Measuring the spatial connectivity of urban public transport. A GIS application of the ICON indicator.

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Barcelona, June 2011

Abstract

A well-designed urban public transport policy provides significant benefits: ensures a more efficient transport system that reduces costs, congestion, accidents 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.

The paper 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. The paper will explain the adaptation of the ICON indicator to the public transport endowment of urban areas.

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 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.

1 Introduction and research context

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 to the transport networks of any urban location 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" of 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. A first connectivity map 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)).

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[1] The authors want to thank Mauro Ravasio and Mario Aymerich of the European Investment Bank for their contribution.

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.

This research is financed with a grant under the STAREBEI programme of the European Investment Bank.

1.1   Evaluation of actions in urban transport

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. 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.

Decision making about implementation of new transport infrastructures or improvement of existing ones 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 URBICON indicator 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 (Ulied 1995). 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.

The opportunity to use GIS 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 thus a major challenge to include in the socio-economic analysis the spatial effects that a project 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.

1.2   Research objectives

The main objectives of the research were:
- To define a suitable URBan Indicator of CONnectivity (URBICON) providing a quantified spatial measure of connectivity to the public transport networks 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 factors 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 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).

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

2   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.

Let's consider the minimum time required to travel between two points, origin (O) and destination (D), by train, which consist in the addition 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 the 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): tad.

Then, the total travel time can be expressed as:

$$TT = t_a + t_w + t_v + t_g$$ (Eq. 2.1)

Since the travel time between any pair of rail or metro stations (tv) is quite stable and predictable, 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).

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 depends on adequate interconnections between modes and scales. These considerations have been incorporated in the adaptation of ICON to the urban set up.

2.1   Basic ICON Formulation

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

$$ICON = f[t_a, t_w, t_g]$$

(Eq. 2.2)

ICON is independently evaluated for each transport network (n, n=1...N). Once the modal values (ICON$_n$) 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,

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

$$\sum_{i=1}^{i=N} p_i = 1$$

(Eq. 2.3)

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 ICON$_n$ 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:

$$ICON_n = ta_{nm} + tw_n + tg_n$$

$$ta_{nm}, tw_n, tg_n \geq 0$$

(Eq. 2.4)

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

$$ta_{nm} \leq ta_{nj} \leq ta_{nx}, j = 1...M$$

(Eq. 2.5)

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):

$$\text{if } ta_{nm} = ta_{nx} \text{ then } S_{nm} = Smax_n \text{ and } tw_n = 0$$
$$\text{if } ta_{nm} < ta_{nx} \text{ then}$$
$$tw_n = \delta_n \cdot [ta_{nx} - ta_{nm}]$$

(Eq. 2.6)

with:

$$0 \leq \delta_n \leq 1$$
$$0 \leq tw_n \leq ta_{nx} - ta_{nm}$$

(Eq. 2.7)

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} in relation to $Smax_n$.

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

$$U_{nj} = S_{nj} e^{-\beta_n (ta_{nj} - ta_{nm})}$$

(Eq. 2.8)

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:

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

(Eq. 2.9)

And then δ_n can be defined with a conventional logistic formulation:

$$\delta_n = \frac{1}{1 + a \cdot e^{-b \frac{Umax_n - U_n}{Umax_n - Umin_n}}}$$

(Eq. 2.10)

where a and b are arbitrary positive parameters to be adjusted. By definition, the maximum utility should be obtained when the closest connection node provides the maximum service level $Smax_n$ ($ta_{nj} = ta_{nm}$), 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.

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. 2.11)

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

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 ($Umax_n$) 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.

The aggregation of $ICON_n$ 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.

3   URBICON, an urban application of the ICON concept

3.1   Formulation

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.

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 transport nodes has no limitations. That could be possible if the transport mode to reach the transport 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 $Umax_n$ is reached in such cases (ta_{nx}> 15 minutes). To avoid this problem a 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:

$$ta_{n,i,s} = twa_{i,s} + AWT_s$$

$$twa_{i,s} \leq twa\_max_n$$

<div align="right">(Eq. 3.1)</div>

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_s 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 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:

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

<div align="right">(Eq. 3.2)</div>

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 $Smax_n$. For instance, in the CITRAME Study (1989), 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

urban enviroment, 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:

$$ICON_{n,i} = ta_{n,i,m} + tu_{n,i} \qquad \text{(Eq. 3.3)}$$

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:

$$tu_{n,i} = pu_n \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m}) \qquad \text{(Eq. 3.4)}$$

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.

$$ta_{n,i,x} = \begin{cases} ta_{n,i,k} & if \ \sum_{j=1}^{k} S_{nj} \geq Smax_n \\ \\ tamax_n & if \ \sum_{j=1}^{N} S_{nj} < Smax_n \end{cases} \qquad \text{(Eq. 3.5)}$$

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 $Smax_n$:

$$Smax_n = \sum_{j=1}^{N} S_{nj} + S_{nd}$$

$$S_{nd} = Smax_n - \sum_{j=1}^{N} S_{nj} \qquad \text{(Eq. 3.6)}$$

The exponential decay function used in Eq. 2.9 to aggregate the utility provided by all feasible nodes does not reflect urban travellers' behaviour, because the utility of the secondary nodes decreases rapidly even when they are near 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 travellers' behaviour in this case. The parameter σ of this function must be calibrated depending on the network and the maximum access time. The aggregated utility is then expressed as:

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

$$\text{(Eq. 3.7)}$$

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

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.

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:

$$\delta_{n,i} = \frac{Umax_n - U_{n,i}}{Umax_n - Umin_n}$$ (Eq. 3.8)

$$Umin_n \leq U_{n,i} \leq Umax_n$$

$$0 \leq \delta_{n,i} \leq 1$$

$Umax_n$ 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 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 $Umax_n$:

$$U_{n,i} = \begin{cases} \sum\limits_{j=1} U_{n,i,j} & or \\ \\ Umax_n & if \ \sum\limits_{j=1} U_{n,i,j} > Umax_n \end{cases}$$ (Eq. 3.9)

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

$$ICON_{n,i} = ta_{n,i,m} + pu_{n,i} \cdot \delta_{n,i} \cdot (ta_{n,i,x} - ta_{n,i,m})$$ (Eq. 3.10)

$$ta_{n,i,m} \leq ICON_{n,i} \leq ta_{n,i,x}$$

3.2   Assessing the level of service

The level of service of one node can be obtained adding the services of the public transport lines connecting the node, which can be expressed as a function of of line's characteristics, such as commercial speed, number of stops and transfers to other networks, comfort and reliability. But in the case of main corridors or common routes, with more than one line serving the same stops, the addition of their services leads to a higher values of utility than they actually provide. To avoid this issue, 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. Then, S_{nj} can be expressed as:

$$S_{n,,j} = \sum_k \alpha \cdot X_{j,k}^{ATT} + \gamma \cdot X_{j,k}^{ATT} \cdot Comfort_k + \lambda \cdot X_{j,k}^{ATT} \cdot Reliability_k$$ (Eq. 3.11)

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, etc.) and their effects not only influence one stop but the whole line, its value should be assessed for each line instead of for each destination k. 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:

$$Reliability_j = \frac{1}{L} \cdot \sum_{line=1}^{L} Reliability_{line}$$

(Eq. 3.12)

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

$$Comfort_k = 1 - \left(\frac{PassLoad_k^{time}}{VehicleCapacity} \right)$$

(Eq. 3.13)

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

$$Comfort_{line} = 1 - \left(\frac{PassLoad_{line}^{time}}{VehicleCapacity} \right)$$

(Eq. 3.14)

$$Comfort_j = \frac{1}{L} \cdot \sum_{line=1}^{L} Comfort_{line}$$

(Eq. 3.15)

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

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

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

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

(Eq. 3.16)

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. 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 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.

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. 3.17)

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.

3.3 Aggregation of modal results

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

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

$$\sum_{n=1}^{n=N} p_n = 1$$

(Eq. 3.18)

In the classical ICON formulation, the relative weight of each mode is evaluated according to the economic development impact of the mode. In URBICON we use instead 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.

Then, knowing the commercial speed and the average travel time (ATT) 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 1 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 2 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 ensuring that 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 3 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.

4   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.

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 data used for the evaluation are:

- 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, commercial speed, comfort and reliability.

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

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.

To avoid this, a rectangular grid of 120x210 cells of equal size, covering the whole region of interest, has been created. The cells are squares of 133x133 meters, corresponding to the dimensions of the blocks of the Eixample district[2], which is located in the downtown and shapes the mobility of large part of Barcelona. Only the cells inside the municipalities under analysis are considered and then, one centroid is created in each one, leading to a set of 10732 sampling points. They are connected to the street network by one or more links in order to reproduce traveller's behaviour as realistically as possible. This grid allows sufficiently detailed mapping of URBICON for its use for spatial information and public transport planning purposes.

4.1 URBICON calculation

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 was obtained aggregating the $ICON_n$ results for the different public transport networks mentioned above using the formulation presented in 3.3. 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.

4.1.1 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 4 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)	Comfort Rush hour	Reliability
L1	3.75	29.8	0.31	83%
L2	3.75	27.7	0.58	90%
L3	3.53	26.4	0.47	83%
L4	4.6	28.4	0.68	85%
L5	3	25.9	0.54	88%
L6	6	21.72	0.5	99.8%
L7	6	25.5	0.6	99.8%
L8	6	35.48	0.5	99.7%
L11	7	25.3	0.89	90%

Table 4 Underground lines of Barcelona and their characteristics
Source: Own elaboration based on TMB and FGC data

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

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

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[2] 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

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 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:

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

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

First of all, it was 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.
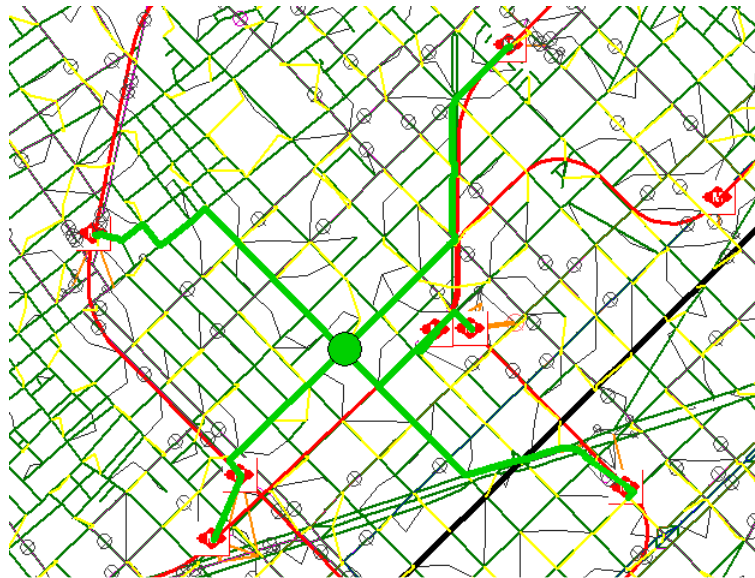

Figure 1 Map of shortest paths to feasible stations from Sicília/Rosselló intersection

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 shown on Figure 1. The access time from point i to the node j of the network n is expressed as:

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

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

Table 5 Feasible stations from Sicília/Rosselló intersection

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

$ta_{nim,}$ 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, 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. Then, ICON$_{metro}$ for cell P1 is calculated following the formulation presented before:

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

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

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 2. 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.

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 nodes that can be reached have a low level of service compared to the maximum.
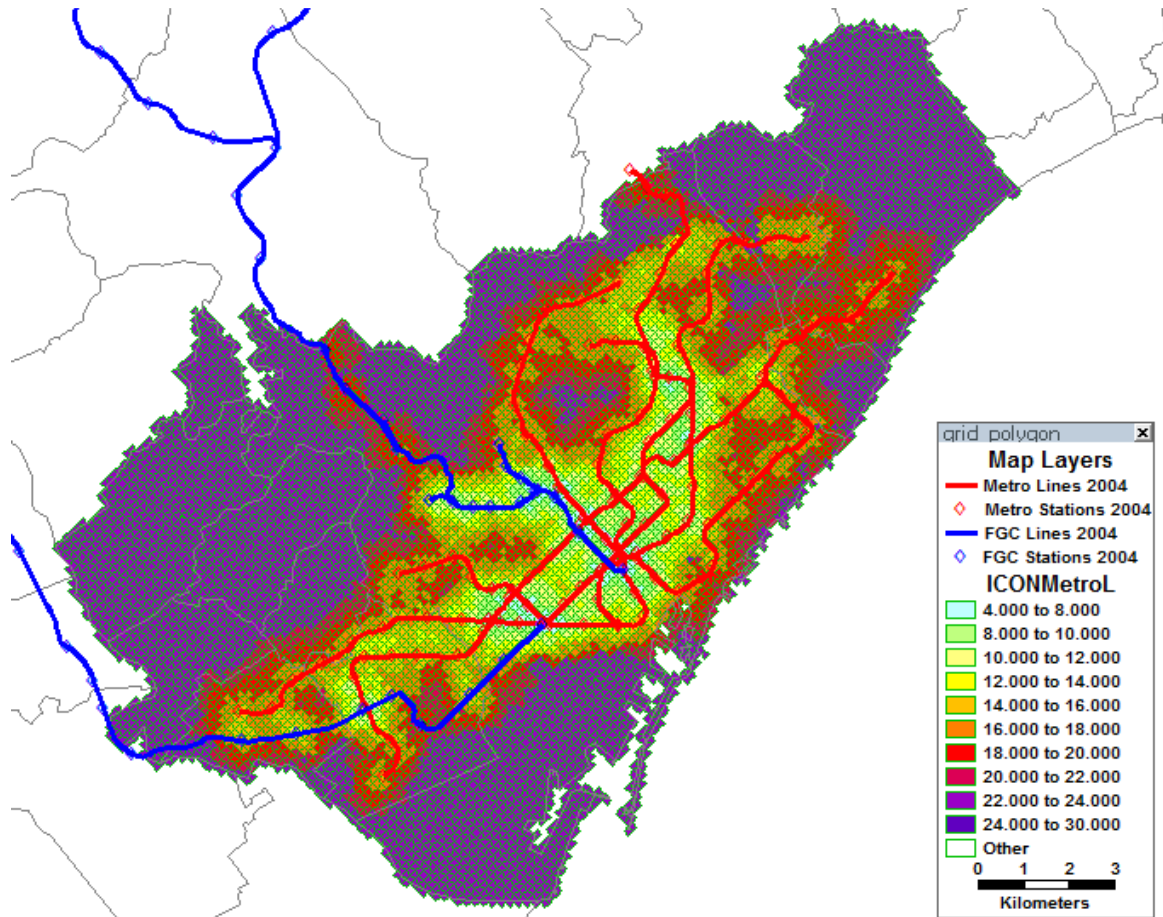
Figure 2 Connectivity to the underground network of Barcelona

4.1.2 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 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.

In this case, $Smax_n$ is set at 160 and $Smin_n$ is set at 0, 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:

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

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 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

Table 6 Feasible bus stops and walking access time from Sicília/Rosselló intersection

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

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

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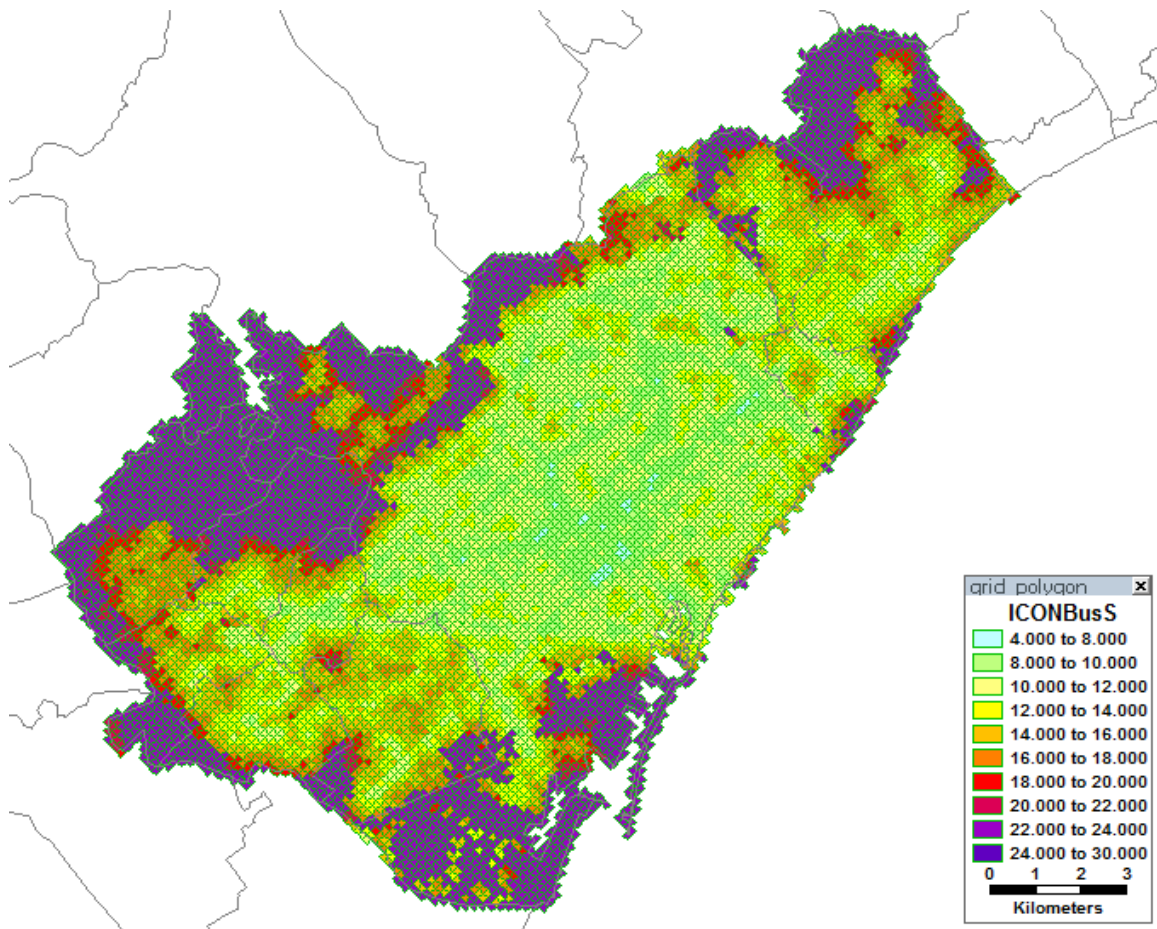

Figure 3 Connectivity to the bus network of Barcelona

The application of the same procedure to all the nodes in the Metropolitan Area is reflected in Figure 3, 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.

4.2   Aggregated results

The methodology described for metro and bus was applied to the tram and commuter rail networks. Once the ICON values for the different modes were calculated they were 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 length, shown in Table 2:

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

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:

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

The levels of connectivity to the public transport networks measured with the URBICON for the year 2004 are presented in Figure 4. 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.

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.
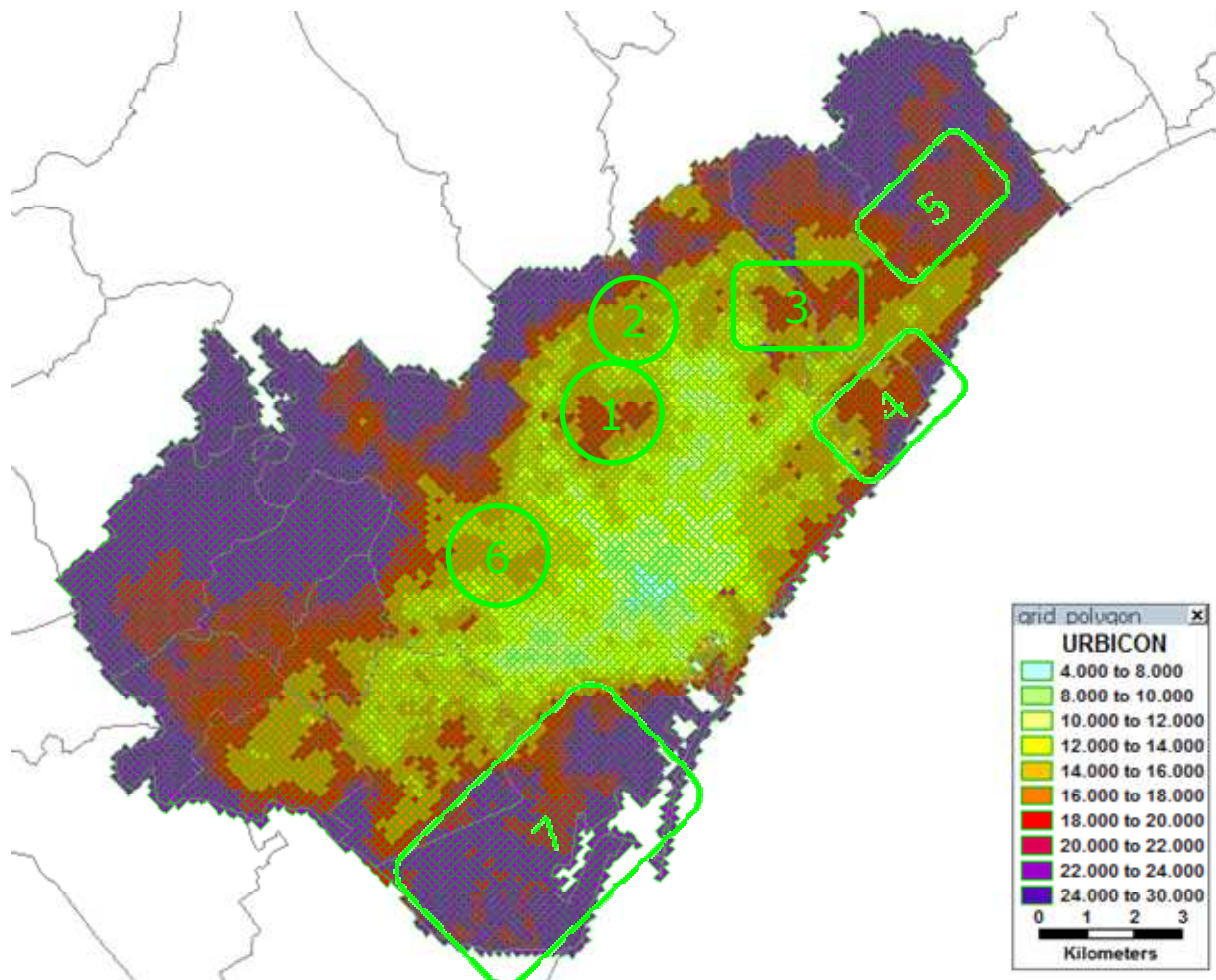
Figure 4 Connectivity evaluation of Barcelona using the URBICON indicator

5   Conclusions and further research

The ICON indicator, widely used in the evaluation of regional accessibility, is presented as an alternative to traditional accessibility measures (see, for instance, Morris 1979, Pirie 1979, Geurs and van Wee 2004), 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 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 assess this utility to be used in the URBICON model a specific formulation has been developed.

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.

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.

6   Bibliography

ESPON (2004) *Project 1.2.1 Transport services and networks: territorial trends and basic supply of infrastructure for territorial cohesion*.

Fagiani, P. & Turró, M. (2009) *Urban Public Transport Project Appraisal Guidelines*. European Investment Bank.

Geurs KT, Ritsema van Eck JR (2001) *Accessibility measures: review and applications. Evaluation of accessibility impacts of land-use transport scenarios, and related social and economic impacts.* RIVM, National Institute of Public Health and the Environment (NL), Bilthoven

Geurs KT, van Wee B (2004) *Accessibility evaluation of land-use and transport strategies: review and research directions.* Journal of Transport Geography 12(2):127–140

Mcrit, (1996) *Estudi d'accessibilitat a la xarxa de ferrocarrils de la Generalitat de Catalunya.*

Mcrit, (1999) *Implementation of ICON-GIS to the European Investment Bank.*

Morris, J.M., Dumble, P.L., Wigan, M.R., (1979) *Accessibility indicators for transportation planning.* Transportation Research A 13, 91–109.

Pirie, G.H., (1979) *Measuring accessibility: a review and proposal.* Environment and Planning A 11, 299–312.

Turró, M. (1988) *Le transport dans le Bassin Méditerranéen. L'apport des régions*, Les Cahiers Scientifiques du Transport, nº 17-18, 231-236

Turró, M., Ulied, A. (1989) *Propuesta metodológica para la definición de índices de accesibilidad regional en la cuenca mediterránea,* Interregional Transport Commission for the Mediterranean (CITRAME).

Turró, M. (1989) *Un indicador de accesibilidad regional*, Research report, Universitat Politècnica de Catalunya (UPC,Barcelona).

Ulied, A. (1995) *Definition of a regional accessibility measure.* PhD dissertation, Universitat Politècnica de Catalunya (UPC, Barcelona)