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KEYWORDS

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R41, R42, L91

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Title: A summary of the empirical transport resilience literature and a review of a case study.
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This study defines the concept of resilience of a mobility system as “the ability of a transport system to resist external shocks, maintain its functions, and return to full service as quickly as possible.” Through an in-depth recognition of the literature, it discusses the components that jointly characterize the resilience of a mobility system, namely robustness, redundancy, resourcefulness, and rapidity, as well as the factors that influence them. Finally, it presents one case study, e-scooters rental in Turin, showing how redundancy and thereby resilience can be positively affected by the integration between the standard public transportation system and forms of sharing mobility.

A summary of the empirical transport resilience literature and a review of a case study

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Abstract

This study defines the concept of resilience of a mobility system as "*the ability of a transport system to resist external shocks, maintain its functions, and return to full service as quickly as possible.*" Through an in-depth recognition of the literature, it discusses the components that jointly characterize the resilience of a mobility system, namely robustness, redundancy, resourcefulness, and rapidity, as well as the factors that influence them. Finally, it presents one case study, e-scooters rental in Turin, showing how redundancy and thereby resilience can be positively affected by the integration between the standard public transportation system and forms of sharing mobility.

Keywords: Transport resilience; Shared mobility; Public transport integration; E-scooters
JEL codes: R41; R42; L91

1. Introduction

Transport resilience refers to the ability of transport networks (both at an infrastructure and a service level) to resist external disruption, maintaining functions as much as possible and return

to a full level of service in a short time. This summary, based on the paper published in Transport Reviews (Bergantino et al., 2024), reviews the relevant empirical literature on transport resilience, categorizing the various factors influencing resilience and identifying the spatial patterns commonly found across case studies. These factors and patterns are contextualized within a typical resilience assessment framework to provide insights for improvement and suggest future research directions for transport scholars. Although several reviews on transport resilience have been published in recent years, limited work has focused on classifying empirical findings or, more broadly, on understanding the role of real-world data in resilience assessments. The main innovation of this study lies in its review of the use of empirical data in transport resilience assessment, its classification of analytical results, and the insights and recommendations derived from this analysis. Under the GRINS topic, the review addresses the need for supporting resilience assessment metrics, particularly focusing on transport networks and their impact on the resilience of territories. To achieve this, the paper collects a set of 127 relevant transport resilience studies, subsetting it down to the 53 that utilize real-world data for analysis. The empirical findings are classified within the 4R framework supporting the resilience triangle (Bruneau et al., 2003; Tierney & Bruneau, 2007), which is the most widely adopted framework in the literature. The paper's key objective, based on this contextualization, is to test this standard framework over several case studies, offering insights for its improvement, and highlight topics worth of further investigation.

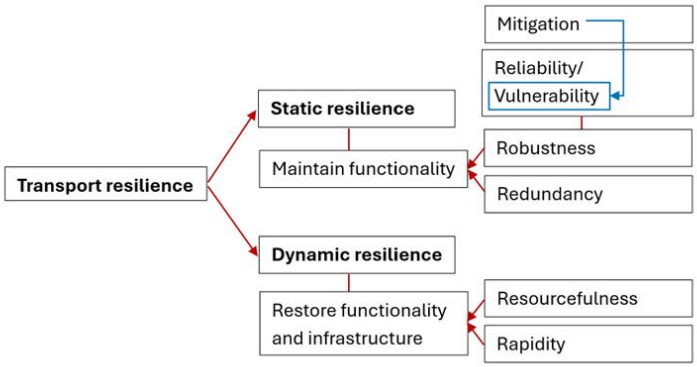
2. Outline of literature background

2.1 Methodology of the review

As anticipated, several review papers have explored the conceptualization of transport resilience, elaborating on its related attributes and the interconnections between them. The literature also overviews in detail assessment metrics. Below, a brief summary of the key insights on both the concepts and the metrics is presented. Transport resilience refers to the ability of a transport system to resist external shocks, maintain its functions, and return to full service as quickly as possible. At the moment of disruption, the concepts of robustness and redundancy are used to describe the extent to which service is maintained (robustness) and the availability of alternative options to offset the disutility of the performance loss (redundancy). Once the disruption is over, the concepts of rapidity and resourcefulness define how quickly, and by what means (in terms of resources deployed), the system's performance returns to its normal operating state.

These four main attributes—robustness, redundancy, resourcefulness, and rapidity—are the 4 ”R”s that form the 4R framework (Bruneau et al., 2003). They define resilience in different stages: static resilience, measured by robustness and redundancy during the disruption, and dynamic resilience, measured by resourcefulness and rapidity during recovery (see Figure 1.1). Several other concepts complement this framework. Vulnerability, the opposite of robustness, defines the amount of performance degradation experienced during the shock. Reliability measures the likelihood of successful functionality under various operational conditions. Mitigation strategies, aimed at strengthening critical infrastructure, focus on enhancing robustness and reducing the risk of performance degradation during future disruptions.

Figure 1.1. Resilience concepts interconnections based on Bergantino et al. (2024)



Regarding assessment metrics, there are generally two types: topological and performance based. Topological metrics assess resilience by examining the static structure of the network (nodes and edges), focusing on changes in network topology (i.e., the connections between nodes). Performance based metrics, on the other hand, include the dynamic aspects of the network, such as flows, speed, and time, providing a quantitative assessment of resilience by measuring lost performance rather than focusing exclusively on changes in connectivity.

A literature keyword search was conducted to identify the most relevant studies on transport resilience. From an initial general search on Scopus, combined with additional papers identified through snowballing, 127 studies were retrieved. After reviewing the abstracts, 53 papers that utilize real-world data were selected for further analysis. Of these, 38 papers use flow data, 30 use on travel time, 7 coordinate tracking, 5 transport costs and 2 use accident data. 17 papers study road networks, 11 railways, 10 metro services, 10 bicycles, 6 airways, 5 bus services, 5 multimodal networks, 2 walking and 1 waterway. These 53 papers were thoroughly reviewed and qualitatively assessed to summarize their main findings and methodologies.

2.2 Main insights

Several spatial patterns and influential factors of transport resilience are found across the set of reviewed papers. As regards the spatial patterns:

1. Central areas vs peripheral areas: central areas are vulnerable to disruptions due to dense passenger flows and infrastructure, but they often recover more quickly thanks to higher redundancy and prioritization in recovery. Conversely, peripheral areas tend to be less vulnerable due to lighter flows but lack of redundancy (few transport options)
2. High vs low accessibility: areas with lower accessibility are generally less vulnerable to disruptions due to lighter gravity, but tend to lack of redundancy, with few alternatives and main corridors that, If disconnected, heavily impacts performance.
3. Distance decay from alternative modes: when connecting alternative modes within a buffer, users disutility from disruption is partially offset. For example, when bike sharing services are located inside a 1km buffer from public transport stops, system resilience is increased.
4. Location of the hazard: When natural hazards like hurricanes hit, regions close to the coastline tend to be more impacted. However, there are countertrend, like local changes in demand and disruption spillovers.

As regards influential factors:

1. Redundancy: as expected, redundancy, both infrastructural and between modes, is associated with higher level of resilience. Infrastructural redundancy refers to the density of infrastructure and consequently all the different paths that can be taken to reach a destination. Between-modes redundancy refers to the quantity of different transport options to be taken by individuals.
2. Provision of real-time information: Effective communication from transport practitioners regarding real-time conditions is associated with higher level of resilience, allowing users to change behavior and find alternative solutions.
3. Institutional plans and management: Pre-, during and post-disruptions institutional actions help the transport system overcome the shock more smoothly. In particular, critical infrastructure identification, mitigation strategies and post-emergencies plans are found to be positive across case-studies.
4. Climate change and intensity of disruption: As expected, the stronger the disruption impact, the worse the drop in performance. As climate change is expected to exacerbate the impact of hazards, severity of disruptions effects are expected to rise.
5. Strengthening of the infrastructure: Improvements on the physical robustness of the infrastructure and on its connectivity (also in terms of integration and compatibility between types of infrastructure) mitigates performance degradation and increases redundancy.
6. Congestion: systematic congestions, also in terms of pre-existing bottlenecks, further strengthens the negative effects of disruptions.

7. Increase in socio-economic indicators: Increase in socio-economic indicators, like GDP growth, does not always automatically associate with increase in transport resilience. Side effects like increased pressure from urbanization can lead to offsets to transport resilience.

The papers found that both spatial pattern and influential factors fit into the 4R framework, meaning that all items identified have some type of effect on the 4 resilience attributes. It is worth noting that some have negative effects (e.g., congestion on rapidity), some have positive ones (e.g. central area on redundancy) and some have effects on more than one attribute (e.g. strengthening of infrastructure on robustness and redundancy). Because of this, multiple attribute resilience metrics should be preferred to single attribute ones. Table 1.1 below categorizes the effects of the identified items on the attributes of the 4R framework.

Table 1.0. Summary of positive and negative effects of the identified empirical factors

	Positive Effect	**Negative Effect**
Robustness	• Institutional plans and management • Strengthening of infrastructure	• Central area • High accessibility • Location of the hazard • Climate change and intensity of disruption • Congestion
Redundancy	• Central area • High accessibility • Distance decay from alternative modes • Institutional plans and management • Strengthening of infrastructure	
Resourcefulness	• Central area • Institutional plans and management	
Rapidity	• Central area • Institutional plans and management • Provision of real-time information	• Congestion

It is also possible to see from the table above that, if practitioners are interested in a specific attribute of resilience, they can leverage on specific factors. For example, policymakers willing to increase rapidity of recovery may consider tackling systematic congestion while making real-time information available during shocks.

2.3 Research gaps

Despite fitting the results into the 4R framework, we identified some issues related to its graphical representation. The first concern regards the definition of the pre-disruption level, which is difficult to ideally identify. In some cases, the pre-disruption reference value is set as the last observation before the shock, which might not be ideal as it could be affected by random operational fluctuations and may not represent the true 100% operational level. The same issue applies to the recovery target, that is often set as the pre-disruption level. Further investigation into these methodological challenges is of utmost importance to improve the framework's real-world applicability. Long-term historical data, for example, could help setting a more ideal standard reference level for pre-disruption performance.

Furthermore, 4 relevant research strands have been identified to be further investigated. Specifically:

- How can disruptive events be categorized for empirical analysis?
- How do different types of disruptions impact various transport modes?
- Is there an association between long-term economic growth and growth in transport resilience?
- Multimodal networks remain underexplored, causing gaps in our understanding of resilience and disruption impacts within networks of networks.

We believe that the research on these underexplored topics will increase our knowledge on transport resilience while helping the adoption of resilience frameworks of assessment based on real data collection.

3. Case study: the contribution of e-scooter services to the resilience of urban transport [1]

3.1 Framework

The aim of this case study is to understand to what extent a greater supply of transport alternatives favors individuals during a disruption in an urban setting. A key concept central to this work is redundancy. Redundancy is the ability of a transport network to offer several alternatives that can support each other in the event of an external shock (Bergantino et al.,

[1] This chapter summarizes the content of the article: Bergantino, A. S., & Gardelli, A. (2024). The contribution of e-scooters services to urban transport resilience. Journal of Transport Geography, 118, 103869.

2024). How is the complementarity/substitution between modes evolving during such events? To answer this question, we take advantage of the natural experiment context of 7 local public transport (PT) strikes in Turin, Italy, between October 2021 and October 2022. During this time span, we observe the hourly number of e-scooters' rents and the length of the rents' trips. We aim to address two research questions:

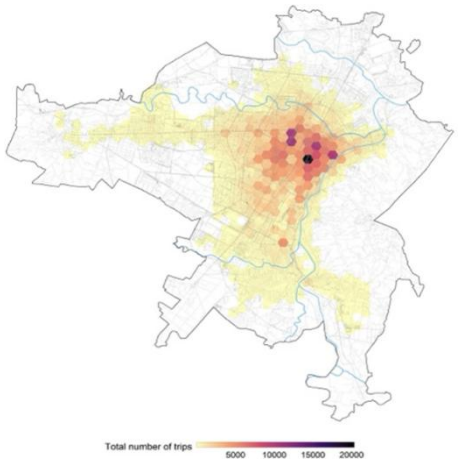
1. Does e-scooter sharing offer redundancy to PT when the latter is disrupted?
2. Does a spatial pattern of proximity to disruption exist?

3.2 Data

For this analysis, three main datasets[2] have been used. The following subsections will briefly discuss the three datasets.

Data of individual e-scooters Origin-Destination (OD) tracks aggregated at different levels, is used in the analysis. Figure 1.2 displays the concentration of starting trips inside a 500m × 500m grid.

Figure 1.2. Density of started trips on a 500m × 500m grid



In the same year window, 7 strike events are identified and double-checked both with the National Strike Authority and the local public transport operator, which provided us with the average participation of drivers to the strike (data available form the Authority).

Transit stop data is downloaded to investigate the spatial patterns. Relevant literature on the topic finds a distance decay pattern on the effect starting from the disruption site. Translated and applied to our case study, that would suggest that the closer the start of the trip is to a

[2] Authors did not have the permission to share data openly but eventually and upon requests in an aggregate form.

transit stop (disruption site), the stronger the effect of the disruption (strike) in terms of e-scooters trips counts and length increase.

3.3 Methodology

To answer the first research question, we observe the number of e-scooter trips and their lengths during a strike day, comparing them to a baseline scenario through econometric modeling. As regards the second research question, we include in the modeling an interaction term of proximity to transit stops to analyze if the strike effect on the e-scooter trips is larger in the vicinity of the disruption sites, i.e., the transit stops. Combining the two aspects, to study the effect the following negative binomial regression model is proposed:

$$E[trips_{it}] = exp(\beta_0 + \beta_1 \times strike_t + \beta_2 \times strike_t \times prox_{it} + \gamma \times X_{it})$$

where:

- $trips_{it}$ the hourly count of e-scooter trips for neighbourhood i,
- $strike_t$ is a dummy variable for the strike event at hour t,
- $prox_{it}$ is a dummy variable that controls proximity of transit stops via buffers,
- X_{it} is a vector of control variables, including weather, special events and fixed effects,
- γ is a vector of coefficients for the control variables.

As regards the length of trips, the following OLS model is proposed to study the effect of strike, interacted with proximity to transit stops:

$$triplength_{it} = \beta_0 + \beta_1 \times strike_t + \beta_2 \times strike_t \times prox_{it} + \gamma \times X_{it} + \varepsilon_{it}$$

3.4 Results

The results of the modeling show that there is a redundancy effect of e-scooters to PT, which is stronger when reaching proximity to the transit stops. During a strike event, on average the e-scooter trips are 89% more than during a regular day within a 50m buffer to transit stops, ceteris paribus. The average length of an e-scooter trip confirms a possible substitution pattern, considering that, during a strike day, the average length is around 9 transit stops. The analysis found temporal heterogeneity, as the effect is stronger closer to the weekends, while it is totally inhibited in the hour window 9am-12am. In terms of complementarity/substitutability, the redundancy effect is likely to be in between the two concepts. On the one hand, there is a substitution effect, as part of the undone PT rides is absorbed by the e-scooter rents. On the other hand, it may also be seen as a support to PT (and ideally a complement to it) when the latter is not able to perform to its operative regime. As regards the spatial pattern of proximity,

which is in line with the relevant micromobility literature, such phenomenon may be explained through the so-called ”announcement effect” (Adler & van Ommeren, 2016), which found that the effect of the strike is influential only when the strike is actually in place, while no effect is observed when the strike is announced but canceled. According to this evidence, it may be that the individuals are not aware of the strike, and part of them decide to look for the closest e-scooter while being at the transit stop. The analysis found a temporal heterogeneity as well. We hypothesize that the reason why the effect is stronger on the weekend and inhibited in the mornings might be because of the user class. Several evidence reports that the typical user class is young males, which use more the e-scooter on weekend days for recreational purposes while use them less during school hours.

To summarize, during disruption events, e-scooters support the PT by absorbing part of the undone transit trips, offering a viable alternative to perform them. The effect is spatially and temporally heterogeneous, being stronger reaching proximity to the transit stops (spatially), being stronger closer to the weekends and weaker in the week morning (temporal). The temporal heterogeneity, being possibly explained by the typical user class - young males - might mean heterogeneity in the redundancy effect as well. The analysis highlights the existence value of e-scooters, that only by being present offers an alternative mode to at least a part of the individuals. However, the benefit, and so this piece of resilience, is class-specific. For this reason, we recommend it to be only a piece in a bigger puzzle of policies to make urban transport network more resilient to all.

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