EVALUATION OF RESILIENCE IN TRAFFIC NETWORKS: MODELS AND CHARACTERISTICS.

Ms Beatriz Martinez Pastor

Ph. D Student

Trinity College Dublin

Dr Maria Nogal

Post-Doctorate / Research Fellow

Trinity College Dublin

Dr Alan O'Connor

Associate professor

Trinity College Dublin

Dr Brian Caulfield

Assistant Professor

Trinity College Dublin

Abstract

The management of transport networks requires useful tools that help decision-making when a perturbation occurs. Nowadays, extreme weather takes place more frequently, which can be appreciated in the increment of the number of catastrophic events, damaging all kind of structures around the world. For that reason, the identification of the critical elements is an essential strategy to a robust, reliable development of a country's infrastructure system, as they are key-elements in the progress and well-being of a society.

The concept that evaluates the behaviour of a traffic network when a perturbation takes place is known as resilience. This holistic concept studies the complete process, from the beginning of the perturbation until the total recovery of the system when the perturbation has finished. Many concepts are included in the definition of resilience, such as vulnerability, redundancy, adaptability and safety.

The most extended definition of resilience was given by [1] as "the capacity to absorb shocks gracefully". This complex concept has been studied in different areas, i.e., ecology, socio-ecological systems, economics, urban infrastructure, telecommunication systems, water distribution systems, or internet protocol networks. In recent times resilience definition has become more complex including concepts such as the ability of a system to prepare and to adapt to changes and the recovery of the system.

In transportation, some authors study this feature. According to [2] resilience consists of four parameters: robustness, redundancy, resourcefulness, and rapidity. In a similar way, [3] asserts that resilience is defined in ten dimensions; redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, ability to recover quickly. Eight resilient design methods containing diversity, adaptability, cohesion, and other characteristics are proposed by [4] and [5] define several qualitative heuristic methods for enhancing the system resilience, considering redundancy, reorganization, adaptation, and other features.

This paper analyses different models to evaluate resilience from several points of view, including quantitative models existing to assess and compare the resilience of different networks. In addition, this paper focuses on a quantitative model proposed by [6], analysing the different parameters involved in the measurement of resilience in a transport network.

1. Introduction

Transport networks are a key element of a modern society, since the human activity revolves around it. Among its main features are the capacity to move people and goods from one location to another, being the ability to move goods the most crucial factor. Goods movements include the shipment of all the things as (a) raw materials, including minerals, energy, food and other resources, (b) finished products, which need to be transported to the final clients and (c) also wastes, which is a vital role, with actions such as their removing and the prevention of their accumulation. Therefore, transport networks develop an essential function in our lives, being necessary its understanding and improvement.

An essential point about transport networks is its vulnerability. Transport networks are exposed to all sorts of perturbations, from natural hazards to man-made perturbation.
During the last years, natural extreme events have caused huge losses, such perturbations as Hurricanes Katrina (2005) with estimated cost of 75 billion in the New Orleans area and along the Mississippi coast, Hurricane Sandy (2012) which caused almost 150 deaths and damaged or destroyed an estimated 650.000 homes or Haiti earthquake (2010) which caused more that 100.000 deaths.

In addition, these perturbations caused by natural hazards or man-made can be unexpected and vary during the lifetime. Despite of this fact, there are systems to predict natural hazards, but these predictions could not be accurate. Also, there are cases where the perturbation is not predicted and the place, the intensity and the duration of the disturbance are totally unknown.

Due to all damages that can be caused by a perturbation, each tool to improve a transport network or its knowledge should developed and used. This paper focuses on one of these tools, which is able to improve a transport network, namely, transport resilience. This concept allows a better understanding of the behaviour of a traffic network when is affected by hazard.

The paper is organized as follows; Section 2 presents the concept of resilience, analysing definitions used by different authors. Section 3 discusses methodologies to evaluate resilience in transport networks. Section 4 describes one of the quantitative models and introduced a real example to measure resilience. Finally in Section 5 some conclusions are drawn.

2. Resilience

The concept of resilience is defined as the ability to quickly return to a previous good condition by the Cambridge dictionary. The origin of the word resilience comes from the Latin word "resiliere" whose meaning is "bounce back". Resilience is a new concept and during the last years, its meaning has been changing and evolving. Starting by [7], in the area of ecology, who can be considered as the first author who studied the concept of resilience. Holling [7] introduced resilience to the scientific world, defining resilience as the ability of ecological system to absorb changes of environment variables. In addition, resilience has been studied in topics, as socio-ecological systems [8], economics [9], urban infrastructure,

[10], telecommunication systems [11], water distribution systems [12], or internet protocol networks [13].

Resilience is applied to the field of transport even more recently. Table 1 shows a set of definitions of resilience applied to a transport network.

Author	Year	Definition
Bruneau et al [2]	2005	The ability of the system to reduce the chance of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance).
Subcommitte on Disaster Reduction	2005	The ability of a community or system to adapt to hazards so as to maintain an acceptable level of service.
Pamela M. Murray-Tuite. [3]	2006	A characteristic that indicates system performance under unusual conditions, recovery speed, and the amount of outside assistance required for restoration to its original functional state.
Batelle et al[16]	2007	A characteristic that enable the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed.
VTPI [25]	2008	A system's ability to accommodate variable and unexpected conditions without catastrophic failure.
Ta et al. [17]	2009	The ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility.
Ramirez-Marquez et al [18]	2011	Describes the ratio of recovery at time t to loss suffered by the system at some previous point in time.
W. H. Ip, Dingwei Wang. [19]	2011	The ability of a system to return to a stable state following a strong perturbation caused by failure, disaster or attack .
Nayel Urena Serulle, Kevin Heaslip etc. [20]	2011	The ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in specified time frame.
Derek Freckleton, Kevin Heaslip etc.[21]	2012	The ability for a transportation network to absorb disruptive events gracefully and return itself to a level of service equal to or greater than the pre-disruption level of service within a reasonable time frame.
Elise Miller-Hooks, Xiaodong Zhang [22]	2012	Both the networks inherent ability to cope with disruption via its topological and operational attributes and potential actions that can be taken in the immediate aftermath of a disruption or disaster event
Lichun Chen, Elise Miller-Hooks. [23]	2012	A networks capability to resist and recover from a disruption or disaster.
T. M. Adams, K. R. Bekkem etc [24]	2012	The capacity to absorb the effects of a disruption and to quickly return to normal operating levels.

The National Academy of Sciences (NAS)	2012	The ability to plan and prepare for, absorb, recover from, and adapt to adverse event.

Table 1: A set of definitions of resilience.

After the study of the transport resilience definitions, some important characteristics are deduced. An adequate resilience definition has to be based on the following items:

- The definition of resilience should specify the perturbation stage; ability to absorb, resist or accommodate a perturbation. In addition, if the perturbation is very strong, the system can break down and this collapse point should be identified.

- Once the perturbation is finished, the definition of resilience should specify the recovery stage; the ability to restore, return or recover from the perturbation. This recovery action has to reach a system equilibrium for which the transport network is able to operate. However, the equilibrium point reached could be equal, greater or worse than the previous level of service of the transport network.

- Finally, both phases, i.e. the perturbation period and the recovery period, should be analysed in a specific time frame. Since the resilience of traffic network will go from the best to the worst depending on the time frame necessary in the process.

3. Evaluation of resilience

Many authors have tried to measure the global concept of resilience. This is not a straightforward task, due to all the parameters involved in resilience.

When previous methodologies to evaluate resilience are studied, a first division can be established. Firstly, the group of authors who analyse resilience in a qualitative manner, and secondly, those authors who present a quantitative methodology to evaluate it.

The focus of this paper are the quantitative methods, a quantitative methodology allows a better understanding of resilience and a systematic comparison between different traffic networks.
Among the experts in resilience, those who present a quantitative method are scarce. Next, some of these models are analysed.

To evaluate resilience, [3] describe ten properties, being redundancy, diversity, efficiency, autonomous components, strength, adaptability, collaboration, mobility, safety, and the ability to recover quickly.
Each property is quantified separately, through its own formulation. This fact makes this approach complicates and impractical. Finally a method to evaluate the whole concept of resilience is not reached. Since, in the paper, four of the ten properties are studied and its study is used to compare the performing among the user equilibrium and the system optimum for the traffic assignment-simulation methodology.

Heaslip et al. [20] evaluates resilience of a transport network through the measurement of eleven variables, namely, prevailing level of service, road density, alternative mode available capacity, average delay, average speed reduction, personal transport cost, commercial/industrial cost, alternate infrastructure proximity, level of intermodality and avenue restriction. This author analyses in detail each variable. These eleven variables are organized in a structure to reach the global value of resilience. To get the assessment of resilience, the author uses soft computing methods based on a fuzzy sets theory.

Finally, the value of resilience is among five values, i.e. very low, low, medium, high and very high.

Ramirez-Marquez et al. [18] calculates resilience through a time dependent quantifiable metric. The author defines resilience as the proportion of delivery function that has been recovered from its disruptive state. Resilience is analysed only during the recovery process. This recovery process is analysed in a given example, where the topology of the network, the number of arcs affected by the perturbation and the number of repair teams available, are input data of the methodology. With these data and knowing the broken links, the different ways to restore the network are studied and an "optimal resilience strategy" is obtained.

Bruneau et al. [2] presents a framework for defining seismic resilience. The author establishes three complementary measures of resilience, namely, "reduced failure probabilities", "reduced consequences from failures" and "reduced time to recovery". In addition, the paper analyses the quantitative measures of the robustness, rapidity, resourcefulness and redundancy and integrates those measures into the four dimensions of community resilience, i.e. technical, organizational, social and economic. The methodology to assess resilience is through system diagrams, which identify the key steps to quantify it.

Table 2 shows the advantages and disadvantages of the quantitative methodologies to measure resilience previously explained.

Murray-Tuite et al. [3]	Advantages	The methodology covers a wide range of properties to define resilience. At the same time, each property is divided in more properties, which are calculated individually. Therefore the definition of resilience based on the measurement of all its properties is very detailed.
	Disadvantages	Due to the big amount of properties involved, the methodology is almost impracticable. Because of this, the author evaluates only four of the eleven properties. Therefore, the concept of resilience is not evaluated in its whole.
Heaslip et al. [20]	Advantages	The author makes a detail study of the parameters involved in the transportation resilience. In addition the resilience definition is very accurate, since this definition comprises all the perturbation processes from the beginning of the perturbation to the total recovery
	Disadvantages	Despite of the high number of properties included at the beginning of the methodology, the final value of resilience is limited to five options: very low, low, medium, high, very high. Therefore, this methodology implies a huge amount of resources to measure the variables and the final result is very poor.
Ramirez-Marquez et al. [18]	Advantages	The author introduces a time dependent quantifiable method to evaluate resilience and presents an illustrative example. Also, this proposed metric allows the systematic comparison among different networks.
	Disadvantages	This methodology only analyses the recovery process of the perturbation. Being the initial perturbation process excluded. In addition, the way of quantifying resilience and introducing the time is limited.
Bruneau et al. [2]	Advantages	The framework presented by the author covers multiples scenarios to assess the resilience. This fact allows the inclusion of a huge number of probabilities.
	Disadvantages	Being established an exhaustive framework to quantify resilience, a real example is not introduced. This would allow a better understanding of the methodology and would prove the real application.

Table 2: Advantages and disadvantages of a set of methodologies to quantify resilience

4. Dynamic Restricted Equilibrium Model to Assess the Traffic Network Resilience

When a disaster occurs, the traffic network is affected mainly through two different ways, namely, (a) user travel costs (generally travel time) increase and (b) users become aware of these greater costs and try to reduce them by changing their route choices, generating a certain stress level in the network. When the alteration stops and the initial state is recovered, the travel costs are recuperated and users eventually return to their initial route choices. On the other hand, if the alteration stops but the initial state is not recovered, users will find other route choices that minimize their costs, though these costs will be greater than before. The explained performance is measured by the concept of resilience.
The assessment of the traffic network resilience requires a dynamic approach. With this aim, [6] propose a Dynamic Equilibrium-Restricted Assignment Model (DERAM), which allows the simulation of the network behaviour when a disruptive event occurs. This approach permits the inclusion of the stress level of the system together with the extra cost generated by the hazard. This model proposes that the network behaviour is restricted by system impedance, denoted by α.

Mathematically, this can be expressed as an optimization problem for each time interval *t*, that is:

$$\underset{\rho_r}{\text{Minimize}}\, Z(\rho_{\mathbf{r}}) = \sum_{a\in A} C_a(\rho_r(t)), \tag{1}$$

subject to:

$$\sum_{r\in R_{pq}} h_{pqr}(t) = d_{pq}(t), \qquad \forall pq \in \mathcal{D} \tag{2}$$

$$\sum_{pq\in D}\sum_{r\in R_{pq}} \delta_{apqr} h_{pqr}(t) = v_a(t), \qquad \forall a \in \mathcal{A} \tag{3}$$

$$h_{pqr}(t) = \rho_r(t) h_{pqr}(t-dt), \quad \forall r \in R_{pq}, \forall pq \in \mathcal{D} \tag{4}$$

$$h_{pqr}(t) \geq 0, \quad \forall r \in R_{pq}, \forall pq \in \mathcal{D} \tag{5}$$

$$|\rho_r(t) - 1| \leq \alpha, \qquad \forall r \in R_{pq} \tag{6}$$

$$\rho_r(t) > 0, \qquad \forall r \in R_{pq} \tag{7}$$

with

$$\delta_{apqr} = \begin{cases} 1, \text{if route } r \text{ from node } p \text{ to node } q \text{ contains arc } a \\ 0, \text{otherwise} \end{cases}$$

where $C_a(.)$ is the integral of the travel cost function, R_{pq}, the set of routes with origin-destination *pq* and h_{pqr}, is the flow on route *r* with origin-destination *pq*. Furthermore, ρ_r, measures the variation of route flows in two consecutive intervals of time, *t- dt* and *t*, and α represents the system impedance to alter its previous equilibrium state. The lower bound of α is zero, which implies the system is unable to reach a new equilibrium state associated with the new conditions and, the upper bound of α is infinite, which means the system reaches the new equilibrium immediately.

The perturbation resilience is defined between (0, 100), 100% being the optimum value. Moreover, a cost threshold is included to assume the system break-down. This value restricts the perturbation resilience and is the limit-state associated with the failure of the travel cost network due to the extreme overcost generated by a strong perturbation. Although the system could theoretically recover, it would imply an unacceptable effort by the system.

To show the results of this method, an illustrative example is introduced, considering the Sioux Fall network.

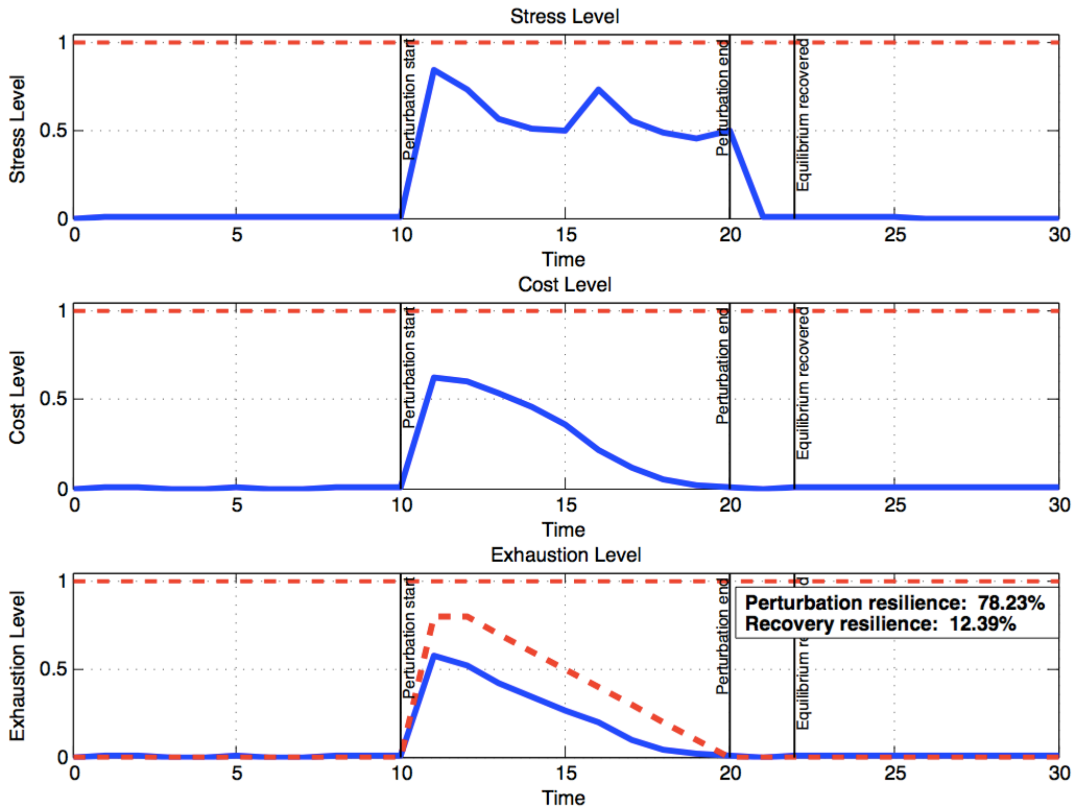

Figure 1: Final results of the model proposed by [6]

The proposed network is affected by a perturbation. In this case, the perturbation is caused by heavy rain, beginning the 10th day, with a maximum the 11th day and finishing the 20th day, drawn in Figure 1 with a red line. The results in Figure 1 also show the evolution in time from the beginning of the damage to the total recovery of the system. Together with the final value of the resilience, it is possible to know the stress level and the cost level of the network at each moment of the disturbance. Combining both levels, the exhaustion level of the network is obtained and its evolution over time is also showed in Figure 1.

5. Conclusions

The numerous definitions and different understandings of resilience in transport is an obstacle to develop a valid methodology and to foment its use.

Therefore, to obtain a common definition, it is necessary to determine which parameters are essential in the evaluation of resilience and which of them are not indispensable. Since, most of the methodologies previously developed are impracticable due to the high number of variables involved.

To reach this goal, three main characteristics should be introduced in the definition of resilience. Firstly, the perturbation stage and how the network absorbs the hazard, secondly the recovery process and how the network returns to an equilibrium point and finally the time frame that is necessary to conclude the disturbance.

To reach a common understanding of resilience is as important as to develop a competitive methodology to evaluate it. This fact implies to accomplish a quantitative method, to allow a systematically comparison of transport networks.

After the study of a set of quantitative methodologies to evaluate resilience, one of the main inconveniences is that most of them need a huge number of properties. These properties should be evaluated in each methodology and usually each of them has a specific formulation to assess it. Due to this fact, these methods could be unviable. Therefore, some of these authors do not specify a real value of whole concept of resilience.

This paper evidences the fact that the concept of resilience has a decisive role in a transport network when a perturbation occurs. Then, a quantitative methodology where real examples are introduced easily is determining, since some methods require large processes to get results and this fact can be a disadvantage.

The model introduced by [6] presents a quantitative and dynamic approach to evaluate resilience in transport networks, from the initial perturbation to the total recovery. A real example is presented, where its validity to measure transportation resilience is manifested. The results show the evolution of the exhaustion level of the network in each instant of the process, as well as the values of perturbation and recovery resilience in a specific network affected by a specific hazard.

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