Pedaling Through Divides: Spatial, Social, and Climatic Inequalities in Trento's Bike-Sharing System

Camilla Bonomo Diego Conti
Paolo Fabbri Sara Lammouchi
Silvia Bortoluzzi

University of Trento

Computational Social Science Lab

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Abstract

This study examines Trento's bike-sharing system through the lens of Computational Social Science, focusing on its spatial integration with public transport, distributive equity, and climatic resilience. Using geospatial accessibility indices, demographic overlays, and Generalized Additive Models, we address three questions: how stations are distributed relative to transit (RQ1), which neighborhoods and groups are underserved (RQ2), and how mobility responds to weather (RQ3). Results show strong polarization: central hubs concentrate intermodal opportunities while peripheral districts remain excluded, reinforcing socio-spatial divides. Rainfall systematically depresses mobility, while temperature effects are non-linear, with extremes reducing usage. Overall, the findings reveal that Trento's bike-sharing system, despite expansion, reproduces inequalities and remains vulnerable to environmental shocks. By integrating spatial, social, and climatic dimensions, the study contributes to debates on mobility justice and sustainable infrastructure in medium-sized European cities.

Keywords: bike sharing; intermodality; mobility justice; urban sustainability; computational social science

[0]Project repository on GitHub: https://github.com/camillabonomo02/CSS_project

Contents

1 Introduction

Urban mobility has become one of the central challenges of contemporary cities, as societies seek to balance accessibility, sustainability, and equity. Bike-sharing has emerged as a promising innovation, capable of reducing emissions, alleviating congestion and promoting active travel, but its benefits are not automatic (Zhang and Mi, 2018; Kou et al., 2020). They depend on how stations are distributed, how the system integrates with public transport, and how users respond to social and environmental conditions (Borowska-Stefańska et al., 2021). Precisely because of this complexity, bike-sharing represents a paradigmatic case for Computational Social Science (CSS), which integrates heterogeneous data to capture the interdependence of infrastructure, behavior, and context (Lazer et al., 2009; Conte et al., 2012). While prior studies highlight both its environmental potential (Zhang and Mi, 2018; Kou et al., 2020) and its risks of exclusion (Cunha and Silva, 2022; Giuffrida et al., 2023), most research has focused on large metropolitan areas. Medium and small European cities, however, remain underexplored, even though they face distinctive trade-offs between accessibility, equity, and sustainability.

The city of Trento offers a particularly relevant case study: it combines investments in sustainable mobility with strong climatic variability and marked socio-territorial divides. Moreover, Trento has recently been recognized as the most smart medium-sized Italian city in the EY Smart City Index 2025[1], which identifies ecological transition, supported by electric charging stations, cycling lanes, and bike-sharing, as the distinctive strength of cities in this category. This positioning underscores both the city's policy ambitions and the need to critically evaluate how inclusively such innovations are distributed across its territory.

Against this background, our project investigates Trento's bike-sharing system by analyzing its spatial integration with public transport, its implications for territorial justice, and its sensitivity to weather variability. By combining geospatial accessibility analysis, equity-oriented overlays, and statistical models capable of capturing non-linear climatic effects, we aim to contribute at three levels. Empirically, we provide systematic evidence on a medium European city[2] rarely analyzed in the literature. Methodologically, we demonstrate how CSS can integrate spatial, social, and environmental dimensions into a unified analytical framework. Politically, we shed light on how sustainable infrastructures may simultaneously support and undermine goals of equity and resilience, offering insights for the design of more just and robust urban mobility systems.

[1] **EY Smart City Index 2025:** `https://www.ey.com/it_it/newsroom/2025/05/ey-smart-city-index-2025`

[2] According to the Eurostat classification of Cities, which distinguishes between small (50,000–100,000 inhabitants), medium-sized (100,000–250,000), large (250,000–500,000) and very large cities (over 500,000 inhabitants) (Eurostat (2017)), Trento — with 118,911 inhabitants as of 31 December 2024 (`tuttitalia.it/trentino-alto-adige/provincia-autonoma-di-trento/88-comuni/popolazione/`) — falls into the category of medium-sized European cities.

2 Literature Review

Bike-sharing and environmental sustainability

Bike-sharing has often been described as an effective measure for reducing urban transport emissions and improving the sustainability of cities. As DeMaio (2009) observes, bike-sharing has the potential to reduce car use, thereby helping to reduce pollution, congestion and fuel consumption. For this reason, it is one of the urban policies aimed at mitigating the impact of private motorised transport, an environmental approach now also recognised at institutional level by the European Commission (2019) and the European Union (2021), which set the goal of climate neutrality by 2050 and a 55% reduction in emissions by 2030, identifying sustainable mobility, and in particular active transport, as a pillar of city decarbonisation strategies.

In the Italian context, the link between mobility choices and air pollution has also been highlighted by Ceremigna et al. (2004), who show that private transport is the main source of pollution in cities and that innovative low-impact modes, such as bike-sharing, must be considered among the strategic levers for reducing these emissions.

A particularly significant contribution applying Computational Social Science methods comes from the study conducted by Zhang and Mi (2018), who developed a research design aimed at estimating the environmental benefits of bike-sharing in Shanghai, using a dataset consisting of over one million trips collected via GPS by the operator Mobike in a single month. To analyse this data, they used advanced computational methods: algorithms to reconstruct routes from GPS points, fuel consumption and emissions models following the calculation standards developed by the Intergovernmental Panel on Climate Change, and GIS tools to assess the spatial and temporal distribution of impacts. The results show an annual reduction of approximately 25,240 tonnes of CO_2 and 8,358 tonnes of oil consumption, with benefits concentrated in central neighbourhoods during peak hours. This study has several strengths: the use of a massive, high-resolution dataset (precise GPS data for each individual trip rather than aggregate statistics); the ability to directly link mobility data and environmental estimates; and the innovativeness of the empirical approach compared to previous studies, which were mainly based on simulated scenarios or sample data. The limitations, on the other hand, concern the focus on a single operator (Mobike) and a limited time period (September 2016), as well as the absence of socio-demographic variables, which prevents us from understanding which social groups generate these benefits.

Other contributions have strengthened and expanded this perspective. Kou et al. (2020) developed a model (BS-EREM) that takes into account actual travel data and choice of transport mode in eight American cities. Their results confirm savings of up to 5,417 tonnes of CO_2 equivalents per year, an average benefit per trip of between 280 and 590 g CO_2 equivalents avoided. They also find that central stations provide greater total reductions due to high usage, while peripheral stations have a greater impact per individual trip, as they more often replace car use and are used for longer journeys. However, it must be taken into account that bike-sharing not only replaces car journeys, but also a significant proportion of already sustainable journeys, approximately 27.9% of bus journeys, 8.1% of metro transport and 33.9% of walking trips, thereby reducing its net effect on emission reduction (Saltykova et al., 2022).

Bike-sharing is, therefore, a tool with significant potential for reducing urban emissions, but in order to reap its benefits it requires a carefully planned integration with local public transport (also called modal shift), from the location of stations to the management practices adopted. Urban policies should also encourage bike-sharing to replace the use of private cars, in order to maximise the environmental benefits.

Integration with public transport

The environmental benefits of bike-sharing depend largely on the type of journeys that are replaced, but also on its relationship with public transport. The literature highlights the potential of bike-sharing as a first/last mile solution, i.e. connecting the journey between home and public transport, or vice versa, so as to extend the catchment area of railway stations and bus stops. Shaheen et al. (2013, p. 3) state that "bike-sharing can serve as a convenient feeder mode, bridging the gap between origins or destinations and transit stops", highlighting how modal integration can increase the overall competitiveness of sustainable mobility.

A prime example of the potential but also the limitations of modal integration is provided by the Dutch case, where the combination of bicycles and trains has been successful thanks to explicit policies and dedicated investments, such as the upgrading of the bicycle rental system at railway stations, which has improved accessibility and reduced the use of private cars for commuting. In contrast, pilot rental projects for students aimed at promoting integration with buses have had little success, indicating that bikes and buses often compete for similar routes rather than collaborating (Martens, 2007). Similar results also emerge from the study conducted by Kou et al. (2020), which shows that in US cities, a significant proportion of bike-sharing trips overlap with journeys normally covered by local public transport. Although both of these contributions are relevant in highlighting the risks of competition with local public transport, they are not based on computational approaches typical of CSS, but on policy analysis and traditional quantitative models.

In contrast, the study carried out by Pfrommer et al. (2013) is a suitable example. Their research design examines the Barclays Cycle Hire system in London, using a dataset of 1.42 million trips over 97 days, 354 stations and 3,708 bicycles to develop a model for optimising the operation of the service. The aim was to assess how to improve integration with public transport by increasing the reliability of stations, particularly those located near transport hubs. The representation of the system as a time-expanded graph with five-minute time intervals is a first strength: this methodological choice allows the fluctuations in bicycle availability to be captured almost in real time, providing a much more realistic picture than static models. In addition, a greedy heuristic was used to plan the routes of redistribution trucks, an approach that is lightweight enough to handle massive datasets while maintaining good quality results in reduced computational time. Once the routes had been defined, the authors refined their decisions through quadratic programming and the introduction of dynamic incentives for users, calculated using Model Predictive Control (MPC). This approach represents a significant innovation because it is not limited to external management solutions but directly integrates user behaviour, offering discounts or bonuses to guide user choices according to the operational needs of the system. However, to make the optimisation manageable, the authors simplify user reactions in linear terms, thus reducing the model's ability to capture the real complexity of individual decisions.

Finally, the model is validated through Monte Carlo simulations, which allow not only the average results to be evaluated, but also the robustness of the proposed solutions in thousands of possible scenarios. The results show consistency and theoretical robustness, but have not been directly tested with real-time operational data, leaving open the question of practical transferability. It is interesting to note that the results of this study show that, especially at weekends, incentives alone can maintain a service level above 87%, while on weekdays integration with redistribution by trucks is necessary. A further limitation of this research is that it focuses almost exclusively on the operational efficiency of the system, namely its ability to reduce imbalances and improve service levels, while equally crucial aspects such as equity of access or optimal station location are not considered. This critical issue emerges clearly when we compare the study with experiences such as the Swedish one analysed by Henriksson et al. (2022), which demonstrates how municipal bike-sharing can be oriented not only towards efficiency but also towards social inclusion objectives, through affordable prices and stations located in working-class neighbourhoods. Finally, the context analysed is that of London's bike-sharing system: this represents a significant test case, but also limits the generalisability of the results, as the structure of demand and intermodal conditions can vary significantly in other cities.

In other words, the literature shows that bike-sharing can play a dual role in relation to public transport: on one hand, it can be a strategic ally in bridging the first/last mile gap and strengthening the sustainability of the system (Martens, 2007); on the other, it can be an unintended competitor when it replaces buses and underground trains on short journeys (Saltykova et al., 2022). Hence, the ability of urban policies to promote complementarity between bikes and local public transport through fare, infrastructure, and social integration is crucial to maximising the environmental and collective benefits of bike-sharing, laying the groundwork for reflection on the role of the spatial distribution of stations.

Spatial distribution and accessibility

The literature emphasises that the location of stations is a decisive factor both for the efficiency of the service and for its socio-territorial equity. In other words, the benefits and critical issues depend largely on where the systems are implemented and who actually has access to them. Giuffrida et al. (2023) show in their research how access to bike-sharing in Dublin is highly unequal, with central areas well served and peripheral neighbourhoods penalised, raising the issue of spatial justice. The innovative aspect of this research is the combined use of spatial analysis methods and equity indicators. The authors construct an index to assess accessibility to infrastructure that integrates an active accessibility component, specifically opportunities that can be reached from a bike-sharing station. This is measured using a Hansen-type gravitational model, a measure that sums up the available opportunities but gives more weight to those that are close and less to those that are far away, based on distance and travel time. This component is complemented by passive accessibility, i.e. the ease with which residents can reach a station and find an available bike, calculated by adapting the Public Transport Accessibility Level (PTAL) indicator to bike-sharing: in practice, a measure that combines the walking distance to a station within 500 metres with the actual availability of the service during peak hours (Giuffrida et al., 2023, pp. 5–6). The two components are then normalised and combined into a composite index, which provides a more realistic representation of actual accessibility to the service, as it takes into account both physical proximity to stations and the opportunities they provide (Giuffrida et al., 2023, p. 7).

To assess spatial justice, the authors use typical distributional analysis tools, such as the Lorenz curve and the Gini coefficient, which allow them to graphically represent and measure how much access is concentrated in a few areas or distributed more evenly across all neighbourhoods (Giuffrida et al., 2023, p. 8). This operationalization is a methodological strength, as it allows the level of horizontal equity to be quantified using standardized metrics and different urban areas or bike-sharing models to be compared. At the same time, though, the research design has some limitations: the thresholds used (for instance the 500 metres walking distance), the parameters of the impedance function, and the weights assigned to opportunities are assumed ex-ante without sensitivity analysis. Furthermore, the approach is static and does not consider intra-daily or seasonal variations over time.

Finally, the focus is exclusively on horizontal equity, i.e. equity between territorial areas considered equal, without addressing vertical equity, the differences between vulnerable social groups (Giuffrida et al., 2023, p. 10).

It is precisely this lack of attention to the social dimension within the territory that helps explain why the benefits of cycling tend to be concentrated in central and wealthier neighbourhoods, often leaving suburbs and vulnerable groups excluded. Cunha and Silva (2022) refer to "cycling-related benefits being spatially biased, reinforcing existing urban inequalities," also highlighting the risk of cycling gentrification, where new infrastructure increases property values in central areas without improving mobility for less affluent residents (Cunha and Silva, 2022, p. 4). Even in the Dutch case discussed previously, Martens (2007) found that the benefits of integrating bicycles and buses were concentrated mainly in rural and suburban areas, where bike-sharing offered a viable alternative to using a car to reach stops that were otherwise inaccessible by foot. In contrast, in dense urban areas, they tended to compete for the same short journeys, demonstrating that the added value of bike-sharing is not uniform across space but depends on existing accessibility conditions.

However, management-oriented studies, such as that by Kou et al. (2020), raise an interesting question of efficiency vs. equity: prioritising central areas maximises aggregate benefits, producing greater overall environmental reductions due to high usage volumes, but risks excluding suburbs and groups most in need of mobility alternatives.

Yet these inequalities are not only the outcome of planning choices, but also of natural morphology. Empirical analyses of station-level flows show that altitude and slope exert a systematically negative effect, with uphill locations recording significantly lower usage even when infrastructure is present, while network density and station capacity remain the strongest positive predictors (Tran et al., 2015, p. 296). The spatial distribution of bike-sharing is therefore not a neutral variable, but determines who can benefit from the service and with what environmental and social effects. For this very reason, planning that takes into account spatial justice and equity of access is essential to prevent bike-sharing from reinforcing urban inequalities instead of reducing them.

Social, behavioural and environmental dimension

Spatial differences in accessibility are closely intertwined with cultural practices, inequalities and contingent environmental conditions, which the literature recognises as decisive factors in shaping the uses of bike-sharing. From a socio-demographic perspective, several studies have emphasised that declared equity objectives do not always coincide with actual usage patterns. The analysis of the municipal system Linbike in Sweden by Henriksson et al. (2022) shows that, despite the declared intent of promoting inclusion, actual users remain concentrated among young, educated and affluent groups. Similarly, the analysis of Cunha and Silva (2022) confirms an unequal distribution of the benefits of cycling, with a clear bias towards middle-to-high-income groups, men and residents in central neighbourhoods, highlighting a contradiction between declared inclusion objectives and actual usage patterns.

These findings are corroborated by the study of Yu (2024), which adopts a quantitative research design using a national dataset of over 160,000 respondents, of which around 1,200 are bike-sharing users. To analyse the factors predicting service usage, Yu employs count data regression models, specifically negative binomial regressions, suitable for handling the strong skewness and overdispersion of reported trips (Yu, 2024, p. 9). The analysis, enriched by data exploration techniques, identifies the main socio-demographic predictors of bike-sharing usage, such as income, ethnicity, gender and age. In this way, the study quantifies at scale the inequalities of access already suggested by qualitative investigations, offering a representative and generalisable picture.

The results highlight an ambivalent dynamic: on the one hand, bike-sharing is more widespread among young men with high education levels; on the other hand, low-income groups and ethnic minorities, particularly African Americans and Hispanics, show a higher-than-average propensity to use the service (Yu, 2024, p. 14). This reveals that bike-sharing is not exclusively an urban elite resource, but can represent an accessible mobility option also for vulnerable segments of the population. The main merits of this approach lie in the ability to combine a large national dataset with advanced analysis methodologies, providing a representative and generalisable picture of access inequalities. However, limitations concern the self-reported nature of the data, which may introduce response bias, the scarcity of contextual information on local infrastructures, and the difficulty of capturing urban heterogeneity with a nationally aggregated sample.

Alongside social variables, weather conditions also play a crucial role in bike-sharing usage. Borowska-Stefańska et al. (2021) show that precipitation, snow and low temperatures significantly reduce daily demand, confirming similar results already highlighted by Pang et al. (2016). This demonstrates that the competition or complementarity between bikes and public transport depends not only on structural or social factors, but also on environmental conditions. bike-sharing, therefore, interacts with public transport not only structurally but also dynamically: adverse weather conditions can shift demand from cycling to local public transport, accentuating modal competition.

To summarize, bike-sharing systems are not only green infrastructure, but complex tools whose use depends on socio-economic, cultural and environmental factors. Urban policies must then not only consider spatial distribution and integration with public transport, but also social barriers and external conditions that influence demand. Measures such as discounted rates for lower income groups and the planning of accessible stations in the suburbs can be useful tools for reducing certain inequalities of access. However, these measures alone are not sufficient to ensure the fairness and sustainability of the system: bike-sharing should not be seen as an automatic solution, but as an urban practice whose impact varies according to local conditions, weather, available infrastructure, policies adopted and the socio-demographic characteristics of users.

Research gaps and positioning of the study

In this framework, the literature has clearly shown that bike-sharing is both a promise and a challenge: it can produce environmental benefits, improve integration with public transport and promote more fair mobility, but it can also amplify existing inequalities if it is not carefully designed. The studies analysed demonstrate the usefulness of Computational Social Science methods in quantifying these effects, from reducing emissions to measuring accessibility, but they also highlight recurring limitations. In particular, there is a lack of analysis investigating vertical equity between social groups and a limited extension of research beyond large metropolitan areas. Furthermore, approaches often treat separately dimensions that are intertwined in reality: infrastructure, social behaviour and environmental conditions. Our project fits precisely into this research space. On one hand, it draws on the tools developed by CSS to analyse accessibility and equity, and on the other, it integrates them into a design that considers spatial, social and climatic factors jointly. The decision to focus on Trento, a medium sized European city, allows us to extend the analysis to contexts that are poorly represented in the literature, where the trade-offs between efficiency and equity take on specific configurations. In this sense, the study aims to contribute both empirically, by providing evidence on a little-studied case, and methodologically, by experimenting with geospatial accessibility metrics, horizontal and vertical equity indicators, and models capable of capturing behavioural responses to environmental and meteorological conditions, so as to systematically assess how bike-sharing interacts with urban infrastructure, social groups, and environmental conditions.

2.1 Research Question

Drawing from the literature on sustainable mobility, intermodality, and transport equity, this study formulates three interconnected research questions that jointly address the spatial, social, and environmental dimensions of bike-sharing in relation to urban mobility.

Spatial pattern of intermodality

The first research question asks:

> **RQ1. How are bike-sharing stations distributed relative to the local public transport network?**

This is a descriptive, measurement-oriented question motivated by work showing that the environmental benefits of bike-sharing materialize only where systems are well integrated with mass transit and concentrated in functionally central areas (DeMaio, 2009; Martens, 2007; Zhang and Mi, 2018; Kou et al., 2020). Identifying spatial patterns of intermodality is a necessary first step for assessing whether bike-sharing acts as a complementary feeder to public transport, as suggested in the literature, or whether it remains an isolated service concentrated in already central and well-served areas. For a medium-sized city such as Trento, where the limited scale of the transport system makes each station strategically significant, the expectation is to find a strong polarization: high levels of integration around the central transport hubs and significant marginalization in peripheral areas.

Territorial and social equity of intermodality

Building on this baseline, the second research question shifts the focus from the infrastructure itself to its territorial and social implications, asking:

> **RQ2. Which urban areas appear underserved from an intermodal perspective?**

This diagnostic question investigates the distribution of opportunities across neighborhoods and highlights potential inequalities in accessibility, in line with research that emphasizes spatial justice and the uneven social reach of cycling infrastructures (Giuffrida et al., 2023; Cunha and Silva, 2022). By linking intermodality data with demographic information, this question allows us to assess whether infrastructural concentration corresponds to uneven benefits for residents. Given the socio-spatial patterns documented in other European contexts, we expect to observe clear disparities in Trento as well, with central districts enjoying higher levels of coverage while peripheral and less affluent areas remain excluded. These expectations also resonate with local evidence from the analysis of 2023 tax returns in the Province of Trento made by ACLI (ACLI Trentine, 2023), which reinforces the importance of considering territorial equity in mobility planning.

Temporal and environmental dynamics

Finally, the third research question extends the analysis to the temporal and environmental dimension:

RQ3. How do urban mobility patterns vary with weather?

This question is designed to explore behavioral responses to exogenous factors such as temperature and precipitation. Prior studies have consistently shown that weather conditions are among the strongest determinants of cycling uptake and, more broadly, modal choice, with rainfall and extreme temperatures discouraging active travel and shaping public transport demand (Borowska-Stefańska et al., 2021). Trento represents a relevant case, as its alpine setting implies pronounced seasonal variation and frequent weather extremes. Based on this context and on international evidence, we expect to observe a measurable sensitivity of mobility patterns to climatic conditions: precipitation is likely to depress daily mobility, particularly towards transit hubs, while temperature may exert a more complex, non-linear influence, encouraging outdoor and collective mobility within moderate ranges but constraining activity under extreme heat or cold. Investigating these dynamics allows us to link infrastructural provision and social equity with the dimension of climate resilience, thereby addressing the temporal and environmental contingencies of sustainable urban mobility.

Together, these three questions are mutually reinforcing. RQ1 establishes the structural geography of intermodality, RQ2 contextualizes its distributive implications across the urban fabric, and RQ3 explores how external shocks such as weather further modulate access and usage. By linking infrastructure, equity, and climate, the study positions Trento as an instructive case for understanding how bike-sharing can contribute to sustainable and just urban mobility beyond large metropolitan contexts.

3 Project Design

The overall design of this project is grounded in the principles of Computational Social Science (CSS). CSS provides a framework for studying complex social systems by integrating heterogeneous data sources, applying computational methods capable of uncovering non-linear and emergent dynamics, and ensuring transparency through reproducible workflows (Lazer et al., 2009; Conte et al., 2012). Urban mobility, and bike-sharing in particular, offers an exemplary case for CSS, since it generates large-scale digital traces of collective behavior and lends itself to computational modeling. Empirical studies confirm this potential: big-data analyses of emission reduction (Zhang and Mi, 2018), and computational models of modal substitution (Kou et al., 2020), all demonstrate how bike-sharing can be fruitfully investigated through CSS methods.

Our research addresses three interrelated aspects: the spatial distribution and accessibility of bike-sharing in relation to the public transport system (RQ1), the identification of underserved areas and the social groups affected by infrastructural gaps (RQ2), and the influence of climatic conditions on collective mobility behavior (RQ3). To answer these questions, we adopt a multi-layered design that integrates infrastructural data (bike-sharing stations, GTFS feeds), socio-demographic registers (district boundaries, household composition), environmental indicators (ERA5 reanalysis of temperature and precipitation), and behavioral traces (Google Mobility Reports). Through this integration, we move beyond single-source analyses and capture the interdependence of behavior, infrastructure, and context that characterizes urban mobility as a complex social system.

Methodologically, the project draws on:

- **Geospatial accessibility analysis** to operationalize multimodality (RQ1),
- **Equity-oriented overlays** to connect infrastructural provision with social stratification (RQ2)
- **Generalized Additive Models (GAMs)** to capture non-linear responses to environmental shocks (RQ3).

Each choice reflects a conceptual alignment with established CSS traditions: spatial interaction models for measuring opportunities for intermodality, territorial justice frameworks for analyzing inequalities in service provision, and complex systems approaches for modeling behavioral adaptation under contextual constraints. This multi-method design not only ensures analytical rigor but also allows us to situate our empirical findings within broader debates on sustainability, equity, and resilience in urban systems.

3.1 Data Collection Strategy

This study integrates infrastructural, behavioral, and environmental records for the city of Trento. In accordance with emerging standards in open social science around transparency, data provenance, and reproducible research (Miguel et al., 2014) we document how each dataset was originally collected, cite its source, and explain the processing steps applied in our workflow. Particular attention was paid to data formats. While raw datasets were often provided in CSV or JSON, these were transformed into interoperable (GeoJSON) or scalable (Parquet) formats. These format conversions were necessary to harmonize heterogeneous datasets into a coherent structure suitable for spatial and temporal integration: GeoJSON supports spatial overlays and visualizations across platforms, whereas Parquet ensures efficient storage and querying for large temporal datasets. By documenting both the raw and processed formats, we facilitate reproducibility and ensure that our analysis can be replicated and extended by other researchers.

Bike-sharing system (municipal open data)

Station-level metadata were retrieved from the Municipality of Trento's open-data portal (dataset: bike-sharing Open Data [3]). These records are generated by the operator's management system and include station identifiers, names, capacity, and geometries. The raw dataset (`stazioni_trento.csv`) was preprocessed using the script `clean_all.py` to ensure consistency and interoperability with the other geospatial layers. The original geometries were provided in Well-Known Text (WKT) format and in the local projection UTM Zone 32N. These were first parsed into valid geospatial objects and then reprojected into WGS84 (EPSG:4326), which is the global standard used by most web-based mapping services and by the other spatial datasets employed in this project. This transformation was essential to guarantee spatial comparability with GTFS transit stops, district boundaries (`circoscrizioni.geojson`), and meteorological grids. Attribute names were standardized into a consistent schema (e.g., `station_id`, `capacity`) in order to reduce ambiguity and facilitate reproducibility across scripts. Duplicate records were also removed to avoid biased accessibility measures and errors in subsequent spatial overlays. The resulting dataset (`stations_clean.geojson`) thus provided a clean and globally interoperable representation of bike-sharing stations. It was subsequently enriched through the script `population_stations_analysis.py`, which combined the cleaned station locations with demographic and transport data to compute accessibility metrics. The final product (`station_accessibility_2025.geojson`) enabled the integration of the bike-sharing layer into multimodal accessibility analyses, ensuring that the network could be studied in direct relation to public transport hubs and household distributions.

Public transport (GTFS, 2025)

Public transport data were obtained from Trentino Trasporti's official GTFS feed[4], which is generated directly by the agency's scheduling system. We used the core GTFS files: `stops.txt`, `routes.txt`, `trips.txt`, `stop_times.txt`, `calendar.txt`, `shapes.txt`, and `transfers.txt`. These files describe stop locations, route geometries, timetables, service calendars, and transfer rules. To integrate these records into our spatial analysis, the script `clean_all.py` was first used to convert stop locations into a geospatial for-

[3]**bike-sharing Open Data:** `https://dati.trentino.it/dataset/bike-sharing-open-data`
[4]**Trentino Trasporti's official GTFS:**`https://www.trentinotrasporti.it/open-data`

mat (`gtfs_stops_2025.geojson`), ensuring compatibility with the cleaned bike-sharing dataset (`stations_clean.geojson`). Service calendars were standardized into a more efficient columnar format (`gtfs_service_calendar_2025.parquet`), allowing for scalable queries across large volumes of schedule data. These transformations were necessary to harmonize the GTFS feed with other datasets, ensuring both spatial interoperability and computational efficiency. Subsequently, the script `build_datasets.py` aggregated routes per stop and calculated buffer-based intermodality indices, counting the number of transit stops and distinct routes located within 300 m and 500 m of each bike-sharing station. The resulting outputs (`station_accessibility_2025.geojson` and `station_accessibility_2025.parquet`) provide a systematic quantification of multimodal accessibility, enabling a direct comparison of central and peripheral areas in terms of opportunities for intermodal integration.

Administrative boundaries & demographics (equity frame)

Equity analysis required socio-spatial baselines. Administrative boundaries (`circoscrizioni.geojson`) were obtained from the official municipal GIS dataset (Circoscrizioni Open Data)[5]. Household counts per district (`famiglie_circoscrizioni_2024.csv`) were sourced from the Municipality of Trento's official 2024 demographic publication (*Tipologia di famiglie nel Comune di Trento e nelle Circoscrizioni, 2024*), based on the population registry. These two datasets were harmonized through the script `population_stations_analysis.py`, which spatially linked demographic information with the accessibility layers created in the previous steps. The procedure computed service coverage indicators such as the proportion of households located within 300 m and 500 m buffers of intermodal hubs. This step was essential to translate infrastructural measures of accessibility into socially meaningful indicators, enabling an equity-oriented perspective that considers who benefits from, and who is excluded from, intermodal opportunities. The final outputs (`reports/tables/intermodal_population_coverage.csv`) provided a tabular representation of accessibility coverage by district. This table formed the basis for the subsequent analysis of equity and territorial justice, ensuring that accessibility gaps were not only identified spatially but also interpreted in relation to the population groups most affected.

Weather (ERA5-based daily series, 2020–2022)

Meteorological conditions were sourced from ERA5, the state-of-the-art global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 combines surface observations, satellite retrievals, and radiosonde profiles through advanced data assimilation, thereby providing a coherent and temporally consistent

[5] **Circoscrizioni Trento Open Data:**`https://dati.trentino.it/dataset/circoscrizioni-open-data`

reconstruction of past atmospheric conditions. For the case of Trento, we extracted daily maximum temperature (°C) and total precipitation (mm) via the Open-Meteo ERA5 API[6], which provides streamlined access to the underlying dataset hosted at the Copernicus Climate Data Store[7]. The raw JSON file (`trento_era5_daily_2020_2022.json`) was validated and converted into a columnar format (`meteo_daily.parquet`) using the script `clean_all.py`. This transformation ensured that the time series covered the full study window (2020–2022) without gaps and that variable names followed a standardized schema, facilitating reproducibility across scripts. Storing the processed data in Parquet also optimized computational efficiency: as a compressed, column-oriented format, it allows for fast subsetting of time ranges and variables, which was essential when integrating weather records with large-scale mobility and transport datasets.

Mobility behavior (Google Community Mobility, 2020–2022)

Aggregated behavioral indices were obtained from Google's Community Mobility Reports[8]. These indices are anonymized and aggregated, based on users who opted into Location History, and express daily mobility changes relative to a pre-pandemic baseline. For Trento, we extracted the relevant entries from the 2022 Italian regional file (`2022_IT_Region_Mobility_Report.csv`). The raw file was processed through the script `clean_all.py`, which filtered observations for the Autonomous Province of Trento and standardized column names into a consistent schema. The cleaned dataset (`mobility_trento_2022.parquet`) retained the two indices most relevant to our research questions: workplace mobility and transit station activity. Converting the dataset into Parquet format ensured efficient handling of temporal panel data and seamless integration with other processed sources. To contextualize mobility dynamics, the script `build_datasets.py` merged these behavioral traces with meteorological records (`meteo_daily.parquet`) and added temporal features (`temporal_2022.parquet`), including weekday, weekend, and holiday indicators. These categorical variables operationalize social rhythms, a central concept in CSS for understanding how routine cycles structure collective behavior. The resulting dataset thus combined behavioral, environmental, and temporal dimensions into a single analytical framework suitable for modeling non-linear mobility responses.

Reproducibility and directory conventions

To ensure reproducibility, all preprocessing and analysis steps were implemented in modular Python scripts. The workflow follows a standardized folder structure (`data/raw`

[6]**Open-Meteo ERA5 AP:**`https://open-meteo.com/en/docs`

[7]**Copernicus Climate Data Store:**`https://cds.climate.copernicus.eu/datasets`

[8]**Google's Community Mobility Reports (2020-2022):**`https://www.google.com/covid19/mobility/`

→ `data/interim` → `data/processed` → `reports`), which makes the provenance of each dataset transparent and ensures that intermediate transformations are preserved. Raw data are stored without modification, interim files capture cleaning and harmonization steps, and processed files contain the analytical inputs used in the statistical models. Documented provenance, code-based transformations, and the generation of shareable intermediate artifacts make analyses transparent and extendable. By structuring the workflow in this way, we not only facilitate replication of our results but also create a platform where additional datasets or alternative analytical procedures can be incorporated systematically.

3.2 Methodology

The methodological design of this study is grounded in the principles of Computational Social Science (CSS). Within this framework, urban mobility is approached as a multidimensional phenomenon shaped simultaneously by infrastructural provision, social stratification, and environmental conditions.

Our empirical strategy combines three complementary components. First, geospatial accessibility analysis operationalizes multimodality by quantifying the opportunities for interconnection between bike-sharing and public transport systems. Second, an equity-oriented interpretation links infrastructural accessibility and behavioral sensitivity to socio-demographic distributions, situating our findings within broader debates on territorial justice and sustainability. Third, statistical modeling of behavioral responses captures the influence of climatic shocks on collective mobility patterns, with methods explicitly designed to accommodate non-linear and context-dependent dynamics. Moreover, a distinctive feature of our design is its diachronic perspective. By combining behavioral traces from 2020–2022 with infrastructural and demographic datasets from 2025, we move beyond a static description of the mobility system. This temporal layering allows us to observe how past shocks (such as pandemic-related disruptions and climatic variability) reveal structural weaknesses that remain embedded in the present-day transport network. In line with CSS principles, mobility is here conceptualized not as a fixed equilibrium but as a dynamic process shaped by infrastructures, policies, and external stressors. This approach positions Trento as a case study in resilience, highlighting how medium-sized cities can be analyzed not only for their current state but also for the trajectories and vulnerabilities that structure their futures.

By structuring the methodology around these pillars, the project directly addresses the three research questions, while ensuring that each analytical step is theoretically grounded, methodologically transparent, and reproducible.

Distribution and accessibility

To assess the integration of bike-sharing with public transport, we constructed a spatial accessibility index based on the co-location of bike-sharing stations and transit stops. Specifically, for each station we calculated the number of GTFS-defined transit stops and distinct routes falling within 300 m and 500 m buffers, using geospatial overlays implemented in `population_stations_analysis.py`. The use of buffer distances as analytical units reflects a methodological choice rooted in spatial interaction modeling theory, which conceptualizes proximity as a key determinant of interaction potential, an approach widely applied in urban and regional analysis (Roy and Thill, 2004).

While such models have traditionally been employed to study flows and accessibility in regional science, our CSS approach adds value by integrating heterogeneous digital traces and demographic registers within the same analytical framework, thereby linking micro-level behavioral data to macro-structural patterns of accessibility. Accessibility is here conceptualized not merely as a measure of distance but as a relational property of urban systems, linking infrastructural distribution to the potential for collective behavior.

Descriptive statistics (histograms, boxplots) were employed to capture the skewed nature of accessibility distributions, while geospatial visualization (`station_accessibility_2025.geojson`) allowed us to identify spatial clusters and peripheral gaps. Together, these tools enabled us to compare multimodal richness across central and peripheral contexts, highlighting structural asymmetries in urban integration. Methodologically, this procedure exemplifies the CSS commitment to combining computational modeling (spatial overlays, buffer analysis) with interpretive frameworks (urban connectivity and equity). By quantifying the infrastructural opportunities for intermodality, we establish a baseline that informs the subsequent analysis of underserved areas (RQ2) and contextual behavioral responses (RQ3).

Underserved areas

To identify underserved areas, we assessed the alignment between transit service richness and the coverage of bike-sharing stations. Service richness was operationalized by aggregating GTFS calendars (`calendar.txt`) and stop-time records (`stop_times.txt`) to calculate the number of routes (`routes.txt`) serving each stop. Stops above the median service frequency were classified as high-frequency hubs, representing structurally central nodes of the transport system.

We then evaluated whether these hubs were supported by proximate bike-sharing stations (derived from `stazioni_trento.csv` and processed through `clean_all.py`); hubs without coverage were flagged as underserved, revealing spatial gaps in intermodal connectivity. The identified hubs were cross-referenced with administrative boundaries (`circoscrizioni.geojson`) and household composition data (`famiglie_circoscrizioni_2024.csv`) to determine which districts disproportionately bear infrastructural disadvantages. All operations were implemented via the modular scripts `build_datasets.py` and `rq2_analysis.py`, ensuring full reproducibility.

Methodologically, this procedure exemplifies a CSS approach to territorial justice: accessibility is analyzed not solely in terms of efficiency but also in relation to equity and distributional fairness. While transport geography has traditionally evaluated service provision through network coverage and centrality measures, our CSS design extends this tradition by explicitly combining digital transit traces with socio-demographic registers, thereby situating infrastructural gaps within broader debates on inequality and territorial justice in urban systems (Fainstein, 2010; Pereira et al., 2017).

Weather and social impact

To evaluate the influence of weather conditions on collective mobility behavior, we estimated Generalized Additive Models (GAMs), a flexible framework well-suited for capturing non-linear and threshold effects in time-series data (Dominici et al., 2002). Unlike linear models, which impose fixed parametric relationships, GAMs allow the shape of the response curve to be learned from the data, thereby accommodating behavioral adaptations to climatic extremes. This makes them particularly appropriate for urban mobility studies, where temperature and precipitation effects are known to be context-dependent and non-linear.

The specification of our models relied on three categories of variables: behavioral outcomes, climatic predictors, and temporal controls. The dependent variables were daily Google Mobility indices for workplaces and transit stations (`mobility_trento_2022.parquet`). Independent variables included smoothed terms for maximum temperature and precipitation, derived from ERA5 reanalysis (`trento_era5_daily_2020_2022.json`, processed into `meteo_daily.parquet`). Finally, categorical dummies for weekdays, weekends, and holidays (`temporal_2022.parquet`) were included to operationalize routine social rhythms, a central concept in CSS analyses of collective behavior.

Model estimation was conducted through the script `analysis_suite.py`. Smoothing functions were applied to meteorological predictors to uncover potential non-linear responses, with model diagnostics used to validate robustness. Partial effect plots and boxplots were employed to visualize the behavioral consequences of climatic variation, illustrating thresholds, diminishing effects, and asymmetries across weather conditions.

Methodologically, this reflects a CSS-informed complex systems approach: rather than assuming mobility responses are linear and additive, GAMs enable the identification of emergent adaptation patterns under environmental shocks. By interpreting these results alongside socio-spatial data, we situate weather-related impacts within broader debates on inequality, vulnerability, and resilience in urban systems (Fainstein, 2010; Pereira et al., 2017).

Taken together, the data collection strategy and methodological design establish a coherent and transparent analytical framework directly aligned with our research questions. By integrating infrastructural, demographic, behavioral, and environmental datasets, the project captures the interdependencies between urban form, social stratification, and external shocks. The computational pipeline, structured into modular scripts for cleaning, integration, and modeling, ensures that every transformation is documented and reproducible, thereby fulfilling the methodological commitments of CSS.

The triangulation of spatial accessibility measures, equity-oriented overlays, and non-linear statistical modeling allows us to move beyond purely descriptive accounts of mobility systems, providing instead a systematic evaluation of how infrastructures are distributed, which populations are excluded from intermodal opportunities, and how collective behavior adapts to environmental variability. This design enhances both the internal validity of the empirical analysis and its external relevance, generating insights that contribute not only to academic debates in urban and computational social science but also to practical discussions on building more sustainable and equitable urban mobility systems.

4 Results

RQ1: Spatial Integration of Bike-Sharing and Public Transport

The analysis begins with the evaluation of the spatial integration between the bike-sharing network and the public transport system. In line with the literature on urban accessibility, intermodality is here conceptualized as the possibility of combining different transport modes within a given proximity threshold. We constructed an index that measures, for each bike-sharing station, the number of public transport stops and corresponding lines reachable within 300 and 500 meter buffers. Although simple, this measure provides a robust proxy of intermodal connectivity potential, capturing both the dense concentration of services in central areas and the infrastructural deficits characterizing peripheral zones.

The intermodality index (Figure 1) reveals strong heterogeneity in the distribution of opportunities for bike-sharing–transit integration across Trento. Within 300 meters, a polycentric pattern emerges: a few central stations register very high values (exceeding 30 connections), whereas the majority of peripheral stations remain at low levels.

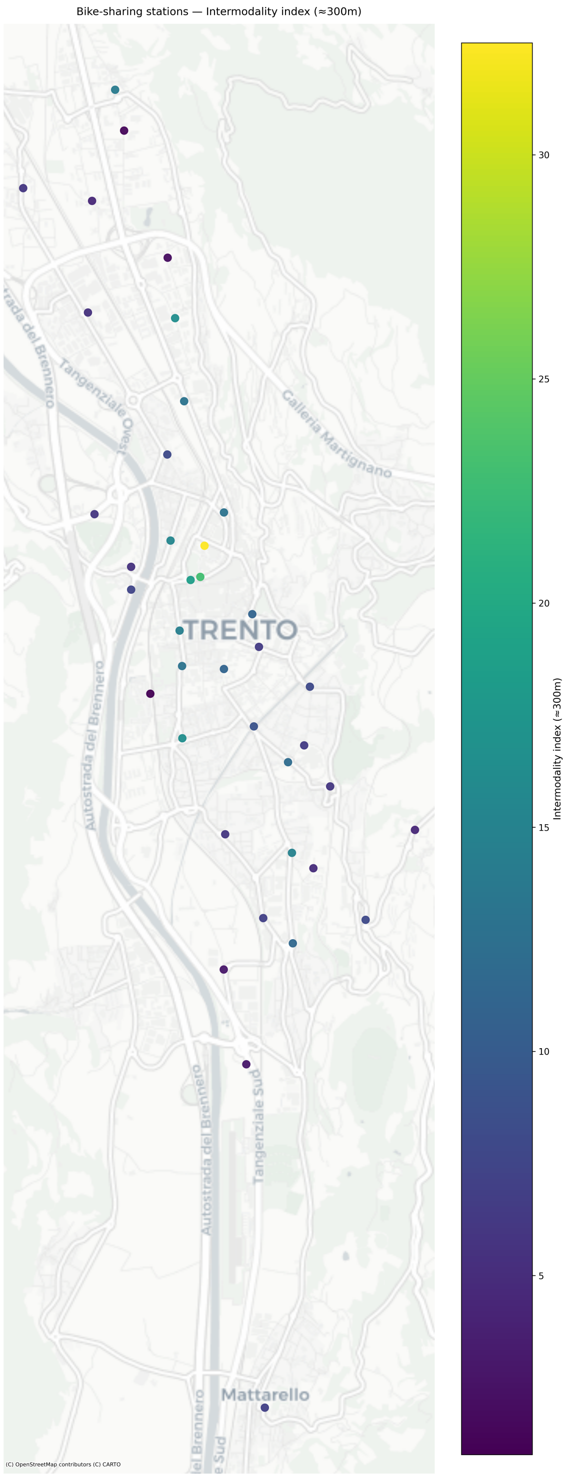

Figure 1: *Spatial distribution of the intermodality index (300 m buffer). Central bike-sharing stations in Trento, particularly around the railway station and city core, show the highest concentration of intermodal opportunities. Peripheral areas remain structurally disadvantaged, often with fewer than three connections.*

The boxplot for 300 meters (Figure 2) confirms this inequality, with a median of only three connections and a distribution skewed by a small number of high-accessibility outliers.

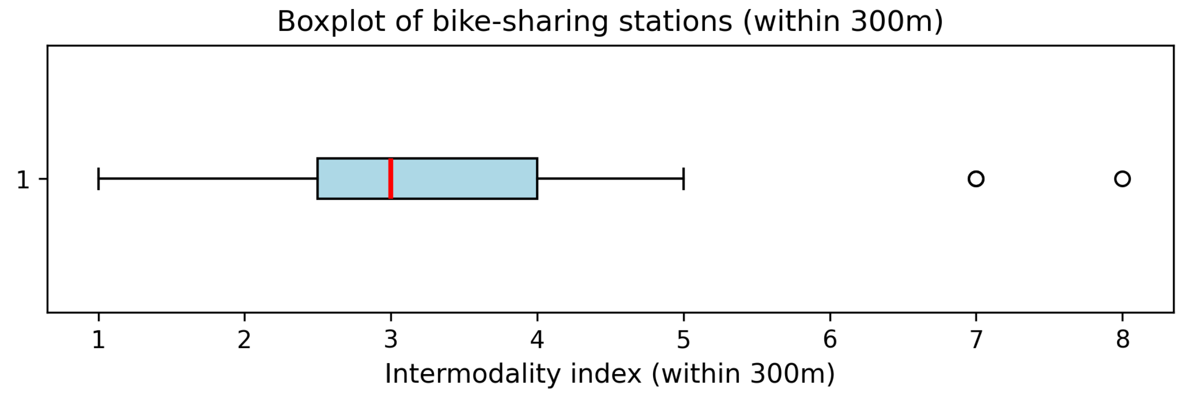

Figure 2: *Boxplot of intermodality index (300 m buffer). Most stations offer only 2–4 connections, with a median of 3. A few high-accessibility outliers drive a skewed distribution.*

The histogram (Figure 3) further illustrates that most stations cluster between two and four intermodal opportunities, while only a few exceed seven or eight.

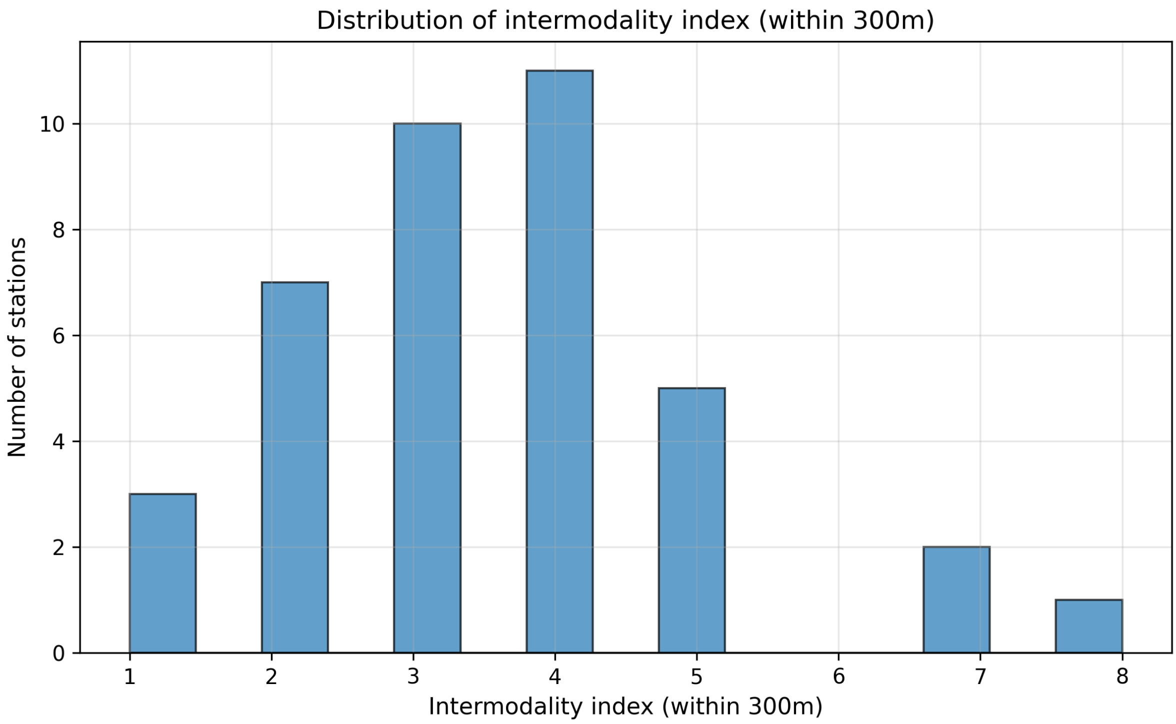

Figure 3: *Histogram of intermodality index (300 m buffer). The majority of stations cluster between 2–4 connections, while very few exceed 7–8.*

When the buffer is expanded to 500 meters, accessibility increases substantially. The median rises to eight connections, and the distribution extends up to a maximum of sixteen (Figure 4).

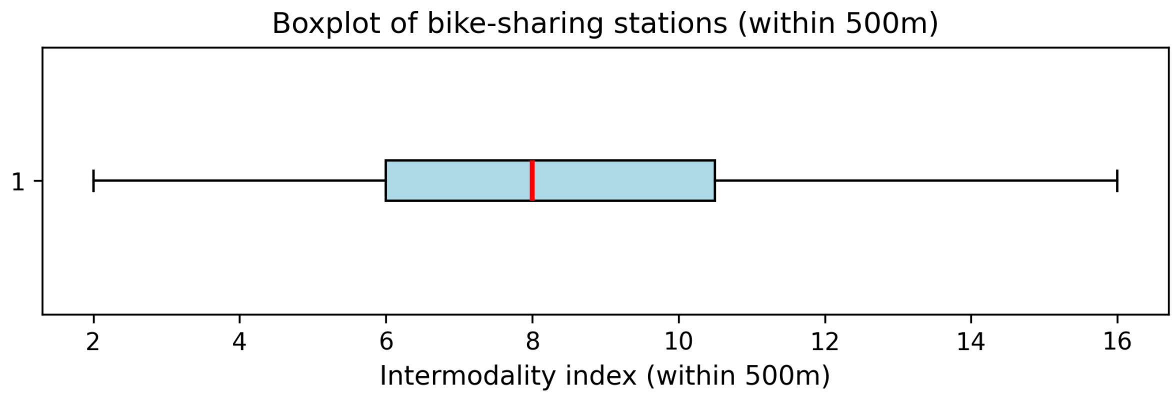

Figure 4: *Boxplot of intermodality index (500 m buffer). Accessibility improves at larger scale (median = 8), but inequalities persist, as only a handful of stations exceed 12 connections.*

Yet disparities persist. The distribution comparison (Figure 5) highlights a clear scale effect: opportunities consistently grow with distance, but central hubs consolidate their dominance, while peripheral stations remain disadvantaged.

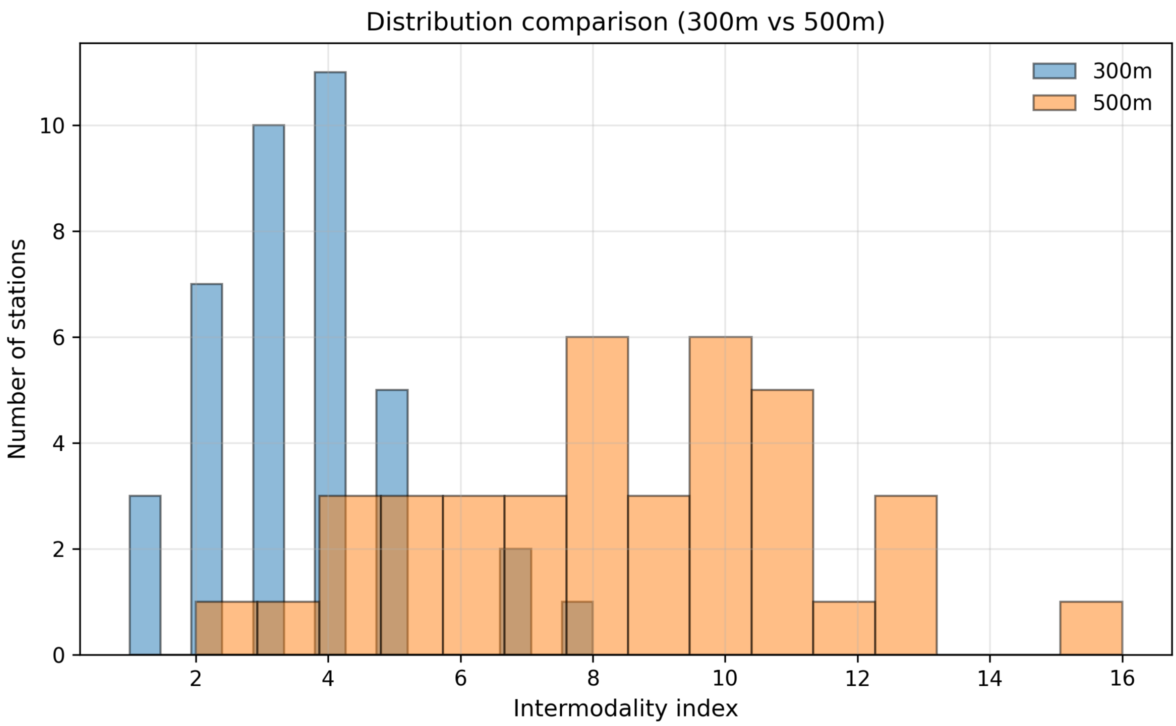

Figure 5: *Histogram comparison of intermodality index (300 m vs. 500 m buffer). Expanding the buffer increases opportunities, yet central hubs continue to concentrate the majority of connections.*

The extreme cases illustrate this divide. At 300 meters, central stations such as Top Center, Via Bezzi, and the railway station score seven to eight connections, whereas peripheral nodes like Muse or Bren Center remain at one to two. At 500 meters, the gap widens further: Top Center reaches 16 connections, together with Piedicastello and Via Bezzi

(13), reinforcing their role as intermodal hubs. By contrast, peripheral stations such as Lidorno and Palatrento remain structurally marginal, with only two to three connections.

Top 3 stations access (300 m)	Connections	Top 3 stations access (500 m)	Connections
TOP CENTER	8	**TOP CENTER**	16
VIA BEZZI angolo via Vittorio Veneto	7	**PIEDICASTELLO** in piazza di Piedicastello nel giardino Andrea Hofler	13
VIA VANNETTI (sede PAT)	7	**VIA BEZZI** angolo via Vittorio Veneto	13
Bottom 3 stations access (300 m)	**Connections**	**Bottom 3 stations access (500 m)**	**Connections**
BREN CENTER via Guardini	1	**MUSE** corso del Lavoro e della Scienza	4
MUSE corso del Lavoro e della Scienza	1	**PALATRENTO** via Fersina/via Bartali	3
CENTRO SPORTIVO GARDOLO via IV Novembre	1	**LIDORNO** – via Lidorno/park Trento sud	2

Table 1: *Top and bottom stations by intermodality index (300 m and 500 m buffer).*

From a methodological standpoint, these results demonstrate that a simple proximity-based measure can effectively capture territorial inequalities in intermodality. The integration of bike-sharing with public transport is highly polarized, with opportunities clustered in the central city while vast areas remain infrastructurally excluded.

RQ2: Equity and Territorial Justice in Intermodality

Building on this first step, the second part of the analysis shifts the focus from stations to neighborhoods, assessing the extent to which different districts are served by intermodal hubs and, consequently, which population groups are disadvantaged.

The coverage map of resident families (Figure 6) highlights a sharp polarization between central and peripheral districts. S. Giuseppe–S. Chiara, Oltrefersina, and Centro Storico–Piedicastello emerge as the best served, with over one third of households covered by intermodal hubs and peaks exceeding 45% in S. Giuseppe–S. Chiara. This reflects the primacy of the urban corridor along the city's main rail and road axis. However, on the contrary, peripheral districts such as Bondone, Povo, Argentario, and Sardagna are virtually excluded, with coverage rates close to zero. Even more populous areas like Meano or Ravina–Romagnano remain below 0.2%, underscoring a deep territorial divide.

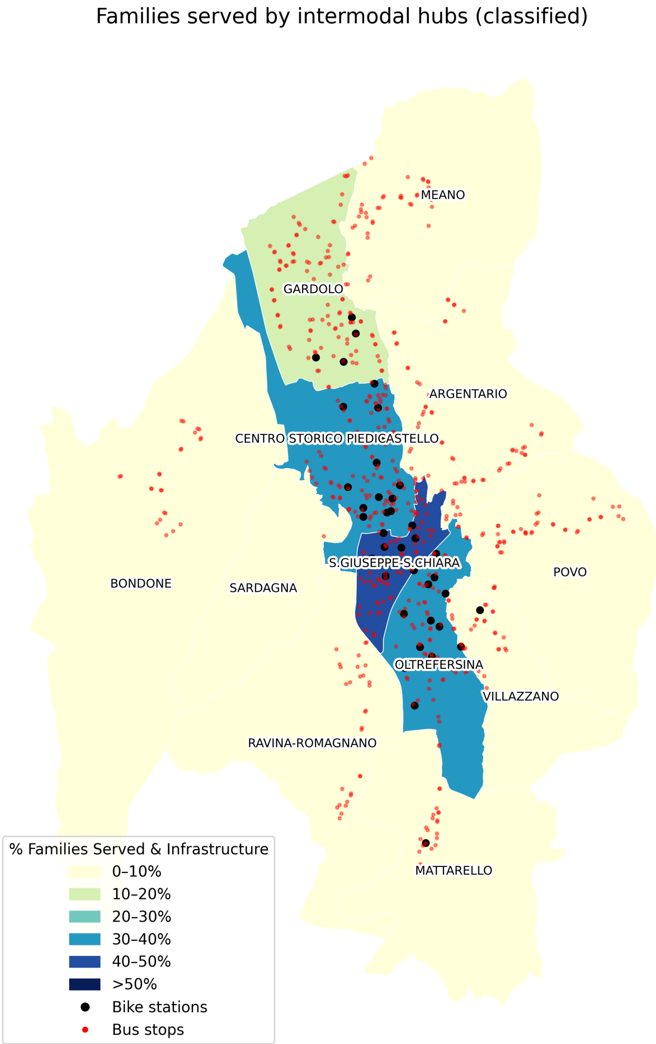

Figure 6: *Families served by intermodal hubs across Trento's districts. Central neighborhoods such as S. Giuseppe–S. Chiara and Oltrefersina achieve the highest coverage rates, while peripheral districts remain almost entirely excluded.*

The bar chart (Figure 7) further illustrates this dichotomy: only four districts (S. Giuseppe–S. Chiara, Oltrefersina, Centro Storico–Piedicastello, and Gardolo) exceed 10%, while all others remain far below.

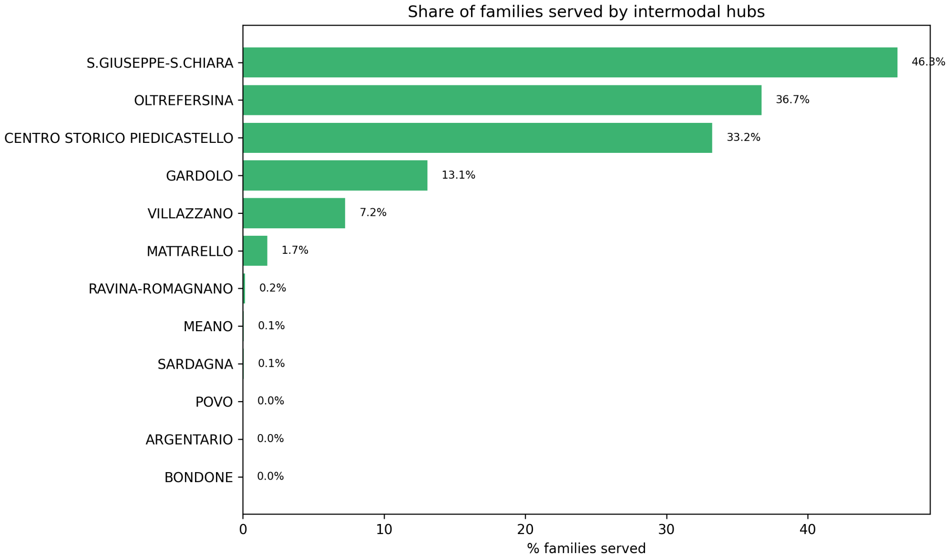

Figure 7: *Share of households served by intermodal hubs by district. Only four districts surpass 10% coverage, highlighting the stark inequalities between central and peripheral areas.*

Methodologically, these results demonstrate how demographic coverage measures allow bridging the infrastructural perspective of RQ1 with distributive and equity concerns. By integrating digital mobility data (GTFS, bike-sharing stations) with administrative registers (households by district), the concept of territorial justice is operationalized into empirical indicators: not only where intermodal opportunities are located, but also who has access to them.

RQ3: Climatic Conditions and Collective Mobility

After examining the spatial distribution of intermodality (RQ1) and the territorial inequalities in coverage (RQ2), the third research question investigates the temporal dimension, focusing on how weather conditions influence collective mobility behaviors. The time series of weekly rolling averages (Figure 8) highlights pronounced seasonal dynamics. Transit station mobility fluctuates strongly, peaking in summer and dropping in winter, while workplace mobility remains comparatively more stable, although still subject to marked contractions during holidays and episodes of adverse weather.

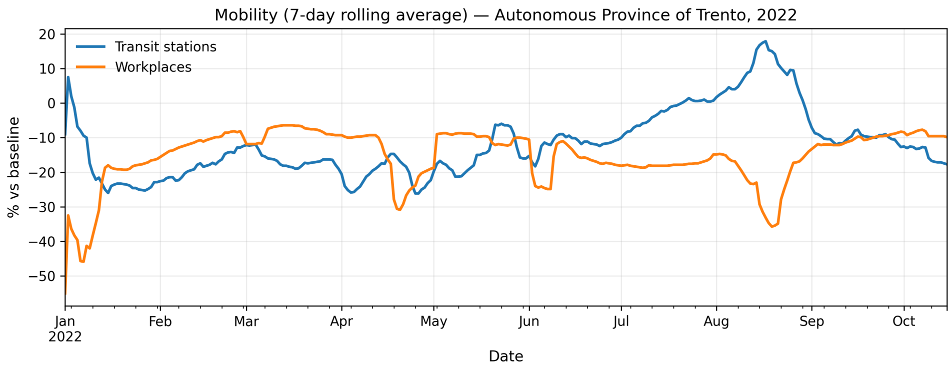

Figure 8: *Weekly mobility trends in transit stations and workplaces (7-day rolling average, 2022). Transit mobility shows strong seasonal variation, with peaks in summer and troughs in winter, while workplace mobility is more stable but sensitive to holidays and shocks.*

Boxplot analyses (Figure 9) confirm that rainfall systematically reduces mobility, with effects intensifying as precipitation increases. Light rain (> 0 mm) is associated with moderate declines, while heavy rainfall (≥ 10 mm) produces more substantial and uniform reductions.

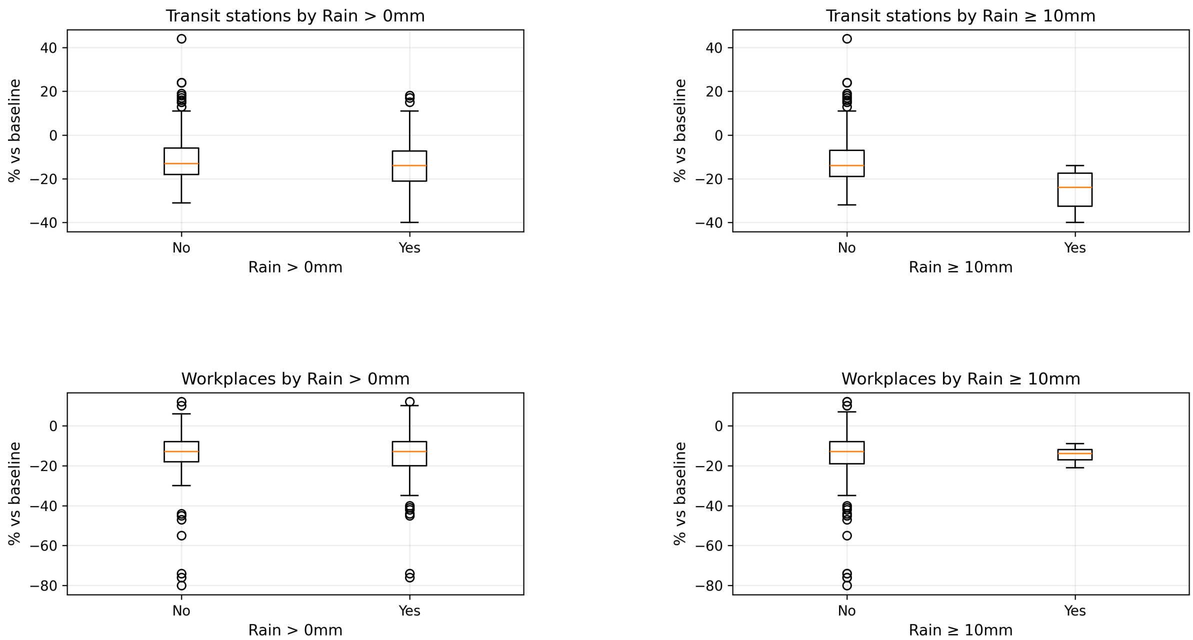

Figure 9: *Effects of rainfall on transit and workplace mobility (% change from baseline). Each panel shows mobility trends under different conditions.*

GAM models refine the rainfall analysis by capturing non-linear effects. For transit stations, mobility decreases steadily as precipitation increases up to about 15 mm, after which it stabilizes at consistently low levels. Workplace mobility, by contrast, shows a more complex pattern: a slight increase under light rain, a sharp decline at 5–10 mm, and a partial rebound under very heavy precipitation (> 15 mm) (Figure 10).

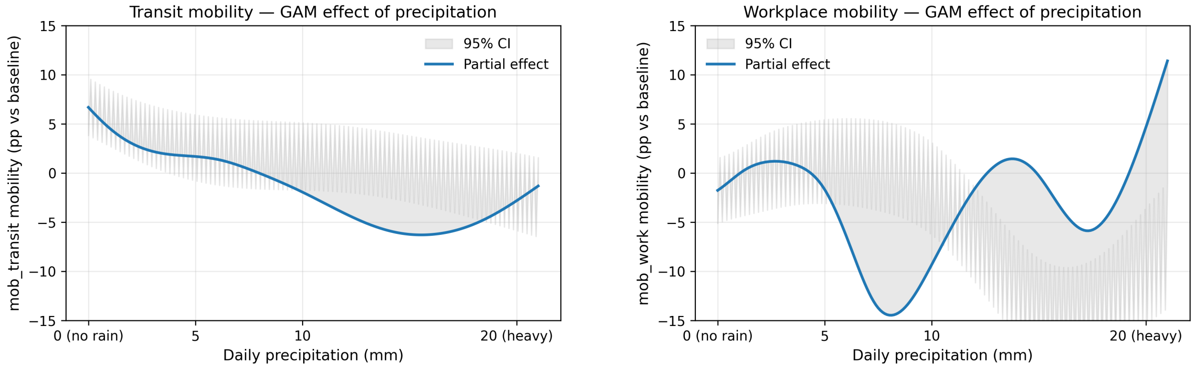

Figure 10: *GAM-estimated effects of precipitation on transit and workplace mobility.*

Temperature effects reveal a different pattern. Scatter plots with binned means (Figure 11) show a positive association between maximum daily temperature and transit mobility, while workplace mobility follows an inverted-U curve.

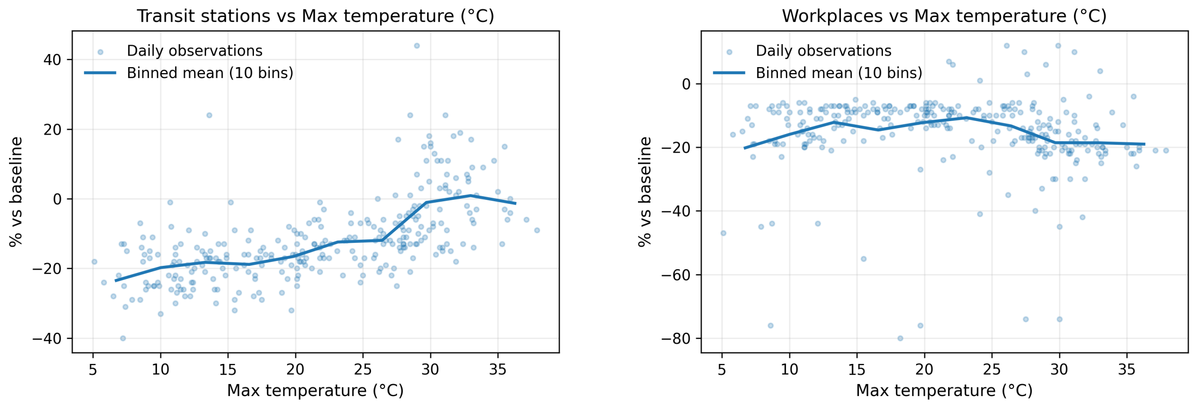

Figure 11: *Scatter plots with binned means of maximum temperature vs. mobility. Transit mobility increases with higher temperatures, while workplace mobility peaks at mild temperatures and declines at extremes.*

GAM estimates (Figure 12) confirm these non-linear patterns. Transit mobility rises steadily with temperature, while workplace mobility peaks at moderate values and declines at higher ones.

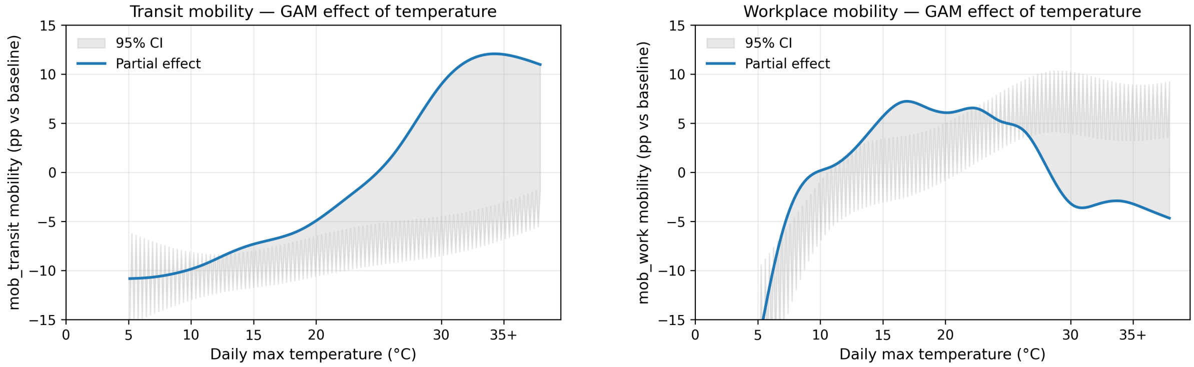

Figure 12: *GAM-estimated effects of temperature on transit and workplace mobility.*

Taken together, these findings underscore the differentiated ways in which weather conditions shape urban mobility. Public transport use appears more flexible and adaptive, increasing during favorable or warm conditions, while workplace mobility is more rigid and vulnerable, showing strong sensitivity to adverse weather and heat stress. When considered in isolation, these patterns describe behavioral vulnerability to exogenous shocks. However, reading them against today's infrastructure reveals a structural continuity: the intermodality indices (Figures 2–3-4-5) and maps (Figures 1-6) show that integration opportunities remain concentrated in a handful of central hubs. The household coverage analysis (Figures 6–7 and Table 1) demonstrates that only a few districts benefit from substantial intermodal accessibility, while most peripheral areas serve less than 10% of families. This distribution indicates that the infrastructural expansion up to 2025 has not altered the central-peripheral divide documented in earlier years.

5 Conclusions

Empirical Conclusions

The study demonstrates that Trento's bike-sharing system is marked by a layered structure of inequality across space, society, and time. At the infrastructural level, intermodality emerges as highly polarized: central hubs such as the railway station and Top Center concentrate opportunities for integration with public transport, while peripheral stations remain structurally excluded.

At the territorial level, these infrastructural divides translate into distributive inequalities, with only a handful of districts enjoying meaningful intermodal coverage and large portions of the population, particularly in less affluent peripheries, effectively excluded. Some peripheral areas, such as Povo, Sardagna, and Bondone, lack stations not only because of their smaller resident populations, but also due to morphological constraints: steep gradients and higher altitude make cycling, and therefore bike-sharing, structurally less attractive. This observation is consistent with previous literature showing how elevation and topography strongly influence bike-sharing demand and supply patterns (Tran et al., 2015).

At the temporal and behavioral level, the mismatch between behavioral data (2020–2022) and infrastructural data (2025) should not be seen only as a limitation but also as a lens that enables interpretation. The Google Mobility Reports capture how Trento's residents actually responded to systemic shocks, such as pandemic restrictions, seasonal variability, and weather extremes. These behavioral patterns show clear vulnerabilities: rainfall consistently depresses mobility, while temperature exerts differentiated effects, stimulating collective mobility within moderate ranges but constraining workplace-related movements under extreme heat.

When these responses are read against the backdrop of today's infrastructure, a deeper insight emerges. The intermodality maps reveal that the bike-sharing system remains concentrated in central nodes, with large districts excluded from integration. This means that the vulnerabilities exposed in 2020–22 remain highly relevant today, since the infrastructural redesign up to 2025 does not appear to have corrected the structural asymmetries. In other words, the mismatch highlights the persistence of vulnerabilities across time; however, in the absence of past infrastructural data, we cannot state with certainty whether this reflects strict continuity or a partial change insufficient to alter the geography of resilience.

The city has expanded its bike-sharing offer, but not in ways that significantly alter the geography of resilience: central areas would still absorb the benefits of integration, while peripheral districts would remain doubly disadvantaged, excluded from infrastructure and more exposed to behavioral sensitivity to weather shocks. Thus, the mismatch allows us to conclude that Trento's mobility system, despite growth, has not yet addressed its systemic weaknesses, and that future shocks are likely to reproduce the same unequal impacts documented in past behavior.

Taken together, these findings provide a clear empirical answer to the research questions. They show that Trento's bike-sharing system cannot be considered a uniformly accessible or resilient infrastructure; rather, it amplifies spatial centralities, reflects pre-existing socio-economic divides, and remains vulnerable to environmental events.

Connection to Research Questions

Each research question provided a distinct but interconnected lens on the challenges of sustainable mobility in a medium-sized European city. RQ1 revealed the geography of intermodality, showing where integration between modes is structurally feasible. RQ2 extended this to issues of territorial justice, exposing how infrastructural concentration translates into unequal accessibility across the urban fabric and across socio-economic groups. RQ3 introduced the dynamic dimension of climate, demonstrating that even where infrastructure exists, its effective use is mediated by weather, raising questions about resilience in the face of increasing climatic variability.

By linking infrastructure, equity, and environment, the study advances an integrated perspective on urban mobility that is rarely applied outside large metropolitan contexts.

Evidence-Based Support

The results contribute to the literature in several ways. The intermodal accessibility index captures the concentration of services around central nodes, while the demographic coverage metrics translate these patterns into tangible social disparities. These findings empirically confirm that the environmental benefits of bike-sharing, emphasized in global research (DeMaio, 2009; Zhang and Mi, 2018), are contingent on intermodal integration, which in Trento is unevenly distributed.

In the specific case of Trento, these dynamics intersect with broader socio-economic inequalities. Data on household incomes for 2023 in Trento collected by ACLI (2023) confirm persistent gaps between central and peripheral districts, providing an additional layer of evidence that infrastructural marginality coincides with lower economic resources. This reinforces the interpretation that mobility inequalities are not only technical or spatial but also embedded in social structures, echoing but also extending recent findings on cycling-related social bias (Giuffrida et al., 2023; Cunha and Silva, 2022).

In addition, the case of Trento highlights how natural geography, particularly altitude, further constrains the expansion of bike-sharing services in mountainous districts. Moreover, by integrating weather data into the analysis, the study introduces a novel climate-resilience dimension, showing how mobility patterns adapt, or fail to adapt, to exogenous shocks.

This combination of spatial, social, and environmental perspectives represents the study's key innovation: it shows how sustainable mobility infrastructures in medium-sized European cities can both support and undermine broader goals of environmental justice, depending on how they are planned and managed.

5.1 Critical Analysis of the Adopted Strategy

The research design adopted for this study carries important strengths but also limitations that must be critically acknowledged.

Strengths

The first strength lies in the integration of multi-source datasets across time and space, combining GTFS transport data, bike-sharing station locations, administrative registers, and ERA5 weather reanalysis with Google Mobility Reports. This allowed the construction of a holistic framework where infrastructural provision, territorial equity, and climate resilience could be analyzed within a unified system.

A second strength is methodological robustness: spatial indices captured intermodality in a transparent way, while GAM models enabled the detection of non-linear behavioral responses to weather, thus enhancing empirical validity. What makes this study innovative overall is its ability to weave together three dimensions – spatial distribution, social equity, and climate resilience – that are often treated separately in the literature. By focusing on a medium-sized European Alpine city rather than a large metropolitan area, it broadens the empirical basis of research on bike-sharing and sustainable mobility, showing that the challenges of intermodality and equity are not confined to global megacities. Moreover, it demonstrates that climate must be integrated as a structural factor in mobility research, not only as a contextual variable.

Weaknesses

Nonetheless, limitations remain. The absence of trip-level data limited our capacity to assess actual substitution patterns between bike-sharing and other modes, restricting the analysis to potential rather than realized intermodality. Similarly, the reliance on relative indices from Google Mobility Reports constrained comparability across regions and precluded precise estimation of absolute behavioral shifts. A further limitation stems from the availability of data across different temporal domains. Google Mobility Reports are no longer updated beyond 2022, which imposed a natural boundary on the temporal scope of behavioral analysis. Conversely, infrastructural data for Trento's bike-sharing system and public transport network are only available in their current configuration (2025), with no historical records accessible. Given this asymmetry, the research design necessarily combined past behavioral data (2020–2022) with present-day infrastructural data. While this temporal mismatch introduces a structural limitation, it also functions as a methodological innovation: by juxtaposing behavioral responses to past shocks (pandemic disruptions, climatic variability) with the infrastructure currently in place, the analysis highlights systemic vulnerabilities and potential misalignments between demand and supply. In this sense, the constraint became an opportunity to develop a "historical-structural" approach that informs prospective planning.

Potential Improvements

Future research should address these gaps by obtaining aligned historical GTFS datasets and, crucially, access to trip-level bike-sharing records. This would allow demand modeling and better assessment of whether intermodality potential translates into actual use. Extending the framework to cross-city comparisons would also enhance generalizability, helping to determine whether the layered inequalities identified in Trento reflect broader dynamics in medium-sized European cities or specific local conditions. Additionally, incorporating socio-demographic microdata (e.g., census-based commuting patterns or income statistics at finer spatial scales) would permit a stronger operationalization of vertical equity, complementing the horizontal measures employed here.

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