NETWORK RESILIENCE AND TRANSPORT SECURITY: AN OVERVIEW

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Abstract

This paper proposes a general conceptual framework which aims to integrate the concept of network resilience within that of transport security.

In particular, methodological reflections on the role of resilience vs fragility in connectivity network structures, such as scale-free networks, are highlighted. Operational measures of resilience are also outlined, in order to enhance resilience in transport and communication networks.

Current policy strategies which focus on resilience show the relevance of this issue and the need for continuing research on the links between complex transport networks and resilience, mostly by exploring this relationship at different scale levels and its impact on the whole network.

Keywords: network resilience, transport security, complex networks, scale levels, policy issues
1. Introduction

The socio-economic features that underlie infrastructure networks as well as the related patterns of development, evolve in time and space in a very complex way: “Societal functions are highly dependent on networked systems. Even the most basic day-to-day functions involve interaction with a variety of critical infrastructure systems” (Murray et al., 2008, p. 573). This is valid for transport, communication, energy, financial networks, etc. Currently, network infrastructures (supply side), as well as the intensity of (physical or virtual) flows associated with them (demand side), are becoming extremely important for public policy considerations, not only for evaluating the possible (dis)equilibrium (demand vs supply) points, but also for preventing intentional attacks, disasters and accidents. There is the need to study and analyse critical infrastructure systems, in order to better understand their operability and functionality, under severe disruption events.

The literature on critical network infrastructures which explores the vulnerability/robustness to disruption, has grown considerably in recent years, demonstrating the relevance of this issue (see, e.g., Jen, 2005; Kim et al., 2010; Matisziw et al., 2009; Murray and Grubesic, 2007). In parallel, a number of different approaches (such as mathematical programming, general equilibrium models, simulation tools, etc), able to identify network vulnerability/fragilities have been investigated: approaches which also show the complexity of the related models and analyses (Matisziw and Murray, 2009; Rose, 2005).

It is clear that the importance of a network infrastructure is largely dependent on the location of its links and nodes, as well as on their connectivity. In this context, the type of topological relationships between the network nodes is a crucial issue worth examining, also taking on board the interesting recent contributions in social network analysis (Barabási, 2002). Understanding the underlying network topology of a transport/communication system poses some challenges, many of which stem from the complexity of the system, in connection with the identification of the critical/vulnerable structures.

Starting from these considerations, in the present paper the relevance of the resilience concept – strictly linked to fragility – is examined, given its strong theoretical/analytical background, stemming from the bio-ecological sciences. In particular, after a brief account of the relationship between resilience and transport security (Section 2), there follows an overview of the definitions and measurements of resilience (Section 3), in order to subsequently focus on the issue of network topology and (the related) network resilience (Section 4). Next, some considerations on policy options for enhancing

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1 The fundamental feature of complexity can be identified as follows (Bossomaier and Green, 2000, p. 5): ‘The essence of complexity is the outcome should not be obvious from the simple building blocks.’ See also Reggiani (2009).
resilience, with a view to improving transport security, are presented (Section 5). Finally, the Conclusions offer some reflections on the resilience concept, its operability and the relevance of its role in the policy strategies oriented to improve transport security, with particular attention to different scale analyses (Section 6).

2 Background: Transport Security and Resilience

Transport security had become a fundamental issue in government policy. See, for example, the website of the UK Government Department for Transport concerning Transport Security\(^2\), where it states that: “The Department for Transport (DfT) aims to protect the travelling public, transport facilities and those employed in the transport industry, primarily from acts of terrorism. We aim to retain public confidence in transport security without imposing requirements that impact on the way they travel. The Transport Security team is also responsible for transport contingency arrangements in response to any actual or threatened disruption.”

On the other side of the Atlantic, the Department of Transportation (DOT) at Washington, D.C., on 26 November 2001, after the 9/11 terrorist attacks in the USA, provided guidance on response plans/emergency support functions for transportation (for an overview and discussion on the response programmes in the various States in the USA after 9/11, see Parsons Brinckerhoff and PB Farradyne, 2002).

Clearly, transport and telecommunication systems – also owing to their network character with the economic and financial sectors – are extremely vulnerable to terrorist attacks.

In this context, it is interesting to note how in the first years of the 2000s prevention and protection were the central issues for critical infrastructure (National Research Council (NRC), 2002). Recently, the necessity to tackle complex systems data fusion/data mining, as well as integrating all hazard approaches and programmes (such as safety, security and emergency management sub-systems) has been emphasized (Federal Transit Administration (FTA), 2007).

In addition, the issue of a “quick layered response of the system with effective surge capability” has been included in the operational objective (Objective 4 below) in the framework of the following six goals for transportation security (Transportation Research Board (TRB), 2010):

1. Social: involve the public, but this makes pre-operational surveillance riskier;
2. Budget & Policy: make risk-informed decisions the norm;
3. Technical: focus on countermeasures & design (instead of vulnerabilities & threats) with dual benefits;

\(^2\) http://www.dft.gov.uk/pgr/security/
4. Operational: quick, layered response with effective surge capability;
5. Psychological:
   – for those who are planning for attacks, transportation needs to be made a more difficult target;
   – for the public, peace of mind/acceptance of risk: security $\approx$ satisfaction;
6. Intelligence: support police/military/intelligence by having trained transportation employees report suspicious activities, and by making the bad guys stretch out their planning time.

The desired outcome is to ensure that an integrated, high level, all-hazard, national incident management system-responsive, multimodal risk management process is incorporated into major transportation agency programmes and activities. Clearly, the all hazards integrated approach (Federal Transit Administration (FTA), 2007) paved the way for the adoption of the resilience concept as the objective. At the Disaster Roundtables held in Washington from 2001 to the present day (Transportation Research Board (TRB), 2010), we can see that two specific objectives deal with resilience:
   a) Creating a Disaster Resilient America: Grand Challenges in Science and Technology (Objective 12).
   b) Community Disaster Resilience (Objective 16).

Even though the resilience concept is often associated with natural disasters, the need to consider – in the US policy strategic actions – transport as a network integrated structure in order to create a resilient US organism to, among other things, terrorist attacks, has recently come centre stage, by enriching the original first goals of protection and prevention. This focus on resilience implies that the resilience concept should be analysed from both the methodological and empirical viewpoint. In this connection, a basic framework in this respect will be presented in the subsequent sections.

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3 The Disaster Roundtable workshops are held three times a year in Washington, D.C. See: http://dels-old.nas.edu/dr/

4 See also the words of President Barack Obama (27 August 2010): “I encourage all Americans to recognize the importance of preparedness and observe this month by working together to enhance our national security, resilience, and readiness” on the website of the recently established Community and Regional Resilience Institute (CARRI) in the USA: http://www.resilientus.org/
3 Resilience: Methodological Reflections

“The etymology of the word ‘resilience’ is the latin verb ‘resilio’, meaning to rebound” (Rose, 2009, p.1). Starting with R.H. MacArthur (1955), the ecologists have investigated the properties of a number of different stability and stability-related concepts: for instance, the concepts of persistence, resilience, resistance, and variability. Of these various concepts, that of resilience itself appears to have been rather resilient (Batabyal, 1998). In recent years, this concept has also been investigated, adopted, and applied in economics and the spatial sciences (see for a review, among others, Fiksel, 2006; Gibson et al., 2000; Reggiani et al., 2002; Rose, 2009), by showing its potential in understanding the evolutionary paths of complex spatial systems.

In general, resilience refers to the “capacity of a system to retain its organizational structure following perturbation of some state variable from a given value” (Perrings, 1994, p. 30).

The concept of resilience is heavily based on the hypothesis that different states of a system involve different equilibria. In other words, it is assumed that the evolution of (ecological, economic, etc.) systems is shaped by the ‘switch’ of these systems from one equilibrium-state (or stability domain) to another.

There are two different ways of defining resilience (see Perrings, 1998, p. 505): “One refers to the properties of the system near some stable equilibrium (i.e. in the neighbourhood of a stable focus or node). This definition, due to Pimm (1984), takes the resilience of a system to be a measure of the speed of its return to equilibrium. The second definition refers to the perturbation that can be absorbed before the system is displaced from one state to another. This definition, due to Holling (1973, 1986, 1992), does not depend on whether a system is at or near some equilibrium. It assumes that ecological systems are characterised by multiple locally stable equilibria, and the measure of a system’s resilience in any local stability domain is the extent of the shocks it can absorb before being displaced into some other local stability domain. Perturbation may induce the system to change from one attractor (stability domain) to another, or not. If not, the system may be resilient with respect to that perturbation.”

The first definition by Pimm, which is more ‘traditional’, focusses on the property of the systems near some stable equilibrium point (engineering resilience).

The second definition by Holling focusses on the property of the systems further away from the stable state (i.e. the size of the stability domain). The measure of resilience using this definition is the perturbation that can be absorbed before the system converges on another equilibrium state (ecological resilience).

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5 It is interesting to note that this article by Gibson et al. has been co-authored with Elinor Ostrom, the 2009 Nobel winner in Economics
The measurement of Pimm’s resilience is therefore easier – from an empirical viewpoint – than Holling’s resilience. However, it appears to be more ‘restrictive’, since it concerns only the equilibrium points, rather than the stability domains or basins of attraction. Moreover, we can observe that, on the one hand, Pimm’s resilience depends on the strength of the perturbation, while, on the other hand, Holling’s resilience depends on the size of the attractor/stability domain (Reggiani et al., 2002).

In the context of socio-economic and spatial systems, Levins et al. (1998) state: “Resilience, the ability to experience change and disturbances without catastrophic qualitative change in the basic functional organisation, is a measure of the system’s integrity (Holling, 1973)” (Levins et al., 1998, p. 224). These authors also argue that a non-resilient system is no longer capable of absorbing the stresses and shocks imposed by human activity, without undergoing a fundamental/catastrophic change involving loss of function and, often, loss of productivity. Hence, it is necessary to be flexible and adaptive to new challenges and sudden qualitative shifts, although it is usually difficult to detect strong signals of change early enough to motivate and induce effective solutions (Levins et al., 1998).

The question is then the following: How much is resilience desirable for a socio-economic and spatial system, in general, and for a transport/communication system in particular? On the one hand, ‘too strong absorbing states’ could lock-in people or actors in behaviour patterns which preclude any positive evolution, by also reducing also their resilience (i.e. their capacity to absorb shocks). Firms, companies, and other communities, which are subject to small continuous changes and have to fight for survival, probably develop a ‘better’ resilience than very stable groups. On the other hand, ‘very low resilience’ may lead the system towards unstable states, likely to be irreversible.

Starting from the above methodological reflections, we can examine the resilience concept in the specific context of transport networks. An extensive literature review in this respect has been given by Rose (2009). In particular, in the light of transport security policies, this author, referring to Bruneau et al. (2003), discusses the resilience concept as follows: “The authors (Bruneau et al., 2003) apply the concept at four levels: technical, organizational, social, and economic. They contend that resilience has four dimensions, which are listed below along with a definition applied to the economic level:

1. Robustness – avoidance of direct and indirect economic losses
2. Redundancy – untapped of excess economic capacity (e.g., inventories, suppliers)
3. Resourcefulness – stabilizing measures (e.g., capacity enhancement and demand modification, external assistance, optimizing recovery strategies)
4. Rapidity – optimizing time to return to pre-event functional levels.”
In addition, Rose (2009, p. 4) reports that: “Bruneau et al. stipulate that the resilience of a system has three aspects:
1. Reduced probability of failures
2. Reduced consequences from failures
3. Reduced time to recovery.”

However, the relationship between the dimensions and aspects of a resilient system – with reference to the definition of resilience given earlier – was criticized by Rose, in the light of a better (less broad) use of the term ‘resilience’, more consistent with the one used in ecology and in the economic literature. Interestingly, Rose (2009) defines: (a) static economic resilience as the ability of an entity or systems to maintain functions (e.g. continue producing), when shocked; (b) dynamic economic resilience as the speed at which entity or a system recovers from a severe shock to achieve a desired state.

Clearly, the Rose’s first definition (a) may be interpreted in the light of Holling’s definition, and the second (b) in the light of Pimm’s.

Keeping in mind these two principal concepts/definitions of resilience, the next step is the exploration of resilience in the context of an increasing complexity in the networks (e.g. when the size increases), such as in the transport and communication networks. In other words, one may ask whether, and if so, to what extent, the scale is relevant (e.g. enhancing resilience at one scale may reduce it at another), as well as the time (how resilience can change through time). In both cases network connectivity structures can play a fundamental role in the identification of resilience. This latter issue is explored in the next section.

4 Network Connectivity Structures and Resilience

Networks can be interpreted as complex interconnected space-time systems, given the nonlinear characteristics of the network structure6 (Reggiani and Nijkamp, 2009).

In the past few decades, there has been an enormous interdisciplinary interest in network concepts, analysis and modelling, arising from the study of complex interconnected dynamic systems. In particular, the fundamental works on social networks, developed by Barabási and his collaborators (see, e.g., Albert and Barabási, 1999), also shed new light on spatial-economic-transport networks, by showing that networks often display common behaviour, based on their topological characteristics (see also Newman, 2005).

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6 For a brief review on complexity and networks, see, for example, Chapter 1 in Reggiani and Nijkamp (2006).
In particular, topological structures matter\(^7\) according to different types of connectivity (Barabási and Oltvai, 2004). Analytically, the statistical distribution of the links between centres/nodes can be expressed as follows:

a) Poisson distribution (random network):

\[
P(k) \propto e^{-\lambda} \frac{\lambda^k}{k!},
\]

where \(P(k)\) is the probability that a chosen node – in a certain network – has exactly \(k\) links. Random networks are also called exponential, because the probability that a node is connected to \(k\) other sites decreases exponentially for large \(k\).

b) Power –law distribution (scale-free network):

\[
P(k) \propto k^{-\gamma},
\]

where \(\gamma\) is the exponent. Networks with this distribution called Scale-Free (SF) networks (with the possibility of hubs). Hubs are the preferential nodes/attractors in a network (hub: a single vertex with a large number of connections). According to Barabási and Oltvai (2004), a hub configuration/hierarchy exists for \(2 \leq \gamma < 3\).

In essence, the above link distribution is associated with exponential/power forms. These analytical forms are also strongly related to the equations that govern spatial interaction modelling, in a transport or communication network.

In other words, the topological (random, SF, or intermediate structures) properties of a network can give useful insights into how the transport network is structured and which are the most ‘important’ nodes. Methodologically, network topology can influence the conventional spatial economic laws (such as equilibrium theory, spatial interaction theory, etc.). These interrelationships between network analysis and spatial economic analysis call for further reflections on the complexity of space-time phenomena and the simplicity of the laws describing these phenomena (Reggiani, 2009).

A further interesting feature envisaged by Barabási and his group (see, e.g., Albert et al., 2000) deals with the vulnerability issue associated with the type of network connectivity. In summary:

a. SF networks (networks with hubs) are highly resistant to random failures, in that a substantial number of links can fail and still not affect the performance of the network as a whole;

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\(^7\) The scientific attention to the connectivity issue has recently given rise to great number of contributions which deal with topology, connectivity and networks (see, among others, Goyal, 2007; Friesz, 2007; Naimzada et al., 2008; Reggiani and Nijkamp, 2009; Vega Redondo, 2007; Vervest et al., 2008).
b. SF networks are very vulnerable to a deliberate attack directed against the major hubs (e.g. the 9/11 attack only indirectly affected the Internet, which continued to function. The Internet would have been less resilient if directly attacked; see Allenby and Fink, 2005);

c. In this latter case, the SF network would break down earlier than the random network.

If we then consider the resilience concept defined in the previous section, we might conjecture that a complete break down of the network (as in the case of SF networks) poses severe problems with regard to resilience, in particular, how much time is necessary to return to the equilibrium point (Pimm’s resilience), or how much the network is able to absorb this complete shock (Holling’s resilience). In both cases, it seems necessary to enhance resilience by first indentifying the type of the network connectivity/topology concerned.

In this vein, several authors in the past decade have examined the relationship between complex networks and resilience (such as Callaway et al., 2000; Cohen et al., 2001). This research has not been without criticism: the discussion has mainly centred on the clear identification of a SF network, in the light of resilience strategies (for a review, see Schintler et al., 2007).

From the methodological viewpoint several research issues are still open, such as:

- How do (unsustainable) sub-sets of network structures affect the resilience of the whole network?
- How do changes in the network connectivity structures lead to changes in the resilience?
- How does resilience affect the user’s behaviour and hence policy strategies?

Undoubtedly, an increase of resilience – in the most possible fragile nodes/areas – can be a first step towards the design of a secure transport and telecommunication network. This will be considered in the next section.

5 Enhancing Resilience in Transport Networks

Given these premises, an essential issue is the problem of measuring – and thus enhancing – resilience in transport and communication networks.

Operational measures of resilience in a ‘dynamic’ network are not easy to deal with. For example, Reggiani et al. (2002) investigated the resilience of the West-German labour market dynamics by means of Lyapunov exponents. Recently, Cox et al. (2009) suggest the following operational measures:
- **Direct Static Economic Resilience (DSER)**: the percentage avoidance of maximum economic disruption that a given shock could bring about.

- **Total Economic Resilience (TSER)**: the difference between a linear set of general equilibrium effects, which implicitly omits resilience, and a non-linear outcome, which incorporates the possibility of resilience.

In addition, Cox et al. (2009), by means of the above measures, quantify and apply resilience using the real-world case of the 2007 London subway and bus bombing. Among others, Matiswiz and Murray (2009) propose a methodology designed to preserve the existing network activity, or system flow, thus enhancing resilience, by utilizing network optimization methods, with reference to Ohio’s interstate system. Kim et al. (2010) present an application of resilience to the case study of the Transit system in the Greater Metropolitan Area of Washington D.C., by using path-probability measures. Interestingly, these latter authors take into account the network topology by means of incidence matrices. Complex network theory has also been implemented by Schintler et al. (2007), in order to analyse the resilience of a portion of the electric transmission grid in Washington, D.C. area. The economic impact of a terrorist attack on the electric power network in Los Angeles has been evaluated by Rose et al. (2007), where the resilient responses are simulated by means of regional computable equilibrium models.

In summary, measuring and enhancing resilience is strictly linked to the identification of critical infrastructures (for a review, see, among others, Casti, 2009; Murray and Grubesic, 2007; Nagurney and Qiang, 2009). Fragile communities are more likely to be susceptible to disasters, attacks, disruptions, and, moreover, are likely to experience subsequent weakness and failure after the attacks (Allenby and Fink, 2005). This is particularly true for SF networks, which seem vulnerable to targeted attacks in their hubs.

The tendency towards a network-centric organization – and hence towards an SF network – has been recently observed not only in the economic (firm) structures, but also in transport and urban networks (such as air and high-speed transport networks, websites, financial networks, etc.). In this context, improvement of (physical and virtual) accessibility certainly plays a significant role in the augment of SF networks.

Consequently, given that these SF structures – even though productive – are fragile and critical in their hubs, an envisaged solution might be the dual-use technologies or other kinds of dual systems. For instance, Allenby and Fink advise policies that encourage a strong tele-working capabilities in local firms. Further examples of resilience enhancement include (Rose, 2007):

- Increase in inventories;
- Improving substitution possibilities for key inputs;
- Broadening the supply chain.
However, it is not easy to implement dual-use technologies or redundancy, because of the high costs involved. More analyses and research studies are necessary in this respect.

6 Conclusions

The interest – in transport security – concerning the analysis and modelling of integrated networks and resilience, also reflects the relevance of this theme from the policy viewpoint. This paper has proposed a conceptual/methodological framework for analysing resilience, mainly in the light of network structure connectivity issues and their impact on transport security.

It appears that resilience, conceived of as the capacity/ability of the system to absorb shocks without catastrophic changes in its basic functional organization, is a potentially effective tool in understanding the evolutionary paths of complex spatial networks, such as transport and communication networks. But there are also limitations in terms of operationalization and measurement.

Empirically, the measure of resilience is still a rather critical issue. Several measures have been proposed in the literature (e.g. time of recovering from shocks, size of the stability domain absorbing the shocks, potential, entropy, transition probabilities, etc.). However, they still remain at a formal-theoretical level. In this context, the two different interpretations (engineering and ecological resilience) advocated in the literature are certainly useful for grasping the resilience concept. In practice, resilience can be – and has been – measured at a static level. In this context, attention should be paid to the relationship between network connectivity and resilience at different scale levels and its impact on the whole network.

From the policy viewpoint, decision strategies that strongly influence the topology and dynamics of the network might consider not only the utility but also the cost of transforming the transport and communication networks into SF networks, since these types of networks can become fragile in the presence of targeted attacks in their hubs.

Thus, among others, new policy issues that can be raised are:

- the formulation of new strategies in relation to innovative policy choices in transport and communication networks (e.g. as the result of the death/emergence of hubs, new clustering and organizations, new locations of firms, etc.), which can lead to a change in the local/global resilience;
- the monitoring and evaluation of these emerging scenarios (new configurations of connections and interactions, etc.) – and their interrelations at different scale levels – in the light of the resilience objectives.
In summary: a comprehensive system approach with reference to the analysis and modelling of complex systems – at various scales – appears to be essential for effective decision making with regard to a global resilience. This knowledge may help in understanding dynamic complex network behaviour, and achieving progress in the enhancing of resilience.

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