INCORPORATING TRANSPORT EMISSIONS IN IDENTIFYING CRITICAL LINKS IN THE TRANSPORTATION NETWORK

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Introduction

Road networks in North America are designed to provide service to millions of urban residents. Toward maintaining acceptable levels of performance (for indicators such as travel time, safety and reliability) on road networks, transportation engineers must address challenges in the form of increasing traffic demand, ageing 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 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 problem of increasing traffic demand while also affected by very 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) allocated over 3.6 billion Canadian dollars to the Fonds des Réseaux de Transport Terrestre (FORT) 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, very large amounts of money 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 transportation 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, 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 greenhouse gas (GHG) emissions and air quality, it is important to develop frameworks to study transportation infrastructure criticality from an 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 urban transportation network level is far from straight forward. But the growing literature on quantitative model development for travel demand analysis and emissions modeling in conjunction with improved computation 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 builds on these recent advances to develop a quantitative framework to examine transportation facility criticality. Specifically, we evaluate link criticality in the Montreal urban transportation network while considering traffic volumes and environmental outcomes.

Earlier Research and Current Study

Link criticality analysis overview

The field of research on network link criticality is a recent phenomenon spurred by excessive congestion and ageing 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 Grubesic, 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.

Link level measures

Due to the easy availability of traffic volumes for urban regions, 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 on networks with clear isolating links. For example, bridges or mountain passes serve as connectors between different parts of the road networks 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 on these isolating links is more critical than failure to 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.

Network level measures

Network level measures that consider the impact of a link on the entire network are likely to provide more accurate 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 the 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 scenario. 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 n links per scenario and j scenarios, we can formulate the following self-explanatory measures:

$$Product_i = Link\ travel\ time_i \times Link\ volume_i$$

$$Sum_j = \sum_{i=1}^{n} Product_i$$

$$NRI_j = Sum_j - Sum_{base\ case}$$

The scenario with the highest value of NRI_j will be deemed the most critical link (or link cluster).

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 partial capacity reduction of single links, or of link clusters (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, the 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. The ability of the NRI to assess system-wide congestion effects combined to its high flexibility and computational ease make it a tool of choice for link criticality analysis.

Recent developments

In recent times, a number of research studies have examined link criticality. For example, Taylor and his colleagues (Taylor and D'Este, 2007; Taylor, 2008) investigated network vulnerability and studied the socio-economic consequences of link closures. 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 have extended those methods to incorporate environmental impacts into their analysis. In their analysis, the authors consider link level emission functions developed through macroscopic relationships. A base network emission estimate is compared with emissions in various scenarios (similar to the NRI approach). Depending on the change in the level of emissions the environmental robustness of the network was determined. Very minor changes in the emissions indicated that the network was environmentally robust. The study considered the impact of user equilibrium based assignment and system optimal based assignment in their analysis.

More recently, the NRI method has been considered for large scale partial or complete disruptions such as partial closures of one or several links (Sullivan et al., 2010). Other authors have investigated spatial disparities of vulnerability (Jenelius, 2009) and how to model large-scale disruptions involving total or partial closure of several adjacent links (Jenelius and Mattsson, 2012) and rerouting in the network (Jenelius, 2010).

Current study in context

The research on link criticality so far has examined the NRI mostly in theoretical networks or high level networks. For instance, the extensive research of Jenelius and his colleagues (Jenelius et al., 2006; Jenelius, 2009; Jenelius and Mattson, 2012) is focused on the Swedish road network - a low density, largely uncongested network. There has been no examination of the NRI in the context of detailed urban transportation networks. Our first contribution is to evaluate the NRI based link criticality using a very fine detailed Montreal transportation network. Specifically, we study network link criticality taking into account specificities of the Montreal urban area such as the origin destination matrix and the unique island based network structure of the region. Moreover, 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 assignment process. The second contribution of our research is to incorporate environmental outcomes defined as vehicle emission based link criticality measures for a real size urban region. The 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 and weather conditions. Finally, the study is the first of its kind to compare link criticality in the context of traffic volumes and environmental outcomes for a large urban region.

Study region

Montreal's road network

According to Statistics Canada, as of 2012, the island of Montreal spanned 499 square kilometres for a population of 1.9 million individuals, whereas the Montreal economic region spanned 1545 square kilometres for a population of 3.4 million people. The Montreal economic region includes amongst others the cities of Laval and Longueuil. The road network used for this study spans the

Montreal economic region. 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 that segment of the population, a significant amount of morning-and-evening commutes is to be expected. In 2010, 82% of Canadian commuters used their car, 12% public transport, and 6% active transportation (Turcotte, 2011). Furthermore, there are over 7.4 million cars registered in Quebec (Statistics Canada, 2013). Hence, it stands to reason that bridges would be amongst the most critical components of the Montreal urban area road network.

Research methodology

The Montreal transportation network created in VISUM has been rigorously validated (see Sider et al., 2013 for more details). The network represents a high degree of detail, with all the roads in the area included, and divided in 5 categories, from expressways all the way to local roads. The network contained a total of 254,044 links, and is shown in Figure 1. The vehicular demand data on the network are generated using the 2008 origin destination survey data (Agence Métropolitaine de Transport, 2010). Traffic assignment for the OD matrix was obtained using stochastic user equilibrium in VISUM. The number of paths to be considered by the software was investigated in order to obtain a high degree of accuracy while maintaining acceptable run times. Several test scenarios were run, with 150 to 850 thousand paths. The results were analyzed using a Matlab script and it was found that the results converged at 650 thousand paths. All subsequent analyses were conducted using the same number of paths.

Subsequent to the base scenario analysis, we selected eight scenarios based on Montreal construction works, network structure with emphasis on bridges and expected closures. For capacity reduction scenarios, two levels of link capacity reduction were considered: a 25% decrease in capacity, and a 50% decrease. For each of the scenarios, the NRI of each scenario was calculated, as well as the ten most important links in each scenario, for the period of 7-8 am on a typical day.

The scenarios considered can be divided into two groups: bridges, and road works. 10 scenarios featured 25 and 50 % capacity reductions of 5 important bridges: Jacques Cartier, Champlain, Victoria, Jacques-Bizard and Charles de Gaulle. 5 of the 6 remaining scenarios featured capacity reductions of Parc Avenue (length of disruption: approximately 1.4 km) and the Henri-Bourassa-Pie IX interchange. The final scenario modelled impacts from the Montreal Jazz festival held in the Quartier des spectacles for two weeks in the summer.

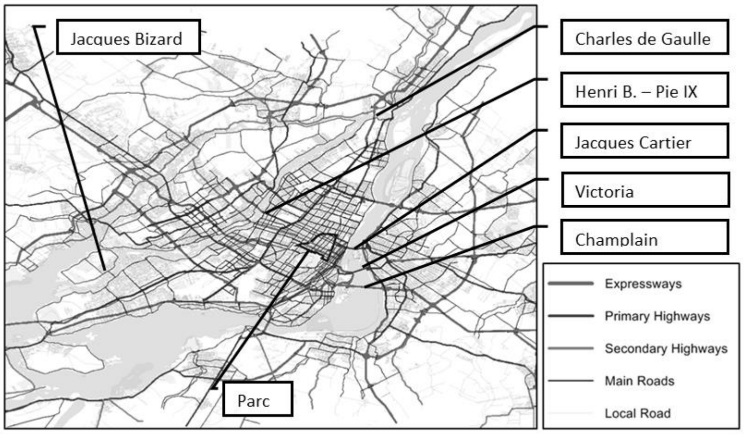

Figure 1: The Montreal urban area road network

NRI computation

In order to compute the NRI for each scenario presented above, we followed the procedure outlined previously in section 2.1.2. 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, with the highest values belonging to the most critical links. However, it was observed that this approach tended to favor longer links. To address this, a second link ranking was generated in which the product of link volume and link travel time was divided by link length. Once again, links were then ranked in descending order, with the highest values belonging to the most critical links.

Green House Gas (GHG) emissions as indicators of link criticality

Going beyond AADT, V/C, and NRI, one of the goals of this study is to introduce the use of GHG emissions as indicators of link criticality. Using the same VISUM network outputs from the NRI analysis, we used Emission Factors (EFs) generated by MOVES (Motor Vehicle Emission Simulator) for the Montreal urban area in order to generate emissions estimates at a link level (Sider et al., 2013). Emissions were calculated by multiplying the product of link volume and link length by the appropriate EF. The EF were generated as a function of vehicle speeds and weather. These computations were undertaken using MatLab. The link-level emissions of CO_2 and NO_x were computed for Summer, Fall, and Winter. In a similar approach to the NRI, total emissions for each pollutant for each season were added up, and the deviation from the base case for each season-pollutant was assessed. The average across all seasons and pollutants was taken to measure the overall variation from the base case. This allowed the scenarios to be ranked in order of disruptiveness. The same length bias that was identified for the NRI results was observed with the initial emissions-based results, which led to the computation of emissions per link on a unit length basis. The approach we just outlined made it possible to compare the NRI results to the emissions-based outputs. In order to make comparisons easier at the scenario level, the percent change from the base case was computed, both for the NRI and the emissions-based metric. The following section will present the results.

Scenario Results

Due to space limitations, we focus the discussion on scenarios results. The results for the link level analysis are available upon request from the authors.

NRI rankings

As Table 1 clearly demonstrates, each of the scenarios under consideration constitutes a deterioration of the base case, as measured by the 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 delays. A 50% capacity reduction of Champlain Bridge would result in nearly 1450 vehicle-hours of additional delay for the morning peak hour. 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.

Table 1: Scenario level results (ranked in descending order of change)

NRI RESULTS			**EMISSIONS RESULTS**	
Scenario	**NRI (Veh.hr)**	**Δ NRI (%)**	**Scenario**	**Δ emissions (%)**
Champlain 50	1445.5	1,481	Cartier 50	0,415
Cartier 50	1170.9	1,200	Champlain 50	0,237
Champlain 25	581.7	0,596	Cartier 25	0,188
Cartier 25	402.9	0,413	Victoria 50	0,171
Victoria 50	394.2	0,404	Champlain 25	0,156
Henri 50	320.6	0,328	Jazz Fest	0,083
Bizard 50	216.1	0,221	Victoria 25	0,061
Victoria 25	189.8	0,194	Felix 50	0,046
Jazz Fest	123.3	0,126	Henri 50	0,044
Henri 25	102.8	0,105	Henri 25	0,024
Felix 50	100.2	0,103	Bizard 25	0,008
Parc one lane	58.8	0,060	Parc one lane	0,006
Bizard 25	39.3	0,040	Base case	0,000
Parc 50	19.0	0,019	Parc 25	-0,001
Felix 25	13.1	0,013	Parc 50	-0,002
Parc 25	1.5	0,002	Bizard 50	-0,010
Base case	0.0	0,000	Felix 25	-0,024

Emissions-based indicator results

The average deviation of all season-pollutants from the base case for each scenario is presented in Table 1. The scenario with the highest impact on emissions is when the capacity of Jacques Cartier Bridge is reduced by 50 %. This scenario features a 0.42 % average increase in emissions. The second most critical scenario is a 50 % reduction in the capacity of Champlain Bridge, which yields a 0.24 % increase in emissions. 5 scenarios present negligible change from the base case, with increases or decreases in emissions on the order of 1/1000th of a percent.

We notice the presence of two negative values in the order of 1/100th of a percent. 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. However, this is likely due to the fact that when the capacity of a link is decreased, the overall emissions on the link also decrease. In most scenarios, the increase of emissions on nearby links more than compensates the slight decrease mentioned above, leading to an overall deterioration of network performance. In the cases when the final change in emissions is slightly negative, one can suppose that the increase on nearby links is not enough to offset the decrease in emissions on the links that had their capacity modified.

It should be mentioned that the recorded changes all have rather small magnitudes. 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 254,044. Hence large variations in emissions were extremely unlikely to occur.

Comparison between NRI and Emissions indicator

From the rankings presented in Table 1, it can be seen that there is a high degree of agreement when it comes to the most critical scenarios - the top 5 critical scenarios are the same across the two measures (with minor differences in exact rank). Disruptions on Jacques Cartier and Champlain bridge have the largest impacts overall. For scenarios that are less disruptive on the network, we observe that the correlation between the two measures subsides. The result is an indication that for smaller changes to the network traffic volumes and emissions need not exhibit perfect correlation. Hence, it might be beneficial to evaluate both NRI and Emissions indicator for such scenarios. For more disruptive scenarios, it appears that the trends between NRI and Emissions indicator are more likely to be similar. An examination of link level traffic volume and emission changes will throw more light on the exact trends. However, due to space limitations we are not discussing these results in the paper.

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 in 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 in conjunction with improved computation capabilities provide us with the opportunity to evaluate link criticality in a more holistic fashion. The current research builds on these recent advances to develop a quantitative framework to examine transportation facility criticality. Specifically, we evaluate link criticality in the Montreal urban transportation network while considering traffic volumes and environmental outcomes.

The traffic and emissions indicators were generated for a host of plausible scenarios for the Montreal region. The results from the scenarios analysis highlighted the importance of major bridges connecting the Montreal island with the North and South Shores. The scenario level comparison offered interesting relationship between the traffic and emissions indicator highlighting that link level analysis will offer more insights.

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