Probabilistic-Based Consequence Analysis for Transport Networks

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Abstract The aim of this paper is to propose a methodological framework for consequence analysis of transportation networks. The probabilistic framework is based on the definition of performance indicators that describe the time-dependent functionality of the asset/system, starting from a pre-existing normal performance state, capturing the time and evolution of disruption during and after the disruption and during the recovery/restoration stage. A proposed case study that will be used for the demonstration of the applicability of the framework is described.

Keywords Consequences · Performance · Probabilistic · Transport network

1 Introduction

The economy of a society and the well-being of its citizens depend on the continuous and reliable functioning of infrastructure systems. Among all infrastructure systems, those which incapacity and destruction impacts the defence and economic security, are generally regarded as critical [1]. Different countries have different lists detailing their critical infrastructure systems but generally, they have the following list of systems in common: transportation, water supply systems, telecommunications, electric power systems, natural gas and oil, banking and finance, government services and emergency services. These infrastructure systems constitute the backbone of modern societies by providing essential services for their functioning. Destructing or damaging assets in such systems either disconnects large areas of networks from each other or causes a rerouting of the flow from one area of the network to another through a longer detour path. Resilience and vulnerability conditions associated with such systems can then have an impact on the resilience/vulnerability of the whole network [2, 3]. Therefore, the disruption consequence analysis of such systems is an essential component of risk and resilience management of systems subjected to hazardous events.

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The European project SIRMA (Strengthening Infrastructure Risk Management in the Atlantic Area) aims to develop, validate and implement a robust framework for the efficient management and mitigation of natural hazards in terrestrial transportation modes at the Atlantic Area. As part of this project a risk and vulnerability assessment system will be developed to assess interceptable and non-interceptable events under various climate change scenarios. An integral part of this system will be a consequence assessment framework which will consider the short-term and long-term, direct and indirect impact of the climate change-induced hazards on transportation infrastructure. This study presents a novel framework for probabilistic consequence analysis of transport networks as a function of performance indicator of the system. This forms an integral component of SIRMA's risk assessment framework.

The paper is organised as follows: Sect. 2 presents a state-of-the-art review of the consequence analysis for transport networks, Sect. 3 provides an overview of the framework and Sect. 4 demonstrates the details of the case study that will be used to illustrate the application of the framework in future studies.

2 Background on Consequences of Failure of Transport Networks

2.1 *Categorisation of Consequence of Failure*

Consequences of failure can often be seen as a good indicator of the importance of an asset, given its form, function and location within a transport network. They can range from casualties and injuries to structural damage, reduction in network functionality and may also extend into environmental as well as societal impact. Table 1 shows a categorisation framework for consequences of failure into four main categories: human, economic, environmental and social consequences. Each of these main four categories can be further sub-divided into a number of more specific areas, so that itemisation and appropriate modelling, where possible, may be undertaken to assess and/or quantify them.

Consequences can be classified as either direct or indirect. Direct consequences are considered to result from damage states of individual components/assets. Indirect consequences, triggered by the former, are associated with reduction in, or loss of, system/network functionality. The differentiation between direct and indirect consequences depends on the system boundaries considered in the analysis as well as on the extent of the time frame that is used; they may, therefore, be subjective to a degree.

An assessment framework for failure consequences should account for their type, the relevant time frame, as well as the network/system boundaries. Therefore, they should be considered within a time domain as well as a spatial domain. The time frame considered (days/weeks/years) plays an important role in consequence modelling; consequences will be different when considering only a short-term post-event time

Table 1 Categorisation for failure consequences of transport networks

Consequence categories	Examples
Human	Fatalities Injuries Psychological damage
Economic	Replacement/repair costs Loss of functionality/downtime Traffic delay/re-routing costs Traffic management costs Clean up costs Rescue costs Regional economic effects Loss of production/business Investigations/compensations Infrastructure interdependency costs
Environmental	CO_2 emissions Energy use Pollutant releases Environmental Clean-up/reversibility Noise pollution
Social	Loss of reputation Erosion of public confidence Undue changes in professional practice

frame or a long-term period extending well after the failure event. The actual duration in considering long-term periods is also expected to affect the magnitude of estimated consequences. For example, a bridge failure in a transport network may result, during the immediate and mid-term aftermath, in loss of business revenue and high traffic delay costs but over longer periods these might change as new regional equilibria are reached within the network. Lastly, consequence estimation is affected by the definition of the system boundaries, i.e. the extent of the transport network that is considered in the analysis that the bridge is within (spatial domain). The extent of the spatial domain is also an important factor, depending on whether a single route (with diversions) or a more widely encompassing spatial network is considered. Here, the level of redundancy of the transportation network in redistributing traffic flows following the bridge collapse plays an important role. Further layers can be added to the above systems by addressing wider societal consequences such as business losses, environmental impact, etc.

The consequences of failure vary significantly from asset to asset, and may depend on a range of factors which are related to the hazard itself, the asset and its utilisation, as well as the surrounding environment. The source and nature of the hazard leading to an asset failure will affect the consequences, considerably. It is expected that the greater the magnitude and duration of a hazard, the greater the consequences will be. Asset location is one of the major factors expected to influence the magnitude of failure consequences. The type of road or rail route served by the asset influences the traffic intensity and, hence, the number of people exposed to any given hazard, as well as the traffic delay costs. Moreover, the availability of emergency services and accessibility to treatment for injuries will most likely be best in urban areas, hence, the number of fatalities may be lower in such locations. Finally, the cost of repair or reconstruction of an asset may be higher in rural areas due to increased labour, materials and transportation costs. On the other hand, access might be easier and interdependency issues might be less critical than in urban areas. The time of the day that an asset failure may take place will also have an effect on human consequences. Assets such as bridges, for example, will experience high levels of traffic during peak times and the potential for mass casualties is thus higher.

2.2 Analysis of Consequences of Failure of Transport Networks

The analysis of consequences of failure of transport networks has been performed in a number of studies for different hazards including earthquakes, extreme rainfall and others [4–10]. Transport network impacts are commonly analysed using two methodologies including those measuring network topology (i.e. graph theory) and system operation (i.e. travel time and cost) [4]. The topological method provides a more simplistic representation of the network with no consideration of route choice and periodic demand (peak and non-peak) on travel time and cost. However, the second method uses traffic models to simulate network flows that are more realistic, although the computational and data demands become more complex. These transport models are used in conjunction with hazard models to quantify the impacts of extreme weather events. A comprehensive review of these analytical assessment modelling techniques for disaster events can be found in [11].

A previous study by [4] assessed the impact of landslide disruptions by coupling hazard data with a transport network model. The methodology followed in the study was to: (i) establish the road network, (ii) evaluate the vulnerability of the road network, (iii) create an event set of landslide disruptions, (iv) develop a micro-meso network model to simulate the traffic flow, and (v) measure the impact of each event. The study however did not capture wider long-term impacts such as reductions in business investments. A further study simulated the impacts of closing different sections of the road network in Switzerland [12]. Failure consequences were calculated using subnetworks and compared against the option of using a full network. The study however was limited in that it assumed each of the failure scenarios to be mutually exclusive, which is an oversimplification for natural hazards such as floods. [5] developed a simple transport network and used a depth-disruption function to represent the vehicle speed through floodwater. The traffic simulations were then coupled with a flood model. This study only focused on one mode of transport (roads). A paper by [6] proposed a new approach to support network operators in quantifying the risk related to their networks. The authors quantified risk from a source event to its societal event over space and time. The consequences were then monetised into direct and indirect costs, considering restoration interventions, prolongation of travel time, and missed trips. The paper also defined four damage states: (0) operational, (1) monitored, (2) capacity-reduced, (3) closed. In another study, a conventional analytical framework to simulate traffic flows was used under different flood scenarios in the Boston Metropolitan Area [13]. Direct costs from the damages were not considered as part of the study as well as no consideration of network restoration, which is crucial to know when estimating indirect consequences.

A study by [14] used a simulation-based model to measure resilience indicators in railway transport systems using different scenarios. The paper showed that efficient crisis management plans could reduce the impact of undesirable scenarios on a system. However, the study was limited in that it did not look into scenarios with consequences such as casualties and injured passengers. In [7], a macroscopic traffic simulation of a road flooded in Portland was performed. The consequence assessment was limited to only one scenario, the complete closure of links, were considered in the study. Others considered the impact of closing different bridges in Stockholm with two scenarios of bad weather leading to a 15% reduction in free-flow speed [15]. The transport model however was not calibrated as part of the study, providing a lower confidence in the results.

3 Methodological Framework

3.1 Probabilistic Consequence Analysis Framework

As shown in the literature review the definition of consequence analysis depends on a type of disruption, type of consequence and means of quantification of consequences. However, the literature is generally in agreement that any form of consequence can be described and linked directly or indirectly to time-dependent asset/system performance indicator/delivery function/figure of merit. Asset/system performance indicator describes time-dependent functionality of the asset/system at status quo, time of disruption, during and after the disruption and during recovery/restoration stage.

One of the traditional forms of performance indicator is the trapezoid function which is often used to describe the behaviour of an asset and/or system in response to a disruptive event and corresponding recovery stage [16]. In this form, the behaviour of the asset/system following a disruption and recovery is generalised as a linear function. Another traditional formulation is the triangular description which assumes a sudden drop in performance indicator following a disruption and a linear recovery afterwards. Imani and Hajializadeh [17] have expanded the trapezoid description to allow for flexibility in different disruption absorption and recovery/restoration trajectories for different assets/systems. Figure 1 shows a schematic representation

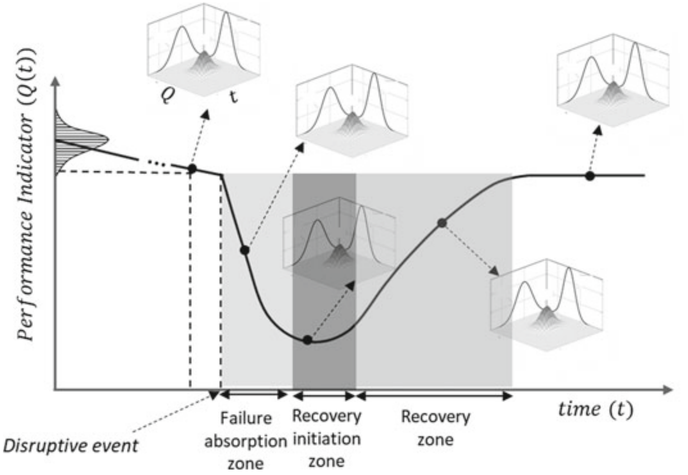

Fig. 1 Schematic probabilistic time-dependent performance indicator function

of a generalized performance indicator variation with time at five distinct zones. These zones include (1) equilibrium during status quo; (2) absorption of disruption; (3) equilibrium following disruption; (4) recovery initiation and absorption; (5) equilibrium following recovery.

The majority of state-of-the-art attempts in formulating asset/system performance have been focused on the deterministic definition, many of which concentrated on post-event recovery analysis. The deterministic assessments may lead to misjudgment of performance indicator of the asset/system which could then result in underestimation of the consequences. On the other hand, a probabilistic framework that can capture the uncertainties in the time-evolution of the performance indicator shown in Fig. 1 can offer useful insight into how failure consequences may be affected by such uncertainties.

The scope of this study is to provide a novel framework to evaluate asset/system performance indicator by accounting for the uncertainties in failure and recovery/restoration trajectories. Figure 1 schematically demonstrates the main uncertainties in describing asset/system performance indicator by joint probability density functions, $p(Q, t \mid z_i)$, for time-dependent performance indicator, $Q(t)$, at each zone/stage, z_i, as a function of time, t.

The joint probability distribution function aims to move past the type of disruption and recovery measures and it focuses on the impact of disruption and recovery on performance indicator. This is advantageous to the deterministic consequence analysis where the performance indicator is defined as a function of the event only. The joint probability of distribution can also be defined as a conditional probability for different types of hazards and disruptions, however, in the absence of required database and/or in cases of low-probability/high consequence events, it is advantageous to formulate the probability functions independently from the type of disruption.

The probability functions can be defined based on the available literature on different types of hazards, disruptions and recovery measures. The main source of the required database for probability functions are empirical qualitative data available in grey literature, reports of National Transport Authorities and news media searches.

To account for different possibilities for disruptive scenarios, a systematic scenario generating strategy is developed. The generated scenarios for a given transport network will include a cohort of Monte Carlo simulated single and multi-asset, simultaneous and sequential disruptions within the network. For single asset failure scenarios, the time of occurrence of the disruption, $t_{d,}$ and total drop in performance indicator of the asset (once the disruption is absorbed), PI_d, will be defined. An example of this would be the drop in traffic capacity of a bridge, or a segment of a road, due to flooding, capturing how quickly the flooding evolves over time leading to the loss of asset performance.

For multi-asset simultaneous disruptions, in addition to time and drop in performance indicator for each asset, the number of disrupted assets, $n_{d,}$ should also be defined. For the sequential multi-assets, the time lag between each disruption, $t_{lag,\,j}$ will be generated as part of the scenario simulation process. This type of scenario can, for example, represent a wider impact of a hazard on the transport network such as wider-scale flooding that may affect multiple stretches of roads and/or bridges. Figure 2 summarizes these inputs for each scenario.

The key in consequence analysis of a system, hence its performance indicator assessment, is to consider the interconnections and interdependencies of individual assets that can cause cascading failures, amplify negative consequences due to these failures and influence the overall performance of the system.

To describe the behaviour of a transport system as a function of its assets, network theory is utilised in this study. Network theory has been widely used to characterize infrastructure network topology and layout features by taking advantage of closed-form expressions and numerical simulations. Mathematically, a topological network can be represented as a graph with nodes and edges representing their connectivity nature. For the infrastructure network A, network properties can be represented by $I_A = \{N_A, E_A, M_A\}$, where N_A, is the node sets, E_A, is edges set and M_A is a $N_A \times N_A$ matrix representing the function of edges to pair-wise nodes. For transport networks, nodes can represent junctions, public transport stations, intersection control systems and traffic signs and edges could represent roads, bridges, tunnels, etc.

Once the system is simplified into its graph network representation, each asset (i.e. node and edge) will be assigned a performance indicator with corresponding joint probability distribution function $p(Q, t|z_i)$, $i = [1, .., 5]$. The performance indicator for each asset defines the level of serviceability and capacity for each asset. Then, by conducting a traffic simulation method (microscopic or macroscopic), the overall performance of the transport network can be defined as a function of the performance of its assets, collectively.

The characteristics of the overall system performance depend on the type of simulation. Macroscopic traffic simulation describes the collective vehicle dynamics as

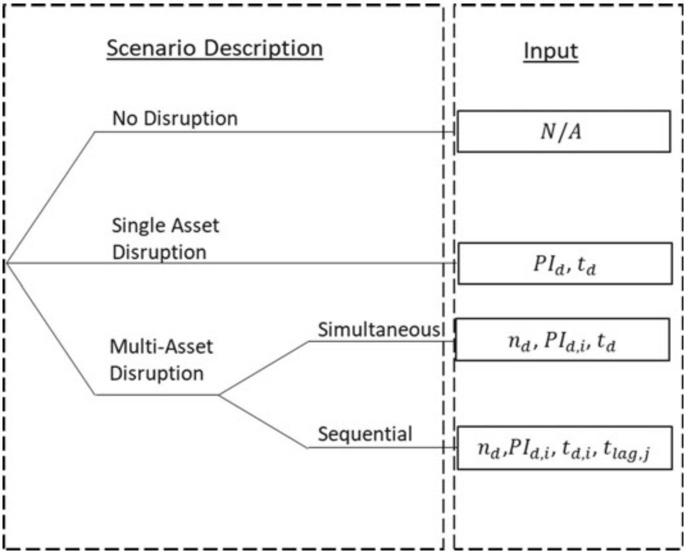

Fig. 2 Disruption scenario generation and inputs

a function of the spatial and temporal distribution of vehicle density and average velocity, whereas the microscopic traffic models define the individual position and velocity of all interacting vehicles in the system.

Once the performance of the system function for a given disruptive scenario is calculated, the consequence of the disruption as a function of the time-dependent performance indicator can be evaluated. The output of this stage will be a time-dependent consequence function for a given disruptive scenario. These steps will be repeated for all simulated scenarios. Once the number of required scenarios has been reached, a consequence spectrum can be constructed based on the time-dependent consequence function for each scenario. Figure 3 demonstrates the overall process of the proposed framework to acquire consequence spectrum. This framework will be used within the context of a case study transport network which is described in the following section.

4 Transport Network Case Study

The test bed for this study is located in Portugal and has been selected within the context of the EU-funded SIRMA project. The test bed includes some sections of the National Road 6 (EN6), which runs along the coast, and the Cascais Railway line, which runs parallel to EN6 at certain sections. The EN6 Road has a length of 16 km and the Cascais Railway line has a length of 25.5 km. The road and railway

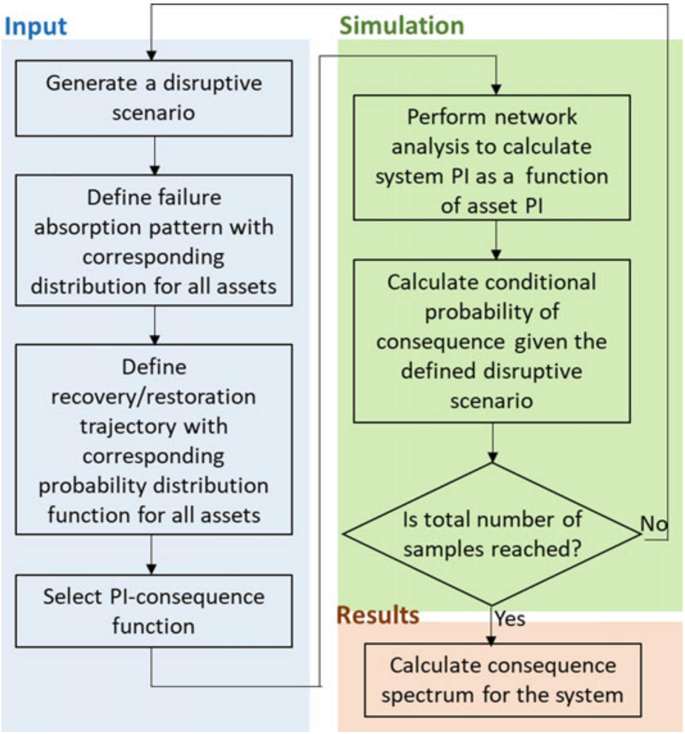

Fig. 3 Flowchart of the proposed consequence analysis framework

both play an important role in connecting the Cascais area, which is a major summer retreat for the local population and tourists, to Lisbon.

The European Commission (EC) have previously reported that 28% of the Portuguese mainland is vulnerable to coastal flooding, which can have severe consequences as 60% of the population inhabits the coastal zone [18]. With this in mind, the most critical natural hazard events in the selected Portuguese test bed have been identified to be coastal flooding from wave inundation and sea level rise. One of the main issues that has been reported by Infraestruturas de Portugal (IP), the major highway and railway infrastructure owner in Portugal and a key partner of the EU-funded SIRMA project, includes exposure to high tides in the Lisbon metropolitan area.

A transport model of the case study has been prepared through the AIMSUN Next transport modelling software that can perform both the macroscopic and microscopic traffic simulations within the same software. The traffic parameters required for the study include the speed, signal timings, traffic volumes from traffic counters, percentage of vehicle types, and the timetabled train services. Further infrastructure data is also required including the road and rail geometry, location of the asset, its construction type and the age of the assets. Part of this data has been provided by

IP towards the development of the transport network model and additional data will be utilized for the calibration of the model. Other data requirements for this study include historic weather and future climate projections data that will assist towards the development of the failure scenarios to be captured in the network analysis. In particular, past disruption/failure events that have taken place in the test bed will be collected from IP to appreciate the different types of hazards that have impacted the test bed as well as the level of disruption that has been experienced to derive the joint probability distribution functions for each asset. The framework proposed in this paper will then be applied to this case study through the work in Work Package 4 of the EU-funded SIRMA project.

5 Concluding Remarks

This paper has presented an overview of a novel probabilistic consequence analysis framework, which forms an integral part of the risk assessment framework that will be developed as part of the EU-funded SIRMA project. The proposed framework is based on probabilistic description of asset performance indicator and can be utilised to assess the uncertainty in the modelling characteristics of the performance indicator on the resulting consequence of failure of transport networks. It is envisaged that the proposed framework will be applied to a multi-modal transport network in Portugal.

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References

1. Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering And System Safety, 121,* 43–60.
2. O'Kelly, M. E., Kim, H., & Kim, C. (2006). Internet reliability with realistic peering. *Environment Planning A, 33,* 325–343.
3. Reggiani, A. (2013). Network resilience for transport security: Some methodological considerations. *Transport Policy, 28,* 63–68.
4. Postance, B., Hillier, J., Dijkstra, T., & Dixon, N. (2017). Extending natural hazard impacts: An assessment of landslide disruptions on a national road transportation network. *Environmental Research Letters, 12*(1), 014010.
5. Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D, Transport and Environment, 55,* 67–81.
6. Hackl, J., Lam, J. C., Heitzler, M., Adey, B. T., & Hurni, L. (2018). Estimating network related risks: A methodology and an application in the transport sector. *Hazards Earth Systems Science, 18,* 2273–2293.

7. Chang, H., Lafrenz, M., Jung, I. W., Figliozzi, M., Platman, D., & Pederson, C. (2010). Potential impacts of climate change on flood-induced travel disruptions: A case study of Portland, Oregon, USA. *Annals of the Association of American Geographers, 100*(4), 1–4.
8. Clarke, J., Corbally, R., & O'brien, E. (2016). INFRARISK Deliverable 8.2—Case Study Results.
9. Carey, C., Clarke, J., Corbally, R., Connolly, L., Hajializadeh, D., Barcena, C., & Clotet, X. (2017). RAIN Deliverable 6.3—Report on Benefits of Critical Infrastructure Protection.
10. Enke, D. L., Tirasirichai, C., & Luna, R. (2008). Estimation of earthquake loss due to bridge damage in the St. Louis Metropolitan Area. II: Indirect Losses. *Natural Hazards Review, 9*(1), 12–19.
11. Faturechi, R., & Miller-Hooks, E. (2015). Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. *Journal of Infrastructure Systems, 21*(1), 04014025.
12. Erath, A., Birdsall, J., Axhausen, K. W., & Hajdin, R. (2008). Vulnerability assessment of the swiss road network. *Transportation Research Record Journal of the Transportation Research Board, 2137*(1), 118–126.
13. Suarez, P., Anderson, W., Mahal, V., & Lakshmanan, T. R. (2005). Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston metro area. *Transportation Research Part D, Transport and Environment, 10*(3), 231–244.
14. Adjetey-Bahun, K., Birregah, B., Châtelet, E., & Laurens-Fonseca, E. (2014). A simulation-based approach to quantifying resilience indicators in a mass transportation system. In: *Proceedings of the 11th International ISCRAM Conference* (pp. 75–79).
15. Berdica, K., & Mattsson, L. G. (2007). Vulnerability: A model-based case study of the road network in Stockholm. In *Advances in Spatial Science* (pp. 81–106). Springer International Publishing.
16. Henry, D., & Ramirez-Marquez, J. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering and System Safety, 99,* 114–122.
17. Imani, M., & Hajializadeh, D. (2020). A resilience assessment framework for critical interdependencies. *Water Science and Technology, 81*(7), 1420–1431.
18. Commission, E. (2009). *The Economics of climate change adaptation in EU Coastal areas: Country overview and Assessment*. Brussels, Belgium: Office for Official Publications of the European Communities.