NETWORK ANALYSIS FOR MOBILITY AND TRANSPORTATION

Mobility engineering

Strategic Resource Allocation During Strikes: the Venice Navigation System Case

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1. Introduction

Venice is a unique city in the world, characterized by a historical city centre free of vehicular traffic and entirely based on a network of canals. In this context, the mobility of residents and tourists relies almost exclusively on the public water transport system, managed by ACTV (Azienda del Consorzio Trasporti Veneziano). The navigation service transports about 95 million passengers per year, highlighting the crucial importance of this infrastructure for the daily life and economy of the city. The ACTV navigation network includes 16 lines and approximately 150 floating piers, connecting the historic centre to the lagoon islands such as Murano, Burano and Lido.

This research aims to analyse the operational dynamics of the ACTV water transportation network in Venice, focusing on key aspects of its structure and efficiency. The study will address two primary research questions: first, identifying the most used nodes and connections within the network through an in-depth analysis of the current network; second, exploring strategies to reallocate available resources during strikes in order to minimize service disruption. By addressing these questions, the research seeks to provide insights into improving the resilience and effectiveness of the city's unique water-based public transport infrastructure.

It is also essential to consider the various stakeholders involved in the ACTV network, as their interests and needs directly influence the overall functioning of the system. First, it’s important to meet the needs of mobility users: Venice is first of all the capital of Veneto Region and, with a population of 250 000 inhabitants, is also the administrative and economic centre, attracting commuters from the mainland. Moreover, Venice is known all over the world for its beauty, with millions of tourists visiting the city every year. With these numbers, it’s clear that a smart management of strikes is fundamental to reduce disruptions both to commuters and tourists. Another key player is ACTV itself: as the unique operator responsible for the entire navigation network, the company plays a strategic role in providing continuity of service. This involves the need to develop and implement effective operational strategies to manage strikes while minimising disruption. An equally important position is played by the Municipality of Venice and the Metropolitan City, which have a strong institutional and political interest in maintaining public order, containing the negative effects on daily mobility and protecting the international image of Venice as a functional and hospitable city.

2. Current network and demand analysis

Venice navigation system is composed by a total of 16 daytime lines, 1 nighttime line and some seasonal lines. In the analysis it has been decided to consider a random working day during the wintertime, therefore only 16 lines will be considered.
The network has 150 piers, each composed of many docks, identified by a letter. The network has been simplified from a transportation perspective, reducing the number of piers to 65. These will be the nodes of the network.

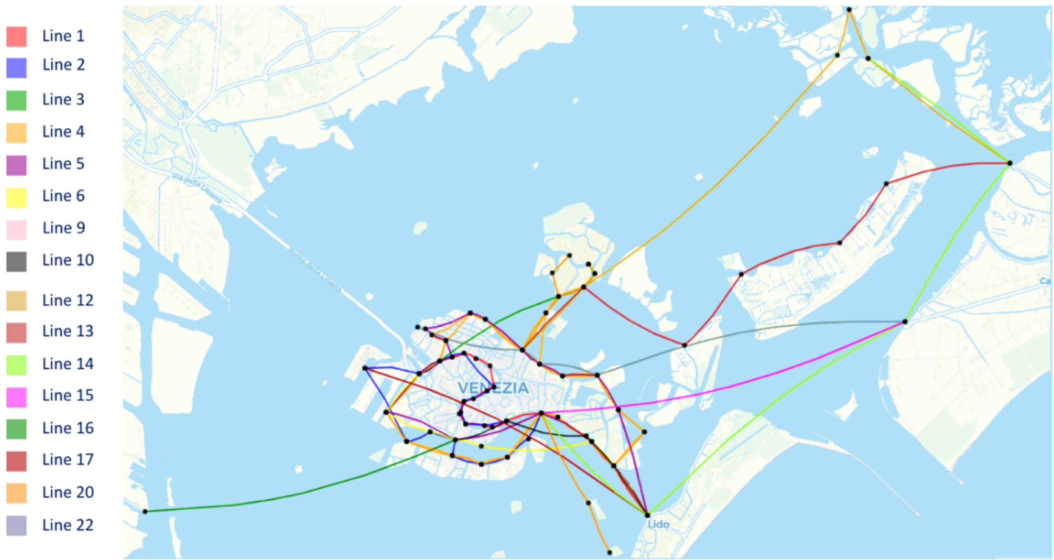

***Figure 2.1** - The Navigation Network of Venice*

Currently, the ACTV's fleet includes four types of boat [1]:

Boat	Capacity [seat/boat]
Vaporetti (Water buses)	210
Motobattelli (Long-distance motorboats)	330
Motoscafi (Motorboats)	220
Motonavi (Motor vessels)	1200

Table 2.1 *- Types of boat in ACTV's fleet*

OD Matrix Construction Method

The estimation of the origin-destination (OD) matrix for the ACTV network is based on the following data [2] and assumptions:

- Available data:
  - For each pier of the ACTV network, the total number of passengers is available, expressed as the sum of boarding and alighting at that stop. However, a distinction between the two flows is not provided.
  - For passengers boarding at Piazzale Roma and Ferrovia, the percentage distribution of their destinations is known.
  - The entire topology of the ACTV network is known, including the association between lines and piers and information on which lines are bidirectional or unidirectional.
- Assumptions:
  - Considering that any differentiation between boarding and alighting passengers is present, flows are assumed to be symmetric: the number of passengers travelling from pier *i* to pier *j* is equal to those travelling in the opposite direction. This brings to a symmetric OD matrix.
  - As a result of flow symmetry, the total number of boarding passengers is equal to the total number of alightings across the network.

These conditions provide a consistent basis for estimating a realistic OD matrix.

To estimate the values of the Origin-Destination (OD) matrix between the network's piers, a quadratic regularization optimization algorithm has been used:

- The sum of departures from each pier (rows) and the sum of arrivals to each pier (columns) must satisfy the given total number of passengers
- Cells corresponding to OD pairs without a direct connection in the network were set to zero, in this way, only solutions without transfers are considered. This is in accordance with the data provided, which do not reflect the entire journey but a single leg of the route
- A penalty is introduced to stay close to an expected average in order to avoid extreme or unrealistic values.

The algorithm has been implemented in Python using *scipy.optimize.minimize* with the *L-BFGS-B* method.

3. Network Analysis

This chapter analyses the ACTV network at three levels: macro (overall structure), micro (individual node performance), and meso (intermediate level structure). The main results and observations are highlighted throughout the analysis.

3.1 Macro Scale Analysis

Macro-scale analysis provides a high-level overview of the structure and performance of a transportation network. It can be easily summarized using the 5 magic numbers, as shown in Table 3.1.

Magic Number	Value
Size of the Network	65
Density	0.0325
Number of components	1
Diameter	18 steps
Transitivity coeficient	0.1395

Table 3.1 *- 5 magic numbers*

The macro analysis provides an overview of the ACTV network, which in our aggregated representation includes 65 stops. The very low density (0.0325) is coherent with the dispersed and insular nature of the Venetian lagoon, where connections cannot be uniformly distributed. The fact that there is only one connected component indicates that the network is fully accessible, a positive result for urban accessibility. The high diameter (18 passages) reflects the distance between extreme areas of the lagoon, while the relatively low transitivity coefficient (0.1395) indicates a low tendency of the nodes to form 'triangles', which is typical of geographic-type networks such as the lagoon.

3.2 Micro Scale Analysis

Micro-scale analysis focuses on the detailed operational aspects of a transportation network, examining the individual nodes.

Degree Centrality

In our case study, degree centrality measures the number of connections for each stop in the ACTV network. Since the lines operate in both directions, in-degree and out-degree are equivalent. An analysis of the boxplots shows that most of the piers have between 2 and 4 connections, but there are also strongly connected nodes, as shown in the boxplot. The node with the highest total degree (18) is San Zaccaria, located near San Marco's Square, confirming its central role in the lagoon transport network.

Figure 3.1 *- Degree Centrality Map*

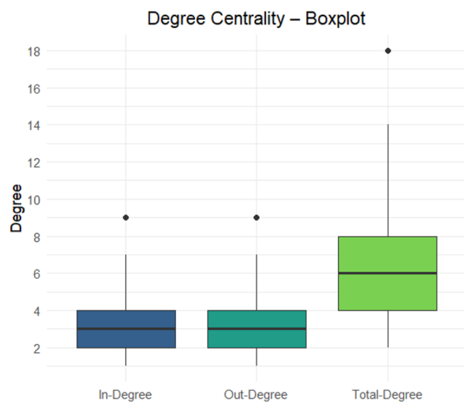

Figure 3.2 *- Degree Centrality Boxplot*

Strength Centrality

Strength centrality measures the intensity of connections for each stop, taking into account the weight of each link. In this analysis, weights are expressed as the number of available seats per day, obtained by multiplying the ferry capacity by the daily frequency of service on each connection.

The all-strength centrality (sum of in-strength and out-strength) reflects the total inbound and outbound traffic at each pier in terms of seats/day. The graph shows that most piers have values between 75,000 and 125,000 seats/day, indicating a medium level of service supply. Only a small number of piers exceed 275,000 seats/day, which are the nodes from which there are the highest number of departures in terms of capacity.

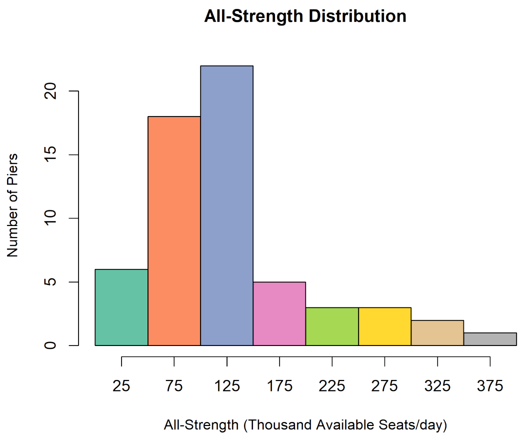

Figure 3.3 *- All Strength Histogram*

This analysis helps to identify the piers of the navigation network that, play a crucial role in terms of service capacity and ability to absorb transport demand.
However, it is important to note that the interpretation and relevance of strength centrality depends on the perspective of the stakeholder:

- For ACTV, strength as available seats [seats/day] is particularly significant. It allows the operator to assess the efficiency of the offer by comparing it with the observed demand. Stops with high capacity but low utilization may suggest opportunities for optimization, e.g. using smaller waterbuses or adjusting frequencies to improve load factor.
- For mobility users or spatial planners (e.g. in the context of a basin plan), a more relevant measure may be the out-strength based on the number of connections, which reflects the number of daily departures from each stop. This indicator provides a measure of the actual connectivity and travel opportunities offered to passengers, regardless of the size of the waterbuses.

For example, stops such as Ferrovia, Piazzale Roma and San Zaccaria present the highest out-strength values, confirming their importance in the lagoon transport system both in terms of service intensity and network connectivity.

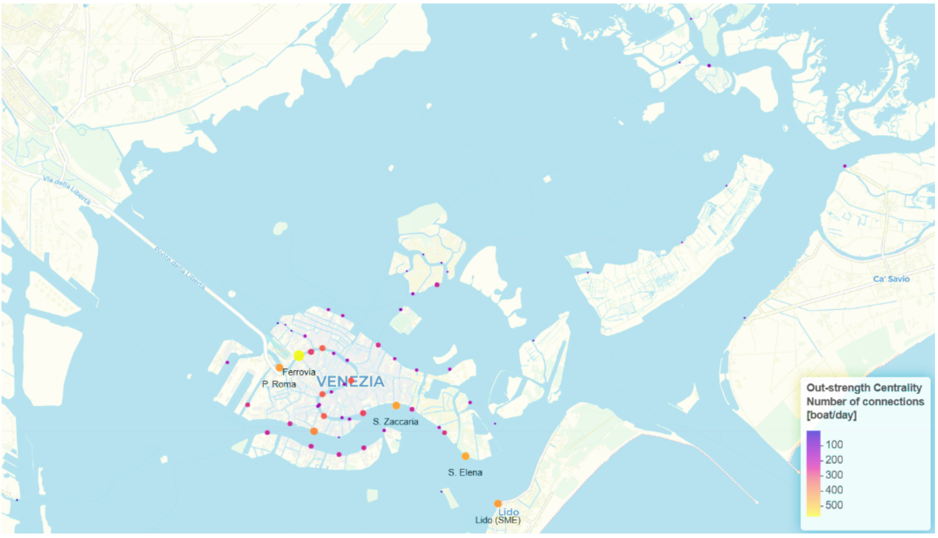

Figure 3.4 *- Out-strength Centrality Map*

Betweenness and Closeness

Closeness centrality was estimated using travel times between the different stops, rather than simple topological distances. This approach makes it possible to identify the stops most easily accessible from the rest of the network in terms of actual time. The San Zaccaria and Ferrovia stops show high values of both closeness and betweenness centrality. This indicates that they are not only well connected with lots of nodes but also play an important role as transit points on minimum routes between other stops.

Figure 3.5 *- Betweenness Centrality*

3.3 Meso Scale Analysis

K-Coreness and S-Core

K-coreness is an indicator of centrality that measures how deeply a node is embedded in a cohesive core of the network. The higher the value, the more the node belongs to a densely connected sub-graph. In metropolitan networks, high K-coreness values are typically concentrated in the city centre. On the contrary, the ACTV network shows a more diffuse distribution of coreness values, mainly due to the geographic structure of the Venetian lagoon and the multidirectional nature of water transport, which does not follow a radial or linear pattern, but connects multiple islands and landings according to articulated logics. The map shows that stops such as Ferrovia, Piazzale Roma, Zattere and San Zaccaria reach the highest K-coreness values, underlining their strategic role in connecting the historic centre with the mainland and with various island destinations. It is interesting to note that these stops are located along the perimeter of Venice's historic centre, forming a sort of ring configuration that reflects the functional structure of the lagoon transport system, in which the most cohesive connections are developed along the margins of the city rather than in its centre. The S-core, on the other hand, extends the concept of coreness to weighted networks, and in this analysis, it is calculated based on travel time between stops, rather than on capacity or frequency. More precisely, the S-core considers the strength of connections in terms of time efficiency: nodes with high values are those that are well connected to many other stops via short travel times, indicating a high level of operational accessibility. This indicator is excellent for capturing the temporal coherence of the network. Stops with a high S-core are not necessarily the most central from a structural point of view, but they allow for rapid and robust movement through the system. These stops are important in the context of service interruption or disruption as, if the stop were to be removed, it would significantly increase the average journey time and significantly reduce the overall time effectiveness of the network.

***Figure 3.6** - K-Coreness Map*

***Figure 3.7** - S-Core Map*

4. Resource allocation strategies during Strikes

This chapter analyses the alignment between passenger demand and transportation supply in the ACTV network, using OD data and GTFS-based simulations to evaluate regular operating conditions and strike scenarios. The effects of various strategies, including frequency reductions and complete line cancellations, on network performance, connectivity, and operational robustness are examined, offering insights on how to adjust supply to balance service continuity and resource constraints.

4.1 Demand vs Supply Analysis

To analyse the relationship between passenger demand and transport supply under regular operating conditions, the origin-destination matrix presented in Chapter 1 was used, supplemented with GTFS data [3] and processed in the PTV Visum software. The entire process was developed through several steps:

- Piers aggregation: all the piers belonging to the same stop were merged into a single spatial entity, consistent with the structure of the GTFS dataset, to ensure uniformity between the real network and the model.
- OD matrix integration: the matrix was loaded into the model as a basis for representing the distribution of demand among the various stops.
- Timetable-based assignment: a simulation of passenger flows was carried out based on the scheduled service times, obtaining an estimate of the loads on each route and on each line.
- Calculating load factor: each line's daily load factor was first estimated, from the number of passengers carried related to the available capacity, determined according to the size of vessel used and frequency of service frequency.
- Identification the highest demand for each line: using a thematic map highlighting the busiest segments of the network, which are also the most vulnerable to any cuts in frequency or full services suspensions.

This mapping of supply and demand provides a framework for assessing the impact of strike-related frequency reductions and line closures, described in the following paragraphs.

Figure 4.1 - Passengers Volume Flow of the Network

4.2 Frequency Reduction During Strikes

To simulate partial service reductions during strike scenarios, four distinct strategies were tested to determine how different allocation criteria affect the resilience of the ACTV network. Each strategy defined a priority ranking for lines to guide the proportional reduction of daily trips. All reductions were applied in two scenarios: a 20% and a 40% system-wide reduction in frequency.

The strategies adopted were the following:

- **CCS – Combined Centrality Score:**

  Based on topological network properties, CCS was defined as a weighted combination of betweenness, degree, and the complement of strength.
  All indicators were normalized in the [0,1] range, and the score for each line was computed as the average of the stops of each line.
    - Lines with high betweenness are central to the flow of the network and should be preserved.
    - Lines with high degree serve well-connected nodes and are structurally important.
    - Lines with high strength have many available trips and may tolerate some reduction, which is why the term (1 – strength) is used.

$$CCS = \alpha \cdot Betweenness + \beta \cdot Degree + \gamma \cdot (1 - Strength) \tag{4.1}$$

$$\overline{CSS} = \frac{1}{m}\sum_{i \in V} \alpha \cdot Betweennes_i + \beta \cdot Degree_i + \gamma \cdot (1 - Strength_i) \tag{4.2}$$

- **CI – Criticality Index**

  This indicator focuses on the demand-side characteristics:
    - A high load factor indicates that the line is heavily used and should be maintained.
    - A high closeness value suggests that many destinations are nearby and quickly reachable; in such cases, some reduction may be acceptable. For this reason, the complement (1 − closeness) is used in the formulation.

$$CI = \alpha \cdot (1 - Closeness) + \beta \cdot Load\ Factor \tag{4.3}$$

$$\overline{CI} = \frac{1}{m}\sum_{i \in V} \alpha \cdot (1 - Closeness_i) + \beta \cdot Load\ Factor_i \tag{4.4}$$

- **CF – Commuter Flow Centrality**

  This metric reflects actual passenger movement through each stop, including boarding, alighting, and pass-through volumes. The cumulative flow values are aggregated at the line level to identify services with the highest functional usage. This strategy is entirely demand-driven [4].

$$C_f(i) = \sum_{j \in V} h_{ij} + \sum_{j \in V} h_{ji} + \sum_{j \in V;\, j,k \neq i;\, j \neq k} h_{jk}(i) \tag{4.5}$$

- **Uniform Reduction**

  This scenario assumes a flat reduction rate applied equally to all lines, regardless of their structural or operational characteristics. It serves as a neutral baseline for comparison.

For all strategies, higher indicator values indicate greater relevance, and lines with higher scores were proportionally protected from frequency reductions. Specifically, the number of trips to be cut was determined based on the total reduction target (e.g. 20% or 40% of the overall daily supply) and then allocated across lines proportionally to their inverse priority score. This means that lines with lower priority received a larger share of the cuts, while those with higher indicator values retained most of their scheduled trips. To ensure the continuity of service across the entire network, a minimum threshold of two trips per line was always maintained, regardless of the reduction strategy adopted. This constraint was imposed to avoid the complete closure of any line, preserving at least a basic level of connectivity even in strike conditions.

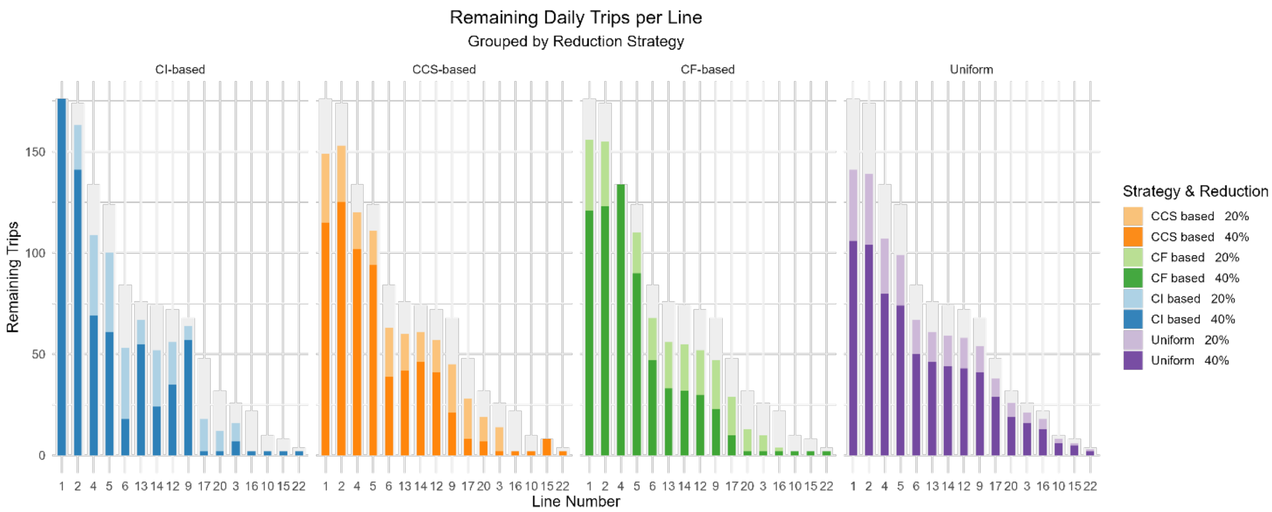

Figure 4.2 *- Number of remaining trips per line after Frequency reduction per different strategy*

To assess the robustness and internal behaviour of the reduction strategies, a sensitivity analysis was conducted on the weighting coefficients used in the CCS and CI formulations. In the baseline scenario, each component was assigned an equal weight — one third of the total — reflecting a balanced contribution from all the indicators involved.

However, to better understand the individual impact of each variable, the strategies were also tested under extreme configurations, where only one component at a time was given full weight (i.e., weight = 1), while the others were set to zero. This procedure made it possible to isolate the effect of each centrality measure or performance metric on the resulting trip allocation and cut distribution.

The results of the sensitivity analysis showed that:

- Across all coefficient configurations, the overall pattern of reductions remained broadly consistent. Most lines experienced similar proportional cuts, regardless of the specific weighting scheme applied.
- However, some lines displayed greater variability, with reduction values more sensitive to the chosen indicator. This variability suggests that relying on a single metric may risk over- or under-penalizing certain services.

Figure 4.3 *- Sensitivity of the CCS per weight combination*

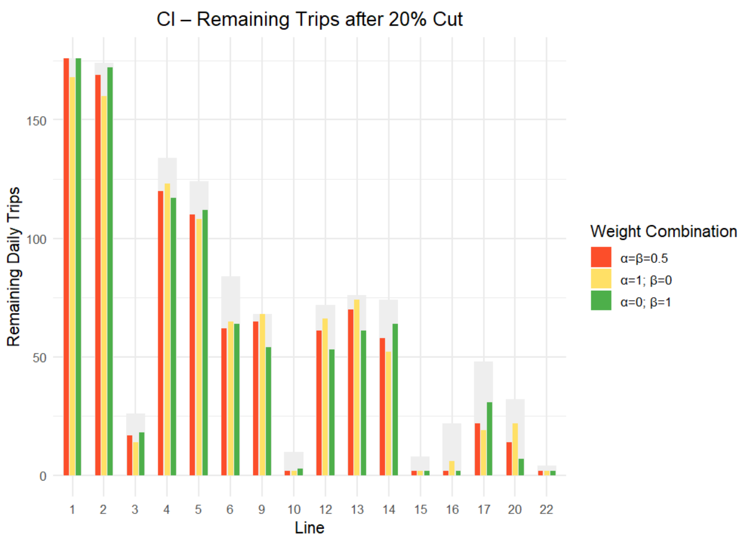

Figure 4.4 *– Sensitivity of the CI per weight combination*

4.3 Line Closures During Strikes

As an alternative to frequency reductions, a scenario involving the complete suspension of selected lines was tested. The aim was to identify a subset of closures that could achieve meaningful resource savings without compromising network connectivity.
A maximum of 234 daily trips (about 35% of the total) could be removed while keeping the network operational. Two criteria guided line removal:

- Connectivity preservation: the network must remain fully connected, avoiding the isolation of islands, a risk that is unique to lagoon transport systems.
- Structural integrity: closures should minimize negative effects on centrality metrics such as betweenness, closeness, degree, and diameter.
  This constraint is especially critical in Venice: unlike in land-based networks, the removal of a single line can completely disconnect an island, leaving it inaccessible.

Lines were evaluated individually. Those that:

- Disconnected the network were excluded,
- Had high structural impact were deprioritized,
- Showed minimal effects were considered for closure.

For each line considered for removal, the following network metrics were recalculated on the remaining graph: Average degree, betweenness, closeness and Network diameter. These indicators allowed a quantitative assessment of the structural impact of each closure. Lines causing significant deterioration in one or more metrics were classified as high-impact and excluded from the final configuration.

Line	Betweenness	Closeness	Degree	Diameter	Effect
3	4.0%	-0.7%	-4.1%	17	High effect
9	-0.1%	0.2%	-0.8%	17	Low effect
10	5.1%	-1.1%	-2.5%	17	High effect
14	0.0%	3.3%	-3.3%	17	Moderate effect
15	0.5%	-0.1%	-0.8%	18	Low effect
17	0.1%	0.0%	-0.8%	17	Low effect

Table 4.1 *- Evaluation of Line Closures on Network Indicators*

4.4 Approach comparison

An additional operational consideration emerged during the analysis: while line closures remove an entire service and thus simplify operational planning, frequency reductions can lead to scheduling and docking issues.

A concrete example is the Burano–Torcello route, where boats run at regular intervals during the day. Reducing the number of runs without completely eliminating the line may lead to irregular waiting times (headways) or overlapping arrivals. In these cases, the docks may not have the physical capacity to accommodate several vessels at the same time.

This highlights a broader problem: the analysis performed focuses on network and demand indicators but does not take into account the logistical and management constraints that may arise during a strike.

From this perspective, line closures may offer a more manageable solution by avoiding partial operations. However, this approach risks significantly reducing accessibility, particularly in a lagoon context where few alternative routes exist. Choosing between the two strategies thus requires balancing operational feasibility with mobility needs.

5. Conclusions

The use of separate indicators to analyse the network has shown that a proportional reduction of trips on all lines is not the most efficient strategy. In contrast, the integration of the three approaches adopted allows a more complete and articulated view of the system, considering both the structure of the network, the actual service capacity and the distribution of the demand.
In particular, the approach based on the targeted closure of lines made it possible to identify manageable and operational solutions capable of mitigating the impact of strikes on the overall performance of the network, while reducing potential management criticalities.

The analysis has some limitations to be considered.
Firstly, the uncertainty related to the actual management of strikes, due to the lack of detailed operational information on how ACTV deals with these situations, could affect the validity of the simulations.
Then, passenger demand has been estimated based on some simplifying assumptions, while maintaining a high level of realism. However, the absence of timely and systematic data introduces a margin of error in the representation of actual user behaviour.

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[1] ACTV S.p.A., «Azienda, Le flotte,» 2024. [Online].

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