A Graphical Analysis of the Multimodal Public Transport Network – The Bay of Cadiz

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***Abstract*—The structure of the current public transport network is the result of many different political, economical and societal decisions over a long period of time. Further developments of these networks require exhaustive analysis of the actual topology and its properties in order to achieve significant improvements. In this work, a statistical analysis and graph theory approach of the multimodal transport network of the Bay of Cadiz is proposed. First, the statistical characteristics of centrality and robustness of the global network are calculated. Later, the influence of specific means of transport on the complete public transport network is analyzed by comparing these parameters against different subnetworks where one or more transport networks have been eliminated. The results obtained evince the importance and influence of the different transport networks in the Bay of Cadiz, highlighting those presenting high robustness on the overall network, as well as those whose influence is limited.**

***Index Terms*—Multimodal transport network; public transport efficiency; graph theory; centrality and robustness metrics.**

I. INTRODUCTION

Society is currently experiencing the migration of population to big cities world wide. It is forecasted that by 2050 over 66 % of the population will live in urban areas [1]. This fact brings many opportunities but also many challenges that governments need to face to overcome traffic congestion, spatial inequalities and promote sustainability and economic development [2]. Among many other issues, an in-depth study of the Public Transport System (PTS) is essential for the development of cities to make them more efficient, sustainable and attractive to users, thus reducing traffic congestion, pollution or noise, and making cities more livable.

However, their design, planning and expansion of PTSs are not straightforward due to the demands of all actors involved. For example, quality of service and passenger comfort are essential to increase ridership. Low operational cost is required to make it profitable for the operator. Efficiency is required not only to reduce operational cost but also to address sustainability, as well as connectivity between different transport networks [3].

Public transport networks can be studied or assessed from different points of view, such as trip and route planning, user ease of use, or graph theory, among others [4]. In the latter, transport networks are represented as a graph, whose nodes and edges determine the shape and composition of the network. The nodes represent the transport stops; while the edges represent the route between stops.

Multimodal transport is defined as the process of transporting a person/goods between two distant points using two or more modes of transport. It is experiencing a great development around the world because of its high flexibility and efficiency and low cost and energy consumption [5]. In this work, we propose an analysis of the multimodal public transport network of the Bay of Cadiz, including train, tram, boat, urban and interurban bus networks. Different characteristic parameters of the network topology are obtained and compared against different subnetworks where not all the means of transport are presented. The results obtained demonstrate the level of network connectivity, as well as the effect of extracting one or more transport networks and the influence of such extraction. Thus, the relevance of each of them and the connections between the different stops of the targeted network are checked.

The remainder of the paper is structured as follows: the most relevant related works are briefly presented in Section II; the methodology used is introduced in Section III; Section IV shows the results obtained; and finally, Section V reflects the main conclusions and outlines some future research lines.

II. RELATED WORKS

The study of multimodal transport networks has been widely addressed in the literature. He et al. [6] study freight transport in the Netherlands, focusing on road, river and rail transport, obtaining a series of critical nodes essential for the stability of the network structure, thus obtaining the key areas of the network. Wang et al. [7] study the multimodal transport network of the China-Europe Railway Express, obtaining that the transfer between road and rail manages to alleviate the cascade failures that can occur. Tympakianaki et al. [8] study the effect of tunnel closures on the Stockholm transport network, resulting in the need for network redistribution to avoid traffic management problems for the city. Guo et al. [5] analyse the multimodal transport network of the Sichuan-Tibet (China) region of rail, road and air to place emergency rescue facilities, concluding that the whole network should be taken into account, especially at the most important nodes and links.

Graph theory has been also applied to analyze transport networks. In [9], the Madrid metro network is analysed through centrality and robustness parameters, focusing on closeness centrality and cluster coefficient. As a result, the vulnerability of the entire network is obtained, as well as the identification of the most important stops to achieve robustness in the network. Similarly, Mariñas Collado et al. [10] carried out a study of the Barcelona metro network using indicators of robustness, cluster coefficient and average efficiency. Thus, they obtained the characteristics of the different stops with the aim of obtaining a specific analysis to plan and restructure the network in search of better viability. Derrible makes use of graph theory in [11], to study the centrality of the metro network of various cities, focusing on centrality measures in search of future efficiency improvement for network planning and sustainable cities. Frutos Bernal et al. [12] analyze the Madrid metro network in terms of centrality measures to verify the location of the different stops, showing that the stops in the center of the city are those with greater centrality and, therefore, greater connection. Cats [13] analyzes the historical evolution of the multimodal rail transport network (tram, light rail, metro, high-speed express connections and local, suburban and regional trains), focusing on the efficiency and centrality of the nodes. In this way, it shows how it is affected by the technological factor in search of better connectivity, taking into account the increase in urban centres and population growth.

III. Methodology and Case of Study

The metropolitan area of the Bay of Cadiz comprises 12 municipalities, with a total of 823,806 inhabitants [14] [15]. These towns are: Cadiz (CA), El Puerto de Santa María (PSM), San Fernando (SF), Puerto Real (PR), Jerez de la Frontera (JF), Chiclana de la Frontera (CF), Rota (RO), Conil de la Frontera (CoF), Arcos de la Frontera (AF), Chipiona (CH), Sanlúcar de Barrameda (SB), and Medina Sidonia (MS). As it can be seen in Figure 1, they are all located in the province of Cadiz, south-west of Andalucia (Spain).

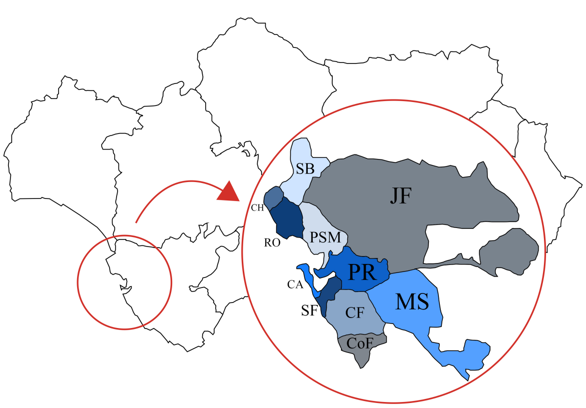

Fig. 1. Location of the municipalities that form the Bay of Cadiz in Andalusia, Spain.

These municipalities are scattered across the territory and require urban and interurban transport systems to interconnect them and meet passenger demands. The Transport Consortium of the Bay of Cadiz operates a transport network comprising train, boat, tram and bus services, both at urban and interurban level. The stops of the train, tram and boat networks are outward and return, thus providing two-way journeys. For the rest of the networks, any stop only refers to one way trip, because they are generally circular lines (see [15] [16] for more detailed information). Table I shows the different types of transport offered in each of the cities [16].

TABLE I
THE DIFFERENT MEANS OF TRANSPORT INCLUDED IN EACH OF THE TRANSPORT NETWORKS FOR THE TWELVE CITIES INCLUDED IN THE METROPOLITAN AREA OF BAY OF CADIZ

City	Pop.	Interurban	Urban	Train	Boat	Tram
CA	113066	✓	✓	✓	✓	✓
PSM	89435	✓	✓	✓	✓	
SF	94120	✓	✓	✓		✓
PR	41963	✓	✓	✓		
JF	212730	✓	✓	✓		
CF	87493	✓	✓			✓
RO	29491	✓	✓		✓	
CoF	23497	✓	✓			
AF	30953	✓	✓			
CH	19592	✓				
SB	69727	✓				
MS	11739	✓				

The representation of the public transport network of the Bay of Cadiz has been determined using the L-Space method initially proposed in [17] [18]. In this method, the nodes represent stops, while the edges represent the given connection between two nodes of a route. The multimodal transport network is represented as a directed graph $G = (V, E)$, where the set of nodes ($V = \{v_1, v_2, ..., v_N\}$) corresponds to the different transport stops, and the trips between any two stops correspond to the set of directed edges (E). The adjacency matrix of G, A_G is an asymmetric matrix of size N x N, where each entry a_{ij} equals 1 if there is a mean of transport that offers trip that goes from stop v_i to stop v_j, 0 otherwise. Figure 2 shows the resulting graph of the complete public transport network in the Bay of Cadiz using Matlab software.

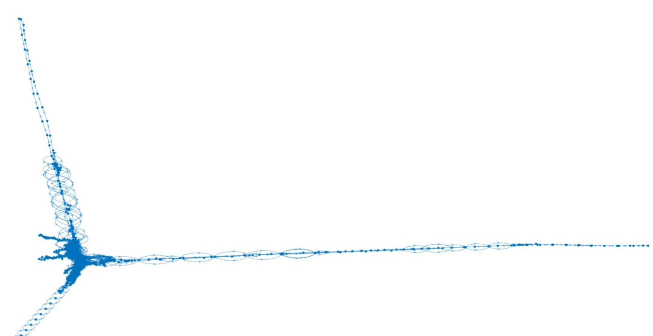

Fig. 2. Resulting graph of the complete public transport network in the Bay of Cadiz.

In order to study the relevance of the different modes of transport that constitute the multimodal network, a set of sub-networks has been created based on the combination of the different existing transports. Specifically, three categories or groups have been considered. They are explained next, and shown in Figure 3. Group A is composed of the different possible combinations that can be obtained from the different interurban networks of the set (train, tram, boat). Group B is related to the interurban bus network and two subgroups are possible. First, the global network is analyzed without the interurban network. Second, only the interurban is considered. Regarding group C, two possible subgroups are considered. On the one hand, all the means of transport are included except the urban bus networks for all cities. On the other hand, there are twelve subgroups C, one per each city whose urban network is not included.

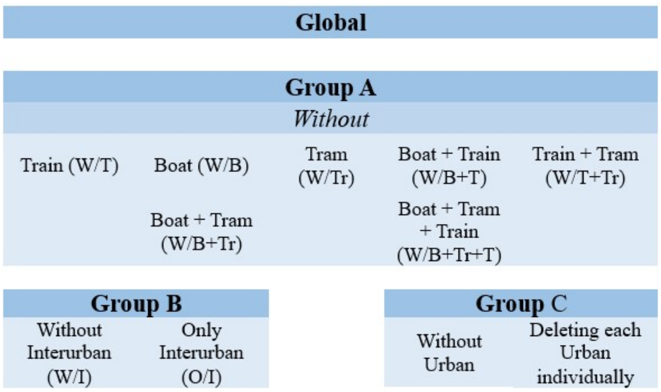

Fig. 3. Classification of Subgraph Groups. In brackets, abbreviation of each, where "W/" stands for "Without" and "O/" stands for "Only".

A. Statistical and robustness parameters

The analysis of a transport network involves examining specific data about its structure, including relevant statistical and robustness parameters [19] [20]. Next, the most relevant features analyzed in this work are presented:

- The *density (d)* of the network is a measure of the number of existing connections in relation to the total number of possible connections in the network.

$$d = \frac{E}{V(V-1)} \tag{1}$$

- The *frequency distribution of degree (P(k))* in a network assigns to each degree k the number of nodes that have that value, describing the proportion of nodes in the network with that value.

$$P(k) = \frac{V_k}{V} \tag{2}$$

  Where V_k is the number of nodes with degree k in the graph, and V is the total number of nodes given. Graphs with a more uniform *degree distribution* tend to have a higher *normalised robustness indicator* compared to those with a more heterogeneous distribution. The value of this is higher when more alternative routes are available, and lower when the system is larger.
- The *diameter (D)* of a graph is defined as the longest distance between any pair of nodes in the network, representing the longest path.
- The *closeness centrality* $C_c(i)$ is defined as the proximity to all other nodes in the graph. It is calculated as stated in (3), where $d_{(i,j)}$ is the shortest distance from node i to node j; while $d_{(j,i)}$ is the shortest distance from node j to node i.

$$C_c(i) = \frac{1}{\sum_{j\neq i}(d(i,j)+d(j,i))} \tag{3}$$

  Nodes with a higher closeness are considered more influential in the network, occupying a more central position. In this way, it is possible to identify those that are most relevant to the connection in the graph.
- The *betweenness centrality* (Bc_i), measures the degree to which a node is on the shortest path between other pairs of nodes in the network, i.e., the number of times a node acts as an intermediary in communication. It is calculated as stated in (4), where σ_{jk} is the total number of shortest paths between nodes j and k, and $\sigma_{jk}(i)$ is the number of such paths passing through node i.

$$Bc_i = \sum_{j\neq i\neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \tag{4}$$

  Nodes with high *betweenness centrality* occupy strategic positions in the network, so their removal can have a significant impact on the connectivity and efficiency of the network.
- The *average efficiency* ($E[\frac{1}{H}]$), represents the overall communication capacity of a network by calculating the average of the efficiencies of all the pairs of nodes that make it up as shown in (5), where $d(v_i, v_j)$ is the shortest path distance between nodes v_i and v_j of the network, using $\frac{1}{V(V-1)}$ as the normalisation factor.

$$E[\frac{1}{H}] = \frac{1}{V(V-1)} \sum_{i,j=1,i\neq j}^{V} \frac{1}{d(v_i,v_j)} \tag{5}$$

  The efficiency of a pair of nodes is defined as the inverse of the shortest distance between them. It ranges between 0 and 1. The higher the value of this parameter, the higher the robustness of the analysed network because it refers to the survivability against random failures or deliberate attacks involving the removal of nodes and links [20] [21].
- The *normalised robustness indicator* ($\bar{r}^T$), which ranges from 0 to 1, evaluates the resilience of a network to failures and its ability to maintain connectivity. $\bar{r}^T$ is given by the ratio between the number of alternative routes in the network and the total number of nodes [20], from the total number of edges *E* and the number of nodes *V*.

$$\bar{r}^T = \frac{ln(E-V+2)}{ln(\frac{V(V-1)}{2})-V+2} \tag{6}$$

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- The *global cluster coefficient parameter* (G_c) indicates how neighbours of a given node are connected to other nodes, ranging between values of 0 and 1.

$$G_c = \frac{1}{V}\sum_{i=1}^{V} G_c(v_i) \tag{7}$$

Where $G_c(v_i)$ represents the individual cluster coefficient of each node, while V means the total number of nodes. The *clustering coefficient* reflects the fault tolerance capability, so as the value of G_c increases, the local fault tolerance increases.

The use of the aforementioned statistical and robustness parameters, in addition to the basic statistical parameters of *standard deviation* σ applied to degree distribution, have been used to compare the subgraphs versus the global network. Thus, by extracting one or several transport networks, the relevance of each transport system on the global network is evaluated.

IV. Results and discussion

This section first presents an analysis of the global multimodal network and then evaluates the influence of each subgroup on the complete network once the following are extracted from it.

A. Analysis of the complete Multimodal Public Transport Network of the Bay of Cadiz

First of all, the *density d* of the network studied, indicates a poorly connected network according to (1), with this value being approximately 0.00183. In comparison with other national transport networks, such as the metro networks of Madrid and Barcelona, which have values of 0.009421 and 0.0157 respectively [9] [10], the connectivity of the Bay's multimodal transport network is lower. This result is reasonable because the targeted network is a multimodal transport network where more than one type of transport is studied.

In terms of the node degree, the studied multimodal network presents a highly variable value varying from 80 to 2. The *average degree* of the network is $\langle k\rangle \approx 4.867$, meaning that most of the nodes has a low degree value. In Figure 4, the *distribution degree* $P(k)$ is shown.

As it can be seen in Figure 4, most of the nodes are concentrated in the first grades, being connected to at least two nodes. This is the most frequent grade (about 60%) although the average is 4.867. It is followed by grade 4 with a little more than 20%, i.e. the stops with the possibility to change route. After that, the decrease in percentage for the following grades occurs from grade 10 onwards, being less than around 2%.

Table II shows the five nodes with the highest degree values. As it can be seen, the station of Jerez presents the highest value, 80. Indeed, this node is included in three different means of transport (urban, interurban and train) and in many different lines in each of them. Table II also shows that there are two more locations in the overall network with a high

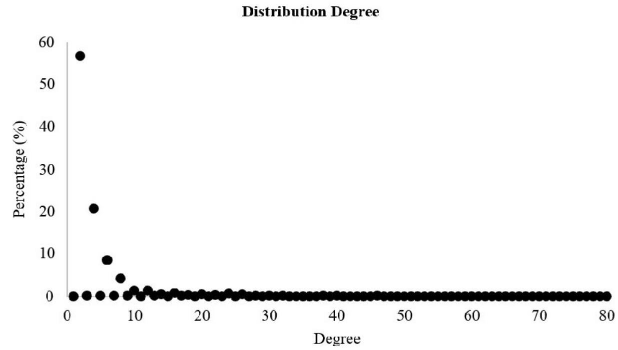

Fig. 4. Distribution Degree of the Public Transport network in the Bay of Cadiz.

degree value: *Asdrubal Square* and *Puerta del Mar* in Cadiz (in both directions), the latter being where the Cadiz hospital is located.

TABLE II
Nodes with highest values of degree in the global multimodal transport graph of Bay of Cadiz

Node	Degree	Transport
Jerez Station	80	Interurban, Urban, Train
Asdrubal Square (to Cadiz)	70	Interurban, Urban
Puerta del Mar (to Cadiz)	64	Interurban, Urban
Puerta del Mar (from Cadiz)	60	Interurban, Urban
Asdrubal Square (from Cadiz)	58	Interurban, Urban

The diameter of the network is 73, representing the longest distance between any pair of nodes. However, the average shortest path is 19,622. In terms of the the centrality parameters, the *closeness and betweenness centrality* of each node forming the global network have been studied. The former reaches a maximum value of 0.090, shown in nodes such as *Telegrafia (to Cadiz), Puerta del Mar (the stop of the hospital* to Cadiz) and El Puerto Station (to Cadiz). The latter, i.e. the betweenness centrality, reaches a maximum value of 0.50 for *Jerez Station*, followed by values of 0.28 approximately, as in the nodes found in *El Puerto Station*. This makes the areas of Cadiz, PSM and Jerez, the most relevant in terms of centrality and, therefore, connectivity.

Regarding to the robustness parameters of the global network, the average *cluster coefficient* of the network is 0.031, a value similar to relevant networks such as the London Metro Network ($G_c = 0.0409$) or Tokyo Metro Network ($G_c = 0.0285$) [21] and, on Spanish territory, exceeding the Barcelona Metro Network ($G_c = 0.0044$) [10].

B. Transport system relevance on the multimodal network

The statistical parameters of groups A, B and C presented in Section III are summarised in Tables III, IV and V, respectively. These tables show the values of the different statistical and robustness parameters for each subgroup. These parameters are: *number of nodes, number of edges, diameter, average degree (k), standard deviation of the nodes' degree*

(σ), cluster coefficient (G_c), average efficiency ($E[\frac{1}{H}]$) and normalised robustness indicator (r^T).

TABLE III
STATISTICAL PARAMETERS OF THE SEVEN DIFFERENT SUBGRAPHS INCLUDED IN GROUP A.

	Global	**W/T**	**W/B**	**W/Tr**
Nodes	1325	1323	1324	1310
Edges	3226	3202	3222	3186
Diameter	73	73	73	73
k	4.867	4.838	4.867	4.861
σ Degree	7.141	7.070	7.148	7.168
G_c	0.031	0.031	0.031	0.031
$E[\frac{1}{H}]$	0.032	0.032	0.032	0.032
r^T	0.986	0.986	0.986	0.986
	W/T+B	**W/T+Tr**	**W/B+Tr**	**W/T+B+Tr**
Nodes	1322	1304	1309	1303
Edges	3198	3162	3182	3158
Diameter	73	73	73	73
k	4.835	4.847	4.859	4.844
σ Degree	7.072	7.110	7.171	7.113
G_c	0.031	0.031	0.031	0.031
$E[\frac{1}{H}]$	0.032	0.032	0.032	0.032
r^T	0.986	0.986	0.986	0.986

In Table III, the statistical parameters of each of the seven subgraphs of group A are compared against the global network. This group considers maintaining the urban and interurban buses in all subgroups, but not considering the other means of transport in turns. As it is shown, there are no remarkable variations in any of the parameters studied. Indeed, the *diameter*, the *normalised robustness indicator*, the *clustering coefficient* as well as the *average efficiency* do not change in any of the studied subnetworks. In terms of the number of nodes and edges, the maximum variation is obviously found when not considering the combination of the three means of transport (W/T+B+Tr). However, when considering the deletion of a single mean of transport, the one presenting a higher impact is the tram. This is mainly because the stops and therefore, the links included in it, are exclusively for this kind of transport.

TABLE IV
STATISTICAL PARAMETERS OF THE TWO DIFFERENT SUBGRAPHS INCLUDED IN GROUP B.

	Global	**W/I**	**O/I**
Nodes	1325	1190	251
Edges	3226	1904	1322
Diameter	73	92	40
k	4.867	3.202	10.534
σ Degree	7.141	2.201	12.372
G_c	0.031	0.015	0.077
$E[\frac{1}{H}]$	0.032	0.015	0.082
r^T	0.986	0.990	0.879

The impact of the interurban bus network is analyzed in Table IV, where the parameters of the two different subgraphs that conform Group B are presented. It is observed that removing the interurban, subgraph (W/I), means losing a total of 135 nodes, a considerable loss, which highly affects all the statistical parameters of the subgraph, as it it is shown in Table IV. This means that some localities are disconnected from the rest of the graph, such as Chipiona, Sanlucar de Barrameda and Medina-Sidonia, and it makes more difficult the access to the rest of the network. Indeed, the value of the *diameter* has highly increased from 73 to 92. Thus, as this network has a smaller number of nodes than the global network, the *standard deviation σ* of the degree distribution is remarkably lower, showing that the distribution is more evenly distributed across the network nodes. In relation to the robustness parameters, it is observed that both the *average efficiency $E[\frac{1}{H}]$* and the *clustering coefficient* are lower than the global network. In contrast, it has a similar value for the *normalized robustness indicator r^T*, indicating that it has a similar number of alternative routes as the global network.

Table IV also analyzes the interurban network by itself. It has a total of 251 nodes, differing greatly from the global network. On the one hand, its *diameter* is 40, so the distance between any two nodes is shorter compared to the global network. In terms of robustness parameters, the *normalized robustness indicator r^T* is close to the values of the other subgraphs in the group, so it has a similar number of alternative routes as the other graphs in this group. Regarding both *cluster coefficient parameter G_C* and *average efficiency $E[\frac{1}{H}]$* present a remarkable increase in their values, indicating a higher robustness in this network.

TABLE V
STATISTICAL PARAMETERS OF THE TEN DIFFERENT SUBGRAPHS INCLUDED IN GROUP C.

	Global	**W/U**	**W/AF**	**W/CA**	**W/CF**	**W/CoF**
Nodes	1325	276	1270	1256	1214	1294
Edges	3226	1390	3151	3092	3116	3179
Diameter	73	41	73	73	73	73
k	4.867	10.072	4.962	4.924	5.008	4.913
σ Degree	7.141	12.098	7.261	7.085	7.405	7.207
G_c	0.031	0.073	0.030	0.032	0.033	0.031
$E[\frac{1}{H}]$	0.032	0.078	0.031	0.033	0.034	0.032
r^T	0.986	0.887	0.986	0.985	0.985	0.986
	Global	**W/PSM**	**W/JF**	**W/PR**	**W/RO**	**W/SF**
Nodes	1325	1193	877	1278	1227	1267
Edges	3226	2975	2470	3079	3079	3133
Diameter	73	73	66	73	64	73
k	4.867	4.987	5.633	4.818	5.019	4.946
σ Degree	7.141	7.334	8.279	7.203	7.378	7.285
C_c	0.031	0.033	0.042	0.029	0.033	0.029
$E[\frac{1}{H}]$	0.032	0.034	0.044	0.030	0.034	0.030
r^T	0.986	0.985	0.976	0.986	0.985	0.986

Finally, the parameters of subgraphs included in group C are shown in Table V. In this case the impact of the urban bus network is studied. As can be seen, the values obtained by removing a single urban network are similar to those of the overall network, having similar characteristics of nodes and edges, as well as in terms of robustness parameters. However, in the case of Jerez de la Frontera it is different. In this case, as it is the largest urban network of those studied, the effect of eliminating it is more significant in comparison with the rest.

It is interesting to note the results obtained when all city buses are eliminated. It can be seen that the impact on the number of nodes and edges is high, as well as the *diameter* becomes smaller and, therefore, there are smaller maximum distances between nodes. Indeed, this behaviour is very similar to the subgroup of group B where only interurban bus network is considered. Both subgraphs present lower number of nodes, edges and diameter than the global network, but higher average degree and standard deviation, as well as similar values for the robustness parameters, meaning that both the interurban and urban networks are the most representative in the global graph.

This analysis shows that changes in the urban and interurban networks will directly influence the global network significantly, i.e. in terms of the robustness and connectivity. However, the tram, train and boat have a low impact. Moreover, independently of the studied subgraph, the *normalized robustness indicator* keeps a high value, highlighting the resilience of the network (in terms of connectivity) to failures.

V. CONCLUSIONS

In this work, a graphical analysis of graph theory has been carried out on the public transport network of the Bay of Cadiz, since it is a transport network that is in continuous growth and can give rise to studies on its efficiency. In order to achieve the objectives of this study, a statistical and graph theory analysis of the network structure is carried out. The global network has been partitioned in different graphs and subgraphs in order to analyze the influence of the different means of transport composing it.

The results of this work show the importance or influence of the different types of transport in the Bay of Cadiz. In this way, the networks that function as the core of the overall network are both the urban and the interurban bus networks. The interurban network presents the highest *normalised robustness indicator* as it is the one that connects the different localities included in the Bay of Cadiz. Some of them become isolated when this subnetwork is not considered. However, it is worth noting that in any of the studied subnetworks, the *normalised robustness indicator* presents a high value (always over 0.87) even when not considering many of the transport modes, meaning that the system is resilient and it maintains connectivity in case of failure of any transport mode.

As future work, the travel time or fuel consumption will be considered, including these features as weights in the network. In addition, a multifractal study of the Bay of Cadiz transport network based on the statistical study can provide more information in this respect, as well as studying how to adapt fractal algorithms to directed graphs of the different types of transport.

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