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# Analysis of socio-economic vulnerability to transport disruptions in the European Union☆,☆☆

Hamza Begic[a],*, Francesco Bruzzone[b], Silvio Nocera[b], Constantinos Antoniou[a]

[a] *Technical University of Munich, Arcisstraße 21, 80333 Munich, Germany*
[b] *Università Iuav di Venezia, Santa Croce 191, 30135 Venice, Italy*

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ABSTRACT

This research investigates the multi-dimensional nature of transport vulnerability among socio-economic groups across the European Union (EU), focusing on their exposure and adaptability to transport disruptive events. The study establishes a comprehensive framework for measuring transport vulnerability through three core pillars: affordability, adaptability, and system resilience, which are synthesized into a Vulnerability Structural Index, a composite country-level score reflecting exposure to future disruptions. Utilizing a macro-level analysis of pan-European datasets, the study employs the COVID-19 pandemic as a universal stress test to evaluate these dimensions. As a first step in interpreting these impacts, the analysis maps the spatial distribution of socio-economic deprivation, revealing a clear divide between Western and Eastern Europe: deprivation is predominantly urban in Western and largely rural in Eastern Europe. Building on the spatial analysis, the results identify a significant resilience gap between EU member states, characterized by persistent vulnerability hotspots primarily located in Southeastern Europe and the Baltics. Populations in these regions face a dual burden: they exhibit the lowest workforce adaptability, while simultaneously being hindered by low transport affordability and public transport systems experiencing a persistent decline in modal share relative to other transport modes following the pandemic. The paper provides a strategic roadmap for policymakers by demonstrating that effective interventions must be calibrated to existing national infrastructure profiles. The analysis offers a context-specific approach to mobility justice, ensuring that policy decisions, ranging from financial subsidies in high-transit regions to structural investments in underdeveloped areas, are aligned with the capabilities of the transport system.

## 1. Introduction

Across Europe, the ability to participate fully in social, economic, and civic life is deeply intertwined with access to safe, reliable, and affordable transport systems. Yet this access is unevenly distributed. Persistent socio-economic inequalities, spatial disparities, demographic change, and the growing frequency of disruptive events, from extreme weather and climate-related hazards to infrastructure failures and strikes, have intensified concerns about transport vulnerability among priority populations (European Commission, 2024; Pregnolato & Dawson, 2018). In this context, transport disadvantage is no longer understood solely as a problem of insufficient mobility supply. Rather, it is a multidimensional condition shaped by exposure to disruptions, sensitivity to their impacts, and (unequal) capacities to anticipate, absorb, adapt, and recover (Reggiani et al., 2015). The recent acknowledgment of these aspects contributed to extending the interests of transport researchers and practitioners, surpassing efficiency-oriented logic and embracing social concepts such as equity, vulnerability and resilience (Bruzzone et al., 2023; Martens, 2017). The relation between vulnerability and resilience, both intended in their socio-technical and social dimensions, is central to understanding transport disadvantage among different population groups. There is growing awareness that the two concepts are deeply intertwined: vulnerability delineates pre-existing conditions of exposure and sensitivity, while resilience reflects the capacity to cope with, adapt to, and recover from disruptive events (Sun et al., 2020). Groups experiencing transport poverty, characterized by limited availability, accessibility, affordability, and

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* Corresponding author.
*E-mail addresses:* hamza.begic@tum.de (H. Begic), fbruzzone@iuav.it (F. Bruzzone), nocera@iuav.it (S. Nocera), c.antoniou@tum.de (C. Antoniou).

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adequacy of transport, tend to display lower preparedness for disruptions and reduced adaptability when services are altered or interrupted. Conversely, enhancing resilience through inclusive design, targeted policies, and improved preparedness can mitigate vulnerability and reduce the risk of long-term social exclusion (European Commission, 2024).

Within the European Union, these issues have gained renewed policy relevance. Recent EU-level evidence highlights that a substantial share of the population faces transport poverty, with marked differences across income groups, regions, and demographic categories. Rural and peripheral areas, outermost regions, and socio-economically deprived urban neighborhoods are particularly affected (Lawrence et al., 2025; Liu & Yu, 2025), often combining weak transport provision with high exposure to climate risks and limited institutional capacity (Bertocchi et al., 2025; Maucorps et al., 2025). Disruptions in these contexts can lead to cascading effects, including job loss, missed healthcare appointments, educational disadvantages, and social isolation (Carvalho & El-Geneidy, 2025).

Against this background, this paper addresses the theme of transport disadvantage among priority populations by focusing explicitly on the link between transport vulnerability and resilience. It synthesizes conceptual and empirical insights on how different vulnerable groups experience, perceive, and respond to transport disruptions across Europe or comparative contexts. By situating vulnerability within a resilience-oriented framework, the paper seeks to move beyond static descriptions of disadvantage and towards a dynamic understanding of how inequalities are reproduced or mitigated through transport planning and policies, particularly in times of uncertainty. The remainder of this paper is structured as follows:

- Section 2 draws a state-of-the-art of the scientific literature, defining transport vulnerability and resilience according to recent understanding of the scientific community.
- Section 3 presents the methodological framework used to operationalize vulnerability at the EU level, including the selection of indicators, data sources, and the analytical approach linking socio-economic characteristics to disruption-related risks.
- Section 4 reports the empirical results of the macro-level analysis, identifying spatial patterns of socio-economic vulnerability, differences in workforce adaptability and transport system resilience, the construction of a vulnerability index synthesizing these dimensions into a single composite score, and the emergence of country-level vulnerability hotspot profiles.
- Section 5 highlights the study's system-level perspective and outlines opportunities for future research, including the potential integration of household-level micro-data and expected availability of updated survey waves.
- Section 6 concludes the paper by summarizing the main findings.

## 2. Literature review

The concepts of transport vulnerability and resilience have evolved along partially distinct but increasingly convergent research traditions. Early contributions emerged primarily from transport engineering and network science, where vulnerability was conceptualized as a system-level property describing the susceptibility of transport networks to failures, disruptions, or capacity reductions. In this strand of literature, vulnerability is typically defined in probabilistic terms, combining the likelihood of a disruptive event with the magnitude of its consequences for network performance, connectivity, or serviceability (Berdica, 2002; Jenelius & Mattsson, 2015; Sun et al., 2015). These studies have provided important insights into critical links, bottlenecks, redundancy, and recovery dynamics, but they largely treat users as homogeneous demand units and rarely address how disruptions translate into differentiated social impacts.

In parallel, resilience was introduced into transport research through ecological and system-thinking perspectives. Drawing on the foundational work by Holling (1973), resilience is understood as the capacity of a system to absorb disturbances, adapt to changing conditions, and maintain essential functions without shifting into an undesirable state. Transport scholars subsequently distinguished between engineering resilience, focused on rapid recovery and return to equilibrium, and ecological or socio-ecological resilience, which emphasizes persistence, learning, adaptability, and transformation under uncertainty (Holling, 1996; Wang, 2015). This distinction has been critical in expanding resilience beyond technical robustness to include governance, institutional learning, and human behavior.

Over time, the literature has increasingly recognized that vulnerability and resilience cannot be adequately understood without considering the social distribution of resources, risks, and adaptive capacities. From this perspective, vulnerability is not merely the inverse of resilience, but a related yet distinct concept describing pre-existing conditions of exposure and sensitivity, while resilience captures the dynamic capacity to respond and recover (Reggiani et al., 2015; Seeliger & Turok, 2013). Treating resilience simply as "low vulnerability" risks obscuring the mechanisms through which inequalities shape adaptive capacity and long-term outcomes.

A growing body of research therefore adopts a socio-technical approach, framing transport vulnerability as a multidimensional condition shaped by the interaction of physical infrastructure, socio-economic characteristics, spatial context, and institutional arrangements. In this view, transport systems do not fail uniformly: disruptions shape and are shaped by demographic, socio-economic, and residential self-selection characteristics of communities. Specifically, income, age, gender, disability, employment conditions, education, migration status, and residential location produce uneven impacts across population groups (Cosco et al., 2018; Lucas, 2012; Martens, 2017). Vulnerability is thus relational and context-dependent, reflecting both the characteristics of transport systems and the capacity of individuals and communities to mobilize alternatives.

Income consistently emerges as one of the strongest determinants of transport vulnerability. Low-income households face heightened exposure to disruption impacts due to affordability constraints, limited access to private vehicles or paid alternatives, and greater dependence on public transport systems that may themselves be fragile or under-resourced (Lucas et al., 2019; Rahimi-Golkhandan & Garvin, 2020). During disruptions, these households are often unable to absorb additional costs associated with taxis, ride-hailing, or longer travel times, leading to trip abandonment, lost wages, or reduced access to life opportunities and essential services (Nguyen-Phuoc et al., 2018). In contrast, higher-income groups demonstrate greater resilience through access to financial buffers, flexible work arrangements, teleworking opportunities, and a wider portfolio of mobility options (Vodopivec & Miller-Hooks, 2019).

Employment characteristics intersect strongly with income-related vulnerability. Workers in low-wage, shift-based, or location-dependent occupations typically have inflexible schedules and limited tolerance for lateness or absence. Empirical studies show that such workers are disproportionately affected by transport disruptions, as delays translate directly into income loss or job insecurity (Nguyen-Phuoc et al., 2018; Pnevmatikou et al., 2015). Conversely, professional and knowledge-based workers often benefit from temporal flexibility and remote-working options, enhancing their adaptive capacity and reducing exposure to disruption-related risks.

Spatial context is another critical dimension of transport vulnerability. Rural, peripheral, and low-density areas tend to exhibit lower transport diversity, fewer alternative routes or modes, and longer distances to essential services. As a result, disruptions in these contexts can produce severe accessibility losses even when physical damage is limited (Jenelius & Mattsson, 2015; Pregnolato & Dawson, 2018). Research on transport poverty highlights phenomena such as "forced car ownership" in rural areas, where households maintain vehicles despite financial hardship due to the absence of viable public transport alternatives, increasing vulnerability to fuel price shocks, vehicle breakdowns, or road disruptions (Lucas et al., 2016).

Urban contexts exhibit different but equally significant vulnerability patterns. Residents of deprived or peripheral urban neighborhoods often experience lower service quality, poorer reliability, and weaker redundancy than those in central or affluent areas. Studies from European and North American cities show that transit routes serving disadvantaged populations are more likely to suffer from delays, diversions, or capacity reductions during disruptions, reinforcing preexisting inequalities in accessibility and safety (Liu et al., 2020; Liu & Shalaby, 2024; Palm et al., 2020). These operational inequities mean that vulnerable groups often experience transport systems as less reliable even under normal conditions, reducing baseline resilience and exacerbating the impacts of already inequitable residential self-selection mechanisms.

Age and physical ability are also widely recognized as key vulnerability factors. Older adults and persons with disabilities frequently depend on specific infrastructure, such as elevators, low-floor vehicles, or paratransit services, and may have limited capacity to switch modes or routes when disruptions occur (Papangelis et al., 2016; Rahimi-Golkhandan & Garvin, 2020). Disruptions that eliminate familiar, accessible options can therefore result in complete immobility, with significant consequences for access to healthcare, social participation, and personal safety. These effects are compounded by digital divides, as older and mobility-impaired individuals may have reduced access to real-time information or app-based services that support adaptive travel behavior (Garritsen et al., 2025; Kaselouris et al., 2025; Oh et al., 2026).

Increasing scholarly attention has moreover been dedicated to the gendered dimensions of transport vulnerability and resilience. Women's travel patterns are often characterized by complex trip-chaining related to caregiving responsibilities, as well as heightened sensitivity to safety and security concerns (Hanson, 2010; Loukaitou-Sideris, 2014). Disruptions that remove key links in these chains can have cascading effects on employment, childcare, and household functioning. Moreover, fear of harassment or violence may limit women's willingness to use unfamiliar routes or modes during disruptions, constraining adaptive capacity and reinforcing vulnerability.

Migration status, ethnicity, and language proficiency further shape vulnerability and resilience. Migrants and ethnic minorities may face barriers in understanding disruption-related information, navigating alternative routes, or interacting with transport authorities, particularly when information is not provided in accessible or multilingual formats (Dong et al., 2020; Markovich & Lucas, 2011). These challenges often intersect with residential segregation and lower-quality transport provision, producing compounded forms of disadvantage during disruptions.

Across these socio-economic dimensions, preparedness and adaptability emerge as central mediators between vulnerability and resilience. Preparedness refers to the extent to which individuals and institutions anticipate disruptions and have plans, knowledge, or resources in place to manage them, while adaptability captures the ability to modify behavior, schedules, or mode choices in response to changing conditions (Hollnagel, 2011; Walker et al., 2004). Empirical evidence consistently shows that vulnerable groups tend to exhibit lower preparedness and adaptability due to constrained resources, limited information access, and rigid daily routines, resulting in reduced resilience even when exposure levels are similar.

Comparative international research reinforces these conclusions. Studies from North America, Australia, and developing country contexts demonstrate that transport disruptions routinely exacerbate existing social inequalities, triggering cascading effects across employment, healthcare access, education, and social networks (Dong et al., 2020; Nguyen-Phuoc et al., 2018). While context-specific mechanisms vary, the underlying pattern is consistent: resilience is unevenly distributed, and those already disadvantaged are least able to absorb and recover from transport-related shocks.

Overall, the literature converges on the understanding that transport vulnerability and resilience are deeply intertwined and fundamentally social in nature. Vulnerability delineates structural conditions of exposure and sensitivity, while resilience reflects differentiated capacities for preparedness, adaptation, and recovery. Addressing transport disadvantage among priority populations therefore requires analytical frameworks and policy approaches that explicitly link these concepts, moving beyond aggregate system performance to foreground equity, safety, and the lived experiences of diverse users.

This literature review refined current theoretical perspectives on transport resilience and vulnerability, with particular attention to how these concepts intersect. Historically, however, the practical application of this theoretical framework, i.e., the study of transport planning, including vulnerability and resilience at the territorial scale, has been largely confined to technical and policy-oriented contributions (Berdica, 2002; Martens et al., 2012). Within the European Union, for instance, European Commission (2024) stands out in this regard. In response to this research gap, this article operationalizes the theoretical framework presented here through an academic approach that is both cross-disciplinary and cross-territorial, in line with the direction suggested by Jenelius and Mattsson (2015). Its objective is to move beyond a purely technical focus by integrating social dynamics and manifestations of vulnerability into advanced conceptualizations of transport resilience and vulnerability. In doing so, it seeks to capture their cross-cutting impacts and contribute to a more comprehensive understanding within the existing literature.

## 3. Methodology for vulnerability assessment

Building on the literature review established in Section 2, this section outlines the methodology for translating these concepts into measurable indicators at the EU macro-level. While the theoretical definitions are multi-dimensional, measuring them across different countries requires identifying specific, consistent proxy indicators from available EU-level datasets. Specifically, this methodology is designed to identify and measure key indicators for preparedness, adaptability and resilience. The core of this chapter is to identify correlations between socio-economic characteristics, such as income, location and work type, along with vulnerability levels to various transport disruptions. This provides the foundation for the analysis in Section 4.

### *3.1. Vulnerability dimensions and indicators*

Acquiring consistent, comparable data for sudden, localized events like natural disasters or energy shocks is challenging. The COVID-19 pandemic provided a rare opportunity in this regard: as a common external shock that impacted every EU member state simultaneously, it generated a valuable dataset allowing for a consistent analysis of the pre-disruption baseline (2019), the shock period (2020–2021), and the recovery phase (2022–2024). While the shock itself was shared, its outcomes were not uniform, as national policy responses, institutional capacities, and behavioral adaptations varied considerably across countries. It is precisely this heterogeneity that makes the pandemic analytically valuable: the divergence in outcomes across countries facing the same external shock reveals the extent to which structural vulnerability and response capacity shape resilience. Based on the conceptual framework and an analysis of available EU-level datasets, including harmonized observations for Norway and Switzerland already integrated into the EU-wide statistical framework, we identified three core dimensions for this macro-level assessment:

1. **Workforce adaptability**: The capacity of a country's workforce to maintain economic activity and access to employment by being able to work from home.

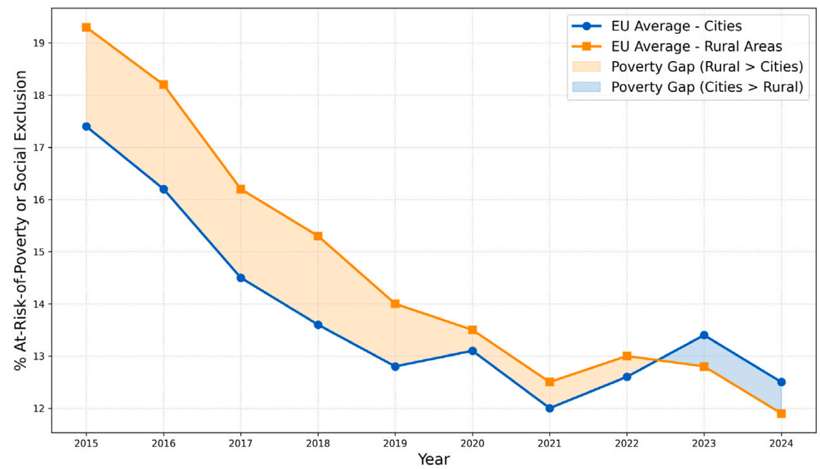


**Fig. 1.** Difference between urban and rural areas in the percentage of population at risk of poverty and social exclusion in the last 10 years.
*Source:* Eurostat (2024d).

- Indicator: Percentage of the population who never work from home in EU countries (Eurostat, 2024a).

2. **Transport affordability and choice**: The degree to which a population is financially constrained in its mobility options, creating forced dependency or immobility.
   - Indicator: Percentage of the population who cannot afford a car in EU countries (Eurostat, 2024c) along with the enforced lack of a car indicator (European Commission, 2024).
3. **Transport system resilience**: The ability of the transport network, specifically public transport, the main alternative to private cars, to withstand a shock and recover its service and user base.
   - Indicator: Percentage of public transport modal share in EU countries (Eurostat, 2024b).

### 3.2. *Analysis and synthesis framework*

The analysis in Section 4 follows a clear narrative structure. We begin by examining each dimension individually, presenting data on the spatial distribution of deprivation, workforce adaptability, and the system resilience of public transport at the EU level. We then synthesize these three dimensions into a Vulnerability Structural Index (VSI), a composite country-level score that reflects structural exposure to future disruptions. Next, we construct a scatter plot of rural car affordability against workforce inflexibility and apply a $k$-means clustering algorithm to identify different vulnerability profiles in this two-dimensional space. We then analyze the consequences for the most vulnerable cluster by exploring divergent trends in teleworking and public transport recovery, which reveal a distinct resilience gap. Finally, the unified findings are discussed in terms of their policy implications, linking the identified vulnerability profiles to context-specific national strategies for strengthening transport resilience and promoting mobility justice.

## 4. Analysis of vulnerability

This section presents the macro-level analysis of vulnerability, following the methodology from Section 3.

### 4.1. *The spatial distribution of vulnerability*

Before analyzing transport-specific factors, it is essential to establish where socio-economic vulnerability is located. The Transport Poverty Report (European Commission, 2024) highlights that although there are issues in rural areas, the vulnerability is not an exclusively rural phenomenon, but an urban one as well. To visualize this, we analyzed material and social deprivation rates by degree of urbanization, using the Eurostat macro dataset *ilc_mdsd09* (Eurostat, 2024d). Fig. 1 shows the EU average “At Risk of Poverty or Social Exclusion” rate, comparing urban (blue line) against rural areas (orange line) over the last decade (2015–2024).

Historically, from 2015 until the pandemic, a consistent poverty gap existed, where deprivation rates in rural areas were significantly higher than in the cities, with the rural–urban gap standing at +1.9 percentage points in 2015 and narrowing steadily to +1.2 percentage points by 2019. During this period, both groups saw a steady decline in poverty, with rural rates falling from 19.3% to 14.0% and urban rates from 17.4% to 12.8%. Following 2021, this long-standing trend inverted. As deprivation rates began to rise again for both groups, the rate in cities surpassed that of rural areas, with the gap shifting to −0.6 percentage points by 2023 and remaining at that level in 2024 (rural: 11.9%, urban: 12.5%). This shows that urban populations are now, on average, at a higher risk of poverty or social exclusion. A possible explanation for this recent shift is the rising cost-of-living, particularly the housing crisis, which is heavily concentrated in urban centers and adds a significant financial burden to households (European Commission, 2024).

However, this EU-average trend masks significant national differences. The spatial distribution of deprivation, whether it is concentrated in cities or rural areas, depends highly on the specific country, as illustrated in Fig. 2. Using the EU averages as reference points (rural: 11.9%; urban: 12.5%), 13 of 29 countries show higher rural than urban deprivation, while 15 show the opposite pattern, and one (Poland) shows perfect parity. This spatial divide is strongly structured along an East–West axis: Eastern European countries show a mean rural–urban deprivation gap of +5.0 percentage points (positive values correspond to higher rural deprivation), compared to −2.5 percentage points in Western Europe, a difference that is statistically significant ($t = 4.18$, $p < 0.001$). Notably, countries where rural deprivation dominates tend to exhibit substantially higher absolute deprivation levels overall: Romania, Bulgaria, and Greece record rural rates of 34.1%, 36.0%, and 32.1% respectively, with urban rates substantially elevated and well above the average at 18.9%, 20.9%, and 28.7%. In contrast, the lowest rural deprivation rates are recorded in Malta (1.7%), Netherlands (3.3%), Austria (4.0%), and Switzerland (4.0%), all of which

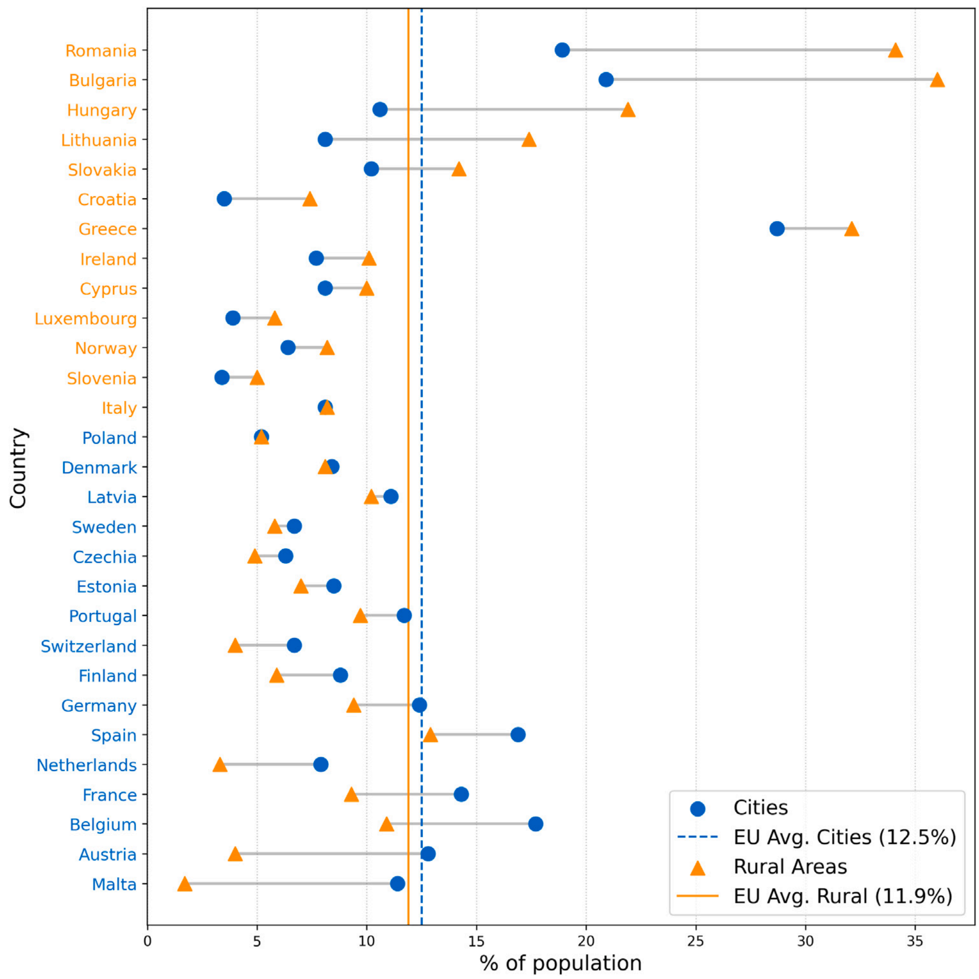


**Fig. 2.** Average differences of the percentage of material and social deprivation rate in the EU, 2024.
*Source:* Eurostat (2024d).

simultaneously exhibit considerably higher urban than rural deprivation rates (11.4%, 7.9%, 12.8%, and 6.7% respectively), reinforcing the pattern of urban-concentrated vulnerability in Western Europe. Poland (5.2% vs. 5.2%), Italy (8.1% vs. 8.2%), and Denmark (8.4% vs. 8.1%) represent countries with the most balanced urban–rural profiles, with near-identical rates across both spatial contexts.

This spatial divide is an important pre-condition. Vulnerability to transport disruptions will manifest differently depending on this context. A deprived household in a dense urban area in Belgium faces different challenges (e.g., affordability of public transport) then a deprived household in a sparse rural area in Romania, that faces a fundamental lack of availability of any alternative to private cars. This spatial isolation is critical because essential services like employment, education and healthcare are often centralized in urban areas (Eurofound, 2022). As the Transport Poverty Report notes, rural populations already face greater accessibility issues and higher car dependency (European Commission, 2024). Therefore, when a major disruption severs a key transport link, this lack of redundancy means rural populations are disproportionately cut off from essential socio-economic activities, facing more severe consequences that their urban counterparts.

### 4.2. The workforce adaptability gap

A population's ability to work from home is a primary measure of its preparedness and adaptability to any disruption that physically severs access to workplaces. Fig. 3 tracks workforce adaptability by showing the reduction in the population that never works from home, relative to a 2019, pre-COVID baseline. A higher bar signifies a greater positive shift towards teleworking. The different colored bars show the change for each year: 2020 (orange), 2021 (light blue), 2022 (medium blue), 2023 (dark blue), and 2024 (black). The plot clearly shows the pandemic's massive positive impact on telework. In 2020 and 2021, nearly every country saw a significant reduction in people who never work from home, indicating a rapid adoption of remote work.

Two distinct trends are visible. Countries with high adaptability, like Norway, Netherlands and Ireland, saw a high reduction (20%–35%) which they have largely sustained into 2024, retaining 100%, 89%, and 84% of their peak gains respectively. In contrast, many countries, particularly in Southern and Eastern Europe, showed a much lower initial adaptation. Slovakia, Bulgaria, Romania, and Poland peaked at only +6.1, +5.5, +5.3, and +4.4% respectively, roughly five times smaller than the leading group. The EU-wide average peak gain stood at 13.2%, but this aggregate masks the highly skewed distribution between the two groups.

The individual country trajectories reveal further nuance in how this adaptation unfolded. Norway and Netherlands stand out as delayed adopters: both recorded negligible 2020 gains of just +1.6% and +4.9%, before surging to +35.5% and +26.7% in 2021, the two largest single-year jumps in the sample, and holding those levels flat through 2024. This suggests an initial period of institutional adjustment followed by a rapid and durable structural shift. Luxembourg followed the opposite pattern: it was among the fastest initial adopters (+21.7% already in 2020), but subsequently consolidated downward to +14.5% by 2024, retaining 67% of its peak. Denmark, Estonia, and Czechia

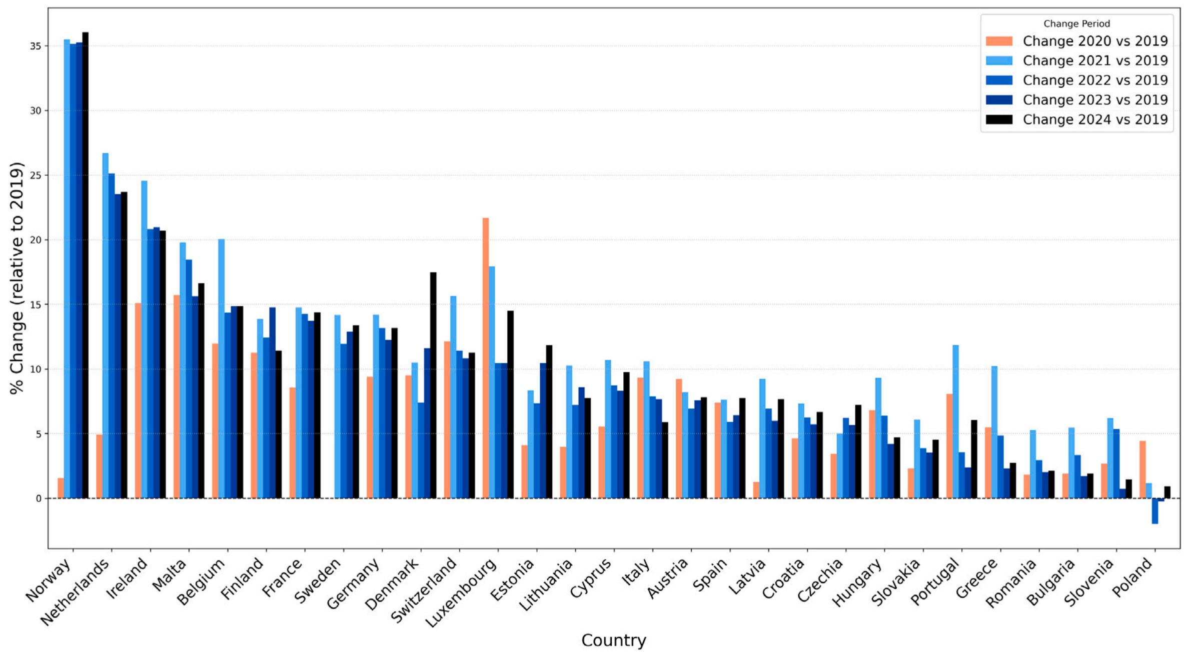


**Fig. 3.** Country-by-country analysis: percentage of reduction of population who never work from home (2019–2024).
*Source:* Eurostat (2024a).

present yet a different trajectory, where all three showed comparatively modest and stable adoption through 2020–2023, followed by a intensive acceleration in 2024 to their highest recorded values of +17.5, +11.8, and +7.2% respectively. Denmark and Estonia exhibit the more pronounced late surge, while Czechia reflects a steadier incremental climb throughout the entire period, with each year broadly building on the last. In both cases, the pattern suggests a delayed but ultimately durable reorientation rather than a crisis-driven spike.

Since the 2021 peak, a general snapback trend has been visible across the board. However, the durability of the shift differs substantially: by 2024, Poland had consolidated to only +0.9% above its 2019 baseline, having briefly dipped below it in 2022 at 2.0%, while Bulgaria stood at +1.9%, Romania at +2.1%, and Slovenia at +1.5%. Critically, all 29 countries still register a positive gain over 2019 in 2024, confirming that the pandemic has produced a lasting, if deeply unequal, structural shift in remote work across the EU.

### *4.3. Transport system resilience*

The resilience of a public transport network is the second key pillar of adaptability. It represents a viable, scalable alternative to private cars. Modal share percentage is used as the indicator for this pillar for two reasons. First, it captures the relative performance of public transport within the overall mobility system. This is empirically significant in the post-pandemic context: while car travel also declined substantially during COVID-19, it recovered to a greater extent than public transport, such that public transport modal share fell persistently between 2019 and 2023 even as total travel normalized (Buehler et al., 2025). This asymmetric recovery is precisely what modal share captures. Second, from a policy-analytical standpoint, modal share serves as a proxy for the structural role of public transport within the national mobility system, reflecting the degree to which public transport functions as a viable alternative to private cars. This is directly relevant to the resilience question at hand: whether a government facing a sudden disruption, such as an energy price shock or infrastructure failure, can realistically redirect travelers towards public transport. A system with chronically declining modal share signals eroding public transport capacity relative to competing modes, irrespective of absolute ridership volumes.

Fig. 4 shows the resilience of public transport systems by tracking their modal share percentage change relative to a 2019 pre-pandemic baseline. The 0% line represents 2019 data, with bars below indicating a drop in usage. The initial 2020 shock was near-universal but far from uniform in scale. The EU-wide average modal share dropped by 26.5%, yet the range spanned from Estonia (−41.3%), Poland (−38.3%), and Lithuania (−38.3%) at the extreme, to Austria (−15.9%), Switzerland (−16.5%), and Romania (−17.5%) at the other end. Notably, ten countries saw their modal share fall by more than 30% in 2020 alone. A further complication emerges in 2021: rather than beginning to recover, thirteen countries recorded a secondary dip, with their 2021 value worse than 2020. Czechia experienced the most severe deterioration, falling a further −13.2% to −40.0% suggesting that the disruption to public transport habits was still deepening well into the second year of the pandemic. The divergence in recovery trajectories is the most analytically significant feature of the data. The 2021–2022 transition marks the decisive inflection point for most countries, with the EU average rebounding from −25.8% to −7.3%, an improvement of 18.5% in a single year. Denmark led this recovery surge (+32.9% from 2021 to 2022), followed by Portugal (+27.1%), Netherlands (+27.1%), and Germany (+24.6%). By 2023, twelve countries had fully crossed back above their 2019 baseline, with Spain (+15.0%), Ireland (+12.6%), and Portugal (+10.3%) recording the strongest rebounds. At the opposite extreme, Bulgaria (−26.8%) and Czechia (−22.0%) remained the only two countries still more than 20% below pre-COVID baseline in 2023, with a further nine countries being in the −10% to −20% range.

Bulgaria warrants particular attention as an outlier within the already underperforming group. After a partial recovery to −14.4% in 2022, its modal share collapsed again to −26.8% in 2023, the only country in the sample to record a meaningful re-deterioration after the initial recovery phase, suggesting systemic rather than purely pandemic-driven structural weakness. Romania presents a contrasting anomaly: despite recording one of the mildest initial shocks in 2020 (−17.5%), it has shown no recovery momentum across the entire observation period, standing at −11.4% in 2023, pointing to a chronic underlying fragility that predates the pandemic disruption itself. Interestingly, Norway and Sweden also show a surprisingly weak recovery (−11.3% and −11.2% in 2023), though this is likely driven by different factors, specifically the permanent cultural shift towards high telework

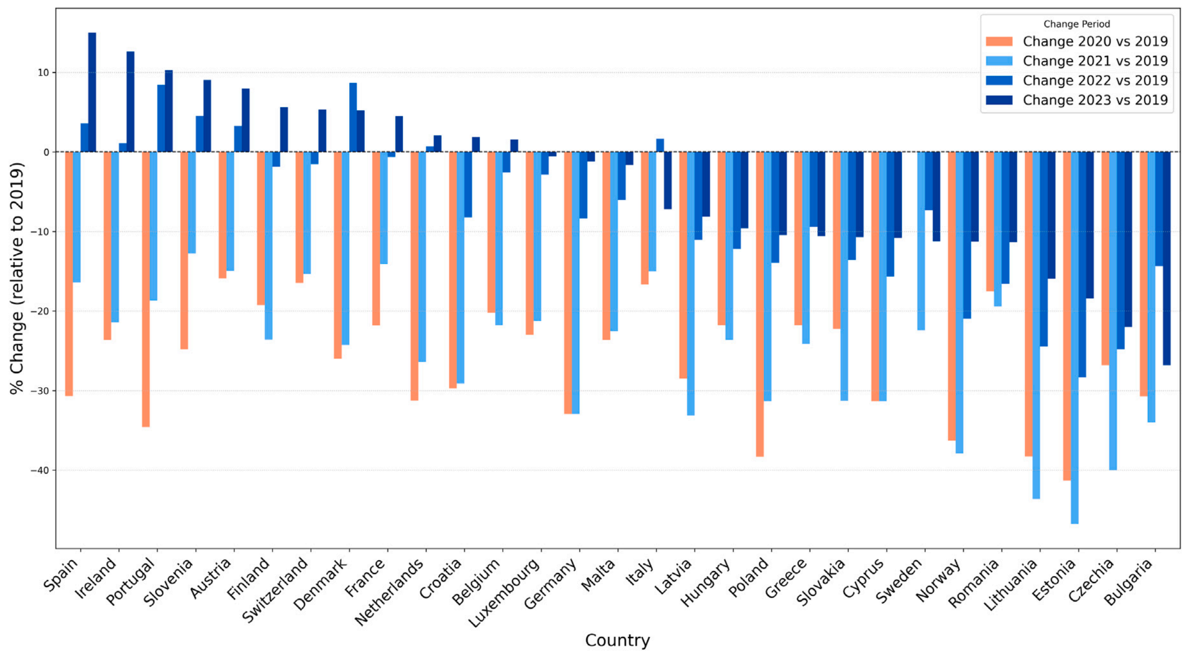


**Fig. 4.** Country-by-country analysis: public transport recovery (2019–2023).
*Source:* Eurostat (2024b).

rates documented in Fig. 3, rather than a failure of public transport supply.

The recovery paths thus reveal two very different stories. A high resilience group, primarily in Western Europe, recovered strongly and surpassed pre-pandemic levels by 2023. Conversely, the low resilience group, particularly visible in Eastern Europe and the Baltics, shows a persistent failure to recover, with modal share still 10%–27% below 2019 levels in 2023. This is not a slow recovery; it appears to be a systematic, multi-year structural weakness.

### 4.4. Vulnerability structural index

The preceding subsections analyzed each vulnerability dimension through the lens of pandemic response, tracking dynamic changes in telework capacity and public transport modal share relative to a 2019 baseline. That temporal perspective reveals how countries adapted during and after the COVID-19 shock. The present subsection complements it by examining the dimensions through their most recent values, constructing a Vulnerability Structural Index (VSI) that reflects each country's structural exposure to future disruptions.

The VSI integrates the three core pillars identified in Section 3 into a single country-level composite score, following established methodology for composite indicators (Nardo et al., 2005). Let $x_{ik}$ denote the raw indicator value for country $i$ ($i = 1, \dots, N$, where $N = 29$ countries) on pillar $k$ ($k = 1, 2, 3$), corresponding respectively to: (1) the share of the workforce that never works from home (2024); (2) the share of the population that cannot afford a car (2024); and (3) the public transport modal share (2023). All three indicators thus reflect the latest available observations at the time of writing.

Because the three pillars are expressed in different units and on different scales, each is first normalized to a $[0, 1]$ interval via min–max normalization. For Pillars 1 and 2, where a higher raw value indicates greater vulnerability, the normalization takes the standard form:

$$\tilde{x}_{ik} = \frac{x_{ik} - \min_j(x_{jk})}{\max_j(x_{jk}) - \min_j(x_{jk})}, \quad k \in \{1, 2\} \tag{1}$$

where $\min_j(x_{jk})$ and $\max_j(x_{jk})$ denote the minimum and maximum values of indicator $k$ across all countries $j$ in the sample. For Pillar 3 the direction is reversed: a higher public transport modal share indicates lower, thus the indicator is inverted prior to aggregation:

$$\tilde{x}_{i3} = 1 - \frac{x_{i3} - \min_j(x_{j3})}{\max_j(x_{j3}) - \min_j(x_{j3})} \tag{2}$$

The VSI for country $i$ is then computed as a weighted sum of the three normalized pillars:

$$\mathrm{VSI}_i = w_1\,\tilde{x}_{i1} + w_2\,\tilde{x}_{i2} + w_3\,\tilde{x}_{i3} \tag{3}$$

where $w_1, w_2, w_3 \geq 0$ and $w_1 + w_2 + w_3 = 1$. In the general-purpose baseline presented here, equal weights are assigned, $w_1 = w_2 = w_3 = \frac{1}{3}$, yielding:

$$\mathrm{VSI}_i = \frac{1}{3}\left(\tilde{x}_{i1} + \tilde{x}_{i2} + \tilde{x}_{i3}\right) \tag{4}$$

Equal weights are adopted to reflect the general-purpose nature of the VSI. Since the index is designed to capture overall transport vulnerability rather than exposure to any specific type of disruption, no single pillar is privileged over the others by default. This design is intentional: policymakers and government bodies should recalibrate the pillar weights $w_k$ to reflect the particular disruption scenario or vulnerable group of interest. For instance, an energy price shock disproportionately affecting low-income households would warrant an increased weight on the affordability and choice pillar, while an infrastructure failure severing physical access to workplaces would call for greater emphasis on workforce adaptability. The VSI ranges from 0 (least structurally vulnerable) to 1 (most structurally vulnerable), with intermediate values reflecting partial exposure across one or more pillars.

Fig. 5 presents the VSI scores alongside the normalized raw values for all three pillars across all 29 countries. Countries are ranked from most to least vulnerable (top to bottom). Each cell is color-coded on a continuous red-to-green scale, where red indicates the highest vulnerability and green the lowest; the vertical separator to the right distinguishes the three individual pillar columns from the composite VSI score column.

Bulgaria (VSI = 0.93), Greece (0.83), Latvia (0.78), and Lithuania (0.77) form the most structurally exposed group in the sample, collectively ranking at the top of the VSI distribution by a substantial margin.

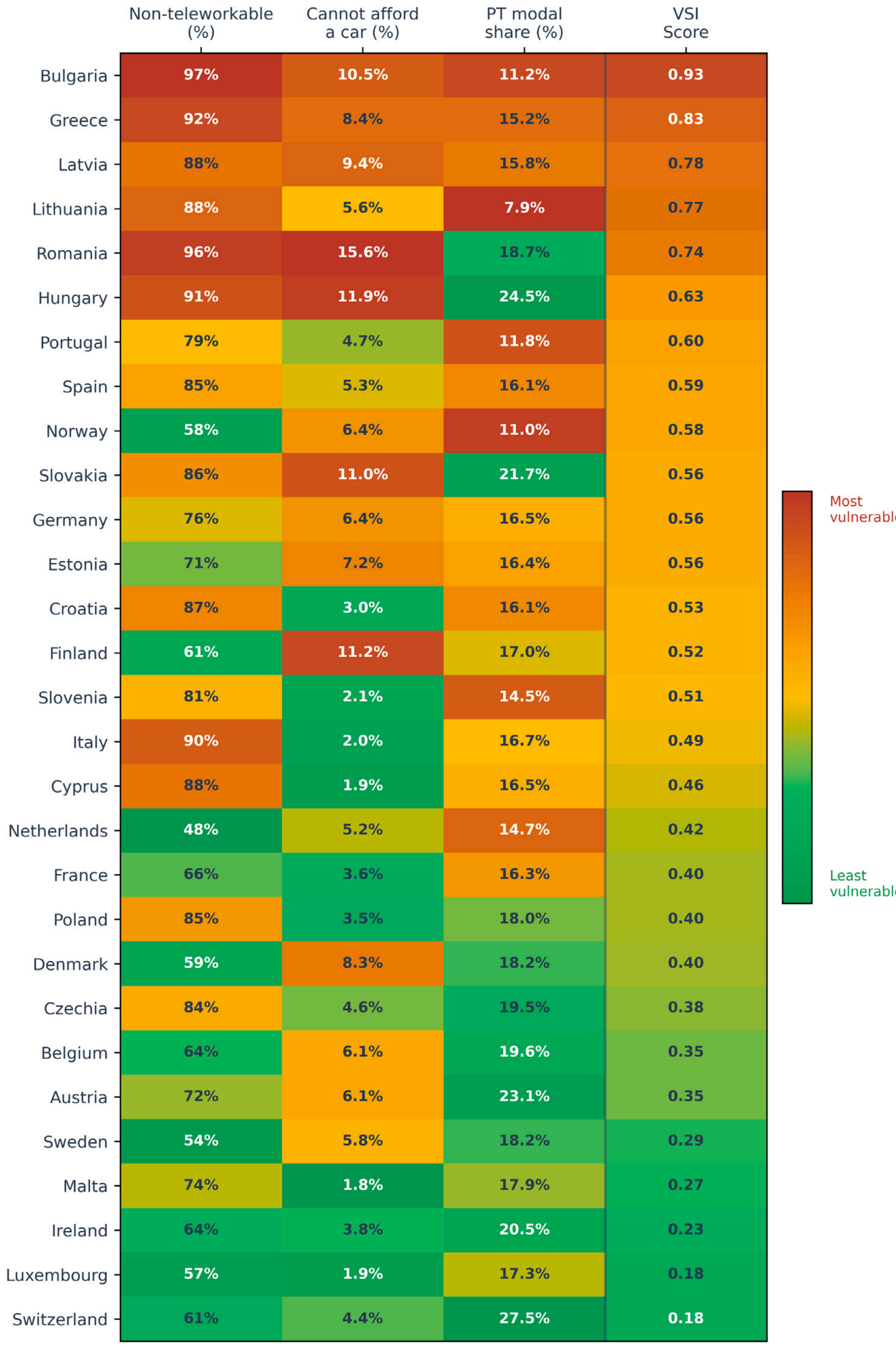


**Fig. 5.** Vulnerability Structural Index (VSI) by country: individual pillar rankings and composite score.
*Sources:* Eurostat (2024a, 2024b, 2024c).

All four countries combine the highest non-teleworkable workforce shares in the sample (97.0%, 92.2%, 87.9%, and 88.1% respectively), significant shares of the population facing car affordability and choice constraints (10.5%, 8.4%, 9.4%, and 5.6%), and among the weakest public transport systems in the EU by modal share (11.2%, 15.2%, 15.8%, and 7.9%). Across all three pillars simultaneously, this group occupies the most vulnerable positions in the sample, with no available coping mechanism able to compensate for weaknesses in the others.

Romania (0.74), Hungary (0.63), and Slovakia (0.56) share a distinct structural profile in which the binding constraints are workforce inflexibility and severe affordability and choice constraints in private transport, while public transport systems retain a comparatively larger modal role. Romania ranks first in the share of the population that cannot afford a car (15.6%), and second in non-teleworkable workforce share (96.5%), yet its public transport modal share of 18.7% places it only 16th on that pillar's vulnerability ranking. Hungary and Slovakia follow the same pattern: both rank among the most exposed on the first two pillars, yet fall in the lower half of public transport resilience vulnerability, reflecting comparatively extensive transit provision. The implication is that these countries possess a public transport infrastructure that is, in principle, available as a resilience tool. The binding constraint is not system absence but the simultaneous financial and choice-based exclusion of large population shares from private vehicle ownership, compounded by the near-total absence of a teleworkable workforce buffer. For this group, policies targeting mobility affordability, such as fare subsidies, means-tested mobility passes, or employer incentives for remote work would more directly address the structural drivers of their high VSI scores than investment in expanded public transport infrastructure and supply.

Portugal (0.60), Spain (0.59), Croatia (0.53), Slovenia (0.51), Italy (0.49), and Cyprus (0.46) form a closely clustered group sharing a third structural profile: large non-teleworkable workforce shares (ranging from 79.2% to 89.7%) and very low shares of the population facing car affordability and choice constraints (1.9%–5.3%), yet with public transport modal shares remaining in the relatively low 11%–17% range. Here the primary vulnerability drivers are workforce inflexibility and underperforming transit systems, while financial exclusion from private mobility plays a secondary role. What is analytically notable about this group is the contrast between recovery dynamics and absolute system strength. Spain and Portugal recorded the strongest public transport recovery trajectories following the pandemic shock, with 2023 ridership rebounding to levels more than 10% above their 2019 baseline (Fig. 4), yet Spain's current public transport modal share stands at only 16.1% and Portugal's at only 11.8%. This contrast illustrates a critical limitation of relying solely on recovery dynamics as a policy metric. Strong relative recovery signals institutional responsiveness and operational capacity, and is an important indicator of governance quality and provides guidance for future decisions. However, if the pre-pandemic baseline was itself low, recovering to that baseline does not translate into a resilient system. Absolute modal share values remain essential for assessing whether public transport genuinely functions as a viable, population-wide alternative to private vehicle use, a distinction that recovery-only metrics systematically obscure.

Norway (0.58) and Netherlands (0.42) constitute an interesting outlier. Their non-teleworkable workforce shares of 57.5% and 48% respectively are among the lowest in the sample, and their population facing car affordability and choice constraints (6.4% and 5.2%) are moderate, yet their public transport modal share of 11.0% and 14.7% ranks them among the most vulnerable on that pillar. Their composite score is therefore elevated not by a uniform concentration of risk but by the combination of a structurally weak transit system and a workforce that has largely substituted telework for commuting, a pattern consistent with the persistent post-pandemic public transport underperformance of Nordic countries observed in Fig. 4. Germany (0.56) and Estonia (0.56) occupy a similar middle-ground position, with moderate exposure across all three pillars but no acute concentration of structural risk in any single dimension.

Switzerland (0.18), Luxembourg (0.18), Ireland (0.23) and Malta (0.27) occupy the least vulnerable end of the distribution. For these countries, no structural weakness dominates, and policy priorities shift accordingly from vulnerability remediation towards maintaining and incrementally improving an already-resilient system.

This pillar-level heterogeneity demonstrates that structural transport vulnerability is not reducible to a single dimension, nor does it follow a simple geographic gradient. A high public transport modal share does not protect against high VSI scores when workforce inflexibility and affordability and choice constraints in private mobility are simultaneously present, as Hungary and Slovakia illustrate. Conversely, strong telework capacity can partially offset system-level weaknesses, as observed in Norway and the Netherlands. The VSI decomposition therefore establishes that the resilience gap between EU member states is a configuration of structurally distinct vulnerability profiles requiring calibrated, context-specific policy responses. Effective EU-level resilience policy must therefore begin from a diagnosis of which structural profile each country occupies, depending on selective disruptions, before prescribing interventions for those disruptions.

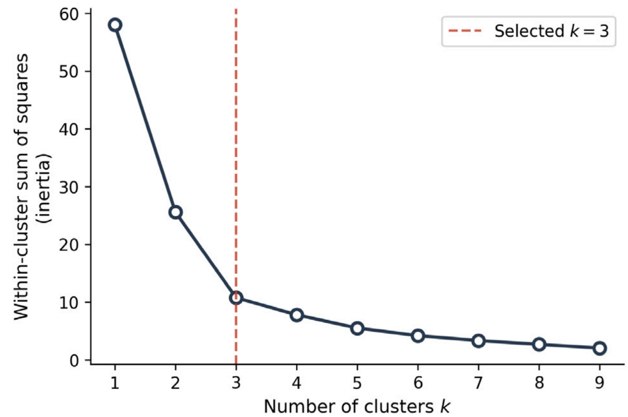


**Fig. 6.** Elbow analysis for $k$-means cluster selection: within-cluster sum of squares across $k = 1$ to 9. The marked inflection point at $k = 3$ indicates that additional clusters yield only marginal reductions in inertia, supporting the selection of a three-cluster solution.

### 4.5. Identifying "Non-teleworkable, Car-less" rural hotspots

While the VSI provides a comprehensive country-level composite of structural vulnerability, it does not differentiate by spatial context. As established in Section 4.1, vulnerability to transport disruptions manifests fundamentally differently depending on whether deprivation is concentrated in urban or rural settings. Rural populations face a qualitatively distinct challenge: the near-total absence of modal alternatives to private car access, which renders any disruption to physical mobility disproportionately severe. To complement the VSI with a spatially grounded perspective, this subsection therefore focuses specifically on the rural population, examining which countries harbor the largest shares of rural residents exposed to low car affordability and low workforce adaptability, the two structural conditions that, in a rural context, leave populations with no viable fallback when transport is disrupted. This also serves as an example how policy-makers and government authorities should adapt the data profiles depending on the specific contexts.

To examine the distribution of this profile across EU member states, we construct a scatter plot placing the percentage of the rural population that cannot afford a car (x-axis, measuring transport affordability) against the share of the workforce that never works from home (y-axis, measuring workforce inflexibility). A high value on either axis signals greater structural exposure on that dimension. To classify country profiles in this two-dimensional space in a statistically grounded manner, we apply a $k$-means clustering algorithm, which groups countries by minimizing within-cluster variance across both dimensions simultaneously, making it well suited to identifying structurally coherent country profiles without imposing any prior assumptions. The optimal number of clusters was determined via an elbow analysis of within-cluster sum of squares (inertia) across $k = 1$ to 9. The elbow criterion identifies $k = 3$ as the point beyond which additional clusters yield only marginal reductions in inertia, and this solution is adopted accordingly, as visualized in Fig. 6. The resulting cross-plot and cluster assignments are presented in Fig. 7.

The algorithm recovers three structurally distinct country profiles:

**Cluster 1: Resilient** (Netherlands, Sweden, Luxembourg, Norway, Finland, Denmark, Ireland, Belgium, France, Switzerland, Austria, Estonia): Countries in this group combine comparatively low workforce inflexibility with low rural car affordability constraints. Profiled citizens in these countries retain multiple coping options when transport is disrupted, as telework is structurally accessible to a substantial share of the workforce, and private car ownership is not a significant financial barrier. This group broadly corresponds to Western Europe.

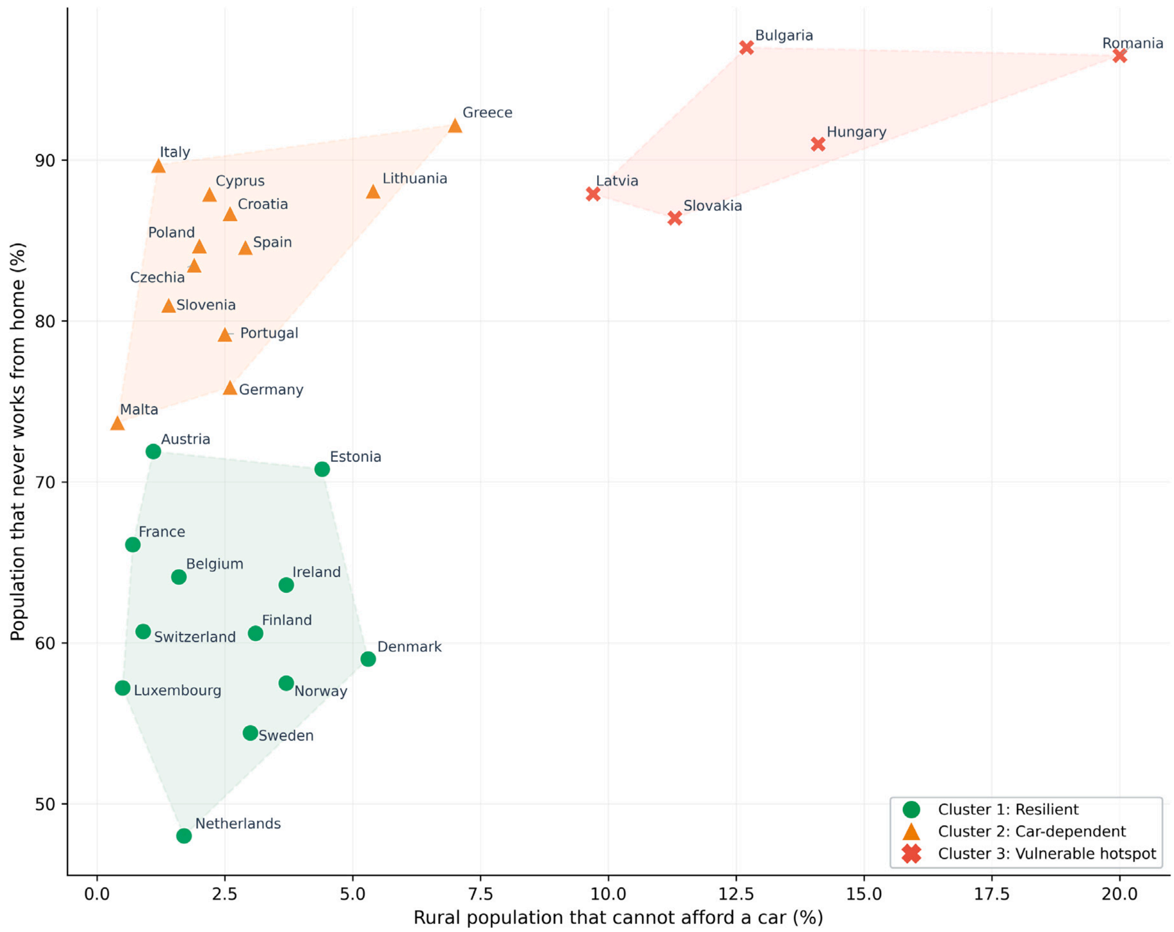


**Fig. 7.** K-means cluster analysis ($k = 3$) of EU countries by rural transport affordability and workforce adaptability in 2024. *Sources:* Eurostat (2024a, 2024c).

**Cluster 2: Car-dependent** (Italy, Cyprus, Croatia, Poland, Czechia, Slovenia, Portugal, Spain, Germany, Malta, Greece, Lithuania): Countries in this cluster are characterized by high workforce inflexibility but comparatively low rural car affordability constraints, making their rural populations primarily dependent on private car access and therefore structurally exposed to fuel price shocks or vehicle-related disruptions. Notably, Greece and Lithuania sit at the boundary of this cluster, with non-teleworkable workforce shares comparable to Cluster 3 countries, yet their rural car affordability constraints (7.0% and 5.4% respectively) fall short of the 9.7%–20% range that defines the hotspot group. The clustering algorithm therefore places them here, confirming that their binding structural risk is workforce inflexibility rather than transport affordability.

**Cluster 3: Vulnerable hotspot** (Bulgaria, Romania, Hungary, Latvia, Slovakia): This is the most critically exposed group. These countries occupy the upper-right region of the scatter plot, combining among the highest shares of non-teleworkable workforce with the largest proportions of rural unaffordability. When a disruption severs physical access to workplaces or raises the cost of commuting, these populations have no readily available alternative: they cannot switch to remote work and cannot rely on private car access. This dual bind places them in a position of compounded structural vulnerability.

It is important to note that this analysis operates as a macro-level screening tool: it identifies which countries have a disproportionately large share of their rural workforce exposed to low car affordability relative to telework capacity, flagging them as requiring prioritized policy attention. The goal is thus to identify vulnerable hotspots and prioritize the groups that warrant detailed statistical investigation. Any individual within a given subgroup faces the same structural bind, irrespective of exact national telework or car-ownership statistics. Concrete policy decisions on a national level therefore require additional relevant statistical analysis to identify the best method in order to decrease the share of the identified vulnerable profiles, and help them with custom strategies based on that analysis.

### *4.6. Resilience of vulnerable groups*

The vulnerable hotspot group identified in the scatter plot is defined by a dual vulnerability: low workforce adaptability and low transport affordability. The following plots analyze the resilience of this group by comparing the average post-pandemic performance of this group (red line) against the average of all other EU countries (blue line).

Teleworking increase plot (Fig. 8) shows that “Other Countries” (blue line) adapted drastically better to the pandemic, peaking at almost 14% change from the 2019 baseline in 2021 and sustaining a high level of telework afterwards. The “Vulnerable Group” (red line) showed a much weaker adaptation, peaking at only 7%. Critically, those small gains eroded significantly by 2023, indicating a return to pre-crisis, non-resilient norms. This adaptation gap is a critical vulnerability, as this group lacks the primary coping mechanism for any disruption, be it a pandemic (health risk), a natural disaster (infrastructure loss), or an energy crisis (unaffordable commute).

Public transport recovery plot (Fig. 9) shows the “Other Countries” (blue line) recovered quickly from the 2020 shock, returning to near-baseline percentage levels by 2023. In stark contrast, the “Vulnerable Group” (red line) experienced a deeper shock and a much weaker recovery, with the modal percentage being at −13% in 2023, compared to the 2019 baseline.

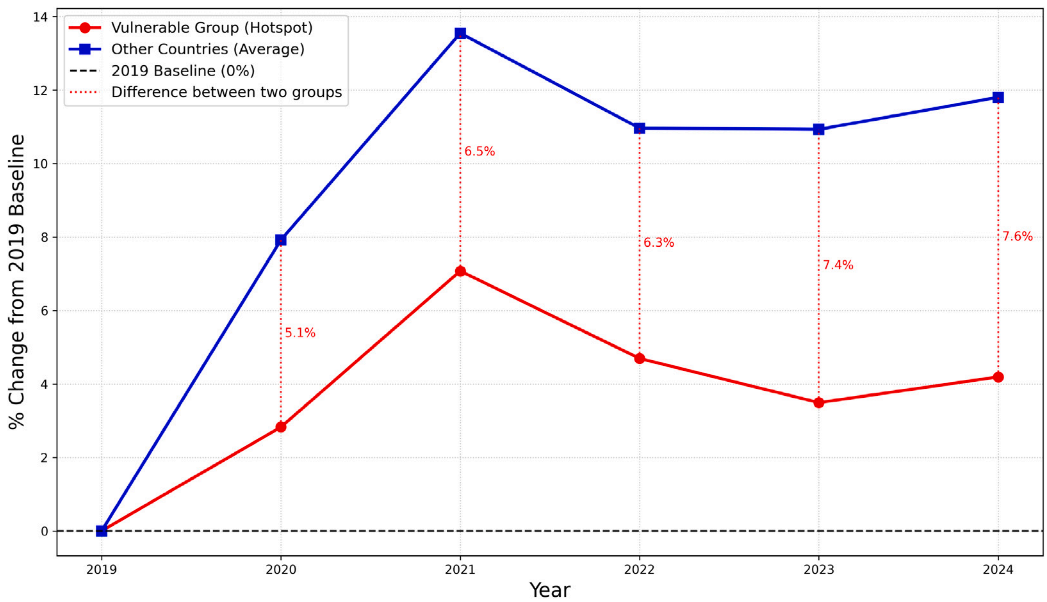


**Fig. 8.** Resilience gap: teleworking increase after COVID (vulnerable group vs. peers).
*Source:* Eurostat (2024a).

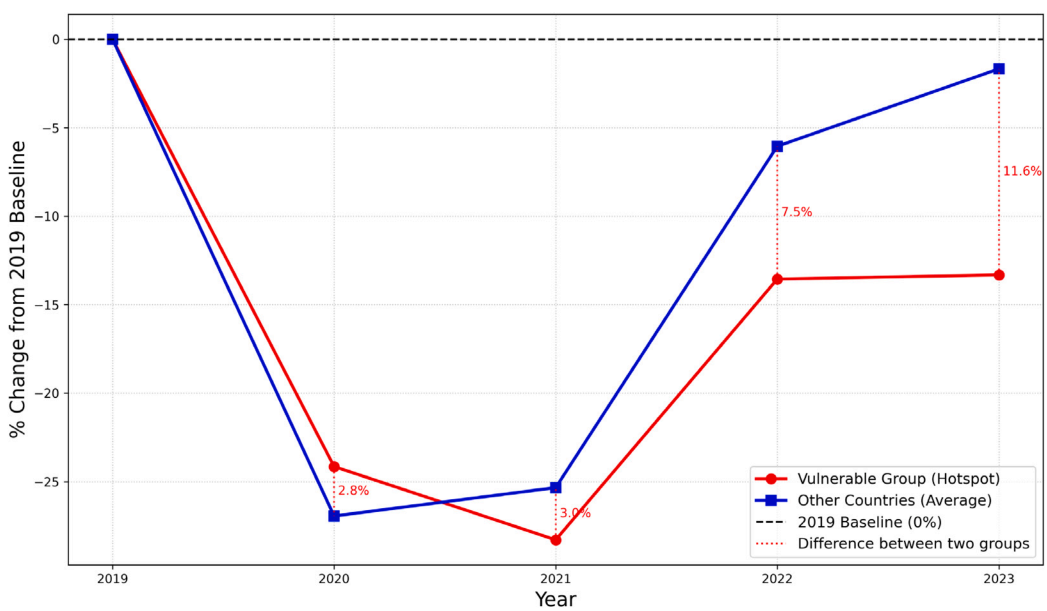


**Fig. 9.** Resilience gap: public transport recovery after COVID (vulnerable group vs. peers).
*Source:* Eurostat (2024b).

The vulnerable countries are caught in a dual bind: they have low workforce adaptability (Fig. 8) and their only alternative, public transport, is a failing system that still has not recovered after the pandemic (Fig. 4, Fig. 9). This has severe implications, especially for an energy crisis. A government's main policy to combat fuel price shocks is to encourage people to use public transport more, as Germany's 9 Euro ticket initiative has shown (European Commission, 2024). This analysis suggests that this policy tool may be structurally harder to deploy in vulnerable countries, given that their public transport systems show limited capacity to absorb demand shifts of this scale.

## 5. Limitations and future work

The macro-level perspective adopted in this study provides a consistent and robust basis for cross-country comparison across the EU. The use of harmonized national indicators makes it possible to identify large-scale structural patterns, spatial divides, and systemic vulnerability trends that would be difficult to observe through more localized datasets. This level of analysis is particularly well suited to examining country-level resilience gaps and broad socio-economic disparities in exposure and adaptability to transport disruptions.

The choice to represent each vulnerability dimension through a single proxy indicator warrants explicit acknowledgment of its construct validity limitations. Workforce adaptability is presented exclusively through teleworking capacity, which excludes other relevant dimensions of workforce adaptability, including occupational schedule flexibility or tolerance for lateness and absence in low-wage employment. Transport affordability is proxied through the inability to afford a car, which reflects a threshold measure of financial exclusion from private mobility but does not directly capture the ongoing financial burden of public transport fares, the costs associated with forced car ownership in areas lacking modal alternatives, or broader household transport expenditure as a share of income. System resilience is represented by public transport modal share, which captures the structural role of public transit within the national mobility system and its relative recovery trajectory. However, this indicator does not reflect service quality, geographic network coverage, transport ridership, schedule frequency, or route redundancy. The additional dimensions identified above represent a structured research agenda for future work to progressively enrich each pillar, depending on identified pan-European datasets, providing a more detailed and nuanced analyses.

At the same time, this system-level perspective can be further refined in future research through the integration of micro-data. Anonymized household-level Eurostat datasets would allow for a more detailed characterization of vulnerability by jointly considering multiple socio-economic attributes such as income, employment conditions or digital literacy. This would enable the identification of more nuanced vulnerability profiles and compound disadvantage mechanisms that are not fully observable when working with national averages. Since such micro-data are not publicly accessible and require a formal application process, the present study focuses on macro-level indicators, while recognizing the added analytical value that micro-scale evidence could provide in subsequent work.

A further limitation relates to the temporal availability of several survey-based indicators. These datasets follow a five-year collection cycle (e.g., 2010, 2015, 2020, 2025). The most recent completed cycle (2025) is currently under processing and is expected to be released in 2026. In addition, the 2020 cycle was not conducted due to the COVID-19 pandemic. As a result, the latest publicly available data stems from the 2015 wave. Given this gap, these indicators were not incorporated into the present analysis to avoid relying on information that may no longer adequately reflect current conditions. Future work will integrate the updated datasets once the 2025 data becomes available.

## 6. Conclusions

This study set out to understand how transport vulnerability and resilience are socially and spatially structured across the EU, moving beyond system-level performance to examine who is most exposed when mobility systems fail. By operationalizing vulnerability through three interlinked pillars: workforce adaptability, transport affordability and choice, and public transport system resilience, and using the COVID-19 pandemic as a common stress test, the analysis reveals a persistent and geographically patterned resilience gap within the EU.

The findings show that transport disadvantage cannot be treated as a universal condition with universal solutions. Instead, vulnerability emerges from the interaction between socio-economic characteristics and the structural profile of national and regional transport systems. Western European contexts, where deprivation is more urban and public transport systems have largely recovered, face challenges primarily linked to affordability, cost-of-living pressures, and maintaining inclusive access within dense networks. In contrast, many Eastern, Southeastern and Baltic Member States combine rural deprivation, limited telework capacity, and public transport systems that have struggled to recover to pre-pandemic levels. In these settings, vulnerability appears more closely associated with structural scarcity of resilient mobility alternatives than with marginal cost barriers alone. The same disruption therefore produces fundamentally different consequences depending on whether people have modal redundancy, digital work flexibility, and system capacity to absorb shocks.

For policy makers, this has a central implication: resilience-building strategies must be context-calibrated rather than uniform. Financial instruments such as fare subsidies, social tariffs, or temporary tickets can be effective in high-transit, high-capacity systems, but they are insufficient where service supply itself is fragile or spatially absent. Conversely, large-scale infrastructure investment alone does not address vulnerability if households remain financially or digitally excluded. Mobility justice in the EU therefore requires aligning policy tools with the existing structural capabilities of national transport systems, combining social policy, labor-market flexibility, digital inclusion, and transport investment in different proportions depending on country profiles.

Strengthening transport resilience is not only a matter of mobility performance; it is a public health, social inclusion, and socio-economic stability strategy. When populations can maintain access to employment, healthcare, education, and social networks during disruptions, societies reduce the risk of cascading effects such as income loss, missed medical care, educational setbacks, and long-term exclusion. In this sense, improving transport resilience directly supports broader societal resilience: healthier populations, more stable labor participation, and stronger social cohesion. The groups identified in this study, particularly the “non-teleworkable, car-constrained” populations in rural and peripheral regions, illustrate how mobility fragility is associated with compound socio-economic risk if not addressed proactively.

Ultimately, the paper contributes a framework that links transport vulnerability to structural system characteristics and socio-economic capacities at the EU scale. By showing that resilience gaps are patterned rather than random, and that coping mechanisms such as teleworking and modal substitution are unevenly distributed, the study provides an evidence base for differentiated, equity-oriented resilience planning. As disruptive events become more frequent under climate change, geo-political tension and energy transitions, such a context-sensitive approach will be essential to ensure that resilience policies do not inadvertently widen the inequalities they seek to mitigate.

## CRediT authorship contribution statement

**Hamza Begic:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Francesco Bruzzone:** Writing – original draft, Investigation. **Silvio Nocera:** Writing – review & editing, Supervision, Funding acquisition. **Constantinos Antoniou:** Writing – review & editing, Supervision, Funding acquisition.

## Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT, developed by OpenAI, for paraphrasing, summarizing, and grammar checking. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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