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A COMMUNITY RESILIENCE APPROACH TO ASSESSING TRANSPORTATION RISK IN DISASTERS

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Abstract

This paper addresses the need for new measures and models of infrastructure performance that can facilitate the strengthening of community resilience to disasters. While many infrastructure measures and models focus on performance in terms of disaster-induced damage, from the perspective of populations and cities that would be affected, there is a need for analysis of service loss and of approaches to rapidly restore service in an emergency. Focusing on transportation, this paper notes limitations of current performance measures, proposes a systems analytic framework that addresses community resilience, and demonstrates how the framework can be applied to analyze and model transportation disruption in earthquakes and other disasters.

The approach is demonstrated for a case study of south coastal British Columbia, Canada, with particular attention to the role of maritime transportation in the distribution of one essential commodity, gasoline fuel. Coastal communities in this region are extremely reliant on maritime transportation for delivery of essential goods such as fuel, and because of the shift towards just-in-time production systems, have very little storage or warehousing capacity. Expert interviews, stakeholder workshops, satellite-based tracking of ships, and network analyses are used to characterize the transportation system and assess risk and resilience. Two approaches to system analysis are implemented: one emphasizing network topology, and the other focusing on network functionality. This enables a comparison of the strengths and limitations of these two major methodological approaches. In the case study demonstration, the topological approach is able to capture, with relatively low data requirements, the relative vulnerability of communities situated in different parts of the network. Resilience-enhancing strategies that are related to network topology, such as adding network links as a response in emergencies, can be readily assessed. The topological approach is limited, however, in its ability to address detailed damage and operational issues related to emergency response actions that are key to resilience analysis. In the second approach, a functional model is developed that emphasizes flows in the network. This enables a more realistic representation of system operations, thereby facilitating more specific understanding of how transportation damage can lead to disruption of fuel flows and impacts to communities. The functional model can be readily integrated with hazard and facility damage models. The approach is particularly advantageous in being able to capture time-dependent variables such as reserve volumes and supply deliveries, which are crucial types of information for assessing how different decision options (e.g., seismic retrofit of port facilities, increasing storage capacity, adding shipping routes) could enhance community resilience. Data requirements are very high, however, and pose an important limitation to this approach.

Keywords: resilience; transportation; shipping; fuel; coastal communities; decision-support

1. Introduction

Infrastructure systems play a major role in the disaster resilience of communities, yet this societal importance is rarely reflected in current measures and models of infrastructure performance. Disaster resilience can be defined as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." [1] When electric power, water, transportation, and other infrastructure services are disrupted, the consequences for cities and populations are severe. By the same token, their rapid restoration is essential to resilience. While many infrastructure measures and models focus on performance in terms of damage, from a community resilience perspective, analysis is needed in terms of service loss and approaches to rapidly restore service.

This paper focuses on methods for assessing transportation performance in disasters from the perspective of community disaster resilience. Its objectives are to: (1) provide an overview and note limitations of current performance measures, (2) propose a systems analytic framework that addresses resilience, and (3) demonstrate how the framework can be applied to model transportation disruption and community resilience. The approach is demonstrated in a case study of local maritime transportation for fuel, an essential commodity following disasters, in south coastal British Columbia, Canada. A central premise is that in order to model resilience, it is essential to consider network flows, network actors, system changes, and pre- and post-disaster actions.

2. Measures of Transportation Performance in Disasters

In a recent comprehensive review, the Applied Technology Council [2] found that societal considerations are largely missing in current codes, standards, guidelines, and performance requirements for infrastructure systems. Codes and other design guidelines largely address component-level rather than system-wide performance; furthermore, there is little systematic understanding of societal impacts and societal expectations of infrastructure failures in disasters. In the case of transportation systems, current design standards focus on components such as bridges, and guidance is lacking on how to plan and design an entire transportation network in order to maintain vital flows of people and goods following a natural hazard event [2].

The importance of addressing systems-level performance is increasingly being recognized. A recent review of approaches to measuring transportation performance in disasters identified two major categories of applied performance measures: those based, respectively, on topology and on function [3] (see also [4]). Topological measures utilize graph theoretic concepts to characterize the transportation system as a network of nodes and links. Connectivity of nodes, for example, is a typical topological measure of transportation performance. Pre- and post-disaster connectivity can be compared to assess service loss. Topological approaches have the advantages of limited data requirements, straightforward methodology, and computational facility for exploring alternative scenarios. They have been used to compare transportation system performance in different earthquake disasters (e.g., [5]) as well as strategies for post-earthquake network restoration to reduce disruptive impacts (e.g., [6]). Their key limitation, however, is their inability to realistically describe behavioral responses in a disruption [4].

Functional measures emphasize flows and serviceability in the post-disaster network; for instance, in terms of increased travel time and/or distance, reduced throughput and/or capacity, or reduced accessibility. While overcoming some of the limitations of topological approaches, they require substantially more data and modeling of behavioral and other responses. The substantially higher computational demand makes it prohibitive to fully investigate network vulnerability [4]. Studies that utilize performance measures to support decision-making in disaster management – especially in post-disaster response and recovery – are few, but growing in number [3, 4]. There is a need for studies that go beyond assessing transport service levels to addressing how populations and communities would be affected by reduced service.

3. Resilience-Based Framework for System Analysis

A framework is proposed here to assess one important aspect of resilience, the transportation of essential supplies to disaster-affected communities. It focuses on the main mode of goods transport within the study region, maritime transportation or coastal shipping. The framework can be applied to differing degrees in both topological and functional methodological approaches, as will be demonstrated in Section 5 below.

The system is defined to include communities (e.g., towns and cities) that are connected by transportation infrastructure and that benefit from the flow of goods, both as producers and consumers. When these flows are disrupted, in the short term, communities may be affected by shortages. The severity of the disruption depends on the capacity of the remaining network and the speed with which capacity is restored. Transport disruptions do not necessarily lead to severe impacts to communities, as they can be mitigated if communities have sufficient reserves on hand, are able to produce the goods locally, or are able to adapt consumption behaviors. Just-in-time delivery systems increase vulnerability by minimizing reserves, especially if there is no local capacity for producing the goods.

Figure 1 provides a summary of the essential elements in this framework. Nodes (communities) are connected by transport links that are characterized by routes, ships, and cargo. Also relevant are factors such as sailing schedules, labor (ship crews), regulations, and stockpiles or reserves, all of which affect system capacity and function. Note that the specific cargo type is important for defining the relevant network; for example, the transport network (supply nodes, ports, routes, ships, etc.) for delivering bulk fuel is different than that for movement of food or people. Vessels may be specialized, and cargo docks are frequently located away from passenger terminals. It is also important to note that because of the focus on the post-disaster supply of essential commodities, there is directionality in the network.

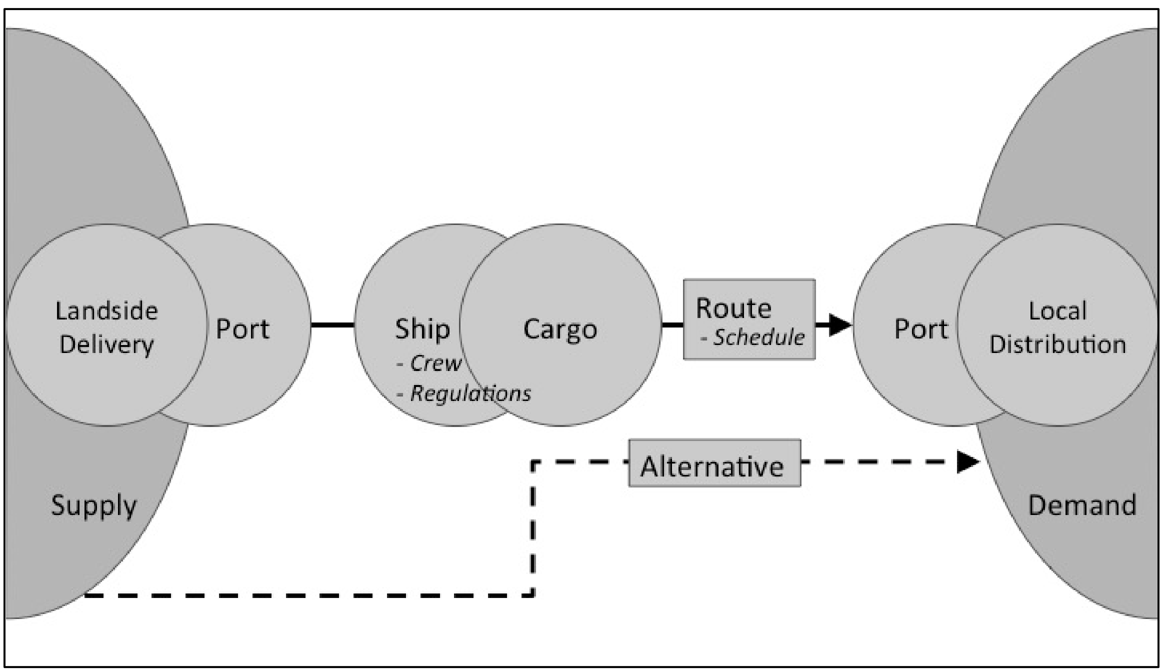


Fig. 1 – Elements of local maritime transportation system

In this framework, the hazard is characterized by how it affects the system; specifically, by which system element(s) are disrupted, and by whether this disruption occurs at a single location or multiple locations. For example, an accident that causes a ship to sink and block a critical navigation channel would be a hazard that disrupts a route at a single location. Framed in this way, earthquakes are characteristically different from most other hazards (e.g., port labour strikes, terrorism incidents, storm surge flooding, undersea landslides) because they affect multiple elements of the transport system – supply and landside delivery, port, route, labour, and demand and local distribution – at multiple locations.

Strategies for reducing risk and enhancing resilience are also characterized in this framework in relation to system elements and hazard attributes. Some actions, such as seismic strengthening of port facilities and grounds, can relate to hardening the system to minimize initial damage and disruption from the hazard. Other strategies can improve the capacity of system entities to respond to the disruption; for example, adding shipping routes, increasing storage, or planning to repurpose port terminals for flexible use during emergencies.

4. Case Study: Maritime Transportation in Coastal British Columbia

4.1 Seismicity and Hazards

The framework is applied to a case study of maritime transportation disruption in coastal British Columbia, Canada, with a focus on its role in the distribution of a critical commodity, gasoline fuel. The region includes major coastal cities in the Vancouver Metropolitan region (population 2.3 million), the provincial capital of Victoria located on Vancouver Island, and numerous small cities and towns, including many located on islands. Coastal shipping is essential for transporting people and goods in this region. Port Metro Vancouver is the largest port in Canada.

The study region is part of the Cascadia Subduction Zone and is at risk from subduction zone megaquakes as well as earthquakes from surface and intraplate fault zones. Recent studies have suggested that a M9.0 subduction zone earthquake with offshore epicentral location about 300km from downtown Vancouver could cause CAD$62 billion in direct damage and an additional $13 billion in indirect loss [7]. Other analyses of "worst-case" shallow, crustal earthquakes directly below population centers in the region are also dire: a M7.3 event below Vancouver or a M7.0 earthquake below Victoria could cause extensive or complete damage to some 30 percent of buildings in those respective urban areas [8]. A recent report by the B.C. Auditor General [9] concluded that the region, and specifically the provincial government, is not adequately prepared for a catastrophic earthquake.

4.2 Data Collection

Data to characterize the maritime transportation network in the case study region were gathered through multiple means. While published reports and online information were accessed, these provided fragmentary data on the network and its operations. They also contained minimal information regarding system vulnerability in hazard events, prior experiences of disruptions, current concerns, ongoing emergency preparedness activities, and coordination (or lack of coordination) between organizations in the network. Expert interviews were therefore used as the primary data source. Over eighteen interviews were conducted with key stakeholders who represented provincial and municipal governments (e.g., emergency managers), shipping and transportation companies, port authorities, and other related organizations. An interactive workshop with a broader cross-section of stakeholders provided supplementary data. A meeting with one local community's emergency response committee provided valuable insights into unique issues facing small, remote communities that are extremely dependent on maritime transportation.

Information on shipping traffic (e.g., specific shipping routes, frequency of service) were sometimes difficult to obtain. Because fuel is transported by private sector companies, many of whom are small and who operate in highly competitive environments, such information was sometimes considered confidential. In addition, some organizations within the fuel sector were reluctant to participate in the study. This may be due to current sensitivities regarding controversial plans to increase fuel export capacity in the region.

It was therefore useful to access independent data on vessel traffic through the Automatic Identification System (AIS) data source. Most commercial shipping vessels are required to have AIS receivers installed, which enable nearly real-time satellite tracking of vessel locations. Through the MEOPAR–ExactEarth partnership, AIS data were made available and analyzed for this project by research staff at the Marine Environmental Observation Prediction and Response (MEOPAR) Network of Centres of Excellence. Commercial fuel transport vessels in the study region were identified, and their trajectories over a one-year period were mapped. The analysis focused on fuel transport to Vancouver Island.

Combining and cross-checking data from these various information sources enabled the fuel distribution system in the region to be broadly characterized. While nodes and links on the network can be specified with some confidence, complete data on system operations and flows could not be obtained. There are also data gaps in the details of many emergency response plans and protocols. Furthermore, data on the demand side of the system, and especially on how this demand may change in a disaster, are unavailable and would require primary data collection. Many of the gaps in this research are a result of data confidentiality. These findings indicate that challenges with obtaining the requisite types of data pose an important limitation to detailed modeling of operational aspects of transportation systems in normal and disaster situations.

4.3 System at Risk

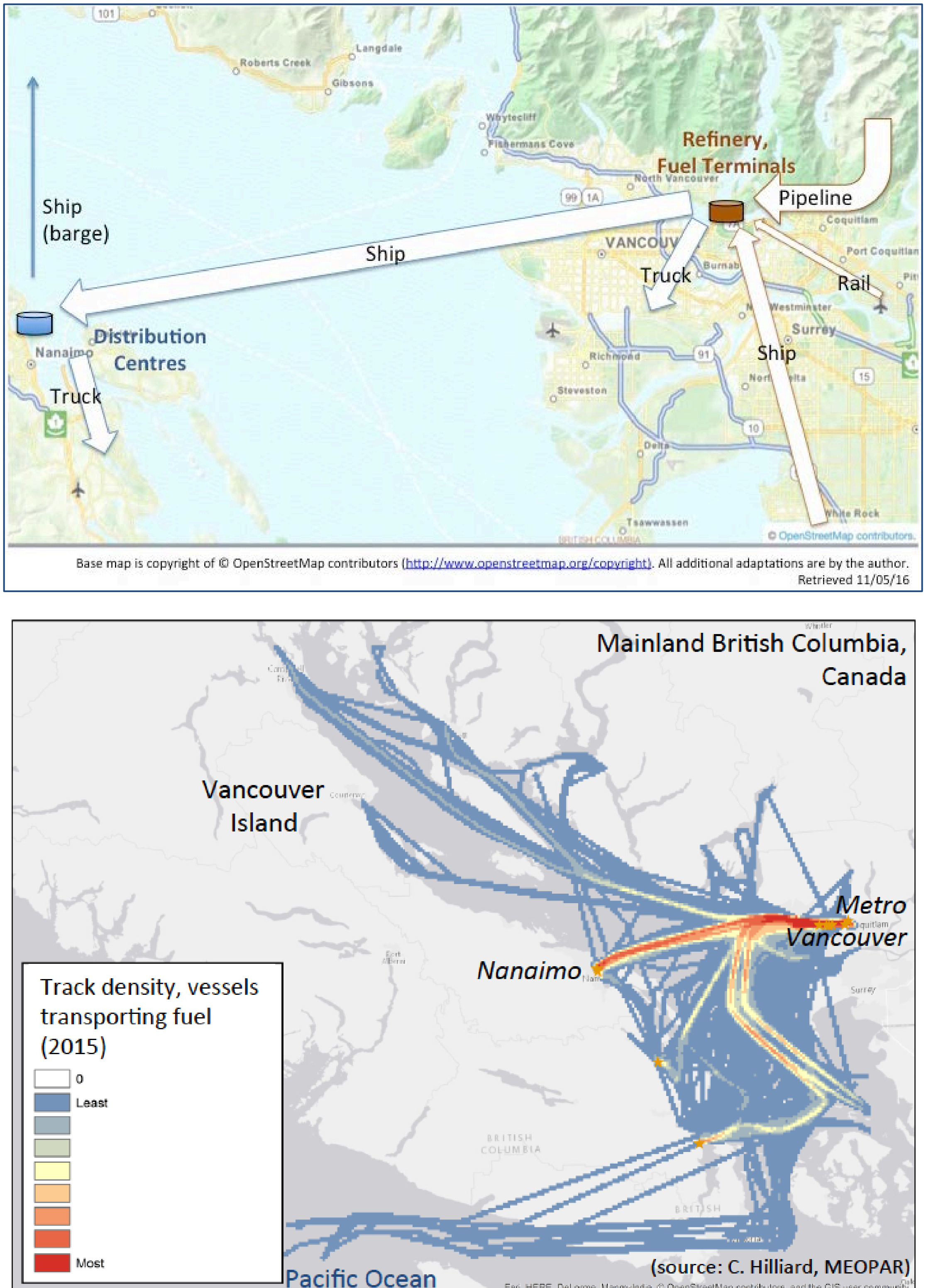
The fuel system in the study region involves pipeline, rail, truck and marine modes of transportation (Figure 2a). Fuel supply derives almost exclusively from Alberta and Saskatchewan provinces by pipeline and rail, with supplementary supply from Washington State refineries (i.e., Shell/Anacortes, British Petroleum/Cherry Point, and Tesoro refineries). With limited refining capabilities in the region (i.e., a small refinery in Burnaby owned by Chevron), the majority of imported fuel is already refined. There are five main fuel distribution centres situated in the Lower Mainland, maintained respectively by Suncor, Imperial Oil, Kinder Morgan, Shell, and Chevron.

Within the region, marine transportation is a central mode of fuel delivery for island and coastal communities. Without refineries or large storage capabilities on Vancouver Island, the Sunshine Coast, or other more remote coastal areas, the Strait of Georgia acts as a marine highway connecting isolated communities to fuel supplies from the mainland. The major fuel companies have tank farm facilities at several locations on Vancouver Island, including Nanaimo, Cobble Hill, and Esquimalt. AIS data enable depiction of the routes, density, and frequency of fuel vessel traffic to these distribution centres (Figure 2b). Marine vessels ferry fuel from both mainland British Columbia and Washington State. Most Vancouver Island fuel distribution centres receive deliveries 2-3 times per week. In contrast, many small, remote communities on the central and northern coast, including a number of First Nations (aboriginal) communities, are serviced much more infrequently, roughly once or twice a month.

Fuel delivery service is provided by a small number of maritime transportation companies using fuel barges and marine tankers. Many leading maritime transport companies have docks situated near Tilbury and Richmond on the Lower Mainland. When fuel trucks arrive at the docks, marine vessels are loaded and transport oil and refined fuels across the Strait of Georgia to various locations along Vancouver Island's east coastline. At these locations ships are primarily loaded by trailers with a roll-on-roll-off system. Roll-on-roll-off also makes the transfer process easier because cranes are not required for loading or unloading at the ports. Once ships have arrived on the Island, fuel trailers are connected to live trucks, and dispensed to their final destinations. Alternatively, larger companies use marine tankers to transport fuel, collecting fuels directly from distribution centres. Tankers are filled and emptied via pipelines directly from storage facilities to tank farms at destination. Once fuel has reached a tank farm, it is collected from the site racks by truck and distributed to end users. For the most part, the transportation between storage and vessels are independently organized by the fuel organization or subsidiary.

There are multiple companies who truck fuel from storage facilities, tank farms or vessels to coastal distribution points and ultimately, end-users. Parkland Industries Ltd manages a large proportion of fuel distribution from the refining facilities. The contract for fuel is between Parkland and the refinery, which determines the volume and location of fuels available. Independent distributors of commercial fuels hold contracts with Parkland, who allocate the fuel resource between their customers. At any time, Parkland can hold fuel contracts with multiple refineries, allowing flexibility in supply in the event of a minor fuel disruption or delay at one of these centres. The delivery side trucks can either be independently owned by the fuel company, or contracted to them to distribute fuel to stores and communities. Details regarding facilities, equipment, and organizations involved in the transportation system are useful for characterizing network responses to disruption, such as capacity constraints and substitution possibilities.

(a)



(b)

Fig. 2 – Fuel transportation flows in study region, (a) schematic and (b) from AIS vessel tracking data

Differences between communities are also relevant to understanding the potential impacts of a disruption in fuel delivery. Preliminary findings suggest that at least in some cases, remote communities that are especially vulnerable because of their isolation may also be better prepared than some larger and better-connected communities; for example, they may have larger storage capacity, plans, and precautionary practices in place to address the risk of potential fuel supply disruptions. On Vancouver Island, with daily service, many places only have a limited supply of storage and rely on just-in-time delivery systems, impacting their ability to operate and respond in the event of an emergency.

5. Modeling Approaches

As noted in Section 2 above, topological and functional models represent two major approaches for assessing the performance of transportation systems in disasters. In this study, both of these approaches are applied to the case study region. Following a brief description of methodology and illustrative findings, the strengths and limitations of the two approaches are discussed from the perspective of community resilience.

5.1 Topological Model

A topological model of the fuel distribution network is described in map form in Figure 3a. The nodes of the network consist of the study region's 50 largest coastal communities (i.e., cities and towns) in terms of population. The links between these nodes are comprised of transportation connections such as roads, bridges, and marine shipping routes. Although not shown in the map, the presence of multiple connections (e.g., multiple bridges connecting a pair of cities separated by water) is accounted for in the characterization of the links. Consistent with the framework in Section 3 above, the network is specific to the commodity under study, gasoline, and is directional with respect to how this fuel is distributed from the source (i.e., refinery and marine fuel terminals in Burnaby) to the destination nodes (i.e., the communities where fuel is consumed).

In Figure 3a, each community is color-coded along a scale that indicates its position on the network relative to the fuel source. The scale indicates the number of links on the minimum path between the source and the destination, ranging from 1 in the case of Burnaby (the location of the refinery and fuel terminals) to 8 in the case of the communities on Vancouver Island that are furthest from the source. In principle, the more links that need to be traversed, the more opportunities there will be for damage to a bridge, port, or other transportation element along the way, and hence the greater will be the vulnerability of the destination community to system disruptions in an earthquake or other disaster. (Further methodological details can be found in [10]).

Figure 3b maps the change in this index of system vulnerability in the event of a site-specific disruption, namely, blockage of the First Narrows Channel through which ships must travel in order to access the refinery and fuel terminals in Burnaby. An increase in the vulnerability index can be seen for many of the communities on Vancouver Island that receive fuel transport via links from Burnaby. Communities located on the mainland, however, are not affected by this pattern of network disruption.

Figure 3c depicts the change in system vulnerability in the event of a different type of event, a M7.0 earthquake with epicentral location at Victoria that causes damage and disruption in multiple locations across the network. Details regarding this scenario can be found in [8]. In terms of transportation system disruption, the impact on southern Vancouver Island communities is much more severe than in the channel blockage scenario because of the loss of multiple marine links between the Island and the mainland, as well as land links between communities on the Island.

These impacts can be ameliorated, however, if new links are rapidly instituted following the earthquake. Figure 3d illustrates the effect of adding new links from U.S. refineries in Washington State to the Lower Mainland and, via marine mode, to the port of Nanaimo on a part of the Island that is expected to be less heavily damaged in the earthquake.

(a) (b)

(c) (d)

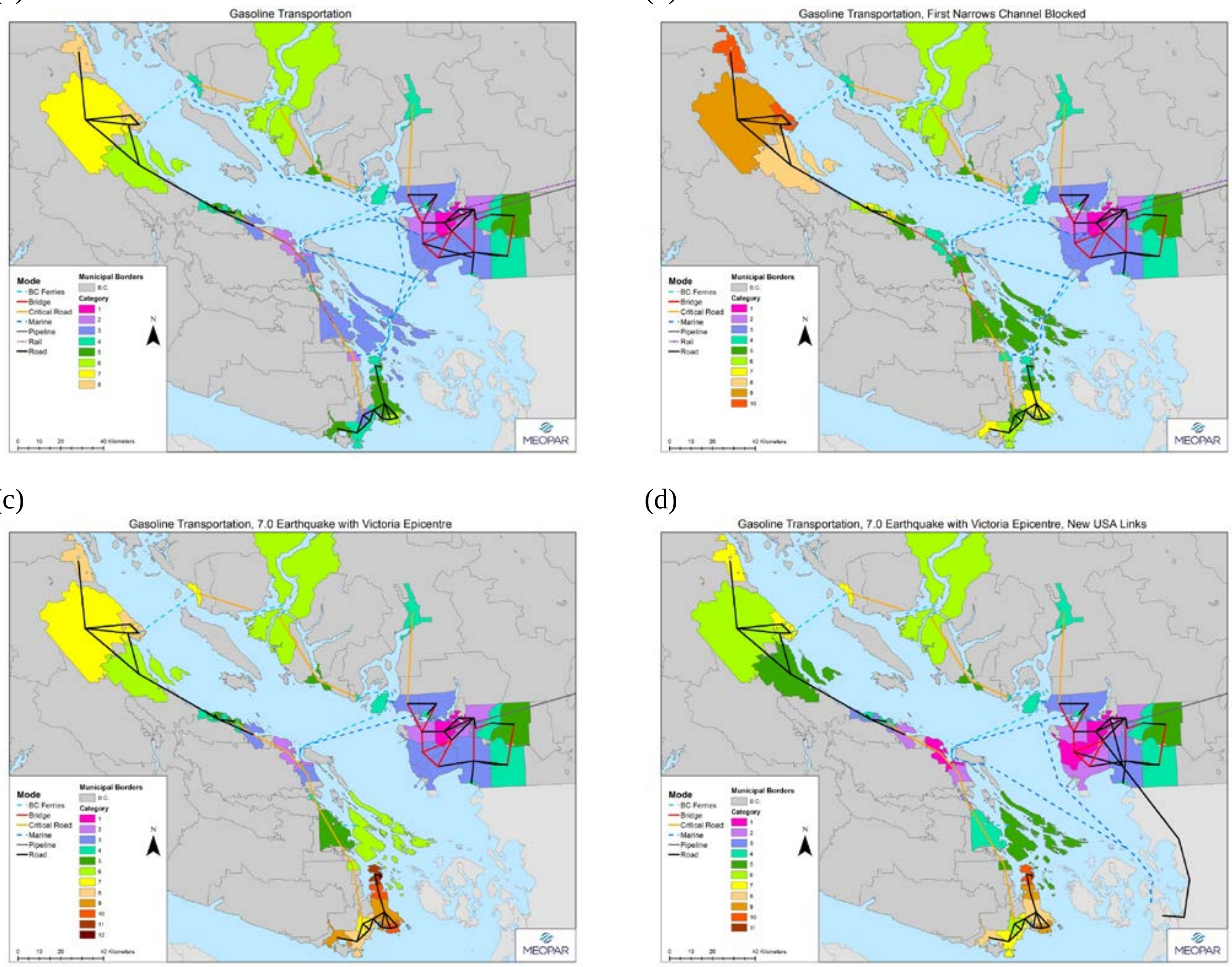


Fig. 3 – Topological analysis of fuel transportation with (a) no disaster, (b) blockage of First Narrows channel, (c) M7.0 earthquake near Victoria, (d) M7.0 Victoria earthquake with new USA link

This analysis demonstrates some of the advantages, as well as limitations, of a topological approach to assessing transportation system performance in disasters from a community resilience perspective. The approach is able to capture, without extensive data requirements, the relative vulnerability of communities situated in different parts of the network. The effects of different types of hazards and damage patterns can be easily portrayed. Resilience-enhancing strategies that are related to network topology, such as planning to add network links in emergencies, can be readily assessed. The approach can be used to assess hazard scenarios of particular concern and to identify critical links in the network. It can also be used to investigate the ameliorative effects of alternative actions such as adding new links during emergencies versus strengthening existing links. The topological approach is limited, however, in its ability to address detailed damage and specific issues related to emergency response actions, for which operational details are important and functional approaches are more appropriate.

5.2 Functional Model

Catastrophic events that manifest themselves over large spatial areas and affect several infrastructural sectors require broad scale analyses that can capture interactions between physical infrastructures and the natural and social systems to which they are intrinsically coupled. The use of networks – ensembles of discrete *nodes* connected by *links* - provides a rigorous mathematical basis for the analysis of connected elements and enables aspects of the aggregate performance of networked systems to be rapidly calculated. In a functional network model, the components responsible for consuming, generating or regulating a resource or service are represented as nodes. If a mechanism for them to exchange resources or services exists, they will be connected by network links. The ease of causal interpretation in network models typically makes them easier to construct than other models, minimizing the knowledge costs and making them easier to modify.

From this perspective, a holistic, functional network-based approach has been developed for the fuel distribution system in the study region, coastal British Columbia. In this network, the flow of fuel packets has been modeled in conjunction with the hazards, on-site structural responses, duration and costs of repairs. The advantage of this approach is the possibility not only to evaluate the damage at the component level (e.g., bridges, ports) but also to estimate general losses, including societal costs related to a fuel shortage caused by the damage. Without properly modeling the interdependencies between system components, the total losses related to disruptions at a given component can be easily underestimated.

The flow in the network is modelled by fuel packets which originate in fuel terminals (sources) located in Burnaby and are sent by truck to ports located in the Lower Mainland. The number of routes that a truck can take is defined depending on the number of "bottlenecks" (i.e. bridges, viaducts, tunnels) that the truck has to cross between the distribution centre and the port. If no bottlenecks exist in a path, it cannot be disrupted. Alternatively, if no route is available, the fuel terminal and the port in question cannot be connected. From the ports in the Lower Mainland, packets are sent to ports in either Vancouver Island or coastal communities in northern BC using ships, barges or ferries. These vessels are modelled with the same route properties as trucks; however, the marine routes can be disrupted by other types of causes such as oil spills, damaged vessels blocking ship channels, etc. The final step is to transport the fuel from destination ports to the communities, where it is usually stored in tank farms. The fuel in these storage structures enable the community to function for a short period of time without receiving new fuel shipments.

The network modelling is being performed in ***Rts*** [11], a software developed by T. Haukaas and collaborators at the University of British Columbia. This software aggregates state-of-the-art models for natural hazards (in particular, earthquakes), structural response, and damage and loss estimation. In Figure 4, an example of the potential of the network-based approach using ***Rts*** is shown. This example considers the scenario where an earthquake disrupts the distribution of fuel to the community of Powell River, in coastal BC. The plot on the left side of the figure is a graph of fuel reserves at the community, which under normal circumstances decrease at a constant rate due to local consumption and are periodically replenished by weekly fuel shipments. At a certain point in time, an earthquake disrupts the Tilbury port and a fuel terminal in the Vancouver area, limiting the fuel supply being sent to the Power River community.

On the right side of the figure are plotted the *functionality ratio* curves for the Powell River tank farm (1) and port (2), as well as for the Tilbury port (3) and the fuel terminal (4). The functionality ratio measures how much of the normal operations can still be performed in a post-disaster scenario. As shown, the infrastructure at Powell River does not suffer functionality loss during this earthquake, due to being distant from the earthquake epicenter. The infrastructure in the Vancouver region, however, sustains significant loss of functionality, with the Tilbury port being able to perform only 75% of its normal operations and the fuel terminal reaching a low of 20% functionality. The immediate effect of these scenarios is the decrease in the fuel reserves at Powell River, which continue to be consumed but not replenished. With time, the functionality in the affected infrastructure is recovered and the shipments to Powell River are reestablished. Note, however, that the functionality for the fuel terminal never reaches its original value, which represents permanent damage to the infrastructure.

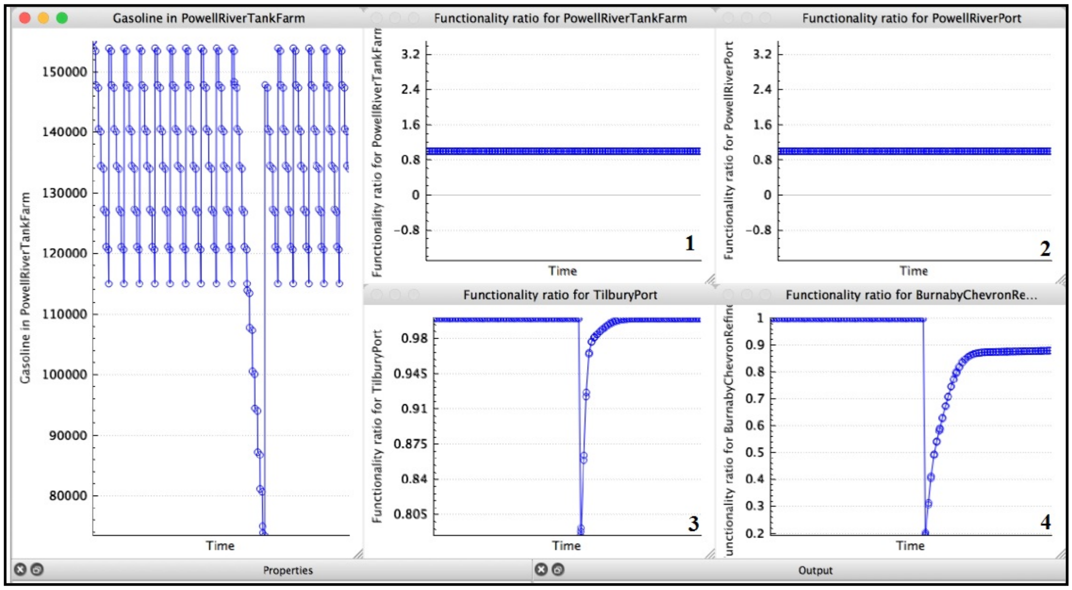


Fig. 4 – Example of the network simulation using *Rts*.

This example illustrates some of the advantages of the functional approach to network modeling relative to topological approaches. Details regarding facility location and capacity, commodity flows, and temporal changes enable a more realistic representation of the fuel distribution system, which facilitates more specific understanding of how transportation damage can lead to disruption and impacts to communities. Damage analysis of components such as bridges and tunnels can be integrated directly into the model. The modeling approach can be readily applied to probabilistic analysis of potential disruptions and impacts, and is amenable to sensitivity analysis regarding key variables and assumptions. The detailed representation of commodity flows can in principle be integrated with models that estimate the socioeconomic impact of flow disruptions such as fuel shortages and the benefits of reducing the duration of those shortages. In other words, the functional model is better at capturing time-dependent variables such as reserve volumes and functionality, which are crucial types of information for deciding which resiliency measures (e.g., seismic retrofit of port facilities, increasing storage capacity, adding shipping routes) would be most effective.

The functional modeling approach does have a number of limitations. First, data requirements are onerous, and it would be unrealistic to seek to obtain sufficient data to fully and accurately represent the system. Thus, assumptions are required to address some data gaps, which can be regarded as a limitation. For example, the model utilizes some of the fragility and restoration curves for earthquake hazard in the HAZUS model [12]. These curves are defined by cumulative distribution functions defined by a median and a dispersion parameter. Obtaining realistic values for these parameters for the study area will be challenging, and extrapolated values available for other regions may need to used, which would introduce some inaccuracies.

In addition, while damage and functionality loss can be evaluated in a relativel straightforward manner, optimizing flows across the network is very complex from a modeling standpoint. Currently, the model does not have a proper algorithm for determining optimal rerouting. Modeling functionality recovery, both without and with emergency response interventions such as rerouting flows, remains an important challenge in the area of system performance modeling.

5. Conclusions

In order to facilitate planning and decision-making for disaster resilience, performance measures of infrastructure systems are needed that take into account not only damage in the event of disasters, but also and system-wide service loss and strategies for rapid restoration. Furthermore, performance measures are needed that address the problem from the perspective of cities and other communities at risk, rather than strictly from the perspective of the infrastructure system or provider. In the case of transportation systems, for example, the number of bridges that experience severe structural damage is less informative for disaster resilience than the increase in aggregate travel times over the damaged network. Even more relevant for community disaster resilience would be measures of the impact of transportation disruption for delivery of essential commodities such as fuel and for critical post-disaster functions such as emergency response or healthcare, as well as assessments of ways to mitigate this impact.

This paper has investigated the issue of assessing transportation performance with a focus on maritime transportation in coastal areas and the supply of a critical commodity, fuel. In the case study of British Columbia, data from numerous expert interviews as well as secondary sources were used to implement two analytical approaches: a topological network analysis and a model of network functionality. Both addressed post-disaster fuel supply from the perspective of communities requiring the fuel. Results indicate that a topological approach can provide generalized insights with relatively low data requirements. Resilience-enhancing decisions that are related to network topology -- for example, adding new shipping routes to bypass damaged parts of the network -- can be evaluated. While functional models have substantially higher data requirements and implementation challenges, they have the advantage of being able to directly assess a much broader array of decisions related to network flows, as well as directly consider the temporal dimension of service restoration. They can also more readily integrate models of physical damage, system operations, and probabilistic hazard.

Data requirements post a fundamental challenge to resilience assessment approaches. Assessment methods need to consider not only the physical performance of components, but also the operational performance of the system, the socioeconomic impacts to populations and communities, and the planning and decision-making options that can reduce those impacts. The latter are particularly difficult to capture, as many effective and innovative options may involve operational responses that are beyond the traditional domain of performance assessment for earthquakes and other disasters.

While this study focused on a particular case study, that of maritime transportation of fuel in coastal British Columbia, the preliminary findings provide generalized insights into the problem of measuring and modeling infrastructure performance from the perspective of enhancing community resilience. First, a focus on essential commodities provides a valuable approach to linking the physical performance of transportation networks to the impacts on communities during disasters. Commodities such as fuel affect the functionality of other critical infrastructures; for example, emergency response vehicles such as fire trucks, or on-site generators for electric power at hospitals and other facilities. The 2011 Great East Japan earthquake, tsunami, and nuclear disaster provides a recent case where fuel shortages hampered emergency response and relief [13]. Fuel is also as essential as the road network itself for general population mobility. Second, a resilience approach requires being able to model operational responses and their effects on network functionality. The data requirements for a fully implemented functional model are, however, prohibitive. Data collection is resource-intensive and involves numerous challenges, including confidentiality of information. This suggests the need to evaluate tradeoffs between different modeling strategies from the perspective of value for analysis to support resilience decision-making.

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