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KEYWORDS

Accessibility | Public transport | Health services | Network analysis

JEL CODE

R41, I18, C63

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Analyzing the Accessibility of Rome's Health Services via Public Transportation: A Complex Network Approach

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January 7, 2025

Abstract

This study, using as a case study the health services in Rome, combines network analysis with different measures of spatial accessibility to comprehensively assess disparities in accessibility. The methodology adopted shows how integration of different data sources is fundamental to have a reliable picture of the complexities of mobility systems and accessibility.

Keywords: Accessibility; Public transport; Health services; Network analysis
JEL codes: R41; I18; C63

1. Introduction

Access to healthcare facilities is a crucial component of urban public health planning. A highly accessible healthcare system increases life expectancy, improving overall quality of life. According to several studies, human development strongly depends on equal access to essential services like healthcare [1]. In this perspective, the literature identifies the availability and accessibility of these services as fundamental to positively influencing economic growth, social equity, and the well-being of communities and territories [2].

When assessing healthcare accessibility, it is key to consider which part of the population most needs these services. The elderly and people with disabilities are among the social groups with the highest demand for healthcare and, at the same time, often lack access to private cars. Therefore, the design of an accessible transit-oriented system is crucial for equitable and effective healthcare provision. Inequities in access to healthcare significantly influence economic development and the quality of life of individuals [3].

The importance of having robust transit access to healthcare under any operating condition raises the need for resilient networks to and from healthcare facilities, which provide a reliable system even when external shocks hit. A resilient transit network is able to cope with disruptions, providing redundancy to users and rapidly recovering to pre-disruption performance levels.

At an empirical level, network analysis emerges as one of the most relevant methodologies for analyzing and studying accessibility to essential services. In general, network analysis allows modeling networks as graphs composed of nodes (e.g., bus stops or health centers) and edges (e.g., distances between services), allowing for an accurate analysis of the structural properties of the network, efficient identification of critical nodes, and an accurate assessment of the resilience of the system.

Although many studies examine access to healthcare facilities or public transportation networks separately, only some have investigated how they interact with each other [4][5][6], and many questions remain to be better addressed. For example, the transit-based accessibility assessment of areas with limited overall connections and resilience to external shocks remains underexplored.

This study aims to fill this gap by offering an integrated analysis that combines network analysis with spatial accessibility measures to comprehensively assess disparities in access to healthcare services through public transportation and its resilience to external disruptions.

This work presents a study specifically focused on measuring the accessibility of healthcare facilities through Rome's bus network under disruptive scenarios. The main objectives are: 1) to assess territorial sustainability by analyzing the equitable distribution and accessibility of healthcare facilities through public transportation in the 155 municipal sections of Rome; 2) to identify disparities in access to healthcare, focusing on areas with limited or difficult connections to hospitals through public transportation; 3) to assess the resilience of the transit network to external shocks that compromise the integrity of the network; 4) to inform policy decisions by providing evidence-based recommendations to improve public transportation infrastructure and enhance accessibility to healthcare services.

The study employs quantitative methods and advanced computational tools to analyze the bus network's structural properties, assess access to healthcare services, and evaluate the network's resilience and reliability. Network topology analysis uses centrality and connectivity metrics to identify critical nodes and paths, while spatial accessibility measurements integrate geographic and transportation data to assess travel distance and time to healthcare facilities. Resilience and reliability assessments explore the network's response to disruptions and the implications for healthcare accessibility. Using real-world data from Rome, the results highlight key transportation hubs, classify stations within the complex network, and measure spatial accessibility to healthcare services, offering valuable insights into how public transportation impacts equity and providing recommendations to improve the Urban Public Transport System's (UPTS) resilience and reliability. By addressing these goals, the research provides critical guidance for policymakers to improve Rome's public transportation infrastructure, promoting a more sustainable and equitable healthcare system for all residents.

The work is structured as follows. Section 2 presents the literature review, analyzing previous studies on spatial inequalities, citizenship services, place-based policies, and network analysis in spatial studies. Section 3 describes the methodology, data, analytical tools, and methodological techniques used. Section 4 presents the results of the analysis, including network mapping and accessibility assessment. Section 5 discusses the policy implications for urban planning and transport policies. Section 6 summarizes the contributions of the study, suggests directions for future research, and concludes.

2. Outline of literature background

As discussed in the introductory section, strengthening access to essential services is crucial to promoting social equity, as these services influence the quality of life of citizens and their ability to fully participate in society [7].

Generally, urban accessibility to healthcare facilities has been assessed with GIS methodologies supported by travel time estimates, such as the floating catchment area methods [4][8][9][10], robust space–time accessibility assessments [11], and network analysis [12][13][5][14][15]. The latter mainly uses estimated or self-reported travel times on a network (e.g., road or transit network) to calculate the number of points of interest (in this case, healthcare centers) reachable within a time threshold. Such an “objective” accessibility measure needs to take into account several factors when dealing with specific user classes, like elderly people. Guida et al. [4] found that using only the transit network and assuming no car access for elderly people, peripheral areas of Milan had significantly lower accessibility to healthcare facilities for this user group compared to central areas, noting spatial patterns of accessibility. Such an example is useful to understand that accessibility measures should be tailored to the user class studied (e.g., elderly people without car access), including relevant modes of transport for the group studied.

Taking a step further into network analysis, complex network analysis can be employed in combination with more traditional elements of network analysis and travel time estimations.

A complex network is made up of a set of nodes that reveal the constituents of the network and a set of links representing the physical connections between each pair of nodes [16]. Several properties and indexes of the network can be used to describe its composition [17][18][19].

Complex network frameworks and tools are also useful for analyzing the network's integrity when external disruptions occur, detailing the resilience properties of the network.

Resilience is generally defined in the literature as the ability of transport networks to resist shocks, maintain functionality, and recover as quickly as possible to a full level of service [20]. In the static part of resilience, at the moment of disruption, robustness defines the amount of performance that the network can maintain. Redundancy, on the other hand, refers to the set of infrastructural and modal alternatives that the system provides to users [21]. Vulnerability, which is the opposite of robustness, indicates the amount of performance loss at the moment of disruption, serving as an index of susceptibility to loss [22].

Important investigations on resilience and vulnerability in transportation studies include, for example, the works of Mattsson and Jenelius [23], Reggiani et al. [24], and Gu et al. [22]. Mattsson and Jenelius [23] indicate that vulnerability analysis can be system-based or topology-based, with the former more focused on the performance of the network (in terms of flows, speeds, etc.), while the latter focuses on the topological features of the networks, i.e., nodes, edges, and their connections. Wang et al. [25] assessed the vulnerability of urban road networks using a system-based approach. Using data from taxi trips, the analysis showed that nodes with high centrality significantly influence network vulnerability and that travel time is directly related to flow loss. Similar studies have been conducted on rail transit networks (e.g., Yang et al. [26]) and urban bus networks (see Sun et al. [27]).

Focusing on transit, an efficient and effective Urban Public Transport System (UPTS) ensures that the transfer of passengers runs smoothly and that stations are properly distributed to businesses and residents [28][29]. Starting from this framework, Baggag et al. [30] used the public transport network (PTN) model to represent nodes, which are the stations and stops of a public transport system, and edges, which connect subsequent stations along a route. The critical nodes identified through the single-modal analysis cannot accurately represent the actual state of public transport. Therefore, it is useful to explore methods to identify pivotal nodes from a topological perspective within multimodal public transport networks [31]. Murray-Tuite [32] introduces the concept of quantitative metrics to measure the resilience of the transport system, analyzing the four dimensions of transport resilience and exploring the influence of traffic assignment on resilience.

This paper builds upon the surveyed literature by combining complex network resilience analysis with classical network-based accessibility assessment to create a healthcare facilities transit-network-based accessibility index tested under several disruption scenarios. The analysis, like that of Guida et al. [4], focuses on transit to address the car-less elderly user group, who are among those most in need of healthcare services. This is a novel contribution to healthcare accessibility analysis that incorporates resilience, an aspect still underexplored.

3. Data and descriptive statistics

The present research used a variety of open sources data and formats to analyze public transportation networks and healthcare accessibility in Rome's urban areas.

- Public Transport Data: The General Transit Feed Specification (GTFS) format was used as the primary data source for public transportation information, including the public bus transportation system across Rome. The GTFS format, developed by R. Kujala and colleagues [21], provided detailed transit schedules, station locations, and route information, which was critical for building transportation networks.
- Healthcare Services Data: Data on healthcare facilities in Rome, with a specific focus on cardiology services, was collected and preprocessed to exclude healthcare facilities outside the city. This ensured that the analysis was limited to healthcare services accessible within the urban area.
- Geographical Data: Geographic coordinates of the urban zones in Rome were sourced from the Rome Municipality website. The coordinates were further processed using the Geocoder Python library to ensure accurate spatial mapping and integration into Geographic Information Systems (GIS) for network analysis [22].

3.1 Software tools and libraries

The analysis was conducted using a variety of open-source Python libraries, including:

- NetworkX for network construction and centrality metric calculations.
- Geocoder for geographic coordinate conversion to find each of 155 urban area locations.
- Folium and Streamlit for interactive mapping and data visualization.
- OpenStreetMap (OSM) and GTFS data for building the transport network background as an actual interactive map.

3.2 Outputs

As we shall discuss, this research work generated the following datasets as outputs:

- The transportation networks of Rome with stations and routes marked.
- Accessibility rankings of healthcare facilities in Rome, illustrating the proximity of public transport nodes to each health service.
- Critical transportation hubs and vulnerable nodes identified through the centrality and resilience analysis.

4. Methodology

This research focuses on evaluating the accessibility of healthcare services through buses as a public transportation network in Rome. The methodology involves the application of complex network theory to analyze transport infrastructure, node importance, and system resilience concerning the accessibility of health services in Rome. The study was carried out in several stages, outlined below.

4.1 Complex network construction

A key part of the research was the construction of a complex network to model the accessibility of health services in Rome, using the bus as a public transportation system.

- Nodes and Links Representation: In the complex network, transportation stations (bus stops) were modeled as nodes, while the routes connecting them (bus lines) were represented as links. This network-based model allowed for analyzing the structural properties of the urban public transportation systems in Rome.
- Multi-layer Network Construction: The research involved the creation of single-mode networks that accounted for the bus network.

4.2 Network topology and centrality analysis

To understand the importance of each station within the transport network and to evaluate the accessibility of healthcare services, several centrality metrics were applied.

Topology-based metrics emphasize the internal dynamics of transportation networks. These metrics, also known as “centrality metrics”, are constructed using the essential graph-based elements of the transportation network, such as nodes and edges for traffic flow [23]. Centrality, a key concept in network theory, measures the importance of a network’s nodes. Public transport stations with high node degrees are more likely to serve as transport hubs, due to their high level of connectivity with other stations. They are likely to receive a higher volume of passenger and vehicle flows and serve as key nodes for the consolidation and distribution of residents.

Researchers have developed numerous centrality metrics to determine the significance of nodes and to characterize the properties of urban public transportation in complex networks [24, 25]. Understanding the significance of transportation network components and protecting them accordingly can help increase the network's resilience and reduce its susceptibility to vulnerabilities. This study employs four centrality metrics to analyze resilience: Degree Centrality (DC), Betweenness Centrality (BC), Closeness Centrality (CC), and Eigenvector Centrality (EC) [26]. A node is considered significant if it keeps the network connected. Centrality measures vary based on the method of measuring the system's coherence, such as the number of shortest paths that pass through a node. Below, we discuss the analytical formulation of each measure, which is considered applicable in transportation systems.

Degree centrality (DC) measures the number of links that a node has and by measuring this feature, it identifies the network hubs [27]. Mathematically, the degree centrality of specific node v is expressed as

$$DC(v) = \frac{Degree(v)}{N-1}$$

where $Degree(v)$ denotes the number of connections of node v, and N is the total number of nodes in the network [28, 29]. Nodes with a high degree centrality in a transportation system are referred to as transportation hubs [30]. A stop with a high degree centrality serves as a significant point for transfers between different modes of transport systems or various lines. While nodes with numerous connections are important, degree centrality does not consider traffic loads, which is a limitation of this metric. Therefore, additional metrics are needed to address this limitation [31].

Betweenness Centrality (BC) measures the importance of a node by evaluating the frequency at which it lies on the shortest path between pairs of other nodes [27]. The formula is given by:

$$BC(v) = \sum_{s \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where σ_{st} represents the number of shortest paths from node s to node t, and $\sigma_{st}(v)$ is the number of paths passing through node v. Nodes with high betwenness centrality are frequently critical because they serve as checkpoints, usually the only nodes connecting to different parts of the network, for example, a bridge on the major route [32]. The application of betweenness centrality has been studied in numerous studies; for instance, to examine the geopolitical aspects of a city, the rank of betweenness centrality was measured [33].

Closeness Centrality (CC) measures how close a node is to all other nodes in a network [27]. The closeness centrality of node i is formulated as follows:

$$CC_i = \frac{N-1}{\sum_{i,j \in V} d_{ij}}$$

where N is the number of nodes, d_{ij} is the length of the shortest path between nodes i and j, and V is the set of all nodes in the network. Based on closeness centrality, the nodes that have a closer distance than the rest are more important. From a transportation point of view, nodes with high centrality are important because they can reach plenty of other nodes, so they are proper to assume as hub points. Wang studied the level of centrality of each node, and the nodes were bus stations in Guangzhou [34].

Eigenvector Centrality (EC) covers the limitation of degree centrality, where the node is important based on the number of connections it has with the other nodes. Degree centrality does not account for the significance of the connected nodes and assumes all nodes are equal [35]. However, eigenvector centrality considers a node important if it connects to other important nodes. Thus, a node's eigenvector centrality is examined by the importance of its neighbors [36]. The formula for Eigenvector Centrality of node v is

$$EC(v) = \frac{1}{\gamma} \sum_{u \in N(v)} EC(u)$$

where γ is a constant, and $N(v)$ is the set of neighbors of node v. Eigenvector centrality can be used to determine nodes that strongly impact the network's overall connectivity and structure. From a transportation perspective, high-ranked eigenvector centrality nodes are transportation hubs that have the most significant influence on the network's overall cohesion. Each measure focuses on a unique aspect of system properties and has potential applications in transportation networks with differing theoretical assumptions. However, nodes with high flow rates can be identified using metrics like degree centrality. Assessments show that some measures are strongly correlated with each other, despite their differing theoretical assumptions, leading to redundant data. For instance, in physical networks, there is a strong correlation between eigenvector centrality and closeness centrality [15]. All the mentioned metrics were proposed for further investigation.

4.3 Spatial accessibility to healthcare services

We obtained the geographical coordinates for 155 urban zones in Rome from Wikipedia. These coordinates were initially in degrees, minutes, and seconds (DMS) format. Using the open-source Python library Geocoder, we converted them into decimal degrees (DD) format, which is commonly used in geographic information systems (GIS). This conversion was crucial for seamless integration into the Folium library, a Python package widely used for interactive mapping and visualization tasks. To process the coordinates, we wrote a script to parse the DMS format and convert it to DD automatically. This script utilized the Geocoder library to ensure accuracy and consistency in the conversion process. Once converted, these coordinates were stored in a structured format suitable for GIS applications.

Accessibility to healthcare services, particularly in Rome, was measured using a transit network-based approach:

- Shortest Path Calculation: The Python library NetworkX was used to calculate the shortest path between urban zones and healthcare facilities, taking into account both the number of stations close to each healthcare service and the route distance (in terms of time and transfers) required to reach those facilities.
- Distance Estimation: The Haversine formula was applied to estimate the geographical distance between urban zones and healthcare facilities, considering the Earth's curvature for accurate results. OpenStreetMap (OSM) data was used to map the transport network and facilitate the distance calculations.
- Service Accessibility Ranking: Healthcare facilities were ranked based on their accessibility from different urban zones. This analysis was conducted by considering the proximity of bus, subway, and train stations to each facility and calculating the transit time required to reach them.

4.4 Resilience and robustness assessment

The research also examined the resilience and vulnerability of the transport systems in Rome. This was essential to evaluate how these networks respond to disruptions, such as infrastructure failures or natural disasters.

- Resilience Triangle Analysis: The resilience triangle concept was applied to measure the time it takes for the transport system to recover from shocks. By simulating disruptions (such as the closure of key transportation hubs), the study assessed how quickly the network could return to normal operations.
- Vulnerability Analysis: The vulnerability of each city's transport system was evaluated by simulating the removal of critical nodes (stations) and observing the resulting changes in network performance. This analysis helped identify which nodes, if compromised, would significantly reduce the system's overall functionality.

5. Findings and discussion

This section presents the analytical and graphical results. This research project focused on evaluating healthcare accessibility across Rome's 155 municipal divisions using public transport networks. By analyzing various metrics and employing advanced computational tools, we identified several key findings related to disparities in healthcare accessibility, the distribution of health services, and the impact of public transport infrastructure. Below, we outline the main findings of this research.

Using a georeferenced approach, the routes of the bus transportation network in Rome have been mapped. Figure 5.1 illustrates the network related to our case study; notably, we constructed an unweighted graph to represent these networks.

To analyze transportation infrastructure using insights from bus centrality metrics, the following parameters have been measured for each node (Bus stop) in the network: Degree Centrality, Closeness Centrality, Betweenness Centrality, and Eigenvector Centrality. Incorporating these centrality metrics into the analysis allows for a nuanced understanding of the transportation network. By visualizing the spatial distribution of top-ranked nodes, as shown in Figure 5.2, urban planners can prioritize key nodes for infrastructure investments, maintenance, and strategic planning to strengthen the network's long-term resilience against potential environmental hazards.

5.1 Disparities in healthcare accessibility

One of the primary outcomes of this research was the identification of areas within Rome that face limited or challenging access to hospitals via public transport. Through a detailed spatial analysis, we uncovered significant disparities in healthcare accessibility across different urban zones. Areas located farther from central transport hubs were found to have reduced access to hospitals, highlighting a need for targeted interventions to improve public transport routes in underserved regions.

Figure 0.1. Illustration of the bus network routes of Rome urban areas

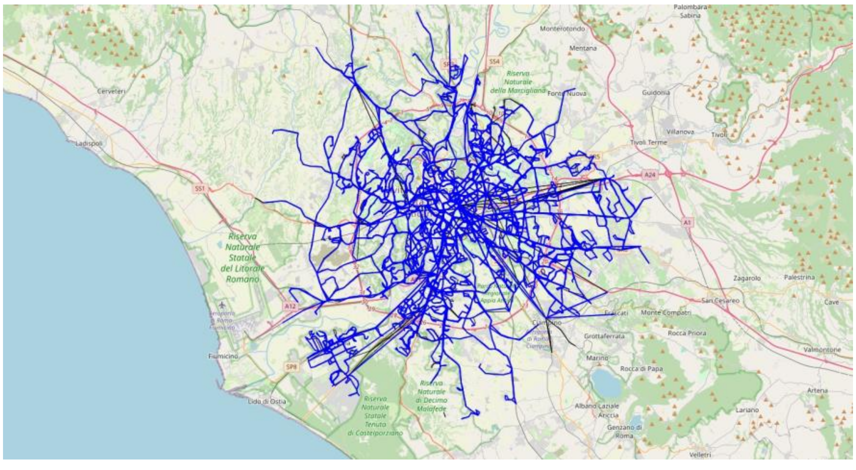
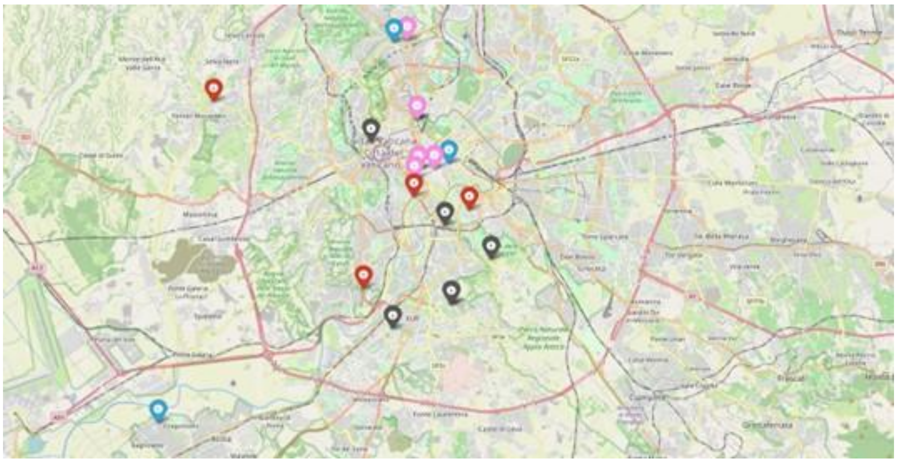


Figure 0.2. Mapping the high-centrality-ranked stops in Rome. The red pop-ups indicate the results obtained from the combined network betweenness centrality analysis, while the pink pop-ups symbolize the nodes with high Eigenvector centrality. The gray pop-ups represent nodes with high closeness centrality, and the blue pop-ups show the results from degree centrality; for each centrality metric, the top 5 have been mapped, but some results have been correlated, so we don't have 5 pop-ups for each color



The results suggest that underserved areas could benefit from expansions in bus routes, increased service frequency, and improved connections between transportation modes. This would enhance accessibility to essential healthcare services and support territorial sustainability, ensuring equitable healthcare access for all residents. Table 5.1 below represents the top 5 node bus stops in decreasing order.

Table 0.1. Top 5 node bus stops

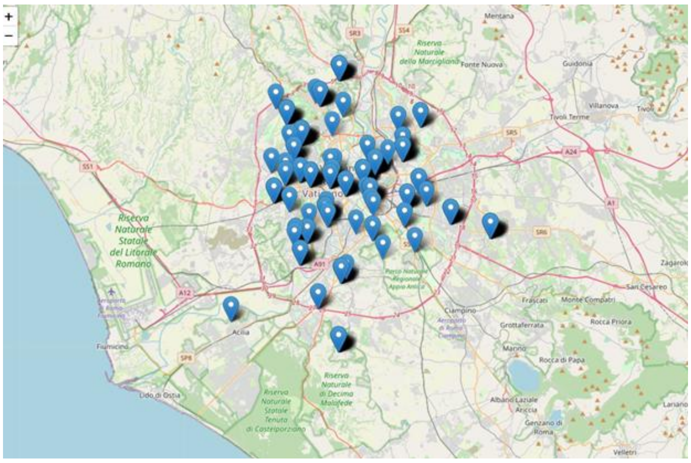
id	Name	latitude	longitude
72	COLLATINA/BIROLLI	1.905024	12.599527
1659	PIAZZALE DELLA FARNESINA	41.937368	12.459218
73	PESENTI/TIBURTINA	41.932137	12.599443
5563	REDATTORI/GRAFICI	41.764272	12.469673
3158	DI MATTEI/S. MARIA PIETA' (H)	41.941596	12.419322

5.2 Visualization of hospital and transport accessibility

We developed an interactive map to visualize the distribution of hospitals and public transport stations, enabling a comprehensive analysis of healthcare accessibility across Rome. We evaluated the spatial distance from the center of each urban zone to the nearest healthcare service using open-source data on health services in Rome and UPTS (Urban Public Transport System). Figure 5.3 shows the location of these health services.

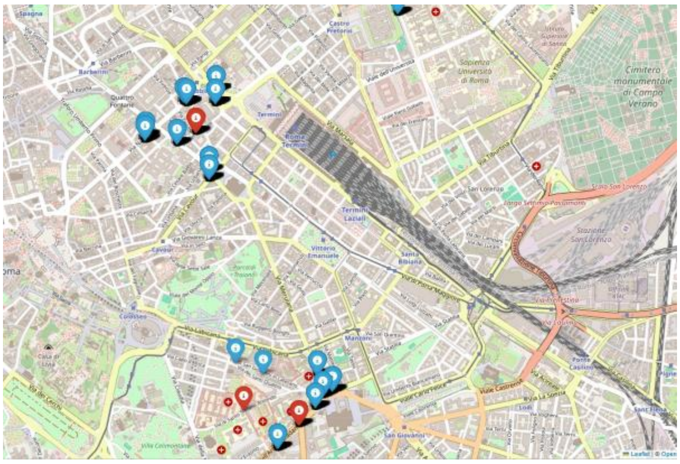
Firstly, we assessed the accessibility of UPTS stops in Rome by measuring the distance from each urban zone to the nearest health service and the number of bus stops within 300 meters of the healthcare main entrance door. This analysis helps determine the ease of access to healthcare services for residents of different zones. In the second part, we analyzed the number of UPTS bus stops that need to be passed to reach the nearest healthcare services. This provides insights into the convenience and efficiency of the public transport routes for health services. The third part of the workflow involved generating interactive maps of the real UPTS network, allowing users to visualize and explore the spatial distribution and accessibility of health services in Rome. This comprehensive approach helps us understand the overall accessibility and identify areas that may require improvements in public transport connectivity to healthcare services.

Figure 0.3. Health services located in Rome



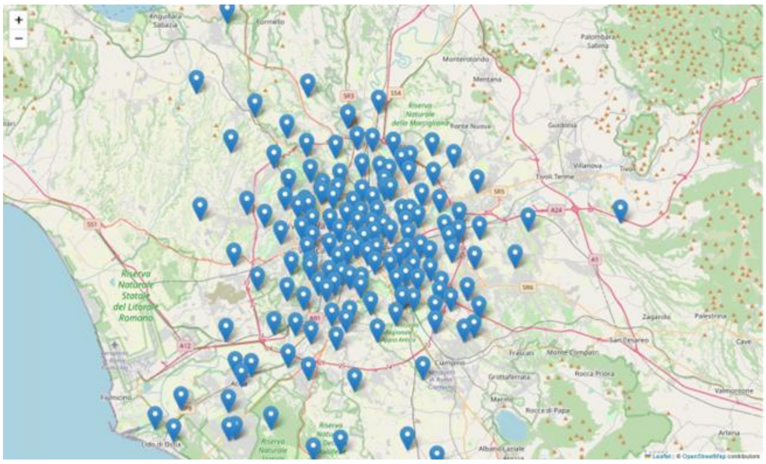
We uploaded the health dataset and overlaid the hospital locations onto the same interactive map. This approach allows users to quickly compare the distribution of hospitals with the locations of the urban zones, enhancing the analysis of accessibility to healthcare services across Rome. Figure 5.4 below illustrates this mapping, with red markers highlighting the hospitals and blue markers denoting the urban zones. To assess the accessibility of bus stops, we identified and mapped the bus stops located within 300 meters of each cardiology health service. In the resulting visualization, red pop-ups represent the healthcare services, while blue pop-ups indicate the urban zones.

Figure 0.4. Bus stops which are within 300 meters of cardiology centers, Red pop-ups are cardiology services and Blue pop-ups show the closest bus stops.



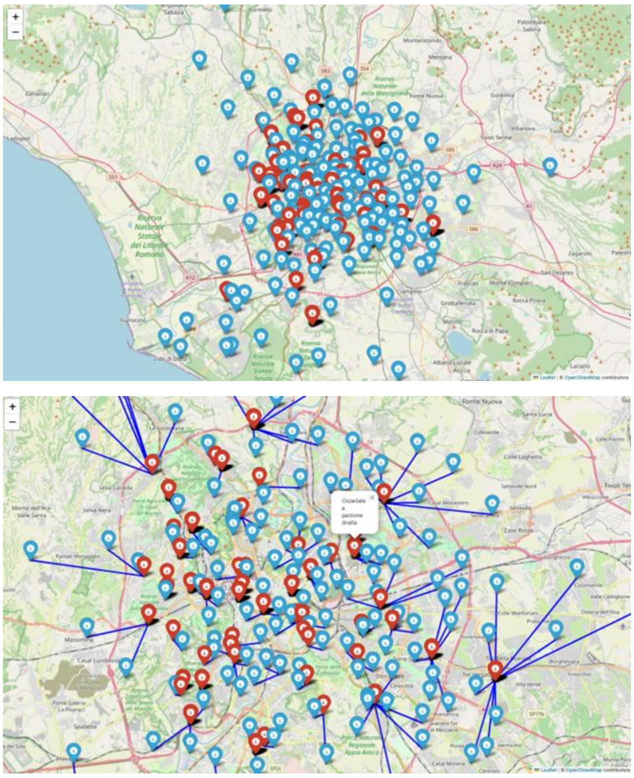
Then, using the Municipality Geoportal of Rome, we find the geometry of all 155 areas located in Rome; utilizing Folium, we created an interactive map displaying Rome's urban zones. Each zone was marked with a blue pop-up for easy identification. The interactive map allows users to explore and analyze the spatial distribution of these zones, providing valuable insights into the geographic layout of Rome. Additionally, the map includes features such as zooming and panning, enhancing the user's ability to interact with and examine specific areas in detail. Figure 5.5 below visualizes the 155 zones in Rome with blue pop-ups. Fig 5.5 maps the location of these 155 areas.

Figure 0.5. 155 Urban areas located in Rome



A framework to study the distance between all Rome zones and healthcare services has been developed. After obtaining the coordinates for 155 urban zones in Rome and converting them into decimal-degree format, the next step involved developing a Python script to calculate the nearest hospital for each zone. This process required implementing the Haversine formula, which calculates the shortest distance between two points on the Earth's surface based on their latitude and longitude. The Haversine formula considers the Earth's curvature, providing accurate distance measurements. By applying this formula to each urban zone's coordinates and the coordinates of nearby hospitals, the script identified the closest hospital and computed the distance. Consequently, we obtained a dataset that included the nearest bus stop station for each healthcare service. Figure 5.6 (left) shows the overview of the location of both areas and health services. We filtered bus data out of UPTS data frames and then combined datasets of UPTS and dataset of healthcare services in Rome, Figure 5.6 (right) illustrates the interactive maps that have been generated to reveal the distance between the center of each zone and its closest healthcare service; the red pop-ups stand for health service and the blue pop-ups show all 155 areas located in Rome.

Figure 0.6. Distribution of Rome areas and health services



To deepen the study on public transit access to healthcare services, we identify the nearest hospital to each rail station in Rome, as illustrated in Figure 5.7.

Figure 0.7. Nearest healthcare service from Rome's railway stations

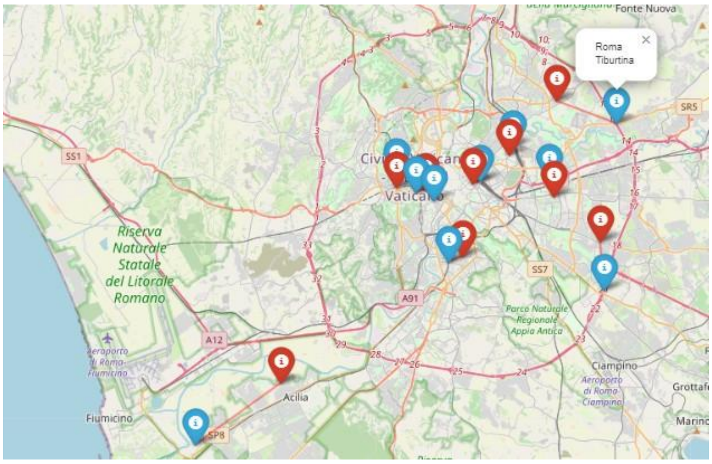
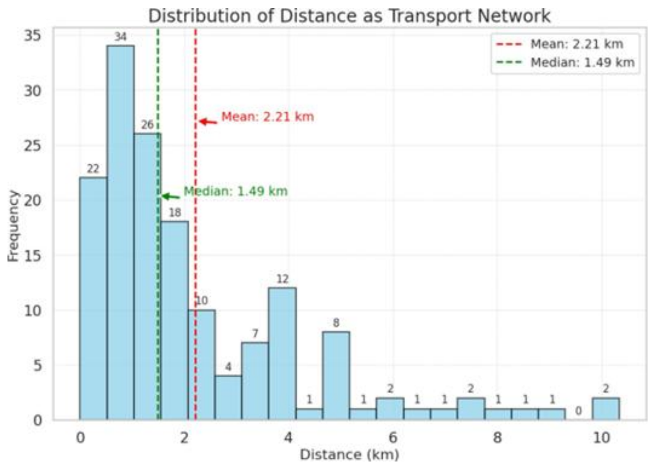


Figure 5.8 summarizes the accessibility of health services from each of the 155 zones, providing an overview of the distance distribution throughout the city. According to the graph analysis, the points closest to hospitals are 11C Garbatella, 19C Ottavia, 17A Prati, 18B Val Cannuta, and 6A Torpignattara, with respective distances of 0.02 km, 0.09 km, 0.12 km, 0.16 km, and 0.18 km. In contrast, the points with the largest network-based distances from health facilities are 20O Martignano, 8H San Vittorino, 20N Cesano, 19H Santa Maria di Galeria, and 12N Santa Palomba, with distances measuring 19 km, 14 km, 13 km, 9.8 km, 8.9 km, and 8.6 km, respectively.

Figure 0.8. Distribution of network-based distances from each zone to the nearest healthcare facility



5.3 Visualization of hospital and transport accessibility

As the next phase of the project, we aimed to enhance the presentation of visualizations by utilizing the open-source library Stream-lit. This allowed us to create both local and public links for the applications. We set up a public GitHub repository containing all the input data and notebooks. This setup enables users to share the application link without requiring them to run all the code themselves. The repository includes detailed documentation, data preprocessing scripts, and interactive visualization tools, making the analysis accessible and easily reproducible. The public link to the application: https://rometerminals.streamlit.app/. Technically, we employed Stream-lit to build a user-friendly interface for data visualization and interaction. The application dynamically loads and processes data, allowing users to interactively explore various aspects of the dataset. The GitHub repository features structured directories for data, scripts, and notebooks, ensuring organized and straightforward navigation. Additionally, the repository leverages GitHub Pages for documentation, providing detailed instructions and context for each project component.

5.4 Resilience analysis

The study of resilience in public transportation networks, such as the bus stop and route system in Rome, is essential for assessing the network's ability to withstand disruptions, such as the removal of certain nodes (bus stops). Resilience in this context refers to the network's capacity to maintain overall functionality and connectivity even when parts of it are compromised or removed. In this analysis, we examined the worst-case scenario and we removed the top five nodes (from the point of view of centrality) in bus network (Nodes: 28, 72, 1659, 29, 304).
LCC Size (Largest Connected Component): This metric represents the number of nodes in the largest sub-network where each node is reachable from every other node. A decrease in LCC size indicates a loss of connectivity. Initially, the LCC size was 7474, and after removing nodes, it reduced slightly to 7471. This minimal change in size indicates that the network retained most of its connectivity, showcasing strong resilience. Despite the node removals, the majority of the network remained interconnected, which is a positive indicator for the system's robustness. LCC Density: Network density is defined as the ratio of the number of edges (connections) to the number of possible edges between nodes. The initial density was 0.000345, which is typical for sparse networks like public transportation systems. After node removal, the density slightly increased to 0.0003451. This suggests that even with fewer nodes, the remaining bus stops became slightly more interconnected, potentially as a result of fewer redundant or isolated nodes. The minimal change here further indicates resilience, as the network structure remained intact.
Global Efficiency: This metric measures how efficiently information (or passengers, in this case) can travel across the network. Higher efficiency indicates shorter paths between nodes. The initial global efficiency was 0.0377, and it dropped slightly to 0.03766 after node removal,

indicating a minor loss in the ability to provide efficient travel routes. The small change in this metric demonstrates that the network remained relatively efficient, but some routes might require longer connections due to node removals.

Average Clustering Coefficient: This measures the degree to which nodes in the network tend to cluster together, forming interconnected groups. A low clustering coefficient, such as the initial 0.0259, suggests that bus stops are primarily organized in linear routes rather than clusters. After node removal, the clustering coefficient increased marginally to 0.02594, indicating a negligible effect on the network's overall structure. The small increase suggests that while some stops were removed, the overall tendency toward forming small clusters of stops remained unaffected.

Average Path Length: This metric represents the average number of steps needed to travel between two randomly selected nodes in the network. Initially, the average path length was 34.86, indicating that traveling between bus stops typically required many connections or transfers. After node removal, the path length increased slightly to 34.88, suggesting that while the overall structure remained intact, the removal of some stops slightly increased the number of connections required to travel between certain points. This slight increase could lead to marginally longer travel times for passengers, which is a factor to consider in resilience studies. Table 5.2 summarizes the resilience metric results.

Table 0.2. Summary of the resilience metrics pre and post node removal

Metric	Description	Initial Value	Post-Removal Value	Interpretation
LCC Size	Number of nodes in the largest connected component.	7474	7471	Minimal change indicates strong resilience; most of the network remained interconnected.
LCC Density	Ratio of edges to possible edges between nodes.	0.000345	0.0003451	Slight increase suggests remaining bus stops became more interconnected despite fewer nodes, indicating resilience in network structure
Global Efficiency	Measures the efficiency of information travel across the network.	0.0377	0.0375	Minor drop indicates slightly longer paths between nodes; overall efficiency remains relatively intact.
Average Clustering Coefficient	Degree to which nodes cluster together.	0.0259	0.02594	Negligible increase indicates that network structure remains primarily linear, with small clusters forming as well.
Average Path Length	Average number of steps needed to travel between randomly selected nodes.	34.86	34.88	Slight increase in connections required suggests marginally longer travel times for passengers, but overall structure remains robust.

From a resilience perspective, the minimal changes in the key metrics after node removal demonstrate that the bus network in Rome is resilient. The slight reductions in global efficiency and the increase in path length indicate that while some localized effects (such as longer routes for certain areas) might occur, the overall structure of the network remains robust and functional. The resilience of this network is especially evident in the small change in LCC size, which suggests that most of the network remains connected even when parts of it are removed.

This analysis is critical for transportation planners aiming to enhance the system's resilience. Even though the network can withstand certain disruptions, further improvements could focus on optimizing routes or adding redundancy to minimize the impact of node failures, thus ensuring both connectivity and efficiency are maintained during unforeseen events. The next phase of the project is to expand the resilience study into accessibility of health services from each urban point through the public bus routes, and the node removal scenario will measure the effectiveness of each critical node in health services accessibility in Rome.

5.5 Interactive application for public use

As the next phase of the project, we aimed to enhance the presentation of visualizations by utilizing the open-source library Stream-lit. This allowed us to create both local and public links for the applications. We set up a public GitHub repository containing all the input data and notebooks. This setup enables users to share the application link without requiring them to run all the code themselves. The repository includes detailed documentation, data preprocessing scripts, and interactive visualization tools, making the analysis accessible and easily reproducible. The public link to the application: https://rometerminals.streamlit.app/. Technically, we employed Stream-lit to build a user-friendly interface for data visualization and interaction. The application dynamically loads and processes data, allowing users to interactively explore various aspects of the dataset. The GitHub repository features structured directories for data, scripts, and notebooks, ensuring organized and straightforward navigation. Additionally, the repository leverages GitHub Pages for documentation, providing detailed instructions and context for each project component. The info which can be found in the interactive map has been summarized in Table 5.3.

Table 0.3. Closest hospital to each train station

Train station	Nearest Hospital	Distance (km)
Roma Termini	CASA DI CURA MARCO POLO	0.441
Roma Nomentana	CASA DI CURA POLICLINICO ITALIA	0.518
Roma San Pietro	OSPEDALE PEDIATRICO BAMBINO GESU*	0.597
Roma Valle Aurelia	OSPEDALE SAN CARLO DI NANCY	0.754
Roma Trastevere	OSPEDALE PEDIATRICO BAMBINO GESU	0.831
Roma Ostiense	CONCORDIA HOSPITAL	0.905
Roma Prenestina	C.D.C. FABIA MATER	1.015
Roma Tuscolana	POLICLINICO CASILINO	2.972
Roma Tiburtina	VILLA TIBERIA HOSPITAL	3.368

Roma Ostia Antica	CASA DI CURA MERRY HOUSE/O.GERIATRICO RO	6.464

6. Policy implications and recommendations

Analyzing Rome's health services spatial patterns reveals that different locations with varying levels of accessibility experience different reaching network-based distances to the closest health service.

Some outer areas fail in terms of vertical equity and average accessibility and have a more than 10 km network-based distance to reach the closest health service using a Bus as a public transportation, which means reaching them is particularly problematic during emergencies. On the other hand, central urban zones are found to be the most accessible through public bus transportation routes. This easy accessibility is due to the high density of health services located in central areas and the availability of alternative routes to get a health service [37]. Enhancing infrastructure leads to physical redundancy, closes infrastructure gaps, and provides various alternatives to create and strengthen more resilient networks. Based on the findings of this research, several key recommendations can be made to improve healthcare accessibility in Rome:

- Expand public transport routes and frequency: Especially in underserved areas, increasing the number of available transport routes and reducing waiting times could significantly enhance access to healthcare facilities.
- Improve connections between transport and healthcare facilities: Establishing direct routes between major transport hubs and hospitals would reduce travel times and improve accessibility for residents.
- Implement fare policies: Reducing travel costs for healthcare-related journeys, particularly for vulnerable populations, could help minimize financial barriers to accessing essential services.

These recommendations, based on data-driven insights, can inform future policy decisions aimed at enhancing the public transport infrastructure in Rome. By improving connectivity and reducing travel costs, the city can foster a more sustainable and equitable healthcare system for all residents.

A key benefit of this research is its potential to contribute to the reduction of health inequities within Rome. By identifying areas with poor healthcare accessibility and providing data-driven solutions, the study offers practical steps toward addressing disparities in healthcare access. Improvements in public transport infrastructure can have a direct impact on health outcomes, especially for vulnerable populations in underserved regions. Enhancing accessibility will not only improve the efficiency of healthcare delivery but also promote a more equitable urban environment.

Policymakers should leverage the data-driven insights provided by this research to inform their decisions. By utilizing network analysis and geographic information system (GIS) tools, decision-makers can:

- Continuously monitor healthcare accessibility and adjust transport policies based on real-time data.
- Use predictive modeling to anticipate future transportation needs in response to demographic or urban changes.

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