Quantifying the Impacts of Transportation-Communication Interdependencies on the Resilience of Diverse Populations

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Introduction and Motivation

Resilience of a community to disruptions in a public transportation system depends not only on the technical systems' ability to maintain service levels, but also on the ability of individuals to cope with and adapt to disruptions. In adapting to travel disruptions, individuals rely on information. Well-informed decisions depend on effective communication with vehicle operators, transit websites, other customers, or social media. Furthermore, the ability to make contingency plans depends on communication with childcare providers, family members, and work supervisors. Thus, a community's resilience to transit disruptions must be considered in the context of a paired public transportation-communication system.

When delays or interruptions in service occur, consequences are different for different users. Different populations have different levels of job flexibility, Low-skilled workers, for example, may only be paid for work performed at the job location. If they are late, they will not only risk wages, but may lose their jobs. If transit disruptions are planned, people with higher incomes may drive or take a taxi to work or simply work from home. Family and friend support systems may enable greater flexibility in departure time for some riders, where for example, childcare is required. Furthermore, the consequences of transit disruptions are less severe for users who are able to make substitutions. This ability may depend on access to (1) physical resources (e.g car, bike, money for a taxi, smart phone), (2) knowledge (e.g. familiarity with bus system), and (3) community resources (e.g. rides from neighbors, carpooling).

It may be reasonable to quantify the resilience of the paired transportation-communication system as a technical system, thus considering its ability for continued operations under disruption. However, understanding how resilient a community is to a disruption in this paired system requires a representation that reflects not only the system's engineered components and connections, but also incorporates user capability and socio-system interactions. Some actions taken by the users may exacerbate the shortcomings of the technical system, while other actions may help. Cyclic interdependencies between engineered components and socio-system actions may result. For example, improvements to a transit website may increase its number of users. However, as demand increases, so does the likelihood that the server will go down thus rendering the website useless. Such interactions create the need for an integrated socio technical framework, wherein people act as part of the system, not just as its end users or decision-makers.

Modeling Framework and Solution Approach

To evaluate the resilience of a community and its subpopulations to a disruption in the public transportation-communication system, this work explicitly considers the populations of users navigating through the transportation-communication system as a single, integrated socio-

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technical system. It accounts for the fact that although each population of users experiences a disruption differently, their experience depends on not only their own resources and flexibility, but how all populations of users who share available capacities adapt under the circumstances.

This work builds on concepts of dynamic fault trees (DFTs), typically used in reliability theory to model dependencies between technical components and to quantify how probabilities of component failure lead to system failure. Due to decades of study and use, DFT models have expanded to incorporate elements such as time-dependent failures, delayed reactions, sequence-dependent behavior, and system repairs (Junges 2016). DFTs are flexible enough to model dependencies between heterogeneous types of components. They are capable of expressing relationships between micro- and macro-level components directly, eliminating the need to capture details not critical to understanding the system's behavior as it relates to pertinent performance measurement. Furthermore, DFT models allow for both a quantitative analysis, whereby the system's probabilistic response to a disruption can be evaluated, and a qualitative analysis, whereby insights about the system's failure mechanisms can be gleaned.

This presentation will introduce an Adaptive Dependency Graph (ADG) model of an integrated socio-technical system which captures the functional dependencies between the system's engineered and social components. The ADG framework presented takes advantage of prior developments in DFTs, but extends the reliability (on/off) concepts for quantifying resilience (involving post-disruption performance levels). Algorithms for setting up the ADG data structure and computing a system state (given in terms of performance level) from component states as guided by encoded functions are presented and proven. The algorithms are used for assessing component criticality in sustained system performance and identifying mechanisms of failure and failure propagation paths. These algorithms contribute to the ultimate computation of resilience for each of the subpopulations.

Application on an example

The proposed modeling framework and solution approach will be applied on an illustrative paired transit-communications example to evaluate the resilience of a community and its subpopulations to a system disruption. The focus of the application will be to demonstrate the ADG framework and steps of the algorithms, as well as how failures propagate both within and between social and technical components. The system's probabilistic response to a disruption will be evaluated, and the system's failure mechanisms will be analyzed.

Conclusions

This work presents a methodology for quantifying resilience of subpopulations to disruptions of varying duration and causes (planned and unplanned) within a transit-communications system. It enables an understanding of how well the system is able to serve different interacting subpopulations given their coping capacities for disruption and reliance on transit. It allows for the identification of the most vulnerable populations under the varying disruption types.

References

Junges, S., Guck, D., Katoen, J. P., & Stoelinga, M. (2016, June). Uncovering dynamic fault trees. In *Dependable Systems and Networks (DSN), 2016 46th Annual IEEE/IFIP International Conference on* (pp. 299-310). IEEE.