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A NETWORK LEVEL UNDERSTANDING FOR USED NUCLEAR FUEL TRANSPORTATION

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ABSTRACT

The Government of Canada established the Nuclear Waste Management Organization (**NWMO**) in 2002 to plan, organize, and implement a long-term strategy for the storage of Canada's used nuclear fuel (**UNF**). This UNF would be transported from the seven existing interim storage facilities in the provinces of Manitoba, Ontario, Quebec and New Brunswick to a permanent deep geological repository (**DGR**). Initial assessments showed that both road and railway modes are viable transportation options of the UNF to all potential DGR locations. However, the NWMO did not provide a detailed description for the route selection due to the complex connectedness between the different transportation modes (e.g. road and railway). As such, the focus of the current study is to investigate the complex nature of the interdependence of multi-modal transportation networks when hazardous materials, specifically UNF, are transported. In this respect, a preliminary analysis is performed on the road and railway networks separately to evaluate different characteristics of these networks which are critical to the safe transportation of UNF. Following the preliminary analysis, the current study develops a network-of-networks (**NoN**) framework for multi-modal transportation networks (i.e. road and railway) that is subsequently applied to the case study of the UNF transportation in Canada. This framework includes detailed characteristics and descriptions for all the network components (i.e. nodes, connectivity links and dependency links) to account for many aspects of complexity and societal impacts associated with the interdependence in multi-modal UNF transportation networks. This study also provides an implementation plan for a NoN model using the developed framework.

INTRODUCTION

Nuclear power generation has been in existence in Canada for over half a century (Brown 2009). All Canadian nuclear reactors use the CANada Deuterium Uranium (CANDU) reactor technology, developed by Canadian scientists and engineers (IAEA 2016). Most nuclear reactor technologies (e.g. pressurized water, boiling water and gas cooled) require complete shutdown for the replacement of the used nuclear fuel (**UNF**), which subsequently increases the station downtime, when no power generation can occur (USNRC 2016, World Nuclear Association 2017). The CANDU uniqueness is due to the fact that, unlike other reactors, removal and replacement of its UNF occurs during operation (World Nuclear Association 2017). This in turn enhances the CANDU reactor performance, allows for optimal runtime and extends the use of the nuclear fuel to its full lifespan (Brooks 2002). As such, the use of nuclear fuel is optimized within the CANDU reactors, not only by maximizing the energy released, but also by minimizing the amount of waste generated (Brooks 2002). Currently, in Canada, UNF is safely stored at licensed facilities on nuclear power plant and laboratory sites within the provinces of Manitoba, Ontario, Quebec, and New Brunswick (Nuclear Waste Management Organization 2016a, Canadian Nuclear Safety Commission 2017). However, all these sites are temporary because the UNF storage containers have a design life of 50 years (Nuclear Waste Management Organization 2016b). As such, similar to other initiatives in Finland, France and Sweden (McCombie 2005) (Nuclear Waste Management Organization 2015a), the federal government of Canada initiated a process to select a suitable and long-term solution for the transportation and storage of the UNF. The need for such a facility is increasing due to the large volume of the existing (2.6 million bundles) and the expected additional UNF (2.6 million bundles) in the coming decades (Nuclear Waste Management Organization 2016a), and the temporary nature of the current interim storage facilities (Nuclear Waste Management Organization 2015b).

Several researchers have focused their attention on developing risk mitigation strategies pertaining to hazardous material transportation using train features and accident characteristics (Verma 2011), a conditional value-at-risk measure (Toumazis and Kwon, 2013), multi-objective location-routing (Samanlioglu 2013) and network design based on a multi-objective mixed integer linear programming model (Zhao et al., 2016). However, no previous strategies adopted a network-of-networks (**NoN**) approach within a multi-modal UNF transportation environment. This approach facilitates better understanding of the complex interdependency between the several infrastructure systems (e.g. transportation, power and communication) that are typically involved in the transportation of such UNF (Boccaletti et al. 2014). More specifically, a NoN model comprises several components (e.g. nodes) that are connected either together within the same network through connectivity links (e.g. physical or digital relationships) or to nodes in other networks through dependency links (Gao et al., 2012, Gale and Kariv 2014). As such, a cascade failure initiated by a single component in one of the networks can be simulated, using a NoN approach, to evaluate the cascade propagation to other nodes in the interdependent networks (Buldyrev et al., 2010, Gao et al. 2012). This NoN simulation approach identifies critical components that, if disrupted, can initiate major cascade failures to several other components within their own and other interdependent networks (Buldyrev et al. 2010).

The current study first looks at complex network theory and provides a description of nodes and links and their associated characteristics. Subsequently, a case study is presented for the transportation of UNF in Canada to potential long-term storage locations. This case study is considered in terms of a road and railway network analysis with shortest distances presented. Finally, a multi-modal (i.e. road and railway networks) NoN framework is presented for the transportation of UNF from the seven interim storage locations to the five potential long-term storage locations in Canada.

COMPLEX NETWORK THEORY

Within the context of complex network theory, a network is a system of connected nodes and links (Barabási 2016). These nodes and links form a web of interconnected components. More specifically, the nodes simulate the components of a system, while the interdependency between these nodes is represented by directed/undirected and weighted/unweighted links (Barabási 2016). A directed network has links which allow for dependency between nodes in one direction only (e.g. one-way street), whereas an undirected network has dependency between nodes in both directions (e.g. two-way street, highway, train track). Some real networks contain both directed and undirected links and are known as multi-directional networks (e.g. city street network). A weighted network consists of specific metrics assigned as link parameters (e.g. link distance in km), while an unweighted network comprises links which do not contain any specific metrics associated with the link parameters. Both weighted and unweighted networks influence the network analysis, as will be discussed further within the NoN framework.

The shortest path has been considered a very effective measure for distance, time and linkages between nodes in complex network theory (Boccaletti et al., 2006). This shortest path is typically evaluated through mathematical representations of the network topology (i.e. the connections between all nodes and links in the network) to coincide with the underlying application (Boccaletti et al. 2006). For example, the shortest path between any pair of nodes can be quantified as: 1) the fewest number of links between these nodes (e.g. in genealogy applications) (Barabási 2016); 2) the shortest physical distance between these nodes (e.g. in transportation applications) (Abraham et al., 2016); or 3) the minimum time between these nodes (e.g. in information transfer applications) (Peer and Sharma, 2007). These definitions of the shortest path are typically used to select the most efficient path between nodes using the network topology.

In transportation applications, the variation between the static and dynamic nature of road and railway network components is important for proper network analysis. More specifically, within the context of complex network theoretic transportation applications, nodes (e.g. intersections and railway stations) and links (e.g. roads and railway tracks) can have either static or dynamic characteristics based on the definition of the network components and the metric and scale required by the model. Static nodes and links have consistent non-time dependent characteristics, while dynamic nodes and links are more complex because of their time-dependent characteristics. The dynamic characteristics of a node or link have been implemented into transportation applications as cyclic, compounding or random (Holme and Saramäki, 2012). This is mainly attributed to the dynamic characteristics (e.g. traffic volume, signal timing and pedestrian volume) associated with a node or link that can vary based on the time of the day when the analysis is performed.

CASE STUDY: TRANSPORTATION OF CANADA’S USED NUCLEAR FUEL

In 2002, the Nuclear Waste Management Organization (**NWMO**) was established by the government of Canada in response to the Nuclear Fuel Waste Act with the mandate to develop and implement a long term UNF management program (Nuclear Waste Management Organization 2015b). In 2007, the NWMO initiated Adaptive Phased Management to transport the UNF to a deep geological repository (**DGR**) location yet to be determined in Canada (Nuclear Waste Management Organization 2016a). This includes a detailed management plan for optimal features based on three technical characteristics: 1) Deep geological disposal in the Canadian shield; 2) Storage at nuclear power generating station sites; and, 3) Centralized storage, above or below ground (Nuclear Waste Management Organization 2005). The management approach allows for “*centralized containment and isolation, flexibility in the pace and manner of implementation, provision for a shallow underground storage facility on the site, continuous monitoring and potential for retrievability”* (Nuclear Waste Management Organization 2005). To address this, twenty-two communities from the provinces of Ontario and Saskatchewan submitted applications to host the proposed DGR (Nuclear Waste Management Organization 2017a). After eight years of investigation, evaluation and community engagement, a short list of only five potential communities currently remains within the selection process (Nuclear Waste Management Organization 2017b). These potential communities still require additional and more detailed studies to ensure the highest level of safety and public involvement before the final DGR location is selected (Nuclear Waste Management Organization 2017b). Critical challenges regarding the selection of the final DGR location include ethics, safety, security, environmental acceptability, public acceptability, economic viability and implementation strategy (McCombie 2005). The objective of the current study is to address safety, environmental acceptability, public acceptability and implementation strategy by developing a NoN framework for the transportation of UNF.

Safe transportation of hazardous materials, such as UNF, is essential to public safety, since any releases can have disastrous consequences on the surrounding communities. This is exemplified by the July 2013 train accident event in Lac-Mégantic, Quebec where about six million litres of petroleum crude oil were released from the tank cars causing several fires and explosions (Transportation Safety Board of Canada 2014). Overall, 47 people were killed, 2,000 people were displaced from their homes and several areas of the downtown core were destroyed (Transportation Safety Board of Canada 2014). More recently, in Ontario, in November 2017, two fuel transport tankers collided north of Toronto. This event yielded a 14 vehicle collision and major explosions on the highway that resulted in three casualties (CBC News

2017). Therefore, such events raise public concerns regarding the safety of hazardous material transportation, including UNF, throughout Canadian road and railway networks.

As part of the preliminary assessments for the DGR selection, the NWMO has indicated that road, railway and a multi-modal method (i.e. road and railway) can be used for the transportation of the UNF (Nuclear Waste Management Organization 2015b). As such, the focus of this case study is to develop a NoN framework for the transportation of UNF to be implemented within the NWMO Adaptive Phased Management in its final stage. In this respect, complex network theory is expected to enhance the analysis and visualization of UNF transportation applications, thus allowing for a detailed problem description and an efficient solution. For example, Figure 1 shows the complex nature of the potential five DGR locations and the seven interim UNF storage facilities. Although there are only 13 nodes shown in Figure 1, the paths from existing interim storage facilities to potential DGR locations are difficult to evaluate using visual assessment. As such, a more accurate representation of the UNF transportation system is still needed to simulate the road network, railway network, and multi-modal NoN. The single network and NoN models can then be used to evaluate the shortest path between the destinations of interest.

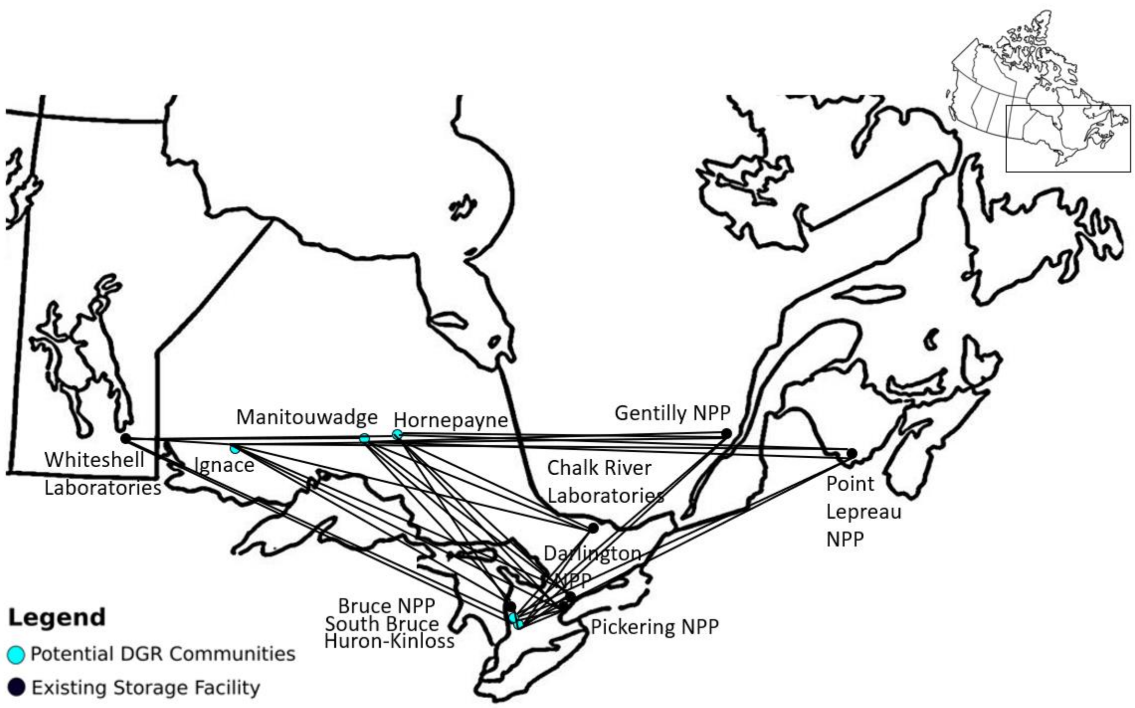

Figure 1. Complex network showing all interim UNF storage locations and potential DGR locations.

ROAD NETWORK

Roads represent the principle conduit of freight transportation in Canada, where trucks transport freight long distances from coast to coast and throughout the interior routes of Canada (Transport Canada 2015). This is mainly attributed to the convenience of road shipping routes because they do not require additional modes of transportation (Transport Canada 2015). These routes can be simulated as a system of nodes (e.g. intersections, highway ramps and destinations) and links (e.g. roads). Although there are multiple routes to reach the targeted destination, complex network theory can facilitate selecting the optimal route, based on specific path selection criteria (e.g. shortest distance, minimum time, least or most use of freeways).

Figure 2 presents the shortest paths using existing road infrastructure from the interim UNF storage facilities to the five potential DGR locations. This provides a more realistic depiction of the road network when compared to Figure 1. There are many instances that the same road is used multiple times for the transportation routes. This is because the shipments of UNF are expected to be transported from similar geographic locations, while the number of roadways in Northern Ontario, Manitoba, Quebec, and New Brunswick is limited. Moreover, the road usage is constrained in this model for two reasons: 1) the route was planned so the UNF would remain within the Canadian border to avoid the need to negotiate additional international agreements; and 2) only major roadways were included in order to avoid the transportation of UNF on local or private roads.

Figure 2. Road network connecting interim UNF storage facilities to potential DGR locations.

RAILWAY NETWORK

The Canadian railway network has been in use for over two centuries, and there have been many upgrades and additional tracks installed to better serve the increasing population over that time (Marsh 2009). In addition, the railway provides a mode of transportation that can haul heavy and large loads over long distances with minimal stoppages. Moreover, railways connect Canada from the East coast to the West coast and provide key routes into Northern Canada. As such, the railway is still considered a major transportation mode for freight throughout Canada (Transport Canada 2015). Although railway tracks are not as prevalent as roadways in Canada, they are strategically located close to major shipping destinations to minimize the loading and unloading time of materials (Transport Canada 2015). This provides a cost effective option for transporting large volume and heavy goods across the country (Association of American Railroads 2015).

Figure 3 presents the shortest paths using the existing railway infrastructure network that connects the interim UNF storage facilities to the five potential DGR locations using existing railway tracks. Several links (e.g. tracks) are used multiple times to connect nodes because there are very few railway tracks throughout Northern Ontario, Manitoba, Quebec, and New Brunswick. In addition, the railway network shown in Figure 3 was designed to maintain train routes within Canada to avoid the need for international agreements with the United States. Moreover, potential DGR site communities are not all serviced directly by railway tracks; however, for the purpose of this paper, additional railway tracks were proposed to connect the end of existing railway lines to the potential DGR communities. As such, an in-depth analysis would still be required once the final site location within the communities is selected. This analysis should review the costs and benefits associated with the proposed additional railway tracks to provide full service from interim UNF storage locations to potential DGR locations for the transportation of the UNF.

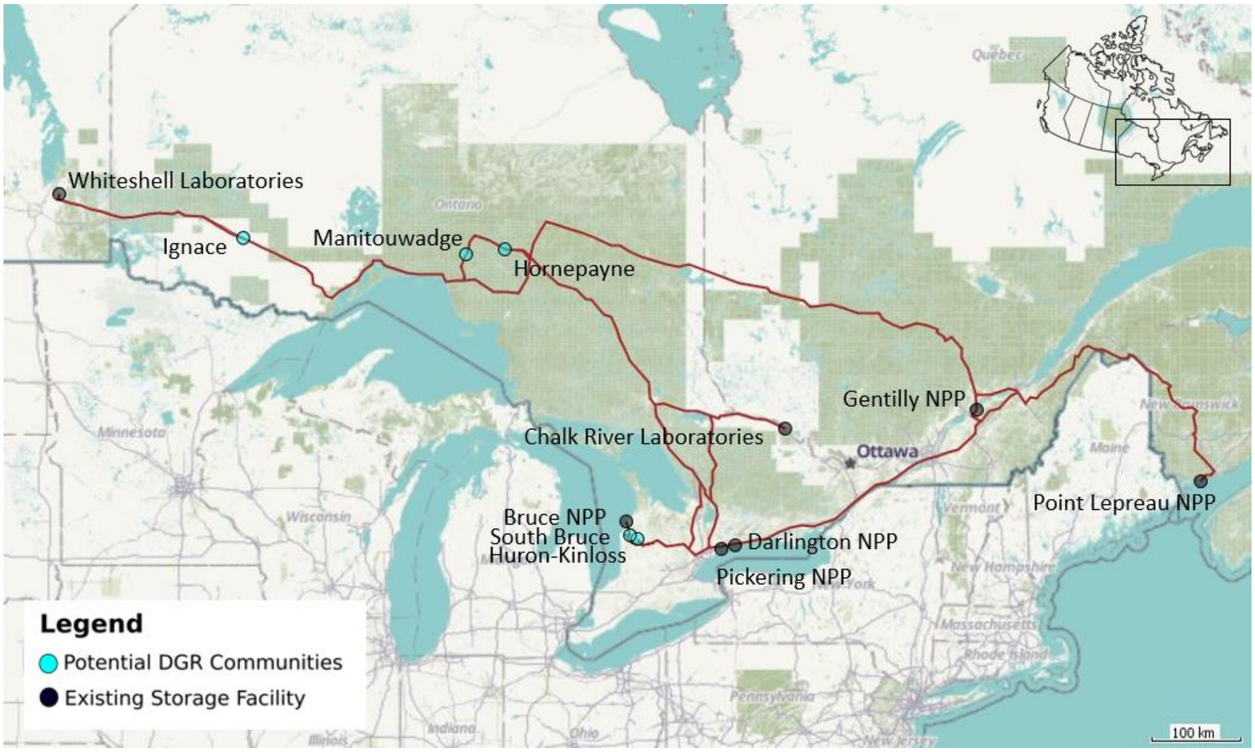

Figure 3. Railway network connecting interim UNF storage facilities to potential DGR locations.

Table 1. Total exposure distances based on conversion of 1 railway shipment equivalent to 10 road shipments. Exposure distances are the summation of 1 equivalent shipment from each of the interim UNF storage locations to the potential DGR locations.

Potential DGR Location	Distance (km)	
	Road	Rail
South Bruce	71,880	7,468
Huron-Kinloss	74,600	7,718
Manitouwadge	113,300	10,803
Hornepayne	109,010	9,995
Ignace	146,460	13,864

Table 1 shows the total exposure distances between each of the interim UNF storage facilities and the five potential DGR locations. The values in Table 1 are presented to incorporate the total public UNF exposure distance for ten road and one railway shipments because the NWMO has projected that one railway shipment will be equivalent to ten road shipments of UNF (Nuclear Waste Management Organization 2015b). This is the reason for the much greater road distances in Table 1. As can be seen in Table 1, South Bruce is the most optimal location for the DGR based on shortest path using road and railway transportation exposure distances. However, these models provide a limited representation of their networks by considering only the shortest distance between nodes and the railway network representation assumes additional infrastructure will be built to accommodate the transportation of UNF from interim storage location to potential DGR locations. Instead, the transportation of the UNF needs a more accurate representation of the networks that includes additional node and link characteristics that can ensure the least risk to the public and incorporate both network's existing infrastructure.

NETWORK-OF-NETWORKS FRAMEWORK

A potential alternative to using either road or railway networks is to use multi-modal transportation routes where both road and railway networks are used for transportation. As such, this study presents a NoN framework that describes the interconnectivity between the road and railway networks shown in Figures 2 and 3, to determine the optimal route between any two destinations. The schematic for the NoN framework is shown in Figure 4. The NoN model would incorporate only existing infrastructure and would therefore not need to make assumptions regarding future infrastructure construction. The NoN framework can be used not only to optimally evaluate the shortest path in terms of time and distance, but also to minimize public safety risks. This section presents a breakdown of the application of this framework, which can then be utilized by the NWMO in Adaptive Phased Management for the transportation of the UNF from existing interim storage facilities to potential DGR locations in Canada.

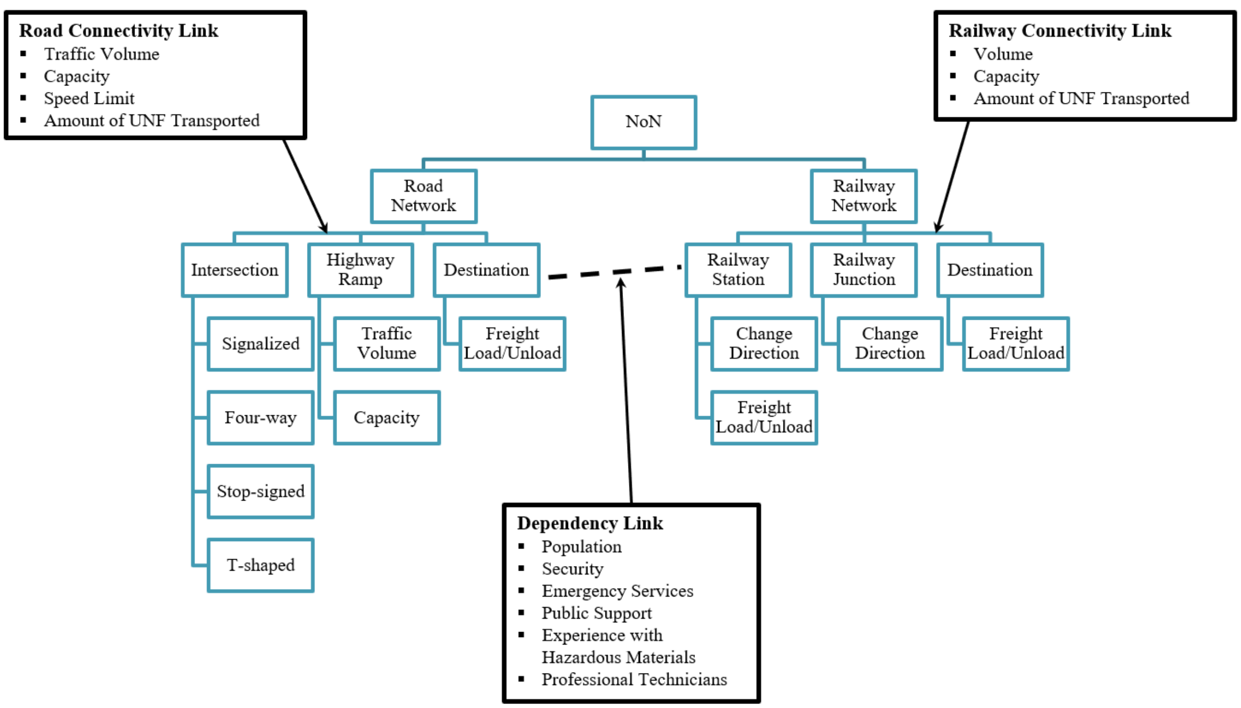

Figure 4. NoN framework schematic with road and railway networks in addition to connectivity and dependency link descriptions.

Figure 4 presents a description of the nodes that would be modeled within a NoN model. The intersections, highway ramps, and destinations would be included for the road network, while the junctions, stations and destinations would be modeled for the railway network. Figure 4 also presents characteristics for each node that describes the behaviour. The node characteristics would allow for a more in-depth model to be developed so that time-based node characteristics could be included which would aid in the understanding of the time-based impacts to the UNF transportation routes. The links of the NoN frameworks are presented in terms of connectivity links that join the nodes within the road and railway network individually and dependency links that connect the road and railway networks together. The connectivity links within a road network are the roads and they have characteristics of traffic volume, capacity, speed limit, and amount of UNF transported. The railway network connectivity link characteristics are presented as volume, capacity, and amount of UNF transported. Both network connectivity link characteristics can be used as link weights for the shortest path determination between interim UNF storage facilities and potential DGR locations. Using these characteristics as the link weights allows the NoN model to develop time-based analysis for the safest UNF transportation route. The interdependency between the road and railway networks is represented through dependency links which are known as intermodal yards where there are existing facilities and equipment capabilities for transferring hazardous materials between trucks and freight cars (Assadipour et al. 2015). The dependency links also have characteristics that would further advance a NoN model to capture the time-based characteristics to ensure a safe and efficient transportation route for UNF between interim storage facilities and potential DGR locations.

NoN Implementation

The NoN framework presented in the current study can be used to evaluate shortest paths based on multiple different objectives and subsequently evaluate the UNF transportation within the NoN framework to find vulnerabilities. More specifically, in order to account for these different objectives within the analysis, the NoN model must be developed first to include the road and railway networks individually before being connected through their dependency links, as depicted in Figure 4. The shortest paths evaluated through the NoN can be based on different objectives pertaining to the least distance, shortest time, fewest intersected nodes (e.g. bridges, bodies of water, ecologically sensitive areas) and least population impact. These objectives can be evaluated individually, and the resulting routes can in turn be compared to identify the optimal route for the UNF transportation.

The risks associated with the UNF transportation can also be evaluated by simulating failure scenarios to different nodes and/or links in the NoN model to investigate how the underlying network can re-distribute the transportation route demands. This evaluation can help planners and decision makers because many failure scenarios are already tested and alternative UNF transportation routes are generated after being licensed by the regulator and approved by the public. Therefore, the NoN approach presented in the current study offers a unique simulation platform to the application of UNF transportation from existing interim storage facilities to potential DGR locations in Canada.

Based on the above, the NoN approach can provide a holistic platform for detailed analysis to be performed in a timely manner projecting accurate and effective results. More specifically, this NoN approach would allow for increased analysis capabilities through the combination of road and railway networks for the transportation of the UNF to identify optimal routes of travel using both modes and to identify and subsequently plan for vulnerabilities in the network. The implementation of the NoN characteristics described within Figure 4 would allow for a real time monitoring for the duration of the transportation of UNF. This real time monitoring would allow for re-routing to occur that had already been planned and approved because of the NoN vulnerability simulation.

CONCLUSION

In 2002, the NWMO initiated the process to select an optimal location for a DGR where Canada's UNF could be stored long term. There are still five communities in the selection process. As such, there is a need to select one community to host the DGR in order to provide proper planning time to ensure the safe transportation of the UNF throughout Canada. This study focused on developing a NoN framework that could be applied to the transportation of UNF with a specific case study to transportation of Canada's UNF from existing interim storage facilities to the potential DGR locations in Canada.

The NoN framework presented in this study provides an overview of the complex nature resulting from the interconnection of the road and railway networks for the transportation of UNF. This framework highlighted the nodes and links which make up the road and railway networks and provided a description for the characteristics of each network component. The node characteristics were described to be static or dynamic to indicate the effect of time on the simulation model. The connectivity link characteristics were described as static or dynamic, directed or undirected, and weighted or unweighted. This characterization allowed for the framework to present an understanding of how the NoN model would be constructed and the impacts of each node and connectivity link characteristic on the result of the NoN model. Specific characteristics were presented also for the dependency links which connected the road and railway networks to develop the NoN structure. The isolation of specific node, connectivity link and dependency link characteristics also allowed for the breakdown of the complex problem into smaller, more manageable tasks which can now be executed according to the described implementation plan of the NoN framework. This also provided a real time monitoring approach for the transportation of UNF from interim storage facilities to potential DGR locations in Canada.

The NoN framework was developed with the constraint that the UNF would not be transported on any local roads and would not be required to cross any borders to avoid further international arrangements. Future work can be done to build the NoN model based on this NoN framework with the inclusion of the node and link characteristics described.

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