

Extending the Network Robustness Index to Include Emissions: A Holistic Framework for Link Criticality Analysis for Montreal Transportation System

Frederic Reynaud

Department of Civil Engineering and Applied Mechanics
McGill University

Ph: 514-663-3003, Fax: 514-398-7361
Email: frederic.reynaud@mail.mcgill.ca

Timothy Sider

Engineer
Atkins

London, UK

Ph: 514-398-6935, Fax: 514-398-7361
Email: timothy.sider@mail.mcgill.ca

Marianne Hatzopoulou

Associate Professor
Department of Civil Engineering
University of Toronto

Tel: 1-416-978-0864
Email: marianne.hatzopoulou@utoronto.ca

Naveen Eluru*

Associate Professor
Civil, Environmental and Construction Engineering,
University of Central Florida

Ph: 407-823-4815; Fax: 407-823-3315
Email:naveen.eluru@ucf.edu

*Corresponding author

Abstract

Road infrastructure in many North American cities is aging and requires increasing investments to maintain current levels of operation. Budgets for road network infrastructure maintenance are limited, and tools designed to optimize the allocation of such budgets are critical for decision-makers. In order to evaluate the importance of individual links in a road network, traditional measures include the Volume-to-Capacity (V/C) ratio and Average Annual Daily Traffic (AADT). Such measures fail to assess system-wide impacts of road network disruptions. Research has thus shifted towards dynamic measures to evaluate the importance of individual links as well as the importance of link clusters from a system-wide perspective. The Network Robustness Index (NRI) was one of the first tools to successfully assess network-wide congestion effects due to single link closures. In recent years, researchers have attempted to widen the scope of indicators used to assess link criticality. This paper investigates the use of system-wide metrics in the context of Montreal's urban road network, and provides a new mechanism to evaluate the importance of individual links while internalizing the environmental perspective. Specifically, the NRI is expanded to include road emissions in the link criticality analysis process, resulting in the creation of an Emissions-based NRI (ENRI), to be used in conjunction with the NRI. The results of this new Emissions-based NRI (ENRI) are compared with the NRI results and we observe that both tools provide similar results for major scenarios (such as capacity reduction on major bridges) while for minor scenarios (such as capacity reduction on arterial roads) the results are quite different. The results suggest that new holistic frameworks are needed to assess link criticality in urban areas.

Keywords: link criticality, link vulnerability, network robustness index, traffic emissions, Montreal

1. INTRODUCTION

Road networks in North America are designed to provide service to millions of urban residents. To maintain acceptable levels of performance on road networks for indicators such as travel time, safety and reliability, transportation engineers must address challenges in the form of increasing traffic demand, aging infrastructure, natural disasters and high infrastructure replacement costs (Nagurney et al., 2010). For instance, a recent American Society of Civil Engineers (ASCE) report card on the state of the infrastructure in the United States highlighted that maintaining the nation's highways at current operation levels between 2008 and 2028 would require about 101 billion dollars annually. Further, an additional 79 billion dollars annually would be required to enhance the highways during the same time period (ASCE, 2013).

Most urban regions in North America are facing increased transportation infrastructure maintenance and upkeep costs. The city of Montreal in Quebec, Canada is no exception. The Montreal urban transportation network is subject to the challenge of increasing traffic demand while also affected by extreme temperature variation across the year (lows of about -40F and highs of 95F in winter and summer respectively). The Ministère des Transports du Québec (MTQ), the provincial ministry of transportation, allocated over 3.6 billion Canadian dollars towards road maintenance in 2011-2012 (MTQ, 2012), while the city of Montreal allocated over 367 million Canadian dollars to the city's road network (excluding public transportation) in its 2013 budget (Ville de Montréal, 2012). Clearly, significant funds are spent each year on road infrastructure in the province of Quebec, and more specifically in Montreal. In spite of these large budgetary allocations, the transportation agencies in Montreal regularly face severe shortages in funding for road infrastructure. In this context, developing tools designed to optimize the allocation of the limited budgetary resources available is critical for Montreal and other urban metropolitan regions.

The optimal allocation of resources to urban transportation infrastructure was traditionally based on the concept of serving as much automobile demand as possible. Hence, the evaluation of individual roadway facilities (typically characterized by a link or a series of links in the network) was based on measures such as Average Annual Daily Traffic (AADT) and the Volume-to-Capacity (V/C) ratio (Scott et al., 2006). While these measures provide useful information on roadway facility usage, they fall short for two reasons: first, these measures ignore that the transportation system is based on an interconnected system of links that interact very strongly with one another. Second, with growing emphasis on the contribution of the transportation sector to Green House Gas (GHG) emissions and urban air pollution, it is important to develop frameworks that internalize the environmental perspective.

Transportation research has rarely examined infrastructure criticality in the context of environmental pollution i.e. failure in which roadway facilities might result in worsening environmental outcomes. Accurately evaluating infrastructure criticality in the context of traffic volumes and environmental pollution at the level of an urban transportation network is far from straightforward. However, the growing literature on quantitative model development for travel demand analysis and emissions modeling in conjunction with improved computational capabilities provide us with the opportunity to evaluate link criticality in a more holistic fashion (Sider et al., 2013; Goulias et al., 2012).

The current research effort aims at expanding the Network Robustness Index (NRI), proposed by Scott et al. in 2006. This tool assesses link criticality by examining how link failures affect congestion in the entire network under consideration. In order to develop a more thorough understanding of link criticality, we expand on the NRI by proposing the Emission-based NRI (ENRI), which relies on the same core concepts as the NRI, but uses GHG emissions instead of congestion as indicators of link criticality. Both measures will be explained in detail in sections 2 and 4. The results from both indicators for Montreal's road network are discussed in detail in section 5.

2. EARLIER RESEARCH AND CURRENT STUDY

2.1 Link criticality analysis overview

Increasing research on network link criticality is a recent phenomenon spurred by excessive congestion and aging infrastructure in the western world (Taylor and D'Este, 2007, special issue edited by Sumalee and Karauchi, 2006, text books edited by Bell and Cassir, 2000, Iida and Bell, 2003 and Murray and Grubestic, 2007). The measures developed in earlier literature to study network criticality can be broadly classified as: (a) link level measures and (b) network level measures.

2.1.1 Link level measures

With ready access to urban region traffic volume data, Average Annual Daily Traffic (AADT) and the volume to capacity (V/C) ratio are used routinely in the assessment of link importance. AADT allows links to be sorted according to traffic volumes, placing emphasis on the links with the highest volumes. However, AADT does not take into account the capacity of links to accommodate traffic demand. Thus, a natural improvement of this measure is the V/C ratio, which is a reliable indicator of local congestion. Once again, it seems intuitively correct to say that the most congested links in a network are the most critical. However, these measures treat links as isolated components and rank them without taking into account the effects of link closures on their surroundings (Scott et al., 2006). These measures are likely to yield erroneous results, especially on networks with clear isolating links. For example, bridges or mountain passes serve as connectors between different parts of the road network and are likely to be more critical than similar links with the same AADT and V/C ratio. The link specific approach ignores the fact that failure of these isolating links is more critical than failure of similar non-isolating links. Despite these shortcomings, it is important to recognize that these measures are very easy to compute and provide useful information for most urban networks.

2.1.2 Network level measures

Network level measures that consider the impact of a link on the entire network are likely to provide more complete estimates of link importance. By considering the interactions across all the links it is possible to observe the impact of isolating links in a network. The computation of network level measures requires substantially higher computing power than is the case for link level measures. It has been conclusively shown that considering link connectivity yields results that emphasize the importance of links that might not have the highest volumes or even the highest V/C ratio (Scott et al., 2006).

In 2006, Scott et al. proposed a measure called the Network Robustness Index (NRI), which measures system-wide congestion effects. The NRI is calculated by comparing selected scenarios to a base case. In the base case, all the links in the network under consideration are open and fully functional, whereas in each scenario, a single link is completely disabled. Once the performance of the network has been assessed for each individual link closure, the difference from the base case is computed for each scenario, which can then be ranked from the smallest to largest deviation from the base case. The links that cause the largest deviation are deemed most critical in terms of traffic flow disruption and congestion effects. Adapting the authors' notation, for $i=1\dots n$ links per scenario and j scenarios, we can formulate the following self-explanatory measures:

$$\begin{aligned}
 Product_i &= Link\ travel\ time_i \times Link\ volume_i \\
 Sum_j &= \sum_{i=1}^n Product_i \\
 NRI_j &= Sum_j - Sum_{base\ case} \\
 Percentage\ NRI_j &= \frac{Sum_j - Sum_{base\ case}}{Sum_{base\ case}} * 100
 \end{aligned}$$

The scenario with the highest value of NRI_j and percentage NRI_j will be deemed the most critical.

The NRI is a more reliable indicator of link criticality relative to AADT and the V/C ratio measures because it considers congestion effects everywhere in the network. Furthermore, in the process of NRI computation we can examine how the product of link flow and link travel time vary across scenarios, allowing us to understand the most critical links across various scenarios. Since 2006, the authors have extended the NRI in order to allow for large-scale partial or complete disruptions such as partial closures of one or several links (Sullivan et al., 2010). The approach remains the same, with the base case results being subtracted from each scenario, and the scenarios being ranked in order of disruptiveness.

For small networks, link criticality can be evaluated by considering all permutations of link closures in the network. Unfortunately, this is not feasible for large urban networks. Hence, it is important to judiciously identify plausible scenarios and assess the impacts of these scenarios on link criticality. For example, transportation planners can evaluate the impact of road closures (for maintenance or cultural events) on the network a priori to plan for the impact of these closures on the network. From a practical perspective, this is a minor shortcoming, since planners typically know their networks well, and are able to develop a finite set of scenarios to be compared. The ability of the NRI to assess system-wide congestion effects combined with its high flexibility and computational ease make it a tool of choice for link criticality analysis.

2.2 Recent Progress

A number of recent research studies have examined link criticality. Nagurney and her colleagues (Qiang and Nagurney, 2008; Nagurney and Qiang, 2009; Nagurney et al., 2010) have developed metrics for measuring network robustness and efficiency, and extended those methods to incorporate environmental assessment in their analysis. The authors incorporated emissions via link level emission functions developed through macroscopic

relationships. A base network emission estimate was compared with emissions under various scenarios (similar to the NRI approach). The analysis was conducted for user equilibrium based assignment and system optimal based assignment.

Jenelius and his colleagues have also studied several aspects of link criticality, including modeling large-scale disruptions involving either total or partial closure of several adjacent links (Jenelius and Mattsson, 2012), rerouting in the network (Jenelius, 2010), and spatial disparities of vulnerability (Jenelius, 2009). Jenelius and Mattsson (2012) built on their earlier methods (Jenelius et al., 2006) to investigate large-scale disruptions to the Swedish road network using Geographic Information System (GIS) raster techniques. Jenelius (2010) examined how disrupting a link in the network resulted in other links emerging as potential re-routing alternatives. The amount of traffic rerouted through an individual link when other links failed was used as a measure of criticality. This approach focused on the capacity of the network to absorb disruptive events.

Several newer modeling approaches have also been suggested. For instance, methods considering socio-demographics and land use attributes in examining network vulnerability to disruptions have been developed (see for example Jenelius, 2009, Erath et al., 2009, Taylor, 2008 and Taylor and D'Este, 2007). Taylor and D'Este developed a large-scale model of the Australian road network and measured the changes in accessibility to markets, services and facilities attributed to network disruptions. Jenelius (2009) developed regression models that considered user travel time and exposure, population density, link length, road density, the beta index (a measure of link redundancy), link importance and regional traffic flows in studying network vulnerability. More recently, Erath et al. (2009) focused on enhancing behavioral realism by incorporating measures such as mode choice shift, destination shift, route shift or trip deletion.

2.3 Current study in context

As is evident, significant progress has been made in examining link criticality and network vulnerability in recent years. The findings from these research efforts have allowed us to better examine the impact of unexpected disruptions to the transportation network. However, earlier research still has a number of limitations. The research on link criticality in general has focused exclusively either on theoretical networks or regional networks (such as national or provincial networks with no congestion). The challenge of evaluating link criticality measures on large-scale urban transportation networks has not been considered. The first contribution of our study is to evaluate the NRI based link criticality using a detailed Montreal transportation network. Specifically, we study network link criticality by considering Montreal's unique island based network structure along with a recently compiled origin destination matrix of the region. Further, the NRI measure is computed using stochastic user equilibrium based traffic assignment (as opposed to the simple user equilibrium approach) to generate more accurate path choices in the traffic assignment process. The second contribution of our research is to propose an Emission-based NRI (ENRI) measure of link criticality, which incorporates environmental outcomes defined as vehicle emissions. Earlier research attempts employed simplified link level emission computations for test networks. In our analysis, we employ a refined emission estimation methodology that incorporates link level speed distributions obtained from stochastic user equilibrium, vehicle type distributions, and weather conditions. The

findings of this new tool in the context of Montreal's road network – a large urban region – are compared to the results from the NRI.

The link criticality analysis is conducted on a host of realistic transportation scenarios (as opposed to theoretical constructs in earlier research) affecting transportation demand in Montreal's network, and identifies critical links in the region. The transportation criticality scenarios analysis can be categorized as follows: (1) Capacity reduction on Montreal's main bridges, (2) Road closures based on current on-going or scheduled repair work and (3) Area-wide shut downs for Montreal urban festivals.

3. MONTREAL ROAD NETWORK

According to Statistics Canada, as of 2012, the island of Montreal spanned 499 square kilometres whereas the Montreal economic region spanned 1545 square kilometres. There are over 7.4 million cars registered in Quebec (Statistics Canada, 2013). In 2008, 76% of commuters in metropolitan Montreal used their car, 19% public transport, and 13% active transportation; with 5% using "other motorized" means of transportation (Board of trade of metropolitan Montreal, 2010). The road network used for this study spans the Montreal economic region. The Montreal economic region includes amongst others the cities of Laval (to the north) and Longueuil (to the south). There are 16 bridges linking the island of Montreal to the neighboring shores (Google Maps, 2013). The study area has a population of 3.4 million, of which 1.5 million live off the main island. Amongst those that live off the main island, a significant amount of morning-and-evening commutes are to be expected. Given the nature of the study region, bridges provide connectivity to and from the Montreal Island to the shores. In fact, bridges are the largest bottlenecks on the Montreal network with large traffic volumes (mostly from north and south shores). Moreover, there are very few re-routing options around the main bridges. Hence, a major focus of our scenarios analysis was based on these bridges, in order to determine whether the methodologies we use identify these known critical links. If they do, then this is a promising sign that these approaches are applicable to urban areas, including urban areas with isolating links.

The Montreal transportation network used for this study was created in VISUM and has been rigorously validated (see Sider et al., 2013; Sider et al., 2014 and Sider et al., 2015 for more details). The network represents a high degree of detail, with all the roads in the area included, and divided into 5 categories ranging from expressways to local roads. The network shown in Figure 1 contains a total of 127,217 road links, 90,467 nodes, and 1552 Traffic Analysis Zones (TAZs). Detailed characteristics of the road network such as road type, length, speed limit, capacity, and number of lanes are included in the model.

The vehicular demand on the network was generated using the 2008 origin destination survey data provided by the Agence Métropolitaine de Transport (AMT, 2010). The AMT survey is conducted every 5 years and constitutes the main source of information about travel patterns on and around the island of Montreal. The survey data used in this analysis is based on the 2008 survey data that was published in 2010, which included 66,100 households representing 4% of the population (156,700 individuals). The random sample of participants was validated against census data including variables such as age, gender, employment status, home and work location. The interviews were conducted over the phone in autumn, when urban travel habits are stable (Sider et al., 2013). The survey

included individual and household socio demographic data as well as information about individual trips: origin, destination, purpose, mode of transportation. Each trip was associated with an expansion factor in order to allow the sample to be scaled up to represent the entire population. A total of 319,915 driving trips were extracted from the OD survey and segmented into 24 1-hr OD matrices based on departure times (Sider et al., 2013). For this study, only the 7-8 am morning peak-hour matrix was considered to allow for manageable run times for a large number of scenarios.

Traffic assignment for the OD matrix was obtained using stochastic user equilibrium (SUE) in VISUM (PTV Vision, 2011). The use of SUE allows for more realistic simulation of routing decisions when compared to a deterministic user equilibrium (DUE) approach. In SUE assignment, the number of allowable paths for the network affects the size of the path array considered for each Origin Destination pair. The optimal number of paths for the assignment process was investigated in order to obtain a high degree of accuracy while maintaining acceptable run times. Several test scenarios were run, with the total number of paths ranging from 150 thousand to 850 thousand paths. The assignment results were analyzed to determine if the size limit affected the path options across OD pairs using a Matlab script. The analysis yielded that the OD path flows did not alter beyond 650 thousand paths. All subsequent analyses were conducted using the same number of paths as the limit.

4. ENVIRONMENTAL ANALYSIS

4.1 Emission Factor Generation

The emission factors (EFs), used in the analysis, were generated using Motor Vehicle Emission Simulator (MOVES). The default settings of MOVES were replaced with Montreal-specific data for the vehicle fleet, fuel composition, and ambient conditions. The EFs vary by vehicle type (passenger car and passenger truck), vehicle age (30 years were considered), fuel (gasoline), average speed (17 speed bins ranging from 2.5 mph to >75 mph), and facility type (interrupted, uninterrupted)¹. EFs of greenhouse gases (GHGs) in CO₂ equivalent, Carbon Monoxide, and Nitrogen Oxides (NO_x) were generated as a function of vehicle speeds and weather. This resulted in an initial multi-dimensional look-up table containing 5,400 EFs. For the purposes of this study, only CO₂ and NO_x were considered, and specific EFs for vehicle ages and types were aggregated into season-pollutant specific EFs. These EFs were then further aggregated by weighing the passenger car and passenger truck EFs based on Montreal's vehicle fleet data obtained from the Société de l'Assurance Automobile du Québec (SAAQ). The final EF dataset was thus based on vehicle speed (17 speed bins), season (3 seasons), and pollutant (CO₂ and NO_x). This resulted in a total number of EFs of $17 \times 3 \times 2 = 102$. Thus our methodology accounts for the variability in the vehicle fleet on the network.

4.2 Emissions estimation

¹ The two types of roadways yield very different driver behaviours, with interrupted roadways experiencing stop-and-go traffic, whereas uninterrupted roadways are meant to be closer to free-flow conditions (Sider et al., 2013).

Going beyond AADT, V/C, and NRI, one of the goals of this study is to introduce the use of traffic emissions as indicators of link criticality. The origin-destination path flows obtained from convergence traffic assignment are processed to obtain link flows, link travel times and link travel speeds. Employing these outputs, and the multi-dimensional EF table created, a routine to estimate link level emissions for the network is created. Emissions were calculated by multiplying the product of link volume and link length by the appropriate EF, based on the link speed. The link-level emissions of CO₂ and NO_x were computed for Summer, Fall, and Winter conditions. In a similar approach to the NRI, total emissions for each pollutant and season were added up, and the deviation from the base case for each season-pollutant was assessed. The average across all seasons was taken to measure the overall variation from the base case. A percentage emissions change from the base was also computed similar to the percentage NRI. The emission measures were employed to rank the scenarios, similar to the NRI measures. To reiterate, the ENRI uses the same approach as the NRI, but instead of measuring the deviation in congestion from the base case, it measures the deviation in system level emissions.

The ENRI allows us to identify links critical from the perspective of emissions. Specifically, it is not necessary that links that cause the highest impact on travel time (as identified by NRI) also might lead to highest impact on emissions (as is shown in scenario results from Section 5). The ENRI provides a quantitative impact of emissions increase due to a disruption on a particular link in the network. The measure is very useful for evaluating the impact of road closures for events and construction. Computing the ENRI up front along with the NRI will allow transportation modellers and planners improved identification of critical links in the network. To be sure, the ENRI would be employed along with the NRI metric, and not as a stand-alone replacement; unless system level emissions are the only outcome of interest.

5. SCENARIO RESULTS

5.1 Scenario selection

The criticality analysis requires us to remove specific links or link clusters and run the assignment modules for travel volumes and emissions. Hence, for a large urban network such as Montreal, we need to identify a set of useful scenarios to compute the NRI and the ENRI. Towards this end, the transportation criticality analysis was undertaken for three categories of scenarios as follows: (1) Capacity reduction on Montreal's main bridges, (2) Road closures based on current on-going or scheduled repair work and (3) Area wide shut downs for Montreal urban festivals. For the bridges Champlain, Jacques-Cartier, Victoria, Charles de Gaulle, and Jacques-Bizard identified in Figure 1, a 25% and 50% reduction in capacity was considered thus accounting for 10 scenarios. Repair work under progress for Parc Avenue (length of disruption: approximately 1.4 km) and planned works on the Henri-Bourassa-Pie IX interchange were also considered, with 25% and 50% link capacity reductions on both sites, as well as the full closure of one side of Parc Avenue thus accounting for another 5 scenarios. Finally, the impact of the closure of the Montreal Jazz festival area held in the Quartier des spectacles in the summer was also examined. Overall, including the base case, a total of 17 scenarios were considered. For each of the scenarios, the NRI and the ENRI were calculated, and the ten most critical links in each scenario were

identified, for the period of 7-8 am on a typical weekday. The link level analysis was subsequently repeated on a unit length basis.

The results from the scenarios proposed can be examined at two levels: (a) scenario level and (b) link level. For instance, in order to model a 50% disruption on Champlain Bridge all the links belonging to Champlain Bridge saw their capacity reduced by 50%. Thus a scenario represents the disruption of a link cluster, and the scenario-level results represent the importance of the entire cluster (Tables 1 and 2). In contrast, the link level results present the individual links that are most critical across all scenarios under consideration (Tables 3 to 5). Thus the two levels of analysis provide a different perspective on link criticality.

5.2 NRI rankings

In order to compute the NRI for each scenario presented above, we followed the procedure outlined in section 2.1.2. The results are presented in Table 1. We can observe that each of the scenarios under consideration constitutes a deterioration of the base case, as measured by percentage NRI. Furthermore, scenarios featuring a 50% decrease in capacity invariably have a greater NRI than similar scenarios with a 25% decrease in capacity. It appears that capacity reductions of Jacques Cartier and Champlain Bridges during the morning peak hour have the greatest impact on the network in terms of travel time. A 50% capacity reduction of Champlain Bridge would result in nearly 1,450 vehicle-hours of additional delay for the morning peak hour. This confirms our initial hypothesis that the main volume-carrying bridges would be the most critical links in the morning peak hour. The fact this analysis identifies Jacques-Cartier and Champlain bridges so clearly is promising as to its ability to identify the most critical links urban networks, including networks containing isolating links. The impact of other bridges and road works on Henri-Bourassa-Pie IX is also significant, resulting in delays up to 394.2 vehicle-hours in the case of Victoria Bridge. Road works on Parc Avenue are considerably less significant, especially in the case of capacity reductions to both lanes.

5.3 ENRI results

For the ENRI several pollutants such as CO₂, NO_x, CO can be considered. Our initial analysis included CO₂, NO_x, HC and CO, but for the sake of brevity we present the results for two pollutants: CO₂ and NO_x. A similar approach can be employed to study virtually any pollutant associated with vehicular traffic.

The average deviation for pollutants (CO₂ and NO_x) across three seasons (Summer, Fall and Winter) from the base case for each scenario is presented in Table 2 and Figure 2. The scenario with the highest impact on emissions occurs when the capacity of Jacques Cartier Bridge is reduced by 50%. This scenario features a 0.956 % increase in CO₂ emissions, and a 0.472 % increase in NO_x emissions. The second most critical scenario is a 50 % reduction in the capacity of Champlain Bridge, which yields a 0.912 % increase in CO₂ emissions, and a 0.380 % increase in NO_x emissions. For both pollutants, some scenarios present negligible change from the base case, with variations in emissions on the order of 1/1000th of a percent. There are 3 such scenarios in the CO₂ results, and 4 in the NO_x results. The NRI only presented one such scenario. We notice the presence of two negative values on the order of 1/100th of a percent, one in the CO₂ results, and one in the NO_x results. This would suggest that those scenarios actually lead to a decrease in

emissions from the base case, and it could thus be considered that the network performance improved, from a GHG emissions perspective. It is difficult to determine whether these negative changes in emissions are due to an actual improvement in the network performance or whether this is the result of emissions decreasing slightly as the average speed on some links decreases with congestion. In other words, there are two plausible explanations for these negative changes: first, Braess' paradox, which states that increasing the capacity of a network does not necessarily improve its performance; conversely, decreasing capacity does not necessarily lead to a deterioration of network performance. However, it is important to note that the NRI identified no such Braess scenarios. Second, there is a potential decrease in emissions as the reduction in speed due to increased congestion moves the vehicle speeds toward optimal emissions in the U-shaped emission curve. As was demonstrated by Nagurney (2000), the generation of emissions in congested urban networks is sometimes counter-intuitive. There is a need for further research to determine which of these explanations is valid here. Overall, the agreement in the rankings between the CO₂ results and the NO_x results is very high; although the magnitude of the percent differences with the base case are different. However, it should be noted that as the percent differences decrease, so does the agreement between the CO₂ and NO_x indicators.

It should also be mentioned that the recorded changes have rather small magnitudes (<1%); these changes were estimated for the total regional emissions. This was expected since all the scenarios under consideration implemented very minor changes with respect to the base case, given the size of the network. The scenarios typically featured less than 100 modified links (conservative upper bound), out of 127,217. Hence larger variations in emissions than the ones recorded were extremely unlikely to occur.

5.4 Comparison between the NRI and the ENRI²

From the rankings presented in Table 2 and the visual illustration provided in Figure 2, it can be seen that there is a high degree of agreement between the NRI and the ENRI when it comes to the most critical scenarios. Both measures identified 50% capacity reductions of Jacques Cartier and Champlain bridges as the most critical (with a slight difference in the ranking). Both methods also identified the 6 scenarios linking bridges from the South Shore to the Island (Cartier 50 and 25, Champlain 50 and 25, Victoria 50 and 25) as being part of the 7 (emissions) or 8 (NRI) most critical scenarios. Clearly, the same crucial pieces of infrastructure were identified by both tools, suggesting either could be used by city planners. However, as the scenarios become less disruptive to the network, we observe that the correlation between the two measures subsides gradually. The result is an indication that for smaller changes to the network, the results obtained by considering traffic volumes and emissions do not necessarily match; even the correlation between the CO₂ and NO_x indicators dwindles. For example, for the Montreal Jazz Festival related closure it is apparent that the percentage increase in CO₂ and NO_x indicators are larger than the corresponding percentage change for NRI. Hence, it might be beneficial to evaluate both the NRI and the ENRI for such scenarios. An examination of link level traffic volume and emission changes will shed more light on the exact trends.

² We have compared the scenarios based on volume and V/C results. The results were not presented as the results from the exercise were less informative on the criticality of links in the Montreal urban network. Interested readers can obtain the results from the authors.

6. LINK LEVEL RESULTS

In order to examine the most important links in each scenario, two approaches were used. The first simply ranked the links in descending order according to the product of link volume and link travel time (NRI) or link emissions (CO₂ and NO_x), with the highest values belonging to the most critical links. However, it was observed that this approach tended to favour longer links (as one would expect). To address this, a second link ranking was generated in which the metrics mentioned above were divided by link length. Once again, links were then ranked in descending order, with the highest values belonging to the most critical links. Average rankings were computed for the ten most critical links for each procedure. The top 9 link rankings are reported in Table 4. The count value indicates the number of scenarios where these individual links appear. Most of the top links reported were consistently ranked as the top ten links in all scenarios.

6.1 NRI rankings

Table 4 presents the original link-level NRI results, and the same results adjusted for length. As can be seen, the original results tend to favour long links, as is evident from the average link length of 1.68 km. On the other hand, the length normalized results tend to favour shorter links, with an average link length of 0.11 km. It is important to note that the unit length based analysis yields completely different link rankings. The top links for both rankings nearly appeared in the top 10 of each scenario, as indicated by the count values close to 17 (total number of scenarios).

6.2 ENRI results

Table 4 presents the link level results for the ENRI. As can be seen, there is significant overlap between the CO₂ results and the NO_x results. In the original (not length-adjusted) results, 7 out of 9 of the top links are identical for both pollutants, although not in the same order. In the length-adjusted results, 5 out of 9 of the top links are identical for both pollutants, with the top 4 being in the same order. These results indicate a high agreement between CO₂ and NO_x as indicators of link criticality. It is important to note that although emission estimates varied from one season to another, the criticality ranking of the links for each type of pollutant showed little variation across seasons. The length effect present in the NRI results is also present here (there are several links in common between the ENRI and the NRI in both the original and length-adjusted results).

Table 5 presents the average changes in link emissions over the 16 scenarios and the base case, for the top links identified by the ENRI presented in table 4. These changes in emissions vary substantially from scenario to scenario. For instance, link 90118 presents an average increase of 11.61% in CO₂ from the base case, and 8.53% in NO_x. However, the average deviation of CO₂ emissions from the base case over all seasons varies from 69.58% for the “Cartier 50” scenario, to -0.05% for the “Parc one lane” scenario. In the case of NO_x emissions, link 90118 shows variation from 57.17% for “Cartier 50” to -3.15% for “Champlain 25”. This suggests that considering scenario level percent deviations could yield much more significant insights for city planners. It appears that the average deviation from the base case is larger for the top scenarios (Cartier 50, Champlain 50). This is likely due to the fact that many top links are located near the disruptions modelled in these scenarios, whereas top links are usually not located near the disruptions modelled in the

less critical scenarios. However, preliminary results investigating these effects have failed to show that the links exhibiting the highest deviations from the base case within each scenario are located near the source of the disruption being modelled. Further research is needed to understand these effects. When the percentage deviation from the base case for an individual link is small, the percent change of CO₂ and NO_x emissions are usually identical. This can be explained by the fact that in such cases, the average speed on the link remains constant, and a change in traffic volume will affect CO₂ and NO_x emissions by the same factor. Similarly, the percentage deviations between the scenarios and the base case should be the same between the length-based and original results, since they differ by a factor of length.

6.3 Comparison of NRI and ENRI

Of particular interest to this research effort are the similarities and differences between the NRI and the ENRI results. In the original results, there are 5 links out of 9 in common between the NRI and the ENRI, with the NRI and CO₂ rankings presenting 7 out of 9 links in common. In the length-adjusted results, the two procedures have 4 out of 8 links in common, and the NRI and CO₂ have 8 out of 9 links in common. Since congestion effects and GHG emissions are related, some overlap was expected.

Overall, the results obtained from the NRI and the ENRI computation highlight the importance of roads located on or near bridges that conduct traffic onto the island of Montreal. Since the analysis period was from 7 to 8 am, this corresponds to the peak flow of commuters onto the island.

However, we find differences between the original results and the length-adjusted ones. The NRI has one link in common between both rankings: link 68846. Unsurprisingly, the link in question is located immediately before an important bridge that carries traffic from Laval onto the island (Médéric-Martin bridge; the cars cannot exit the link before the bridge). The ENRI results have no links in common between the original and length-adjusted results. In the original results, we notice few clustering effects and a high influence of bridges that carry flow from the South Shore onto the island (Victoria Bridge, Champlain Bridge), as well as from the North Shore (Charles de Gaulle Bridge) and Laval (Autoroute des Laurentides).

On the other hand, the length-adjusted results yield more emphasis on small links near downtown, and demonstrate clear clustering effects, with short adjacent links being present in the final link rankings. This suggests that the length-based results might constitute a more fine-grained analysis than the original results which had a tendency to favour longer links. Since link length is greatly dependent on the network model (some critical areas might be parsed into several short links and not be picked up in non-length-adjusted analysis), a procedure that favours long links might be misleading in terms of criticality analysis. Furthermore, links in the downtown core tend to be shorter when compared to links further from the high-density areas, which would put them at a disadvantage in our initial analysis. To be sure, since downtown and denser areas require a different type of driving than large highways and bridges, the length-adjusted results are likely to be more sensitive to driver behaviour. At the same time, as can be seen in Table 4, both sets of results identify bridges quite clearly as some of the most critical links in Montreal's road network.

Finally, it is interesting to note that individual links on or near Jacques Cartier, Champlain and Victoria Bridges appear in the top link rankings, while the scenarios featuring disruptions of these bridges are amongst the most disruptive, from a scenario-level approach. In other words, both the scenario-level and the link level results place a high emphasis on these three bridges, outlining them as crucial parts of Montreal's road network infrastructure. This led us to include Figure 3, which presents a visual illustration of percent changes in traffic volumes between the three scenarios featuring 50% reductions on the three bridges mentioned earlier, and the base case. This figure shows a clear interdependence of the three bridges, with traffic being re-routed through the other two when each one of them is subject to a capacity reduction. More specifically, when Jacques Cartier or Champlain have their capacity reduced, the other one suffers a large increase in traffic volume, while Victoria has a smaller increase. When Victoria has its capacity reduced, both Champlain and Jacques Cartier see similar increases in traffic volumes.

6.4 Interpretation and policy implications of the Emissions Index

It has been shown that the ENRI correlates well with the NRI for major disruptions and that this correlation fades for minor disruptions. This suggests that the ENRI proposed in this paper could be a useful tool for practitioners when analyzing link criticality. Using the ENRI in conjunction with the NRI will enhance critical link identification. It is important to stress that we are not advocating the use of a single emission indicator based solely on CO₂ and NO_x. Rather, we are developing a framework that can be used to analyze any pollutant-season individually, and which should be used in addition to the NRI. The CO₂ and NO_x results presented earlier are independent illustrations of how to apply the methodology in the context of Montreal. Our initial results included results for hydrocarbons (HC) and carbon monoxide (CO) but were excluded for the sake of clarity.

It should be noted that this approach implies a large degree of flexibility. Whether planners are concerned with NO_x emissions in the Summer, VOCs in the Fall, or CO throughout the year, the traffic assignment need only be computed once (unless a different traffic assignment is available for each season), with the EFs being the only variable changing between the different analyses. To summarize, we are illustrating a framework to incorporate emissions in the link criticality analysis process. Unlike the NRI which provides a single clear picture for the network, our framework will provide a different picture for each pollutant-season. This is unavoidable due to the heterogeneity in the effects of different pollutants. CO₂ is harmful due to its global warming potential, whereas NO_x are harmful on a more local scale, notably as ozone precursors.

As we saw earlier, some of the links identified in the CO₂ analysis also appeared in the NO_x analysis. This suggests that it might be possible to examine the results from several different pollutant-seasons and identify the common links between these analyses as the most crucial links in the network. Once again, as the scale of disruptions reduces, so does the correlation between CO₂ and NO_x. Investigating these aspects could be the topic of future studies. In summary, when studying link criticality, we recommend the use of a multi-faceted framework resting on the ENRI used in conjunction with the NRI and other indicators of link criticality. To be clear, if planners are solely concerned with emissions, then the ENRI can be used exclusively; but for most link criticality analyses, the ENRI is meant to be used in conjunction with the NRI. This would allow policy-makers to make

better informed decisions which should in turn lead to the design and implementation of more effective policies.

7. CONCLUSIONS

The traditional evaluation of individual roadway facilities was based on measures such as Average Annual Daily Traffic (AADT) and the Volume-to-Capacity (V/C) ratio. These measures ignore the interconnected nature of the transportation network while also falling short of considering the environmental implications of link criticality. In fact, transportation research has rarely examined infrastructure criticality in the context of environmental pollution. The growing literature on quantitative model development for travel demand analysis and emissions modeling combined with improved computational capabilities allow us to develop more holistic frameworks in order to assess link criticality. The current research has built on these recent advances to develop an emissions-based indicator of link criticality – named Emissions-based Network Robustness Index (ENRI), and has compared it to the Network Robustness Index (NRI).

The traffic and emissions indicators were generated for a host of plausible scenarios for the Montreal region. In total seventeen scenarios, including the base scenario were identified for generating NRI and emissions index for CO₂ and NO_x. The results from the scenario analysis highlighted the importance of major bridges connecting the Montreal Island with the North and South Shores. The scenario level comparison highlighted an interesting relationship between the traffic and emissions indicators. Specifically, we found that for major scenarios (such as capacity reduction on bridges) the results for the NRI and the ENRI were very highly correlated while for minor scenarios (such as capacity reduction on Parc Avenue) the results indicated the absence of correlation between the NRI and the ENRI. Even the correlation between the CO₂ and NO_x indicators subsided as the percent change from the base case decreased. We can conclude that for major scenarios it might be possible to just run either the NRI or the ENRI while for minor scenarios it might be beneficial to run both analyses to identify the affected links.

The relationship between the measures was further investigated using link level results. Overall, these results emphasized the importance of major bridges. However, an interesting distinction was drawn between the original results and the length-normalized results. The original results favoured long links on the major bridges, while the length-normalized results favoured shorter links, some of which were located near downtown.

The notion of link criticality cannot be understood in a uni-dimensional framework. The results obtained from link volume, V/C, NRI and emissions, are simply too heterogeneous to conclude that link *i* is the “most critical link”. Link criticality can only be a valid concept when the determining criterion of importance is well-defined. This is especially true in the context of road emissions due to the diverse effects of various pollutants. In this context, we recommend using integrated frameworks providing indices of link criticality from different perspectives. For instance, in our paper we examined NRI, ENRI (for CO₂ and NO_x) results – AADT and V/C results were also computed but were not presented here for the sake of brevity. These are by no means the only criteria worth examining, but constitute a good example of the kind of approach we are advocating.

Further research could examine ways of integrating these various indicators into an overall index that would be easy to use for transportation practitioners. A starting point

could be to develop further additions to the NRI, which rely on the same basic methodology while incorporating new perspectives, as we did here by using road emissions. Such an approach would be practically feasible while constituting a substantial improvement upon the state-of-the-art analysis tools currently in use. Further research could also investigate clustering effects focussing on aggregate impact of link clusters (as opposed to individual links). Future efforts would also benefit from more detailed link level results, since crude rankings do not capture the magnitude of the gaps. The choice of scenarios is also very region specific and will depend on the urban region based preferences. Incorporating mode and departure time shift into future research efforts would certainly be a worthwhile effort, even though it would be quite challenging given the scope of the network under consideration. Finally, the ultimate goal of this type of research would be to incorporate travel cost, environmental outcomes and socio-economic consequences of link closures into a united, comprehensive, and holistic framework.

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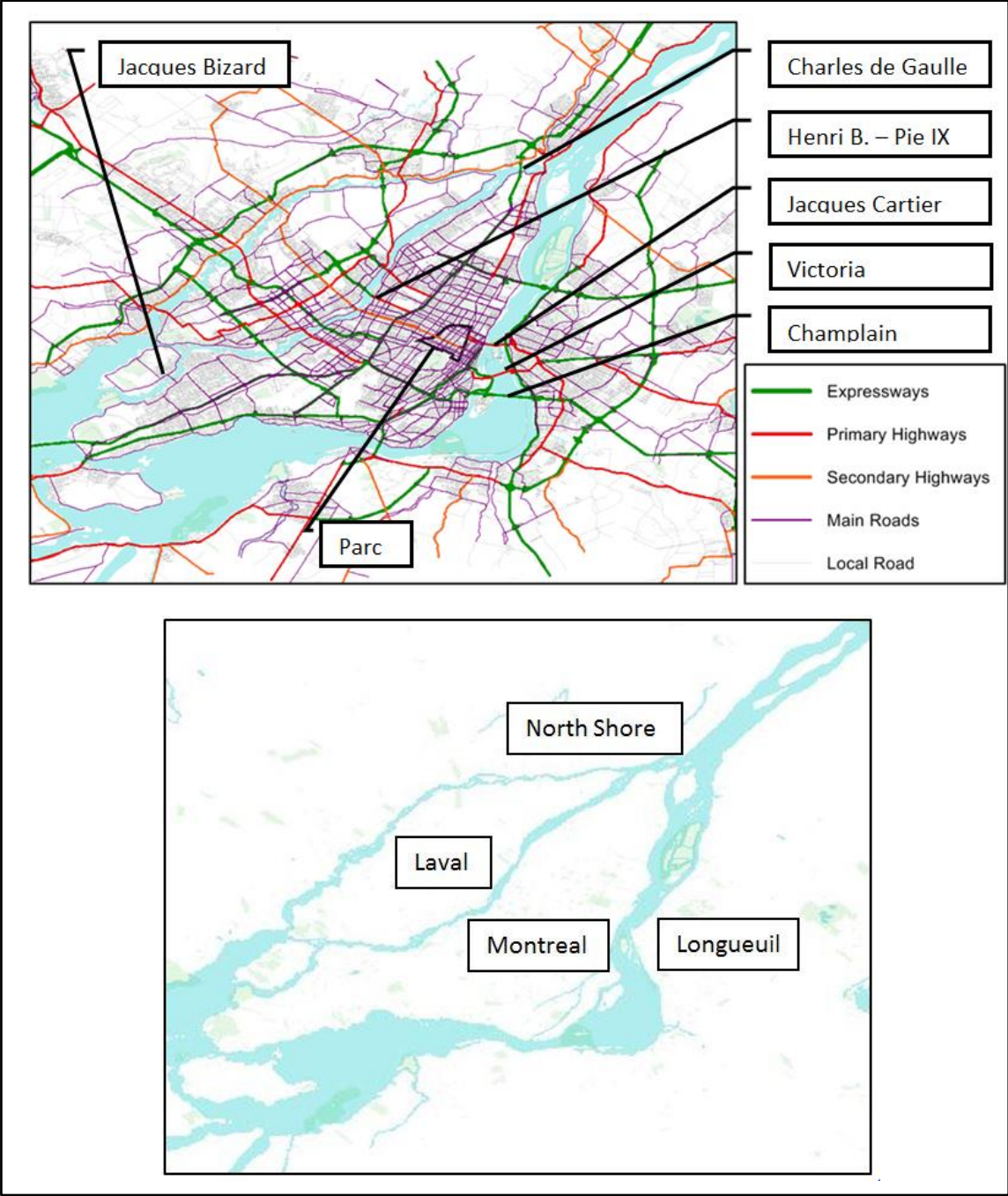


Figure 1: The Montreal urban area road network

Table 1: Scenario level NRI results

Scenario	$\Sigma_{network}(\text{Link flow} \times \text{Link travel time})$ (Veh.hr)	NRI (Veh.hr)	% change in NRI (compared to base)	Rank
Champlain 50	99041.8	1445.5	1.481	1
Cartier 50	98767.3	1170.9	1.200	2
Champlain 25	98178.1	581.7	0.596	3
Cartier 25	97999.3	402.9	0.413	4
Victoria 50	97990.6	394.2	0.404	5
Henri 50	97916.9	320.6	0.328	6
Ile Bizard 50	97812.5	216.1	0.221	7
Victoria 25	97786.2	189.8	0.194	8
Jazz Fest	97719.7	123.3	0.126	9
Henri 25	97699.2	102.8	0.105	10
Felix 50	97696.6	100.2	0.103	11
Parc one lane	97655.1	58.8	0.060	12
Ile Bizard 25	97635.7	39.3	0.040	13
Parc 50	97615.4	19.0	0.019	14
Felix 25	97609.4	13.1	0.013	15
Parc 25	97597.9	1.5	0.002	16
Base case	97596.4	0.0	0.000	0

Table 2: Scenario level results¹

NRI RESULTS		ENRI RESULTS			
Scenario	Δ NRI (%) (compared to base)	Scenario	Δ CO₂ (%) (compared to base)	Scenario	Δ NO_x (%) (compared to base)
Champlain 50	1.481	Cartier 50	0.956	Cartier 50	0.472
Cartier 50	1.200	Champlain 50	0.912	Champlain 50	0.380
Champlain 25	0.596	Victoria 25	0.377	Victoria 50	0.198
Cartier 25	0.413	Victoria 50	0.363	Cartier 25	0.190
Victoria 50	0.404	Cartier 25	0.303	Victoria 25	0.180
Henri 50	0.328	Jazz Fest	0.287	Jazz Fest	0.160
Bizard 50	0.221	Champlain 25	0.261	Champlain 25	0.133
Victoria 25	0.194	Henri 50	0.197	Henri 50	0.073
Jazz Fest	0.126	Felix50	0.151	Felix50	0.039
Henri 25	0.105	Bizard 25	0.096	Henri 25	0.031
Felix 50	0.103	Bizard 50	0.075	Bizard 25	0.017
Parc one lane	0.060	Henri 25	0.031	Parc one lane	0.005
Bizard 25	0.040	Parc 50	0.001	Bizard 50	0.004
Parc 50	0.019	Base case	0.000	Base case	0.000
Felix 25	0.013	Parc 25	-0.005	Parc 25	-0.008
Parc 25	0.002	Felix 25	-0.009	Parc 50	-0.009
Base case	0.000	Parc one lane	-0.024	Felix 25	-0.023

¹ The scenarios were ranked from largest to smallest deviation from the base case; for the NRI and the emission indicators

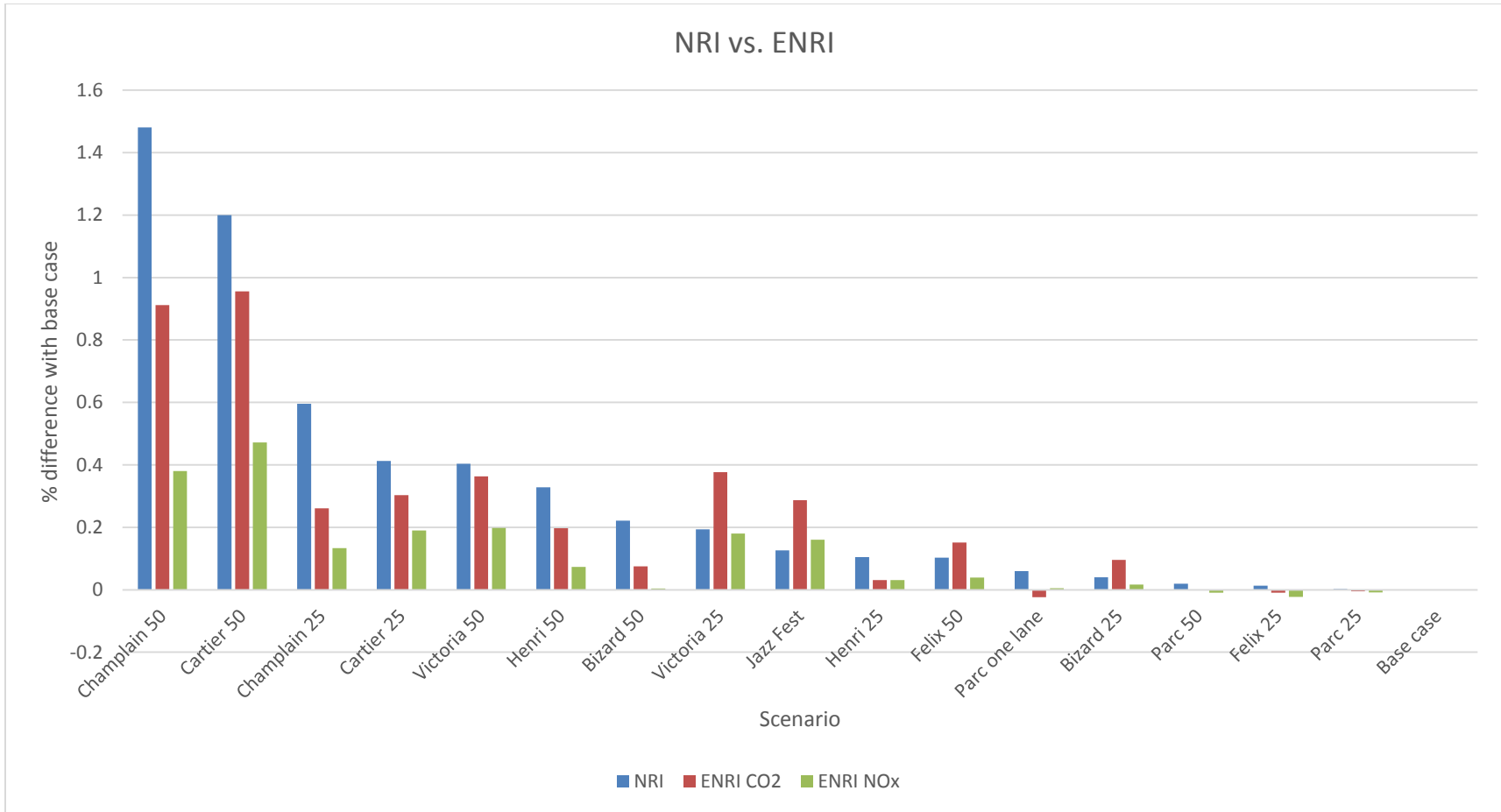


Figure 2: NRI and ENRI comparison

Table 3: Location of main links (NRI and ENRI)

Link	Location
Non-length based	
90118	Champlain bridge, going on to the island
198118	Charles de Gaulle Bridge, going on to the island
147778	Aut. Félix Leclerc, between Boulevard St Charles and Boul St Jean
125324	Aut. 20 and 132
198072	Victoria bridge, going on to the island
68846	Médéric Martin bridge (Transcanadian), going on to the island
206998	Autoroute Jean Lesage, near Decarie expressway, going towards downtown
199996	Aut. Chomedey, near Louis Bisson bridge, going on to the island
68802	Adjacent to 199996, Aut. Chomedey
26046	Ile-aux-tourtes bridge, going on to the island
67978	Aut. Laval, bringing traffic from Terrebonne to Laval
84700	Aut. 640, brings traffic from Terrebonne to Charles de Gaulle Bridge
124206	Aut. 20 and 132. Opposite direction as 125324
98444	Aut. Des Laurentides, seems to bring traffic from Blainville to Laval
Length based	
178646	Jacques Cartier bridge, going on to the island
68846	Médéric Martin bridge (Transcanadian), going on to the island
228496	Adjacent to 68846, Médéric Martin bridge
206496	Adjacent to 68846, Médéric Martin bridge
211704	Exit from Aut. Ville-Marie to downtown
225654	Adjacent to 211704, exit from Ville-Marie to downtown
225656	Adjacent to 211704, exit from Ville-Marie to downtown
211706	Adjacent to 211704, exit from Ville-Marie to downtown
199996	Aut. Chomedey, near Louis Bisson bridge, going on to the island
202308	Adjacent to 199996, Aut. Chomedey
118478	Adjacent to 199996, Aut. Chomedey
205310	Adjacent to 199996, Aut. Chomedey
89248	Aut. 40 and Aut. de la Côte de Liesse

Table 4: Link level results

NRI RESULTS				ENRI RESULTS					
Link ¹	Count ²	Average Ranking	Length (km)	CO ₂			NO _x		
				Link	Count	Average Ranking	Link	Count	Average Ranking
198072	17	1.2	1.80	90118	17	1.1	125324	17	1.4
90118	17	1.8	2.36	198072	17	2.4	90118	17	1.9
68846	17	3.1	0.36	125324	17	3.0	198118	17	2.9
198118	17	4.7	2.67	198118	17	3.6	26046	17	3.8
199996	17	5.4	0.47	26046	17	4.9	67978	17	5.1
147778	17	5.7	1.73	147778	17	6.0	147778	17	6.1
68802	17	6.7	0.74	67978	17	7.2	84700	17	7.5
206998	17	8.2	1.30	206998	17	7.9	198072	16	7.6
125324	13	9.1	3.67	68802	17	9.5	124206	17	9.5
NRI RESULTS: DIVIDED BY LENGTH				ENRI RESULTS: DIVIDED BY LENGTH					
Link	Count	Average ranking	Length (km)	CO ₂			NO _x		
				Link	Count	Average	Link	Count	Average
178646	15	1.0	0.06	178646	15	1.0	178646	15	1.0
211704	17	2.3	0.10	68846	17	1.9	68846	17	1.9
225654	17	3.3	0.08	206496	17	3.2	206496	17	3.2
225656	17	4.3	0.10	228496	17	3.6	228496	17	3.6
211706	17	5.3	0.02	89248	16	5.0	202308	17	4.9
68846	17	6.4	0.36	211704	16	7.1	199996	17	6.6
228496	17	7.4	0.05	211706	16	7.5	118478	17	6.8
206496	16	8.3	0.19	211764	16	8.1	205310	17	7.2
211764	14	8.8	0.01	225656	16	8.1	89248	15	9.0

¹ The exact link definitions are available with the authors. For the sake of brevity the information on links was summarized briefly in table 3.

² Count represents the number of scenarios (out of a total of 17) in which the link has appeared in the top rankings.

Note: gray cells identify links representing or in close proximity to bridges.

Table 5: Average percent change in emissions from the base case¹

ENRI RESULTS (non-length based)			
CO₂		NO_x	
Link	Average deviation	Link	Average deviation
90118	11.61	125324	-2.23
198072	14.65	90118	8.53
125324	-3.12	198118	-0.92
198118	-1.15	26046	-0.03
26046	-0.03	67978	0.02
147778	-0.21	147778	-0.21
67978	0.02	84700	0.42
206998	0.20	198072	4.74
68802	0.06	124206	1.64

¹ Average change over Summer, Fall, and Winter, over the 16 scenarios under consideration

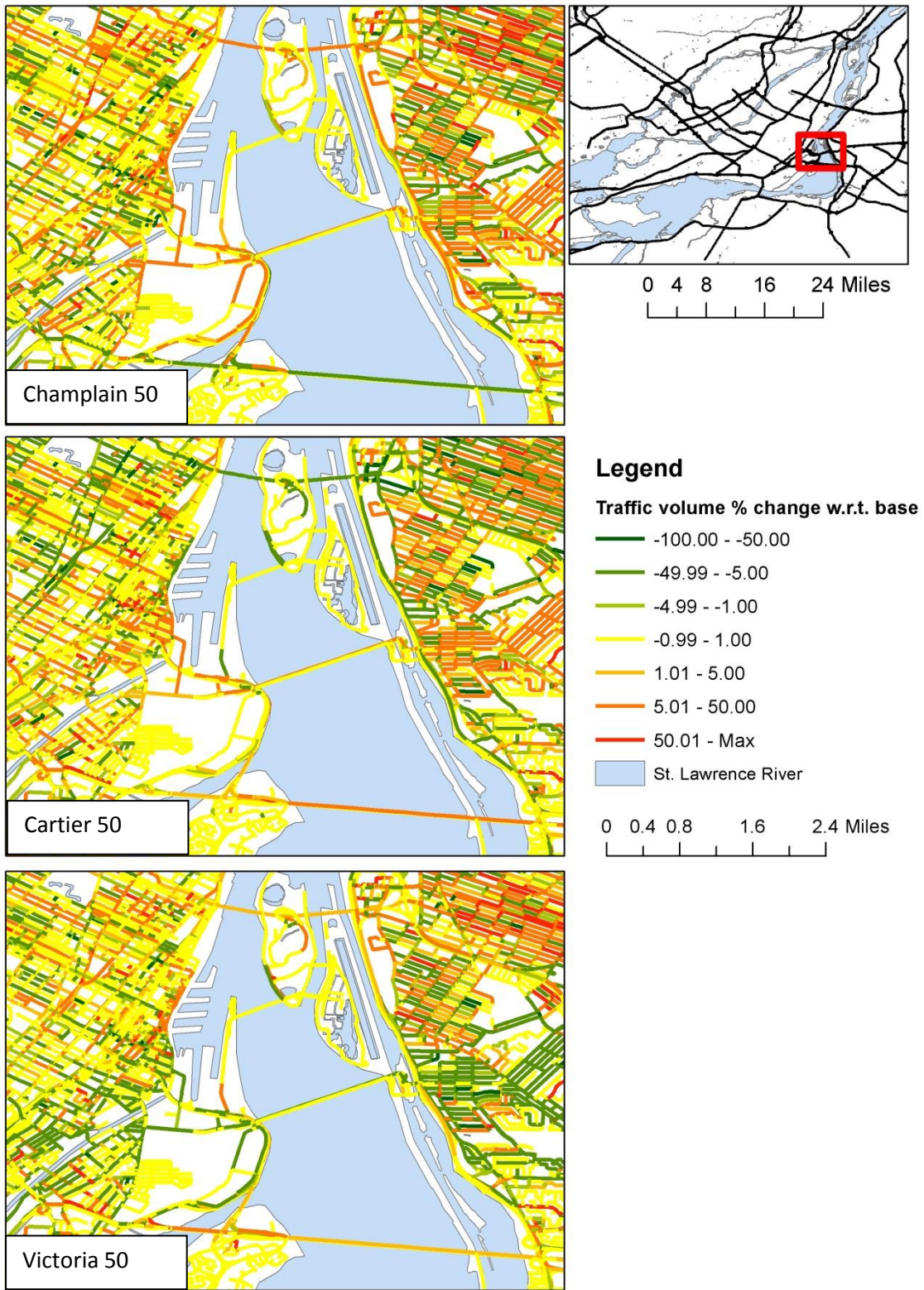


Figure 3: Percent change in traffic volume with respect to the base case on three main bridges