8th International Forum on Engineering Decision Making

Decision-Making Beyond the Engineering Community

May 6 – 9, 2015 Hieizan, Enryakuji-kaikan Shiga, Japan

STATISTICAL TOOLS TO HELP THE DECISION-MAKING PROCESS WITHIN THE RISK ANALYSIS OF TRANSPORTATION NETWORKS IN RESPONSE TO EXTREME WEATHER EVENTS

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RAIN PROJECT

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THE UNIVERSITY OF DUBLIN

Project funded by
the European Union

Extreme weather events on traffic networks

Winds in Austria, 2015

Source: www.bbc.com/news

Intergovernmental Panel On Climate Change (IPCC): "*Confidence has increased that some extremes will become more frequent, more widespread and/or more intense during the 21st century.*" (2014)

The impact on infrastructure systems is catastrophic, resulting in **high social, economic and environmental costs**.

As transportation systems are a cornerstone of functioning society, it is imperative to develop tools and mechanisms (a) to allow the **early warning response** to the impacts of extreme weather events, (b) to support the **decision-making process** and, (c) to permit the **improvement** of the existing networks and the generation of **more efficient designs**.

1 **IMPORTANCE**

European research project **RAIN** (**R**isk **A**nalysis of **I**nfrastructure **N**etworks in response to extreme weather) arises with the aim of developing a systematic risk management framework that **explicitly considers the impacts of extreme weather events** on critical infrastructure and develops a series of mitigation tools to enhance the security of the pan-European infrastructure network.

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   Holistic approach. **Resilience**: *capacity of a system potentially exposed to hazards to adapt by resisting or changing in order to reach and maintain an acceptable level of functioning*.

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3. **NOVELTY**
   The literature is not abundant. Resilience is analysed in a qualitative way. Description of the observed effect of different weather events on road performance.

Some important questions are still unanswered:

- How will a given traffic network **respond** to a specific extreme climatological hazard?
- How can the traffic response be **improved**?
- What are the **vulnerabilities** of a traffic system to this kind of events?

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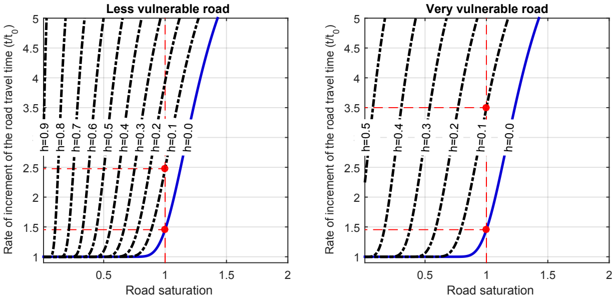
We will attempt to answer these questions and will see a useful statistical tool to help the decision-making process, paying a special attention on **the role that traffic users play**.

Outline

- **Transportation networks suffering extreme weather events**.
  Analysis of the observed behaviour.
- **Resilience assessment**.
  With the aid of the Sioux-Falls Network.
- **Importance and uncertainties of model variables**.
  The most relevant variables have large uncertainties.
- **Statistical tool to help the decision-making process**.
  Based on the statistical relation between the intensity of a weather event and the resilience of the system.
- **Conclusions**.
  And some recommendations to improve the traffic network response.

Influence of the climatological events on travel cost

Climatological events affect the user speed and the road capacity, resulting in a **reduction of travel time**.



The level of influence of a specific weather event will depend on (a) the **intensity** of the hazard; (b) the **features of the road and the traffic characteristics** and; (c) the **cultural and socio-economic** factors.

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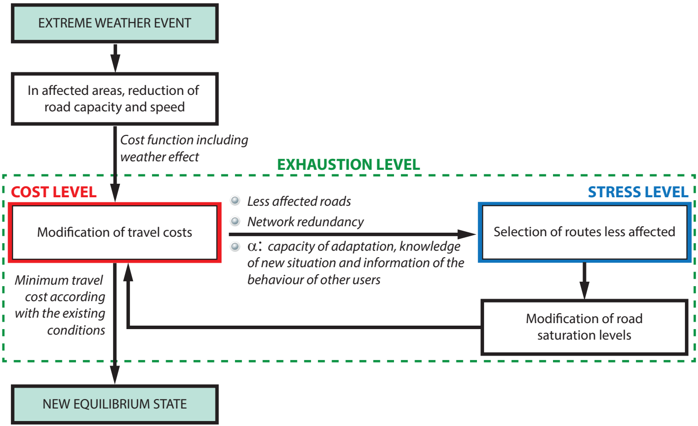
Traffic response of a traffic network suffering a weather impact



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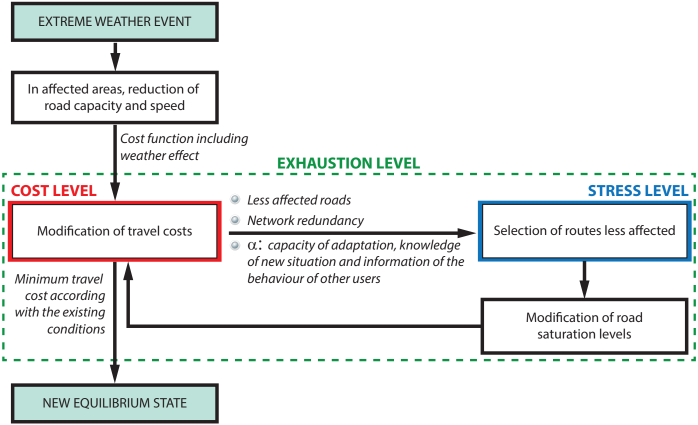

Travel costs can remain low after a perturbation if a **certain degree of adaptability, redundancy, etc. exists**, resulting in an increase in the stress level. Since the **mechanism of response cost-stress** is limited, the larger the disruption, the lower the remaining response capacity. Therefore, the traffic network behaviour when suffering a disruption can be assessed by means of its **exhaustion level, that is, its portion of used resources**.

$$\underset{\mathbf{h},\mathbf{v},\boldsymbol{\rho}}{\text{Minimize}}\; Z(\mathbf{v}) = \sum_{a \in A} C_a(v_a(t)),$$

subject to:

$$\begin{aligned}
\sum_{r \in R_{pq}} h_{pqr}(t) &= d_{pq}(t), && \forall pq \in \mathcal{D} \\
\sum_{pq \in D} \sum_{r \in R_{pq}} \delta_{apqr} h_{pqr}(t) &= v_a(t), && \forall a \in \mathcal{A} \\
h_{pqr}(t) &= \rho_r(t) h_{pqr}(t - dt), && \forall r \in R_{pq}, \forall pq \in \mathcal{D} \\
h_{pqr}(t) &\geq 0, && \forall r \in R_{pq}, \forall pq \in \mathcal{D} \\
|\rho_r(t) - 1| &\leq \alpha, && \forall r \in R_{pq} \\
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- Dynamic approach.

Nogal, M., O’Connor, A., Caulfield, B., and Martinez-Pastor, B. (2014). “Dynamic restricted equilibrium model to assess the traffic network resilience: from the perturbation to the recovery.” *Transportmetrica A: Transport Science*, Submitted.

"Dynamic Equilibrium-Restricted Assignment" (DERA) model

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- Dynamic approach.
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- Extreme weather event is introduced directly through the cost function.

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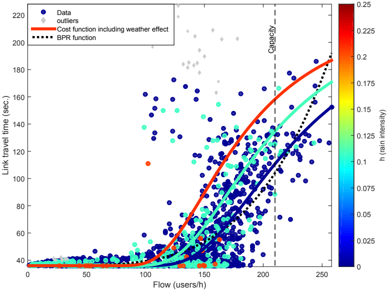
Cost function to include the weather effect on a traffic network



$$t = t_0 \left\{ 1 + m \exp\left[- \left(\frac{\beta S + p h}{1 - h} \right)^{-\gamma} \right] \right\}$$

- Introduction of the normalized intensity of the climatological hazard (rain, snow, floods, wind, etc.)

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Cost function to include the weather effect on a traffic network

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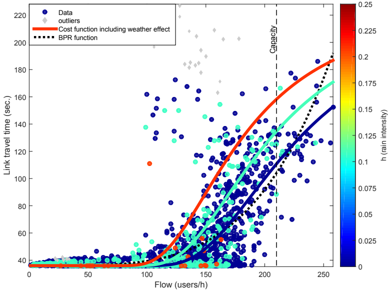

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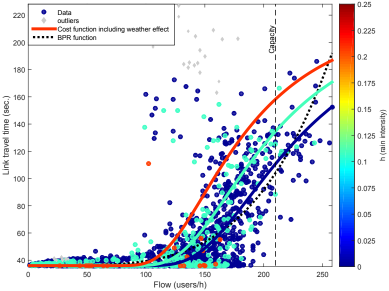

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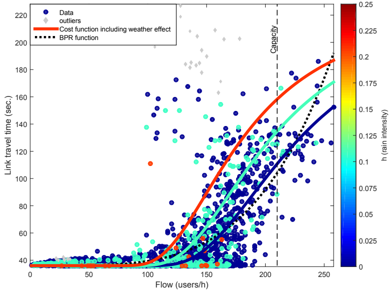

$$t = t_0 \left\{ 1 + m \exp\left[-\left(\frac{\beta S + ph}{1 - h} \right)^{-\gamma} \right] \right\}$$

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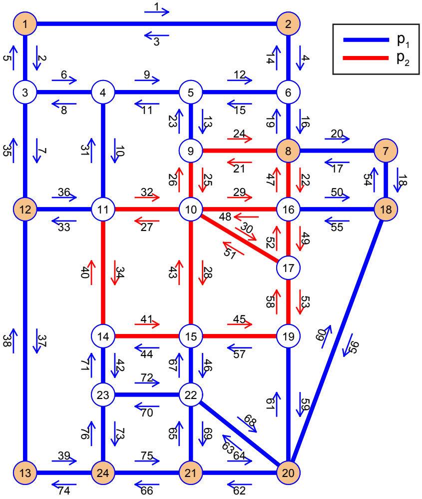
Sioux-Falls network (USA)



- $\mathbf{24}$ nodes (junctions)
- $\mathbf{76}$ links (roads)
- $\mathbf{10}$ origin-destination pairs
- $\mathbf{60}$ routes
- Demand: $\mathbf{350}$ users per OD
- $\boldsymbol{\alpha = 0.10}$
- $\mathbf{2}$ different vulnerabilities ($\boldsymbol{p_1 = 0.1}$ and $\boldsymbol{p_2 = 0.4}$)

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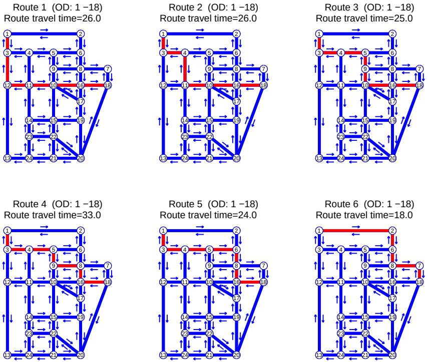

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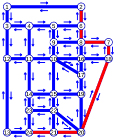
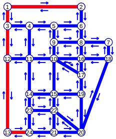
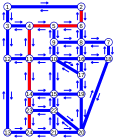
Route 13 (OD:24 − 2)
Route travel time=25.0



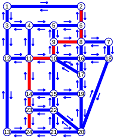
Route 14 (OD:24 − 2)
Route travel time=21.0



Route 15 (OD:24 − 2)
Route travel time=27.0



Route 16 (OD:24 − 2)
Route travel time=35.0



Route 17 (OD:24 − 2)
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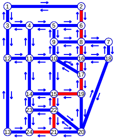
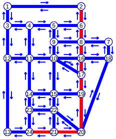


Route 18 (OD:24 − 2)
Route travel time=29.0



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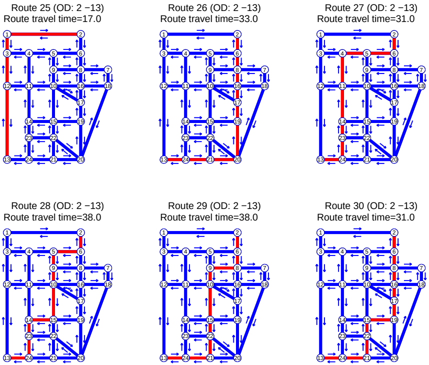

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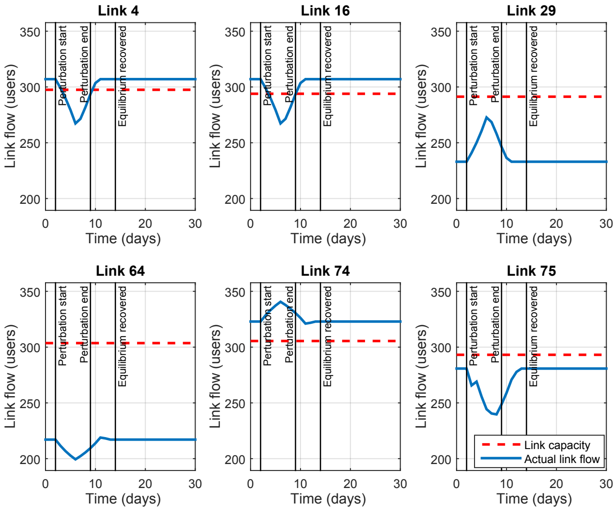
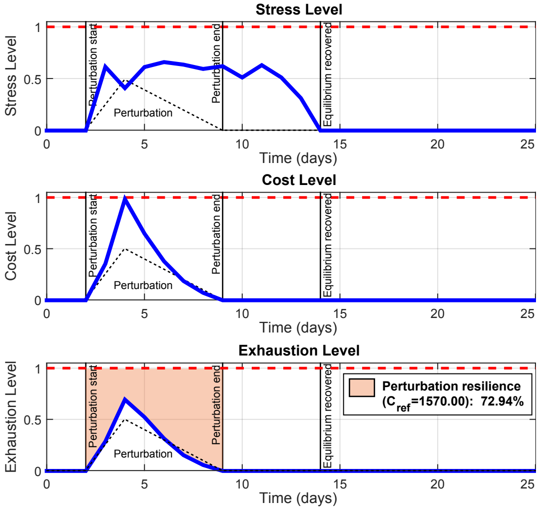
Link flow during the weather impact and the posterior recovery

A strong weather impact of intensity $h = 0.5$ from day 2 to day 9 with a peak in day 4 has been considered.



Resilience assessment



The response capacity of the system is measured by means of the **resilience (capacity of the network to absorb a shock)**, which is computed as the normalized area over the exhaustion curve, in order to measure **how far the system is from complete exhaustion**.

Resilience assessment

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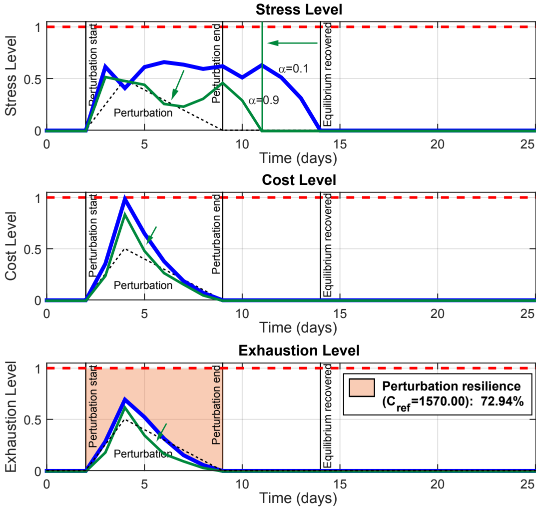

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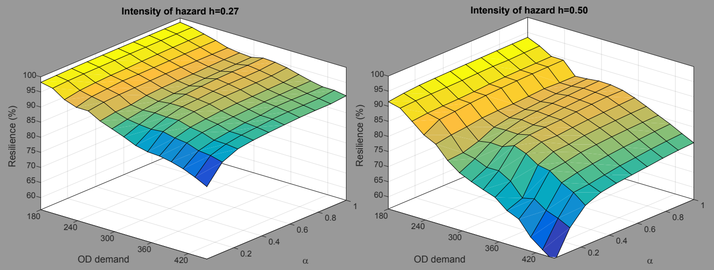
Sensitivity of model variables

The resilience of a traffic network mainly depends on

1. **Perturbation degree**; its intensity and its evolution.
2. Network **congestion**.
3. **Impedance** of the users to adapt to the changes, α.



The sensitivity of α is larger when users play an active role, when they can improve their situation by changing their routes. **High congestions shown that bad-informed users with low capacity of adaptation lead to less resilient systems**.

4. **Uneven characteristics** of different **connected areas**. *Redundant networks with some stronger corridors are essential.*

Uncertainty of model variables

Local vulnerability defined based on previous experiences and expert opinion. Information about extreme weather events is not so common. **Significant uncertainty**.

System impedance calibrated for real networks by means of surveys about the dissuasive effect of the delays on the user route choices. The results of the surveys have to be quantified using real past cases. **Difficult to be accurately estimated**.

Traffic demand directly affected by the intensity of the climatological event. **Uncertainty** in a very sensitive variable.

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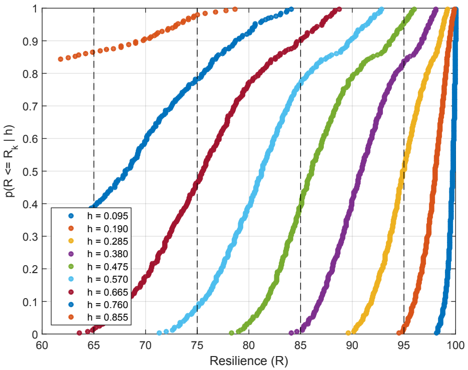
Consequently, these **variables that include an important degree of uncertainty**, namely, the impedance, the local vulnerability and the demand, are **considered as random variables**.

Parameters	Definition	Distribution
p_1	Local vulnerability associated to those links less exposed. It is assumed to have low level of uncertainty	Beta, $B(10, 82)$
p_2	Local vulnerability associated to those links very exposed. Its level of uncertainty is assumed to be larger	Beta, $B(4.5, 6.25)$
α	Impedance of the users to adapt to the changes	Beta, $B(5.5, 26.5)$
OD demand	Demand for each origin-destination pair	Gamma, $G(20, 2.11)$

CDF of the resilience for different hazard degrees

Using the Latin Hypercube sampling method (algorithm proposed by Viana et al. (2010)) and the Monte Carlo simulation method, different **scenarios of traffic networks suffering increasing intensities of hazard** are conducted, obtaining the associated resilience indices.



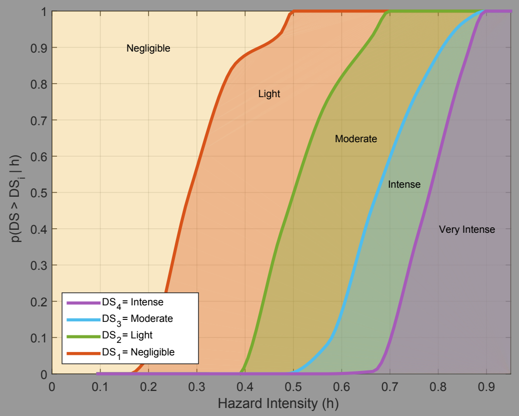
Discrete damage states:

- negligible (resilience $\geq$ **95** %)
- light ($\geq$ **85** %)
- moderate ($\geq$ **75** %)
- intense ($\geq$ **65** %)

Viana, F., Venter, G., and Balabanov, V. (2010).“An algorithm for fast optimal latin hypercube design of experiments.” *International journal for numerical methods in engineering*, 82(2), 135–156.

Statistical-based curves to help the decision-making process

Statistical-based curves on the traffic network response



Protocols of action can be defined according to the different discrete damage states.

Conclusions

- The quantification of the damage suffered by a traffic network and its capacity to respond to extreme weather events requires a **holistic approach** that includes, among other essential aspects, the human response. It is noted that **a low degree of information might cause a slow, and inopportune, response**.
- The methodology used to evaluate the system resilience takes into account concepts such as the **network redundancy, the adaptability, the local vulnerability**, etc.
- The **uncertainties** in the demand, the local vulnerability of the network and system impedance has been considered. These variables have a key role in the system response.
- The presented graphical tool allows an **easier and more efficient decision-making process**. These statistical-based curves, in conjunction with **adequate protocols of action** will result in a **reduction of the societal risk**.

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The resilience of a traffic system suffering from severe weather events is enhanced by,

1. Providing **stronger and well connected** main corridors.
2. Reducing the **traffic demand**.
3. Providing users with more knowledge of the new situation and **more information** of the behaviour of other users.

MANY THANKS FOR YOUR ATTENTION

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