuals at a location, whereas potential measures represent accessibility of a location assuming all individuals in the same location have the same level of accessibility.

The major disadvantage of this measure is that it is not easily interpreted and cannot be explained without reference to relatively complex theories of which most planners and decision-makers will not have a complete understanding (Koenig, 1980).

3.3 Comparative analysis of measures

Location-based or activity-based measures are very useful to calculate accessibility to certain activities and were widely used in the accessibility to jobs evaluation. As seen before, the transport demand in urban areas depends now more on personal purposes than for commuting. Thus, this type of measure applied to one particular activity cannot be generalised as a measure of accessibility for a given point.

Person-based measures are very difficult to apply due to the detailed individual activity-travel data required and the lack long-term tested algorithms.

Topological measures are easy to use and to explain as they basically compute travel times, but don’t incorporate the utility provided by the transportation networks.

Utility based measures are good option for urban accessibility evaluation as they incorporate the distance or time impedance and the utility perceived by the users, but they are really difficult to explain and interpret.

An alternative to these measures is the ICON indicator, developed in previous researches for the evaluation of regional accessibility. Because ICON is focused on the supply side (analysing the transportation endowment of a given place), no personal information is needed and it is easy to explain and understand, it is reviewed to assess if their application in urban environments is feasible.

4 Review of the ICON concept

The Connectivity Indicator (ICON) aims at quantifying with a time value the proximity of a given point to the basic transport networks. ICON evaluates the connectivity as a function of the minimum time required to reach the closest node (or nodes) of a network and the utility provided at this node for each of the transport networks considered. In the original formulation, the adopted approach for measuring the connectivity to the "spaces of the flows" (or where the economic activity circulates) was to consider the motorway network, the main rail lines, ports and airports. The utility of the nodes in these networks was associated to the continuity of the networks and to the traffic handled.

This approach is not adopted to urban areas where "activity flows" are much more complex and diffuse. The concept was thus adapted to measure the time to access public transport services of sufficient quality. This quality depends on the number and characteristics of the mobility opportunities supplied in the accessible (closest) transport nodes of the different networks. In a first approach, the utility provided by a node may be negatively associated to the average time needed to get a pre-defined type of service.

Theoretical travel times based on standard conditions can, in some cases, substantially differ from real travel times (due to delays, due to discontinuities in the quality of networks, bottlenecks, congestion…). They should also be included in a general ICON formulation.

Let's consider the minimum time required to travel between two points, origin (O) and destination (D), which consist in the summation of the time spent in the following stages:

- The access time from the origin (O) to the closest station: tao.
- The average waiting time for the first train linking this station with the one closest to destination: tw.
- The normal travel time between the two stations: tv.
- The non-predictable delays in the trip: tg.
- The access time from the station to the destination point (D): tdo.

Then, the total travel time from O to D is:

$$TT = t_{ao} + t_w + t_v + t_g + t_{ad} \qquad \text{(Eq. 4.1)}$$

This model can be more if the travel between the two points needs more than one transport mode, considering also the access time from one mode to another and the waiting time in the transfer stations.

$$TT = t_{ao} + t_{w1} + t_{v1} + t_{g1} + t_{at} + t_{w2} + t_{v2} + t_{g2} + t_{ad} \qquad \text{(Eq. 4.2)}$$

Simplifying, the total travel time can be expressed as:

$$TT = t_a + t_w + t_v + t_g \qquad \text{(Eq. 4.3)}$$

Since the value of the travel time between any pair of nodes (tv) is quite stable and predictable for most transport technologies, the values of the terms (ta), (tw) and (tg) are of particular importance to reflect changes in transport endowment levels. There is a growing demand for more flexibility and for reducing non-predictable delays. In the context of growing congestion, transport utility depends today much more on (tg) than on (tv).

These considerations do not mean that tv has no spatial impact and its value must be neglected, but continuous improvements in transportation technologies have allowed huge increases in speed. Usually, the maximum commercial speeds are today limited by economical, social and environmental criteria, rather than by technological constraints.

With the current aircrafts and high speed trains, the travel times have been decreased dramatically. Now, it is in the connections between these high speed networks and the urban networks where the major delays are produced. This effect is clearly seen in the following example. The travel time flying between Barcelona and Paris would be around 90 minutes, but access times from the city to the airport or vice versa, would be of around 30-40 minutes, depending on the transport mode or congestion. Also, it's necessary to spend some time for the checking process and for accessing the gate, which can be seen as a wait time in the airport. Thus, the total access plus waiting time is bigger than the travel time.

Given these facts, the traditional emphasis on in-vehicle travel time reductions is changing towards an emphasis on easy interconnection between transport networks, on quick access and on managing the integrated system efficiently.

Furthermore, given the evolution of transport systems towards the simultaneous integration of scales and networks, the improvement of mobility opportunities increasingly depend on adequate interconnections between modes and scales. These considerations have been incorporated in the adaptation of ICON to the urban set up.

4.1 Basic ICON Formulation

For a given network, the general expression of ICON is the following one:

$$ICON = f[t_a, t_w, t_g] \qquad \text{(Eq. 4.4)}$$

ICON is independently evaluated for each transport network (n, n=1...N). Once the modal values (ICONn) are obtained, they are aggregated in proportion to their relative importance. The relative weight of each mode can be evaluated according to the economic development impact of the mode. Mathematically,

$$ICON = \sum_{n=1}^{n=N} p_n \cdot ICON_n$$
$$\sum_{i=1}^{i=N} p_i = 1 \qquad \text{(Eq. 4.5)}$$

where, $ICON_n$ is the value of the indicator for mode n (n=1..N) and p_n is the relative weight of mode n.
The value of ICONn at a given place is based on the minimum access time (ta_{nm}) to reach the closest transport node of the network (n).

To take into account that not all transport nodes in the network (n) provide the same utility to the users connected to them, an additional time (tw_n) is added to the minimum access time to the closest node. This additional waiting time reflects the total utility provided by all alternative connection nodes (j=1, ..., M) beyond the closest one. Above a prefixed total utility level no additional waiting time is considered. The existence of physical gaps and service discontinuities in the networks can be reflected with an additional gap time (tg_n). Therefore, $ICON_n$ can be formulated as follows:

$$ICON_n = ta_{nm} + tw_n + tg_n$$
$$ta_{nm}, tw_n, tg_n \geq 0 \qquad \text{(Eq. 4.6)}$$

The minimum time to reach by car a generic connection mode (j) in the network (n) from the point where ICON is calculated can be expressed as (ta_{nj}, j=1...M). From that set of alternative connection nodes (j=1, ..., M), two have special consideration:

- The closest node to the point, with access time ta_{nm}.
- The node that, among those providing a level of service above the utility threshold required to grant $tw_n = 0$, has the minimum access time, being $ta_{nj} = ta_{nx}$.

Therefore

$$ta_{nm} \leq ta_{nj} \leq ta_{nx}, \; j = 1...M \qquad \text{(Eq. 4.7)}$$

Nodes located at access times between (ta_{nm}) and (ta_{nx}) are considered to provide feasible connection alternatives for the point where ICON is calculated.

Let's define S_{nj} as the level of service of the nodes (j) included in the network (n) and S_{nm} the level of service of the closest node (at minimum time ta_{nm}). $Smin_n$ and $Smax_n$ will denote the minimum and maximum service levels prefixed for the network (n). Nodes with service levels lower than $Smin_n$ are not considered as feasible alternatives. $Smax_n$ is defined as the high level of service above which any improvement has negligible impacts on increasing accessibility. In points where $S_{nj} > Smax_n$, no additional waiting time is considered ($tw_n = 0$).

Following that, when the closest connection node (at minimum time ta_{nm}) reaches or exceeds $Smax_n$, the value of the additional time is zero (tw_n=0). Otherwise, it will have a positive value. In this case, all alternative connection nodes with higher access times ($ta_{nj} > ta_{nm}$), with corresponding S_{nj}, will be considered and their services properly aggregated.

Based on these considerations, the following condition is adopted to calculate (tw_n):

$$\begin{aligned} &\text{if } ta_{nm} = ta_{nx} \text{ then } S_{nm} = S_{nx} \text{ and } tw_n = 0 \\ &\text{if } ta_{nm} < ta_{nx} \text{ then} \\ &\qquad tw_n = \delta_n \cdot [ta_{nx} - ta_{nm}] \end{aligned} \qquad \text{(Eq. 4.8)}$$

verifying:

$$\begin{aligned} 0 \le \delta_n \le 1 \\ 0 \le tw_n \le ta_{nx} - ta_{nm} \end{aligned} \qquad \text{(Eq. 4.9)}$$

δ_n is an aggregated measure of the utility provided by all alternative connection nodes whose access times ta_{nj} are above ta_{nm} and below ta_{nx}.

The utility provided in a connection node supplying a service S_{nj} is defined according to a conventional diffusion formula as follows:

$$U_{nj} = S_{nj} e^{-\beta_n (ta_{nj} - ta_{nm})} \qquad \text{(Eq. 4.10)}$$

where β_n is a free parameter depending on the network.

The aggregated utility provided by all connection nodes is evaluated according to the following formulation:

$$U_n = \sum_{j=1} U_{nj} = \sum_{j=1} S_{nj} e^{-\beta_n (ta_{nj} - ta_{nm})} \qquad \text{(Eq. 4.11)}$$

And then δ_n can be defined as:

$$\delta_n = \frac{1}{1 + a \cdot e^{-b \frac{Umax_n - U_n}{Umax_n - Umin_n}}} \qquad \text{(Eq. 4.12)}$$

where a and b are arbitrary positive parameters to be adjusted. $Umax_n$ is the utility provided by the service level $Smax_n$ when $ta_{nj} = ta_{nm}$, therefore $Umax_n = Smax_n$. $Umin_n$ is the utility provided by $Smin_n$ when $ta_{nj} = ta_{nm}$, therefore $Umin_n = Smin_n$.

The utility of a given mode can be quantified by one or more of these indicators:

- Value of mobility opportunities it supplies. For instance, for a railway station, the number of services linking it with major destinations and/or the opportunities for daily round-trips to them.
- Infrastructure capacity, for long-term evaluations.

- Existing traffic, for short-term evaluations.
- Qualitative evaluation using comparative standards and/or public surveys.

Very often the only available information to evaluate utilities is related to overall infrastructure capacities and traffic demand. Thus, this information can be used to its statistical correlation with the opportunities of mobility provided by the node, i.e., the more annual passengers an airport has, the more likely it is that it provides a wider range of services. The determination of the minimum threshold value ($Umin_n$) is crucial, since all nodes having equal or higher utility will be selected and those having lower ($U_j < Umin_n$) will be rejected.

In conclusion, given a set of networks (n=1...N), with nodes (j=1...M) having level of services S_{nj}, the connectivity of a given point in the region can be formulated as follows:

$$ICON = \sum_{n=1}^{n=N} p_n \cdot ICON_n$$

(Eq. 4.13)

$$ICON_n = ta_{nm} + tw_n + tg_n = ta_{nm} + \delta_n \cdot [ta_{nx} - ta_{nm}] + tg_n$$

According to this formulation, for any point ICON provides the measure of its connectivity to the transport networks, basically considering the relative economic weight of each mode (p_n) and the minimum time (or cost) required to reach the closest node in each network (ta_{nm}) increased by the additional waiting times in each node (tw_n) to get a predetermined utility (U_{nx}) and by non predictable delays, discontinuities or gaps during the trip (tg_n).

Regarding the geographical context, it is important to note that the specific scale adopted on each application (local, regional, interregional), requires a specific definition of the physical networks of the selected transport modes. For instance, at the interregional level, only railway stations providing long distance services should be considered, while in a metropolitan analysis all railway stations in the commuter lines should be included.

In the case of an interregional application, the basic transportation modes to be considered could be the following ones: road passengers, railway passengers, air passengers, road freight transport, freight transport by rail, maritime freight transport and inland navigation.

The aggregation of ICONn modal values is made according to a simple weighted addition. The weights represent the relative importance of each mode in the generation of development opportunities, i.e., added economic value of the services carried out by each mode, intermodal traffic or even social perceptions resulting from public surveys.

4.2 Application of the ICON indicator

As an application example of the ICON indicator the *Analysis of the Atlantic Regions* (DGXVI-CEDRE Atlantic Arc Study 1991) is presented. This study was focused on the analysis of the transport situation in the Atlantic European Regions in the context of a prospective study carried out in the European Centre for Regional Development (CEDRE) for the European Commission (General-Directorate of Regional Policies, DG XVI).

The basic objective of the ICON application was to clarify the synergy and conflicts between the different transport infrastructure proposals for the 1995-2000 period, in order to facilitate the definition of a common Atlantic Transport Infrastructure Scheme. The regions analyzed were Andalucía, all the Portuguese Regions and the Spanish Cantabric Regions, all Atlantic French Regions, all United Kingdom Regions and Eire.

The modes included in the calculation of the connectivity were: roads, motorways, railways, ports and airports. The following table contains the value of the basic parameters:

	Roads	Motorways	Railways	Ports	Airports
p Modal Weight	0.25	0.30	0.15	0.15	0.15
Ux Max. Utility	85 km/h	120 km/h	Qualitative index	5 M tons	1.50 M pass
Uo Min. Utility	65 km/h	120 km/h	30	> 1 M tons	> 0.10 M pass
β	37	32	91	—	

The urban structure of Portugal is similar to that of Mediterranean Regions, with a relatively dense urbanized zone along the coast (axis Lisbon-Porto). There is a progressive reduction in transport endowment when moving from the coast towards the interior zones located close to the Spanish border. It is especially interesting to note that this gradient is only partially a consequence of severe topographical or natural development constraints. The upgrading of the road system and the improvement of multimodal connections in ports were considered the most important transport needs. Other needs clearly identified in the analysis were the improvement of interregional connections, especially in the north with Galicia.

The Spanish Cantabric regions have severe topographical constraints and the infrastructures tend to be more oriented towards the Spanish center. Excepts in the case of the Base Country and Asturias, these links were also insufficient and they were perceived as the major transportation constraints for regional development, especially the missing motorway extensions to Galicia. In the next ICON application, the analysis of the Spanish Plan Director de Infraestructuras, the impact of the new Spanish motorway links to Galicia was studied.
The Atlantic French corridor is fragmented in different axes: Bordeaux-Poitiers-Tours-Paris, Nantes-Paris and Brest-Rennes-Paris. There is neither motorway nor railway continuity along a North-South corridor linking these axes. The connections with French central regions as well as the connections between Atlantic ports were felt as the major regional concern.

In the United Kingdom the quasi-continuous urbanized area London-Liverpool-Manchester leaves parts of the coast and the mountains, mostly in Wales and in the northern Scottish

Highlands, as the less accessible areas. The establishment of a regional network of peripheral links between the already existing Atlantic Axe and the different British Atlantic ports along the coast was the major regional objective of the British regions.

In Ireland the basic aspect was the development of a comprehensive motorway network linking the coast (Dublin-Cork) with the interior of the island.

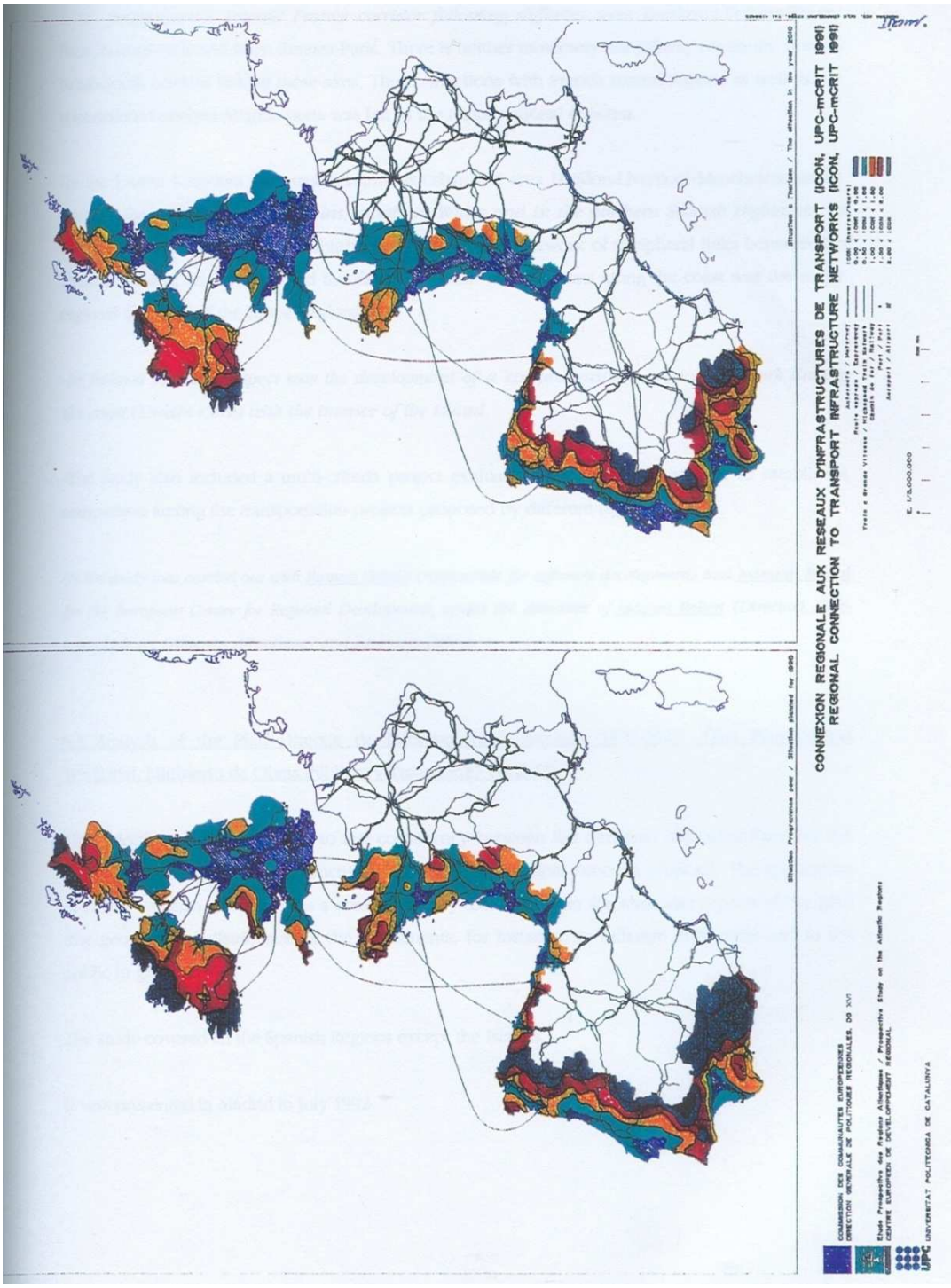


Figure 2. Analysis of the Atlantic Regions: ICON results
Source: UPC - Mcrit

5 URBICON definition

The objective of URBICON is to provide a public transport connectivity indicator for each location (represented as a pixel in the GIS) in the reference area. At a regional or national scale a location has only a few nodes of access to the transport networks nearby. The traveler can choose, for example, between a couple of motorway accesses, two railway stations, a few bus stops and, probably only one port and one airport. On the other hand, inside a medium-sized city, the user may have within a ten minutes walking distance several commuter train, underground, tramway and bus lines. In this case the traveler may use different modes and combinations of modes to reach his destination.

Figure 3 Transportation nodes in the downtown of Barcelona

The needs of travelers and the purpose of their trips are also different depending on the territorial scale considered. At the urban or metropolitan scale, about 40% to 50% of the trips are for commuting, related to work or educational purposes, and are repeated in the same way every working day. The rest are trips for personal mobility, including work-related travel, time-constrained travel, such as for administrative, medical or learning purposes and shopping, leisure and social trips. These trips could be repeated daily, weekly or be one-off. The time budget for each trip in a major urban area depends on its utility, but it is typically around 30 to 40 minutes for commuting. On the other hand, at a national or international scale most trips are singular and seldom repeated. Their purpose (mostly business, holydays, tourism, social, for specific medical treatments, etc.) and destination types are quite different than those for urban trips and may require passing through main railway stations, airports or ports. Also the required time budget for these trips is several times the amount allowed for urban trips.

To adequately deal with an indicator of total mobility for urban travelers it is thus proposed to define 3 levels of connectivity: a) at the urban or metropolitan scale: b) at the urban or metropolitan scale with a regional scope; and c) at the metropolitan scale with an interregional scope. A different methodology to evaluate the connectivity of the places will be applied to each of these levels.

5.1 Urban or metropolitan scale

5.1.1 Urban ICON Calculation

In the classical ICON calculation, the measure of the connectivity at a given place to a network *n*, $ICON_n$, is based on the minimum access time (ta_{nm}) to reach the closest transport node of the network n, increased by both, an additional time (tw_n) which, at most, will be the access time needed to reach a node providing a predetermined (maximum) utility ($Umax_n$), measured according to the transport service provided (see later) and a gap time (tg_n) that reflects the non predictable delays, discontinuities or gaps during the trip.

This formulation considers that the user can reach at least one node with maximum utility $Umax_n$. If the closest connection node (at minimum time ta_{nm}) reaches or exceeds $Umax_n$, then $ta_{nm}= ta_{nx}$ and the value of the additional time is zero, $tw_n= 0$. Otherwise, it will have a positive value. In this case, all alternative connection nodes with access times (ta_{nj}) between ta_{nm} and ta_{nx} will be considered and their services properly aggregated.

This works properly if the time allowed to reach the transportation nodes has no limitations. That could be possible if the transport mode to reach the transportation networks is a private vehicle. But, as Ulied (1995) pointed out, *assuming that connections are established only by car, if the distance to the closest railway station is more than 100 Km, its utility is rapidly decreasing, being almost zero around 250 Km. As a result of this, in some cases, remote connection nodes can be considered as non-available. Then, the network has to be substituted for another to solve the gap.*

In the urban environment, most displacements to reach the transport nodes are made on foot or, less frequently, by bike. Thus, if access time to the closest node is more than 15 minutes, its utility decreases rapidly, being almost nil when the time to reach it gets above 20 or 30 minutes, depending on the service provided by the node's transport mode.

Peripheral urban areas seldom have rail or metro stations within a 15 minutes walking distance. Therefore, it does not make sense to establish that a maximum utility U_{nx} is reached in such cases (ta_{nx}> 15 minutes). To avoid this problema new formulation for **URBICON** is proposed.

First of all, to calculate the connectivity of a point i to a transport network n, a maximum walking time to the network nodes to be considered(twa_max_n) is set in order to ensure that these nodes can provide a minimum utility to the traveller. The utility of a node, as later

presented in more detail, depends on different characteristics, such as commercial speed, number of transfers to other lines or networks, comfort and reliability.

Then, network nodes *s* (stops of public transport lines) reachable from i within this maximum walking time are selected and their access time (ta_{nis}) calculated as follows:

$$ta_{n,i,s} = twa_{i,s} + AWT_s \qquad \text{(Eq. 5.1)}$$
$$twa_{i,s} \leq twa\_max_n$$

The access time to reach the n network from the point i is the addition of the walking time from i to the stop s (twa_{is}), which includes the access time to the platform in the case of underground or rail stations, and the expected average waiting time at the stop. In the case of high frequency services, AWT will be half of the line's headway and, in lower frequency or scheduled services, a maximum waiting time may be prefixed. As one stop may be served by one or more routes (typically a bus stop is used by several bus lines), a weighted average access time may be calculated taking into account the different levels of service of the lines.

All selected stops and their access time (ta_{nis}) are included in a set of feasible stops (FS). If one line can be reached through different stops, only the nearest one is included in the FS set.

If no transport node can be reached within twa_max_n, then ta_{nis} takes the value of a maximum access time to the network n, defined as follows:

$$ta\_max_n = twa\_max_n + \frac{1}{2} \cdot headway\_max_n \qquad \text{(Eq. 5.2)}$$

The maximum access time to reach the n network is the addition of the maximum walking time (twa_max_n) and the maximum expected waiting time at the stop, being in that case half of the maximum headway of all the lines in the network. This is to maintain consistency with the previous ta_{nis} calculation, ensuring that ta_{nis} is always lower than or equal to ta_max_n.

The maximum access time parameter will strongly affect the results of the URBICON calculation, so its value must be carefully set for each transport mode. Typical coverage distance for different transport modes can be found in the literature: for bus stops it is 400 meters or 5 minutes walking, for underground stations it is 800 meters or 10 minutes, etc. As URBICON is focussing on identifying locations where there is insufficient connectivity to the networks, i.e. areas with low public transport endowment, the coverage radius for the analysis may be greater, for instance, 10 minutes for bus stops and 20 minutes for underground stations. This would give a more accurate measure of the connectivity to the networks in poorly served areas.

In the classical formulation, it is considered that a single node can provide the maximum level of service. For instance, in the CITRAME Study (1988), it is regarded that a rail station

reaches the maximum utility if it has more than 75 trains per day. In urban areas, a single bus stop or tram station may not usually provide the maximum network utility. Thus, the maximum utility can be reached by adding the services of the stops near to the point under analysis. $Smin_n$ is the lower level of service. In our case, as frequencies are rather high, $Smin_n$ is equal to the lowest utility found in any node of the network lines. Therefore in our particular model no nodes are neglected.

To take into account the utility provided by each node (in the set of FS of network n), an additional time (similar to tw_n, in ICON) is added to the access time to the closest node in order to take into account its utility gap with relation to the maximum $Smax_n$. The connectivity of a given point (i) to the network (n) is thus calculated as:

$$ICON_{n,i} = ta_{n,i,m} + tu_{n,i} \qquad \text{(Eq. 5.3)}$$

corresponding to the access time to the closest stop (ta_{nim})plus a component tu_{ni} that is a function of the utility provided by the other network nodes in FS. By definition, this component diminishes as the utility increases (more nodes are reachable) and it is null if the utility provided at the closest node equals or exceeds the maximum level:

$$tu_{n,i} = pu_{n,i} \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m}) \qquad \text{(Eq. 5.4)}$$

δ_{ni} is an aggregate measure of the utility provided by all the nodes whose access times are below ta_{nix}.
pu_n is a parameter that establishes the relevance of the penalty for the utility gap with relation to the prefixed maximum. It must take values between zero and one to keep tu_{ni} under the value ta_max_n.
ta_{nix} is the access time to the closest node that allows an accumulated level of service above $Smax_n$, i.e., the addition of the services provided by the nodes with access times $ta_{nij} <= ta_{nix}$ is equal to or greater than $Smax_n$. If the utility accumulated by all the N nodes of FS is lower than $Smax_n$, then ta_{nix} is set to ta_max_n

$$ta_{n,i,x} = \begin{cases} ta_{n,i,k} & if \ \sum_{j=1}^{k} S_{nj} \geq Smax_n \\ & or \\ tamax_n & if \ \sum_{j=1}^{N} S_{nj} < Smax_n \end{cases} \qquad \text{(Eq. 5.5)}$$

In the second case, the following assumption is made: there is always a set of nodes located in $tamax_n$ or beyond able to provide the additional service (S_{nd}) required to reach the maximum level $Smax_n$:

$$Smax_n = \sum_{j=1}^{N} S_{nj} + S_{nd}$$
$$S_{nd} = Smax_n - \sum_{j=1}^{N} S_{nj} \qquad \text{(Eq. 5.6)}$$

The utility provided by a connection node with access time ta_{nij} supplying a service S_{nj} is defined according to a conventional diffusion formula as follows:

$$U_{n,i,j} = S_{nj} e^{-\beta_n (ta_{n,i,j} - ta_{n,i,m})} \qquad \text{(Eq. 5.7)}$$

where β_n is a free parameter depending on the network.

The aggregated utility provided by all connection nodes of the network (n) in the calculation point (i) is evaluated according to the following formulation (Ulied 1995):

$$U_{n,i} = \sum_{j=1} U_{n,i,j} = \sum_{j=1} S_{nj} e^{-\beta_n (ta_{n,i,j} - ta_{n,i,m})}$$
$$U_{n,i} = S_{n1} + \sum_{j=2} S_{nj} e^{-\beta_n (ta_{n,i,j} - ta_{n,i,m})} \qquad \text{(Eq. 5.8)}$$

That means that the utility perceived by any user in (i) is equal to the service provided by the nearest node plus the service provided by all the nodes located between ta_{nim} and ta_{nix}, the utility of which decreases with the increase of the access time in relation to the first stop, by an exponential function.

δ_{ni}, is formulated in such way that tu_{ni} is reduced as utility increases and is null if the nearest node achieves the maximum utility:

$$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n} \qquad \text{(Eq. 5.9)}$$
$$Umin_n \le U_{n,i} \le Umax_n$$
$$0 \le \delta_{n,i} \le 1$$

$Umax_n$ is the utility provided by the service level $Smax_n$ when the travellers have the maximum level of service at the closest node of the network ($ta_{nix} = ta_{nim}$). In this case $Umax_n = Smax_n$.

$Umin_n$ is the utility provided by $Smin_n$ when $ta_{nij} = ta_{nim}$, therefore $Umin_n = Smin_n$.

In order to keep δ_{ni} between zero and one, U_{ni} must be never greater than $Umax_n$:

$$U_{n,i} = \begin{cases} \sum_{j=1} U_{n,i,j} & or \\ Umax_n \text{ if } \sum_{j=1} U_{n,i,j} > Umax_n \end{cases} \quad \text{(Eq. 5.10)}$$

The proposed formulation implies that ICON values will always be between ta_{nim} and ta_{nix}:

$$ICON_{n,i} = ta_{n,i,m} + pu_{n,i} \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m}) \quad \text{(Eq. 5.11)}$$
$$ta_{n,i,m} \leq ICON_{n,i} \leq ta_{n,i,x}$$

An example is presented to check if the proposed formulation of the URBICON indicator works fine in urban environments. The scenario proposed is the following one:

- Maximum service level of the network $Smax_n$ = 200.
- Minimum service provided by one node of the network $Smin_n$ = 10.
- There are only 2 accessible nodes from point (i).
- The access time from point (i) to the first reachable node is tani1.
- The access time from (i) to the second feasible node is tani2 = tani1 + 2 (minutes)
- The maximum access time to the network is set to $tamax_n$ = 23 minutes.
- tani1 will be incremented from 0 to 21 in steps of one minute, not exceeding then $tamax_n$.

The objective of this example is to test the behaviour of the indicator under extreme situations. For instance, when there are two close stops, in this case separated two minutes by foot, with very different utilities. First the service of Stop1 is set at 180 and the service of Stop2 is set at 10, and then these values are interchanged in order to assess how the level of the service provided at the closest node influences the results.

Because the addition of services provided by the nodes included in the FS does not reach the maximum service level of the network (Sn1+Sn2=190 and $Smax_n$=200), the following assumption is made: there is always a set of nodes located in $tamax_n$ or beyond which overall will provide an additional service (Snd) that is high enough to compensate the deficit gap, i.e., Sn1+Sn2+Snd=Smax. Thus, Snd=Smax-(Sn1+Sn2) = 10.

In this case, the aggregated utility will be:

$$U_{n,i} = S_{n1} + S_{n2} \cdot e^{-\beta_n (ta_{n,i,2} - ta_{n,i,m})} + S_{nd} \cdot e^{-\beta_n (ta_{n,i,x} - ta_{n,i,m})}$$

The parameter βn is set to 0.15 in order to have a value close to zero in the maximum access time to the network ($tamax_n$). The decay function, shown below, has a value of 0.03 for 23 minutes:

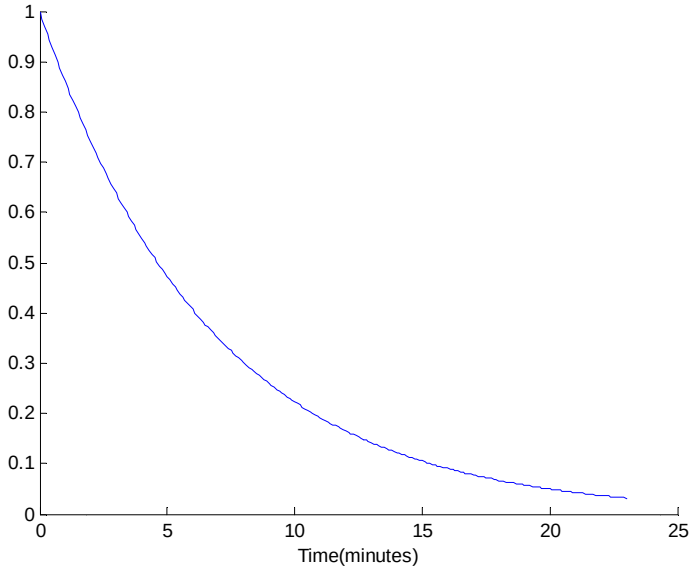


Figure 4 Exponential decay function with βn = 0.15

If the nodes are located at tani1=2 minutes and tain2=4 minutes with service levels Sn1=180 and Sn2=10, the value of ICON will be calculated as following:

$$U_{n,i} = 180 + 10 \cdot e^{-0.15(4-2)} + 10 \cdot e^{-0.15(23-2)} = 187.83$$

$$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n} = \frac{200 - 187.83}{200 - 10} = 0.064$$

$$ICON_{n,i} = ta_{n,i,m} + tu_{n,i} = ta_{n,i,m} + pu_{n,i} \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m})$$

$$ICON_{n,i} = 2 + 0.75 \cdot 0.064 \cdot (23 - 2) = 3 \text{ minutes}$$

When services of both stops are interchanged, i.e., Sn1=10 and Sn2=180, then:

$$U_{n,i} = 10 + 180 \cdot e^{-0.15(4-2)} + 10 \cdot e^{-0.15(23-2)} = 143.8$$

$$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n} = \frac{200 - 143.8}{200 - 10} = 0.296$$

$$ICON_{n,i} = 2 + 0.75 \cdot 0.296 \cdot (23 - 2) = 6.66 \text{ minutes}$$

The situation from the point of view of the user is quite similar, because increasing two minutes the access time to the stop with higher service has not much significance. However, ICON shows an increase of 3.66 minutes because tu_{ni} is very high in the second case, when the service of the first node is only 10. This means that the issue must be taken into account.

The following figure shows the values of ICON for different values of tani1, which are set between 0 and 21 minutes and thus tani2 fall between 2 and 23 minutes.

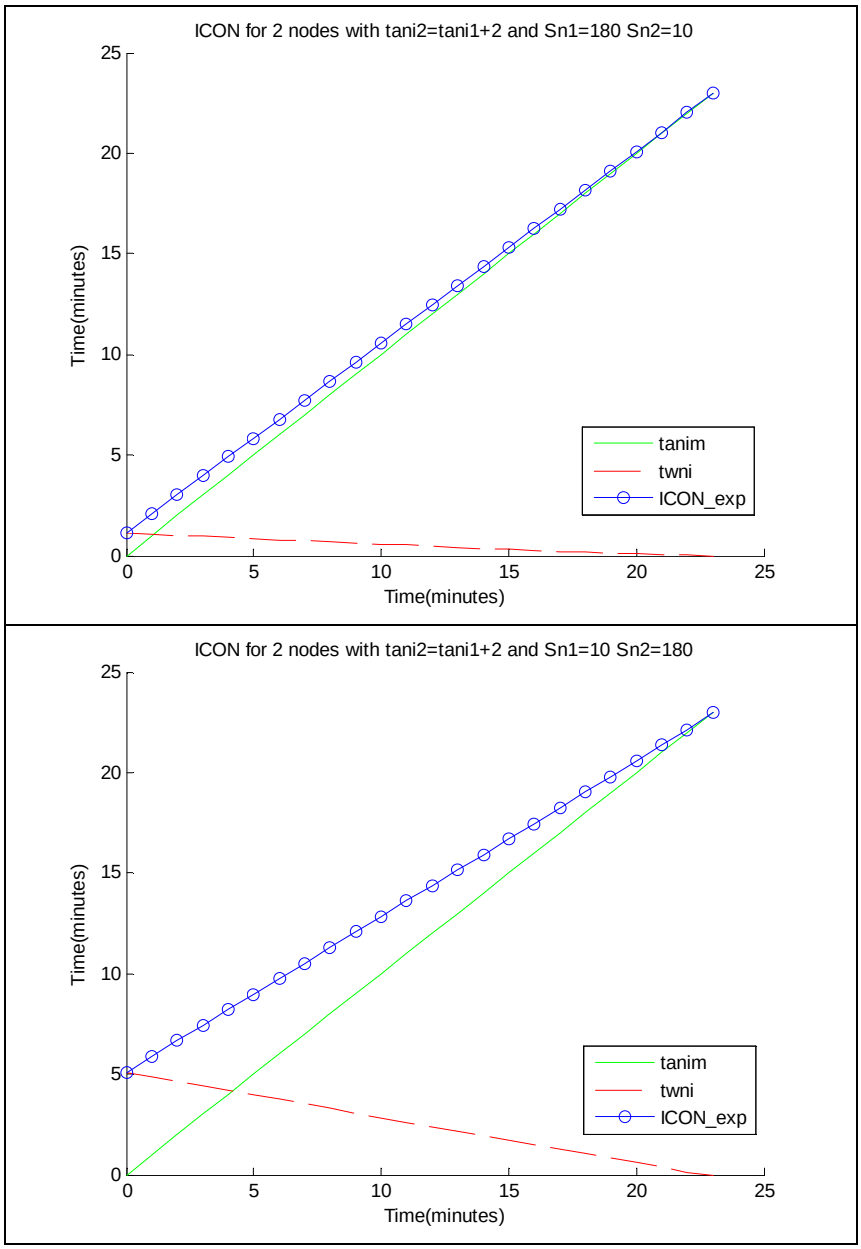


Figure 5 Comparison of ICON results when interchanging *Snj* between two nodes

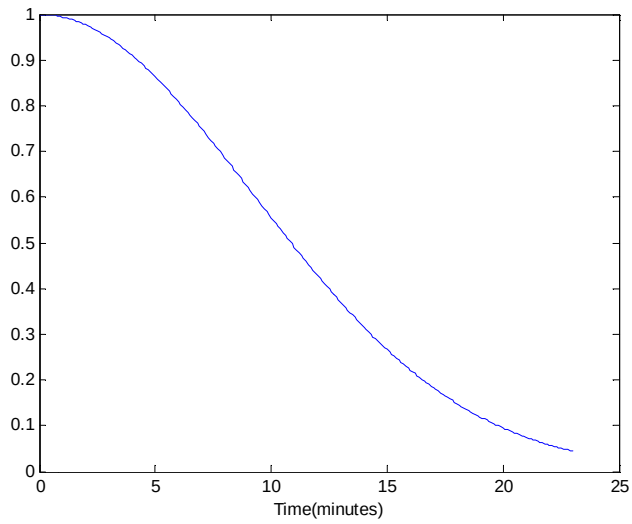
The results show that the difference in ICON values in both situations is more significant when the nodes are located near the calculation point (i) than when they are far away. This is because the relevance of tu_{ni} decreases as the access time to the first accessible node increases, i.e., as the first accessible node is closer to $tamax_n$.

A possible way of solving the problem is to give more relevance to the nearest nodes, in order to reduce the utility penalty associated with distance. This appears logical because travellers use, indeed, different stops and public transport lines in the vicinity depending more on their destinations and characteristics of the provided services than on the distance at which stops are located. However, distance becomes more relevant for those stops farther away.

The exponential decay function used does not reflect this travellers' behaviour, because it decreases a lot the utility of the nodes even when they are near the origin. For instance, the exponential function with beta =0.15, reduces in 36% the utility of a stop located 3 minutes from the origin.

Several decay functions have been tested (Geurs and Ritsema van Eck, 2001), being the Gaussian function the one that we consider better reflects traveller's behaviour. The parameter σ of this function must be calibrated depending on the network and the maximum access time. For this example the decay function used is:

$$f(ta_{n,i,j}) = e^{-\frac{(ta_{n,i,j-\mu})^2}{2\sigma^2}} = e^{-\frac{ta_{n,i,j}^{\ 2}}{170}}$$



The aggregated utility is then expressed as:

$$U_{n,i} = \sum_{j=1} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} = S_{n1} + \sum_{j=2} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})}$$

The utility perceived at point (i) is equal to the service provided by the nearest node plus the service provided by all the nodes located between ta_{nim} and ta_{nix}, the utility of which decreases with the increase of access time with regard to the time to the first stop, by the proposed Gaussian function.

If the nodes are located at tani1=2 minutes and tain2=4 minutes with service levels Sn1=180 and Sn2=10, the value of ICON is:

$$U_{n,i} = 180 + 10 \cdot \frac{0.91}{0.9767} + 10 \cdot \frac{0.0445}{0.9767} = 180 + 9.31 + 0.45 = 189.76$$

$$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n} = \frac{200 - 189.76}{200 - 10} = 0.054$$

$$ICON_{n,i} = ta_{n,i,m} + pu_{n,i} \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m})$$
$$ICON_{n,i} = 2 + 0.75 \cdot 0.054 \cdot (23 - 2) = 2.85 \text{ minutes}$$

In the case of Sn1=10 and Sn2=180, δ_n is equal to 0.116 and ICON=3.82 minutes. This value is closer to 4 minutes, the access time to the second node with a service level of 180. Thus, the ICON value is closer to the time that traveller will spend to reach the node with higher level of service. In the previous mode this value was 6.66 minutes.

In the following figure there is the calculation of ICON for different values of tani1, which is set between 0 and 21 and thus tani2 between 2 and 23 minutes.

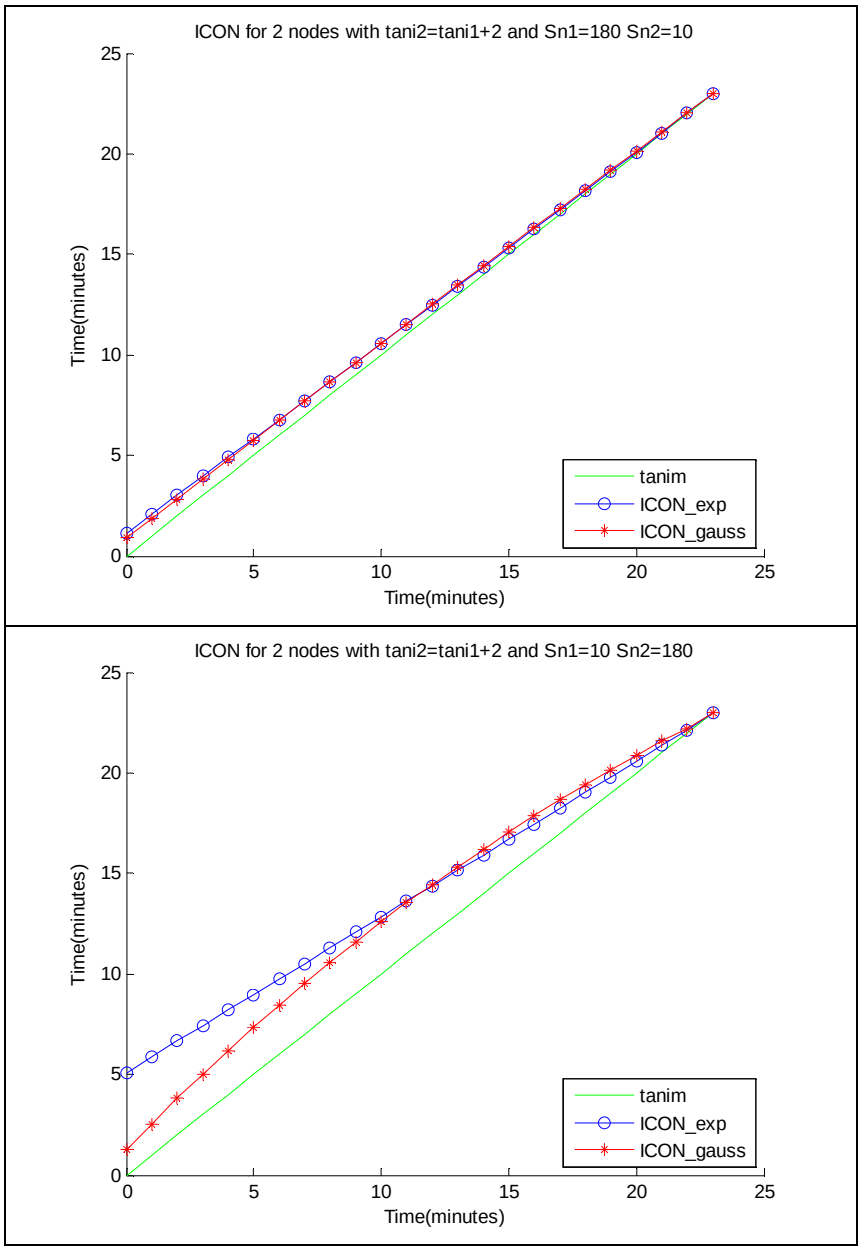


Figure 6 Comparison of ICON results applying exponential and Gaussian decay functions

Summarising, the proposed formulation for the URBICON indicator is:

$$ICON_{n,i} = ta_{n,i,m} + pu_{n,i} \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m}) \qquad \text{(Eq. 5.12)}$$

Where ta_{nim} is the access time to the nearest network node, ta_{nix} is the access time to the closest node allowing an accumulated level of service above $Smax_n$, $pu_n$is the parameter to establish the relevance of the penalty for the utility deficit, and $\delta_{n,i}$, is an aggregate measure of the utility provided by all the stops (and lines) whose access times are below ta_{nix}:

$$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n} \qquad \text{(Eq. 5.13)}$$

The utility perceived in point (i) is equal to the service provided by the nearest node plus the service provided by all the nodes located between ta_{nim} and ta_{nix}, whose utility decreases, by a Gaussian function, with the increase of access time in relation to the first stop.

$$U_{n,i} = \sum_{j=1} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} = S_{n1} + \sum_{j=2} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} \;\Big|\; ta_{n,i,j} \le ta_{n,i,x} \qquad \text{(Eq. 5.14)}$$

Example application

To check the consistency of the indicator an example application of ICON calculation for an underground network is presented ($ICON_{metro}$). Different frameworks are proposed in Figure 7 and Figure 8. In each one the transport endowment changes and the ICON is calculated in different points.

Line	Headway (mins)	Utility
L1	3	60
L2	6	50
L3	4	70
L4	8	40

Table 2 Characteristics of the underground lines

The maximum walking access time (twa_n) is set to 20 minutes.

In setting A there are two operating underground lines, L1 and L2. The minimum utility is set to 50 and the maximum utility is set to 110, considering that having access to both lines provides the maximum level of service. Point P1 has none feasible stop within the maximum walking access time but from point P2 it is possible to reach a L2 station. Then the ICON value calculated in P1 is:

$$ICON_{n,\mathrm{P1}} = ta\_max_n = 20 + \frac{1}{2} \cdot headway\_max_n = 20 + \frac{1}{2} \cdot 6 = 23 \text{ minutes}$$

To keep consistency in the indicator, parameter ta_max_n needs to be calculated with the maximum headway of the current lines, otherwise it would produce that points having a reachable station would have a higher ICON value than others without any station.

In point P2 only S22 station can be reached within ta_maxn. Then ta_{nim}=ta_{nP2S22}, Snd=110-50=60 and ta_{nix}=ta_max_n.

$$ICON_{n,\mathrm{P2}} = ta_{n,\mathrm{P2},m} + pu_n \cdot \delta_{n,\mathrm{P2}} \cdot (ta_{n,\mathrm{P2},x} - ta_{n,\mathrm{P2},m})$$

$$ICON_{n,\mathrm{P2}} = ta_{n,\mathrm{P2,S22}} + pu_n \cdot \frac{Umax_n - U_{n,\mathrm{P2}}}{Umax_n - Umin_n} \cdot (ta\_max_n - ta_{n,\mathrm{P2,S22}})$$

$$ta_{n,\mathrm{P2,S22}} = twa_{\mathrm{S22}} + \frac{1}{2} \cdot H_{\mathrm{L2}} = 18 + 3 = 21 \text{ minutes}$$

$$U_{n,\mathrm{P2}} = 50 + 60 \cdot \frac{f(ta\_max_n)}{f(ta_{n,\mathrm{P2,S22}})} = 50 + 60 \cdot \frac{0.045}{0.075} = 86$$

$$ICON_{n,\mathrm{P2}} = 21 + 0.75 \cdot \frac{110-86}{110-50}(23-21) = 21.6 \text{ minutes}$$

This value denotes that having a station near to the maximum walking distance is almost the same of having none, due to the poor utility that the user perceives.

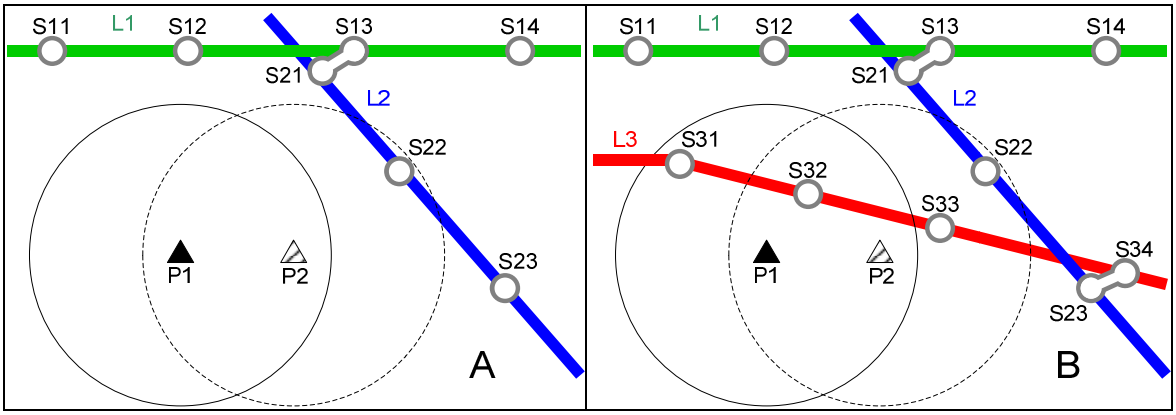


Figure 7.Example of URBICON calculation for the underground mode

In framework B, line L3 is added to the network. To assess the impact of the new line, the reference scenario is not changed. Thus, the minimum utility is set again to 50 and the maximum utility is set to 110, considering that having access to two of three lines is still a good measure of the maximum level of service. Now both calculation points P1 and P2 have a feasible underground station within the maximum walking time. In P1 any traveller can reach line L3 in stations S31 and S32. For the ICON calculation, the algorithm only considers the nearest station per line. Then ta_{nim}=ta_{nP2S32}, Snd=110-70=40 and ta_{nix}=ta_max_n.

$$ICON_{n,i} = ta_{n,i,m} + pu_n \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m})$$

$$ICON_{n,\mathrm{P1}} = ta_{n,\mathrm{P1,S32}} + pu_n \cdot \delta_{n,\mathrm{P1}} \cdot (ta\_max_n - ta_{n,\mathrm{P1,S32}})$$

$$ta_{n,\mathrm{P1,S32}} = twa_{\mathrm{S32}} + \frac{1}{2} \cdot H_{\mathrm{L3}} = 10 + 2 = 12 \text{ minutes}$$

$$U_{n,\mathrm{P1}} = 70 + 40 \cdot \frac{f(ta\_max_n)}{f(ta_{n,\mathrm{P1,S32}})} = 70 + 40 \cdot \frac{0.045}{0.429} = 74$$

$$ICON_{n,\mathrm{P1}} = 12 + 0.75 \cdot \frac{110 - 74}{110 - 50}(23 - 12) = 17 \text{ minutes}$$

In P2 it is possible to get on L3 in two stations, S32 and S33, and reach L2 in S22. The nearest node is S33, then ta_{nim}=ta_{nP2S33}.As the addition of the services provided by S33 and S22 is greater than Smax (70+50>110), then Snd=0 and ta_{nix}=ta_{nP2S22}. ICON is then calculated as follows:

$$ta_{n,\mathrm{P2,S33}} = twa_{\mathrm{S33}} + \frac{1}{2} \cdot H_{\mathrm{L3}} = 8 + 2 = 10 \text{ minutes}$$

$$ta_{n,\mathrm{P2,S22}} = twa_{\mathrm{S22}} + \frac{1}{2} \cdot H_{\mathrm{L2}} = 18 + 3 = 21 \text{ minutes}$$

$$ICON_{n,\mathrm{P2}} = ta_{n,\mathrm{P2,S33}} + pu_n \cdot \frac{Umax_n - U_{n,\mathrm{P2}}}{Umax_n - Umin_n} \cdot (ta_{n,\mathrm{P2,S22}} - ta_{m,\mathrm{P2,S33}})$$

$$U_{n,\mathrm{P2}} = 70 + 50 \cdot \frac{f(ta_{n,\mathrm{P2,S22}})}{f(ta_{n,\mathrm{P2,S33}})} = 70 + 50 \cdot \frac{0.075}{0.55} = 76.8$$

$$ICON_{n,\mathrm{P2}} = 10 + 0.75 \cdot \frac{110 - 76.8}{110 - 50}(21 - 10) = 14.56 \text{ minutes}$$

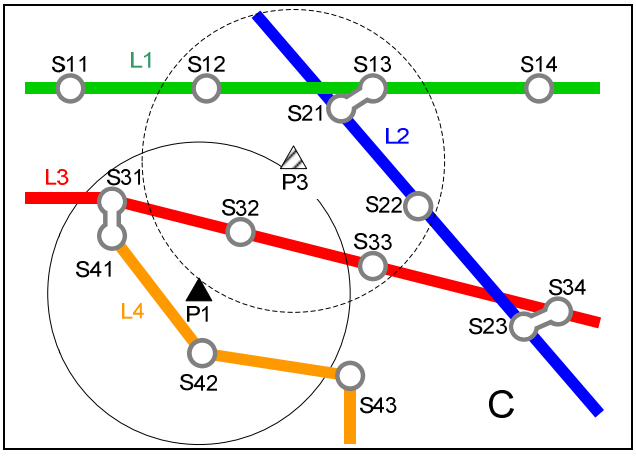


Figure 8.Example of URBICON calculation for the underground mode (2)

In framework C a new line is created. Setting B is considered as the reference scenario. Minimum utility is now set to 40 and maximum utility is set according to have access to three of the four lines represent the maximum level of service (Umax=Smax=150). The calculation points are now P1 and P3. The maximum access time must be recalculated in order to keep consistency in the calculations:

$$ta\_max_m = 20 + \frac{1}{2} \cdot headway\_max_m = 20 + \frac{1}{2} \cdot 8 = 24 \text{ minutes}$$

In P1 is possible to reach lines L3 and L4. The nearest node is S42, then ta_{nim}=ta_{nP2S42}. Snd=Smax-(Sn1+Sn2)=150-(40+70)=40 and ta_{nix}=ta_max_n. ICON is then calculated as follows:

$$ta_{n,\text{P1,S42}} = twa_{\text{S42}} + \frac{1}{2} \cdot H_{\text{L4}} = 6 + 4 = 10 \text{ minutes}$$

$$ta_{n,\text{P1,S32}} = twa_{\text{S32}} + \frac{1}{2} \cdot H_{\text{L3}} = 10 + 2 = 12 \text{ minutes}$$

$$ICON_{n,\text{P1}} = ta_{n,\text{P1},m} + pu_n \cdot \delta_{n,\text{P1}} \cdot (ta_{n,\text{P1},x} - ta_{n,\text{P1},m})$$

$$ICON_{n,\text{P1}} = ta_{n,\text{P1},S42} + pu_n \cdot \frac{Umax_n - U_{n,\text{P1}}}{Umax_n - Umin_n} \cdot (ta\_max_n - ta_{n,\text{P1,S42}})$$

$$U_{n,\text{P1}} = 40 + 70 \cdot \frac{f(ta_{n,\text{P1,S32}})}{f(ta_{n,\text{P1,S42}})} + 40 \cdot \frac{f(ta\_max_n)}{f(ta_{n,\text{P1,S42}})} = 40 + 70 \cdot \frac{0.429}{0.55} + 40 \cdot \frac{0.045}{0.55} = 97.9$$

$$ICON_{n,\text{P1}} = 10 + 0.75 \cdot \frac{150 - 97.9}{150 - 40}(24 - 10) = 15 \text{ minutes}$$

In P3 any traveller can reach lines L1, L2 and L3 within the maximum access time. The nearest node is S32, then ta_{nim}=ta_{nP3S32}. As the addition of the services provided by S32, S21 and S13 is greater than Smax (70+50+60>150), then Snd=0 and ta_{nix}=ta_{nP3S13}. ICON is then calculated as follows:

$$ta_{n,\text{P3,S32}} = twa_{\text{S32}} + \frac{1}{2} \cdot H_{\text{L3}} = 9 + 2 = 11 \text{ minutes}$$

$$ta_{n,\text{P3,S21}} = twa_{\text{S21}} + \frac{1}{2} \cdot H_{\text{L2}} = 10 + 3 = 13 \text{ minutes}$$

$$ta_{n,\text{P3,S13}} = twa_{\text{S13}} + \frac{1}{2} \cdot H_{\text{L1}} = 12 + 1.5 = 13.5 \text{ minutes}$$

$$ICON_{n,\text{P3}} = ta_{n,\text{P3,m}} + pu_n \cdot \delta_{n,\text{P3}} \cdot (ta_{n,\text{P3,x}} - ta_{n,\text{P3,m}})$$

$$ICON_{n,\text{P3}} = ta_{n,\text{P3,S32}} + pu_n \cdot \frac{Umax_n - U_{n,\text{P3}}}{Umax_n - Umin_n} \cdot (ta_{n,\text{P3,S13}} - ta_{n,\text{P3,S32}})$$

$$U_{n,\text{P3}} = 70 + 50 \cdot \frac{f(ta_{n,\text{P3,S21}})}{f(ta_{n,\text{P3,S32}})} + 60 \cdot \frac{f(ta_{n,\text{P3,S13}})}{f(ta_{n,\text{P3,S32}})} = 70 + 50 \cdot \frac{0.37}{0.49} + 60 \cdot \frac{0.34}{0.49} = 149.4$$

$$ICON_{n,\text{P3}} = (9 + 2) + 0.75 \cdot \frac{150 - 149.4}{150 - 40}(13.5 - 11) = 11 \text{ minutes}$$

5.1.2 Assessing the level of service

The application of URBICON requires giving a level of service value to the network nodes to which the calculation point is connected. These nodes are underground or rail stations, tram or bus stops that belong to one or more public transport lines. To assess the utility of a public transport line, different variables must be considered. The methodology proposed takes into account the following variables:

$$S = \alpha \cdot CSpeed + \beta \cdot NWStops + \gamma \cdot Comfort + \lambda \cdot Reliabilit\ y \qquad \text{(Eq. 5.15)}$$

- Commercial speed. The level of service of a public transport line depends on the commercial speed provided. The faster the line, the more useful it is.

- Number of (Weighted) Stops. This variable counts the number of stops of the line. The more stops, the more possible destinations can be reached with this service. To assess the network effect of the current line with other lines, a weight is given to each station depending on the number of transfers it has. For instance, if one station doesn't have any transfer, its weight equals 1, with one transfer, its weight equals 1.5, and so on. More number of transfers implies that the line is more connected to the others, allowing the users a more quickly access to them, and therefore a bigger utility.

  Let's see how to calculate the NWS of the Budapest Metro lines. Figure 9 shows a map of the Budapest underground network. Lines M1, M2 and M3 are currently operating, line M4 is under construction and line M5 is only in project stage.

Figure 9 Map of the underground network of Budapest

Following the exposed methodology and giving weight of 1 to single stations, weight of 1.5 to 1-transfer stations and weight of 2 to 2-transfer stations, the values obtained for each line are:

Line	Weighted Stations (2010)	Weighted Stations (+M4)
M1	12	12
M2	12	12,5
M3	21	21,5
M4	-	15

- Comfort can be evaluated by users' surveys on each line. Another method is to considerer the average occupancy of the vehicles by analysis' time of day (peak or off-peak). The Transport Capacity and Quality of Service Manual proposes a passenger load Level of Service based on two measures: "load factor (passengers per seat), when all passengers can sit, and standing passenger area, when some passengers must stand or when a vehicle is designed to accommodate more standees than seated passengers" (pag. 3-45):

LOS	Load Factor (p/seat)	Standing Passenger Area (ft^2/p)	Standing Passenger Area (m^2/p)	Comments
A	0.00-0.50	>10.8†	>1.00†	No passenger need sit next to another
B	0.51-0.75	8.2-10.8†	0.76-1.00†	Passengers can choose where to sit
C	0.76-1.00	5.5-8.1†	0.51-0.75†	All passengers can sit
D	*1.01-1.25**	3.9-5.4	0.36-0.50	Comfortable standee load for design
E	*1.26-1.50**	2.2-3.8	0.20-0.35	Maximum schedule load
F	*>1.50**	<2.2	<0.20	Crush load

*Approximate value for comparison, for vehicles designed to have most passengers seated. LOS is based on area.
†Used for vehicles designed to have most passengers standing.

Figure 10 TCQSM Fixed-Route Passenger Load LOS

Instead of using a letter coded Level of Service, comfort can be expressed as a function of the vehicle occupancy:

$$Comfort_{line} = 1 - \left(\frac{PassLoad_{line}^{time}}{VehicleCapacity} \right) \qquad \text{(Eq. 5.16)}$$

Thus, the comfort variable takes values between 1, when all passengers can choose where to sit (maximum LOS), and 0, when the acceptable vehicle capacity is reached, most of passengers are standing and even new passengers could not get on the vehicle (minimum LOS).

- Reliability includes both on-time performance and the regularity of headways between successive vehicles. Reliability depends on several factors like traffic conditions, road and track maintenance, vehicle maintenance, regularity of passenger demand, etc. If a service tends to arrive later than it is scheduled, it means that the travel time is usually increased and passengers may choose an earlier departure to ensure that they arrive on time, even if it implies arriving much earlier than desired.

Uneven headways produce the typical "bunching" phenomenon on line buses. The late vehicle must pick up not only its regular passengers but those passengers that have arrived for the following vehicle, increasing its delay and having more standing passengers. In contrast, the following vehicle will have fewer passengers than normal and will tend to run ahead of schedule.

To quantify reliability in public transport services scheduled by headways, the TCQSM proposes a LOS measure (pag. 3-48) based on the coefficient of variation of headways c_{vh}:

$$c_{vh} = \frac{\text{standard deviation of headway deviations}}{\text{mean scheduled headway}}$$

Headway deviations are measured as the actual headway minus the scheduled headway.

LOS	c_{vh}	$P(h_i > 0.5\ h)$	Comments
A	0.00-0.21	≤1%	Service provided like clockwork
B	0.22-0.30	≤10%	Vehicles slightly off headway
C	0.31-0.39	≤20%	Vehicles often off headway
D	0.40-0.52	≤33%	Irregular headways, with some bunching
E	0.53-0.74	≤50%	Frequent bunching
F	≥0.75	>50%	Most vehicles bunched

NOTE: Applies to routes with headways of 10 minutes or less.

Figure 11 TCQSM Fixed-Route Headway Adherence LOS

Instead of using this letter code LOS, what is proposed is to use a Reliability variable that represents the percentage of compliance with headways in each line, data which may be asked to network operators. Reliability will take a value between 0 and 1.

The formulation of the level of service uses variables with different units and magnitudes. To avoid those variables with higher absolute values might dominate the function, "commercial speed" and "number of weighted stops" variables are divided by its maximum value, leading to a dimensionless measure of service.

$$S_{n,line} = \alpha \cdot \frac{CSpeed_{line}}{CSpeed_{\max}} + \beta \cdot \frac{NWStops_{line}}{NWStops_{\max}} + \gamma \cdot Comfort_{line} + \lambda \cdot Reliability_{line}$$

(Eq. 5.17)

The weight given to each variable (parameters $\alpha,\beta,\gamma,\lambda$) should be calibrated using data obtained from users' surveys. However, at this stage, suitable data are not available and we have been forced to use weights that we consider are producing reasonable values of utility.

It is necessary to remark that commercial speed of a public transport line usually appears in operator's reports, number of transfers can be found in network maps, but occupancy and reliability data are usually hard to obtain.

5.1.3 Urban ICON Calculation. Alternative method.

As presented before, URBICON calculation requires giving a utility value to the network nodes to which the calculation point is connected. In the previous method the utility is evaluated taking into account measurable characteristics of public transport lines to which these nodes belong, like commercial speed, comfort and reliability.

In networks where there is not overlap of transport lines, the methodology presented before is easy to use and results represent correctly the utility perceived by travellers.

Figure 12 Map of the underground network of Wien

The underground networks of Wien, Budapest, Barcelona and many other cities, have no overlapped services. But in other transport networks is usually to find different lines serving the same stations or sections. This could be the case of some lines that run together in the city centre and then are separated to serve different suburbs. Applying the previous methodology to calculate utility in the downtown, may present values of utility at some nodes higher than the utility perceived by travellers. That's because the utility of the lines is aggregated regardless they serve the same stations or not.

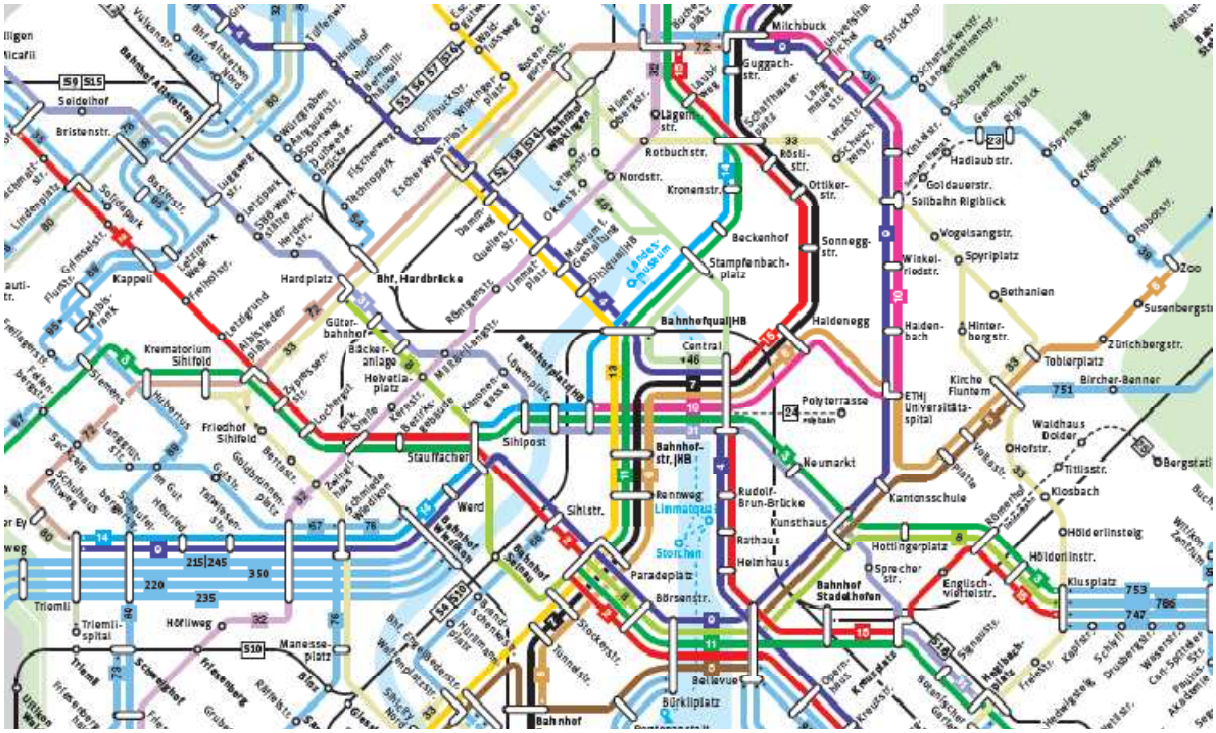


Figure 13 Detail of the tram and bus network of Zurich

In the tram network in Zurich there are some main corridors served by more than one line. For instance, tram lines 9 and 14 run together from the downtown to Triemli Hospital, lines 2 and 3 serve the same stations in the west of the city, and lines 9 and 10 go parallelto the north. In this cases, aggregating the utility of both lines leads to a higher values of utility than the ones provided by the nodes of the network.

To avoid this issue, another way to measure the level of service of each node of the network n is presented here. The level of service of a node j (S_{nj}) will depend on the number of stops that can be reached from it within a given time. This measure implicitly combines the commercial speed and the number of transfers, thus giving the utility of each node instead of the whole line. The travel to each feasible destination k will also have a certain level of comfort and reliability. Thus S_{nj} can be expressed as:

$$S_{n,,j} = \sum_k \alpha \cdot X_{j,k}^{ATT} + \gamma \cdot X_{j,k}^{ATT} \cdot Comfort_k + \lambda \cdot X_{j,k}^{ATT} \cdot Reliability_k \qquad \text{(Eq. 5.18)}$$

X_{jk}^{ATT} is a dichotomous variable that equals one if the k stop can be reached from node j within an average travel time (ATT) and zero if not.

As reliability depends on several factors (traffic conditions, road and track maintenance, vehicle maintenance, regularity of passenger demand) and their effects not only influence one stop but the whole line, its value can be assessed like in the previous method. The Reliability variable indicates the percentage of compliance with headways in each line, and will take a value between 0 and 1. The Reliability value of the node *j* is calculated as the average of reliability values of the L lines serving the node:

$$Reliability_j = \frac{1}{L} \cdot \sum_{line=1}^{L} Reliability_{line} \qquad \text{(Eq. 5.19)}$$

Comfort$_k$ is a variable that can be expressed as a function of the vehicle occupancy for each destination k, taking values between 0 and 1:

$$Comfort_k = 1 - \left(\frac{PassLoad_k^{time}}{VehicleCapacity} \right) \qquad \text{(Eq. 5.20)}$$

In order to simplify the calculations, we define *Comfort*$_j$ as the average comfort level of the L lines serving the node *j*:

$$Comfort_{line} = 1 - \left(\frac{PassLoad_{line}^{time}}{VehicleCapacity} \right) \qquad \text{(Eq. 5.21)}$$

$$Comfort_j = \frac{1}{L} \cdot \sum_{line=1}^{L} Comfort_{line} \qquad \text{(Eq. 5.22)}$$

Then, the service provided by each node j (S_{nj}) can be expressed as:

$$S_{n,,j} = \sum_k \alpha \cdot X_{j,k}^{ATT} + \gamma \cdot X_{j,k}^{ATT} \cdot Comfort_k + \lambda \cdot X_{j,k}^{ATT} \cdot Reliability_j$$

$$S_{n,,j} = (\alpha + \lambda \cdot Reliability_j + \gamma \cdot Comfort_j) \cdot \sum_k X_{j,k}^{ATT}$$

$$S_{n,,j} = (\alpha + \lambda \cdot Reliability_j + \gamma \cdot Comfort_j) \cdot NRS_j^{ATT} \qquad \text{(Eq. 5.23)}$$

The variable NRS_j^{ATT} counts the number of stations or stops that can be reached by travellers within an average travel time (ATT) from the node j. For transport modes with high transfer rates between lines, such as the underground services of big cities, or for mesh networks, such as the upcoming RetBus in Barcelona, this variable also includes stops reachable doing one or more transfers within the average travel time. In that case, travel time is considered as the addition of *in vehicle time* and *transfer time*, excluding access and egress time at origin and destination. Average travel time for each mode can be obtained from travellers surveys. For modes with low transfer rates between lines, like the currently bus network of Barcelona, this variable counts only the stops reachable by lines serving the node, that means, without any transfer.

In the Figure 14 there is the schema of an underground line. Giving an average travel time (ATT), from the station S1 (the nearest to calculation point A) any user can reach up to 14 stations, and from station S2, up to 8 stations. The expected average waiting time is 2 minutes in both stations, i.e., half of line's headway.

Let's consider now a new extension of the line, with two branches. The number of stations that a user can reach from station S1 remains the same, but in station S2 is increased up to 20 stations. On the other hand, the average waiting time observed by users in S1 will be the same, but in S2 will be different depending on destinations. Thus, the utility calculation of one stop as a function of reachable stations leads to a different calculation of the expected average waiting time.

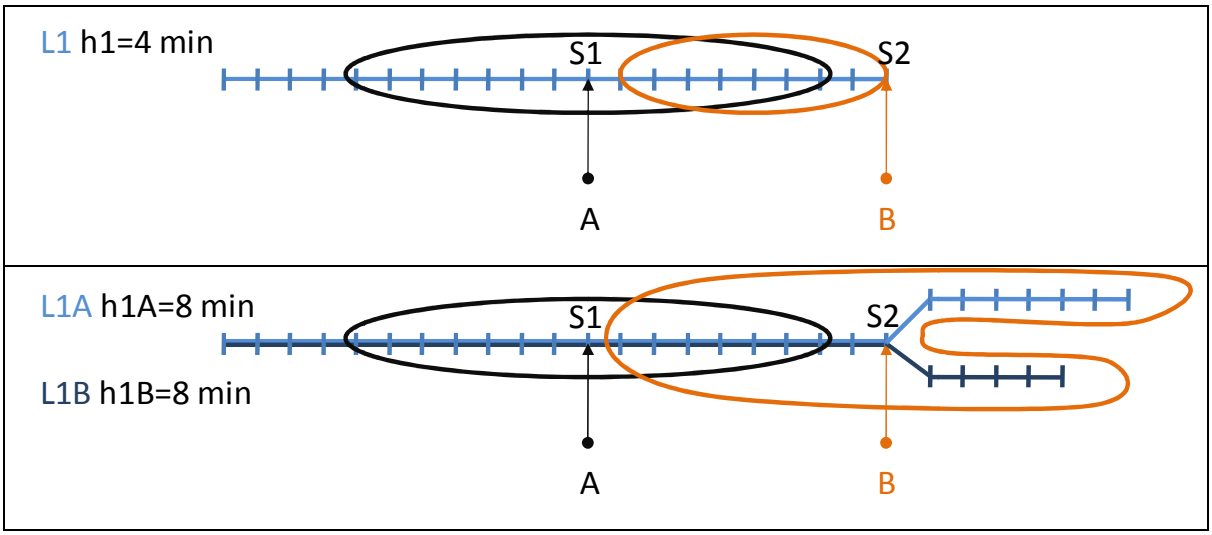


Figure 14.Example of utility evaluation of underground lines.

In the previous method the average waiting time is the half of line's headway, because no destinations are considered and utility depends only on the characteristics of the whole line. Now average waiting time is calculated as the average of the waiting times related to the reachable destinations:

$$AWT_j = \frac{1}{NRS_j^{ATT}} \cdot \sum_{i=1}^{NRS_j^{ATT}} EWT_i$$

$$EWT_i = \frac{1}{2} \frac{1}{\sum_l f_l} \qquad \text{(Eq. 5.24)}$$

For instance, AWT in stations S1 and S2 is:

$$AWT_{S1} = \frac{1}{14} \cdot \sum_{i=1}^{14} \frac{1}{2} \cdot \frac{1}{\frac{1}{H1A} + \frac{1}{H1B}} = \frac{1}{14} \cdot \sum_{i=1}^{14} \frac{1}{2} \cdot \frac{1}{\frac{1}{8} + \frac{1}{8}} 2$$

$$AWT_{S2} = \frac{1}{20} \cdot \left(\sum_{i=1}^{8} \frac{1}{2} \cdot \frac{1}{\frac{1}{H1A} + \frac{1}{H1B}} + \sum_{i=1}^{7} \frac{1}{2} \cdot \frac{1}{\frac{1}{H1A}} + \sum_{i=1}^{5} \frac{1}{2} \cdot \frac{1}{\frac{1}{H1B}} \right) = 3.2$$

Following with this example, in Figure 15 a new line is created. Now the number of reachable stations from S1 is increased up to 18 due to the new connection in S3 with line L2. Taking into account these new stations, the model gives an estimation of the network

effect provided by new infrastructures. The average waiting time in S1 keeps the same value because it is independent of the waiting time in the transfer to L2.

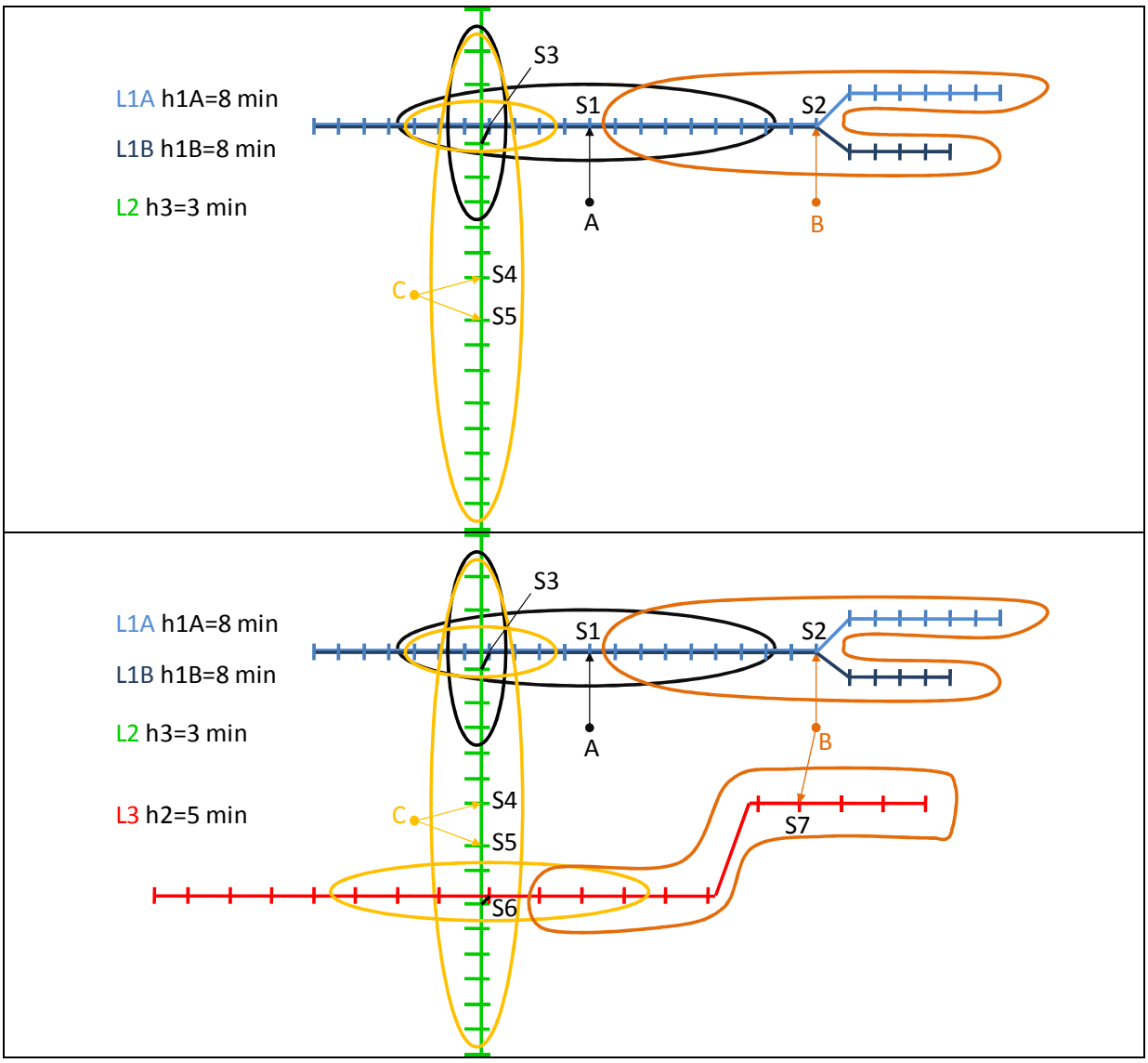


Figure 15.Example of utility evaluation of an underground network.

Calculation Point C didn't have underground service before the creation of line L2. Now, any user in point C has the possibility of choosing between S4 and S5, because both stations are inside the maximum walking distance. From S4 the traveller can reach up to 14 stations in line L2 and 4 stations in L1 within the average travel time. From S5 the traveller can reach up to 14 stations in L2 (one more to the south and one less to the north that from S4) and 2 stations in L1. The AWT is equal to 1.5 minutes in both stations S4 and S5.

In a later extension, line L3 is added to the network. Consequently the utility of point C is incremented because any user can reach 6 more stations within the average travel time due to the new transfer in S6 station. From calculation point B, there are now two underground stations within maximum walking distance. Then, the ICON calculation shall take into account stations S2 and S7 and their utility.

Another point to consider is that, in a transport system with hierarchical networks, one mode may become the main mode, for instance the underground services, and the other modes, typically bus and tram, may act as feeders of this main mode. In the case of Transantiago, for instance, a main trunk bus network (BRT) is fed by neighbourhood or district buses.

In order to assess the utility of stops of the feeder modes, it is necessary to somehow take into account if there is a transfer to the main mode within a given time that can be useful for the traveller. Then, the dichotomous variable TTM (Transfer to Main Mode) is added to the model. It takes the value one if there is a transfer to the main mode within half the average travel time and zero if there isn't.

$$S_{n,,j} = (\alpha + \beta \cdot TMM_j^{ATT/2} + \gamma \cdot Comfort_j + \lambda \cdot Reliability_j) \cdot NRS_j^{ATT}$$

(Eq. 5.25)

Table 3 summarizes the two possible methods of URBICON calculation.

Line utility based method	**Stop utility based method**
ICON calculation for the network n in point i: $$ICON_{n,i} = ta_{n,i,m} + tu_{n,i} = ta_{n,i,m} + pu_n \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m})$$	
ta_{nim} is the access time to the nearest network node, ta_{nix} is the access time to the closest node that provides an accumulated level of service above $Smax_n$: $$ta_{n,i,x} = \begin{cases} ta_{n,i,k} & if \ \sum_{j=1}^{k} S_{nj} \geq Smax_n \\ tamax_n & if \ \sum_{j=1}^{N} S_{nj} < Smax_n \end{cases}$$ pu_n is the parameter to establish the relevance of the penalty for the utility deficit	
Access time to stop s in network n. If one stop is served by more than one line, the model considers it as separate stops. $$ta_{n,i,j} = twa_j + AWT_j$$	Access time to stop s in network n. If one stop is served by more than one line, the model considers it as one unique stop. $$ta_{n,i,j} = twa_j + AWT_j$$
Average waiting time is the half of line's headway. $$AWT_j = \frac{1}{2} \cdot headway_{line}$$	Average waiting time is calculated as the average of the expected waiting times when travelling to the reachable stations within an average travel time. $$AWT_j = \frac{1}{NRS_j^{ATT}} \cdot \sum_{i=1}^{NRS_j^{ATT}} EWT_i$$
If no transport node can be reached within twa_max_n, then ta_{nis} takes the value of a maximum access time to the network n ta_max_n: $$ta\_max_n = twa\_max_n + \frac{1}{2} \cdot headway\_max_n$$	
$\delta_{n,i}$, is an aggregate measure of the utility provided by all the stops or lines whose access times are below ta_{nix}: $$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n}$$	
Utility perceived in point i considering the nodes of the network n:	Utility perceived in point i considering the nodes of the network n:

$U_{n,i} = \sum_{j=1} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} = S_{n1} + \sum_{j=2} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} \mid ta_{n,i,j} \leq ta_{n,i,x}$	$U_{n,i} = \sum_{j=1} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} = S_{n1} + \sum_{j=2} S_{nj} \frac{f(ta_{n,i,j})}{f(ta_{n,i,m})} \mid ta_{n,i,j} \leq ta_{n,i,x}$
Each node n_j is served by one unique line, providing a level of service S_{nj}, which depends on the characteristics of the whole line. $S_{n,line} = \alpha \cdot \frac{CSpeed_{line}}{CSpeed_{\max}} + \beta \cdot \frac{NWStops_{line}}{NWStops_{\max}} + \gamma \cdot Comfort_{line} + \lambda \cdot Reliability_{line}$	Each node n_j is served by one or more lines, providing a level of service S_{nj}, which depends on the characteristics of the node: number of stops and transfers than can be reached within an average travel time from it, and comfort and reliability of lines serving the stop. $S_{n,,j} = (\alpha + \beta \cdot TMM_j^{ATT/2} + \gamma \cdot Comfort_j + \lambda \cdot Reliability_j) \cdot NRS_j^{ATT}$

Table 3 Summary of Urbicon calculation methods

Below is a summary of the parameters to be calibrated in the model:

- twa_max_n: Maximum walking access time in network n. For instance, double of stop coverage radius in each mode m.
- pu_n: Weight of utility penalization in network n. It must be set between 0 and 1, depending on the relevance that modeller gives to utility.
- $Umax_n$: Maximum level of service in network n.
- $Umin_n$: Minimum level of service in network n.
- $\alpha,\beta,\gamma,\lambda$: Weight of different utility variables.
- ATT: Average travel time, not considering access and egress time.

5.1.4 Aggregation of modal results

Once the different modal values ($ICON_n$) are obtained, they must be aggregated in proportion to their relative importance.

$$ICON_i = \sum_{n=1}^{n=N} p_n \cdot ICON_{n,i}$$
$$\sum_{n=1}^{n=N} p_n = 1 \qquad \text{(Eq. 5.26)}$$

In the classical ICON formulation, the relative weight of each mode is evaluated according to the economic development impact of the mode. In URBICON, instead of this, it is used the utility of each mode in the city or area under analysis to assign the relative weight of each mode.

For small cities, for instance less than 100000 inhabitants or less than 30 km2, bus will be the best mode, in economic, operational and social terms, to connect all the important places and to serve most of the population. For medium cities, for instance between 100000 and 500000 inhabitants, bus and tram are the best options and for larger cities an underground network is usually needed to connect all districts in an acceptable time.

The adopted method works as follows: the first step is to calculate the street network distance between all the ICON evaluation points, thus having an O-D distance matrix that surely will not be completely symmetric due to one-way streets.

Following that, a distribution of the distances between the O-D pairs is obtained, like the one presented below for the case of Barcelona.

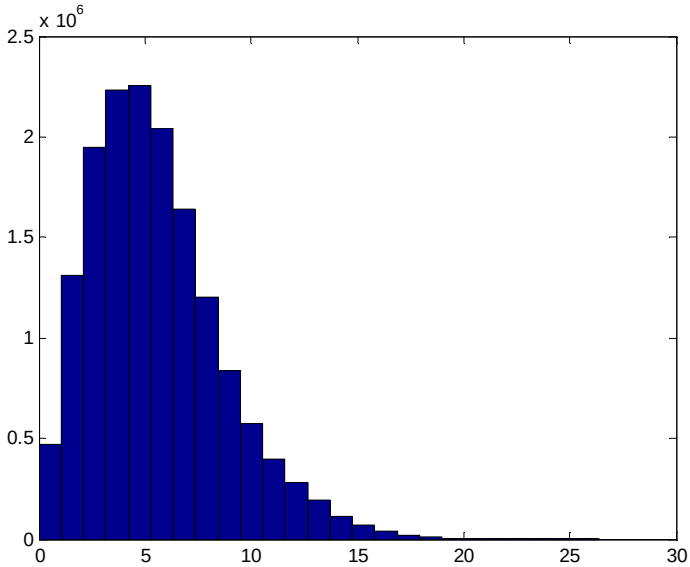


Figure 16 Distribution of distances (Km) between O-D pairs

Then, knowing the commercial speed and the average travel time of each mode, it is possible to calculate the maximum distance that can be covered by each mode in the given time. For the case of Barcelona we can consider these modes:

Mode	Max Speed (Km/h)	ATT (mins)	Max Distance (Km)
Non motorized	10	17	2.8
Bus	15	20	5
Tramway	18	20	6
Underground	33	22	12.1
Commuter rail	45	60	45

Table 4 Characteristics of each mode

Source: Transport operators and Daily Mobility Survey 2006 (EMQ 2006)

Next, distance intervals must be assigned to each mode in order to calculate the number of trips that can be carried out by it and, thus, the relative weight of each mode:

Mode	Travel interval (Km)	% Trips	p_m weight
Non motorized	0-2.8	0.19	0
Bus	1-5	0.32	0.16
Tramway	1-6	0.59	0.29
Underground	1-12.1	0.93	0.46
Commuter rail	8-45	0.19	0.09

Table 5 Distribution of trips and relative weight of each mode

In the URBICON calculation the non-motorized modes are not included. Then, the weight given to each mode must be calculated in order to their addition equals 1.

In small cities it is more useful to have bus services with short distances between stops and commercial speeds around 10-15 Km/h. In bigger cities tram or underground lines, with

commercial speeds above 20 Km/h, will service most O/D with shorter times than the bus lines. At the metropolitan scale commuter rail services will take more importance.

The other characteristics of the mode, which are also particular to each line (e.g. headways) or to each stop (e.g. access time), are incorporated in the ICON calculation for each specific point, as described before.

Another way to aggregate the modal results is to consider the current demand of each mode in the area under analysis, although the original idea of the URBICON indicator was that its formulation should be independent of the demand. In this case the relative weight of each mode is set according to the distribution of trips carried by the public transport system.

Mode	% Trips (*)	p_m weight
Bus	34.4	0.36
Tramway	2.4	0.03
Underground	48.9	0.52
Commuter rail	8.5	0.09
Others	5.8	0
Total	100	1

Table 6 Weekday distribution of trips by public transport and relative weight of each mode
(*)Source: Daily mobility survey 2006 (EMQ 2006)

It should be pointed out that the weights obtained for the underground and rail modes are quite similar in both methods of calculation. The differences observed in bus and tram modes are due to the fact that the *distance coverage method* supposes that the network is more or less uniformly distributed over the city for each transport mode. This is not the case of Barcelona, whose small and not interconnected tram network has only small lines in the extremes of the city. This explains why the potential demand of the tram mode is really mostly captured by the bus and underground modes.

Taking into account these issues what seems to be more adequate is to use the *distance coverage method* in the areas where there is an available tram service and the *demand distribution method* where there isn't, i.e., where the $ICON_{tram}$ is maximum.

5.1.5 Selection of points of interest for ICON calculation

First of all, it is necessary to define the area to be analyzed. To do that, a polygonal grid is generated covering the region of interest. The shape of the cells will depend on the form of the streets or the area to be covered, being square or hexagonal. The streets layer contains several nodes corresponding to the intersections, crossings and diversions.

In the Figure 17 is shown how this methodology is applied to the case of Barcelona. A grid of 120x210 zones covering the city and surroundings is created; being each zone a square of 133x133 meters. This measure is selected according to the dimensions of the streets in the

Eixample[1] district, which is located in the downtown and shapes the mobility of the whole city.

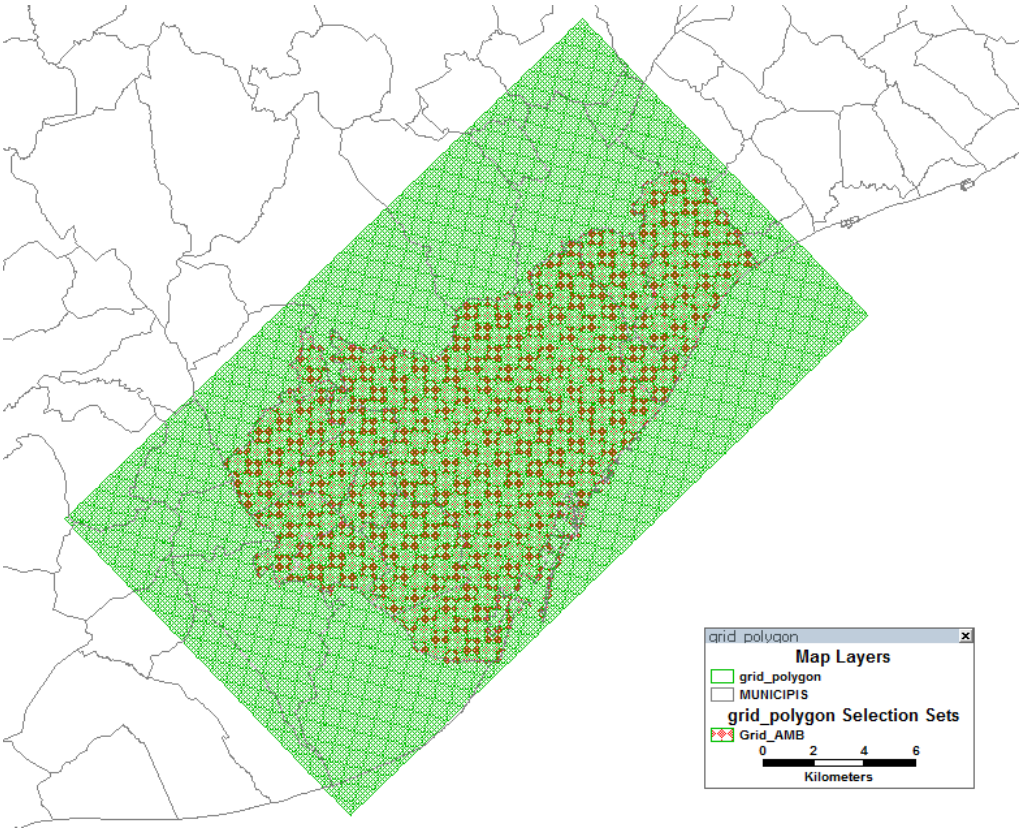


Figure 17 Grid of feasible sampling zones over the city of Barcelona

After that, one centroid is created in each cell, ensuring that all sampling points are uniformly distributed. Then, they are connected to the street network by one or more links in order to reproduce traveler's behavior as realistic as possible.

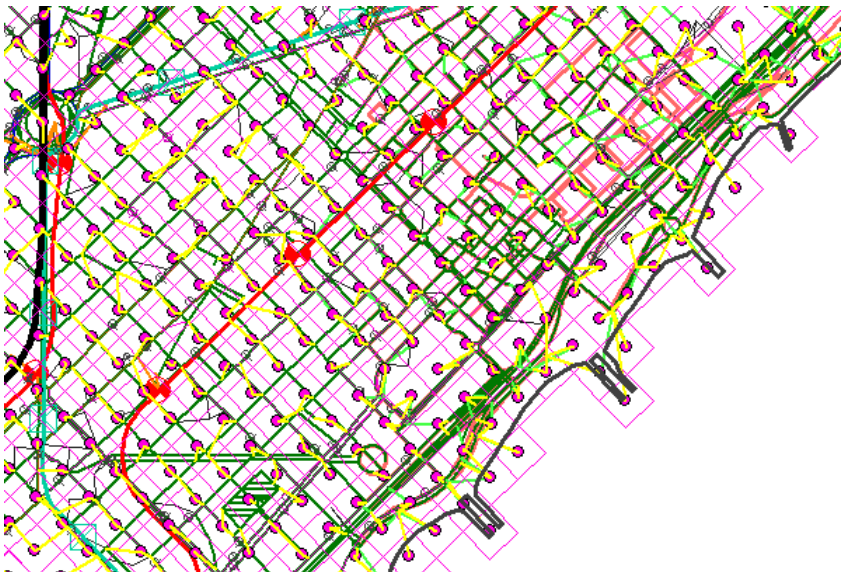


Figure 18 Connecting sampling points to the street network

[1] The Eixample, developed by Cerdà from the 1850's, is the first paradigm of modern urban planning. He adopted a square module of 133x133 for the grid that presently covers most of the central area of Barcelona

5.2 Metropolitan scale with regional or interregional scope

As presented before, in urban and metropolitan scale the URBICON calculation takes into account the walking access to public transport networks, considering only the modes that are useful within the metropolitan area. But the access to regional networks is not yet contemplated.

In this regional scope the classical ICON evaluation reviewed in 4.1 can be applied. The transportation modes considered in the calculation can be the following ones: bus services, medium and long distance trains, air and maritime lines.

For instance, in the case of the city of London and with a national scope, main railway stations can be considered as feasible nodes of the regional transportation networks.

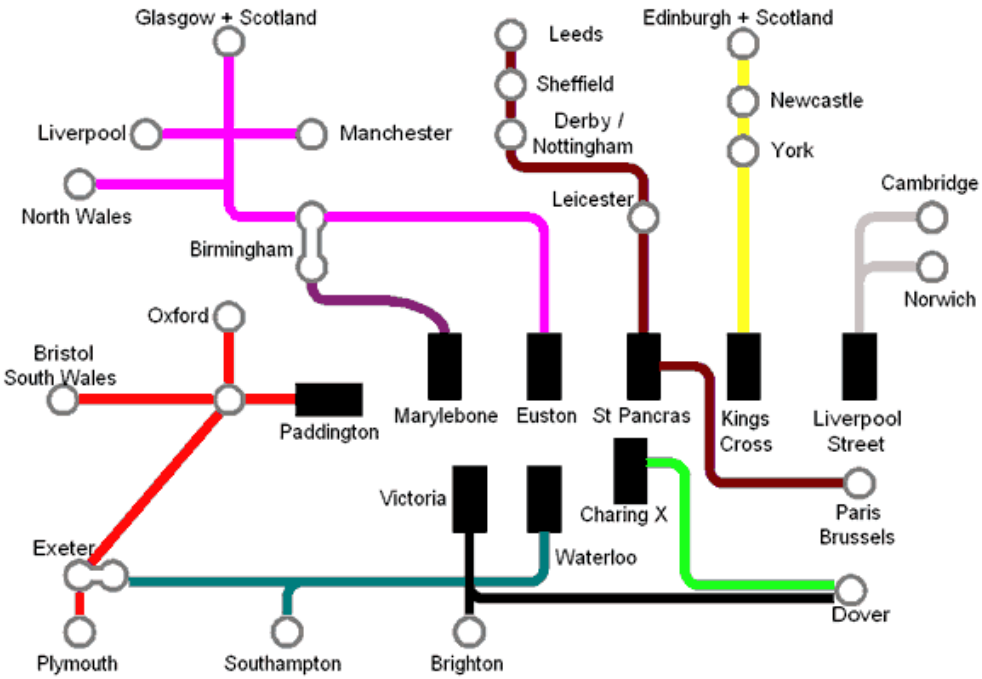


Figure 19 London's main railways station and the main cities they serve

London city has in a less than one hour access time several airports that provide national and international flights. Thus, the airports considered in the air mode ICON evaluation must be: Heathrow, Gatwick, Luton, Stansted and London City.

The new proposed concept here is the way how the access time to transportation nodes is measured. In the classical ICON formulation, the access time is calculated by the *in car travelling time* to the networks, because it is assumed that this is the only way to reach these networks in a regional scale.

In the situation exposed here, the users are located in an urban or metropolitan scale, thus having a public transportation network more or less equally distributed over the city. Even

more, the main regional transportation nodes are almost always well connected to the local transportation networks. Then, the estimation of the access time to regional network nodes can be formulated as the minimum access time between going walking and taking public transport services:

$$ICON_n = ta_{nm} + tw_n + tg_n \quad \text{(Eq. 5.27)}$$

$$ta_{nm} = \min(twa_{nm}, tta_{nm}) \quad \text{(Eq. 5.28)}$$

where ta_{nm} is the access time to the closest node of the network n, twa_{nm} is the walking time and tta_{nm} is the access time using local transit networks.

To measure the travelling time from one point to another it's possible to use some methods like the shortest path, but in urban areas, with common lines serving the same points, other methods must be considered.

Although existing network analysis and path finding algorithms serve well for road routing and traffic assignment, many researchers have pointed out the inadequacy of applying them to solve the minimal path finding problems for public transport networks (Dial, 1967; Le Clercq, 1972; Chriqui and Robillard, 1975; De Cea and Fernandez, 1989; Spiess and Florian, 1989). That's because transit networks have significantly different characteristics from road networks:

- One street segment may serve different bus routes and many routes may stop at the same bus stop. This is the so-called ``common bus lines problem'' (Chriqui and Robillard, 1975).
- Transit transfers depend on the arrival time of another bus. Hence the best path between an origin and destination can change depending upon the timing of services available.
- Unlike the highway routing problem, where the computation of shortest path is symmetric with respect to an origin/destination pair, the routing on transit networks from origins to destinations is not symmetric with that from destinations to origins.
- Transit services are time dependent, different times of the day or different days of the week have different levels of transit service. Some services are available only at the peak time period.

Taking into account all these characteristics, to calculate the travel time with public transport modes, some algorithms for finding the shortest path in transit networks must be assessed, like the ones proposed by Chriqui and Robillard (1975) or Spiess and Florian (1989) (see Appendix A).

6 GIS Comparison

In a broad sense a geographic information system (GIS) is an information system specialized in the capture, storage, management, analysis, reporting and presentation of spatially related data. The GIS link geographic and statistical information stored in a database with cartography tools.

Geographic Information Systems for Transportation (GIS-T) refers to the application of geographic information technologies to transportation problems. There is several GIS software specialised in transport systems, like TRANSCAD or EMME/2.

While the basic transportation analysis procedures (e.g. shortest path finding) can be found in most commercial GIS software, other transportation analysis procedures and models (e.g. transit assignment algorithms) are available only selectively in some commercial software packages.

6.1 TransCAD

TransCAD combines GIS and transportation modeling capabilities in a single integrated platform. TransCAD provides:

- A GIS engine with special extensions for transportation.
- Mapping, visualization, and analysis tools designed for transportation applications.
- Application modules for routing, travel demand forecasting, public transit, logistics, site location, and territory management.

TransCAD includes the Geographic Information System Developer's Kit (GISDK) that allows building custom applications. GISDK is a simple object-oriented scripting language with hundreds of spatial data structures and functions. GISDK contains both a debugger and a compiler.

TransCAD has special data structures for handling transit routes, which can be stored, displayed, edited, and analyzed. Public transport routes can be directly placed on the streets and stops don't need to be placed at street intersections, but instead can be located where they really are and on the correct side of the street.

Transit networks are created from a route system layer, using information from the routes, the stops, and the underlying line geographic file (streets layer, rail layer, node layer, etc.). Using transit networks, the user can solve shortest path problems, calculate transit path attributes between stops in the route system, perform transit assignments, work with transit schedules, and measure accessibility.

TransCAD provide three methods for calculate the best transit path:

- *Shortest Path method*: finds the single best path from an origin to a destination that minimizes the total generalized travel cost. On any path segment only one transit line

will be chosen, even if the segment is served by several transit lines with identical travel times.

- *Optimal Strategies method*: The result of applying this method, presented in A.2, is a subnetwork or "hyperpath" that contains all the paths that will be used.
- *Pathfinder method*: Pathfinder differs from the previous methods that fares are taken into account in determining the best path. This is done by using the generalized cost of travel in place of travel time as the measure to be minimized. Then, hyperpaths are constructed in a similar way that the optimal strategies method does.

TransCAD allows three primary types of accessibility measures:

- *Access measures*: the cost of access to the nearest service point in the network. For example, this measure calculates the percent of people older than 65 in your region that have frequent bus service within a quarter mile walk from their home. The results are the total and the proportion of the target population that is served.
- *Threshold measures*: the ability to reach a desired destination within a time, distance, or cost limit. The measures identify the zones that are within the threshold cost and the target population served by each destination zone.
- *Continuous measures*: compute the attractiveness of zones based on their accessibility to destination zones that have jobs and services. While threshold measures focus on the nearest desirable destination, continuous measures handle the range of potential destinations.

These three accessibility measures are focused on the demand-side, but don't can be used to calculate the access time to the networks, as URBICON proposes, giving a measure of the supply-side and public transport coverage.

Anyway, the main advantage of TransCAD is the capability to create and manage public transport routes and stops and possibility to build custom functions and applications. GISDK will allow the creation of the necessary functions to calculate the URBICON indicator with the transit routes stored in TransCAD files.

One great disadvantage is that for any of these calculations (shortest path algorithms, accessibility measures, etc.) it is mandatory to create a public transport network with all the routes involved on them. For each scenario or for each modification in services, it's necessary to create again a new network and set up all the parameters.

6.2 ArcView GIS and Accessibility Analyst

ArcView GIS environment provides functions for collecting, managing, manipulating, and mapping the data required for accessibility analysis. Spatial Analyst provides tools for spatial analysis and modeling, including buffer generation, proximity analysis, neighborhood and zone analysis, terrain modeling (for example, contour generation and slope), and map algebra. Network Analyst provides functions for basic network analysis, such as finding the shortest path, finding the closest facility, and identifying a service area around a site.

Accessibility Analyst was developed by Liu and Zhu (2004) as an extension to ArcView, using ArcView Avenue programming language. It is integrated into the ArcView GIS environment (Version 3.2). Accessibility Analyst provides a set of accessibility measures and allows users to select the accessibility measures suited to their needs, to specify the selected measures, and to implement the specifications.

Six functions are available in Accessibility Analyst for measuring travel impedance.

- *Straight-line Distance Matrix* function calculates the straight-line distance from each origin to every destination. It does not take into account the effects of the transportation network.
- *Shortest-Path Distance Matrix* function uses the Network Analyst functions for finding the best route to calculate the distance over the shortest path along the transportation network for every OD pair. To use this function, origins and destinations must be points located exactly on the transportation network.
- Normally, origin and destination points are not located on the transportation network. In that case, the travel distance can be considered to consist of three parts: *d1*, distance from the origin point O to the nearest transportation node OTN; *d2*, the shortest network distance by the specified travel mode (car, bus, train) from OTN to the transportation node nearest to the destination point DTN; and *d3*, distance from DTN to destination point D. The *Network Distance Matrix* function is designed to calculate the total travel distance from each origin to every destination based on the measurements of these three distances.
- *Network Time Matrix* function calculates the travel time between origins and destinations based on the three parts of distance. Each part may involve only a single travel mode. This function is based on the distance data generated by using the distance matrix functions described above and the average travelling speed of a particular travel mode for each part of distance. The result is an OD matrix containing the travel time for each OD pair.
- *Network Cost Matrix* function is specially designed for Singapore. It calculates travel cost according to the adult Farecard fares on the different transportation modes.
- *Matrices Operation* function is designed for mathematically manipulating OD matrices. It allows users to perform mathematical operations on two OD matrices with the same origins and destinations. The mathematical operations it supports include calculation of the minimum or maximum value, and sum, difference, product, and division.

Accessibility Analyst provides six functions to measure accessibility:

- Catchment profile analysis: is used to find the nearest destinations for each origin. The result of the function is a table, called the catchment profile table, containing the origin IDs, the nearest-destination IDs, and the distances (time or cost values) between each origin and its nearest destination.
- Cumulative-opportunity measure
- Potential model
- Modified potential model
- Double constrained potential model
- Utility-based measure

All these functions, except the Catchment Profile Analysis function, produce an output table with the following fields: origin identification number (ID), total distance (time or cost) from one origin to all destinations, calculated accessibility value, and normalized accessibility value.

Accessibility Analyst is a good alternative for quantify these types of accessibility involving demand or opportunities, but is not able to assess the accessibility from the supply side as the Urban ICON does. Also, *Network Time Matrix* allows only one travel mode. Then, network shortest path methods can be used but not the optimal strategies method, which reflects better the user behaviour and multi-modal trips in urban environments.

A feasible solution could be to modify this software package by adding some functions in order to calculate the ICON indicators. But the main drawback is that Accessibility Analyst was developed for the ArcView 3.2, which is no longer supported by the development company. The last version was ArcView GIS 3.3, released on 2002. Since then this product was discontinued and included in the platform ArcGIS Desktop, which has a different programming environment.

6.3 SIMCAT and ATMax

SIMCAT is a modelling and information system for the evaluation of regional policy in Catalonia applied to road traffic.

The SIMCAT includes forecasting, mobility and road traffic models, evaluation models, management and network analysis utilities, a databases manager, analysis and statistical tools and tools that enable graphical outputs. It was commissioned by DPTOP and is currently used by the Institute of Territorial Studies, Barcelona Regional, etc.

ATMax is an information and modelling system for the collective public transport networks of the Metropolitan Region of Barcelona. It contains databases with information associated with 170,000 road infrastructure elements, rail and metro and intercity bus (450 services), regional areas (census tracts, EMO96 and EMQ96 areas, price zones) and other GIS information reference.

One of the main advantages of ATMax is the possibility to storage different public transport networks or services in different layers. Also it is possible to select some elements of one layer to make the calculations. For instance, if there are some lines that are planned but still not commissioned, they can be unselected in the calculation scenario.

ATMax is a closed system, but all data are stored in an Access data base, so they can be processed by standard commercial software.

These both applications will be useful in order to obtain all the necessary data to analyse the accessibility in the Metropolitan Region of Barcelona with the URBICON indicator.

7 Applying URBICON to Barcelona

Barcelona is a city located in the north-east of the Iberian Peninsula in the Mediterranean coast. With a population of 1.6 million inhabitants and 100 km^2 it is the second city of Spain. The Metropolitan Area of Barcelona is constituted by 36 municipalities with a total population of 3.2 million inhabitants and an area of 636 km^2.

Figure 20. Metropolitan Area of Barcelona

The main objective of this first application of URBICON is to evaluate the connectivity of Barcelona and its adjacent municipalities, specifically Badalona, Sant Adrià, Santa Coloma, L'Hospitalet, Esplugues de Llobregat i Sant Just Desvern, to the public transport networks. The analysis is made for the year 2004, for which good information is available,and allows an eventual comparison with the present situation. The networks considered are:

- Bus: all the bus lines of the TMB operator and the different operators of the EMT (Metropolitan Entity of Transport).
- Tramway: the tram lines of TramBaix and TramBesós.
- Underground: the metro lines of the operators TMB and FGC.
- Commuter rail: the lines of the operator Renfe.

The idea is to compare, in future applications, the results obtained for the year 2004 with the ones expected for the year 2014, when new major infrastructures, such as the underground lines L9 and L10, should be completed.

The data needed for the evaluation is:

- The graph of the street and road network.

- The location of all bus and tramway stops.
- The location of all underground and rail stations.
- The characteristics of each transport line: headway, length, commercial speed and number of stops.

The necessary data have been provided by MCrit and the ATMax system. Only the stations and the stops inside the municipalities under study are considered.

ATMax stores all geographic and transportation data in a standard Access data base (mdb file). As ATMax is a closed system and it doesn't provide programming utilities, the process to calculate the ICONn for each network has been implemented in Visual Basic functions inside the Access data base.

In a first approach the sampling points were the centroids of the 2001 census areas (a total of 2124 points). The census areas have very different sizes; some census areas are 20 times bigger than others due to their population density, complicating comparisons. Besides, for these big areas it is not reasonable to consider a single connectivity value for the entire census area.

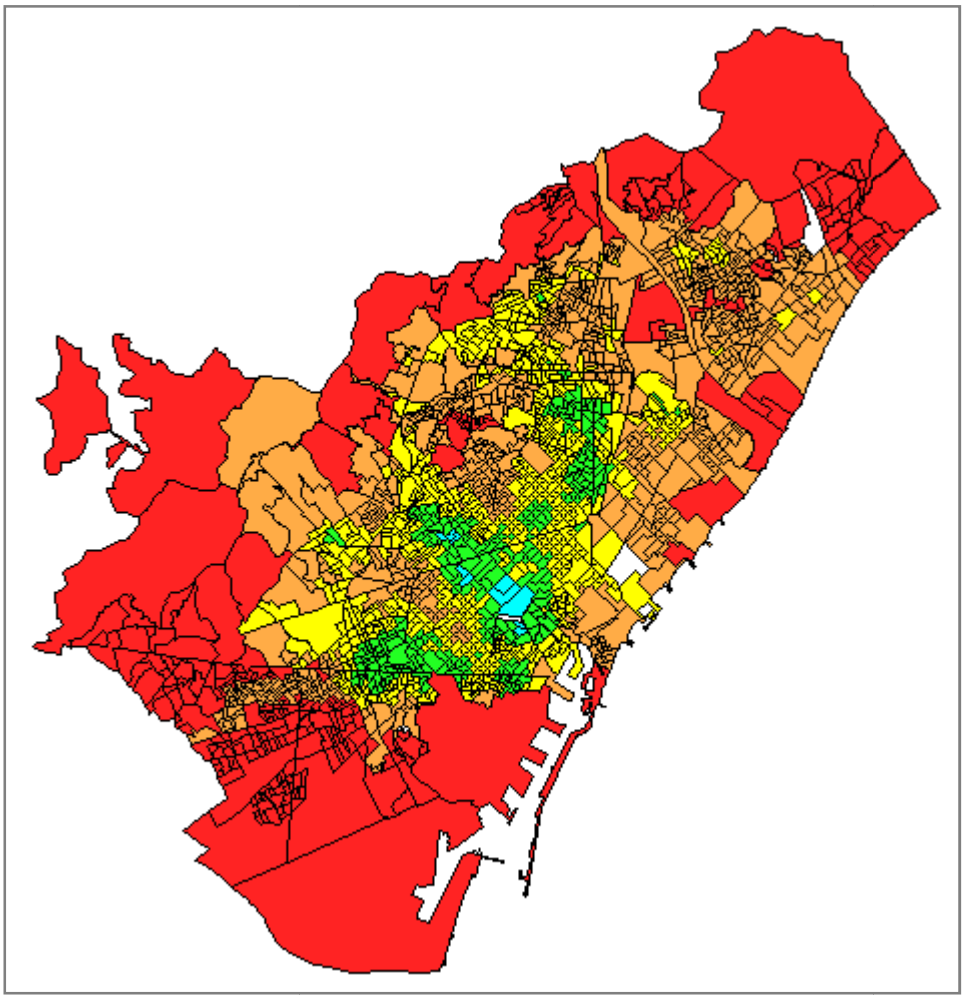


Figure 21 Access time to the underground network for each census area

To avoid this, a rectangular grid of 120x210 cells of equal size (Figure 17), covering the whole region of interest, has been created. The selection of evaluation points is made according to

section 5.1.5. The cells are squares of 133x133 meters, corresponding to the dimensions of the blocks of the Eixample district. Only the cells inside the municipalities under analysis are considered and then, one centroid is created in each cell, leading to a set of 10732 sampling points. They are connected to the street network by one or more links in order to reproduce traveler's behavior as realistic as possible. This grid allows sufficiently detailed mapping of URBICON for its use for spatial information and public transport planning purposes.

7.1 URBICON calculation using the line utility method

To evaluate the connectivity of the study area, the URBICON methodology presented before has been applied. In this case URBICON has been calculated using the *line utility method*, which means that each node of the network is characterized by a level of service depending on the features of the line to which it belongs.

The URBICON calculation can be made for different time periods (peak – non peak) and days (working days, weekends and holidays). In this case, data of working days at peak-hour are used.

URBICON is obtained aggregating the $ICON_n$ results for the different public transport networks mentioned above using the formulation presented in 5.1.4.

The process to calculate the $ICON_n$ for each network, proposed in 5.1.1, has been implemented using a Visual Basic function. The calculations for the metro and bus networks for a particular cell are presented here as examples of the work that has been carried out.

7.1.1 Underground network

The underground (Metro) network of Barcelona is operated by two different public companies, Transports Metropolitans de Barcelona (TMB) and Ferrocarrils de la Generalitat de Catalunya (FGC). Table 7 shows the lines of this network and their characteristics in 2004. Lines L9 and L10 are not included because they started to be commissioned in 2010.

Line	Headway Rush hour (mins)	Commercial Speed (km/h)	Number of Weighted Stops	Comfort Rush hour	Reliability	Service
L1	3.75	29.8	35.5	0.31	83%	77.61
L2	3.75	27.7	20.5	0.58	90%	61.66
L3	3.53	26.4	30	0.47	83%	71.51
L4	4.6	28.4	25.5	0.68	85%	70.50
L5	3	25.9	26.5	0.54	88%	68.43
L6	6	21.72	13	0.5	99.8%	47.87
L7	6	25.5	10.5	0.6	99.8%	48.02
L8	6	35.48	11.5	0.5	99.7%	51.82
L11	7	25.3	5.5	0.89	90%	45.67

Table 7 Underground lines of Barcelona and their characteristics
Source: Own elaboration based on TMB and FGC data

The service provided by each line has been calculated using the following formulation and parameters:

$$S_{n,line} = 20 \cdot \frac{CSpeed_{line}}{CSpeed_{\max}} + 50 \cdot \frac{NWStops_{line}}{NWStops_{\max}} + 20 \cdot Comfort_{line} + 10 \cdot Reliab_{line}$$

$Smin_n$ is set to 45.67, as it is the minimum level of service of the underground lines. $Smax_n$ is set to 200, considering that the traveller obtains a maximum utility if he can reach 3 of the 5 biggest lines within the maximum access time.

The utility decay function used in this network is the Gaussian function with parameter σ=9:

$$f(ta_{n,i,j}) = e^{-\frac{(ta_{n,i,j-\mu})^2}{2\sigma^2}} = e^{-\frac{ta_{n,i,j}^{\ 2}}{2 \cdot 9^2}}$$

The average distance between stops in the underground network of Barcelona is about 800 meters, which can also be set as the coverage radius of an underground station. With a typical pedestrian speed of 4 km/h it is equivalent to 12 minutes. As URBICON is focussing on identifying locations where there is insufficient connectivity to the networks, i.e. areas with low public transport endowment, the coverage radius for the analysis may be greater. Thus, the maximum walking access time (twa_max_n) to reach an underground station is set to 20 minutes and the maximum access time (ta_max_n) for the underground network is calculated as follows:

$$ta\_max_n = twa\_max_n + \frac{1}{2} \cdot headway\_max_n$$

$$ta\_max_n = 20 + \frac{1}{2} \cdot 7 = 23.5 \text{ minutes}$$

The parameter pu_{ni}, which establishes the relevance of the penalty for the utility deficit, is set at 0.75.

Once these parameters are defined, the access time to the underground network can be calculated.

The graph included in the ATMax system contains all the information about the street and road network, location of all bus and tramway stops, underground and rail stations and the characteristics of each transport line.

First of all, it is necessary to compute the cost of reaching the underground stations from the grid cells' centroids used in the analysis. Each arc of the street graph contains information about its length and travel speed by foot and by car. The typical speed used for pedestrians is 4 km/h, but it changes depending on the characteristics of the street. Even the access to the underground stations is modelled by links with speeds between 2 and 4 km/h. This

calculation can be made usually with any GIS. In this case ATMax creates a cost matrix between the origins (centroids) and destinations (TMB and FGC stations) with information about distance and time costs, and stores it in an Access table. Once this matrix is created, the URBICON algorithm must be processed in the Access data base.

Below it is shown how the $ICON_{metro}$ has been calculated for a centroid near Sagrada Família, in the intersections of Sicília and Rosselló streets.

The set of feasible stops FS, nodes that can be reached within twa_max_n, is:

Stop Name	twa_{nij} (mins)
METRO L4 - VERDAGUER	7.97
METRO L5 - SAGRADA FAMILIA	8.33
METRO L2 - SAGRADA FAMILIA	8.34
METRO L5 - VERDAGUER	11.49
METRO L4 - JOANIC	13.81
METRO L5 - HOSPITAL DE SANT PAU	15.22
METRO L2 - MONUMENTAL	15.38

Table 8. Feasible stations and walking access time from Sicília/Rosselló intersection

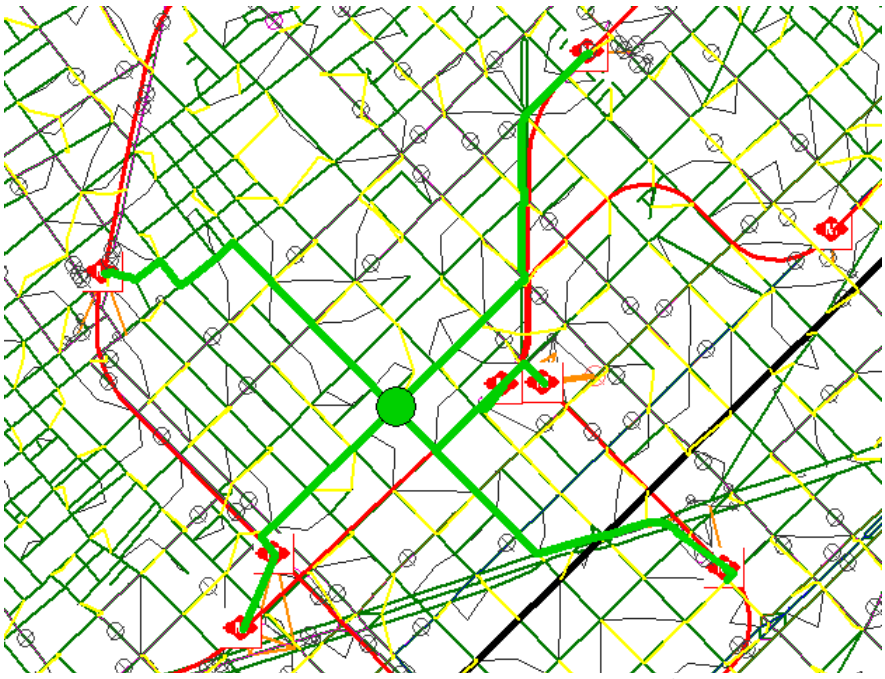


Figure 22 Map of shortest paths to feasible stations from Sicília/Rosselló intersection

Following that, the algorithm selects only the nearest station per line and calculates the access time (ta_{nij}) as the addition of walking access time (twa_{nij}) plus the average waiting time in the node, which is considered as half of the line's headway:

$$ta_{n,i,j} = twa_{\mathrm{i,j}} + \frac{1}{2} \cdot H_{\mathrm{Lx}}$$

Stop Name	Line	Headway	twa_{nij}	ta_{nij}	S_{nj}	AccService
METRO L5 - SAGRADA FAMILIA	L5	3.00	8.33	9.83	68.4	68.4
METRO L2 - SAGRADA FAMILIA	L2	3.75	8.34	10.22	61.7	130.1
METRO L4 - VERDAGUER	L4	4.62	7.97	10.28	70.5	200.6

S_{nj} is the level of service of the node *j* and *AccService* is the accumulated level of service by the nodes of FS.

ta_{nim}, the access time to the closest node, is then 9.83 minutes. ta_{nix} is equal to the access time of the first node providing and accumulated service higher than $Smax_n$. In this centroid ta_{nix} = 10.28 minutes and S_{nd} = 0 because the addition of the service provided by the nodes in FS is higher than $Smax_n$.

Then, $ICON_{metro}$ for cell P1 is calculated following the formulation presented in Chapter 5:

$$ICON_{n,\mathrm{P1}} = ta_{n,\mathrm{P1},m} + pu_n \cdot \delta_{n,\mathrm{P1}} \cdot (ta_{n,\mathrm{P1},x} - ta_{n,\mathrm{P1},m})$$

$$ICON_{n,\mathrm{P1}} = ta_{n,\mathrm{P1},S42} + pu_n \cdot \frac{Umax_n - U_{n,\mathrm{P1}}}{Umax_n - Umin_n} \cdot (ta\_max_n - ta_{n,\mathrm{P1},S42})$$

$$U_{n,\mathrm{P1}} = 68.4 + 61.7 \cdot \frac{f(10.22)}{f(9.83)} + 70.5 \cdot \frac{f(10.28)}{f(9.83)} = 193.8$$

$$ICON_{n,\mathrm{P1}} = 9.83 + 0.75 \cdot \frac{200 - 193.8}{200 - 45.67} \cdot (10.28 - 9.83) = 9.84 \text{ minutes}$$

This value represents the access time to the closest node (ta_{nim}) plus an additional time in order to take into account its utility gap with relation to the maximum level of service. The value obtained falls between ta_{nim} and ta_{nix}, depending on the utility of the nodes in FS. In the P1 centroid, the utility is very high, near the maximum level of service perceived by users and, as a consequence, the ICON result is very close to ta_{nim}.

The results of $ICON_{metro}$ for all the grid cells of the Metropolitan Area of Barcelona are presented in Figure 23. The map shows that the zones with the best connectivity (i.e. the lowest access time) to the underground system are those located in the main interchange stations, like Plaça Catalunya, Plaça Espanya and Sagrera stations, which have access times lower than 8 minutes.

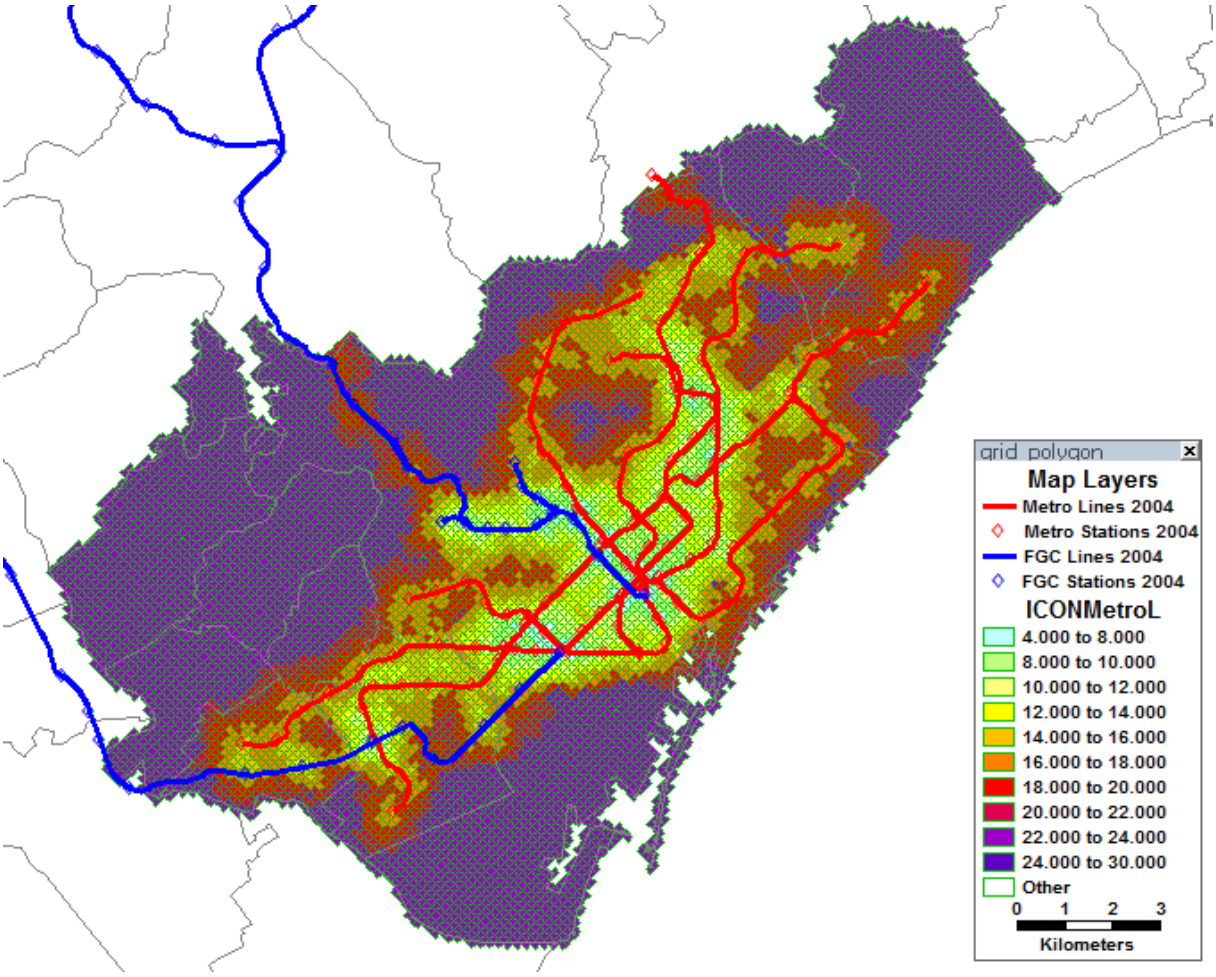


Figure 23 Connectivity to the underground network of Barcelona

The zones in violet colour are the ones with the highest $ICON_{metro}$ values, featuring access times above 22 minutes. In these areas no line can be reached within the maximum access time (23.5 minutes) or the lines that can be reached have a low level of service compared to the maximum.

7.1.2 Bus network

The bus network of Barcelona is operated by the public company Transports Metropolitans de Barcelona (TMB) and by several companies under the supervision of the EMT (Metropolitan Entity of Transport).

The service provided by each line is calculated using the same formulation and parameters as for the underground system:

$$S_{n,line} = 20 \cdot \frac{CSpeed_{line}}{CSpeed_{\max}} + 50 \cdot \frac{NWStops_{line}}{NWStops_{\max}} + 20 \cdot Comfort_{line} + 10 \cdot Reliab_{line}$$

In this case, it is considered that the traveller obtains the maximum level of service if he/she can reach 8 bus lines within the maximum access time. Taking into account that the average level of service of bus lines is around 55, $Smax_n$ is set at 400. $Smin_n$ is set at 26, which corresponds to the line with lowest level of service.

The maximum walking access time to reach a bus stop is set at 12 minutes. Then, the maximum access time for the bus network is calculated as follows:

$$ta\_max_n = twa\_max_n + \frac{1}{2} \cdot headway\_max_n$$

$$ta\_max_n = 12 + \frac{1}{2} \cdot 20 = 22 \text{ minutes}$$

The Gaussian decay function is calibrated for this network with the parameter σ=7.

As an example, the connectivity to the bus network for the same centroid near Sagrada Família has been calculated. The set of bus nodes accessible from this point within 12 minutes is shown on the map:

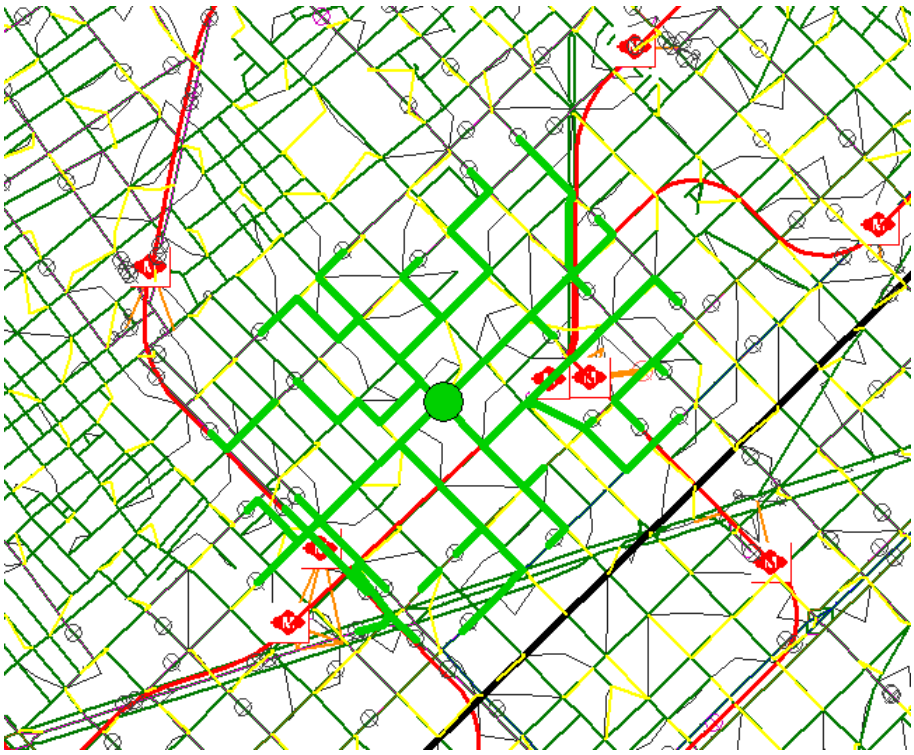


Figure 24 Map of the shortest paths to feasible bus stops from Sicília/Rosselló intersection

In the bus network, each node may be served by more than one line. In the methodology used, the node's utility is measured according to the line's level of service and, to be consistent, the algorithm must consider each line's stop as a separate node, although they may belong to the same physical stop. On the other hand, even if bus lines can be reached through different accessible nodes, the algorithm only selects the nearest stop per line.

Given these conditions, the set of accessible stops FS sorted by the access time ta_{nij} is:

StopID	Stop name	Line	Headway	twa_{nij}	ta_{nij}	S_{nj}	AccService
1269	Marina-Av Gaudí	10 A	7	5.42	8.92	57.47	57.5
1318	València-Av Diagonal	33 A	6	6.66	9.66	59.26	116.7
1318	València-Av Diagonal	34 A	6	6.66	9.66	63.82	180.5
1297	Pl Sagrada Família	33 T	6	6.80	9.80	59.26	239.8
913	Indústria-Sardenya	15 T	6	6.92	9.92	53.97	293.8
1297	Pl Sagrada Família	43 T	7	6.80	10.30	73.16	366.9
1317	St Antoni M. Claret-Sardenya	15 A	6	7.34	10.34	51.93	418.9
1297	Pl Sagrada Família	34 T	7.5	6.80	10.55	60.76	479.6
1141	Lepant-Av Gaudí	10 T	7	7.12	10.62	54.40	534.0
1318	València-Av Diagonal	19 A	8	6.66	10.66	63.44	597.5
1318	València-Av Diagonal	43 A	8	6.66	10.66	68.06	665.5
1297	Pl Sagrada Família	19 T	8	6.80	10.80	64.46	730.0

Table 9. Feasible bus stops and walking access time from Sicília/Rosselló intersection

For the centroid P1, ta_{nix} = 10.34 minutes, corresponding to the access time of the first node providing an accumulated service higher than $Smax_n$. S_{nd} is zero because the addition of the service provided by the nodes in FS is higher than $Smax_n$.

Then, the value of $ICON_{bus}$ is:

$$ICON_{n,\mathrm{P1}} = ta_{n,\mathrm{P1},m} + pu_n \cdot \delta_{n,\mathrm{P1}} \cdot (ta_{n,\mathrm{P1},x} - ta_{n,\mathrm{P1},m})$$

$$ICON_{n,\mathrm{P1}} = 8.92 + 0.75 \cdot \frac{400 - 354.18}{400 - 26} \cdot (10.34 - 8.92) = 9.05 \text{ minutes}$$

The application of the same procedure to all the nodes in the Metropolitan Area is reflected in Figure 25, which shows that all the urbanized areas have a good coverage of bus services. The zones in violet colour are the ones with the highest $ICON_{bus}$ values, featuring access times equal or higher than the maximum access time (22 minutes). These zones correspond to industrial areas, like the Zona Franca and the harbour in the south, and to forest areas, like the Serra de Collserola in the North and Montjuïc near the harbour.

The same methodology is applied to the tram and commuter rail networks and the results are presented in Appendix B.

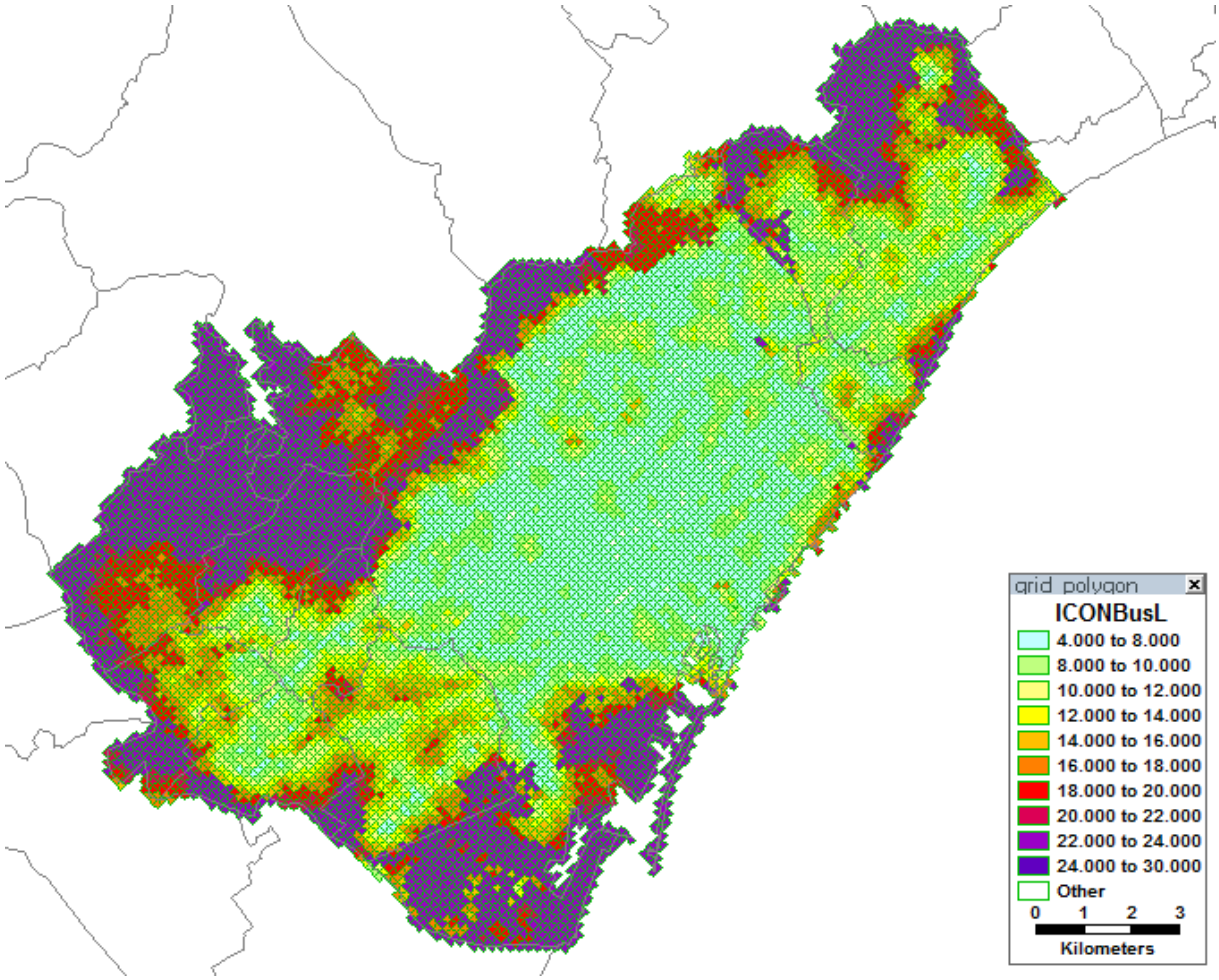


Figure 25 Connectivity to the bus network of Barcelona

The calculation of URBICON from the different modal ICON is explained later. Before that it is interesting to observe the differences that would appear should the ICON for the underground and the bus systems be calculated using the *stop utility method*.

7.2 URBICON calculation using the stop utility method

URBICON may be calculated in an alternative way using the *stop utility method*. In this case the level of service of each node of the network depends on the number of stops that can be reached within a given time and the features of the lines serving the node.

The process to calculate the $ICON_n$ of each network, proposed in 5.1.3, has been implemented using a Visual Basic function.

7.2.1 Underground network

The level of service in each node of the underground network is calculated using the following formulation and parameters:

$$S_{n,j} = (0.7 + 0.2 \cdot Comfort_j + 0.1 \cdot Reliab_j) \cdot NRS_j^{ATT}$$

NRS_j^{ATT} is the variable that counts the number of stops that can be reached by travellers within an average travel time (ATT) from the node j. In the case of Barcelona, the rate of trips with transfers between the lines of the underground network is very high, so NRS_j^{ATT} counts also the stops that are accessible with transfers.

$Smin_n$ is set at 10, as it is the minimum level of service of the underground lines and $Smax_n$ is set at 105, corresponding to the level of service of the stations in the central area of Barcelona, where NRS_j^{ATT} is above 120.

The utility decay function used in this network is the Gaussian function with parameter σ=9.

The maximum walking access time to reach an underground station is set at 20 minutes. Then, the maximum access time for the underground network is calculated as follows:

$$ta\_max_n = twa\_max_n + \frac{1}{2} \cdot headway\_max_n$$

$$ta\_max_n = 20 + \frac{1}{2} \cdot 7 = 23.5 \text{ minutes}$$

The access time from point i to the node j of the network n is expressed as:

$$ta_{n,i,j} = twa_{\mathrm{i,j}} + AWT_j$$

In the previous method, the average waiting time AWT is calculated as half the line's headway, because no destinations are considered and the utility only depends on the general characteristics of the line. In the current method, the average waiting time is calculated as the average of the waiting times perceived by users travelling to any of the stops (s) of NRS from node j:

$$AWT_j = \frac{1}{NRS_j^{ATT}} \cdot \sum_{s=1}^{NRS_j^{ATT}} EWT_s$$

The set of accessible stops FS sorted by the access time ta_{nij} is:

StopID	Stop Name	twa_{nij}	AWT_j	ta_{nij}	NRS_j^{ATT}	S_{nj}	AccService
6	METRO L5 - SAGRADA FAMILIA	8.33	1.5	9.83	106	92.22	92.22
160	METRO L2 - SAGRADA FAMILIA	8.34	1.875	10.22	2	1.74	93.96
184	METRO L4 - VERDAGUER	7.97	2.307	10.28	4	3.48	97.44
4	METRO L5 - VERDAGUER	11.49	1.5	12.99	3	2.61	100.05
182	METRO L4 – JOANIC	13.81	2.307	16.11	0	0	100.05
8	METRO L5 - HOSPITAL DE SANT PAU	15.22	1.5	16.72	0	0	100.05
158	METRO L2 - MONUMENTAL	15.38	1.875	17.26	0	0	100.05

In order to avoid double counting of reachable stops and to have a fictional high level of service, NRS_j^{ATT} only counts the stops that are accessible from node j but have not been included amongst those reachable from the nodes of FS previously considered. This is why the farthest nodes have a very low value of NRS.

The addition of the services provided by all nodes in FS does not reach the maximum level of service ($Smax_n$ =105). Then ta_{nix} is set to ta_max_n (23.5 minutes) and S_{nd} = 105-100.05 = 4.95.

The value of $ICON_{metro}$ is:

$$ICON_{n,\mathrm{P1}} = ta_{n,\mathrm{P1},m} + pu_n \cdot \delta_{n,\mathrm{P1}} \cdot (ta_{n,\mathrm{P1},x} - ta_{n,\mathrm{P1},m})$$

$$ICON_{n,\mathrm{P1}} = 9.83 + 0.75 \cdot \frac{105 - 99.14}{105 - 10} \cdot (23.5 - 9.83) = 10.46 \text{ minutes}$$

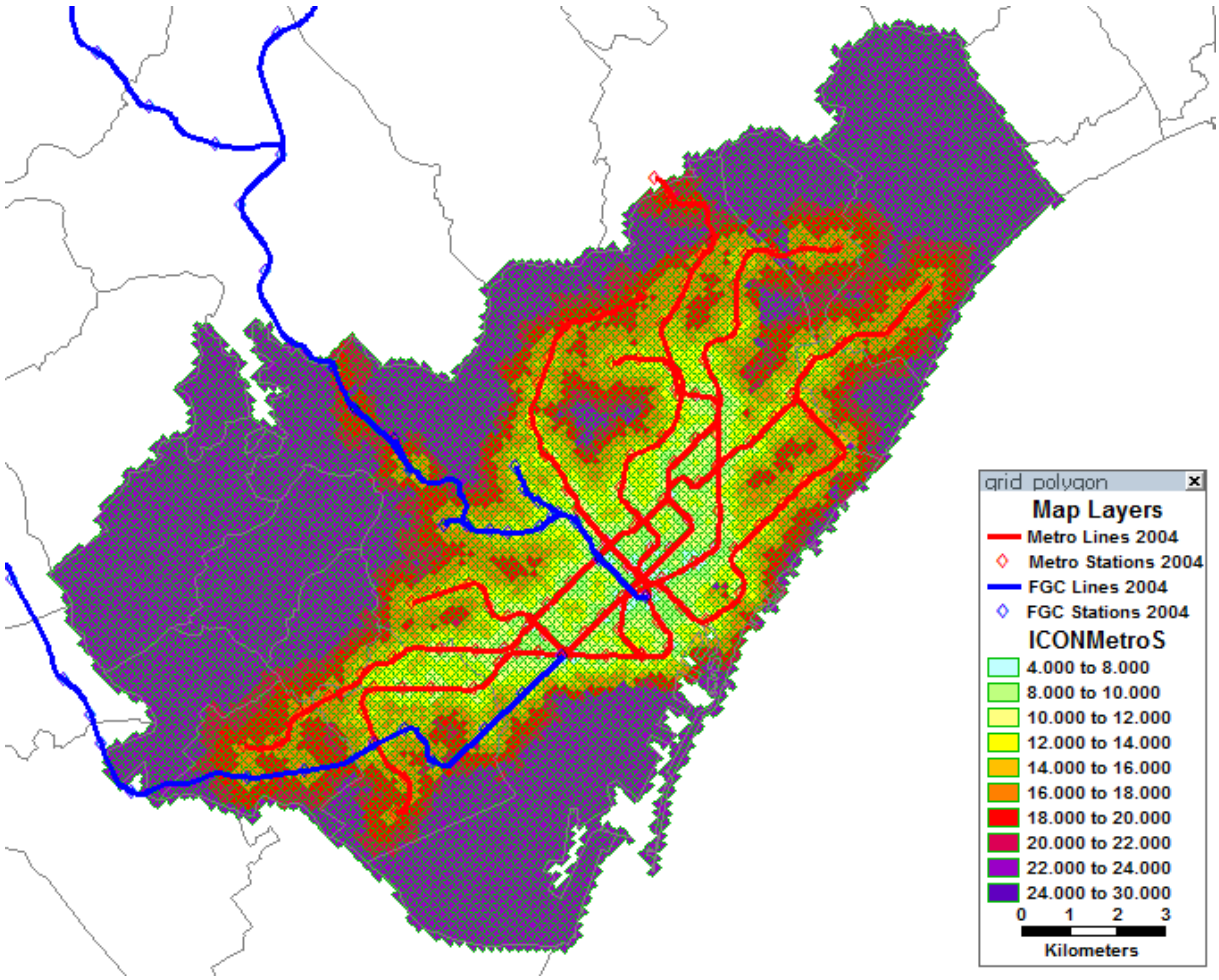


Figure 26 Connectivity to the underground network of Barcelona

The results of the method applied to all cells in the area are quite similar to those obtained using the previous methodology, detecting the same areas with a low underground services endowment. The difference lies that in the *line utility method*, the surroundings of transfer

stations have low values of ICON while in those areas with only one accessible line the access times obtained are higher. This is because the node's utility depends on the line characteristics regardless of the destinations that can be reached from it

With the *stop utility method*, the utility depends on the number of stops that can be reached from it within an average travel time. Thus, the nodes with only one line but near transfer stations have a higher utility than before, leading to a low value of ICON.

7.2.2 Bus network

The service provided by each node is calculated using the following formulation and parameters:

$$S_{n,j} = (0.5 + 0.2 \cdot TMM_j^{ATT/2} + 0.2 \cdot Comfort_j + 0.1 \cdot Reliab_j) \cdot NRS_j^{ATT}$$

NRS_j^{ATT} is the variable that counts the number of stops that can be reached by travellers within an average travel time (ATT) from the node j.

The dichotomous variable TTM (Transfer to Main Mode) is set to one if there is a transfer to the main mode (for the city of Barcelona it is the underground network) within half the average travel time and zero if there isn't.

The variables Comfort and Reliability of the node j are calculated as the average values of the lines serving the node j.

$Smax_n$ is set at 160. $Smin_n$ is set at 10, which corresponds to a node near the end of a line, with TMM=0 and the lowest levels for the comfort and reliability variables.

The maximum walking access time to reach a bus stop is set at 12 minutes. Then, the maximum access time for the bus network is calculated as follows:

$$ta\_max_n = twa\_max_n + \frac{1}{2} \cdot headway\_max_n$$

$$ta\_max_n = 12 + \frac{1}{2} \cdot 20 = 22 \text{ minutes}$$

The utility decay function used in this network is the Gaussian function with parameter σ=7.

The set of accessible stops FS sorted by the access time ta_{nij} is:

StopID	Stop Name	twa_{nij}	AWT_j	ta_{nij}	NRS_j^{ATT}	S_{nj}	AccService
1318	València-Av Diagonal	6.66	2.21	8.86	37.00	32.19	32.19
1269	Marina-Av Gaudí	5.42	3.49	8.91	14.00	12.18	44.37
213	Pg de Sant Joan-Còrsega	7.00	3.51	10.50	31.00	26.97	71.34
949	Indústria-Roger de Flor	7.12	3.52	10.64	2.00	1.74	73.08
913	Indústria-Sardenya	6.92	3.72	10.65	2.00	1.74	74.82
1297	Pl Sagrada Família	6.80	3.93	10.73	52.00	45.24	120.06
1265	Pg de Sant Joan-Rosselló	7.58	3.34	10.92	13.00	11.31	131.37
1141	Lepant-Av Gaudí	7.12	3.80	10.92	8.00	6.96	138.33
1317	St Antoni M. Claret-Sardenya	7.34	3.63	10.96	23.00	20.01	158.34
1227	Mallorca-Roger de Flor	7.39	3.97	11.36	3.00	2.61	160.95

For this centroid, ta_{nix} = 11.36 minutes, corresponding to the access time of the first node providing an accumulated service higher than $Smax_n$. Then, the value of $ICON_{bus}$ is:

$$ICON_{n,\mathrm{P1}} = ta_{n,\mathrm{P1},m} + pu_n \cdot \delta_{n,\mathrm{P1}} \cdot (ta_{n,\mathrm{P1},x} - ta_{n,\mathrm{P1},m})$$

$$ICON_{n,\mathrm{P1}} = 8.86 + 0.75 \cdot \frac{160 - 124.1}{160 - 10} \cdot (11.36 - 8.86) = 9.31 \text{ minutes}$$

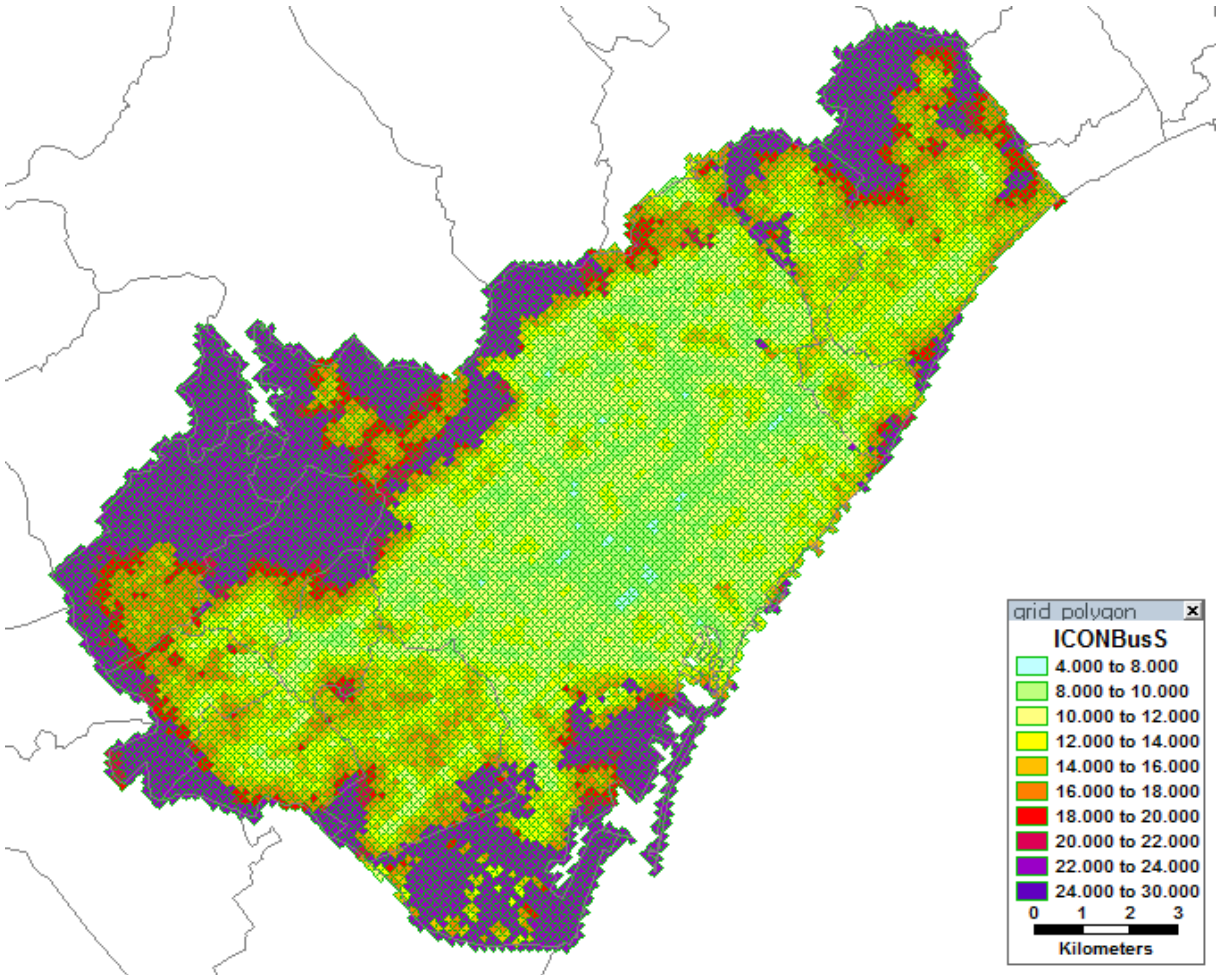


Figure 27. Connectivity to the bus network of Barcelona

The same calculation was carried out for all the centroids of the area (Figure 27) using the same procedure. The obtained map is again similar to that obtained with the previous methodology but, in general, the ICON values are higher. In this case, however, it is easier to identify where the main bus corridors and the best connected nodes are located.

These results could be closer to reality because in the *line utility method* the level of service of all accessible lines is aggregated, regardless if they are serving the same stations within a corridor, which leads to a higher utility than the one perceived by users.

The results of applying the same methodology to the tram and commuter rail networks are presented in Appendix B.

7.3 Aggregated results

Once the ICON values for the different modes are calculated they can be aggregated to obtain the URBICON index for each centroid (i):

$$ICON_i = \sum_{n=1}^{n=N} p_n \cdot ICON_{n,i}$$

$$ICON_i = p_{bus} ICON_{bus,i} + p_{tram} ICON_{tram,i} + p_{ugnd} ICON_{ugnd,i} + p_{rail} ICON_{rail,i}$$

The value of the weights given to each mode (p_m) was set according to the distribution of possible trips and their lenght, shown in Table 5:

$$ICON_i = 0.16 ICON_{bus,i} + 0.29 ICON_{tram,i} + 0.46 ICON_{ugnd,i} + 0.09 ICON_{rail,i}$$

In the case of Barcelona, whose small and not interconnected tram network has only two unconnected lines that are not crossing the centre of the city, the potential demand of the tram mode is, in reality, mostly captured by the bus and the underground modes. For this reason in the areas without accessible tram service the weights will be the ones obtained in the Daily Mobility Survey of 2006, which are quite similar to the previous ones in the case of underground and rail modes:

$$ICON_i = 0.36 ICON_{bus,i} + 0.03 ICON_{tram,i} + 0.52 ICON_{ugnd,i} + 0.09 ICON_{rail,i}$$

.

The levels of connectivity to the public transport networks measured with the URBICON for the year 2004 are presented in Figure 28. The areas with the lowest access time are located in the downtown area and around the main intermodal stations.

The areas with higher access time to the transport networks (i.e. lower accessibility levels) are framed in green. These areas correspond to neighbourhoods that are poorly served by bus and not having any underground or tram stop within a reasonable walking distance. The

rectangle number 7 marks an industrial area called “Zona Franca”, which is only served by few a bus lines, thus having poor connectivity.

Since 2010, the underground line L5 has been extended to serve the areas 1 and 2. The commissioning of L9, started in 2010, covers areas 3 and 5 and, when it will be finished in 2014, L9 will also serve areas 6 and 7. In a future application, a connectivity measure of the city in 2014 will be made, and the improvements of these underground network extensions evaluated.

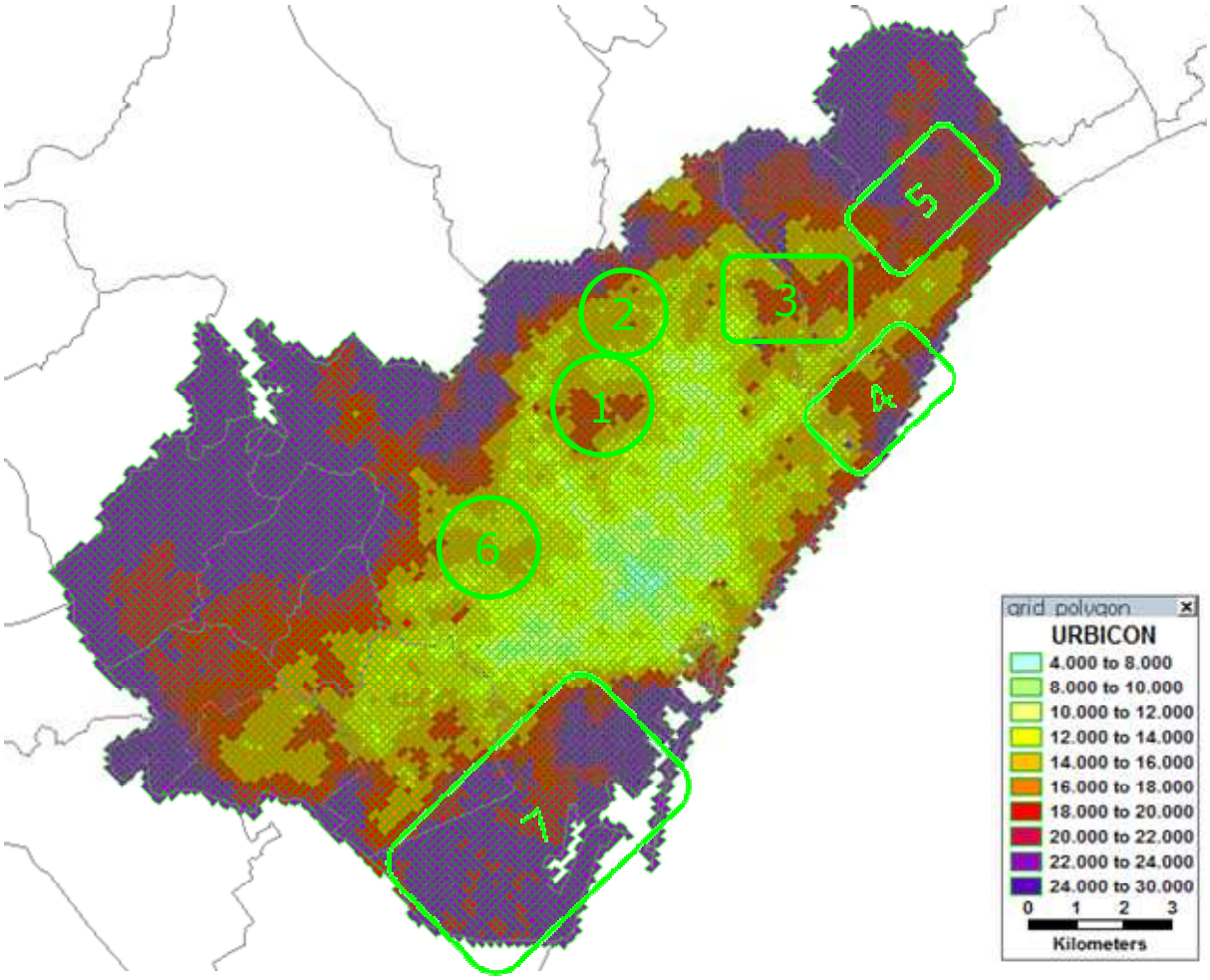


Figure 28 Connectivity evaluation of Barcelona using the URBICON indicator

The URBICON has provided an easy way to detect the areas of Barcelona that were poorly covered by the public transport system in the year 2004. Some of these areas are covered by new or improved infrastructures and others are expected to be served by 2014. In that way, the zones detected by the URBICON as requiring the most urgent actions to give them the minimum conditions of service match with the places where planners have decided to improve public transport services.

8 Conclusions and further research

The development of the city requires continuous improvement of existing transport infrastructures and the creation of new capacity and new and better services. Decision making about implementation of these projects needs to estimate their financial and technical feasibility, as well as their socio-economic profitability to ensure good use of society's resources. To improve the efficiency of the decision-making processes it is necessary to reinforce the capacity of technicians to facilitate the negotiation between all relevant parties.

The main measures of accessibility studied by many authors have been reviewed, assessing if they can be applied to urban environments. Activity-based measures are very useful to calculate accessibility for certain travel purposes, such as commuting to the work place. But transport demand in urban areas increasingly depends on non-repetitive personal purposes, so job opportunities cannot be generalised as the sole measure of accessibility for a given point. Person-based measures for such diffuse mobility are more challenging to apply due to the detailed individual activity-travel data required and Utility-based measures are very difficult to interpret and explain.

The ICON indicator widely used in the evaluation of regional accessibility is presented as an alternative to traditional accessibility measures, because it is focused on the supply side, analysing the transport endowment of a given place, and because its results are simple time measures, it is easy to explain and understand. Moreover, the data needed, basically geographical and transport data, are easier to obtain while detailed personal information is not requested.

The mobility of a city's inhabitants is better understood when divided by its outreach. To better deal with the different behavior of travelers, 3 connectivity measures are proposed: one restricted to the urban or metropolitan scale; a second one for the urban or metropolitan scale but with a regional scope; and a third one for the wider metropolitan scale with an interregional scope. For each of these levels a different methodology to evaluate the connectivity of the places needs to be applied. This research has focused on the first measure, analyzing the public transport services for the mobility at the urban or metropolitan scale.

The ICON indicator has mostly been applied to regional and interregional accessibility studies. For its application to the urban or metropolitan context, in particular to public transport, its methodology needed to be adapted. This was done establishing maximum access times to public transport networks and adapting the utility decay functions to correctly reflect users' behaviour. The research has developed URBICON, a new mathematical formulation for the connectivity indicator that reproduces well the quality of service provided by the public transport service on the urban area.

In the classical ICON formulation, the relative weight of each mode is evaluated according to its economic development impact; instead of that, in URBICON the relative weight is estimated according to the utility of each mode in the city or area under analysis. To support

this calculation, a methodology to appraise the transportation needs of a given city has been presented.

The URBICON analysis has been applied to the city of Barcelona and adjacent municipalities, to detect the areas where the public transport system has poor coverage. URBICON has demonstrated that it is a reliable tool to measure the global supply of public transport and is easy to deploy, interpret and explain.

This application has been made under the ATMax system and the URBICON formulation has been developed in Visual Basic functions inside an Access data base. But, as the formulation is relatively simple, it can be programmed in other languages and used in several GIS.

It is necessary to stress that while geographical (i.e., location of the public transport stops) and transport data (i.e. line headways or schedules and travel times) are public information, data from the transport operators, such as the occupancy levels of the vehicles at different periods of the day or the reliability of the services, are hard to obtain.

This research will continue with the integration of the URBICON indicator with other GIS information (i.e. population, economic activity, pollution) in order to generate complex spatial indicators adapted to planning and evaluation requirements. As a first step it is envisaged to analyse the possible relationship between public transport endowment and noise pollution.

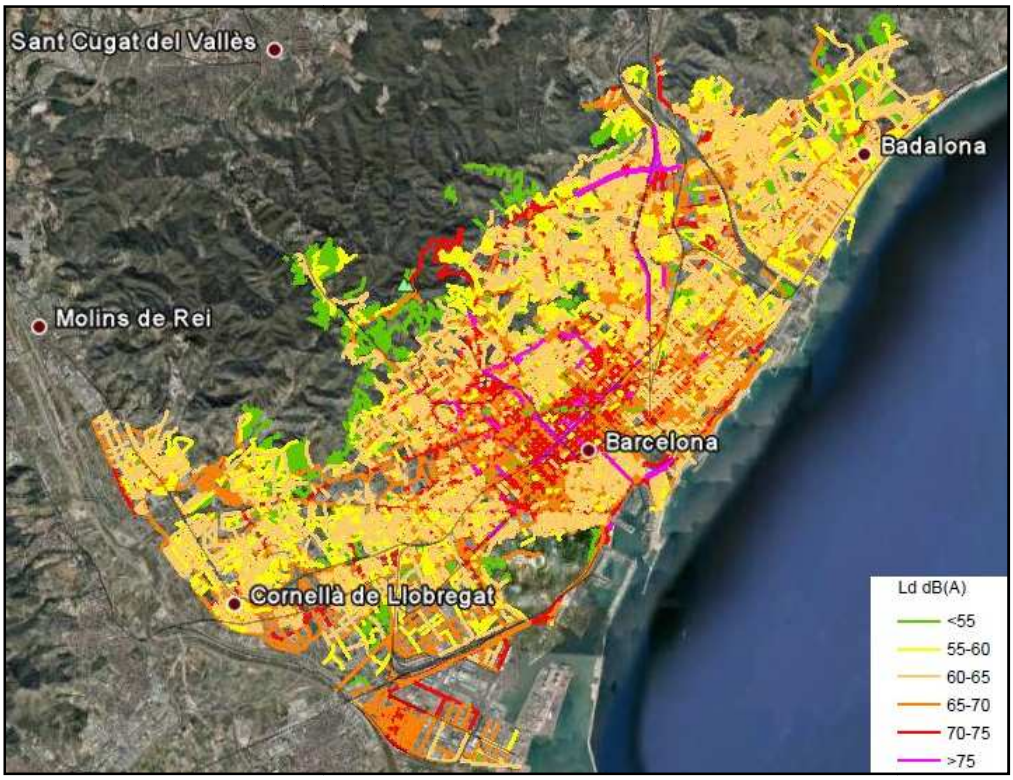


Figure 29 Acoustic map of Barcelona and adjacent municipalities
Source: Generalitat de Catalunya. Departament de Medi Ambient i Habitatge.

The final aim of the research is, however, to analyse the potential of the proposed connectivity indicators in the planning process and in project appraisal, particularly in assessing the impact of public transport investments on the most disadvantaged urban areas.

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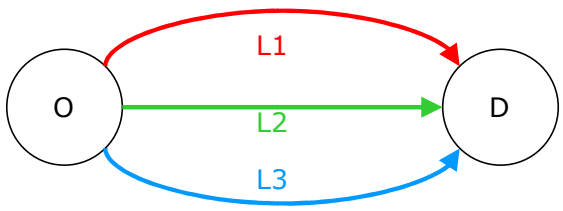
A Apendix A: shortest path in transit networks

A.1 Chriqui and Robillard algorithm

Chriqui and Robillard propose a method to find the set of attractive lines that minimizes the total travel time. Lines are sorted by length of trip and then are added to an initially empty set while each new addition does not increase the total expected travel time.

Let's consider the following case with 3 lines serving the same two points:



t1 = 18 min.
t2 = 22 min.
t3 = 26 min.
$h_{L1}=h_{L2}=h_{L3}=12$ min.

In that model, the user can choose between a set of bus lines to travel from origin point O to destination point D, taking the first coming bus.

The average waiting time at the stop can be estimated as follows:

$$W = \frac{1}{2}\frac{1}{\sum_i f_i}$$

The probability to take one determined line is:

$$P(i) = \frac{f_i}{\sum_j f_j}$$

Then, the average in vehicle travel time is estimated as:

$$ITT = \sum_i t_i \frac{f_i}{\sum_j f_j}$$

And the total expected travel time:

$$ETT(O,D) = W + ITT = \frac{1}{2\sum_i f_i} + \frac{\sum_i t_i f_i}{\sum_i f_i}$$

As proposed, at the beginning the selection set of attractive lines S is empty, S = 0. The first line L1 is added, obtaining an expected travel time of:

S = {L1}: ETT = 6 + 18 = 24 min.

Then, the line L2 is added to the selection set and the expected travel time becomes:

S = {L1, L2}: ETT = 3 + 20 = 23 min.

Finally, line L3 is added:

S = {L1, L2, L3}: ETT = 2 + 22 = 24 min.

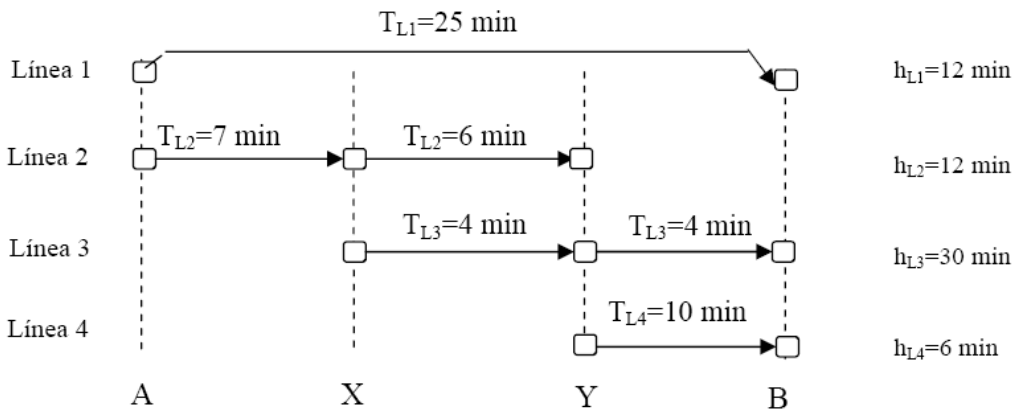
In that case, the expected travel time is increased, thus line L3 must not be included in the selection set, being the final result:

S = {L1, L2} and ETT(O, D) = 23 minutes

A.2 Optimal strategies algorithm

Based on the assumption that passengers will take the first transit line which will get them to their destination in a reasonable amount of time, different paths are utilized based on service times and frequencies. A line segment going out of a stop will be used only if its addition to the optimal strategy will reduce the total expected travel cost from that stop to the destination.

Let's see the example proposed in Spies and Florian (1989) in which the objective is to minimize the travel time between the points A and B, taking into account the available combinations of bus lines. The strategy proposed is to take the first coming bus, thus leading to a set of possible combinations.



As presented in the Chriqui and Robillard algorithm, the average waiting time and the probability of boarding one line can be estimated as:

$$W = \frac{1}{2}\frac{1}{\sum_i f_i}; \qquad P(i) = \frac{f_i}{\sum_j f_j}$$

Then, the average time in each node and the probability of taking a line in this example are shown in the following table:

Node	Chosen line	Average waiting time	Probability
A	L1	3,00	0,50
	L2	3,00	0,50
X	L2	4,29	0,71
	L3	4,29	0,29
Y	L3	2,50	0,17
	L4	2,50	0,83

There are three possible strategies depending on where the user decides to alight the bus or not. The travel time in each strategy is calculated below:

a) Take the next coming bus among lines L1 and L2; if L1 was taken alight at B; if L2 was taken, alight at node X and take L3 to the destination point:

$$ETT = E[W_A] + P_{L1}*T_{L1} + P_{L2}*(T_{L2} + E[W_{L3}] + T_{L3}) =$$
$$3 + 0.5*25 + 0.5*(7 + 15 + 8) = 30.5 \text{ minutes}$$

b) Take the next coming bus among lines L1 and L2; if L1 was taken alight at B; if L2 was taken, alight at node X, take L3 to node Y and there take L4 to the destination point:

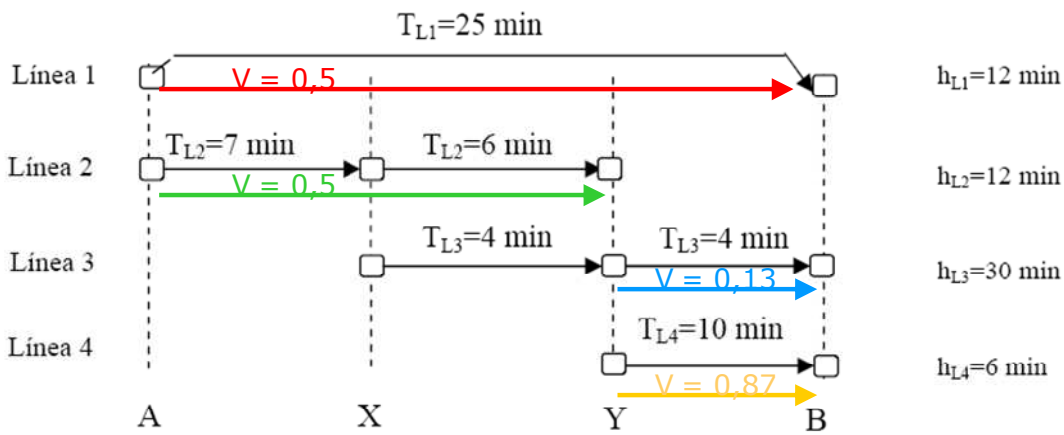
$$ETT = E[W_A] + P_{L1}*T_{L1} + P_{L2}*(T_{L2} + E[W_{L3}] + T_{L3} + E[W_{L4}] + T_{L4}) =$$
$$3 + 0.5*25 + 0.5*(7 + 15 + 4 + 6 + 10) = 35 \text{ minutes}$$

This alternative does not make much sense because if the user is on the L3 bus that takes 4 minutes from Y to B, he or she will not get off on Y to wait for a L4 bus that takes 10 minutes to do the same route.

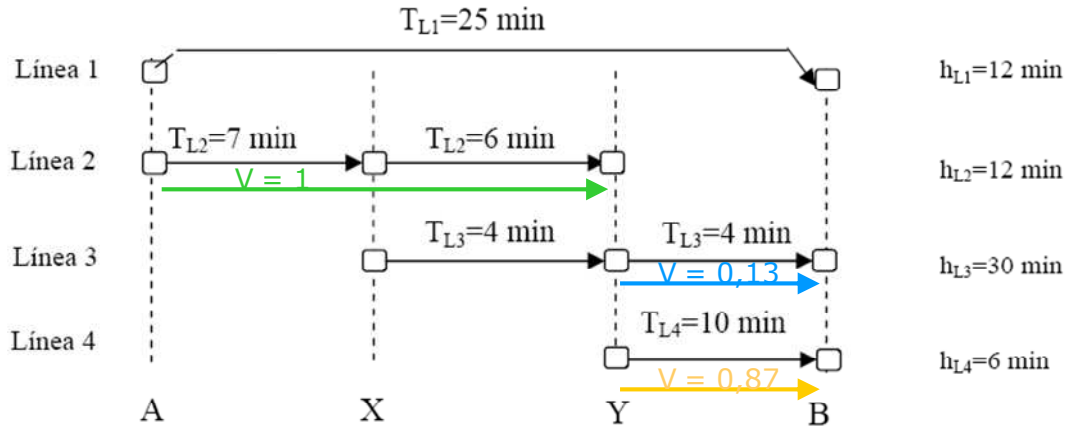
c) Take the next coming bus among lines L1 and L2; if L1 was taken alight at B; if L2 was taken, alight at node Y and take L3 or L4 to the destination point:

$$ETT = E[W_A] + P_{L1}*T_{L1} + P_{L2}*(T_{L2} + E[W_Y] + P_{L3}*T_{L3} + P_{L4}*T_{L4}) =$$
$$3 + 0.5*25 + 0.5*(13 + 2.5 + 0.17*4 + 0.83*10) = 27.74 \text{ minutes}$$

Thus, the optimal strategy is the last one:



This solution found by the optimal strategies algorithm proposed by Spies and Florian provides a lower expected travel time than the one obtained with the Chriqui and Robillard algorithm, shown below:



The total travel time from A to B is 30.5 minutes.

B Maps of the connectivity analysis of Barcelona

B.1 Rail networks of Barcelona

Figure 30 Map of the underground, tram and rail lines of Barcelona

B.2 Results for each network

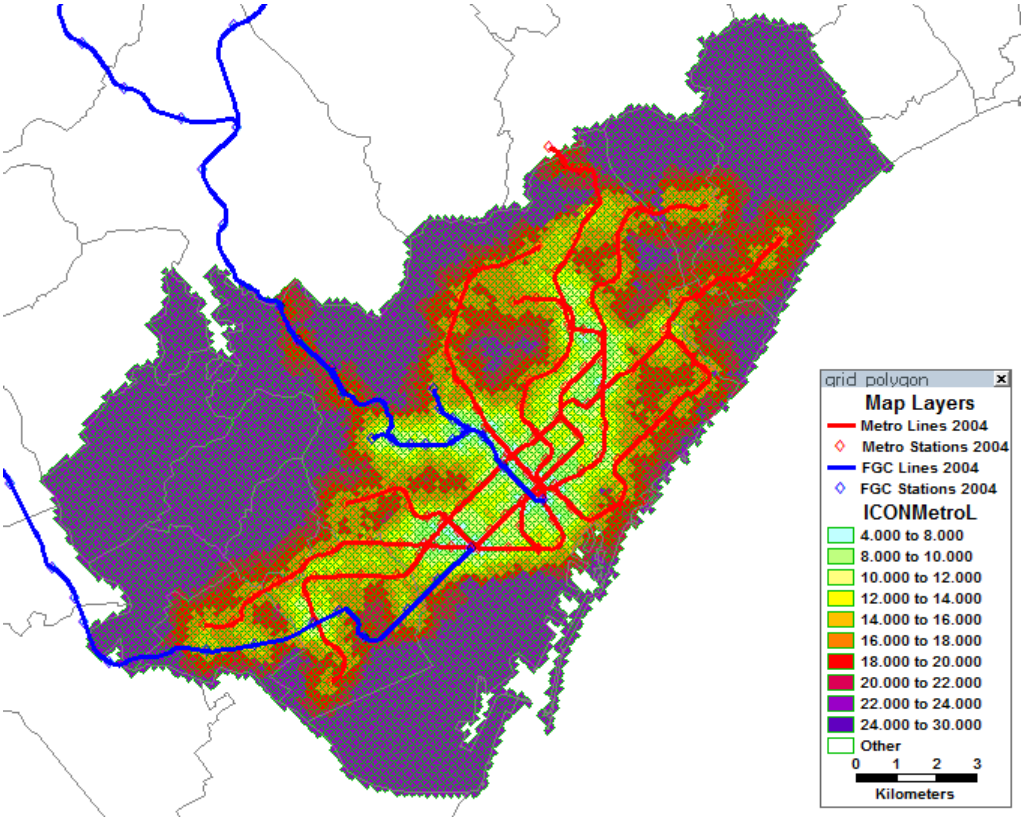


Figure 31 Connectivity to the underground network using line utility method

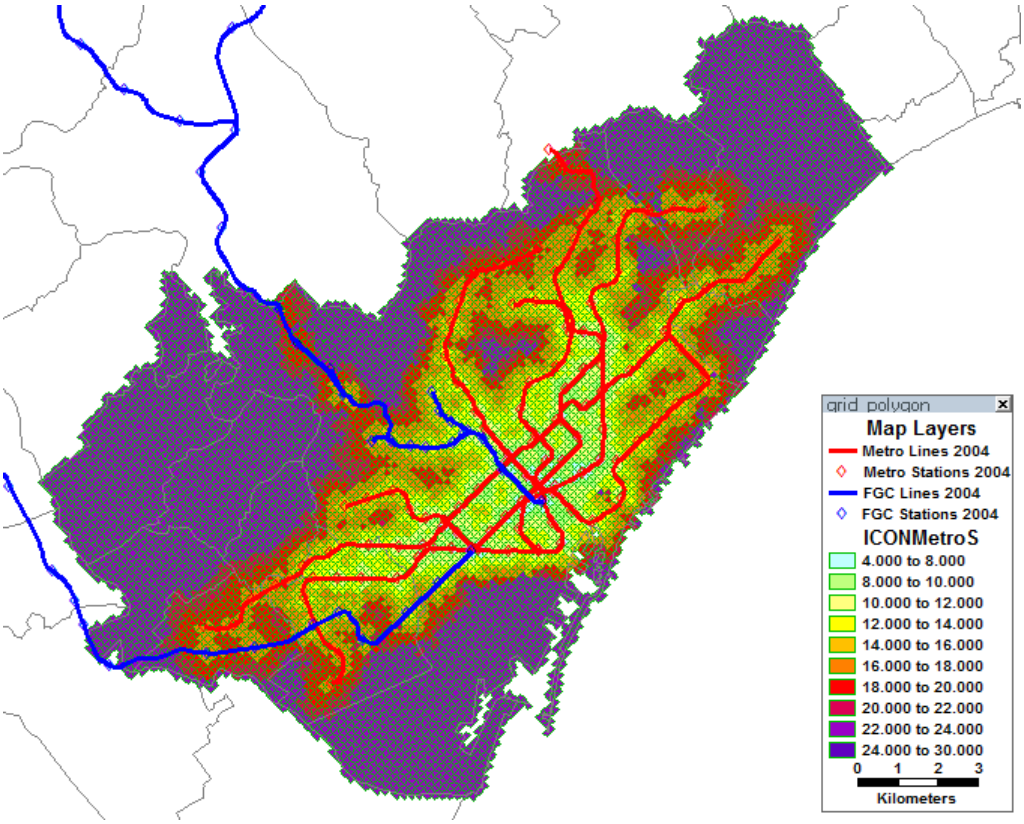


Figure 32 Connectivity to the underground network using stop utility method

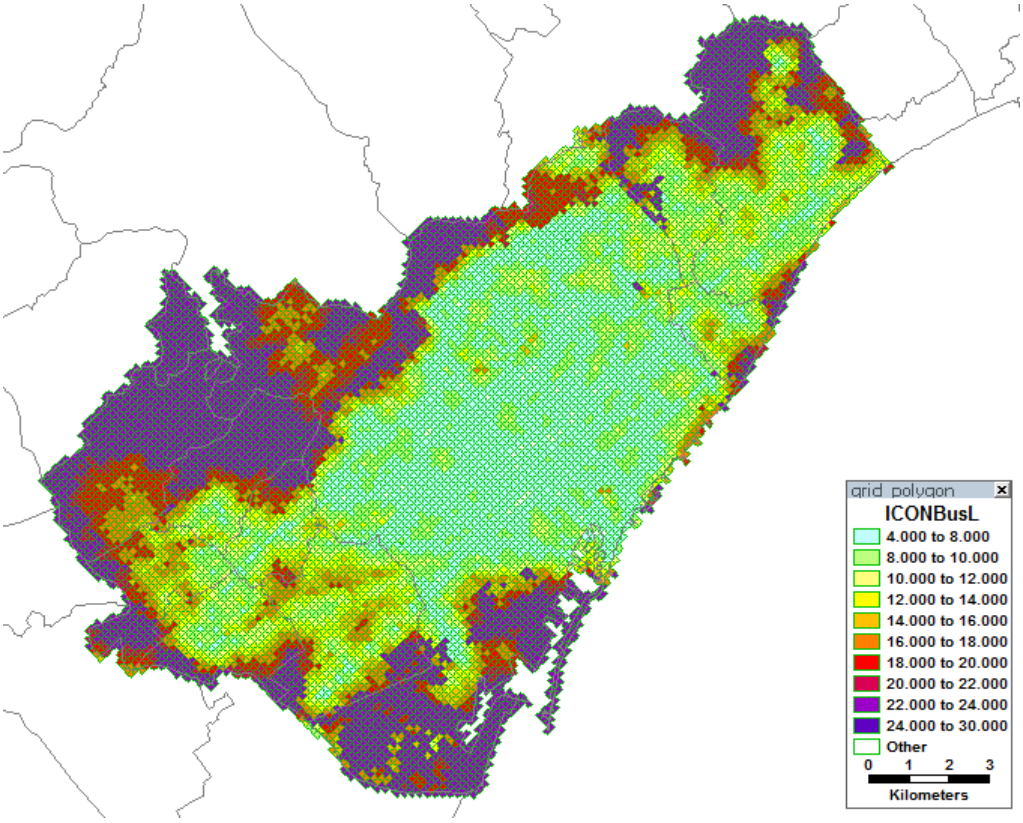


Figure 33 Connectivity to the bus network using line utility method

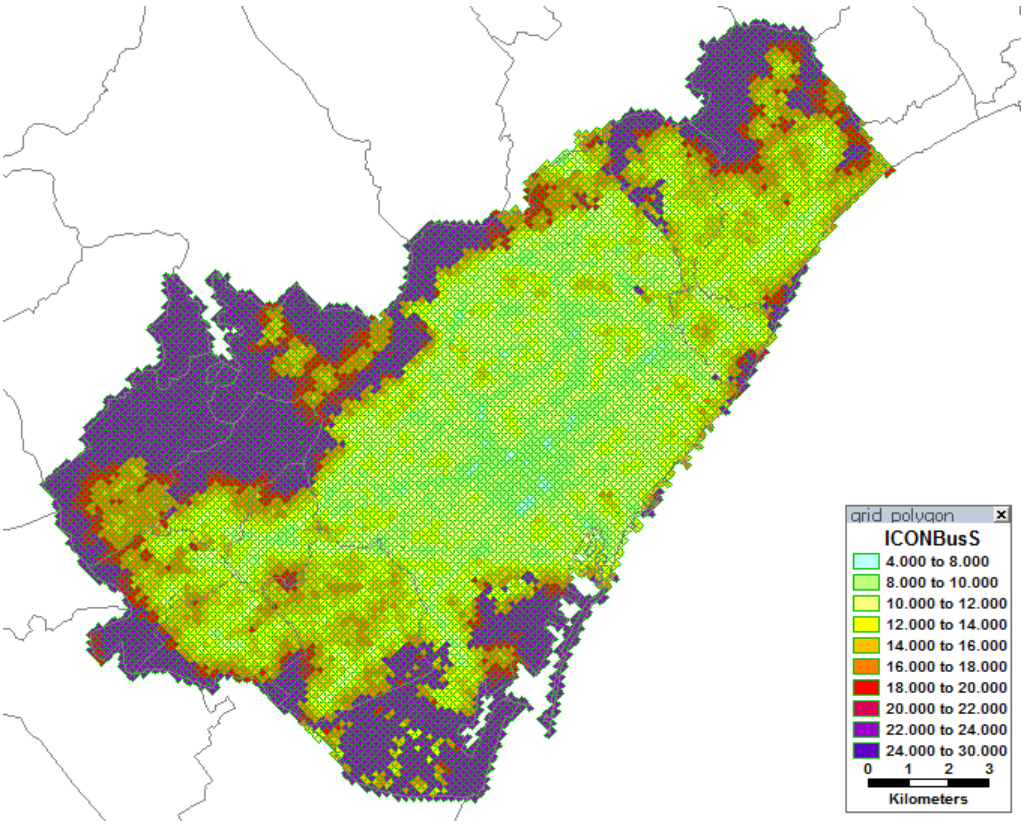


Figure 34 Connectivity to the bus network using stop utility method

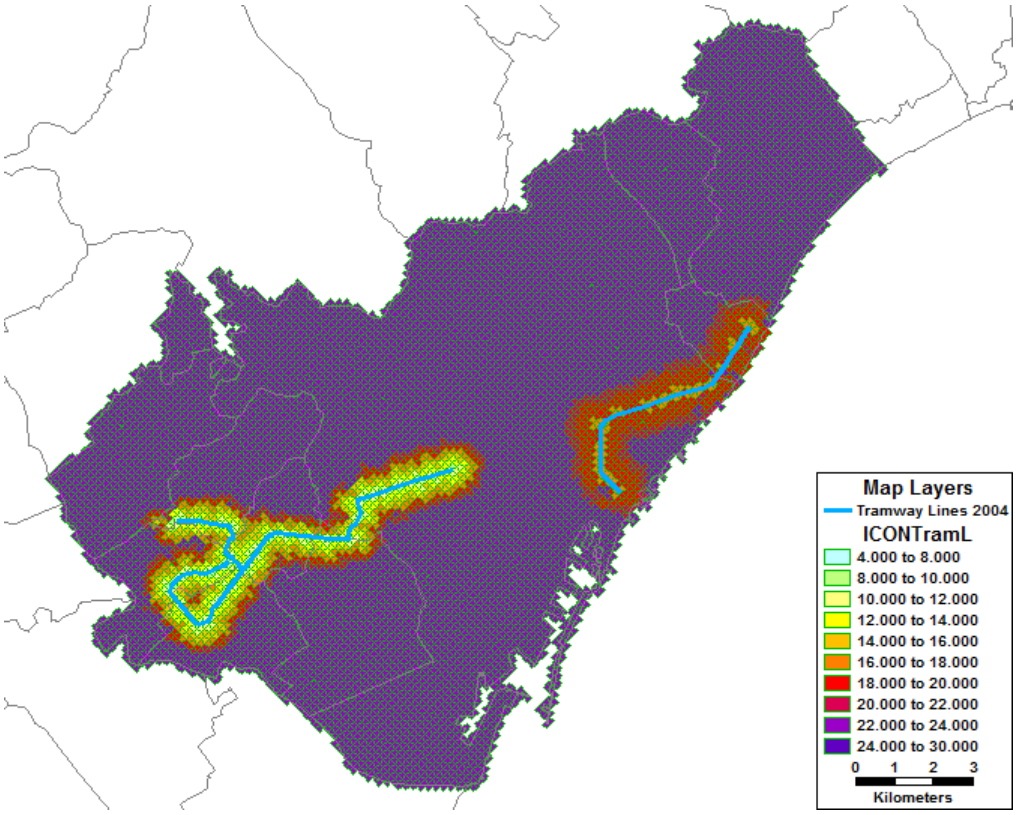


Figure 35 Connectivity to the tram network using line utility method

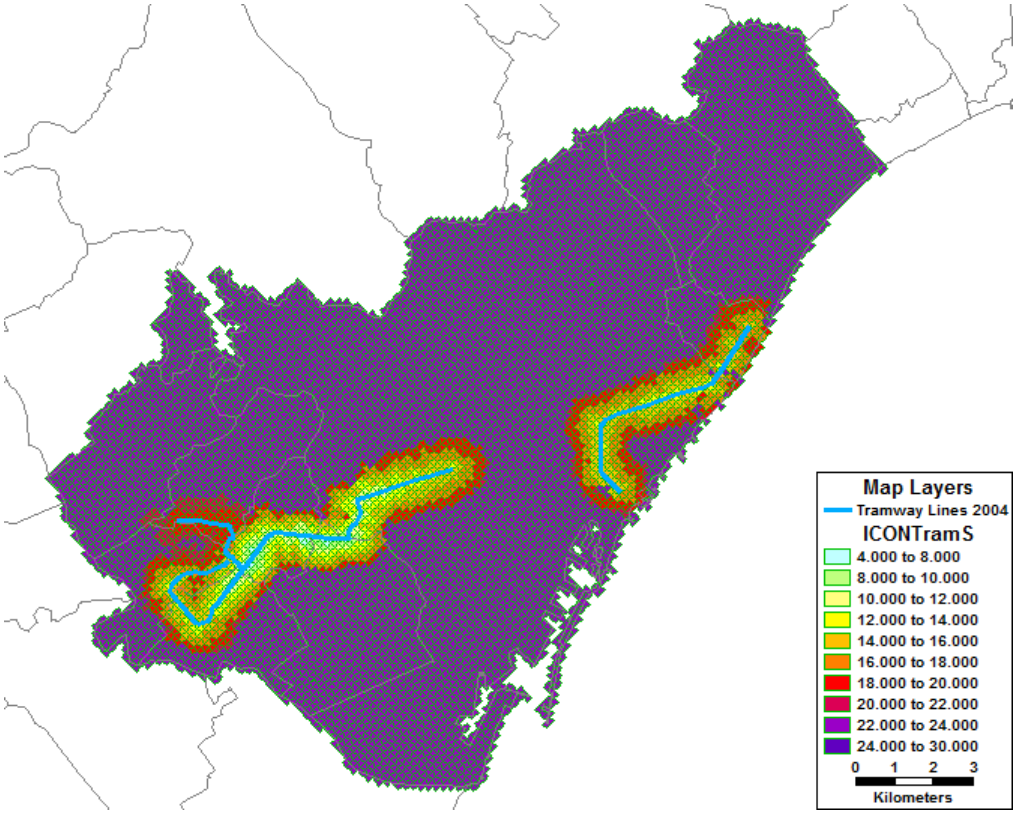


Figure 36 Connectivity to the tram network using stop utility method

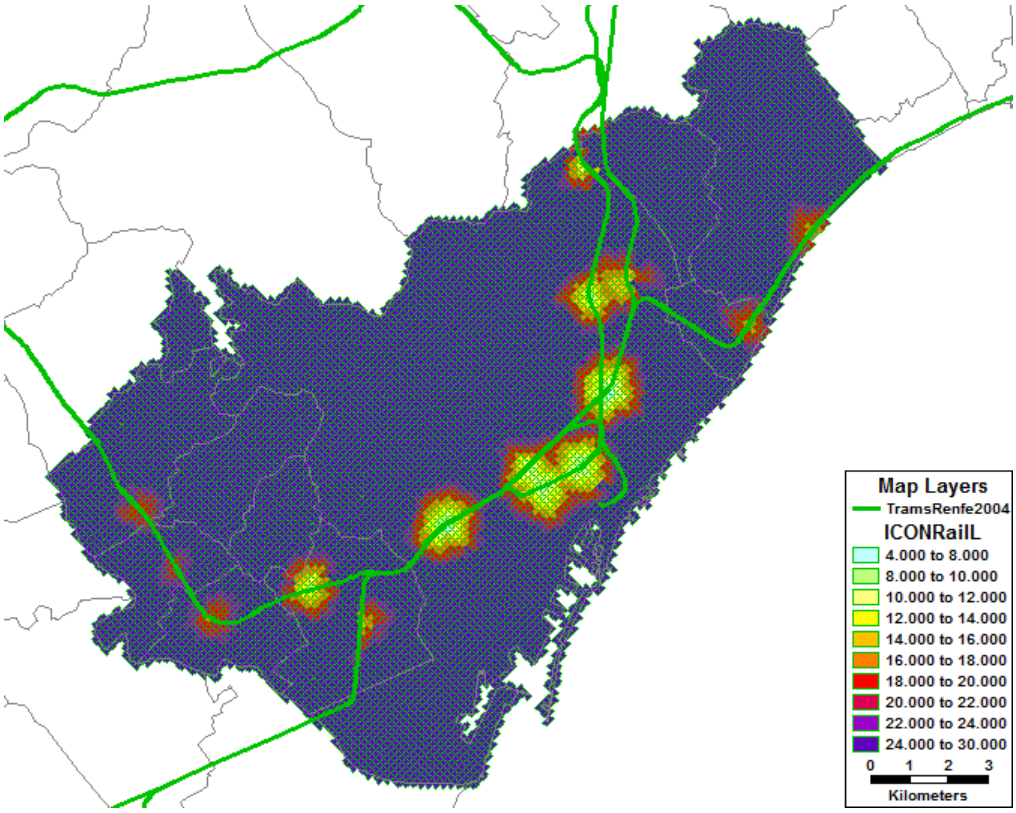


Figure 37 Connectivity to the rail network using line utility method