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Nogal, Maria; Morales Napoles, Oswaldo; O'Connor, Alan

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UNDERSTANDING THE VULNERABILITY OF TRAFFIC NETWORKS BY MEANS OF STRUCTURED EXPERT JUDGMENT ELICITATION

Ph.D. Maria Nogal

Research Fellow

Trinity College Dublin (Ireland)

Ph.D. Oswaldo Morales Napoles

Assistant Professor

TU Delft (The Netherlands)

Ph.D. Alan O'Connor

Associate Professor

Trinity College Dublin (Ireland)

Abstract

There is a lack of consensus in relation to the operationality of important concepts and descriptors of traffic networks such as resilience and vulnerability. With the aim of determining a framework with mathematical sound to objectively define and delimit these concepts, the expert judgment uncertainty quantification has been selected to assess the vulnerability of a traffic network when non-disruptive events have been previously identified. Moreover, the expert judgment for dependence modelling is used to establish to what extent common indicators of the traffic network performance, such as accessibility and reliability, explain the vulnerability. Although applied to the case of the metric vulnerability, the methodology arises as an effective tool to explain many other traffic indicators such as resilience, robustness, effectiveness and serviceability.

Introduction

Road traffic networks are exposed to a number of incidents, from vehicle crashes or roadworks, to severe weather events and even terrorist attacks. The first step to mitigate and adapt to these complex and, sometimes, uncertain threats necessarily involves the analysis of the traffic network vulnerability. This will allow the prioritisation of the most adequate actions, and the development and the implementation of satisfactory action plans.

The problem arises when trying to identify and evaluate the vulnerability of the system.

According [1], vulnerability is the susceptibility to incidents that can result in considerable reductions in road network serviceability. In [2] a network node is defined as vulnerable if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node.

Some authors, such as [1] and [3], state that the vulnerability depends on the scenario affecting the traffic network, and can be assessed by analysing the system response to the disruption. This implies to assume the location, the intensity and the duration of different hazardous events ([4; 5]). Nevertheless other authors ([6; 7]) agree that the concept of vulnerability is related to the consequences of the incident, irrespective of the probability of failure. Thus, the vulnerability is obtained through the system response when a partial or complete failure is given in a specific link, independent of the cause of the failure ([8; 9; 10]).

The drawback of the scenario-specific approach is that covering the full range of possible combinations location/intensity/duration becomes an impossible task. Meanwhile the second approach implies the consideration of different degrees of failure, together with all possible combinations of affected links.

On the other hand, as noted by [9], most of the research on vulnerability measures and methodologies have focused on assessing the impact, rather than focus on the link characteristics that lead to vulnerability.

It is noted that vulnerability is commonly mixed up with criticality. Vulnerability is related to the susceptibility to incidents, meanwhile criticality refers to the consequences. Therefore, the identification of the most critical links or nodes of a traffic network can be analysed directly through mathematical traffic models (e.g., [11]), or using graph theory (e.g., [12]).

Regarding the numerical evaluation of vulnerability, no single metric can adequately describe the diversity of key vulnerabilities or support their ranking. Some key vulnerabilities may be linked to thresholds; in some cases these may cause a system to shift from one state to another, whereas others have thresholds that are defined subjectively and thus depend on societal values. Examples of these thresholds are the vulnerability component of UNDPs Disaster Risk Index ([13]), the vulnerability indicators of the HOTSPOT project, and the results of vulnerability measurement in the Indicator Program of the Americas ([14]). A number of past research projects have dealt with vulnerability in Europe, such as RISK-EU, ARMONIA, and MOVE. On the other hand, other ongoing projects (RAIN and INTACT), focus on how climate change and extreme weather events affect the European critical infrastructure, and aim at developing a methodological frameworks for vulnerability assessment of the land based transport infrastructure and telecommunication systems.

The lack of consensus exhibited in the definition and the assessment of the traffic network vulnerability may result in different identifications of the most vulnerable links or nodes, and, as a consequence, complicate the decision-making process.

With these issue in mind the obvious question to ask is: Can an agreement be reached regarding the concept vulnerability? This would imply to consider all kind of threats, even those that are completely unknown. Therefore, the previous question should be rewritten as; does an *intrinsic vulnerability* exist, independent of the hazardous event considered? If so, the identification of the intrinsic vulnerability and the definition of the parameters what it depends on, would emerge as the main issues.

With the aim of reaching a better understanding of the meaning of vulnerability and its associated properties, Structure Expert Elicitation (SEE) is proposed. Traditionally experts' advice is required regarding judgments that go beyond well-established knowledge. In this paper the SEE will be explained and the different approaches, discussed, highlighting their main advantages and drawbacks (Section 2). Based on the most adequate approach, the questions above try to be answered. This requires a thorough research plan, which is described in Section 3, underpinned by the Irish Road Network case study presented in Section 4.

Structured Expert Elicitation

Expert elicitation refers to the process of synthesis of subjective judgments of experts on a subject where there is uncertainty due to insufficient data because of physical constraints or lack of resources. Structured Expert Elicitation, SEE, implies that the process is based on structured protocols that try to identify and to reduce potential sources of bias and error among experts. These protocols use systematic procedures for elicitation to generate more carefully constructed uncertainty bound, resulting in more reliable and better-calibrated estimates ([15;16]). A relation of the most common sources of bias is given by [17], including framing, overconfidence, anchoring, halo effects, availability bias and dominance.

The elicitation processes can be classified into behavioural and mathematical approaches ([18]). Behavioural approaches aim at producing some type of group consensus among experts, who are typically encouraged to interact and share their assessments. The most well-known behavioural methods are the Delphi technique and the Nominal Group. On the contrary, mathematical approaches deals with experts' individual assessments, combine them mathematically after their elicitation. Within this group, the Cook's method is the most used.

According to [19], while behavioural methods may help identify experts' errors and misunderstandings during the process, there are no formal rules to reconcile differences when the consensus is difficult to achieve among different experts. Conformity induced by the group interaction is a major concern with such an approach. In fact, mathematical approaches are generally agreed to yield more accurate results in aggregating expert opinions ([18]), and [20] points out that the group interaction tends to make the participants overconfident, producing more extreme probability estimates.

The elicitation process has been used to quantify uncertainty, provide rank, produce quantitative estimates, and build dependence modelling.

It is noted that dependence modelling is a more complex issue. It requires to identify the subspace of possible dependence structures, which can be defined through copula-type functions, that is, positive monotonic functions in the range [0,1], conforming a compatible multidimensional cdf. With this aim, statistical samples of joint observations of realisations are needed, however, they are usually scarce, especially in the Science field. Under this perspective, the practical solution implies expert elicitation, where experts are asked about dependence structures.

[21] classify the SSE for dependence modelling into three approaches, according to the relationships between model input and output variables. The first group, which includes Bayesian Networks, copulas, parameterised families of multivariate distributions and Bayes Linear methods, models the dependence relations between the stochastic variables directly. The second approach is characterised because it includes auxiliary variables that are not directly part of the model variables, in order to make the quantification easier. The regression model belongs to this group. Finally, the last approach considers some output variables on which the uncertainties can be assessed, to obtain the aimed uncertainties on the stochastic variables. The probabilistic inversion is studied in this context.

Given that there are no data available to support other kind of approaches, either single or joint observations, and SEE has been extensively used in many topics providing satisfactory findings on very complex aspects, such as climate change ([22]), volcanic eruptions ([23]), air transport safety ([24]), and sea level rise ([25]), SSE seems to be a suitable approach to investigate the traffic network intrinsic vulnerability.

Research approach based on SEE

In this section, the process to investigate the traffic vulnerability through the SEE is presented.

The questions arisen before can be clearly divided into two big issues, namely, (a) the estimation of the intrinsic vulnerability, and (b) the dependence modelling of the vulnerability in relation to other parameters or indicators.

To address the first question, the Cooke method is selected to quantify experts' uncertainty on this regard. This method is a performance-based linear pooling or weighted averaging model. The weights are derived from experts' calibration and information scores, as measured on seed variables. Seed questions are a tool for addressing overconfidence and providing an appropriate calibration for responses. The performance-based weights use two quantitative measures of performance, i.e. calibration, which measures the statistical likelihood that a set of experimental results statistically correspond to the expert's assessments, and information, which considers how concentrated a distribution is. For a complete review of the Cooke method, the reader is referred to [20].

The second question will examine the relation between vulnerability and a series of indicators that quantify system attributes (e.g., reliability, accessibility, redundancy, etc.). The aim is to select a list of indicators that, when combined, explain a high percentage of the system vulnerability. Given that a complete scrutiny of all related indicators is inapproachable, the identification of the most relevant indicators describing the vulnerability is important. According to the literature, vulnerability seems to be highly related to aspects such as accessibility, serviceability and reliability.

It is noted that the selected indicators might overlap some characteristics, resulting in overweighting of some aspects. For instance, the accessibility might involve the network connectivity, therefore, considering the indicators accessibility and connectivity would overestimate the latter when assessing vulnerability. On the other hand, the selection of the most suitable weights to combine the indicators is crucial. The SEE of dependence modelling via Bayesian Networks allows the dependence structure, removing the problem of overlapping and eventually providing the adequate combination of indicators. Therefore the dependence relations will be investigated through a Bayesian Network modelling framework. It is noted that Bayesian network eases the elicitation burden and, at the same time, it allows building models that replicate the important behaviour of real world systems ([25]).

The next steps within the research process in the context of SEE are the following; (a) Definition of a relevant case study on which the elicitation will be conducted; (b) Identification and definition of the variables of interest and the seed variables. [26] highlight that a problem with the seed variables lies in the ability to find questions for which answers are (or can be) known, and are directly relevant. In this stage, the subset of indicators that are potentially related to vulnerability can be used as seed variables; (c) Preparation of elicitation document, where the aim of the elicitation process, the definition of the variables, the case study and the questions are presented in a clear and consistent manner, removing all kind of uncertainty. The elicitation will consist of two parts; elicitation of uncertainty and elicitation of dependence modelling; (d) Selecting and evolving a group of experts; (e) Elicitation process, where experts are trained on SEE prior to the elicitation, and guided throughout the process, providing the best estimates possible; and (f) analysis of results.

The following section presents the case study in detail, meanwhile the rest of steps will be addressed in future publications.

Case Study; Irish Road Network

The Irish traffic network presented in Fig. 1 is selected to conduct the elicitation process on the traffic vulnerability. For the sake of simplicity, the typology of the roads has been reduced to three generic types, i.e., highways, primary and secondary roads. Their characteristics for good ambient conditions are given in [27] and shown in Fig. 2.

The OD pairs and the probabilistic distribution of demands associated to each OD pair in the interval of time studied are given in Fig. 3. These values has been obtained considering the NRA traffic data corresponding to the working days of January 2016.

A C-logit stochastic user equilibrium model is used to reproduce the traffic during the period of interest, based on the formulation proposed by [28]. Using the Monte Carlo method, a number of simulations will be carried out. The combination of different traffic demands will be introduced to obtain the travel time and the link flow associated with the links and routes of the traffic network. For each simulation, the seed variables will be computed.

The data obtained from this case study will be used for the preparation of the elicitation process.

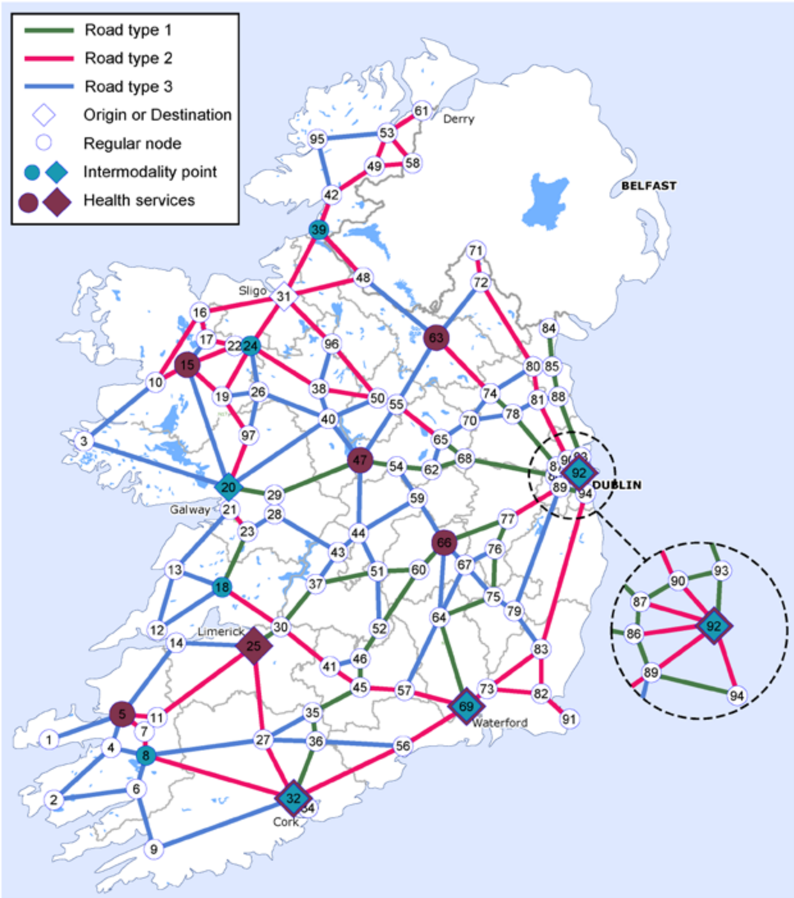

Figure 1. Traffic network under study; Ireland case study.

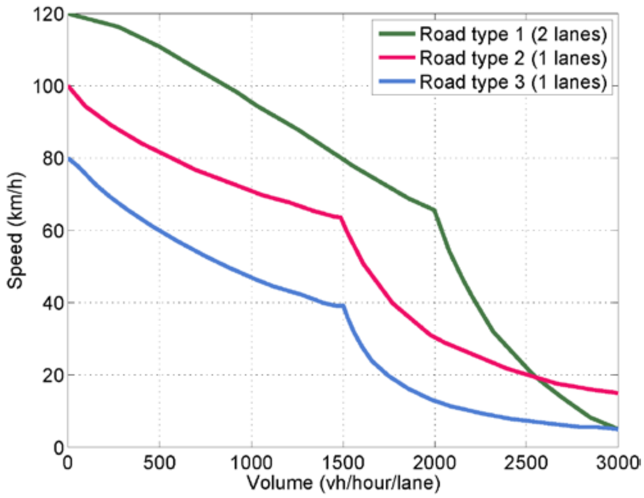

Figure 2. Characteristics of the road types.

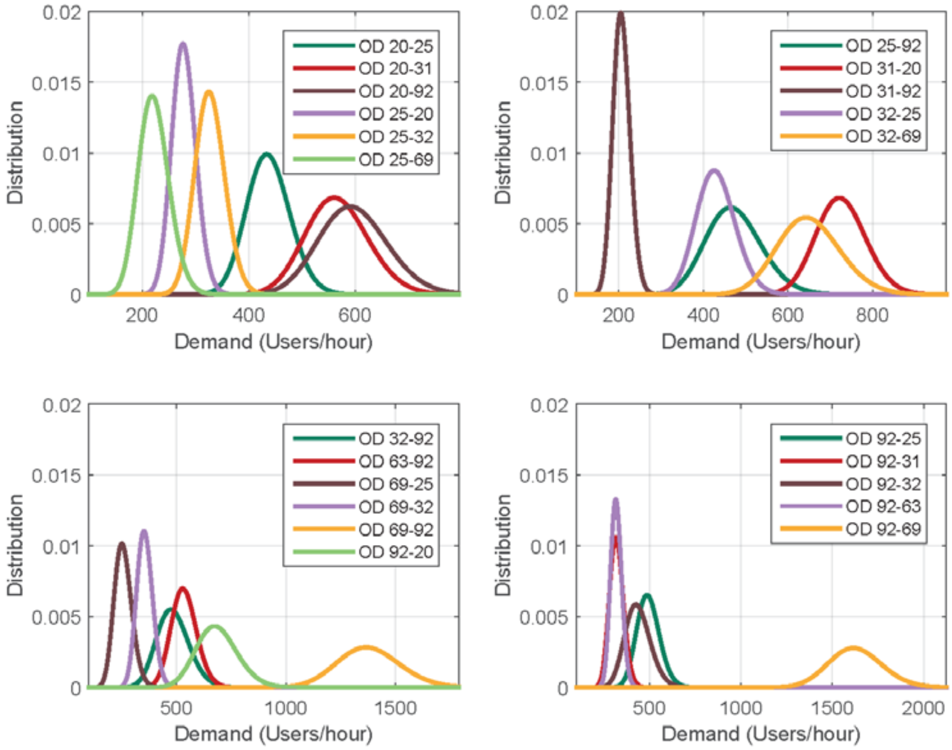

Figure 3. Probabilistic distribution of the traffic demands.

Conclusions

Although there has been significant progress in the study of the traffic network vulnerability, there is still a long way from achieving a deep understanding regarding its definition and the most relevant parameters involved.

In this paper, a series of convenient questions has been presented, such as (a) Does an intrinsic vulnerability exist? (b) What does it depend on? (c) How can it be assessed? and (d) Can any mathematically-quantifiable indicator(s) be used as a systematic framework to evaluate it? Answering these questions will allow a deeper knowledge of the system vulnerability and, as a consequence, taking decisions in a more effective way, conceiving and implementing actions together to reduce efficiently the traffic network vulnerabilities.

Structured expert elicitation (SEE) has been long used to answer questions that are difficult to answer via other methods. Under the presented context, it is discussed if SEE is a valid approach. More precisely, different methods within SEE are presented in order to choose the most adequate to answer the questions risen. Finally, the Cook method is selected to identify the intrinsic vulnerability, and the elicitation of dependence modelling based on Bayesian Networks, to determine the statistical relations between vulnerability and other related indicators.

This paper is intended to justify the use of SSE to identify traffic vulnerability, nevertheless, this is the first step toward this goal. Future steps will include those presented in the research plan, including the SSE process itself, and the analysis of the results, providing important insights into the understanding of traffic networks.

Although applied to the case of the metric vulnerability, the use of SSE rises as an effective tool to explain a number of concepts and descriptors of traffic networks such as resilience, robustness, effectiveness and serviceability.

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