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Identifying critical disruption scenarios and a global robustness index tailored to real life road networks

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ABSTRACT

The ability to maintain functionality in transport infrastructure is critical during disruptions. To ensure operational robustness in transportation networks, it is necessary to identify the most vital or critical roads (or links), then reinforce them to increase their resilience. In the literature, conventional approaches to analyze road network robustness have involved efforts to first remove selected road segments (one by one, not collectively), then measure the impact of these changes. Based on these results, the levels of impact are ranked and links that demonstrate the most significant impacts are deemed to be the most critical. One of the most significant limitations of such approaches, however, is that they disregard the combined effect of road connectivity. This study advances the state of knowledge in transportation-based resilience analysis through the development of an approach to assess the impact of "critical combination scenarios". The methodology involves a two-phase process. The first phase is based on the sensor (loop detector) location problem, within which, a selected number of high demand roads are identified as "candidate" critical links. Then, the second phase employs a series of discrete network design problem (DNDP) to find a variety of critical combination scenarios. The DNDPs are solved based on a system optimal relaxation method using Bender's Decomposition. Building further from these results, the extent to which a road network is robust (or fragile) is analyzed. The results of the DNDP solutions are demonstrated to be similar to a Lorenz Curve in which the area under the Lorenz Curve (in percentage) can be viewed as a global robustness index. This index can be used to compare and assess the robustness of different road networks and mitigation scenarios. To illustrate the practical utility of this method, this research applied the methodology to the Winnipeg, Canada road network.

1. Introduction

Disruptions to transportation networks; whether large or small, expected or unexpected, or resulting from natural or man-made events, demonstrate the vulnerability of such systems to conditions that can delay or halt the movement of people and goods. Because of the enormous impact that these disturbances can have on the productivity and efficiency of entire

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regions as well as the health and safety of their populations, the study and assessment of ways to better understand, resist, and recover from incidents and hazards has become an area of rising concern to commercial and governmental institutions. When combined with an increasing awareness of threats posed by sea-level rise, climate change, and other unintentional or intentional destructive acts, there has also been growing interest in research related to resilience, reliability, vulnerability; flexibility, robustness, and fragility of transportation networks and related systems (Nagurney and Qiang, 2012). Although these concepts have yet to be formally or clearly defined within the context of transportation (Maltinti et al., 2011), each of these subjects represents an area of interest and concern. More fundamentally, they all suggest the need to answer a key question - How are transport systems effected by and respond during disruptive events?

Although disruptions can result from a wide spectrum of events, from as simple and routine as traffic crashes (Bagloee and Asadi, 2016) to as extreme as a hurricane, maintaining maximum functionality in their aftermath is always the goal. In this research, the focus was on the assessment of resilience aspects of highway networks, though the concept can be extended to other areas such as supply chain (Hasani and Khosrojerdi, 2016), air transport (Lordan et al., 2014) and maritime transport (Lam and Bai, 2016). In light of emerging technologies in the intelligent transportation system (Sarvi and Kuwahara, 2008; Sarvi et al., 2004) and connected vehicles (Bagloee et al., 2016b), understanding the resilience of the system is a prerequisite for any preparedness or mitigation plan.

In the past, simple heuristic methods were employed to identify and evaluate critical links on an individual basis then combine them to assess resilience or robustness of an entire road network. The literature present a unanimous definition for the critical roads: critical elements (e.g. set of links or nodes) of a network are the ones whose failure would bring the most serious impacts on the entire system (Chen et al., 2012; Zhu et al., 2010). Broadly, this would involve rating the "importance" of each link in terms of its capacity, connectivity, or other similar measure of performance. While it would seem to be a simple task, it can actually be quite challenging and suffers from many shortcomings, among the most notable, an inability to observe and measure impacts over the network. Alternatively, one common method to accomplish this has been to examine the effect of removing road links from a network, individually, to reassess the performance of the network, incrementally, based on its level degraded state (see for example brute-force simulation-based approach (Taylor et al., 2006) and also works of Nagurney and Qiang (2012) and Scott et al. (2006)). From this, the most critical links could be identified based on the most significant loss of functionality. A major flaw of these types of methods, however, was that they ignored the potential for combined-effects of multiple, concurrent losses (Maltinti et al., 2011). For instance, if a city is bisected by a river with two bridge crossings, it is possible that either bridge could be lost and the remaining bridge would be able to accommodate traffic now shifted to it from the other. Under such an assumption, it could be possible that neither bridge, on its own, would be viewed as "critical." However, if both bridges were lost simultaneously, the resulting loss of mobility could be devastating network-wide.

These types of combined and cascading effects are suggestive of interdependence; wherein the functionality of one system is dependent upon another and vice versa. When viewed from a transportation system analysis perspective, the interdependence of road networks can create significant challenges to evaluating link criticality (this concept can also be used in the prioritization of the roads' construction (Bagloee and Asadi, 2015; Bagloee and Tavana, 2012)). These include, most notably, the computational efficiency and theoretical development of an evaluation of an assessment process (Taylor, 2012).

In this research, the authors seek to advance the state of knowledge in road resilience evaluation with the development of a two-phased assessment approach to rate road link criticality. By applying this new approach, the combined effect of individual link disruptions in a network can be analyzed in combination to allow more realistic assessments of the overall effect of potential disruptions to a network. The first phase of this new approach was inspired by the sensor (loop detector) location problem (SLP) (Larsson et al., 2010), in which any number of high demand roads can be designated as "critical." Although the loop detector problem is an intractable, multi-faceted problem, the method proposed in this research applies a more intuitive and heuristic algorithm to find links in a network that can represent a broader range of origin-destination (OD) demand. This method is known as "OD-demand coverage." Using this, an initial set of potentially "critical" roads were identified for further evaluation in the second phase of the process.

It should also be noted that the first phase of the approach examined the criticality of the road links based solely on traffic volume and congestion. As such, it ignored equally important considerations such traffic crashes and incidents. If needed, however, other parameters of interest, such as these, could be substituted into the computational process to reflect any disruptive event, including major disaster conditions. For example, events like earthquakes, floods, tornados, etc., where a rich literature on predictive road modelling roads affected by such conditions exists (Anaya-Arenas et al., 2014; Bayram et al., 2015; Bell et al., 2014; He et al., 2015; Sherali et al., 1991; Y. Wang et al., 2014; Zhen et al., 2015), could be evaluated.

In the second phase of the approach, an incremental process was used to first remove the potentially critical links identified in phase one, then add them back one-at-a-time to assess the performance improvement of the network. A key need in this phase, however, was an identification of which candidate segments roads to include and the order in which to include them. It is assumed that those that are included early were presumably more important. To accomplish the replacement process, a discrete network design problem (DNDP) method was applied. Specifically, the researchers applied a DNDP model to optimize network performance by wisely adding more roads to the network in the presence of a limited budget (known as budget constraint).

The DNDP was conventionally formulated as a mixed integer nonlinear bi-level programing problem in which network performance was optimized at the upper-level while accounting for the commuters' route selection behaviour at the lower-level. Unfortunately, however, being bi-level made the problem of highest computational difficulty; commonly