Transport Disruption Vulnerability in Europe: Who Is Worse Off?

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Abstract. Mobility inequality remains a persistent dimension of social disadvantage across Europe, yet its spatial patterns and structural determinants are insufficiently understood across scales. This study offers a dual-scale analysis of transport vulnerability, combining an EU-wide assessment with a regional focus on Italy, with particular attention to disparities between inner and non-inner areas. At the European level, vulnerability is operationalized through three key dimensions: workforce adaptability, transport system resilience, and transport affordability and choice. Using harmonized Eurostat data and the COVID-19 pandemic as a stress test, the analysis identifies a significant resilience gap across EU member states. Italy, together with eight other EU countries, falls within a car-dependent profile in which limited telework capacity and widespread car ownership mask structural fragilities, especially in peripheral areas. Zooming into this context, the Italian case reveals how car dependency translates into tangible mobility. Residents of inner areas (with limited access to essential services) exhibit significantly lower mobility dispersion, with women displaying more spatially confined movement patterns. By linking EU-level structural conditions to territorial evidence, the study contributes to a multi-scalar understanding of mobility justice and argues that effective measures, from ticketing and fares reforms to infrastructure investment, must align with local capacities to advance mobility justice, foster resilience, and ensure that no region or group remains persistently "worse off" in the face of future disruptions.

Keywords: Transport disruption · Transport vulnerability · Inner areas · Transport policy

1 Introduction

Across Europe, participation in social, economic, and civic life depends on access to safe, reliable, and affordable transport, yet this access is highly uneven across territories and social groups. Persistent socio-economic disparities, spatial inequalities, demographic change, and the increasing frequency of disruptive events have heightened concerns about how vulnerable populations cope when transport systems are disrupted [1]. In this perspective, transport disadvantage is best understood not as a simple lack of mobility supply, but as a multidimensional condition shaped by exposure to disruptions, sensitivity to their impacts, and unequal capacities to anticipate, absorb, adapt, and recover [2].

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Recent research highlights the close interdependence between transport vulnerability and resilience. Vulnerability captures pre-existing conditions of exposure and sensitivity, while resilience refers to the capacity of systems and users to cope with and recover from disruptive events. Groups already facing transport poverty, i.e., limited availability, accessibility, affordability, and adequacy of transport, tend to have lower preparedness and adaptability, making them less able to cope with shocks. Conversely, inclusive system design, targeted policies, and better preparedness can enhance resilience and reduce risks of long-term social exclusion [3].

Within the European Union (EU), these issues increasingly manifest along a core–periphery gradient. A substantial share of the population faces transport poverty, with significant disparities across regions, income groups, and demographic categories. Rural and peripheral areas, outermost regions, and socio-economically deprived urban neighborhoods are particularly affected, often combining limited transport provision with high exposure to climate risks and weak institutional capacity. Disruptions in such contexts can trigger cascading effects, including job loss, missed healthcare, educational disadvantages, and social isolation [4].

This paper examines how vulnerability to transport is structured across socio-spatial scales in the EU, with a particular focus on inner and peripheral areas, using Italy as a case study. Vulnerability is operationalized through three interlinked pillars: affordability (financial constraints and car dependence), adaptability (workforce capacity for remote work), and system resilience (recovery of public transport systems). Using the COVID-19 pandemic as a universal stress test, we examine how these dimensions interact across EU member states and identify where car-dependent populations in rural and inner areas are most exposed to structural weaknesses of mobility.

The study makes two main contributions. Conceptually, it advances a multi-scalar framework that links EU-level structural conditions with small-scale territorial evidence, treating transport vulnerability as a relational and context-dependent phenomenon shaped by the interaction between socio-economic characteristics and transport system configurations. The three-pillar approach, exploring adaptability, resilience, and affordability, captures labor-market, infrastructural, and financial constraints simultaneously, offering a more comprehensive perspective than single-dimension frameworks. Methodologically, the research integrates two analytical approaches that are rarely combined: (i) a macro-level statistical analysis of harmonized European datasets, enabling cross-country comparison and the conceptualization of vulnerability profiles; and (ii) a regional analysis based on mobile phone data, using an entropy index to measure the spatial dispersion of mobility with high granularity. The COVID-19 pandemic serves as a temporally consistent benchmark for assessing system responses across all EU member states. Structural vulnerabilities identified at the European scale are traced in their concrete regional manifestations, providing a replicable framework for multi-scalar analysis of transport disparity.

The remainder of the paper is structured as follows. Section 2 reviews the evolution of the concepts of transport vulnerability and resilience, with particular attention to socio-spatial inequalities. Section 3 presents the methodological framework for operationalizing vulnerability at the EU macro-level and at the regional scale, including the selection of indicators and data sources. Section 4 reports and discusses empirical results,

highlighting spatial patterns of deprivation, adaptability gaps, and resilience gaps, and identifying vulnerability hotspot profiles in inner and peripheral areas at both scales of analysis. Finally, Sect. 5 concludes by outlining policy implications for mobility justice and territorial resilience.

2 Literature Review

Research on transport vulnerability and resilience has developed along partly distinct but increasingly convergent stands. Early work in transport engineering and network science conceptualized vulnerability primarily as a system-level property, focusing on the susceptibility of networks to failures or capacity reductions and measuring impacts on performance, connectivity, and serviceability [5]. While this approach was effective in identifying critical links, bottlenecks, and recovery dynamics, it largely treated demand as homogeneous and paid limited attention to the differentiated social consequences of disruptions. In parallel, resilience was included in transport research through ecological and system-thinking perspectives. Starting with Holling's [6] work, resilience was defined as the capacity of a system to absorb disturbances, adapt to changing conditions, and maintain essential functions without shifting into an undesirable state. Subsequent distinctions between "engineering" resilience (rapid return to equilibrium) and broader socio-ecological resilience (adaptation, learning, and transformation) shifted the focus beyond technical robustness toward governance, institutional capacity, and user behavior. Within this perspective, vulnerability and resilience are increasingly understood as complementary dimensions: the former captures structural exposure and sensitivity, the latter reflects the dynamic capacity to respond and recover [2, 7].

More recent literature reframes transport vulnerability as a multidimensional and relational condition arising from the interaction between infrastructure, socio-economic characteristics, and spatial context. Disruptions do not affect all users equally; rather, their impacts are mediated by income, employment conditions, gender, age, disability, and residential location. Low-income households, for example, face affordability constraints and greater dependence on often fragile public transport systems, limiting their ability to absorb additional costs or adapt to service disruptions. In contrast, higher-income groups typically benefit from diversified mobility options and greater flexibility, including access to remote work [3]. Employment conditions and spatial context further shape vulnerability. Workers in location-dependent or low-wage occupations have limited flexibility and are more exposed to service disruptions, whereas knowledge-based workers can more easily adjust schedules or work remotely. Rural, peripheral, and low-density areas tend to have less modal diversity, fewer alternative routes, and longer distances to essential services. In such situation, even minor disruptions can produce significant accessibility losses. The notion of "forced car ownership" captures how residents may rely on private vehicles despite financial constraints due to the absence of viable alternatives, thereby increasing exposure to fuel price volatility and maintenance costs [8]. In urban settings, deprived or peripheral neighborhoods often experience lower service quality, weaker redundancy, and higher disruption risks than more central areas, reinforcing pre-existing inequalities in accessibility and safety [9].

Other socio-demographic factors reinforce these inequalities. Older adults and persons with disabilities depend on specific infrastructure and accessibility features and

may lack the capacity to reroute or switch modes during disruptions, leading to temporary or prolonged immobility. Gendered travel patterns, shaped by care responsibilities and safety concerns, make women particularly sensitive to disruptions that break trip chains or require unfamiliar routes. Migrants and ethnic minorities may face language and information barriers, especially when disruption information is not accessible or multilingual, with direct impacts on residential segregation. Across these dimensions, limited preparedness, constrained resources, and reduced access to information translate into lower adaptive capacity and resilience, even where nominal exposure to disruptions is similar [10].

Comparative research confirms that transport disruptions exacerbate pre-existing socio-spatial inequalities, with consequences for access to employment, healthcare, education, and social participation. In the EU, recent evidence highlights that transport poverty is widespread, with particularly acute problems in rural and peripheral areas, outermost regions, and socio-economically deprived urban neighborhoods. These territories often combine weak transport provision, higher exposure to climate and infrastructure risks, and limited institutional capacity. Inner and peripheral areas thus emerge as key arenas where socio-economic disadvantage intersects with fragile mobility systems.

The literature review provides three key insights for this study. First, transport vulnerability and resilience are deeply social as well as technical, and must be analyzed jointly, as interdependent dimensions linking structural conditions with dynamic responses. Second, vulnerability is inherently multi-scalar and shaped by the interaction between socio-economic characteristics and spatial context, with peripheral areas often facing compounded disadvantages in both exposure and adaptive capacity. Third, addressing transport disadvantage requires analytical frameworks and policy approaches that explicitly link equity, mobility justice, and territorial resilience. These insights motivate the analytical approach adopted in this paper, combining EU-wide assessments with regional analyses to capture how structural vulnerabilities materialize across territories.

3 Method and Data

This section translates the conceptual framework into measurable indicators at the EU and regional levels. The goal is to capture how affordability, adaptability, and system resilience combine to shape vulnerability to transport disruptions, then looking at how the analytical framework translates in people's behavior at the regional scale.

3.1 EU-Level Vulnerability Assessment

The macro-scale analysis draws on Begic et al. [11] and uses harmonized Eurostat datasets to operationalize transport vulnerability across three dimensions. Workforce adaptability is measured by the percentage of employed persons who never work from home [12]; transport system resilience by the change in public transport modal share relative to the 2019 pre-pandemic baseline [13]; and transport affordability and choice by the share of the population who cannot afford a car, complemented by the enforced lack of a car indicator [8, 14]. Coverage extends to all EU member states plus Norway and Switzerland, which are already integrated into the EU-wide statistical framework.

The COVID-19 pandemic serves as a universal stress test, providing a temporally consistent dataset that allows comparison of a pre-disruption baseline (2019), a shock phase (2020–2021), and a recovery trajectory (2022–2024). The analytical approach combines spatial mapping of socio-economic deprivation, country-by-country tracking of each vulnerability dimension, and a synthesis graph that classifies national profiles by workforce adaptability and car affordability, enabling the identification of distinct vulnerability hotspot typologies across the EU landscape, with emphasis on the core-periphery divide.

3.2 Regional-Scale Empirical Case: Friuli Venezia Giulia (FVG)

To investigate how the structural vulnerability conditions identified at EU level materialize in territorial mobility patterns, the study proposes a regional-scale analysis of FVG, in northeastern Italy, building on a recent big-data approach by Bertocchi et al. [15]. FVG is a border region with strong rural-urban and rural-touristic divide (Fig. 1).



Fig. 1. Friuli Venezia Giulia (FVG): location and inner and non-inner areas. Own elaboration on [15, 16].

The empirical base is a cell phone big data (CBD) dataset using cell-ID signal covering trips performed within FVG throughout 2023 by 86 million unique travelers across 204 analytical units (i.e., the smallest possible administrative subdivision, either a municipality or a district of a larger town). Data are disaggregated by gender and residential location, and trips are classified into five user clusters based on distance and origin-destination characteristics. These are short- and long-distance commuters (who return to the starting point daily; SC and LC), short- and long-distance travelers (who do not start and end the day at the same location, ST and LT), and Italian visitors (who enter or exit FVG from neighboring regions). To measure mobility dispersion across the region's 204 analytical units, a Shannon entropy index [17] is calculated separately by gender and traveler type (Formula 1):

$$H = -\sum_{i=1}^{n} p_i \cdot \ln(p_i) \tag{1}$$

Where:

- n is the total number of destinations;
- p_i is the proportion of trips directed to each area i relative to total trips;
- ln is the natural logarithm, used to calculate the contribution of each destination to the entropy H.

The index is then normalized enabling cross-group comparability (Formula 2):

$$\overline{H} = \frac{H}{\log(n)} \tag{2}$$

Where $log(n)$ is the maximum possible entropy if movements are evenly distributed across all 204 areas.

A key analytical distinction is drawn between inner areas (defined as municipalities with restricted access to essential services; Italian Territorial Cohesion Strategy [16]) and more connected non-inner areas, allowing the study to empirically examine how car dependency and territorial isolation compound mobility disadvantage at the sub-national scale.

4 Results

Before examining transport-specific dimensions, it is essential to establish where socio-economic vulnerability is concentrated. Analysis of material and social deprivation rates by degree of urbanization, based on [8, 18] reveals a clear and policy-relevant divide: in Eastern and Southern European countries (Romania, Bulgaria, Hungary, Greece, Slovakia, Croatia), deprivation is predominantly rural, while in many Western European countries (Belgium, Netherlands, France, Germany, Spain), it is concentrated in urban areas. This spatial pre-condition is critical because it determines how transport vulnerability manifests [19]: a deprived household in a dense Belgian city faces primarily affordability challenges within a relatively functional public transport network, whereas a deprived rural household in Romania confronts a fundamental lack of viable alternatives to the private car.

The workforce adaptability analysis confirms a deep resilience asymmetry. Countries with high adaptability (Norway, the Netherlands, and Ireland) recorded reductions of 20–35% in the share of workers who never work from home during the pandemic peak and have largely sustained these gains. In contrast, countries in Southern and Eastern Europe showed much weaker adaptation, peaking at only 7.5% for the most vulnerable group, with a notable snap-back toward pre-crisis norms by 2023. The public transport resilience dimension compounds this picture: while high-resilience countries such as Spain, Portugal, and Ireland rebounded to modal share levels more than 10% above their 2019 baseline by 2023, the low-resilience group, predominantly Eastern European and Baltic states, remained 20 to 30% below pre-pandemic ridership.

A graphical synthesis of these dimensions is shown in Fig. 2, linking car affordability and workforce adaptability based on Eurostat [12, 14]. Four national vulnerability profiles emerge. The most critical is the "vulnerable hotspot" quadrant (Bulgaria, Greece, Hungary, Latvia, Lithuania, Romania, Slovakia), where people can neither work from

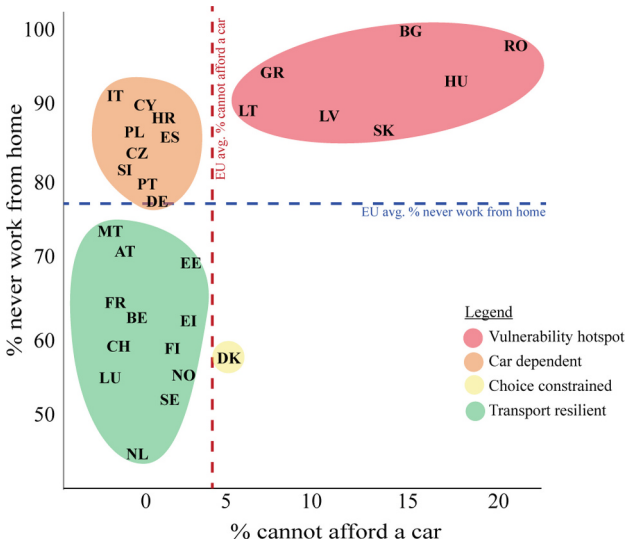

Fig. 2. Transport vulnerability, car dependency, choice constraint, and transport resilience in the EU. Own elaboration on [11].

home nor afford a car, leaving them trapped between low adaptive capacity and poorly performing public transport. Italy, together with Croatia, Germany, Poland, Portugal, and Spain, falls within the car-dependent quadrant: limited telework capacity is combined with predominantly sufficient car ownership, masking a structural fragility: households are vulnerable to fuel price shocks and any disruption that severs car-based access, precisely because no robust public transport alternative exists. This profile sets the context for the regional-scale investigation, which uses CBD to understand who moves where, and how, looking at disparities between inner and non-inner areas as well as between genders.

Across approx. 427 million trips recorded in FVG in 2023, volumes vary considerably by user type (Table 1). SC and ST generate by far the largest shares (252 and 90 million trips respectively), reflecting the dominance of routine, local mobility. LC and LT account for smaller flows, while IT exhibit, as expected, a strong seasonal pattern, peaking in August and driven primarily by tourism.

Entropy analysis reveals meaningful differences in the spatial dispersion of mobility across user groups and gender (Table 1). ST record highest entropy, reflecting a high degree of variability in destination choices. In contrast, LC show lowest entropy, indicating more spatially concentrated and predictable movements. SC score an intermediate value, with high trip volumes and limited territorial range. User type classification, then, is confirmed as a strong predictor of regional mobility behavior, showing the potential of CBD analysis in understanding mobility choices and patterns and thus effectively targeting transport policy. Gender analysis introduces a secondary but consistent modulation of this pattern: men display slightly higher entropy (i.e., spatial reach) than women across all user types, a different that becomes more pronounced in inner areas and during the winter months, suggesting that the mobility disparities in disadvantaged territories are

Table 1. Trips by user cluster and gender, and normalized entropy. Own elaboration on [15]

User cluster	Total trips	Trips by men & women (%)	Normalized Entropy Index $\overline{H}$
LT	17,701,603	59–41	0.0226
ST	90,121,171	56–44	0.0234
IT	19,284,705	60–40	0.0226
SC	252,323,371	55–45	0.0225
LC	47,406,740	56–44	0.0201
Total	426,837,590	56–44	0.0222

even more pronounced for women, worsening gendered constraints on mobility range and opportunity access, in line with findings of recent literature [20, 21].

The contrast between inner and non-inner areas provides other significant findings. In addition to exacerbating the gender gap, inner areas (82 small municipalities in FVG) exhibit substantially and statistically significant lower entropy for all users, throughout the year. This gap is most pronounced in the winter months, when the absence of leisure-driven travel removes the partial compensation that seasonal tourism provides during summer. Read in conjunction with the EU-level finding that Italy falls within a car-dependent vulnerability profile, these results indicate that territorial isolation in inner areas translates into a concrete and measurable reduction in mobility range, even more so for women and for residents of inner areas. This condition, reflecting the absence of viable public transport alternatives, carries direct implications for access to employment, healthcare, and essential services.

5 Conclusions

This study has examined how vulnerability to transport disruptions and mobility disparity are socially and spatially structured across spatial scales, from the EU-wide distribution of socio-economic exposure and adaptive capacity to the concrete patterns of territorial mobility in a car-dependent regional context. By critically elaborating on a macro-level statistical framework [11] with a regional big data analysis [15], it has shown that vulnerability is neither random nor uniform, but follows identifiable structural patterns shaped by the interaction of transport system profiles, labor market characteristics, and territorial conditions.

At the European scale, the findings confirm a persistent and geographically patterned resilience gap. The "non-teleworkable, car-constrained" hotspot, concentrated in Southeastern Europe and the Baltic states, represents a dual bind in which individuals lack both the crucial option of remote work and access to a recovering public transport system. Italy and comparable car-dependent countries occupy a structurally distinct but equally fragile position: widespread car ownership masks an underlying vulnerability to any disruption that raises the cost or feasibility of private car use, without a resilient public transport network available as a substitute. The same disruptive event therefore

produces fundamentally different consequences depending on whether populations have modal redundancy, digital work flexibility, and system capacity to absorb shocks.

At the regional scale, the FVG analysis gives empirical substance to these structural observations. Traveler type emerges as the primary determinant of mobility dispersion, with short-distance commuters (SC) and intra-province travelers (ST) generating the largest volumes of routine, local trips, while long-distance travelers (LT) exhibit more concentrated spatial patterns. The most consistent and statistically significant divide, however, runs between inner and non-inner areas: residents and travelers originating in inner territories display systematically more confined mobility throughout the year, a gap that widens for women and in winter.

Together, these findings demonstrate that transport disadvantage cannot be treated as a universal condition tractable with uniform solutions. Indeed, it requires differentiated, context-calibrated policy responses that align financial instruments, labor market flexibility, digital inclusion, and transport investment with the specific structural profile of each territory. Strengthening transport resilience should be framed as a public health, social inclusion, and socio-economic stability strategy, capable of reducing cascading risks such as income loss, missed healthcare, and long-term exclusion from civic life.

Despite allowing for interesting and high-value policy insights, this research has some limitations. At the EU scale, the analysis relies on macro-level national indicators that, while enabling consistent cross-country comparison, necessarily mask within-country heterogeneity and sub-national variation in vulnerability conditions. At the regional scale, the cell phone big data (CBD) approach captures spatial mobility patterns with high granularity but does not provide information on trip purpose or transport mode, limiting the extent to which observed differences in mobility dispersion can be directly attributed to specific structural constraints such as car dependency or public transport absence. Across both scales, the descriptive and typological nature of the analysis means that causal mechanisms behind observed patterns cannot be fully established. Future research could bridge these levels more explicitly by integrating micro-data, applying multilevel modelling or causal inference methods to test which socio-economic characteristics and system features jointly produce or sustain transport vulnerability. By identifying where vulnerability hotspots are located and how they manifest across scales, from structural resilience gaps at EU level to mobility disparities in inner areas, this paper provided a system-level basis for designing integrated policies that support territorial resilience and ensure that no region or group remains persistently worse off in the face of future disruptions or lasting disparities.

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