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Resilience of traffic networks: From perturbation to recovery via a dynamic restricted equilibrium model

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ABSTRACT

When a disruptive event takes place in a traffic network some important questions arise, such as how stressed the traffic network is, whether the system is able to respond to this stressful situation, or how long the system needs to recover a new equilibrium position after suffering this perturbation. Quantifying these aspects allows the comparison of different systems, to scale the degree of damage, to identify traffic network weaknesses, and to analyse the effect of user knowledge about the traffic network state. The indicator that accounts for performance and recovery pattern under disruptive events is known as resilience. This paper presents a methodology to assess the resilience of a traffic network when a given perturbation occurs, from the beginning of the perturbation to the total system recovery. To consider the dynamic nature of the problem, a new dynamic equilibrium-restricted assignment model is presented to simulate the network performance evolution, which takes into consideration important aspects, such as the cost increment due to the perturbation, the system impedance to alter its previous state and the user stress level. Finally, this methodology is used to evaluate the resilience indices of a real network.

1. Introduction

Perturbation of a traffic network is the temporal modification of the physical characteristics of the traffic network, or the conditions to which users are subjected, or both of them, resulting in an overall deterioration of the traffic quality indices, such as travel times, polluting emissions, etc.

When a perturbation takes place in a traffic network, two main effects occur: (i) user travel costs (generally time) increase and (ii) users become aware of these greater costs and try to reduce them by selecting routes less affected, generating a certain stress level in the network. Then, the new selected routes become more saturated, leading to an increase in the corresponding travel costs. This process continues until an eventual equilibrium is achieved.

The described process can clearly be divided into two different phases, the perturbation stage and the recovery stage. The former implies a modification in the initial network conditions, resulting in a cost increment and a certain degree of user stress. In this phase, it is important to analyse the network capacity to absorb the impact and to adapt to changes. In the recovery stage, when the perturbation has stopped, the system reaches a new equilibrium state compatible with the final network conditions. The critical parameter in this phase is the time necessary to achieve this equilibrium state.

The indicator that accounts for performance and recovery pattern under disruptive events is known as resilience. Resilience was defined by [1] as “the ability for [sic] a transportation network to absorb disruptive events gracefully, maintaining its demonstrated level of service, or to return itself to a level of service equal to or greater than the pre-disruption level of service within a reasonable timeframe”. This definition highlights the crucial factors to be taken into account when analysing the traffic network performance.

Due to the complexity of estimating resilience of a traffic network, some authors have broken down the most relevant features of this concept with the aim of simplifying its evaluation. 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.

In many cases, the evaluation of these aspects leads to a qualitative characterisation of the system rather than a quantitative analysis. Other authors propose numerical models to assess some of these resilience parameters. For instance, [6] study reliability, vulnerability, survivability, and recoverability; [7] carry out a

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Nomenclature

c_a	travel cost associated with link a
c_{0a}	free travel time associated with link a
d_{pq}	demand associated with origin–destination pq
h_{pqr}	flow on route r with origin–destination pq
n_{pq}	number of routes with origin–destination pq
t	time interval
t_r	interval of time at which equilibrium is reached
v_a	link flow associated with link a
v_a^*	link flow associated with link a corresponding to the UE state
$v_a{}^{max}$	link capacity to provide a certain service level
C_a	integral of the travel cost function of link a
C_{th}	cost threshold associated with the system break-down point
C_T	actual total cost
C_0	initial total cost ($t=0$)
R_{pq}	set of routes with origin–destination pq
T_{th}	reference value associated with the recovery time
$\mathcal{A}$	set of links
$\mathcal{D}$	subset of origin–destination pairs of nodes
$\mathcal{N}$	set of nodes
α	system impedance
β_a	saturation parameter of the cost function
γ	saturation parameter of the cost function
θ_κ	normalized slope associated with the exhaustion level curve
κ	state of perturbation
χ_κ^p	perturbation resilience associated with state of perturbation κ
χ_κ^r	recovery resilience associated with state of perturbation κ
ρ_r	net flow variation among routes within the same origin–destination pair in two consecutive intervals of time
σ_κ	stress level of traffic network associated with state of perturbation κ
τ_κ	cost level of traffic network associated with state of perturbation κ
ψ_κ	exhaustion level of traffic network associated with state of perturbation κ

measure of resilience through the restoration of system performance and the required resource expenditures, and [8] analyse the vulnerability. The vulnerability of traffic networks is also studied under the game theory perspective in [9], where for instance, Gao et al. [10] propose an heuristic approach to minimise the congestion of traffic networks governed by an UE, when some random links have been attacked. They aim is to plan defense strategies by securing some selected links so that they cannot be blocked. The variable time when assessing the resilience of complex systems is efficiently introduced by [11], who proposes three time-related metrics, by [12], through the comparison of the system performance over time, and by [13] who state resilience as a ratio of recovery to loss at a given time, showing the recovery as a function of the time. This deterministic formulation is equivalent to that proposed by [14] for the worst-case quantity. Resilience in the restoration process of a transportation system when an earthquake damages a bridge is assessed by [15]. The aim of this method is to establish the bridge restoration activities which maximize the system resilience and minimize costs and time in the restoration activities. Finally [16] propose an optimization program to evaluate the reliability associated with a intermodal freight transportation networks.

Nevertheless, few approaches have been developed that provide a comprehensive assessment of the resilience of a traffic network including its ability to prepare and to adapt to changes and its capacity of recovery, over time.

Within this context, this paper presents a novel methodology to assess the resilience of a traffic network suffering from a progressive impact. It is based on a macroscopic traffic model that simulates the dynamic response of the network when suffering a disruption, from the beginning of the perturbation to the total recovery of the system.

The model provides information about the effect of the perturbation upon the travel costs and upon the stress level of users. This information is combined to evaluate the perturbation resilience and the recovery resilience.

It is highlighted that the proposed approach takes into account the system impedance to alter its previous state, given that the actual capacity of adaptation of the system to the new situations determines the traffic network behaviour. User's habits were addressed before, by Hausken and Zhuang [9], who analyses the traffic performance when the route choice is based on en-route information. In this case, the author considers a constant inertia to reflect the user's resistance to the recommended route guidance information.

The methodology presented in this paper to numerically evaluate the resilience of a traffic network, involves the majority of the qualitative concepts studied by previous authors such as the redundancy, adaptability, ability to recover quickly, etc.

The paper is organized as follows: Section 2 presents a new traffic assignment model, defined as "dynamic equilibrium-restricted assignment model". Section 3 discusses the important role of the variable ρ to measure the stress level of the system. Section 4 describes how to estimate the resilience associated with the perturbation stage and recovery. Section 5 analyses the influence of the system impedance in the evaluation of the resilience. Section 6 gives a real example of application to illustrate the performance of the proposed method. Finally, in Section 7 some conclusions and future research lines are drawn.

2. A dynamic equilibrium-restricted assignment model

This section is devoted to presenting a new dynamic assignment model, which is used to analyse the system performance before, during and after a perturbation. This model is based on the following assumptions: (a) the global behaviour of users is analysed in a day-to-day basis, that is, the problem of within-day dynamics (see [17,18]) is neglected. (b) Only negative perturbations are taken into account, i.e., those perturbations which imply a travel cost increment. (c) Users selects their route choices that reduce their individual travel costs. This selection is based on the complete information about the past day's travel costs. (d) The capacity of adaptation of the users to the changes, the lack of knowledge of the new situation and the lack of information of the behaviour of other users impede the immediate response and recovery of the system.

According to the well-known Wardrop principle, an User Equilibrium (UE) state is reached when, for each origin–destination pair, the actual route travel cost experienced by travelers within a traffic network is equal and minimal (see [19]). Consequently, a "equilibrium-restricted" state can be obtained when, for