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Resilience of guided transport systems against natural risks

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Abstract

The vulnerability of guided transport systems exposed to natural disasters is demonstrated in particular through the part of incidents on international railway networks due to intense weather conditions. Moreover, in the future, the frequencies of natural hazards will likely be intensified by climate change, increasing the consequences on transport systems and thus on railway mobility. The concept of resilience brings a new way of analyzing the impacts of natural risks on technical systems according to a systematic approach. Resilience can be defined as the capacity, for a system, to absorb changes and to persist beyond a disturbance. This approach offers the opportunity to investigate the complex interactions between a transport system and a natural hazard by analyzing the failures caused by cascade effect within the system. All these failures can be determined by using a combination of dependability and safety methods: the functional analysis, the failure mode and effects analysis and the event tree analysis. This methodology allows to build a tool based on the identification of the scenarios of successive failures that allows to assess related costs and repair times. The Prague subway flooding in 2002 is considered as a case study application of this tool.

1. Vulnerability of guided transport systems facing natural hazards: towards a more systemic approach

1.1. Facts and figures

As many other urban infrastructures, rail transport systems are regarded as vulnerable on material and functional levels to adverse weather conditions, extreme meteorological conditions and more generally, to natural hazards. Weather can affect operation efficiency, physical infrastructure and both freight and people safety. Although this vulnerability is not theoretically demonstrated particularly due to the fact that studies investigating the effects of weather on rail transport and infrastructure are scarce (Koetse & Rietveld, 2009), facts and figures reveal it empirically (Gonzva *et al.*, 2015). Many European projects already showed how many and complex the weather impacts on rail infrastructure (EWENT, 2012; MOWE-IT, 2014) and critical infrastructures (INFRARISK, 2016) are. For example, on China railway network between 2013 and 2015, 31 incidents have been caused by flood causing 5 derailment accidents of freight car, 4 derailment accidents of passenger car and 22 incidents with an interruption of operation superior to 1 hour (Liu *et al.,* 2015). Moreover, the vulnerability in the railways sector against several natural hazards has also been highlighted through interviews of 27 critical infrastructure stakeholders concerning past direct and indirect impacts. This review shows that rail sector infrastructure is more vulnerable than other because the functioning can be impaired even before damage sets in (Groenemeijer, 2015). Furthermore, these effects due to natural hazards have a high societal impact, especially the wind storms, the snow storms and the heavy rainfall (Fig.1).

Besides, many functional interdependencies exist between urban technical systems increasing their vulnerability. But, these interactions also exist within the urban systems and enhance their complexity. Rail transport systems are complex by virtue of three dimensions: the number of elements in the system, the functional differentiation of each element, and the interdependence among these functionally different elements (Roe, 1998). In this context of multiple interconnections between urban technical systems, some authors refer to a "system of systems" rather than systems (Kröger, 2008) in the context of urban risk management.

Furthermore, two major facts require to be included in all studies dealing with the rail transport systems vulnerability. The first fact concerns the climate changes which projects that the major weather events would become more frequent and more severe in the next years. The second element is about the growth of the world population; indeed, in 2014, 54 % of the world's population is urban and this proportion is expected to continue to grow until 66 % in 2050 (United Nations, 2014). This figure would have significant consequences on the current ways of operating rail transport systems, both freight and public transport systems, because of a greater need of urban and interurban mobility. The need of innovative, systemic and integrative methodologies is crucial and the frameworks and tools for modelling natural hazard risks should be understandable by all involved specialists, including the decision makers (Straub, 2005).

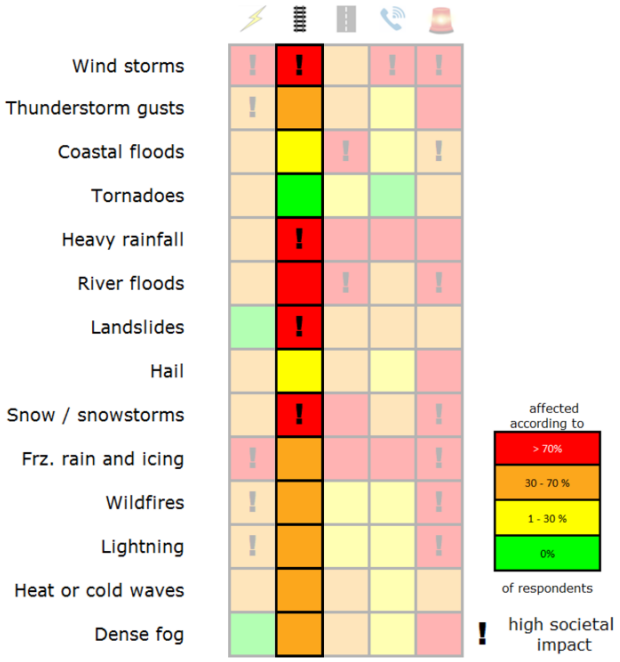


Fig.1. A qualitative review of natural hazards and their past impacts in the railways sector (Groenemeijer, 2015)

1.2. A more systemic approach: the resilience concept

Since 2000's, a new theoretical concept conveys a systemic view for analyzing risks that affect cities: resilience. Indeed, the concept of resilience is relevant for risks studies affecting urban technical systems because this concept provides a systemic approach taking into account the interactions and feedback mechanisms between the system itself, its components but also with elements of its environment. For urban systems, the resilience can be defined as the capacity to absorb a disturbance and to recover its functions after it (Lhomme, 2012). Besides, the theoretical concept of resilience may be applicable taking risk management as an entry point for operationalizing it (Mitchell & Harris, 2012). An analysis of technical systems' resilience appears to be essential for improving their own resilience and converging towards urban resilience. Therefore, management of risks affecting urban areas requires innovative and global methodologies integrating numerous challenges such as the complexity of systems operation, multiple technical interactions within the system, social external interactions and environmental pressures.

This article provides the construction of a qualitative and systemic methodology to assess the vulnerability of rail transport systems against natural hazards. To illustrate the capabilities of the methodology, it is applied for the flood hazard. In fact, the resilience ability of rail transport systems is analyzed through the failure mechanisms to which they are subjected under flood conditions. Indeed, these mechanisms lead to numerous failure scenarios due to cascading effects and modelling these scenarios enables to identify the components in the system that are successively damaged as a result of a disruption. A first part presents the construction of the methodology. A second part proposes a tool based on the identification of these scenarios of successive failures that allows to assess related costs

and repair times. Lastly, a third part shows the application issues of the methodology and the tool, the Prague subway flooding in 2002 has been considered as case study.

2. A methodology for assessing vulnerability of rail transport systems facing flood hazards

The systemic methodology proposed in this article is based on dependability concepts (Villemeur, 1997). Three methods are used to build the methodology: the functional analysis, the Failure Mode and Effects Analysis (FMEA) and the events trees. This last method provides a graphic representation of the sequence of events formed by a combination of components failures due to cascading effect.

2.1. Functional analysis

The functional analysis aims at modelling the way systems operate on the basis of two mutually dependent analyses: structural analysis and functional analysis. Structural analysis defines the components in the system and provides the interactions between them in order to formulate the functions of each component in the functional analysis. Three types of interactions between subsystems are taken into consideration: contact relationships, materializing the existence of one or several physical contact between two elements; dependence relationships, indicating that the interaction from a first component to a second component is conditioned by the fact that the first component functions correctly; and, vulnerability relationships, revealing a qualitative vulnerability level to a flood hazard for each element of the system. The first two interactions are related to a situation in which the system normally operates whereas the last interaction – vulnerability – is related to a crisis situation, which means during the occurrence of a flood hazard.

Thus, between 19 and 20 components have been identified, according to whether the transport system is at the ground, the overground or the underground level, within 8 sub-systems.

2.2. Failure Mode and Effects Analysis (FMEA)

FMEA applied on a system allows to identify the critical functions of a system and the critical components and the causes of their failures in order to implement preventive maintenance strategies Inherent in this objective is the requirement of a solid knowledge of degradation mechanisms and their spread in the system (Zwingelstein, 1996). In this research, FMEA aims at analyzing the failure modes of all the components in the system when they are facing a flood hazard. The FMEA lists for each component of each sub-system the functions provided by the component, the failure mode which here corresponds to the non-achievement of these functions due to the hazard, the events causing the failure mode to occur and, lastly, the resulting effects of the component's dysfunction on the rest of the system.

2.3. Event trees

The events trees aim at graphically representing the successive failures of components due to cascade effect (Figure 5). Indeed, in some cases, the effect of a component failure on the system is the cause of another component failure, and so on. Thus, thanks to a developed computer tool, it is possible to obtain and represent all the chains of failures due to cascade effect by iteratively querying the FMEA to determine if the last failed component of a causal graph is not the cause of the failure of another component. This global methodology can be considered as powerful inasmuch as it enables to highlight the functional interdependences that exist between all the components in a rail transport system, leading to a chain of material failures and, finally, to the overall dysfunction of the system.

Therefore, several conclusions can be presented at this point. Firstly, the methodology is innovative because, on the one hand, it is based on three established methods from dependability concepts successively applied on the same system plus on an informative tool that exploit the exhaustiveness of the FMEA; on the other hand, the methodology allows the assessment of the impacts of disruptions from outside the system such as a natural hazard – here, a flood hazard. Secondly, the produced chains of failures bring semi-qualitative results in terms of vulnerability. Indeed, the chains of failures relatively emphasize the components behavior when a flood hazard occurs. Some components have been shown to be sensitive to a flood hazard and other spread the risk through the system *via* cascading effects failures. But, the results of the methodology are qualitative because the vulnerability of each component of the rail transport system is not absolutely assessed but comparatively to the vulnerability of other component. To bring a quantitative approach to the methodology, the proposed solution is to assign for

each successive failures scenario values relating to the cost and the time repair, according to the intensity of the flood hazard. These elements provides the functioning principles of a tool for assessing the vulnerability.

3. Building a quantitative approach for assessing the vulnerability

To move towards a quantitative approach, the objective is to assess the successive failures scenarios in terms of costs and time repairs when a flood hazard occurs with a given intensity. Three steps are necessary to build a tool for assessing the vulnerability.

3.1. Identifying costs and time repairs values

The first step is to identify an average value of cost and an average value of time repair for each component of the system. These values refer to the type of guided transport system and the configuration of installation; indeed, the repairing or the reconstruction of the control-command and signalling system highly differ according to whether the transport system studied is a high-speed line at ground level, an underground metro or an urban light rail system. Besides, the choice has been made to consider values interval rather than absolute values for the costs and time repairs; indeed, the objective is to estimate the magnitude of the damages in case of a flood hazard occurred. Thus, for each of the 20 components of the rail transport system, a range of values has been assigned with the help of railways maintenance experts to quantify the cost and the repair time corresponding to the damages due to a flood hazard, as follows :

- Intervals of repairing costs :
  - From zero to a few hundred euros;
  - From a few hundred euros to a few thousand euros;
  - From a few thousand euros to a few tens of thousands of euros;
  - From a few tens of thousands of euros to a few hundred thousand of euros;
  - From one to several millions.

- Intervals of repair times :
  - From zero to a few hours;
  - From a few hours to a few days;
  - From a few days to a few weeks;
  - From a few weeks to a few months;
  - From one to several years.

3.2. Calculation principles

The second step is to compute the cost and the time repair associated to a given successive failures scenario. Two calculation hypotheses have been made:

- The global cost relating to a successive failures scenario is the sum of the costs of all individual impacted components;
- The global time repair relating to a successive failures scenario is the maximum of all individual time repairs of impacted components.

For the second hypothesis, the idea is to consider that the highest value among all individual time repairs of involved components in a failure scenario is a majoring value of the time needed to perform repair works.

3.3. Taking account gradual intensities of flood hazards

The third step consists in taking account the intensity of the flood hazard. Indeed, three types of damages scenarios with an increasing intensity have been chosen:

- Scenario (1): A flood with slow kinetics whose effects can imply cleaning and inspection of the components;
- Scenario (2): A medium flood whose effects can imply an identical replacement of several components;
- Scenario (3): A major flood whose effects can imply an identical reconstruction of the whole system.

The three scenarios are not necessary possible for all components. For example, control-command and signaling components can be damaged according to the second or the third scenario. The first scenario is not relevant in as much as these types of electric and electronic components have to be replaced and not just cleaned.

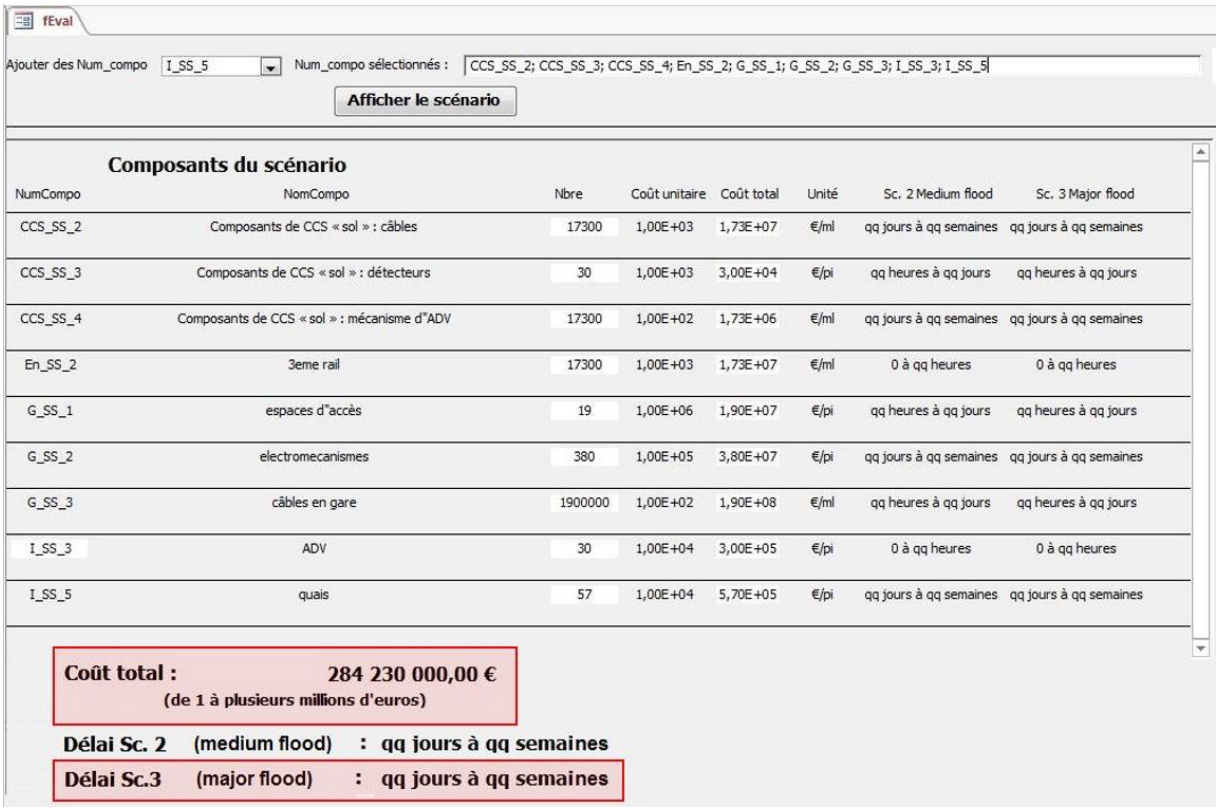
4. Case study: Flooding of the Prague metro during the August 2002 floods

In August 2002, Southern Bohemia was affected by extremely heavy rainfall, which lasted for two weeks. On August 14, 2002, the Vltava River and the Berounka River converged simultaneously in their confluence area near Prague. As a result, Prague was struck by a severe flood. Besides, The Prague Metro system presently operates 3 lines (A, B, C) with 53 stations and a total length of 53,7 km. Due to the 2002 floods, approximately one third of the Prague metro system was flooded, including 19 stations and 17,3 km long tunnel (Chamra, 2006). Even though the flood wave did not affect integrity of structures, it caused extensive damage to the structural parts and equipment of the metro (Jakoubek, 2007). This case study is an interesting example of a global disruption due to several component failures caused by cascading effects. Indeed, initially, three stations on the line C and four stations on the line B have been flooded. Then, mainly due to unsealed cable grommets, the flood waves spread within the tunnels. Lastly, the water flows reached other stations through the tunnels.

The tool is used for identifying, on the one hand, if these failures of components are linked within a scenario of successive failures due to cascading effects and, on the other hand, for assessing the cost and time repair associated to Prague metro flooding. For these purposes, several hypotheses have been made:

- The following punctual components have been damaged: a few tens of electric mechanisms (such as elevators and escalators) per station (about 20), a few tens of switches and crossings within the rail transport system (about 30), several platforms (4) per flooded station
- The following linear components have been damaged : signalling cables and the third rail on a length of 17,3 km
- The starter component for the cascading failures can be considered as the “station”;
- The damages due to this flood event corresponds to a scenario numbered (2) (see 3.3) : the replacement of several components

The cost and the time repair have been assessed by entering data relating to the damaged components (Fig.2). The tool calculates a cost of repair of 284 million euros and a time repair from a few days to a few weeks. These results of modeling failures scenarios are positive because, finally the total restoration costs reached nearly 7 billion CZK, approximatively €250 million, and about a few months of time repair (Chamra, 2006).



fEval

Ajouter des Num_compo I_SS_5 Num_compo sélectionnés : CCS_SS_2; CCS_SS_3; CCS_SS_4; En_SS_2; G_SS_1; G_SS_2; G_SS_3; I_SS_3; I_SS_5

Afficher le scénario

Composants du scénario

NumCompo	NomCompo	Nbre	Coût unitaire	Coût total	Unité	Sc. 2 Medium flood	Sc. 3 Major flood
CCS_SS_2	Composants de CCS « sol » : câbles	17300	1,00E+03	1,73E+07	€/ml	qq jours à qq semaines	qq jours à qq semaines
CCS_SS_3	Composants de CCS « sol » : détecteurs	30	1,00E+03	3,00E+04	€/pi	qq heures à qq jours	qq heures à qq jours
CCS_SS_4	Composants de CCS « sol » : mécanisme d"ADV	17300	1,00E+02	1,73E+06	€/ml	qq jours à qq semaines	qq jours à qq semaines
En_SS_2	3eme rail	17300	1,00E+03	1,73E+07	€/ml	0 à qq heures	0 à qq heures
G_SS_1	espaces d"accès	19	1,00E+06	1,90E+07	€/pi	qq heures à qq jours	qq heures à qq jours
G_SS_2	electromecanismes	380	1,00E+05	3,80E+07	€/pi	qq jours à qq semaines	qq jours à qq semaines
G_SS_3	câbles en gare	1900000	1,00E+02	1,90E+08	€/ml	qq heures à qq jours	qq heures à qq jours
I_SS_3	ADV	30	1,00E+04	3,00E+05	€/pi	0 à qq heures	0 à qq heures
I_SS_5	quais	57	1,00E+04	5,70E+05	€/pi	qq jours à qq semaines	qq jours à qq semaines

Coût total : 284 230 000,00 €
(de 1 à plusieurs millions d'euros)

Délai Sc. 2 (medium flood) : qq jours à qq semaines

Délai Sc.3 (major flood) : qq jours à qq semaines

Fig.2. Assessing cost and time repair of the Prague metro flooding in 2002

5. Conclusion

This article provides the construction of a qualitative and systemic methodology to assess the vulnerability of rail transport systems against natural hazards. This systemic methodology is based on the resilience concept and is focused on the failure mechanisms to which the components of the systems are subjected under extreme weather conditions. These mechanisms lead to numerous failure scenarios due to cascading effects. Modelling these scenarios enables to identify the most critical and sensitive components within the system and thus, facilitate the implementation of strategies for improving the resilience.

A tool based on the identification of these successive failures has been built for assessing related costs and repair times in case of the occurrence of natural hazard. The Prague subway flooding in 2002 has been considered as case study and shows the capabilities of the tool for identifying if given components are linked within a scenario of successive failures, and for assessing the cost and time repair associated to such a scenario. Thus, the tool can be diagnosis-oriented and prevention-oriented, respectively after and before the occurrence of a flood hazard. The methodology and the tool could be improve according several areas: enriching the costs and time repairs databases for different types of rail transport systems, including temporal and spatial issues relating to the failure processes of the components during a flood hazard, applying both the methodology and the tool for evaluating the vulnerability against other natural hazards such as earthquakes.

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