A SIMULATION APPROACH TO MODELING THE ROBUSTNESS OF THE ONTARIO TRUCK ROAD NETWORK

Georgiana Madar, University of Windsor
Hanna Maoh, University of Windsor
William Anderson, University of Windsor
Proceedings of the 52nd Annual Conference
Canadian Transportation Research Forum

Introduction

Regional economic growth is significantly reliant on a road transportation network that is robust and dependable, since a considerable amount of goods is moved between regions by trucks on the road network. Events that cause disruptions along the transportation network and reduce or eliminate the capacity of certain links can have negative impacts on the flow of freight and must be appropriately studied and mitigated. These events can be either natural (e.g. weather events) or manmade (e.g. terror attacks) and their impacts can range in severity from having a minimal effect to a complete closure of the link. With an aging infrastructure in the province of Ontario, it is imperative to study the potential effects of link capacity reductions or closures, in order to provide appropriate mitigation measures that would minimize the negative effects to the users of the network as much as possible. Identifying the most critical links on the network will allow for a study of the most significant potential impacts of disruptions.

Robustness refers to the ability of a road network to maintain its functionality intact when exposed to some perturbation. The concept of the Network Robustness Index (NRI) was explored by Scott et al (2006) and is defined as the difference in travel time on the road network between the existing condition and a simulated condition where the capacity of a link or segment is reduced or completely eliminated. Another previous work by Maoh et al (2012) examined the critical links along the Ontario major roads network and identified the segments that serve as the shortest path between the most origin-destination pairs. The work presented in this paper builds on these two previous studies and aims to examine the robustness of the critical segments of the Ontario trucking network, using a sensitivity analysis simulation approach. Six segments in particular were identified as the most critical, serving as the shortest paths between the largest number of origin and destination regions in the province of Ontario. Conditions that would be encountered with capacity and speed reductions due to roadworks were replicated and examined through a series of simulation models. A sensitivity analysis was undertaken for each of these critical segments, simulating increasing levels of capacity reductions. The NRI for the entire network, for each reduction scenario, was used as a measure to examine the robustness of Ontario’s major roads network.

The remainder of this paper is organized as follows. The next section provides a background of the existing literature on network robustness and related studies on this subject. Next, the study area, methodology, and simulation scenarios used for this study are described. A discussion of the results is next, followed by the final section, detailing concluding remarks and recommendations arising from this research.

Background

The concept of the Network Robustness Index was detailed by Scott et al (2006), who proposed this measure to identify highly congested links, instead of the traditionally used volume/capacity (V/C) ratio. The latter method is a localized approach and requires detailed data; the volume and capacity of the link in question must be obtained in order to determine its performance, and system-wide impacts are not captured. Using a set of artificial networks of different levels of connectivity, the NRI was developed as a new measure for determining the travel-time cost to the entire network associated with closure of a link. The NRI was defined as the difference in cost (travel time) between the original network and the network subject to the removal of a link. The NRI was calculated iteratively for each link in the model networks and compared to the V/C ratio for each respective link. The results found that the NRI identified different links as being critical than the V/C measure was able to do, and provided a better indication of link criticality. The NRI accounts for rerouting possibilities and the traffic demand of the entire network, as well as the capacity of individual links, thus providing a better measure than the traditional method.

The NRI concept was applied by Lupa et al (2015) to produce a ranking system for critical links in the region of Colorado Springs, Colorado. The critical links were identified with respect to evacuation, resilience, and emergency preparedness scenarios. The application of the NRI concept was found effective and flexible for applications to regional preparedness and transportation planning. Network robustness and criticality were studied by Koulakezian et al (2012) with a focus on vehicle-to-vehicle and vehicle-to-infrastructure communication systems. Through a convex optimization problem, network robustness was achieved when assigning traffic to road links. Network criticality was used as a robustness metric. The results were tested under varying conditions of increased traffic demand and reduced capacity, simulated for the Toronto region.

A different measure for identifying network robustness with links of decreased capacities was presented by Nagurney and Qiang (2009). Two relative cost indices were proposed, for user-optimal and system-optimal traffic flows, to quantitatively assess the changes in transportation cost on a network when link capacities are decreased. Travel time was used as a proxy for the cost. Jenelius (2009) explored the effects of link closures on regional importance and exposure. These two factors respectively describe the efficiency and dependence of links in the network. Through regression models, it was found that the regional importance of links is influenced by the structure of the network and the regional traffic load, while the regional exposure depends on network structure and average travel time. In a more recent study, Matsson and Jenelius (2015) provide an overview of recent research effort in network vulnerability and resilience. They provide some definitions of these concepts from the points of view of a number of researchers and outline study methodologies that have been developed. The authors encourage cross-disciplinary collaboration for future research.

In a subsequent work, Maoh et al (2012) examined the resilience of the Ontario road network by exploring redundancy in the network. The study used Ontario's 19 major CMAs as its origin and destination zones, along with the associated traffic demand among them. Redundancy in the network, the presence of multiple routes connecting an origin-destination pair, was explored by determining the shortest path network joining the origin-destination markets. This primary level network was then removed and a secondary shortest path network was determined from the remaining links. A third iteration was conducted after this. The paper detailed that connectivity to more outlying regions was removed in the second and third level networks, which would intuitively result in increased travel times or even an inability to reach those zones. Based on these findings, a set of links was identified as the most critical links on the Ontario road network, serving as part of the shortest path for the highest number of routes. The critical links that were identified in that research were used in the present paper to model the robustness of the network.

Methods of Analysis

Study Area and Data

The target study area is the major roads network of the province of Ontario, shown in Figure 1 below. A significant amount of goods trade occurs in Ontario, which generates a large amount of truck traffic within and between regions. Events that cause disruptions along the routes that join these markets, reducing their capacities or entirely eliminating segments of the network, can have significant impacts, not only on the provincial economy, but also nationally. The province of Ontario is home to 19 of the country's Census Metropolitan Areas (CMAs), which serve as the origin and destination zones in this research. Figure 1 shows the locations of these CMAs and the labels are identified in Table 1.

Table 1: List of Major Census Metropolitan Areas (CMAs) in Ontario

Label	CMA Name	Label	CMA Name
1	Ottawa - Gatineau	**11**	Guelph
2	Kingston	**12**	London
3	Belleville	**13**	Windsor
4	Peterborough	**14**	Sarnia
5	Oshawa	**15**	Barrie
6	Toronto	**16**	North Bay
7	Hamilton	**17**	Greater Sudbury
8	St. Catherine's - Niagara	**18**	Sault Ste. Marie
9	Kitchener - Cambridge - Waterloo	**19**	Thunder Bay
10	Brantford		

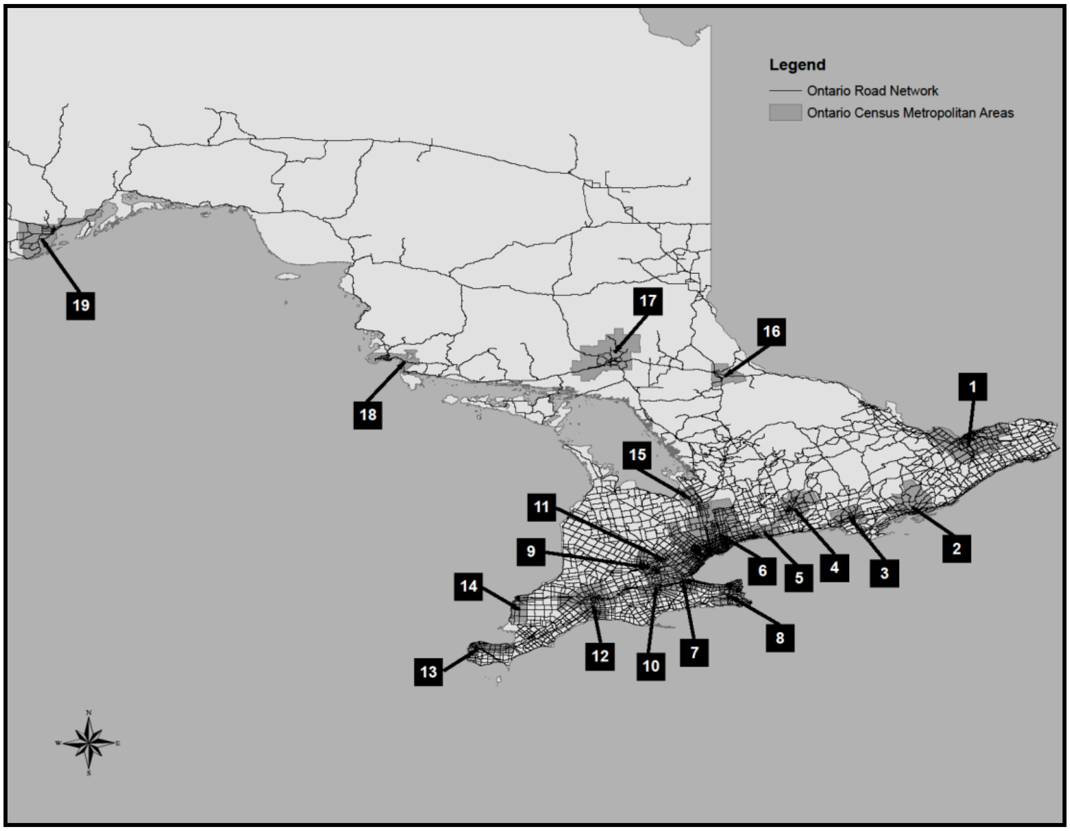

Figure 1: Major Census Metropolitan Areas (CMAs) in Ontario

The road network and the associated data used in the previous work by Maoh et al (2012) was utilized in this study. In order to determine the total truck trips for the region, data was extracted from the Trucking Commodity Origin-Destination (TCOD) survey, comprising the total tonnes shipped by commodity type between Ontario's CMAs. These values were translated into truck trips to comprise the origin-destination matrix of truck flows. Intra-CMA flows were not considered. The inter-CMA flows were used as the demand to be assigned to the road network in the current study. The background flow of passenger traffic between each origin-destination pair was also included in the simulation.

The road network of Ontario was obtained as a Geographic Information System (GIS) shapefile from Desktop Mapping Technology Inc. (DMTI) for the year 2013. This shapefile included information on the posted speed limit, length, and free-flow travel time for each link. The design capacity was determined for each link using a shapefile acquitted from the GeoBase database, part of the GeoConnections program supported by Natural Resources Canada.

The scope of this research was to examine the robustness of the Ontario road network in the presence of simulated disruptions along the network's most critical segments. The previous work of Maoh et al (2012) identified critical links on the network based on the number of origin-destination pairs that used the respective links as a shortest path. The segments that were deemed most critical were selected for NRI analysis. Figure 2 shows the locations of these critical segments and Table 2 lists a description of each segment. The analysis was conducted using ArcGIS software and shapefiles were constructed for each reduction scenario. Slight differences exist between the currently used shapefile and that used in the previous work, however, efforts were made to match the critical segments as closely as possible to those originally identified. It should be noted that, in cases where a road was represented by two parallel links (e.g. east-bound and west-bound segments of Highway 401), the critical segment did not always contain both parallel links. The reason for this is that the demand between origins and destinations is not equivalent in both directions. Ramps were not included in the critical segments.

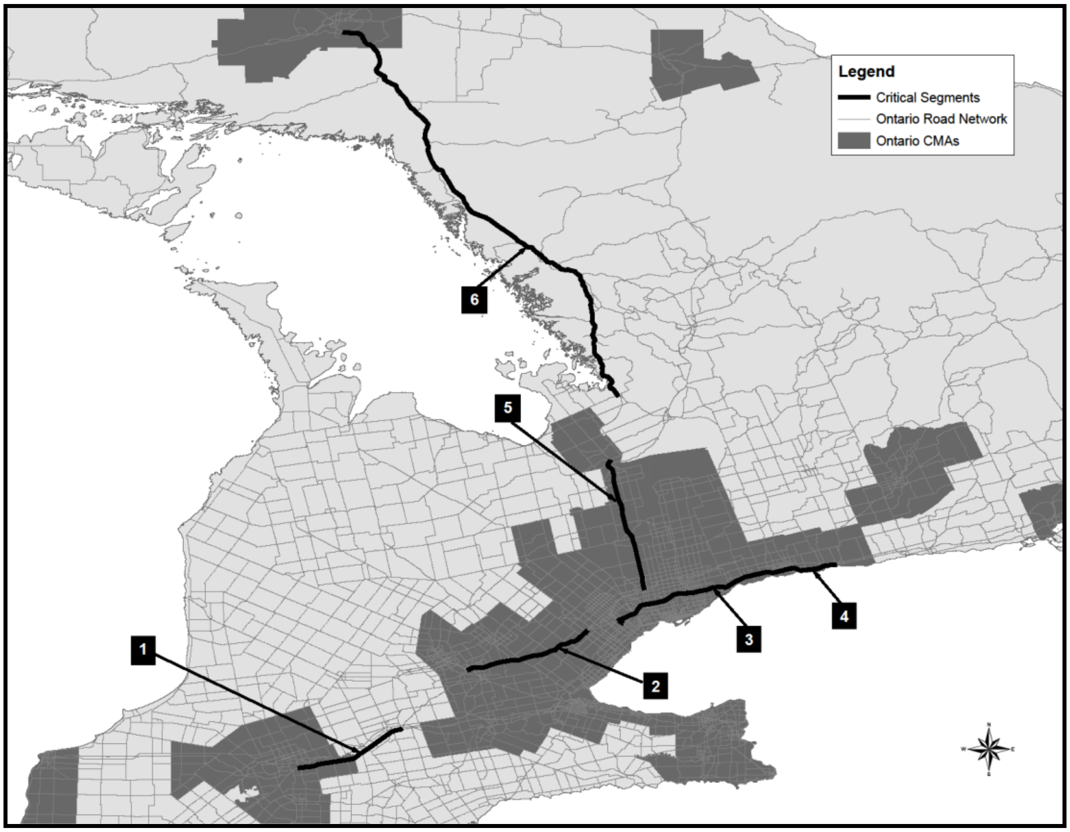

Figure 2: Critical Segments on the Ontario Road Network

Table 2: List of Critical Segments in the Ontario Road Network

Label	Segment description	Label	Segment description
1	Highway 401, east of London	4	Highway 401, east of Oshawa
2	Highway 401, east of Kitchener	5	Highway 400, Toronto to Barrie
3	Highway 401, through Toronto	6	Highway 400/69, Barrie to Sudbury

Simulation Scenarios

The six segments identified as most critical were examined in terms of the number of lanes present on each respective link and the link characteristics. The modeled scenarios were devised to simulate construction works, modeling gradual reduction in link capacity and speed. A traffic assignment routine was run for each simulated scenario, following user equilibrium, and using the specified characteristics of capacity and speed.

The capacity of each lane was assumed to be equal for each respective link, so lane reductions were specified by dividing the total capacity by the simulated number of lanes to be closed. One additional lane was removed with each successive scenario, with the exception of a few cases where too few links existed in a segment that had a certain number of lanes. For example, Segments 2 and 6 contained fewer than five links with four lanes, so a scenario where only these links were reduced by one lane would have had a minimal effect. In cases such as this, the reduction was combined with the next scenario (e.g. all four-lane links and three-lane links reduced to two lanes). The final reduction scenario for each segment was a complete removal of the segment.

Capacity reductions were used to simulate lane closures. However, it was also necessary to reduce the speed by a corresponding amount for each scenario. The Ontario Traffic Manual (2014) dictates that temporary speed reductions for construction zones cannot exceed 20 km/h less than the posted speed limit. Therefore, for the first reduction scenarios in each segment, when the capacity reductions were less than half, the speed reduction was calculated as 10 km/h below the speed of the respective link. In the latter reduction scenarios, where more than half of the capacity was removed, the speed was reduced by 20 km/h. Simulating complete link reductions was done by setting very small values to the capacity and speed fields. This was done to ensure that traffic assignment could occur without any errors that would arise from having zero speed or capacity (i.e. dividing by zero). Setting these small values would simultaneously ensure that the links in question would have utilities that were effectively zero, making it highly unlikely that traffic would be assigned to them. In examining the traffic assignment results it was found that only a negligible proportion of the demand (less than 0.5%) was assigned to the completely removed links.

Modeling Approach

As mentioned in the previous section, each scenario was adjusted accordingly for capacity and speed reductions. Given these parameters, a user equilibrium traffic assignment routine was run for each scenario. The output results included the traffic flow on each link in both directions (for links on which travel is allowed in both directions). The simulated volume for the links is, then, given as the sum of the traffic volumes in each direction. This parameter is used in the subsequent calculation of the NRI.

Robustness has been defined as a network's ability to maintain its functionality when exposed to disruptions that cause reductions in capacity and speed along a subset of links. Traditionally, the volume/capacity ratio has been used to examine the performance of networks and their links, however, this measure does not capture the full extent of the effects of such disruptions. The work presented by Scott et al (2006) demonstrates that the NRI is better able to depict the effects of a capacity reduction on a subset of links, on the entire network. The total cost on the network (TT), in the unit of vehicle-minutes, is calculated using the conventional link performance function, as follows:

$$TT = \sum_i \left[t_i \left(1 + 0.15 \left(\frac{v_i}{c_i} \right)^4 \right) \right] * v_i$$

where

t_i = free-flow travel time on link i, calculated using the length link *i* and the speed on link *i*
v_i= traffic volume modeled on link *i* (sum of both directions of flow)
c_i = capacity for link *i*

This measure was calculated for the network under current conditions (base case with no adjustments) and for each capacity reduction scenario after the traffic assignment was executed given the respective capacity and speed adjustments. Knowing these values, the Network Robustness Index could then be determined as the difference in travel time between the base case and the respective reduction scenario, measured in vehicle-minutes:

$$NRI = TT_{base} - TT_{reduction}$$

where

TT_{base} = total travel time for the base case under current conditions, without reductions
$TT_{reduction}$ = total travel time modeled for a given capacity and speed reduction scenario

Additionally, the marginal NRI was also calculated, measuring the difference in travel time along the network between successive reduction scenarios. The following section presents and discusses the results of these simulations.

Results and Discussion

The results from the sensitivity analysis models for each of the six critical segments are presented in Table 3. The table summarizes the total travel time through the network for each given scenario, the NRI, and the percentage change in total travel time between each respective scenario and the base case. Additionally, the marginal NRI and marginal percentage change were calculated for successive reductions. The results are given at the provincial network level and were not normalized in a per-vehicle basis. The reason for this is because the Ontario road network is dispersed over a large area and the effects to reduction scenarios near the vicinity of critical segments would be diffused by the remainder of the traffic throughout the provincial road network. Such a normalized measure would not accurately convey the effects of the reduction scenarios, since these effects are not equally felt by all of the network's users.

As expected, the reduction scenarios for each of the six critical segments act to increase the total travel time in the network. The travel time also increases across successive reduction scenarios for the same segment. This result is intuitive, since reducing the capacity and speed of a road segment, especially one as heavily used as the critical segments that have been identified, while the demand remains the same, will force the traffic to secondary routes. The largest increase in total travel time compared to the base case resulted from the complete removal of Segment 3, which represents the portion of Highway 401 passing through Toronto, Canada's largest CMA. It can also be noted that the largest change from the base scenario in each case occurs when a segment is removed in its entirety, as anticipated. The magnitude of the NRI among the six segments can be attributed to the characteristics of the surrounding CMAs and the road network itself. A larger NRI is expected for larger CMAs that are more heavily involved in trade and will produce more freight trips. The road segments connecting CMAs nearest to these zones (e.g. Toronto) are expected to experience relatively heavy flows as well and be subjected to higher NRI values. The robustness of these segments is lower.

The simulation results show that Segments 1, 2, and 4 experience the largest marginal reductions in travel time when the segments were modeled as completely removed. This is not the case for the remaining three segments, where the largest marginal reduction is seen to happen when all links in the respective segments are reduced to one lane. This observation could be attributed to the location of the segments, the characteristics of the CMAs that they connect, and the characteristics of the surrounding road network. Segments 1, 2, and 4 are links that join the CMAs of London, Kitchener, and Oshawa to Toronto;

removal of these links is expected to have a notable impact to freight traffic, considering the amount of trade that takes place to and from the Toronto CMA. Of the remaining three segments, one passes through Toronto, experiencing very heavy flows, while the other two are located in more northern regions, where alternative routes are sparser. Reducing these links to minimal capacity and speed is expected to cause long delays and bottlenecks, where the segments operate at conditions resembling complete closure.

Table 3: Results from Sensitivity Analyses and NRI Calculations

Scenario	Description	Total Travel Time (veh-min)	NRI (veh-min)	% Change	Marginal NRI (veh-min)	Marginal % Change
Segment 1						
Base Case		4,250,975.0				
Reduction 1	3-lane to 2-lane	4,260,872.5	9,897.6	0.23%	9,897.6	0.23%
Reduction 2	All down to 1-lane	4,264,363.7	13,388.7	0.31%	3,491.1	0.08%
Reduction 3	Completely removed	4,290,248.9	39,274.0	0.92%	25,885.3	0.61%
Segment 2						
Base Case		4,250,975.0				
Reduction 1	4- and 3-lane to 2-lane	4,266,689.1	15,714.2	0.37%	15,714.2	0.37%
Reduction 2	All down to 1-lane	4,309,858.9	58,883.9	1.39%	43,169.7	1.01%
Reduction 3	Completely removed	4,359,909.7	108,934.8	2.56%	50,050.9	1.16%
Segment 3						
Base Case		4,250,975.0				
Reduction 1	5-lane to 4-lane	4,251,410.6	435.7	0.01%	435.7	0.01%
Reduction 2	5- and 4-lane to 3-lane	4,270,510.8	19,535.9	0.46%	19,100.2	0.45%
Reduction 3	5- 4- and 3-lane to 2-lane	4,304,907.0	53,932.0	1.27%	34,396.1	0.81%
Reduction 4	All down to 1-lane	4,341,768.7	90,793.7	2.14%	36,861.7	0.86%
Reduction 5	Completely removed	4,367,930.8	116,955.8	2.75%	26,162.1	0.60%
Segment 4						
Base Case		4,250,975.0				
Reduction 1	3-lane to 2-lane	4,260,278.7	9,303.8	0.22%	9,303.8	0.22%
Reduction 2	All down to 1-lane	4,272,231.1	21,256.1	0.50%	11,952.4	0.28%
Reduction 3	Completely removed	4,322,509.5	71,534.5	1.68%	50,278.4	1.18%
Segment 5						
Base Case		4,250,975.0				
Reduction 1	4-lane to 3-lane	4,251,969.9	995.0	0.02%	995.0	0.02%
Reduction 2	4- and 3-lane to 2-lane	4,262,390.1	11,415.1	0.27%	10,420.1	0.25%
Reduction 3	All down to 1-lane	4,283,352.1	32,377.1	0.76%	20,962.0	0.49%
Reduction 4	Completely removed	4,288,321.9	37,347.0	0.88%	4,969.9	0.12%
Segment 6						
Base Case		4,250,975.0				
Reduction 1	4- and 3-lane to 2-lane	4,252,752.4	1,777.4	0.04%	1,777.4	0.04%
Reduction 2	All down to 1-lane	4,284,795.4	33,820.4	0.80%	32,043.0	0.75%
Reduction 3	Completely removed	4,292,897.1	41,922.1	0.99%	8,101.7	0.19%

Conclusions and Recommendations

The results of this research show that network robustness will decrease for capacity reductions and closures of segments that are associated with larger CMAs, which produce higher traffic demands. The NRI also indicates that network segments that connect more remote regions, where fewer alternative routes exist, are less robust. These findings are important from a policy and planning aspect, since care must be paid to ensure that possible events along these critical segments where reductions in capacity occur are properly mitigated. Being aware of the portions of the road network that experience significant increases in travel time when exposed to such perturbations, decision-makers can better prepare for such events to minimize the effects on the network's users.

The current paper presented analysis that simulated the effects of lane and link closures due to construction activities. Future research can explore the simulation of different kinds of events, such as extreme weather events or severe roadway accidents that cause an immediate and complete closure of links. Also, as was explained, the physical size of the province of Ontario and its road network can act to diffuse the impact of simulated scenarios. A road closure in the south-west of the province, for example, will have a notable effect on the regional network, but likely have a minimal effect on the northernmost portion of the network. Future work can attempt to capture these regional effects.

Overall, it can be seen that the NRI provides an important measure of truck network robustness, allowing for the identification of critical portions of the network and for the simulation of the effects of capacity reductions along these segments. The results of this research quantify the potential impacts of lane closures as would be experienced under roadwork conditions along six of Ontario's most critical segments. This information can help the Ministry of Transportation of Ontario (MTO) to devise mitigation plans for any future improvement works to these segments such that freight demand is met and disruption to trade remains at its minimum.

References

Jenelius, E. (2009). Network structure and travel patterns: explaining the geographical disparities of road network vulnerability. *Journal of Transport Geography*, *17*(3), 234-244.

Koulakezian, A., Soliman, H. M., Tang, T., & Leon-Garcia, A. (2012, September). Robust traffic assignment in transportation networks using network criticality. In *Vehicular Technology Conference (VTC Fall), 2012 IEEE* (pp. 1-5). IEEE.

Lupa, M. R., Prather, K., Paz de Araujo, M., & Casper, C. (2015). Network Robustness Index Application at Pikes Peak Area Council of Governments, Colorado Springs, Colorado. *Transportation Research Record: Journal of the Transportation Research Board*, (2499), 10-17.

Maoh, H., Anderson, W., & Burke, C. (2012). *Modeling the Resilience of Surface Freight Transportation Systems: An Application to Ontario, Canada.* Proceedings of the 47th CTRF Annual Conference, Calgary, Alberta.

Mattsson, L. G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems–a discussion of recent research. *Transportation Research Part A: Policy and Practice*, *81*, 16-34.

Nagurney, A., & Qiang, Q. (2009). A relative total cost index for the evaluation of transportation network robustness in the presence of degradable links and alternative travel behavior. *International Transactions in Operational Research*, *16*(1), 49-67.

Ministry of Transportation, Ontario (2014) *Ontario Traffic Manual, Book 7: Temporary Conditions*. St. Catherine's, Ontario

Scott, D. M., Novak, D. C., Aultman-Hall, L., & Guo, F. (2006). Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks. *Journal of Transport Geography*, *14*(3), 215-227.