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

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Introduction

- Multimodal transport is defined as the process of transporting a person/goods between two distant points using two or more modes of transport.
- 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.
- 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.**

Aims

- Study of the multimodal public transport network of the Bay of Cadiz under graph theory.
- Analysis of statistical parameters of centrality and robustness.
- Comparison of study subgroups divided according to types of transport and locations.

Theoretical Foundations

The study of transport networks has provided information throughout the progress of their evolution.

Transport networks can consist of several types of transport networks, thus considering networks as multimodal in concept when they include two or more types of transport.

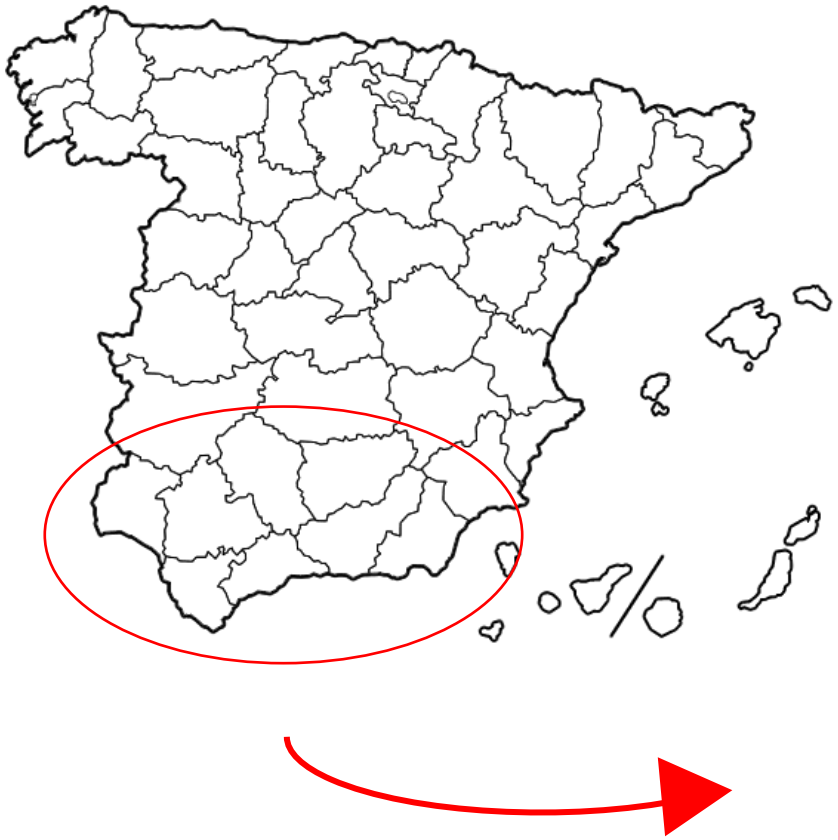
In this case, it can be studied under different parameters. In the case of applying graph theory:

Checking for weaknesses in the structure of the transmission network.

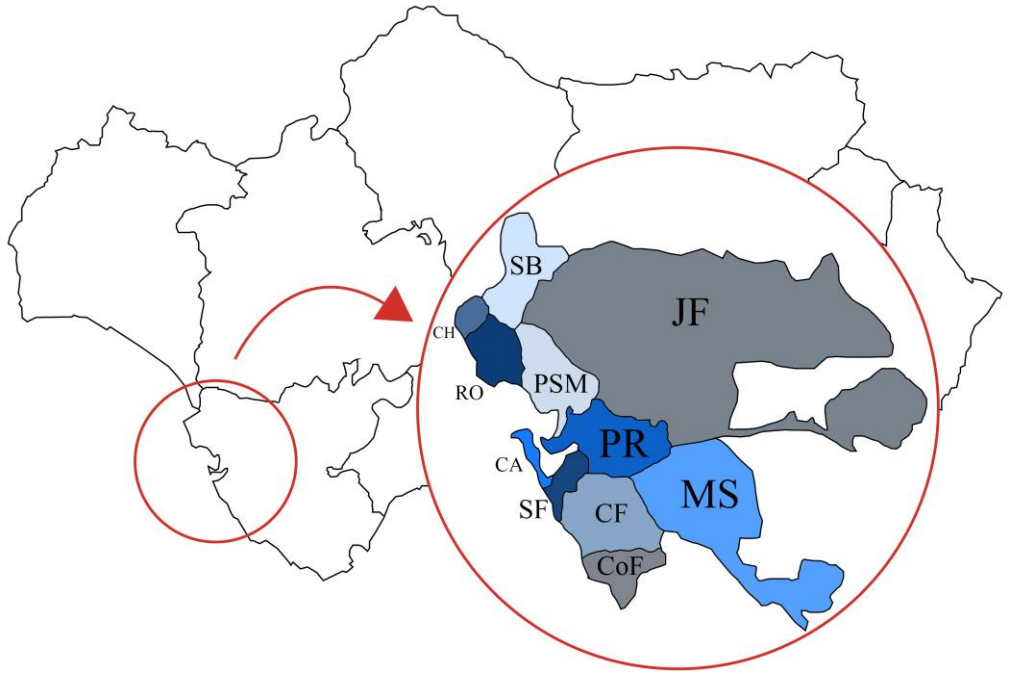
Restructuring of the network to avoid travel flow failures and congestion.

Studies of centrality and robustness parameters to check the state of the network.

Methodology and Results. *Bay of Cadiz. Public Transport*



The study area is located in Andalusia, southern Spain. Within it, the multimodal transport network of the Bay of Cadiz is studied.

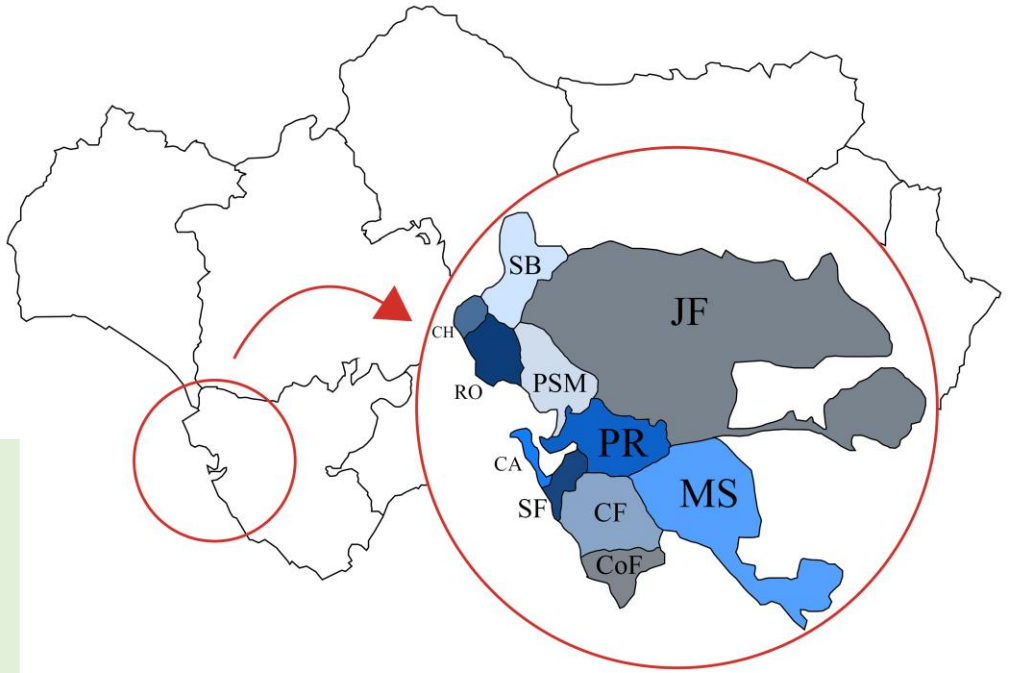


Methodology and Results. *Bay of Cadiz. Public Transport*

The Bay of Cadiz is made up of the different localities mentioned above. They all form part of the *Bay of Cadiz Transport Consortium*, to which new localities or types of transport are continually being added, as has recently been the case with the tram.

Cádiz (CA)
El Puerto de Santa María (PSM)
San Fernando (SF)
Puerto Real (PR)
Jerez de la Frontera (JF)
Chiclana de la Frontera (CF)

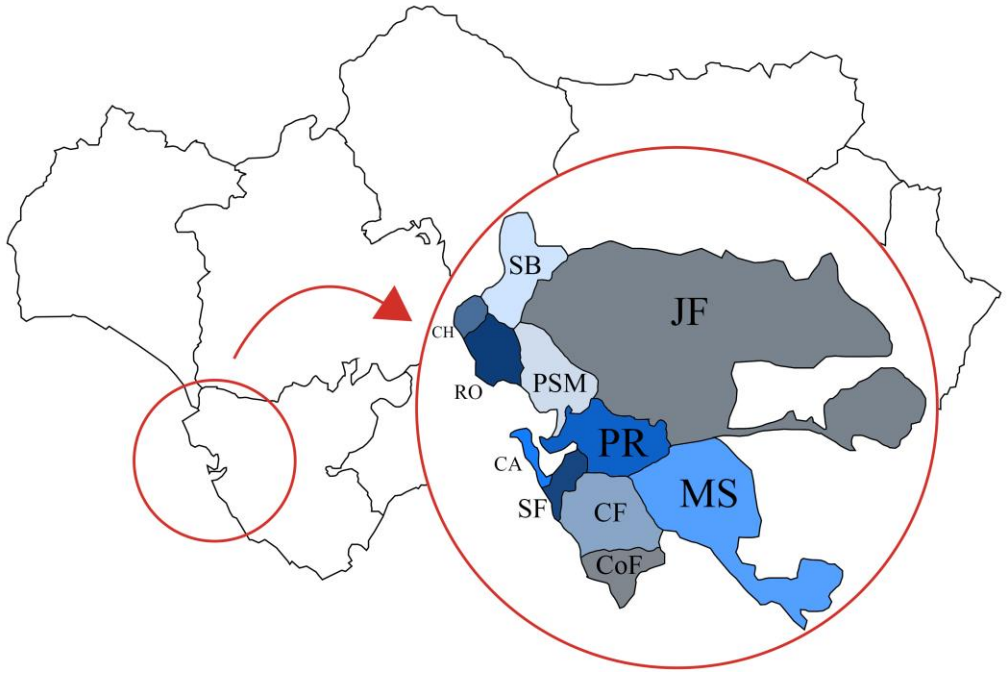
Rota (RO)
Conil de la Frontera (CoF)
Arcos de la Frontera (AF)
Chipiona(CH)
Sanlúcar de Barrameda (SB)
Medina Sidonia (MS)



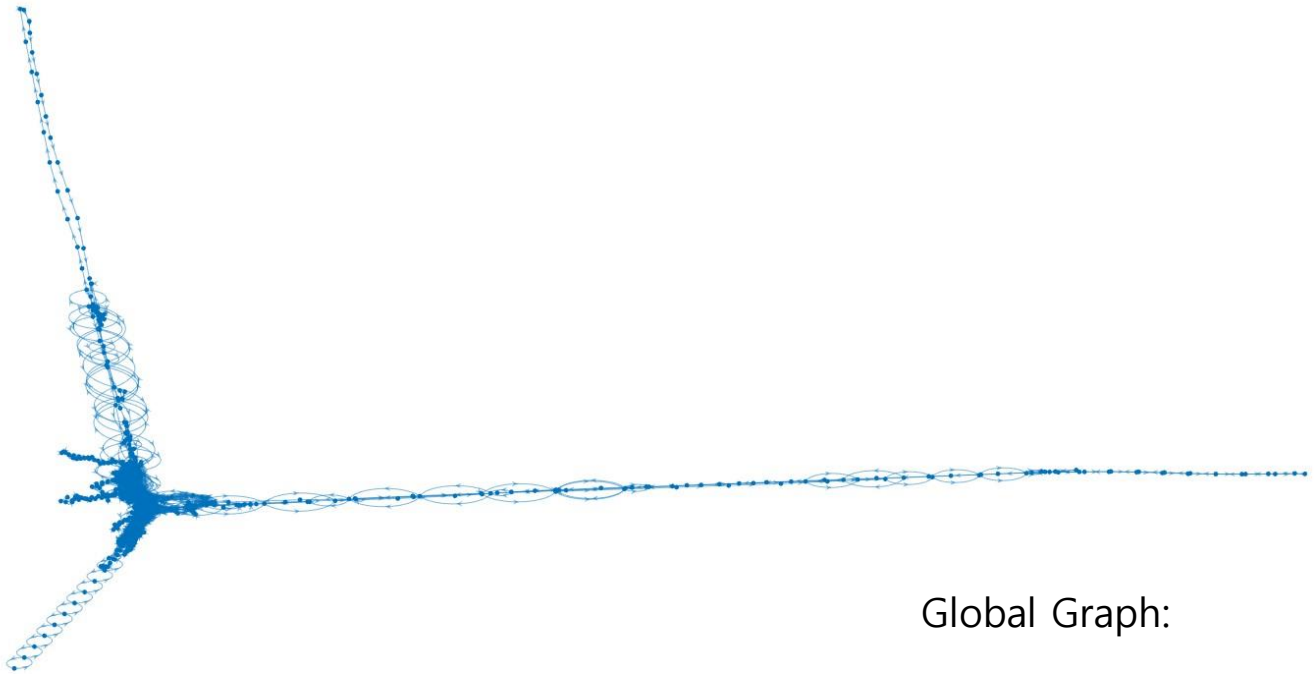
Methodology and Results. *Bay of Cadiz. Public Transport*

In the different localities, there are different types of transport:

	Interurban	Urban	Train	Boat	Tram
Cádiz (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)	✓				
Medina Sidonia (MS)	✓				



Methodology and Results. *Bay of Cadiz Multimodal Transport Network as a Graph*



Global Graph:

$V = 1325$; $E = 3226$

Taking into account the transports and the different stops that make up the network, it can be treated under the graph theory as:

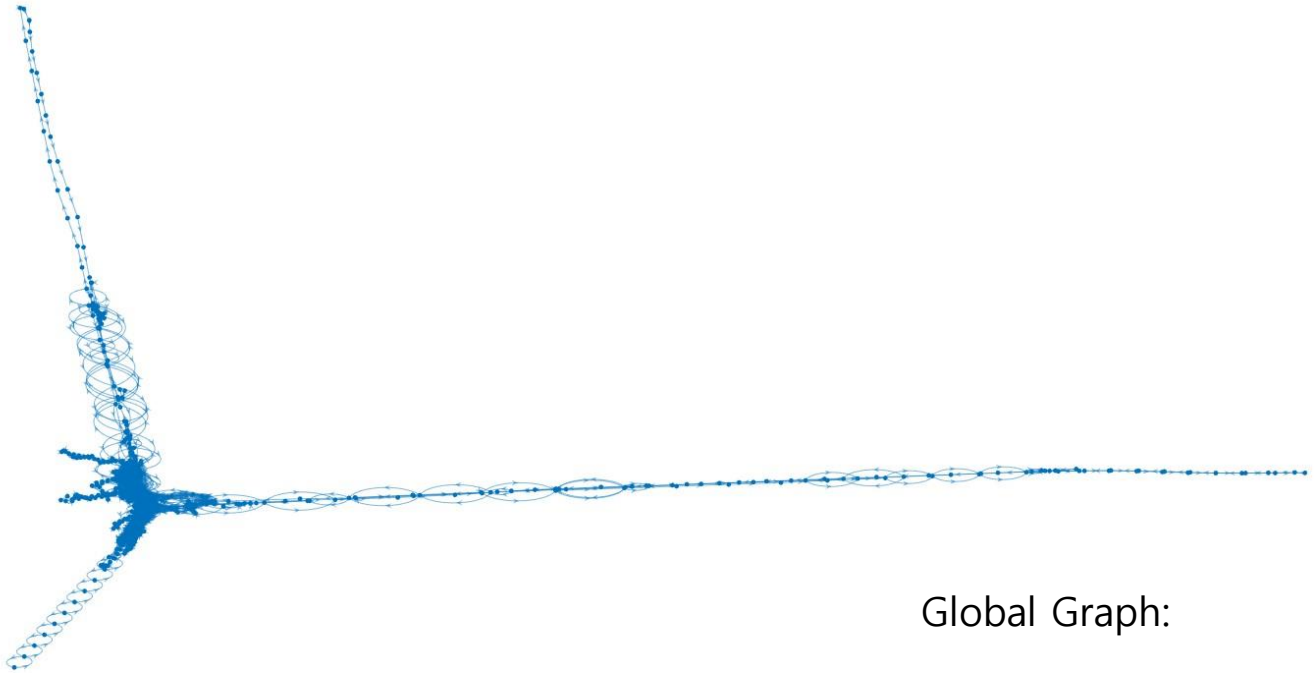
Directed graph

$G = (V, E)$

V = Nodes (Transport stops)

E = Edges (Trips between two stops)

Methodology and Results. *Bay of Cadiz Multimodal Transport Network as a Graph*



Global Graph:

$V = 1325$; $E = 3226$

In order to study the network in depth, a series of statistical parameters and robustness tests will be used to check the status of the network. Along with this, the network is varied by removing one or more networks to see the influence of them.

Methodology and Results. *Statistical Parameters. Division of sub-network groups*

Checking basic statistical data to see how nodes, links and network size (across diameter) vary, as well as the number of average links each node has.

Statistical parameters

- Nodes
- Edges
- Diameter
- Average degree (k)
- Standard desviation of the nodes' degree (σ)

The robustness of the network to failures that may occur in the network is tested, as well as the efficiency of the graph.

Robustness parameters

- Cluster coefficient (G_c)
- Average efficiency ($E\left[\frac{1}{H}\right]$)
- Normalised robustness indicator (r^T)

Methodology and Results. *Statistical Parameters. Division of sub-network groups*

Global				
Group A				
Without				
Train (W/T)	Boat (W/B)	Tram (W/Tr)	Boat + Train (W/B+T)	Train + Tram (W/T+Tr)
	Boat + Tram (W/B+Tr)		Boat + Tram + Train (W/B+Tr+T)	

Group B	
Without Interurban (W/I)	Only Interurban (O/I)

Group C	
Without Urban	Deleting each Urban individually

Starting from the overall network, it is divided into a total of three groups of subnetworks:

- *Group A* corresponds to the elimination of interurban transport networks except intercity bus.
- *Group B* corresponds to the study of the influence of the interurban bus network.
- *Group C* corresponds to the elimination of the urban bus networks in each locality.

Methodology and Results. *Results of Group A*

	Global	W/T	W/B	W/Tr
Nodes	1325	1323	1324	1310
Edges	3226	3202	3222	3186
Diameter	73	73	73	73
$\bar{k}$	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
$\bar{k}$	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

Group A				
Without				
Train (W/T)	Boat (W/B)	Tram (W/Tr)	Boat + Train (W/B+T)	Train + Tram (W/T+Tr)
	Boat + Tram (W/B+Tr)		Boat + Tram + Train (W/B+Tr+T)	

- There are not remarkable variations in any of the parameters studied.
- In terms of the number of nodes and edges, the maximum variation is found when not considering the combination of the three means of transport (W/T+B+Tr).

Methodology and Results. *Results of Group B*

	Group B	
	Without Interurban (W/I)	Only Interurban (O/I)

	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

- 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. Some localities are disconnected from the rest of the graph.
- Regarding robustness parameters from interurban network, they present a remarkable increase in their values, indicating a higher robustness.
- If O/I is observed, the diameter is decreased, but it has high robustness values, thus having alternative routes for the different nodes.

Methodology and Results. *Results of Group C*

Group C	
Without Urban	Deleting each Urban individually

	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

- The values obtained by removing a single urban network are similar to those of the overall network.
- In Jerez de la Frontera, as it is the largest urban network of those studied, the effect of eliminating it is more significant in comparison with the rest.
- 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*, being smaller and therefore having smaller maximum distances between nodes.

Conclusions

- A graphical analysis of graph theory has been carried out on the public transport network of the Bay of Cadiz.
- A statistical and graph theory analysis of the network structure is carried out.
- Urban and interurban bus networks as the core of the overall network.
- 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.

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