MODELING THE RESILIENCE OF SURFACE FREIGHT TRANSPORTATION SYSTEMS: AN APPLICATION TO ONTARIO, CANADA

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Introduction

Goods producers in Canada rely on transportation networks to move raw materials and intermediate goods among production sites and finished goods to domestic and international markets. Firms in the retail, tourism and other service sectors also depend on transportation networks to assemble supplies and goods for sale and to bring customers to their facilities. Events that disable parts of the transportation network – ranging from weather emergencies to terrorist attacks – may affect freight transportation, degrade economic productivity and in extreme cases may trigger economic crises. The ability of public and private providers of transportation infrastructure and services to mitigate and recover from such events is therefore an important determinant of aggregate economic performance. Avoiding disruptions in freight movement between regions is vital for healthy trade and economic production.

The attacks of September 11, 2001 spurred development of assessment methodologies to help plan for emergency preparedness. However, basic risk assessment methodologies have been the subject of much criticism and major revisions over the past decade. Strategies for reducing consequences can be organized under three categories: hardening, response and resilience. Hardening involves making the physical assets (i.e. critical elements) of a system more damage resistant. Response, on the other hand, entails improving the ability of first responders to limit damage immediately following the event. As for resilience, the term can be used to describe how well a system can function in the aftermath of the event. It involves improving the ability of infrastructure to bounce back to its pre-event condition. While “response” pertains to mobilized action plans, “hardening” and “resilience” are more concerned with the critical elements comprising the infrastructure. It can be argued that proper response plans can only take place if the critical elements of the infrastructure are identified.

In this paper, an intuitive yet appealing modeling approach is devised and applied to assess the resilience and critically of road transportation networks. More specifically, we examine the resiliency of the Ontario-Canada highway network for inter-city freight transportation, and examine the performance characteristics of the critical network elements with the help of Geographic Information Systems (GIS). Following Sheffi (2005), we contend that a resilient surface freight transportation system is one that is flexible or redundant (or a combination of the two). Flexibility refers to the ability to find alternatives to disrupted links by re-tasking existing links within the infrastructure to facilitate freight movement. This can be achieved through network redundancy. Intuitively, redundancy relates to the existence of alternative links that can be used to facilitate freight movement if the most critical links are disabled. To our knowledge, the approach proposed in this paper to handle highway network resilience is novel and has not been attempted in the past.

The remainder of our paper is organized into four sections. Section 2 provides a literature review on critical infrastructure and network disruption analysis. Next, the third section provides an overview of the data used in the analysis as well as the devised methods used to assess redundancy and criticality of the Ontario road network. This is followed by a presentation and discussion of the results from the analysis in section 4. The last section provides a conclusion to our study and some directions for future research on the topic.

Literature Review

In recent decades transportation network analysts have attempted to quantify certain indicators of network performance. More recently overlaps with the field of hazard risk assessment and emergency management have led to the study of network performance under disruption of certain parts of the transportation network due to hazards. Initial transportation network studies were concerned with the reliability of the network, often measured in travel time. Simply stated this was a measure of the ability to consistently get from Point A to Point B. For example Asakura and Kashiwadani (1991) associated reliability of the network with the probability of reaching a destination from an origin within a specific time threshold. This was a useful measure in calculating network performance under normal circumstances.

Following several major earthquakes that caused severe damage to transportation infrastructure in Loma Prieta, California in 1989; Northridge, California in 1994; and Kobe, Japan in 1995; researchers became interested in quantifying network performance outside the norm, specifically in response to natural or manmade hazards (Guilano, 1998). In this case network reliability became a consequence of the disruption a network experienced during the hazard and recovery. Thus reliability was expanded to specifically examine different aspects of overall network performance in case such a disruption did occur. Some such indicators are: network vulnerability, criticality, robustness, and overall resilience.

Vulnerability is measured by the degree of accessibility loss in the presence of one or more linkage failures (D'Este and Taylor, 2003). Quantifying network vulnerability has emerged as a major paradigm, especially following the terrorist attacks of September 11, 2001; after which the vulnerability of all types of critical necessity networks came into question (Srinivasan, 2002). Since then a number of transportation network disruption studies have attempted to measure network vulnerability.

A common approach is to use trip movements through the transportation network to measure the vulnerability of the network in disruption. These flows can be used to measure connectivity loss between nodes as a means to measure vulnerability (Jenelius et al, 2005), or to measure increases in travel time to assess the impact of lost linkages versus normal operating circumstances (Taylor and D'Este, 2007). Utilizing thresholds are common to vulnerability studies as many have used travel time measurements in conjunction with user defined thresholds to assess the performance of the network under disruption (Murray and Grubesic, 2007; Holmgren, 2007).

A related measure to vulnerability is criticality. This indicator is specific to linkages in the overall network. Criticality is measured by two factors, the probability of linkage failure and the consequence of linkage failure to the network as a whole (Jenelius, 2005). Generally transportation network degradation analysts are concerned with identifying the latter measure as quantifying event probability can be problematic due to lack of historical information and adaptive threats (Sheffi, 2005; Cox, Prager and Rose, 2011).

Critical linkages are identified through modeling trip flows throughout the network and are based on ranking links and nodes depending on their consequence to overall network accessibility (Jenelius 2005 & 2007; Scott et al, 2006, Chen et al, 2007). Once identified critical linkages can be degraded or removed from the model to assess the functionality of the network, mimicking a hazard scenario. Some studies sole purpose is to identify critical linkages on the network (Ham et al, 2005; Sohn, 2006).

Studies related to identifying vulnerability and criticality through factors of network capacity is known as robustness research. Robustness is a measure of the flexibility of the network to accommodate shifting capacity due to the degradation or loss of linkages (Scott el al, 2006). Network robustness is present when minimal increases origin-destination costs occur as capacity is shifted to alternative linkages in the presence of link degradation or loss and may be indicated by a robustness index (Ibid). Such costs can be quantified as increased travel time or associated monetary costs. Because of the focus on capacity and monetary cost, network robustness studies are often associated with the field of supply chain management (Dong, 2006; Wilson 2007).

One final term that has grown in common use is resilience. Resilience refers to the ability of the network to absorb or maintain function while shocked (McDaniels et al 2008; Rose, 2007) and bridges the terminology between persons in the field of risk assessment and emergency preparedness with those in network analysis. To adequately measure the response of a network to hazard one must account for a multitude of network performance indicators (Schintler et al. 2007). Thus our work follows closely to the approach of Schintler (2007) by assessing the Ontario highway network. For a more comprehensive review of the study of transport networks under stress of hazard see: Sullivan et al, 2009.

Methods of Analysis

Study Area and Data

The Province of Ontario in Canada, as shown in Figure 1, is the targeted study area. Ontario is the economic heartland of Canada and as such generates a lot of goods movement activities and trucking within and between its various local markets. Therefore, road network disruptions can have detrimental outcomes not only for the Province's economy but also the economy of Canada as a whole. The province is house of 19 major Census Metropolitan Areas (CMAs) including the CMA of Toronto, which is the largest in Canada. Given the regional scope of our study, the analysis is concerned with the interregional economic flows among the 19 major CMAs of Ontario. Trucking flow data from Statistics Canada were employed in the analysis. Those data are extracted from the trucking commodity origin-destination survey (TCODS) for the years 2007, 2008 and 2009. The data represents the total tonnes shipped by commodity type between the different CMAs within Ontario. A method is devised to translate tonnage flows into truck trips using data from the vehicle inventory and use survey (VIUS). The latter, which was retrieved from the US census bureau, contains information about the average empty and loaded trucking weights by commodity, distance traveled, and number of empty loads by commodity type. The average weight $w(c,d)$ of loads shipped by commodity type *c* and distance traveled *d* is used to convert tonnage shipped $g(c,d_{/ij})$ into truck trips by commodity type *c*, that is:

$$T_{ij}^{c} = \frac{g(c, d_{/ij})}{w(c, d)}$$

The total truck trips between origin *i* and destination *j* is then calculated by summing over all commodities c. The result of the above calculation is an origin-destination matrix (342×342) of truck flows among the 18 major CMAs in Ontario.

The other dataset used in the analysis is the road network of Ontario. The latter is a Geographical Information System (GIS) shapefile that is extracted from the 2009 Desktop Mapping Technology Inc. (DMTI) route logistics GIS database. The extracted shapefile contained links representing major roads in the province including freeways, provincial highways and county/rural highways. The data also has the posted speed limit, length and free-flow travel time for each link in the network. The design capacity for each link is built into the DMTI shapefile using another road network shapefile that is acquired from the GeoBase database supported by the GeoConnections program supported by Natural Resource Canada. The latter dataset includes information on the number of lanes that each road link has. Consequently, the number of lanes was transferred from the GeoBase shapefile to the DMTI shapefile using a spatial overlay and joint procedure in ArcGIS. Passenger car per hour per lane (pcphpl) factors from the highway capacity manual (HCM) are then employed to calculate the design capacity of each link based on the type and speed limit of the link. The result is a highway road network for the province of Ontario with approximately 30,000 links each having information on posted speed limit, free-flow travel time and design capacity.

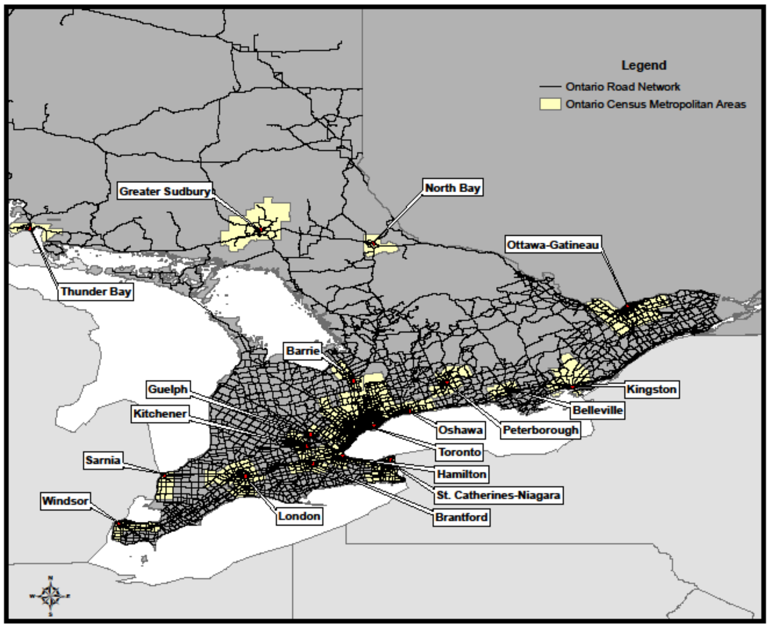

Figure 1. Major Census Metropolitan Areas (CMAs) in the Province of Ontario, Canada

Modeling Approach

To understand the concept of network redundancy, consider the following example of Just in Time (JIT) delivery, in which engines produced by an auto-engine plant at origin city *i* has to be JIT delivered to an auto-assembly plant in city *j*. If we assume that Route 1, as shown in Figure 2, guarantees a JIT delivery, then the network enjoys complete redundancy if and only if travel time τ_1 on Route 1 is equal to travel time τ_2 on Route 2. On the other hand, if Route 2 did not exist, then the network is said to have zero or no redundancy and consequently no resiliency. Typically, complete redundancy is hard to achieve in most regional networks since the designed capacity of roads is highest for the links comprising Route 1 or what can also be referred to as the primary route. The links comprising this route would be the ones with highest capacity and speed and as such guarantee the shortest path between origin *i* and destination *j* even in the presence of traffic.

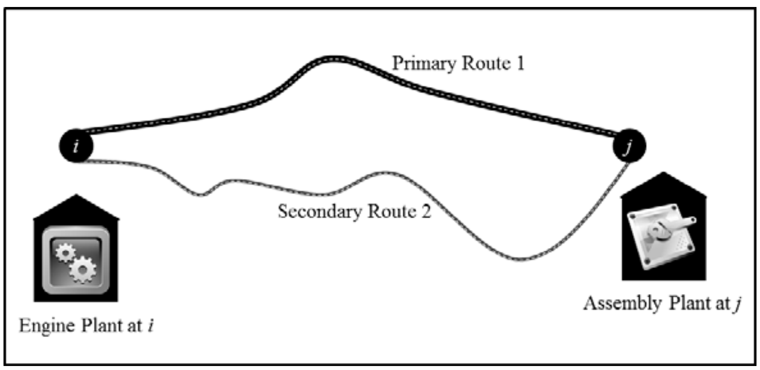

Figure 2. Example of two routes connecting an origin-destination pair

Although redundancy is a pre-condition for resiliency, it can be argued that complete redundancy is not necessarily the ultimate objective in order to have a resilient network. Recall that the main characteristic of a resilient system is flexibility which is guaranteed through redundancy. In the above example, the network can be considered redundant if Route 2 can be used as a feasible alternative in the absence of Route 1. This does not mean that the travel time τ_2 on Route 2 should be equal to the travel time τ_1 on Route 1.

Instead, redundancy could exist if $|\tau_2 - \tau_1| \leq \varepsilon$, where ε here is an acceptable difference in time that still guarantees a JIT delivery for the above example. Following the above notion, a way to determine the existence of network redundancy in a real interregional network, like the Ontario network, is to identify the most critical links other than primary links. Subsequently ε can be calculated for each connected origin-destination pair *i*, *j*. To achieve this goal, a hierarchical approach is devised to explore the redundancy of the Ontario road network and to calculate ε at various levels of hierarchy.

First, the hierarchy level 1 network, which represents the primary network connecting all major origin-destination markets, is identified using the existing Ontario highway network. The hierarchy level 1 network is based on calculating the shortest paths connecting all origin-destination pairs *i* and *j* on the network. The shortest path (SNP1) will return $\tau_{ij,1}$ for each origin-destination pair *i* and *j*. Next, road links pertaining to the hierarchy level 1 network SNP1 are omitted and the shortest path (SNP2) representing the hierarchy level 2 network (i.e. secondary network) connecting the various origin-destination markets is re-calculated. The shortest path SNP2 for the secondary network will return $\tau_{ij,2}$ for all the origin-destination pairs *i* and *j* that have connectivity under this secondary network. It is worth noting that in the absence of the primary network links certain origin-destination pairs *i*, *j* might lose connectivity. That is, for some origin-destination pairs (*i*, *j*), only the primary shortest path route is the available route to allow flows between those *i* and *j* pairs. Lastly, the road links corresponding to the first and second hierarchal level networks are dropped from the Ontario highway network to calculate and explore the existence of a third hierarchal level network which could provide redundancy. The resulting shortest path links SNP3 will return $\tau_{ij,3}$ for the connected origin-destination pairs *i* and *j*. Again, certain origin-destination pairs will lose their connectivity in the absence of those links representing the primary and secondary networks.

The shortest path routes for each hierarchal level are calculated via the Network Analyst Extension of ArcGIS 10.0. At first the calculated shortest path under each hierarchal network was calculated using the free-flow travel time associated with each link. However, the effect of traffic on the networks had to be accounted for in order to obtain a more realistic measure of the estimated travel time $\tau_{ij,h}$ for each hierarchal level h. This is important since the interaction between traffic flow and road capacity determines travel time in practice. For this, the estimated truck trips T_{ij} were assigned to the shortest path networks to determine the flows on each road link. Passenger Car Equivalency (PCE) rate of 2.5 was used to convert trucks into passenger cars before a traffic assignment can be performed. Also, we assumed that 8 percent of the total truck trips occur within a typical peak hour of the day. Upon these adjustments, the truck trips were assigned to the network. Furthermore, to capture the effect of passenger vehicles, we followed the literature by assuming that each truck on the network will be faced with 27 passenger vehicles. The estimated overall traffic flow f_l on each link l in a typical peak hour of the day is then used to calculate the congested travel time tt_l' on each link l of the hierarchal networks using the following conventional link performance function:

$$tt_l' = tt_l^0\left(1 + 0.15\left(\frac{f_l}{D_l}\right)^4\right)$$

where tt_l^0 and D_l are the free flow travel time and design capacity of link l, respectively.

Results and Discussion

The hierarchy level 1 network connecting the major 19 CMAs in Ontario is shown in Figure 3. The map indicates that most CMAs are connected via the major 400 series highways as expected. All 19 CMAs are connected via 342 shortest paths which share common links from the Ontario road network. We contend that the number of times a road link is used by the different shortest paths provide a meaningful measure of criticality. Figure 4, on the other hand, presents a map which highlights the most critical road links of the Ontario network. After exploring the generated data, we are able to identify the critical links as those that are used by at least at least 80 shortest paths. On the other hand, we are also able to define the most critical links as those that gets used by at least 120 shortest paths. Following this classification, the most critical links in Ontario are highway 401 southwest of Ontario through Toronto, highway 400 from Toronto through Barrie and highway 69 which stretches to northern Ontario.

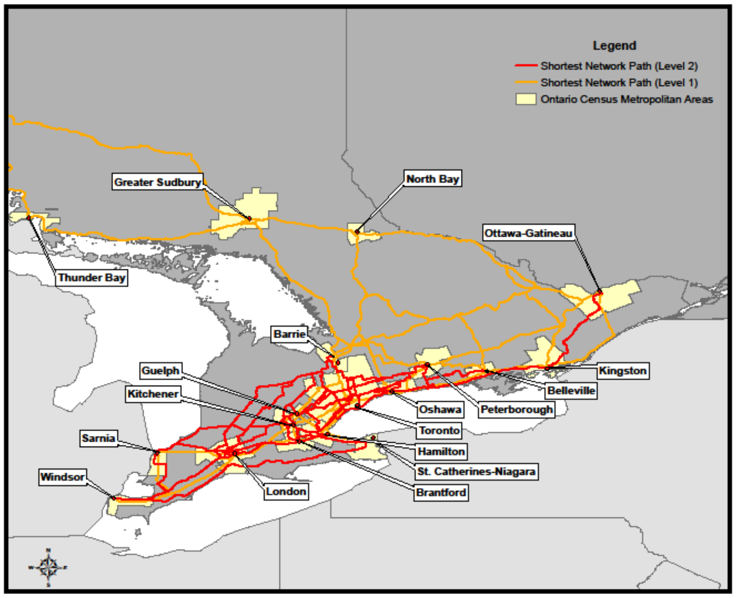

Figure 3. Hierarchy level 1 and 2 road networks

Figure 3 also represents the hierarchy level 2 network of Ontario. It is found that when moving from hierarchy level 1 to hierarchy level 2, the number of possible paths reduces from 342 to 210. This is reflected in Figure 3 as northwestern Ontario becomes unreachable via the hierarchy level 2 network. Obviously, this situation is a clear illustration of the vulnerability of remote CMAs in the province. In terms of travel time, the average uncongested travel time between origin-destination pairs from level 1 and level 2 only increases by 46 minutes (i.e. 29%). The observed increase represents a reasonable high level of network redundancy for southern Ontario, as can be also discerned from Figure 3. It should be noted that the increase in uncongested travel time is due to both network circuity and lower maximum speed on secondary (rural) highways used by the level 2 type network. Table 1 provides a summary statistics for the calculated average uncongested travel times from SNP1 and SNP2. The generated statistics indicate that ε can range from 8.6 minutes to 132.1 minutes. This suggests that certain origin-destination pairs are more resilient with a relatively small ε while others have very low resiliency.

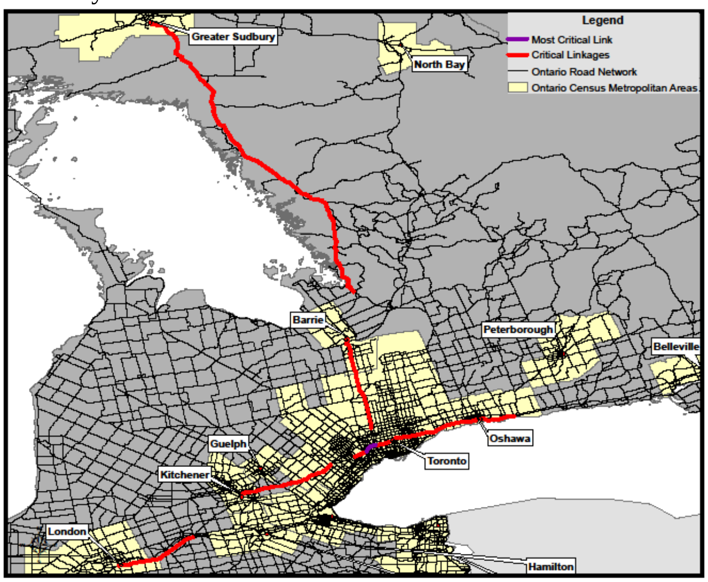

Figure 4: Critical links on the Ontario road network

Table 1. Summary Statistics of uncongested average travel time of SNP1 and SNP2

	SNP1	SNP2	$\lvert\tau_2 - \tau_1\rvert$
Count	210	210	
Mean	159.8	205.9	46.1
Maximum	487.8	619.9	132.1
Minimum	19.2	27.8	8.6
Range	468.6	592.1	

Variance	9466	15532
Standard Deviation	97.3	124.7

When considering hierarchy level 3 network, the possible paths connecting markets reduce down to 62 shortest paths. Under level 3, critical origin-destination pairs such as Toronto and Windsor become unreachable. Given that $|\tau_2 - \tau_1|$ for this pair is 74 minutes (33%) and $|\tau_3 - \tau_2|$ approaches ∞ one can deduce that the network supporting this pair is not highly resilient. Moving from level 1 and level to level 3 hierarchy, the average uncongested travel time increases in excess of 1 hour (i.e. 53%) and many of the origin-destination locations lose connectivity, as shown in Figure 5. The loss of connectivity among the majority of markets suggests a weak level of overall redundancy. However, certain market pairs are more resilient as suggested by the figures shown in Table 2.

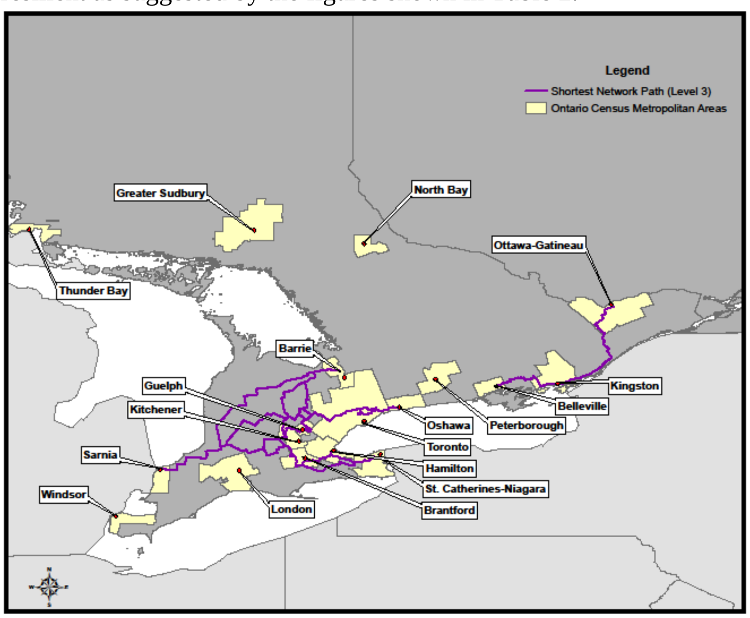

Figure 5. Hierarchy level 3 road network

Congestion will have a significant impact on the redundancy and resiliency of the network. Table 3 presents the results for the

Windsor-Toronto corridor. It is clear that under congestion the level of resiliency will deteriorate when moving from level 1 to level 2. $|\tau_2 - \tau_1|$ is equal to 145 minutes which is almost a 60% increase. Overall, the maximum congestion index for the level 1 is estimated to be 7.02. The index increases to 8.67 when moving to the level 2 hierarchy and to 9.10 under the level 3 hierarchy.

Table 2: Summary Statistics of uncongested average travel time of SNP1, SNP2 and SNP3

	SNP1	SNP2	$\|\tau_2 - \tau_1\|$	SNP3	$\|\tau_3 - \tau_2\|$
Count	62	62		62	
Mean	97.4	124.8	27.4	190.7	65.9
Maximum	215.2	268.8	53.6	329	60.2
Minimum	19.2	27.7	8.5	34	6.3
Range	196	241.1		295	
Variance	2462	3669		6817	
Standard Deviation	49.6	60.6		82.6	

Table 3: Congested travel time under hierarchal levels 1, 2, and 3 for the Windsor-Toronto case

Windsor - Toronto	**SNP1**	**SNP2**	**SNP3**	$\|\tau_2 - \tau_1\|$
Average Congestion	1.27	1.53	Not possible	
Congested Travel Times (min)	245	390	Not possible	145

Conclusion

This paper presented a simple and intuitive approach for assessing the resilience of road surface transportation networks. A hierarchal network approach is devised and used to identify critical links and also assess the level of redundancy on the network using the interregional highway network of the province of Ontario in Canada as a case study. While the devised approach can be applied to individual link disruptions, several observations emerged from the large scale application. We found that the southern Ontario road network has at leave 1 level of built in redundancy. However, certain corridors connecting certain markets are more resilient than others. On the other hand, northern regions are especially vulnerable to network disruptions due to lack of redundancy.

Furthermore, the Toronto CMA, which is the largest in Ontario and Canada, has only one level of redundancy. The devised approach enabled us to identify the most critical links on the network. Critical links are those that are heavily utilized by the various shortest paths connecting the different origin-destination markets. Therefore, enumerating the number of times a road link is used provides a simple index of criticality of the network. In this regard, highly critical links are found in both the south and north parts of the province. Finally, congestion and network road capacity has a major impact on travel time and consequently the resiliency of the road network.

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