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Analysis of Transport Networks in the Urban Environment in order to Plan the Integration of High-speed Rail

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Abstract: This paper mainly analyses the degree of accessibility of high-speed rail stations within the local context aiming at establishing a comparative framework on the different integration policies carried out in similar cities. A model based on graph theory and the dynamic study of networks applied to urban bus transport.

Keywords: High-speed rail, accessibility, centrality, graph theory.

This paper is dedicated to the memory of Professor José Sousa Ramos.

1 Introduction and methodology

Accessibility is a concept used in several scientific fields such as transport planning, urban planning or geography and plays a key role when establishing economic and social policies. The implementation of High-Speed Rail (HSR) definitely renders the connection between a large number of cities possible, and its competitiveness is based on the transport marketplace, service quality and access time to the main centres of activity [10]; for this reason, in order for it being efficient, excellent connections with the access point of secondary transport networks that spread the node's positive impact are a key aspect. This performance is vital in Europe, where urban agglomerations are located hundreds of kilometres far from each other, which has obvious consequences for the development potential of the regions served [14] and the distribution of economic activity in Europe [4].

Nevertheless, this concept has a complex definition in unequivocal and objectively unquantifiable terms. Under its most abstract form, accessibility implies the combination of two key elements: the location of an area about the appropriate destinations and the features of the network(s) that link the different points in that area [24] with a wide range of indicators to measure accessibility, as pointed out by several authors [4,26]. However, there is very little research on accessibility through public transport, probably due to the fact that data regarding public transport are not available and that setting up models of the different routes is very difficult [15]. Nevertheless, accessibility through public transport means is becoming increasingly important due to aspects of a diverse and current nature: the price of oil's vulnerability [20], the traffic congestion [13] or the connection between public transit services, such as railway or air transportation.

The measurement of accessibility based on infrastructures plays a key role in transport policies and therefore the planning of transport policies in many countries is subject to the mathematical application thereof, just the way transport has been nationally planned in the UK [6]; or the Netherlands [2]. There are many aspects inherent to the measurement of accessibility. On the one hand, those based on the importance, as in this particular case, have certain advantages that focus on the location and are related to commissioning, interpretability and communicability criteria and also join the access to opportunities in the framework analysed, and its use can be used for the

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spatial-economic assessment of transport projects by reviewing both the long-term and short-term impacts of investment in infrastructures in the economic growth of the region.

Several prior studies measure the access by public transport but do not take the different kinds of destinations of the different frameworks into account. Nevertheless, as per the definition above, the access to different potential opportunities is a key element given that it does not only take how easy it is to get to a certain location into account [5] through the spatial modelling of public transport networks and the incorporation of valued approaches to the possible destinations as described by [11], who estimated the access to those location that generate opportunities by means of transport, creating a transit network when estimating the accessibility between census sections and opportunities. Burns and Inglis [3] create an area cost of the journey to access to commercial areas, estimating the travel time of three different means: by car, on foot and by bus, in which case the cost depends on the type of road and the frequency of the lines. Yigitcanlar et al. [27] generated the LUPTAI (Land Use and Public Transport Accessibility) model, which assessed the access to different locations depending on whether the route is followed on foot or by bus, assigning the resulting indexes to the breakdown of an area represented by a grid. Silva [21] developed the SAL (Structural Accessibility Layer) system, which developed a measurement of the external contour used for sub-regions that are spatially unbundled that is defined for every specific case. A regional diversity of the accessibility index for each sub-region is estimated. It is the population weighted average of the number of different type of accessible destinations by three means of transport: non-motorised transport, public transport and private car.

Curtis and Scheurer [5] have recently described the accessibility model for the SNAMUTS (Spatial Network Analysis for Multimodal Urban Transport Systems) strategic planning, which assess the connectivity and the centrality of a range of activities in the context of any town's land use depending on the average travel time.

Construing transport networks as arterial systems of land and urban organisation, acting as linking channels between generating poles and flow attractions, is directly linked to the identified need for irradiation of the impacts of HSR from the station to the broadest area possible. Therefore, the network is one of the territory elements that reflect the laws of spatial organisation, doing and undoing itself while the socioeconomic environment evolves [7]. Networks that are fairly balanced, linked and developed make exchanges at different scales possible, while those that are unlinked, unbalanced and unstructured polarise territories and increase the existing inequalities [8]. This way and by means of this methodology, the analysis of local public transport networks is presented, aimed at spreading the positive aspects inherent to HSR through an appropriate degree of connectivity between the city and its potentialities with the station node.

Based on the modelling of the real object, i.e. the public transport network, the analysis of the way the networks are linked and the organisation into hierarchies of their links has traditionally been carried out by applying the graph theory through the connectivity's topological features. Since Garrison's paper was published in 1962 [9] (quoted by Potrykowsky [18]), generalising its application to the study of networks, not only transport. This way, each spot can represent a city, a station or a computer belonging to a network (or any set of linked objects). The lines that link them can represent roads, railways or cables (or any physical element linking certain objects). Those spots are called vertexes and those lines are called edges. A graph can thus be defined with elements that are related to each other and applied to situations where data modelling so allows, ranging from road, and transport and telecommunication networks to the Internet or industrial processes. Based on this possibility, Garrison [9] and Kansky [12] presented approaches to transport networks through the mathematical theory of graphs by reducing them to sufficiently abstract terms. This paper focuses on the study of connected graphs, if there is a trajectory between any pair of nodes (vertexes), i.e. a road that links them, and on the study of labelled graphs, if the segment (and/or nodes) are assigned any kind of data.

In the case of labelled graphs, a value is generally assigned to an edge and the trajectory's value is thus defined as the addition of the values of the segments that are part of it.

In the case of urban bus transport networks, they have different directions and generally $(i,j) \neq (j,i)$. The fact that i vertex is connected with vertex j does not necessarily imply that vertex j is connected with vertex i. Furthermore, the edges will have an additional piece of information, i.e., the distance (length in metres) between the vertexes connected by them.

This length is defined as follows:

$$\mathrm{L}(i,j) = \begin{cases} d(i,j) & \text{if } (i,j) \text{ are directly connected} \\ 0 & \text{if } \quad i=j \\ \infty & \text{if } (i,j) \text{ are not directly connected.} \end{cases}$$

Therefore, the work methodology will be based on the application of both connected and labelled graphs, graphs $G=(v,e)$ defined by means of:

- An n set of vertexes, v, which corresponds to bus stops of the urban bus transport network.
- An m set of edges, e, which connect the vertexes between each other, if any.

The studies of networks that use the graph theory can be either static, through the application of shape indexes and connection, or dynamic, through the assignment of values for the network's connection elements with actual variables such as the distance in kilometres.

The static study of networks analyses the capacity of communication between all the spots of the route. The distance between vertexes is not taken into account but the extent there is cohesion between them, and therefore connectivity between the nodes increases as there are a higher number of routes. The more arches a graph has the higher the cohesion level is. There are a high number of indexes to measure the networks' cohesion level: coefficients such as Z, η, γ indexes of Kansky or the Zagozdzon index have frequently been used when analysing the configuration of routes [8], mainly when studying their level of development.

The dynamic study of networks analyses the measurement of accessibility and centrality of the network's vertexes. Given that certain values are assigned thereto, not only the number of vertexes and its connections are taken into account but their measurements, in order to construe accessibility as the ease of getting from one spot to another within the network. In topological terms, it can be analysed taking into account the distance between one stop from the other stops. The indicative measurement of centrality and accessibility within the networks can be obtained by calculating the minimum distance matrix, which shows the distance using the shortest route between the graph's nodes [8]. This matrix can be calculated using the Floyd algorithm since it can be implemented quickly and easily [1].

Measuring the network and the different ways to go through it is useful to find accessibility measurements of each of the nodes that are part of it. Different accessibility measurements can be found: the graph's diameter -or the longest distance from one vertex to another through the shortest way-, the Shimbel index or the index of actual accessibility -which varies for each vertex and is the addition of the distances between that vertex and the other vertex of the network through the shortest way-, the average length route from each vertex of the network -which constitutes the quotient between actual accessibility and the number of vertexes- or the Ω relative accessibility index proposed by Stutz [22], which is useful to clarify which one is the network's core node as follows

$$\Omega_i = \frac{A_i - A_*}{A^* - A_*} \times 100,$$

Ω_i = index of i node; A_i = Shimbel index of this node; A^* = highest Shimbel index within the network and A_* = lowest Shimbel index within the network.

As in many static indexes, the values of the Shimbel Index mostly depend on the number of nodes in each graph, which poses difficulties when comparing networks with a different number of nodes. In order to omit this difficulty, the relative accessibility index Ω_i is calculated, if $A^* = A_i$, then Ω_i=100 and $A_* = A_i$, then Ω_i=0, considering that the core node is that having a value of relative accessibility closer to zero. In other words, the vertex with a value of 0 will provide key values to define the level of accessibility not only corresponding to the HSR station stop, but also relevant data regarding its relationships with other poles and a comparative analysis of public infrastructures in the cities analysed and their level of development.

By analysing the vertexes' accessibility and combining it with the average values and its standard deviation, values below the average minus a deviation are obtained. In other words, the lowest values are the most accessible within the network. On the contrary, those nodes that are deemed to be scarcely and minimally accessible are those above the average plus once or twice the standard deviation, respectively.

By applying the Floyd algorithm to this case, i.e. the urban bus transport network in Ulm-Neu Ulm (Germany), minimum distances matrix of 177 rows and 177 columns are obtained. In order to operate them, a commercial program of symbolic calculation has been used, the *town planning* function having been created (see [16]) to calculate the aforesaid static and dynamic indexes. In this function, the Floyd algorithm is applied to the matrix defined by the distance between two bus stops.

2 Case study: Ulm-Neu Ulm (Germany)

We are now going to analyse the accessibility and centrality of the main attractions of Ulm-Neu Ulm (Germany) through the urban bus transport network in the urban environment to integrate HSR applying the methodology previously outlines. In last place, we are going to compare other case studies in Europe: Fulda (Germany), Toledo (Spain) and Lleida (Spain).

Given that it is very important to extrapolate the methodology to different networks for the enrichment based on the analysis of the differences found making sense to the comparison, the cases chosen have to be structurally similar. A medium-sized city has been chosen because the assessment of the effects derived from the integration of HSR is more ponderable therein [19] because the implementation of HSR has a dramatic impact in accessibility. For this reason, the studies interested in verifying these impacts frequently choose this kind of locations, such as the research carried out by the authors cited as well as by Ureña [23] and Wolfam [25] .

The study of the station's accessibility with the city by urban buses requires a mathematic modelling of reality. There are a few interesting examples presented by Pollack [17], which intend to bring problems alien to their scope closer to mathematical formulation by presenting assessable and reasonable results in the context of the real world. In order to analyse the network of local public transports and its accessibility to the station (and the rest of the city), it is necessary to perform a cartographical analysis at an urban level with respect to the surroundings of the HSR station.

Upon assessment of the city's main attractions and having interviewed local agents, they are placed on the map through a GIS (Geographic Information System) an environment in which the urban bus transport network is represented by the corresponding location of the stations thereof. The objective consists on extrapolating them to the graph by means of which they are represented, which will better allow us to perform a further study of the accessibility and centrality level both of the HSR station and the city's main attractions, as well as their relationship with key elements of the mobility policy: public car parks, other stations or taxi ranks (see Fig. 1).

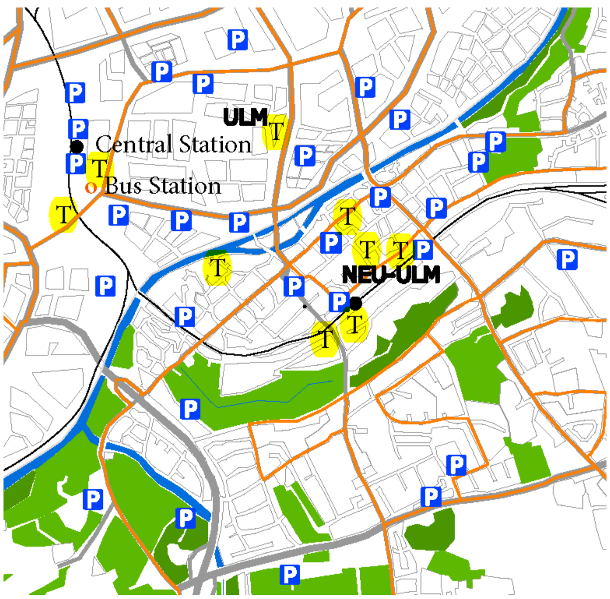

Fig. 1: Transport map in the Ulm-Neu Ulm HSR station area. T. Taxi rank; P. Public car park.

In Fig. 2 you can see Ulm-Neu Ulm's historic quarter and main attractions: 1. Cathedral; 2. Oath House; 3. Fishermen's Quarter; 4. Historic Wall; 5. Theatre; 6. Motorway; 7. City Council; 8. Water Tower; 9. Glacis Park; 10. University; 11. Ratiopharm Factory; 12. Neu Ulm Convention Centre; 13. Ulm Convention Centre; 14. Industry; 15. Danube River; 16. Iller River.

The urban bus transport network has 13 lines having stop in the Central Station and therefore all parts of the city are directly linked to it.

2.1 Identifying vertexes and edges

The 13 urban bus lines have 297 stops and many of them are coinciding (spots for possible connections), so the final number of vertexes is 177. Edges, which are the routes that connect two different stops of the network,

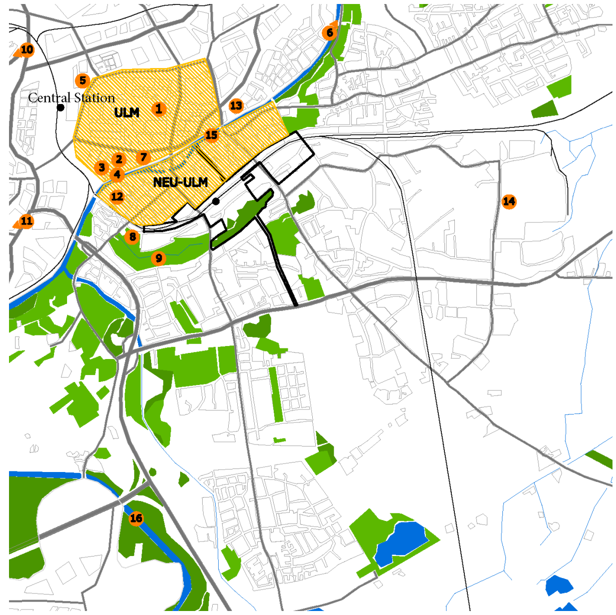

Fig. 2: Ulm-Neu Ulm's Historic Quarter and main attractions.

amount to 196. We are only interested in presenting the possibility to connect the locations or otherwise, and the minimum distances gone through. We are thus representing Ulm-Neu Ulm's valued public transport network by means of a graph (see Fig. 3) and generate the connection matrix between the vertexes.

In order to generate this matrix, we are going to assign the distances (in metres) between two vertexes (i, j) if they are directly connected; a value of 0 will be assigned if $i = j$ and Inf value (Infinity) to indicate that (i, j) are not directly connected. As an example, the data from the first 10 stops (vertexes) of a total of 177 belonging to the urban bus transport network is presented (see Fig. 4).

The total length of the network is $76,378\,m$ ($76.38\,Km$) serving an area of $71.70\,Km^2$ and a population of $177,986$ people between the towns of Ulm and Neu Ulm.

2.2 Dynamic study of the network: accessibility and centrality

The following results have been obtained upon carrying out the static study of Ulm-Neu Ulm's urban bus transport network: i) the number of connections is notably below the highest maximum possible; ii) the network's cohesion is low; iii) it is not a complex network; iv) there is a lack of edges in each vertex to complete the graph and the average distance between stops. Despite the foregoing, in this paper we are going to focus on the dynamic study of the network since a better analysis of the vertexes' accessibility and centrality measurements can be

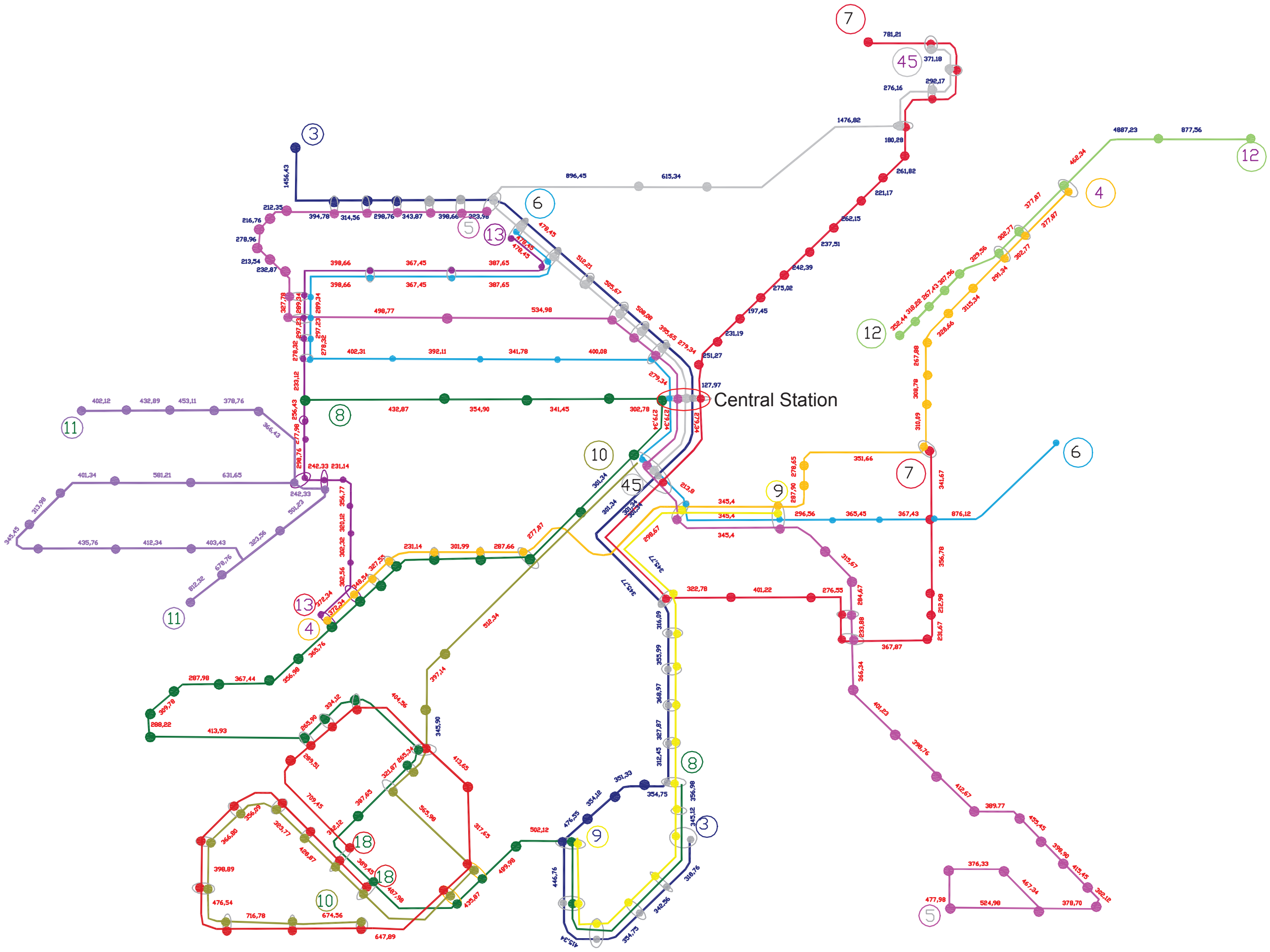

Fig. 3: Representation of the Ulm-Neu Ulm's network of local public buses by means of a graph.

	1	2	3	4	5	6	7	8	9	10
1	0	318.76	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
2	318.76	0	342.56	Inf	Inf	Inf	Inf	Inf	Inf	Inf
3	Inf	342.56	0	354.75	Inf	Inf	Inf	Inf	Inf	Inf
4	Inf	Inf	354.75	0	415.34	Inf	Inf	Inf	Inf	Inf
5	Inf	Inf	Inf	415.34	0	446.76	Inf	Inf	Inf	Inf
6	Inf	Inf	Inf	Inf	446.76	0	476.55	Inf	Inf	Inf
7	Inf	Inf	Inf	Inf	Inf	476.55	0	354.12	Inf	Inf
8	Inf	Inf	Inf	Inf	Inf	Inf	354.12	0	351.33	Inf
9	Inf	Inf	Inf	Inf	Inf	Inf	Inf	351.33	0	354.75
10	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	354.75	0

Fig. 4: Matrix identifying the vertexes and connection values (in metres) associated to the first 10 stops (out of 177) belonging to Ulm-Neu Ulm's urban bus transport network.

performed, as well as a comparative study of different networks.

In order to perform the dynamic study, we are going to generate the minimum distances matrix to calculate, by using the *town planning* function, the actual accessibility, the diameter, the average length and the relative accessibility of each vertex. When calculating this matrix (see Fig. 5), we can note that all vertexes are connected between them, i.e., any spot in the network can be accessed by the relevant connections.

As an example, the accessibility indexes of the first 22 (out of 177) vertexes calculated by using the *town planning* function, where the Railway Central Station is ranked among the 10 best communicated (see Fig. 6).

We can note that the vertex with a higher accessibility, with a relative accessibility equal to 0 is no. 17, the network's core node, which coincides with the Railway Central Station. On the contrary, the least accessible node is no. 55, a marginal area of the city where local industries are located. The bus station, on vertex no. 18, next to the railway station, is the third most accessible vertex out of 177, its relative accessibility amounting to 0.50. The main tourist attractions, such as the centre of the Historic Quarter (node no. 39), the City Council and the Cathedral (both next to node no. 41) are also among the best connected nodes. Certain places that attract a large number of visitors, such as the Theatre, the Ulm Convention Centre and a University's administration premises are also among the best connected nodes, being vertexes no. 15, 40 and 16. In last place, vertexes no. 19, 105 and 114, are also among the ten best connected, correspond to industrial and business locations mainly in the North of the city and attract a large number of flows. If the average and the standard deviation values are combined, we can note that all these vertexes are below the average minus the deviation, i.e., they are all very accessible.

Vertexes no. 55, 56, 57, 155 and 54 (in decreasing order) are the most marginal (least accessible) vertexes since they are above the average plus twice the standard deviation. Other potential poles notes in the city have the following relative accessibility indexes: industry, vertex no.108, with 19.68 (rank: 52 out of 177); the Fairgrouds, vertex no. 32, con 76.00 (rank: 171 out of 177) and the Science Park, node no. 44, with 11.27 (rank: 27 out of 177).

The average length's minimum value of the route from each vertex belonging to the network is located in vertex no. 17 ($3,043.40\,m$), the maximum distance between it and the furthest one through the shortest way (diameter) amounting to $8,012.39\,m$. The highest value of this index corresponds to vertex no. 55 ($8,790.84\,m$), the maximum distance for this vertex being $14,959.40\,m$.

The graph's degree of dispersion amounts to $154,210\,Km$, which is the addition of the total number of kilometres to go through each and all of the vertexes with the others through the shortest way.

In Fig. 7 easily shows relative accessibility of the different vertexes. The most accessible vertex, no. 17, is highlighted and coincides with the location of the high-speed Railway Central Station, and the least accessible vertex, no. 55, which coincides with a marginal area of the cities, as it has been previously mentioned.

This methodology has also been applied to other three European cities: Fulda (Germany), Lleida (Spain) and Toledo (Spain). These cities have similar features and, on the basis of the detailed study, the fact that the networks serving to German cities are much bigger and broader than those serving Spanish cities. However, in order to serve population as a whole, there is a similar number of local bus lines, Fulda (9 lines), Ulm-Neu Ulm (13 lines), Toledo (12 lines) excepting Lleida's case, which has 18 lines. On the basis of the foregoing, the station location with respect of the cities' relative accessibility is best positioned in the case of German cities (Fulda: rank 4 out of 249; Ulm-Neu Ulm: rank 1 out of 177), whereas the location in the case of Spanish cities is places in lower positions (Toledo: rank 8 out of 73; Lleida: rank 10 out 226).

3 Conclusions

Despite the fact that it has traditionally been conceived as a source of opportunities, the implementation of HSR, based on the development of high-speed train projects in several European countries, show that the objectives set may not always be easily achieved, whereas several risks may arise therefrom. Measuring centrality/accessibility offers the opportunity to assess transport planning.

Upon applying the methodology to the study of HSR stations within the urban framework by means of urban bus transport networks, very different results are obtained depending on the city studied. Upon comparing and assessing these results over time, they turn to be a very valuable tool when planning mobility policies that assure both the profitability and the social performance of the inversions made.

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	1	2	3	4	5	6	7	8	9	10
1	0	318.76	661.32	1,016.07	1,431.41	1,878.17	1,762.30	1,408.18	1,056.85	702.10
2	318.76	0	342.56	697.31	1,112.65	1,559.41	2,035.96	1,726.94	1,375.61	1,020.86
3	661.32	342.56	0	354.75	770.09	1,216.85	1,693.40	2,047.52	1,718.17	1,363.42
4	1,016.07	697.31	354.75	0	415.34	862.10	1,338.65	1,692.77	2,044.10	1,718.17
5	1,431.41	1,112.65	770.09	415.34	0	446.76	923.31	1,277.43	1,628.76	1,983.51
6	1,878.17	1,559.41	1,216.85	862.10	446.76	0	476.55	830.67	1,182.00	1,536.75
7	1,762.30	2,035.96	1,693.40	1,338.65	923.31	476.55	0	354.12	705.45	1,060.20
8	1,408.18	1,726.94	2,047.52	1,692.77	1,277.43	830.67	354.12	0	351.33	706.08
9	1,056.85	1,375.61	1,718.17	2,044.10	1,628.76	1,182.00	705.45	351.33	0	354.75
10	702.10	1,020.86	1,363.42	1,718.17	1,983.51	1,536.75	1,060.20	706.08	354.75	0

Fig. 5: The minimum distances matrix (in metres) with the first 10 vertexes (out of 177) for the dynamic study to Ulm-Neu Ulm's urban bus transport network.

	Vertex	Actual accessibility	Diameter	Average length	Relative accesibility
	1	911,961.37	11,042.97	5,152.32	36.69
	2	947,966.36	11,361.73	5,355.74	40.23
	3	985,506.63	11,704.29	5,567.83	43.92
	4	1,022,196.45	12,059.04	5,775.12	47.53
	5	1,009,678.82	12,017.81	5,704.40	46.30
	6	935,633.86	11,571.05	5,286.07	39.02
	7	922,717.39	11,401.07	5,213.09	37.75
	8	884,535.41	11,046.95	4,997.38	34.00
	9	845,461.81	10,695.62	4,776.62	30.16
	10	804,713.43	10,340.87	4,546.40	26.15
	11	769,074.55	10,028.42	4,345.05	22.65
	12	726,903.08	9,700.55	4,106.80	18.50
	13	674,674.52	9,331.58	3,811.72	13.37
	14	622,844.45	8,975.59	3,518.90	8.27
THEATRE	15	576,814.02	8,659.50	3,258.84	3.75
UNIVERSITY	16	541,520.70	8,313.73	3,059.44	0.28
RAILWAY CENTRAL STATION	17	538,681.94	8,012.39	3,043.40	0.00
BUS STATION	18	543,728.78	7,825.47	3,071.91	0.50
INDUSTRY	19	576,062.35	8,104.81	3,254.59	3.67
	20	625,147.41	8,500.46	3,531.91	8.50
	21	669,257.51	8,500.69	3,781.12	12.84
	22	744,039.86	9,006.36	4,203.62	20.19

Fig. 6: First 22 (out of 177) vertexes together with their accessibility indexes calculated by using the *town planning* function based on the minimum distances matrix of the network of public transport bus services of Ulm-Neu Ulm.

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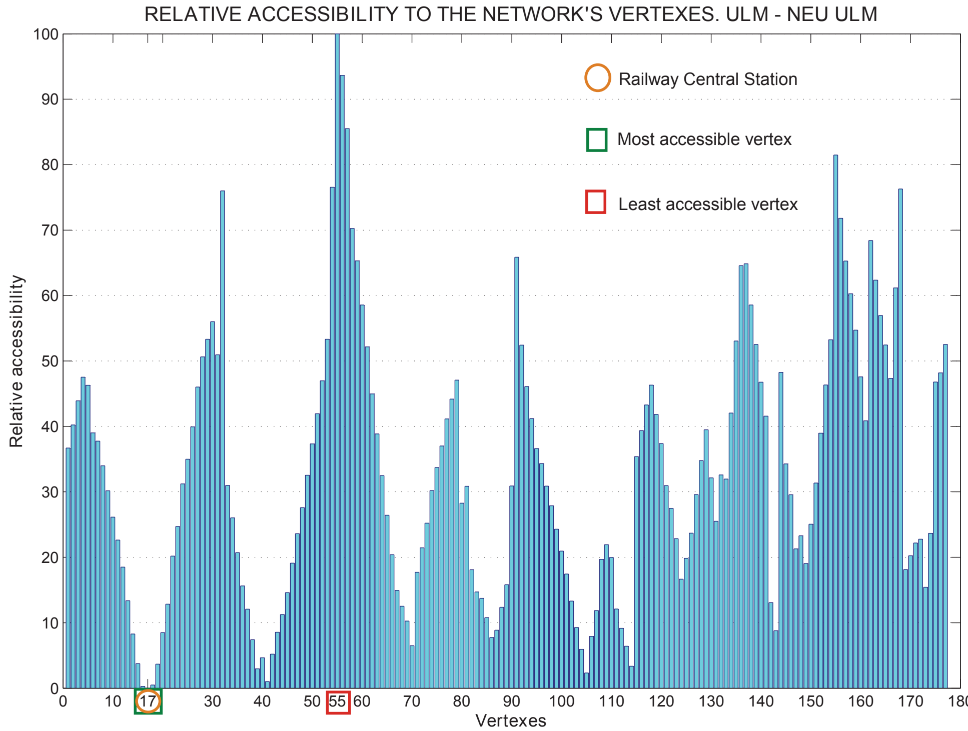

Fig. 7: Graphical representation of the relative accessibility of the vertexes of Ulm-Neu Ulm's urban bus transport network.

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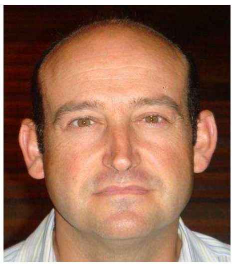

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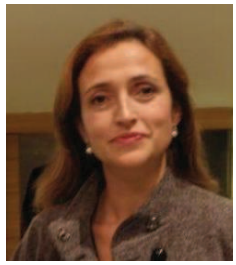

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