Modelling Network Resiliency to Prepare for Climate Change

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Abstract

Climate change has the potential to transcend our way of life, and a key element of that is how we get around. Increasingly severe weather events such as snowstorms, hurricanes, or flash floods, or slower processes such as rising water levels, may leave our highways underwater, our transportation hubs isolated, and our rail lines blocked. Under these conditions, the ability of the overall transportation network to continue to allow emergency responders to act and people to evacuate will be placed under a severe strain. At this point, a transportation network unable to cope with the conditions may result in mobility chaos at best and disaster at worst, making it critical to incorporate resilience testing into future network planning.

The Greater Golden Horseshoe Transportation Plan, currently under development by the Ontario Ministry of Transportation (MTO), will test network and service elements in the region under pressure to ensure proofing of transportation infrastructure in Southern Ontario against future conditions. One way in which this could be tested is by assessing the resilience of the existing network to major and recurring events using long range modelling and macroscopic forecasting tools. Using such tools we can stress-test the busiest and most critical network elements and mimic the impact of inclement weather events, or emergency situations, such as the closure of a major rail terminal or highway corridor, or the blockage of interchanges along the busiest freeways, and evaluate for each scenario how resilient the overall network is in reacting to and accommodating demand.

A different application of a similar approach could be considered when planning for future road and rail infrastructure in an attempt to act pre-emptively and offset the impact of climate change. Certain locations, such as floodplains, areas susceptible to blowing snow, and urban heat islands, inherently place more stress on infrastructure, and pose higher risks to people and goods travelling through them. Using macroscopic forecasting models and GIS tools we can identify the demand that a potential corridor would generate and compare the extent of infrastructure or the demand in terms of people, vehicles, and value of goods that would use the risk-prone corridors. This approach could help us identify “safer” routes, corridors and infrastructure elements in order to build resilient transportation networks.

Introduction

In July 2013 a thunderstorm dropped over 100mm of rain on Toronto in a few hours, creating flash floods that cut power, blocked roads, shut down the city's subway system, and inundated commuter rail lines in the middle of the afternoon peak period. Later the same year in December of 2013 (Figure 1), a disastrous ice storm paralyzed most of the city's transit system, caused traffic signal failures, and left hundreds of thousands of households without power for many days.

In the aftermath of the storms, with tens of thousands of commuters left stranded, the need to have a network that has resilience and redundancy to allow for alternative routings when some are closed off came to the forefront of attention.

Given the long time frames, often multiple decades, associated with planning and implementing high-capacity infrastructure improvements, it is essential to make efficient use of modelling and forecasting tools to identify the susceptibility of the existing network to climate-driven events, test the impact of events that block critical infrastructure and the ability of the network to adapt, and evaluate the resilience of potential future networks in this regard.

This paper investigates approaches in which networks can be tested for resilience in dealing with extreme weather events, identifies key metrics by which the success or otherwise of the network to adapt can be measured for diverse scenarios, and demonstrates sample results of these procedures. It presents the applications and tools, and examines ways in which travel demand forecasting models can be used in conjunction with GIS tools and evaluation frameworks to test a network for resiliency to guide long-term planning decisions in establishing a safer and more resilient transportation network in the face of future adverse events such as climate change.

Figure 1: Toronto Ice Storm 2013, Source Flickr: Crushed!

Long-term resilience planning

The Ontario Ministry of Transportation (MTO) is currently developing a long-term Transportation Plan for the Greater Golden Horseshoe (GGH), which will include identification and evaluation of long-term network options into the second half of the century to provide for transportation infrastructure needs in Southern Ontario. One of the goals for the plan is to establish a resilient network, and in consequence it has been important to test the networks for resilience against major events, such as the 2013 storm, that are anticipated to become more frequent and severe in the face of climate change trends.

As part of the MTO Plan, five very distinct “stretch” futures were developed. These futures did not reflect ideal conditions that the region should aspire to, but rather attempted to stretch the plausible realities as they may be shaped by the economy, the environment, major technological advancements, disruptors and volatile geopolitical conditions. These five futures guided the development of different urban structures and underlying population and employment concentrations in the region, which were tested using a custom-developed tool to identify important demand connections. This scenario testing exercise provided valuable information about how to build a resilient network and which connections are essential or too stressed in a variable future set.

Macroscopic multi-modal travel demand forecasting models, as used in most major metropolitan areas, are commonly used to simulate travel demand conditions and extract key forecast metrics such as congestion, delay, trip lengths and mode choices, but these usually represent typical conditions and assess the ability of the multi-modal network to meet projected peak-period demand. However, by taking further steps, and varying the network characteristics, models can also be used as a tool to assess extreme as well as recurring conditions, such as the emergency situations forcing the closure of a major rail terminal, interchange, or highway corridor. By testing and evaluating multiple scenarios for network performance, the model can provide input into how to build a resilient network. This requires the identification of at-risk areas, identifying appropriate scenarios and performance metrics, running the forecasting model and evaluating each scenario accordingly.

Identifying at-risk areas

Our transportation infrastructure is an essential capital asset that has an enormous value as it contributes to a productive economy. As such, beyond the obvious goal to maintain the capital asset, there is an ongoing need and benefit of smoothly and efficiently operating the existing network and planning for the most resilient system.

In recent years, numerous weather-related events hit the Greater Toronto Area, Canada and the rest of the world leaving a disastrous footprint on human life and our infrastructure. Although these events are characterized as "extreme" there is a definite increase in frequency and a pressing need to explore ways of incorporating such considerations in the planning and evaluation of transportation infrastructure. There are two types of considerations that can be incorporated in the evaluation of transportation infrastructure:

- **Ongoing and plannable considerations** of known effects and cumulative results of climate change that are being documented and categorized. Examples include urban heat areas, floodplains, or areas at risk of blowing snow (such as open flat areas).
- **Emergency considerations** of abrupt conditions that need to be examined in order to build a resilient and adaptable network. To help examine emergency considerations, such as ice storms, floods or infrastructure failure/closure, it is important to identify the network components that are under high stress and serve high demand. Those are critical links that should be first identified and then evaluated under extreme conditions.

Ongoing and Plannable Considerations

There is currently a large list of data that are made available by cities, agencies and authorities and that could assist in building a rich dataset for project-specific needs. Conservation authorities and environmental agencies maintain historical data on inclement weather events and track incidents based on their magnitude and geographic location over time. Examples of data sources in the Greater Toronto Area include open data websites, such as City of Toronto's Data Catalogue (http://www.toronto.ca/basementflooding), and the Toronto and Region Conservation Area https://trca.ca/conservation/flood-risk-management/flood-plain-map-viewer/#map.

These datasets can help policy makers, private practitioners and academics to build the data context in order to assess the risk of existing infrastructure and evaluate the potential risk of proposed infrastructure alternatives.

Floodplains

Flood plains provide a spatial representation of areas that are in high risk of being flooded if a river/watercourse experiences extreme flows because of heavy rain or snowmelt. Knowing the location of natural features and the severity of past events can be a helpful tool for land use, transportation planning and emergency management.

Other flood data that are typically available through cities and agencies, include flooding incidents such as basement flooding reported by residents, millimetres of rain by planning districts/wards or a different geographic breakdown as well as duration of the event.

Existing and historical flooding data can be cross-referenced and/or compared to road and rail infrastructure and can be ranked based on the passenger volumes or value of goods that they carry daily. Identifying existing areas of our networks that are exposed to higher risk should help inform the need for redundant routes in an effort to build a resilient region and it should also help avoid or view unfavorably infrastructure alternatives that traverse through flood prone areas.

Extreme Heat

Heat does not affect all places equally; there is considerable spatial heterogeneity and there are multiple factors that contribute to heat vulnerability, including the topography, vegetation, and settlement density. In most urban areas there are hot spots where temperatures are consistently hotter and that pose higher risk to infrastructure and users. Heat variability is important for transportation infrastructure as all pavements, light and heavy rail tracks, and expansion joints for bridges are designed for specific temperature ranges and will fail beyond certain extremes.

Figure 2 below illustrates train tracks in Kaiapoi, New Zealand that buckled due to extreme heat. In Canada, where temperatures have historically been lower and our infrastructure is designed to sustain less heat stress, it is particularly important to realize the reality of the changing climate and what this means for the design standards and the estimated maintenance costs. The increasing cost of materials and maintenance or the shorter lifecycle of infrastructure due to effects of climate change should be built as an added variable in transportation planning. Project cost estimates should be adjusted to adhere to the inflating costs and should help inform the real benefits and costs of alternative transportation solutions.

Figure 2: Buckled train tracks near Kaiapoi

Similar to the approach for floodplains, urban heat locations, or areas with documented high temperatures can be cross-referenced with the length of rail or road that cuts through them and where appropriately weighted by the traffic volume that passes through them.

Other Areas at Risk

Other locations that can be used for this analysis include areas susceptible to blowing snow or flat rural areas which inherently place more stress on infrastructure and pose higher risks to people and goods travelling through them. This approach could help us identify “safer” routes, corridors and infrastructure elements in order to build resilient transportation networks.

Emergency Considerations

Beyond the ongoing and recorded weather-related considerations there are emergencies where the transportation system needs to respond and provide alternative route options for the users. Emergency management situations include the evacuation of a busy building, a stadium or a whole city, or the failure of critical components of the transportation network, including the busiest freeway interchanges or the central train station. In planning for these emergency situations it is important to first test and determine what the impact to the system would be and then identify proposed solutions to alleviate the pressure.

Quantifying the risk

Long range transportation plans can use this approach to assess proposed road or rail alternatives that have higher probability of being affected by inclement weather events in the future due to their proposed location. Using macroscopic forecasting models and GIS tools we can identify the demand that a potential corridor would generate and compare the extent of infrastructure or the demand in terms of people, vehicles, and value of goods that would use the risk-prone corridors.

As an example, two proposed roadway alternatives can be assessed based on the route lane km that passes through flood prone areas. The road alternative that has lower route lane km going through the areas at risk will score better. Depending on the level of detail or the importance of the proposed infrastructure, additional considerations can be applied as weighting factors to emphasize the risk to which each alternative is exposed. For example, the route lane km of roadway/ or length of rail track can be weighted by the estimated passenger or vehicle demand that is forecasted to use the corridor. Alternatively, if the proposed roadway or railway is an important goods movement corridor, the estimated value of goods that will be transported through the corridor can be used as the applicable weight.

Table 1 presents examples of key metrics that can be used, with the help of a travel demand model, to test the network for resilience.

Table 1: Examples of key resiliency metrics

Metric	Example	Question
Evacuation time	Percentage of residents who are able to exit the region within 45 minutes	How effective is the network at facilitating evacuation (one-way flows)
Risk areas	Km through areas susceptible to blowing snow	How susceptible is the network to extreme weather events?
	Km of network in flood-risk areas	
	Km of network through urban heat islands	
Infrastructure closure	Station removed: impact on travel times and congestion levels	How does the network respond if a key facility is unavailable?
	Major facility (highway or transit line) removed: impact on travel times and congestion levels	How does the network respond if a key link is unavailable?

Assessing network resilience

In long-term travel demand models, network performance and the need for enhanced capacity is typically based on projections of recurring demand. Capacity increases are also focused on augmenting the existing network—whether this is adding more traffic lanes or transit lines, this will not necessarily improve network resilience if that additional capacity is simply added to a facility or group of facilities that are susceptible to blockage by extreme weather events.

These scenarios can be compared and assessed either numerically or graphically (or through a combination of both) measures. Hours of delay, proportions of the network susceptible to extreme weather events, and the proportion of the population that can be evacuated within a specific interval can be quantified and assessed for various scenarios. Using this evaluation framework enables modellers and planners to provide an informed opinion on which network is the most resilient.

The examples below present a way to show, in the case of Toronto, the impact of how both travel times out of the core and congestion will be affected if a key highway (which runs adjacent to a river and was flooded during the 2013 storm) is unavailable.

Figure 3 *shows the time that it takes people to leave the core of downtown Toronto. The core is illustrated with a white dot in the centre of the image.* ***Figure 4*** *illustrates the travel times out of core when an important highway east of the City is removed. The removed highway is illustrated in red color. The "after" image illustrates the significant increase in travel times for travelers going to the east and north of the City centre*

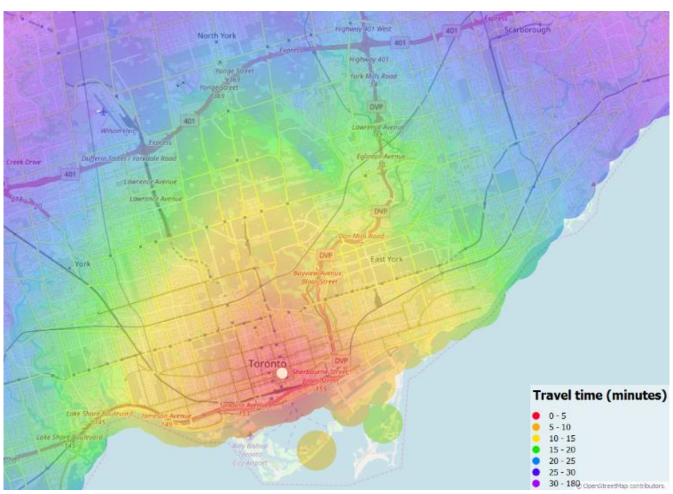

Figure 3: "Before" Travel times from the core, which is illustrated with a white dot

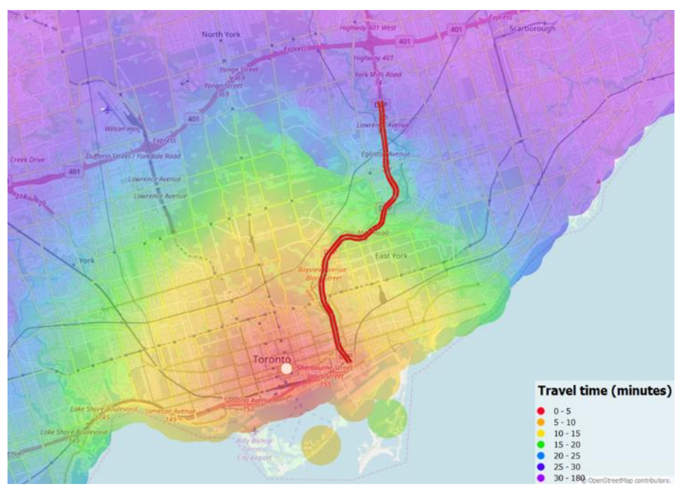

Figure 4: "After" Travel times from the core when removing highway. Core is illustrated with a white dot, and the removed corridor is shown in red

Similar **Figures 5** and **6**, show congestion in and around the city in the before and after scenario. It becomes obvious that the removal of the highway caused delays and chokepoints not only to the network adjacent to the removed highway but in multiple other areas miles away from the affected corridor.

Figure 5: "Before" traffic congestion

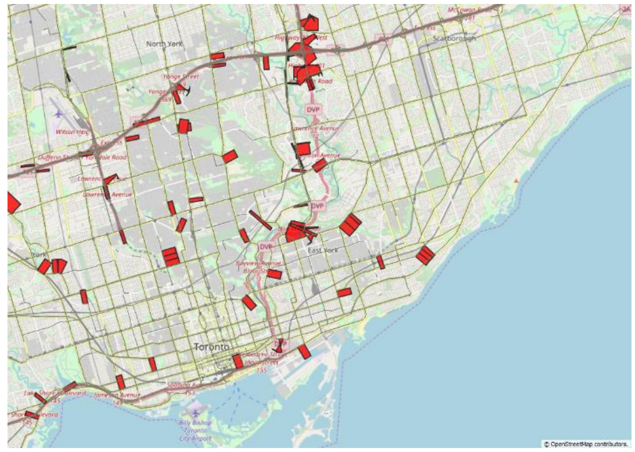

Figure 6: "After" traffic congestion

These results provide at a glance comparisons and views of the impact of closures and the facilities that would be most greatly affected.

Conclusions

Research suggests that the Earth's climate will continue to warm throughout the 21st century[1] and that "extreme" weather events will become more frequent. There is an undeniable need for governments at all levels to more effectively and consistently incorporate climate forecasts in infrastructure and land planning decisions. There is also a pressing need to review and update design standards for road and rail infrastructure and ensure to the degree possible flexibility and resiliency.

More detailed and consistent mapping is required to depict flood plains, urban heat locations, and areas that are susceptible to extreme weather events. These should be standardized, kept up to date and be openly shared with invested parties to ensure that decisions regarding infrastructure and land use decisions are driven by accurate information.

Extreme events need to be taken into consideration when planning and designing transportation infrastructure in order to facilitate access to and egress from affected areas. This goes beyond standard transportation forecasting scenarios that usually focus on standard peak period conditions (or sometimes special events) where the whole network is presumed to be available. Part of the process requires the identification of critical infrastructure in the existing and planned network. By selecting and testing the components of the network that are at highest risk, future plans and recommendations should provide redundancy and solutions for emergency management.

A truly resilient network should, within reason, be able to resist closure of key connection points or corridors and provide people with a viable exit or evacuation route and allow first responders to access affected areas.

Major infrastructure projects, such as highways or rapid transit lines capable of carrying large numbers of people, take many years to be developed and thus the importance of creating resilient plans that incorporate risk assessment of alternative scenarios becomes evident. Long-term forecasting models can evaluate these based on prospective development plans and enable different networks to be compared and evaluated for their effectiveness at responding. This provides long-term planners with important insight into potential network scenarios and supplies guidance into infrastructure recommendations.

[1] https://www.toronto.ca/legdocs/mmis/2013/pe/bgrd/backgroundfile-55152.pdf

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