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CONSTRAINTS IN THE CANADIAN TRANSPORT INFRASTRUCTURE GRID

JEAN-PAUL RODRIGUE

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FOREWORD

THE CANADIAN NORTHERN CORRIDOR RESEARCH PROGRAM PAPER SERIES

This paper is part of a special series in *The School of Public Policy Publications*, examining the potential for economic corridors in Canada. This paper is an output of the Canadian Northern Corridor Research Program.

The Canadian Northern Corridor Research Program at The School of Public Policy, University of Calgary is the leading platform for providing information and analysis necessary to establish the feasibility and desirability of a network of multi-modal rights-of-way across middle and northern Canada. Endorsed by the Senate of Canada, this work responds to the Council of the Federation's July 2019 call for informed discussion of pan-Canadian economic corridors as a key input to strengthening growth across Canada and "a strong, sustainable and environmentally responsible economy." This Research Program will help all Canadians benefit from improved infrastructure development in Canada.

This paper *"Constraints in the Canadian Infrastructure Grid"* falls under the Strategic and Trade Dimensions theme of the program's eight research themes:

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Dr. Jennifer Winter
Program Director, Canadian Northern Corridor Research Program

CONSTRAINTS IN THE CANADIAN TRANSPORT INFRASTRUCTURE GRID*

Jean-Paul Rodrigue

KEY MESSAGES

- **The corridor as a bottleneck co-ordination mechanism.** The core foundation of corridor development is to maximize the density of flows along an axis by identifying and mitigating bottlenecks. Canadian transport infrastructure grids are not a fully integrated system because of Canada's inherent geographical and economic characteristics. Corridor identification and development becomes a strategy to co-ordinate infrastructure investment.

- **Limited latent demand of northern corridors.** Developing and operating a transport corridor in northern areas is more costly and has much more limited commercial opportunities than a similar corridor in lower latitudes. Population and economic density are unavoidable constraints in corridor development. Outside punctual resource development, there is limited latent demand that a northern corridor could unleash.

- **Development of latitudinal corridors in the medium term and longitudinal corridors in the long term.** Developing a northern corridor is challenging to integrate with the existing transportation infrastructure pattern, while latent demand benefits appear marginal. There are no apparent commercial incentives to build a northern corridor, but segments can be considered on a case-by-case basis. Developing latitudinal corridors that would eventually be reinforced by longitudinal corridors appears to be a more effective strategy.

- **Enduring opposition and governance issues to corridor development.** Different levels of opposition and delays to infrastructure projects undermine the co-ordination potential of corridor development and the commercial viability of crucial infrastructure. Outside specific northern connectors to resources such as mining, energy and logging, the private sector has limited incentives to provide infrastructure or services to low-density areas. Sole private ownership and operation of infrastructure are unlikely unless supported by massive subsidies.

* This research was financially supported by the Government of Canada via a partnership with Western Economic Diversification.

CONTRAINTES DU RÉSEAU CANADIEN D'INFRASTRUCTURES DE TRANSPORT*

Jean-Paul Rodrigue

MESSAGES CLÉS

- **Le corridor comme mécanisme de coordination des goulots d'étranglement.** Le fondement sous-jacent au développement des corridors est de maximiser la densité des flux le long d'un axe, en identifiant et en atténuant les goulots d'étranglement. Au Canada, les réseaux d'infrastructures de transport ne constituent pas un système pleinement intégré, et ce, en raison des caractéristiques géographiques et économiques inhérentes au pays. L'identification et le développement des corridors sont une stratégie pour coordonner les investissements dans l'infrastructure.

- **Demande latente limitée pour les corridors nordiques.** Le développement et l'exploitation d'un corridor de transport dans les régions nordiques sont plus coûteux et les opportunités commerciales y sont beaucoup plus limitées que pour un corridor similaire dans des latitudes plus basses. La population et la densité économique sont des contraintes inévitables dans le développement de corridors. Hormis le développement ponctuel des ressources, la demande latente que pourrait libérer le corridor nordique canadien demeure limitée.

- **Développement de corridors latitudinaux à moyen terme et de corridors longitudinaux à long terme.** L'aménagement d'un corridor nordique est difficile à intégrer au modèle d'infrastructure de transport existant, tandis que les avantages liés à la demande latente semblent marginaux. Il n'y a aucun incitatif commercial apparent pour construire un corridor nordique, mais des segments pourraient être considérés au cas par cas. Le développement de corridors latitudinaux, qui seraient éventuellement renforcés par des corridors longitudinaux, semble une stratégie plus efficace.

- **Problèmes persistants d'opposition et de gouvernance.** Les différents niveaux d'opposition et les retards des projets d'infrastructure sapent le potentiel de coordination pour le développement de corridors ainsi que la viabilité commerciale des infrastructures essentielles. En dehors des connexions nordiques spécifiques aux ressources telles que l'exploitation minière, l'énergie et l'exploitation forestière, il y a peu d'incitatifs pour favoriser l'installation, par le secteur privé, d'une infrastructure dans les zones à faible densité. La propriété privée et l'exploitation de l'infrastructure sont peu probables sans l'apport de subventions massives.

* Cette recherche a été soutenue financièrement en partie par le gouvernement du Canada via Diversification de l'économie de l'Ouest Canada.

SUMMARY

In support of the Canadian northern corridor research agenda, the purpose of this report is to compile a review and evaluation of the constraints impairing the Canadian transport infrastructure grid. The corridor concept aims to reduce the costs, duplication and delays associated with the construction of transportation and ancillary infrastructure. These include diversification of export markets, supporting Indigenous and northern development, expanding interregional and international trade, enhancing northern security and relieving bottlenecks and constraints to the existing transportation infrastructure grid.

Corridors have become important geographical constructs that help articulate public policy and infrastructure investments. They can be functional entities, meaning that they are commercially used and provide economic opportunities for surrounding communities and returns on investment for their users. Corridors can also be notional when they are part of a planning exercise that seeks to create a new functional entity.

Transportation infrastructure supporting corridors is complex, capital intensive and subject to an array of constraints in construction, maintenance and upgrade. These constraints include physical and environmental restrictions, level of transport demand, financial capabilities, construction and maintenance capabilities and costs, and regulatory oversight.

Constraints in the transportation system commonly take the form of bottlenecks, imposing delays and restrictions in the normal flow of transportation. They underscore that a constraint to transportation infrastructure usually occurs at specific locations and for specific causes. There are three major types of bottlenecks — infrastructure, regulatory and operational — that are applicable to the northern corridor concept.

Transportation infrastructure and networks have unique vulnerabilities that vary by mode. A review of the major vulnerabilities by modal network reveals that the hubbing propensity (command of flows and logistics by a limited number of nodes) is particularly subject to vulnerabilities. Rail networks are especially important to the Canadian economy and are structured as a linear nodal hierarchy that is vulnerable to disruptions.

Due to its geographical attributes, Canada has unique constraints on the development and operation of its transport infrastructure. The most salient bottlenecks related to the northern corridor initiative include:

- Ports on the Canadian East Coast have some draft limitations but provide extensive hinterland accessibility by rail. Montreal and the St. Lawrence remain inaccessible to the majority post-Panamax container ships, notably the Neopanamax class, able to transit the expanded Panama Canal. This represents a long-term risk that the St. Lawrence (Montreal) could be marginalized as a gateway to Eastern Canada, with some of the traffic handled by American East Coast ports.

- Due to ice conditions, the Port of Churchill is only open from late July until November, severely undermining its commercial potential. Its poor inland connectivity undermines its use as an Arctic port, even as a base to resupply Arctic communities.
- Summer sealift and ferry services are essential to resupply local communities and bring project cargoes. However, they have limited capacity and are seriously constrained by a short operational window (July to September).
- There are limited incentives to connect northern Canadian towns with jet and propeller services, mainly because of the low volumes generated. While jet services allow for carrying a good quantity of cargo, the runways that can accommodate them are more limited.
- Low economic density and vast distances undermine the Arctic's potential as an air transport market. The structure of the northern air transport network does not allow for direct connections between northern and Arctic communities since they do not generate enough traffic. Connections between communities must thus use a southern hub such as Edmonton, Winnipeg, Toronto, Ottawa or Montreal.
- Permafrost remains a severe impediment to the construction and maintenance of road, rail and pipeline infrastructure. The more northern the infrastructure, the higher the construction and maintenance costs, and therefore the more economically attractive the infrastructure project needs to be to justify an investment.
- The lack of pipeline capacity to the West Coast and the United States is a major impediment to Canada's energy exports and expanding this capacity remains controversial.
- Winter impairment of road and rail operations remains a constant issue in northern areas, requiring the costly positioning of equipment and crews over long distances.
- Because of its high reliance on hydro power, Canada requires long-distance, high-voltage power lines that have some vulnerability to geomagnetic storms and freezing rain.
- The availability of telecommunication services is bound to population density, particularly for wireless services. While northern communities have access to telecommunication services, they are generally of lower bandwidth and limited spatial coverage.

RÉSUMÉ

En appui au programme de recherche sur le corridor nordique canadien, le but de ce rapport est d'examiner et d'évaluer les contraintes qui nuisent au réseau canadien d'infrastructures de transport. Le concept de corridor vise à réduire les coûts, les dédoublements et les retards associés à la construction d'infrastructures de transport ou auxiliaires. Cela comprend la diversification des marchés d'exportation, le soutien au développement des communautés autochtones et du Nord, l'expansion du commerce interrégional et international, le renforcement de la sécurité dans le Nord ainsi que l'atténuation des goulots d'étranglement et des contraintes qui caractérisent le réseau d'infrastructures de transport actuel.

Les corridors sont devenus des constructions géographiques importantes qui aident à articuler les politiques publiques et les investissements dans l'infrastructure. Ils peuvent être des entités fonctionnelles, c'est-à-dire qu'ils sont utilisés à des fins commerciales et offrent des opportunités économiques aux communautés environnantes ainsi qu'un retour sur investissement pour leurs utilisateurs. Les corridors peuvent également être théoriques lorsqu'ils font partie d'un exercice de planification visant à créer une nouvelle entité fonctionnelle.

L'infrastructure de transport le long des corridors est une entreprise complexe, capitalistique et soumise à un éventail de contraintes en matière de construction, d'entretien et de mise à niveau. Ces contraintes comprennent les restrictions physiques et environnementales, le niveau de la demande de transport, les capacités financières, les capacités et les coûts de construction et d'entretien ainsi que la surveillance réglementaire.

Les contraintes du système de transport prennent généralement la forme de goulots d'étranglement, lesquels imposent des retards et des restrictions dans le flux normal de transport. Ils font voir que les contraintes à l'infrastructure de transport se trouvent généralement à des endroits précis, pour des causes spécifiques. Trois principaux types de goulots d'étranglement s'appliquent au concept du corridor nordique : les goulots d'étranglement infrastructurels, réglementaires et opérationnels.

L'infrastructure et les réseaux de transport présentent des vulnérabilités propres, lesquelles varient selon le mode. L'examen des principales vulnérabilités, selon le réseau modal, révèle que la propension à une organisation en étoile, ou « hubbing » (c'est-à-dire que les flux et la logistique sont assurés par un nombre limité de nœuds), est très sujette aux vulnérabilités. Les réseaux ferroviaires sont particulièrement importants pour l'économie canadienne et ils sont structurés en une hiérarchie nodale linéaire vulnérable aux perturbations.

En raison de ses caractéristiques géographiques, le Canada connaît des contraintes particulières en matière de développement et d'exploitation de l'infrastructure de transport. Les principaux goulots d'étranglement liés au projet du corridor nordique sont les suivants :

- Le tirant d'eau des ports de la côte est du Canada est limité, mais ces ports offrent une grande accessibilité à l'arrière-pays par chemin de fer. Montréal et le fleuve Saint-Laurent demeurent inaccessibles à la majorité des porte-conteneurs de type post-Panamax, notamment ceux de la classe Neopanamax, capables de transiter par le canal de Panama élargi. Il y a risque à long terme que le Saint-Laurent (Montréal) soit marginalisé en tant que porte d'entrée pour l'Est du Canada, une partie du trafic étant gérée par les ports de la côte est américaine.
- En raison des glaces, le port de Churchill n'est ouvert que de la fin juillet à novembre, ce qui compromet fortement son potentiel commercial. Sa mauvaise connectivité intérieure compromet son utilisation comme port arctique, et même comme base de ravitaillement pour les communautés arctiques.
- Les services estivaux de transport maritime et de traversier sont essentiels pour réapprovisionner les communautés locales et pour le transport de charges lourdes. Cependant, leur capacité est faible et ils sont sérieusement limités par le court créneau saisonnier d'activités (de juillet à septembre).
- Il y a peu d'incitatifs à relier les villes nordiques canadiennes par service aérien, principalement en raison des faibles volumes d'activités. Alors que les avions à réaction permettent de transporter une quantité appréciable de marchandises, les pistes en mesure de les accueillir sont plus rares.
- La faible densité économique et les longues distances sapent le potentiel de l'Arctique en tant que marché pour le transport aérien. La structure du réseau de transport aérien du Nord n'assure pas de liaisons directes entre les communautés nordiques et arctiques puisque le trafic n'y est pas suffisant. Les connexions entre ces communautés se font via une plaque tournante plus au sud, comme Edmonton, Winnipeg, Toronto, Ottawa ou Montréal.
- Le pergélisol demeure un obstacle majeur à la construction et à l'entretien de l'infrastructure routière, ferroviaire ou pipelinière. Plus l'infrastructure se trouve au nord, plus les coûts de construction ou d'entretien sont élevés et plus le projet doit être économiquement attrayant pour justifier l'investissement.
- Le manque de capacité pipelinière vers la côte ouest et vers les États-Unis constitue un obstacle majeur à l'exportation d'énergie du Canada. L'augmentation de leur capacité reste controversée.
- La dégradation hivernale des routes et des chemins de fer demeure un problème constant dans les régions nordiques, ce qui demande un coûteux positionnement d'équipement et de travailleurs sur de longues distances.
- En raison de sa forte dépendance à l'hydroélectricité, le Canada a besoin de lignes électriques longue distance à haute tension, ce qui constitue une certaine vulnérabilité aux tempêtes géomagnétiques et à la pluie verglaçante.
- La disponibilité des services de télécommunication est liée à la densité de la population, en particulier pour les services sans fil. Bien que les collectivités du Nord aient accès aux services de télécommunication, ils se font généralement au moyen d'une bande passante plus faible avec une couverture spatiale limitée.

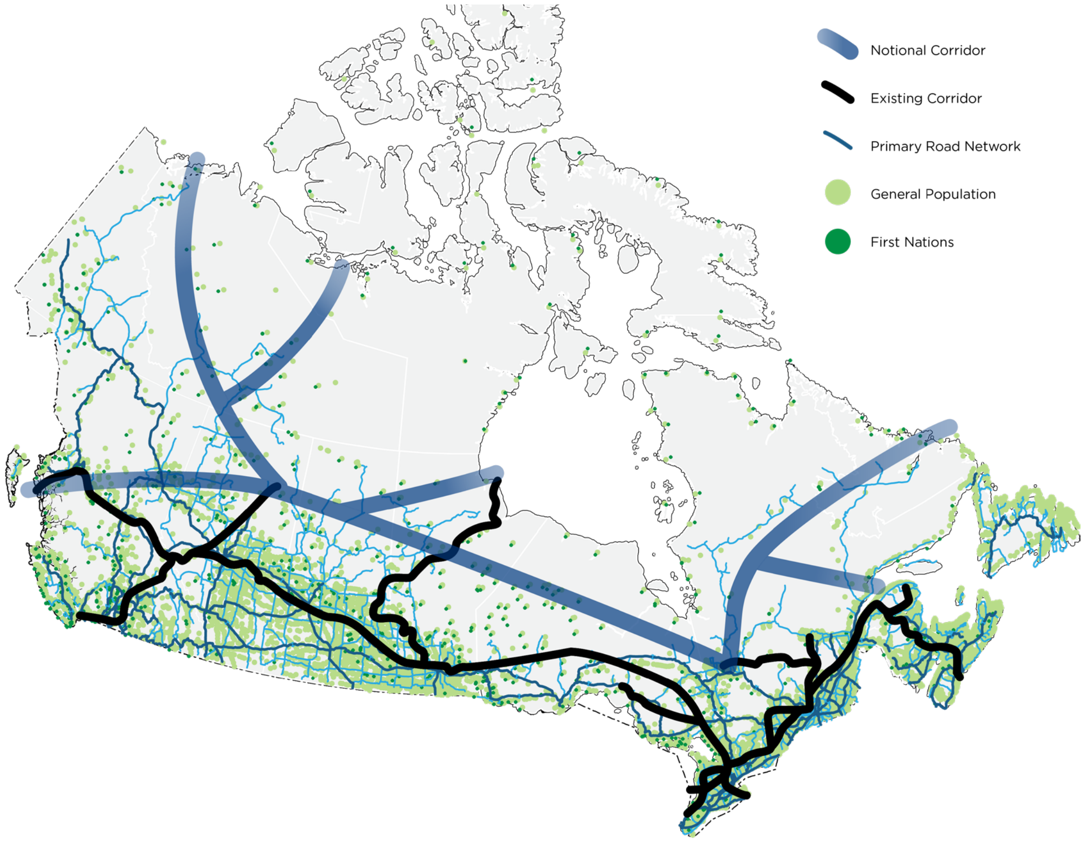
INTRODUCTION: THE RELEVANCE OF CANADIAN CORRIDORS

Transport corridors are considered backbones of transportation networks, linking major gateways with their hinterlands. They support freight and passenger flows along a linear orientation of infrastructure that can span thousands of kilometres and are crucial to the function of a continental-sized economy such as Canada's. Corridors lie at the intersection of economic, demographic and geographic processes as they perform market-serving and market-connecting functions (Primus and Zonneveld 2003). Thus, a corridor is neither temporally nor spatially immutable, but rather dynamic, contingent on the economic context, e.g., trade liberalization (Fellows and Tombe 2018a, b), investments in infrastructure and technological changes (e.g., information corridors) and public policy. Corridors come in two main categories:

- **Functional corridors**. An operational corridor represents an existing structure of flows along modal and intermodal infrastructure. The corridor is thus an operational reality that is acknowledged and used for commercial purposes, which allows for recovering infrastructure investments. A functional corridor is profitable through the generation of economic opportunities for the communities it connects and revenue for operators and carriers.
- **Notional corridors**. A notional corridor is a construct that attempts to expand the planning and investment framework of the involved public and private actors. Often, a form of governance, or at least a forum, has been set up to address some of the corridor's challenges, such as articulating investments and mitigating bottlenecks. The corridor is thus a political or a planning agenda pursued by public authorities and advocacy groups.

The most advanced corridors combine notional and functional characteristics since they convey observed economic benefits and are recognized by public authorities. A significant risk is that a notional corridor expressed as a planning goal does not become a functional corridor supported by commercial usage, which can lead to misallocations of infrastructure investments (Bradbury 2002). Figure 1 emphasizes this distinction as the existing Canadian corridors reflect actual passenger and freight flows. In contrast, the notional corridors are an expectation of corridors that future infrastructure development could help create. All these notional corridors are being considered as potential northern corridors.

Figure 1. Notional and Functional Corridors in Canada[1]



Transport corridors can display physical variations on a modal basis as infrastructure layout becomes a determining factor. Rail tends to be the support for long-distance corridors while roads support medium- to short-distance interactions. Therefore, transport infrastructure is a crucial element supporting corridors, and this report considers the main Canadian infrastructural constraints with the purpose of assessing the potential of northern corridors that have so far remained more notional than functional realities. Such an approach first requires an overview of the major constraints impacting transportation infrastructure, particularly in terms of bottlenecks and vulnerabilities (Section I). Then, a comprehensive overview of the Canadian transport infrastructure grid is provided, and for each infrastructure category, its main bottlenecks (Section II). Finally, the report proposes a series of strategies to help mitigate infrastructure bottlenecks, considering the constraints of northern corridors (Section III).

I. TRANSPORT INFRASTRUCTURE AND ITS CONSTRAINTS

Transportation infrastructure is the fixed element of the transportation system that supports the mobility of vehicles and conveyances. This element also includes

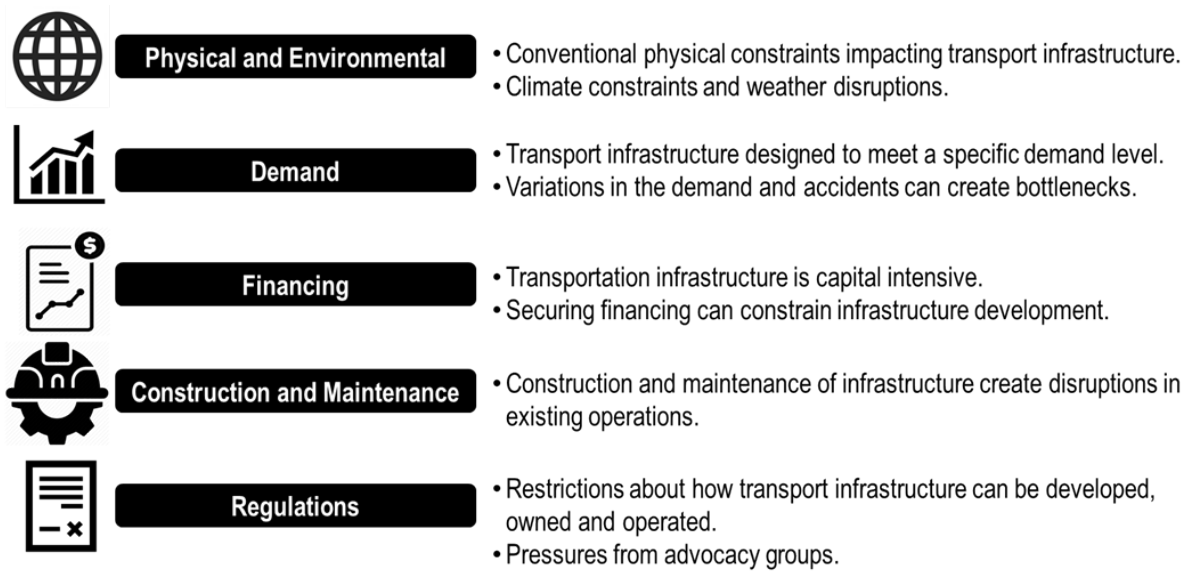
1 Source: University of Calgary, School of Public Policy.

superstructures that are moveable assets required for the infrastructure to function, such as signage, terminal equipment and buildings. Infrastructure has capacity limitations that define the volume and level of service it can offer under normal circumstances.

A. WHICH FACTORS CONSTRAIN TRANSPORTATION?

To operate efficiently, a transport system must function with as few constraints as possible. However, transport infrastructure remains constrained by several factors, including the physical environment, the level of demand, the availability of capital and the regulatory environment (Figure 2).

Figure 2. Factors Constraining Transport Infrastructure



Physical and Environmental Restrictions

Conventional physical constraints, such as topography and hydrography, have enduring impacts on transport infrastructure. They impose barriers that have shaped the development of transportation infrastructure for centuries. Any physical constraints impose higher construction and maintenance costs that can only be justified by higher economic and social opportunities. Transportation network density and connectivity are usually at their highest in areas with low physical constraints, underlining the standard geographical influence on mobility and productivity. Weather disruptions and climate also constrain transportation infrastructure by increasing its construction and maintenance costs as well as by impairing operations.

Demand

Transport infrastructure is designed to meet a specific demand level by offering a defined capacity and a level of service. For instance, a road segment can handle a specific number of vehicles per hour, or a port can transship a defined quantity of cargo per work shift. Variations in the demand, often linked with seasonality, can create bottlenecks as parts of the network do not support additional volumes. Peak periods of traffic activity are usually above the design capacity of the supporting infrastructure, creating delays. This also involves accidents creating disruptions, which are more likely to occur at high-traffic locations in the transport network.

Inversely, there is a latent demand issue that transportation infrastructure can support and occasionally reveal. The lack of transport infrastructure may undermine economic opportunities in terms of production, consumption and distribution.

Financial

Transportation infrastructure is capital intensive, and securing financing can constrain its development or even its maintenance. Allocating scarce resources for transportation infrastructure requires careful consideration of the expected economic and social benefits. If these benefits are uncertain, infrastructure development could be impaired, which is particularly the case for peripheral areas. For some infrastructure, such as rail, airports and port terminals, the private sector is willing to commit capital since the return on investment can be estimated. For other infrastructure, namely roads, the public sector can invest using a taxation base but with limited expectations of direct recovery of invested funds. The infrastructure is provided on the grounds of public service. Typically, the mutual availability of private and public funding can help the development of transport infrastructure since public commitment can help mitigate risk.

Construction and Maintenance

Transport infrastructure is intensive in construction, maintenance and repair activities that involve heavy equipment and materials. These activities create disruptions in existing operations by reducing the available capacity (e.g., lane closure) and reducing operational speed. They require the organization of labour, equipment and material resources that may not be readily available on site, and that would need to be brought in, which comes at a cost. This is particularly the case in remote areas or developing economies where labour, equipment and materials cannot be sourced locally. Moving what is called project cargo[2] can be a notable constraint to the construction and maintenance of transportation infrastructure.

Regulations

Regulations impose restrictions on how transport infrastructure can be developed, owned and operated, namely through compliance. Compliance with environmental regulations has become an essential constraint in infrastructure development, adding costs and delays. Pressures from advocacy groups that increasingly see transport infrastructure negatively also impose additional costs, delays and even the

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2 The transportation of large and complex pieces of equipment and the associated materials to complete a construction project.

abandonment of a project. The promoter of a transport infrastructure project may, therefore, face a multiplicity of regulations and advocacy groups.

B. WHAT ARE THE MAIN TRANSPORTATION BOTTLENECKS?

Bottlenecks impose delays and restrictions in the normal flow of transportation and demonstrate that a constraint to transportation infrastructure usually occurs at specific locations and for specific reasons (Cambridge Systematics 2005). Three major types of bottlenecks — infrastructure, regulatory and operational — apply to the northern corridor.

Infrastructure Bottlenecks

Infrastructure bottlenecks can be the outcome of chronic or temporary conditions. Climate change can alter conditions that could damage transport infrastructure and shorten its useful life. Physical restrictions can form bottlenecks as traffic expands, such as for a bridge or a port. Under-investment in infrastructure can produce chronic bottlenecks when rapid economic growth occurs, suggesting that the capacity is insufficient to keep up with demand. Natural or market forces can cause temporary bottlenecks. Weather disruptions, such as a storm, are among the most prominent of these, as well as construction, accidents and labour conflicts (strikes). These events are usually expected but cannot be predicted. A surge in demand can also create a bottleneck as infrastructure is designed to convey a constant level of service. Dis-investment, often through lack of maintenance, can cause temporary bottlenecks as the transport infrastructure degrades.

Regulatory Bottlenecks

Regulations that delay the movement of goods for security or safety inspections create bottlenecks as a direct consequence (Brooks 2008). If international movements are concerned, custom procedures for passengers and freight are a common source of delays, mainly through physical inspections and documentation. There is also the potential for corruption, imposing uncertainty and a burden on transport operations through delays, inspection costs and bribes (Kenny 2009). In advanced economies such as Canada, corruption is not perceived to be a relevant issue since such economies usually rank high (low corruption) on transparency indexes (Transparency International 2019). However, the construction industry is considered to be one of the sectors most prone to corruption, particularly for public transportation infrastructure subject to large, long-term contracts. This corruption can be apparent, such as in developing economies, or subjective when subject to advocacy and lobbying efforts by political and trade groups or individual firms.

Cabotage restrictions, competition policies and fiscal policies are three causes of bottlenecks created by the indirect effects of regulation. Cabotage restrictions prevent foreign carriers from carrying passengers or freight within a country; their capacity is thus not available on the national market. Cabotage rules thus allow domestic operators to be more profitable, particularly in situations of limited demand and high operating costs characterizing remote and marginal markets. Competition policies can create bottlenecks by supporting a monopoly in which the operator engages in rent-seeking strategies or by complete deregulation, when many carriers will compete with similar transport segments. Fiscal policies can deter and delay investments through taxation and create bottlenecks.

Operational Bottlenecks

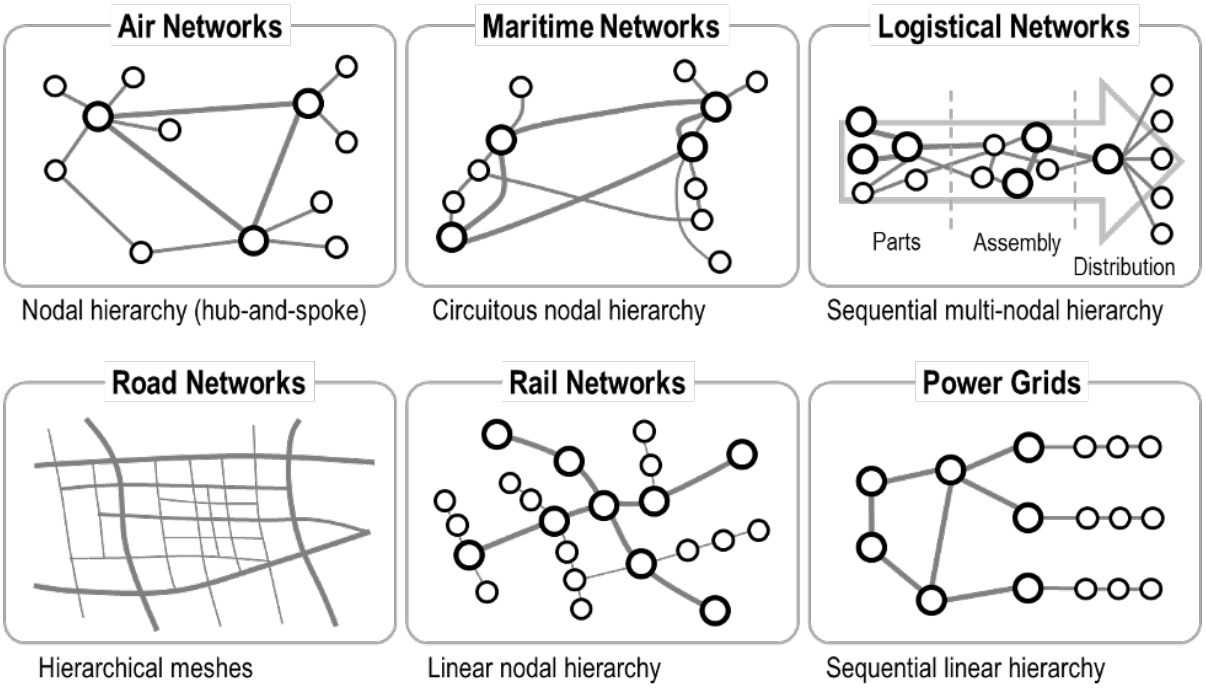
Specific tasks and procedures in the management of transportation modes and terminals trigger bottlenecks. From a capacity perspective, the availability of equipment and vehicles can create bottlenecks as the necessary conveyances may not be where their capacity is needed. Positioning or repositioning transportation assets such as aircraft, ships, trucks or empty containers adds costs.

Further, labour availability, such as work shifts, may impose time-dependent capacity shortages. From an efficiency perspective, the productivity of modes and terminals can vary along the transport chain and can create bottlenecks. This is particularly the case when tasks and sequences along a transport chain are not adequately co-ordinated or when labour skills are lacking. Different information exchange protocols can create delays in information processing and therefore delays in shipments (or transshipment).

C. THE VULNERABILITY OF TRANSPORTATION NETWORKS

The transport industry has undertaken massive investments in infrastructure and facilities that have expanded the capacity and efficiency of transportation networks across the world. Added flows and infrastructure capacities have increased the demands on the management of physical distribution systems, which includes activities such as transportation, transshipment, warehousing, insurance and retailing. They are of strategic importance to national economies, but this importance varies according to their physical and economic geography. Due to their scale and connectivity, transportation networks are particularly vulnerable (Linkov and Palma-Oliviera 2017), but this vulnerability is related to the unique characteristics of each modal network (Figure 3).

Figure 3. Types of Transportation Networks and Vulnerabilities



Air Networks

Air networks are commonly a nodal hierarchy articulated around a hub-and-spoke structure. Nodes (airports) are crucial elements. A node's importance is usually related to the traffic (passengers and freight) it handles and its level of connectivity (links to other nodes). A hierarchy of flows ranges from regional (short-distance feeders) to international (inter-hub). Due to their high degree of hubbing, air transportation networks are particularly vulnerable to disruptions at major hubs, while disruptions at smaller hubs will have limited consequences.

Maritime Networks

Maritime networks are a circuitous nodal hierarchy, meaning that services are commonly arranged along a sequence of nodes (ports) with inter-range services that loop back to the port of origin. While point-to-point services are reflective of bulk shipping, container shipping is organized between deep-sea and feeder services with transshipment hubs acting as the interface. The vulnerability of maritime networks has different considerations depending on whether the node is a hub or a gateway. Disruptions at a hub will mostly impact maritime shipping networks, while disruptions at a gateway will primarily affect the hinterland.

Logistical Networks

Logistical networks are a sequential multi-nodal hierarchy, which means there are separate networks within networks. A typical logistics sequence is organized along three stages: raw materials and parts, manufacturing and distribution, each supported by a specific network (manufacturing network, distribution network). They represent sourcing relationships between actors. Logistical networks are vulnerable to disruptions impacting one actor (e.g., a manufacturing plant, a distribution centre) and the connected activities (upstream and downstream). This is commonly known as the cumulative effect, where a small disruption could result in significant impacts along a supply chain since a product is often made of numerous components, and if a part is missing, a supply chain could come temporarily to a halt.

Road Networks

Road networks are hierarchical meshes, each servicing a different scale. They have no tangible nodes; instead, they have fixed paths with known capacity. While an interstate highway system is designed to connect a nation or a large region, local streets connect only adjacent activities to a broader framework. Because of their mesh structure, road networks are not highly vulnerable to disruptions unless this disruption is on a wide scale (e.g., a significant snowstorm or a hurricane) or impacts a strategic connector such as bridges or tunnels. Still, many large national road networks, such as for Canada, are linear and with more limited connectivity. They can be disrupted if a high-level connection is closed, which forces traffic onto lower level connections that may not have the capacity to handle the load.

Rail Networks

These networks are a linear nodal hierarchy with nodes related to intermodal yards, train and transit stations. Because of the fixed character of their paths and capacity, they are allocated usage windows during which grouped units circulate. While linear rail networks are vulnerable to disruptions, complex rail and transit networks have a mesh-like structure, making them more resilient.

Power Grids

Power-supply networks have a sequential linear hierarchy. The primary nodes are power-generation facilities from which electricity is distributed across high-voltage transmission lines to stations for regional distribution. These substations transform electricity from high to low voltage, which is distributed to facilities for final use. Very close to the final consumer, transformers may further reduce the voltage to safer levels. Power-grid networks are usually highly redundant but subject to a hierarchical vulnerability; the higher up they are in the hierarchy, the more extensive the potential disruption.

Pipelines

Like power grids, pipeline networks have a sequential linear hierarchy (not shown in Figure 3). To fulfil their role, pipelines have four functional hierarchical levels. The first is collecting pipelines that move oil and natural gas from extraction fields to processing facilities. The second is feeder pipelines that move products from processing and storage facilities to transmission pipelines. The third is transmission pipelines, which are major conduits, mostly transporting crude oil and natural gas over long distances and commonly across international jurisdictions. They are essential as they allow major oil- and gas-producing regions to export to major consumption markets. The last level is the distribution pipelines which are small conduits that deliver natural gas to homes, businesses and industries.

II. CANADIAN TRANSPORT INFRASTRUCTURE AND ITS BOTTLENECKS

Due to its geographical attributes, Canada has unique constraints on the development and operation of its transport infrastructure (Anderson, Maoh and Burke 2011; Sulzenko and Fellows 2016). Most of Canada's population lives under a continental humid climate with warm summers and cold winters characterized by notable snow accumulation (Koppen Climate Classification). The main exception is the British Columbian coast, which is under an oceanic climate with mild winters. The rest of the nation, including the Rockies with its alpine climate, is mostly under a dry sub-arctic climate with short summers and harsh winters. Significant temperature variations tax transportation infrastructure with cycles of thermal expansion and contraction that may damage infrastructure made from, or resting on, concrete and asphalt. Bridges, railways and pipelines require expansion joints to absorb thermal expansion and contraction of their materials.

Snow covers about 65 per cent of Canada's land area for more than six months per year. One of the most salient climate constraints concerns permafrost since it impacts the construction, cost and maintenance of every type of transport infrastructure (Transportation Association of Canada 2010). Permafrost is perennially frozen ground that is associated with subsurface ice. As this ice moves, thaws and collapses, the surrounding soil becomes unstable, undermining the integrity of any infrastructure built on top. Permafrost can be impacted by thermal disruptions related to the construction, or the long-term presence, of infrastructure as well as climate change. Building transport infrastructure over permafrost substantially increases costs because of the requirements to mitigate the potential thawing effects. This mitigation can take two forms. The first is to design infrastructure that would prevent thawing; namely, through types of insulation. The second is to develop infrastructure able to handle the destabilization permafrost causes. Constructing transport infrastructure in permafrost conditions tends to be avoided unless it provides clear economic or social benefits.

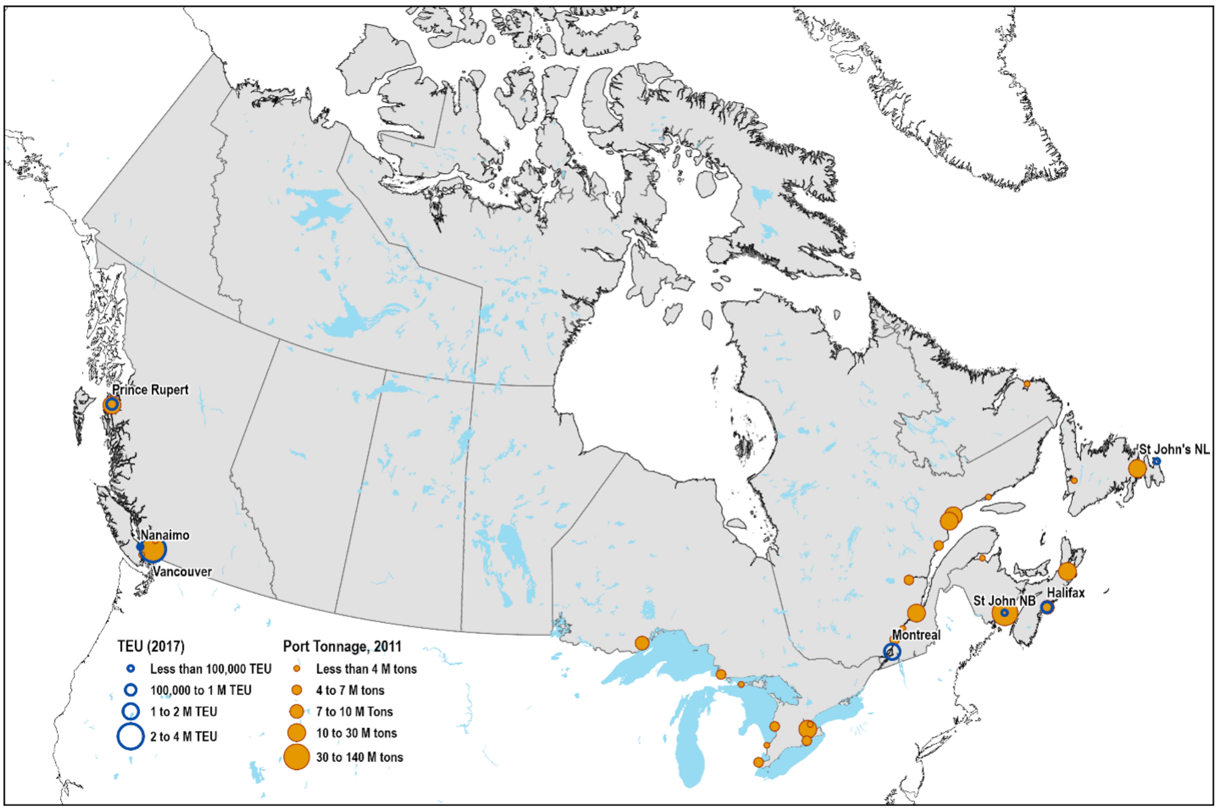
A. TERMINALS: PORTS AND AIRPORTS

The Port System

Canadian port infrastructure is challenged by the comparatively smaller size of the national economy as well as extensive hinterland distances. On each of its coasts, Canada can effectively support two major container ports, limiting commercial options for additional port facility development (Figure 4). On the West Coast, both Prince

Rupert and Vancouver fared well in the last decades. Until the opening of Prince Rupert in 2007, Vancouver was Canada's leading container port on the Pacific, its growth on par with the dynamism of transpacific trade, whose growth rate justified the opening of a new Pacific gateway. However, Prince Rupert's opening came at a very challenging time at the onset of the 2008 financial crisis, which had notable impacts on transpacific container volumes. Nevertheless, the port developed a successful niche based on low transit times and exceeded one million TEU[3] for the first time in 2018.

Figure 4. The Canadian Port System



The situation on the East Coast is one of duality between Montreal and Halifax. While Montreal was able to experience ongoing growth, in part because of its excellent hinterland accessibility, volumes in Halifax have barely changed over two decades. This is a paradoxical situation since Halifax has better maritime accessibility than Montreal. Still, Montreal's market access to Ontario and the American Midwest remains its main advantage despite its nautical limitations.

The East Coast is also supported by the St. Lawrence Seaway and the Great Lakes, which are mainly used to ship heavy, raw materials such as grain, iron ore, coal and steel. The system is closed for about four months each year (mid-December to mid-

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3 Twenty-Foot Equivalent Unit. A standard unit based on an ISO container of 20 feet in length (6.10 m). The TEU is used as a statistical measure of traffic flow or capacity. One standard 40-feet ISO Series 1 container equals two TEUs.

April), limiting commercial opportunities. This is the main reason why the Seaway has not experienced changes in the nature of its traffic, and the volume it handles is steadily declining.

The expectation of developing port infrastructure in the Arctic has led to limited outcomes, with Churchill the only Arctic port of significance. However, Churchill's commercial appeal is seriously challenged, as it never handled more than half a million tonnes of grain per year. The port has seen limited traffic and its rail corridor remains underused. While active since 1931 and connected to the Canadian rail system, the port, privatized in 1991, was closed between 2016 and 2019. In 2019, grain exports resumed under a new private investor, but so far on an experimental basis. Churchill's future as a viable port remains uncertain. Churchill's neglect, its lack of appeal and its rail corridor illustrate the challenges of developing Arctic corridors; Canada's main Arctic port has trouble generating cargo under normal market conditions due to the lack of connecting rail and potentially pipeline infrastructure.

A more specific look at container terminals reveals substantial differences between Canada's east and west coasts (Table 1).

Table 1. Main Container Terminals at Canadian Ports

Terminal	Draft	Capacity (TEU)	Traffic (TEU)	Vol / Cap
Halifax				
South End Container Terminal, Halterm (Macquarie Infrastructure)	16.2 m	780,000	275,000	0.35
Fairview Cove Container Terminal (Ceres)	16.7 m	750,000	290,000	0.39
Saint John (NB)				
Rodney Container Terminal (Dubai Ports World)	12.2 m	150,000	60,000	0.40
Montreal				
Montreal Gateway Terminals (Cast Terminal; Axium Infrastructure)	11.3 m	800,000	385,000	0.48
Montreal Gateway Terminals (Racine Terminal; Axium Infrastructure)	11.3 m	500,000	450,000	0.90
Termont Terminal (Maisonneuve; Ceres)	11.3 m	450,000	580,000	1.29
Termont Terminal (Viau; Ceres)	11.3 m	350,000	100,000	0.29
Prince Rupert				
Fairview Container Terminal (Dubai Ports World)	18.7 m	1,350,000	1,035,000	0.76
Vancouver				
Deltaport (Global Container Terminals)	15.9 m	1,800,000	1,500,000	0.83
Centerm (Dubai Ports World)	15.5 m	750,000	550,000	0.73
Vanterm (Global Container Terminals)	15.5 m	850,000	560,000	0.66

Source: Author and Drewry Shipping Consultants. Note: Capacity is capacity under ideal circumstances either provided by the terminal operator or calculated by Drewry. Traffic is either traffic from the port authority or estimated as a ratio of total port traffic.

The Port of Montreal is a strategic gateway located deep within the North American hinterland. With a draft of about 11.3 metres, the port's terminals can handle standard container ships of around 2,500 TEUs. However, this limitation was improved, and ships of 4,200 TEUs can call Montreal (5,000 TEU is also possible under specific load configuration and higher than average water levels). Further, a new generation of wide-beam container ships handling 5,000 to 6,000 TEU with the same draft is available. However, the St. Lawrence navigation channel between Montreal and Quebec was designed to handle the joint circulation of one Panamax-sized ship in each direction. Without widening the navigation channel, using wide-beam ships would create notable disruptions since the channel is only able to handle one ship passage at a time. The port remains unreachable for most post-Panamax ships, particularly those of the Neopanamax class.

Halifax, on the great circle route, is a convenient location for entry to the North American market from Europe. It has a deep draft (16 metres) and connectivity to the continental rail network with ships up to 11,000 TEUs calling. Unlike Prince Rupert, Halifax does not have large rail volumes towards Central Canada and the American Midwest. It was unable to capitalize on its great-circle advantage with associated long-distance rail services. The Panama Canal expansion, with its associated shipping services, may represent an opportunity to do so.

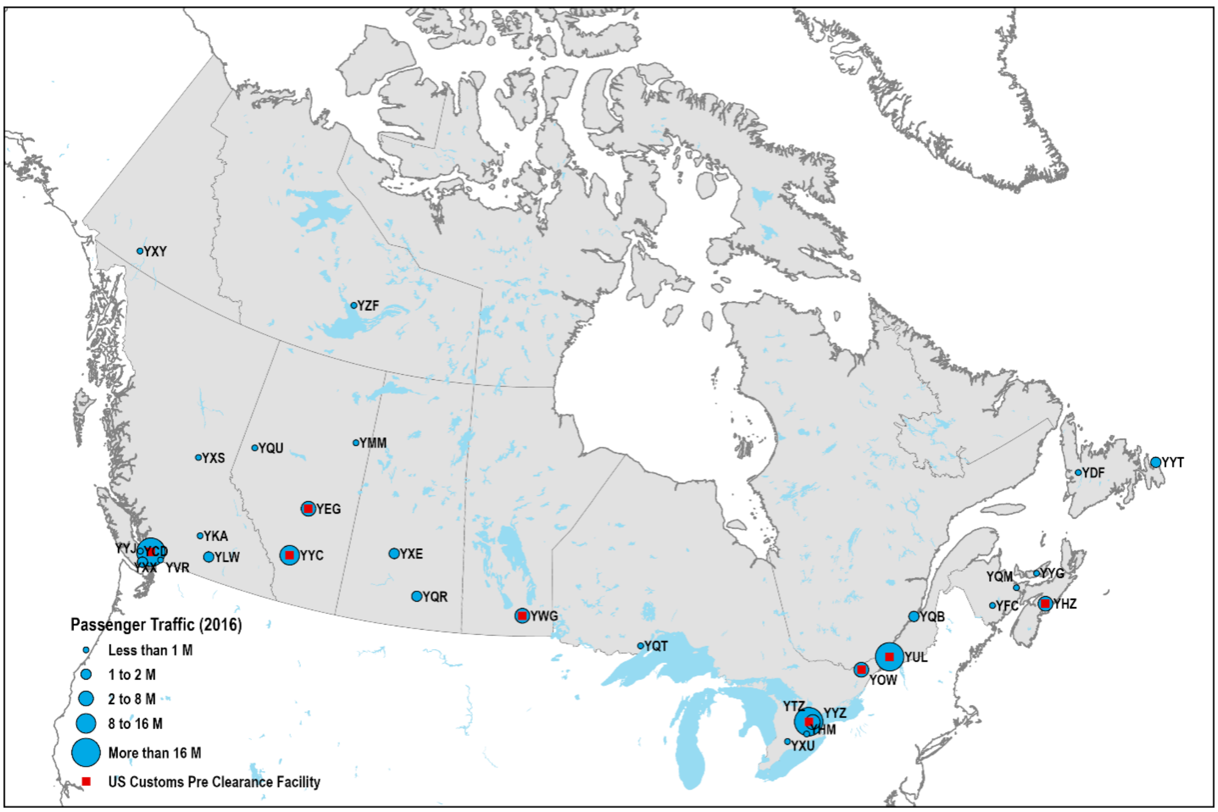
A marginal dimension involves summer sealift and ferry services to resupply local communities and bring project cargoes. Typical ships have about 14,000 dwt and a draft of eight metres, allowing them to navigate shallow waters. They have gantries, since small communities do not have crane equipment. For convenience, a growing share of the cargo handled by sealift services is containerized (in the range of 60 per cent). A ship can undertake two to three voyages during the summer (July to September), with small communities only called once. The main hub ports are Montreal and Quebec City, with a network of cities and communities around the Labrador Sea, Hudson Bay, Baffin Bay and the Northwest Passage, with Cambridge Bay as the westernmost destination. The government of the Northwest Territories owns another operator, Marine Transportation Services, which uses barges and tugboats to haul materials from Hay River (the main port of call on the shore of Great Slave Lake and the northernmost rail service) to communities along the Mackenzie River with service up to Cambridge Bay and Sachs Harbour on the Beaufort Sea. Both of the Arctic sealift services have strong seasonal limitations and a limited frequency. Thus, they cannot provide effective logistical support to the regional development of northern communities, even if the resupply services they offer are essential (Prolog Canada 2010).

The Airport System

The Canadian airport system is mainly designed and structured to service three circulation systems. The first is longitudinal and connects major Canadian cities, with direct flights for large city pairs or the use of major hubs to connect smaller centres. The second is latitudinal and connects Canadian airports with an array of American airports accessible to Canadian carriers through the U.S./Canada Air Service

Agreement, which applies third- and fourth-freedom air travel rights to cross-border services.[4] Eight Canadian airports are U.S. Customs pre-clearance facilities, allowing flights to connect to any airport in the United States, even if this airport is not a port of entry. This allows Canadian airports and the airlines servicing them a broad range of options to service American airports. However, this promotes the convenience of latitudinal flows more than longitudinal flows. These two circulation systems are complemented by a third dealing with international connections that are predominantly transatlantic (mostly from Toronto and Montreal) and transpacific (mostly from Vancouver). These three major hubs feed the longitudinal and the latitudinal systems into the international system (Figure 5).

Figure 5. The Canadian Airport System



With many large Canadian cities close to the border (e.g., Montreal, Toronto, Vancouver) and lower airfares in the United States (a more competitive market), millions of Canadians drive across the border each year to take a flight at a U.S. airport. A plane ticket to the same destination can cost twice as much at a Canadian airport compared to an American airport, which results in higher average airfares. The

4 The third and fourth freedoms are the basis for direct commercial services, providing the rights to load and unload passengers, mail and freight in another country. They are commonly reciprocal agreements in which the two involved countries will open commercial services to their respective carriers at the same time.

differences are mainly attributed to higher taxation rates in Canada,[5] which are around 40 per cent of the total fare compared to around 15 per cent in the United States (Gill and Raynor 2013). As a result, several American airports close to the border have actively marketed their services to Canadian customers and attracted air connections that would otherwise have been unwarranted. Such airport pairs include Vancouver and Bellingham (Washington), Toronto and Niagara/Buffalo (New York), or Montreal and Burlington (Vermont). In 2011, close to five million Canadian passengers flew from an American border airport instead of a Canadian airport, a trend labelled as cross-border leakage (Senate Standing Committee on Transport and Communications 2012).

Air services are crucial for northern and Arctic communities, but supplying costs, including mining settlements, are very high. The only year-round transportation for many locations is by air, but this is mainly done with small propeller aircraft using short, gravel landing strips. The cost of extending and paving runways and using larger jet aircraft is prohibitive despite the potential benefits in terms of additional passenger and cargo capacity. Arctic weather tends to be unreliable, leading to delayed and cancelled flights, which reduces the return on assets. Cargo remains a vital function assumed by Arctic air carriers but is linked to a high price of goods on northern markets. Because of limited transport options and capabilities, food prices in the North are 2.5 to three times higher than in the rest of Canada. In the winter, ice roads bring large quantities of essential supplies, but the cost of converting them to all-weather roads is prohibitive.

Bottlenecks

Port draft limitations on the East Coast, particularly for Montreal, are an important bottleneck. As ships are getting bigger, port and maritime infrastructure is pressured to accommodate them. The expansion of the Panama Canal in 2016 led to the deployment of post-Panamax ships on the Atlantic, which was mostly serviced by Panamax ships. The American East Coast has responded with massive port infrastructure investments, including dredging and expanded terminal facilities. The Canadian West Coast has few draft limitations but requires extensive hinterland accessibility.

Montreal and the St. Lawrence remain inaccessible to the majority of post-Panamax container ships, notably the Neopanamax class, able to transit the expanded Panama Canal. This represents a long-term risk that the St. Lawrence (Montreal) could be marginalized as a gateway to Eastern Canada, with some of the traffic handled by American East Coast ports. With this risk in mind, the Port of Quebec started planning a post-Panamax container terminal at its Beauport facilities. In May 2019, the Port of Quebec announced the signing of a long-term commercial agreement with Hutchison Ports, the world's leading port network, and CN to build and operate the container terminal. Dubbed Laurentia, its fully intermodal deep-water port (15 metres) is

5 A flight between Toronto and an American destination would include in addition to the base fare (the fare charged by the airline), navigation surcharges to use Canadian airspace, airport improvement fees, security charges, U.S. taxes and fees charged for flights into the United States, as well as sales taxes such as the GST (goods and services tax) and the HST (harmonized sales tax).

expected to fill a niche allowing Neopanamax ships to access the St. Lawrence and use a high-capacity rail corridor controlled by CN towards Ontario and the Midwest.

Container terminal capacity is running tight on the West Coast. The Fairview Container Terminal in Prince Rupert is to be expanded from its current capacity of 1.35 million TEUs to an expected capacity of 1.8 million TEUs, doubling the terminal's footprint by 2022. This is to cope with one of the fastest terminal growth rates in North America. The situation is even more acute in Vancouver, where terminals are running at close to, or above, design capacity. According to the Vancouver Port Authority, its terminals are running at 85 per cent of design capacity. In comparison, 80 per cent is considered the margin at which a terminal starts to face operational hurdles due to congestion.

Canadian ports contribute an annual levy to the federal government that is a function of their revenue and property taxes for the municipality to which they contribute. This impedes their revenue and their ability to fund capital development projects. There are limitations on a port authority's capability to borrow capital or to use its real estate base as collateral. Ports are based on the landlord model, which means that terminals are usually leased to private operators that are in either the shipping or industrial sector. Therefore, port investment and development are contingent on the private sector's perspective assessing the market potential of the goods transiting. For container ports, private companies, through concession agreements, build, operate and maintain container terminals that require a minimal customer base to be profitable.

The government privatized many airports, handing them over to local authorities in the 1990s, which led to the introduction of airport taxes and major investments in airports, runways and air cargo handling facilities. Successful airports are, therefore, able to secure financing for infrastructure improvements, including new terminal facilities. This also allowed for new regional entrants and WestJet's emergence as a national carrier with connections to the United States. However, there are limited incentives to connect northern Canadian towns with jet and propeller services, mainly because of the low volumes generated. While jet services allow for carrying a good quantity of cargo, the runways that can accommodate them are fewer, although several B737s have been modified to use unpaved airstrips.[6] Propeller planes can accommodate more constrained landing strips' conditions (short length) but have limited cargo capacity. Further, the structure of the air transport network does not allow for direct connections between northern and Arctic communities since they do not generate enough traffic to justify services. Connections between communities must thus use a southern hub such as Edmonton, Winnipeg, Toronto, Ottawa or Montreal. Low economic density and vast distances undermine the Arctic's potential as an air transport market. It is much more profitable for an airline to prioritize links between major Canadian cities and develop services to the United States.

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6 These are called gravel kits and include nose gear gravel deflectors, protective shields for cables in the landing gears, reinforced flaps, vortex dissipators under the engines and abrasion-resistant paint for undersurfaces.

As international air travel increases, Canadian airports need to play a more significant role as hubs to connect intercontinental flights. Because of their geographical position, Canadian airports are well placed to act as hubs between Pacific Asia, Europe and Latin America. Air connectivity between Asia and Latin America is particularly low. U.S. Customs policies require passengers transiting to a third country via the United States to clear customs and recheck their luggage for an outbound flight. Offering transit visas for international travel connecting through a Canadian airport could improve their volume.

Winter has noticeable impacts on air and port operations, which increases costs. For air operations, winter-related activities such as plowing runways and de-icing planes add to costs and delays. At the same time, snowstorms can create flight delays, cancellations and even force airports to temporarily cease operations. All the Canadian ports on the Atlantic and Pacific coasts can be operated during the winter. Montreal has a level of vulnerability in winter because of ice jams on the St. Lawrence, but those are rare events. Due to ice conditions, the Port of Churchill is only open from late July until November, severely undermining its commercial potential. Even if this window were suitable for grain exports, it would not be sufficient to justify the Arctic port’s regular use, even as a base to resupply Arctic communities.

The Great Lakes and St. Lawrence Seaway are closed to operations during winter (late March until mid-December), but climate change is expanding the open navigation period, which stands at about 275 days. While the Seaway is closed, cargo movements must use more expensive alternative modes such as road or rail, which is avoided. The Seaway’s market potential is thus limited to sectors that can stockpile reserves for a few months, such as bulk cargo, coal and grains. This is ironic since the Seaway services one of North America’s most dense manufacturing and commercial markets.

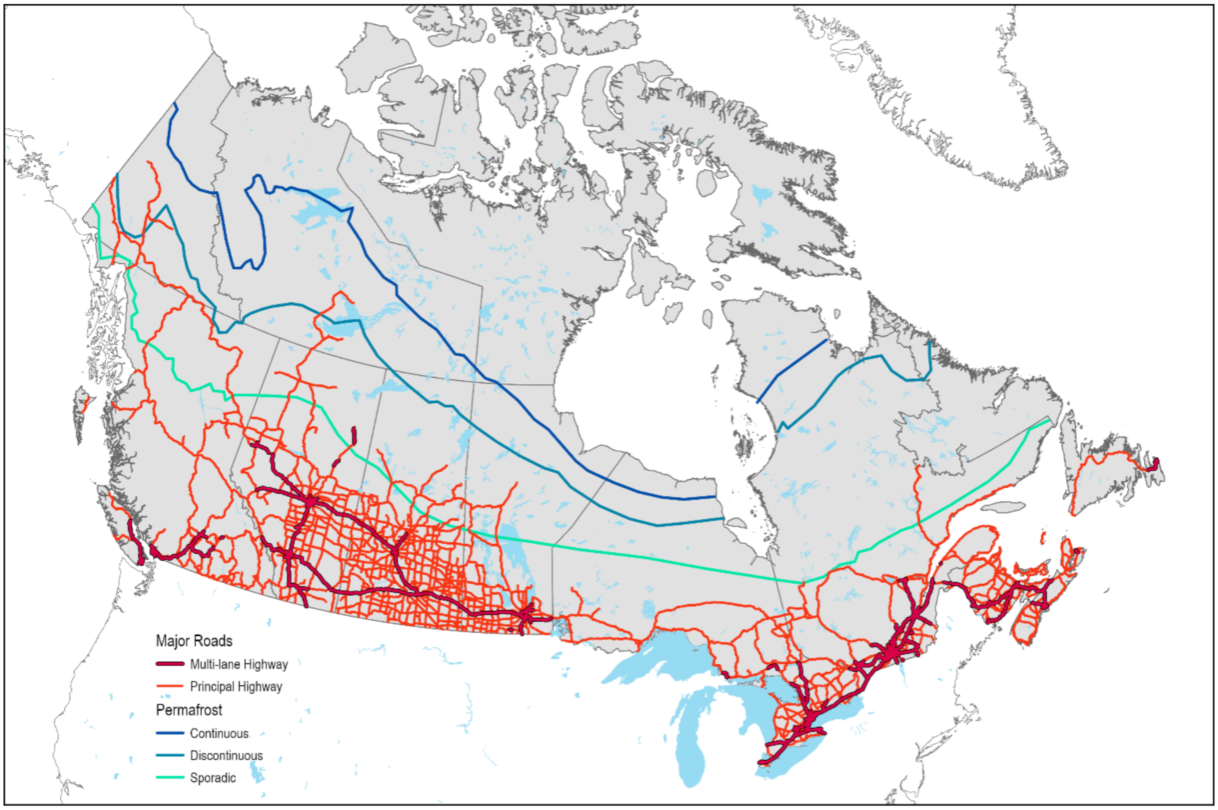
B. CONNECTORS: ROADS, RAILWAYS AND PIPELINES

The Road System

Unlike its American counterpart, the Canadian road system is unintegrated as it is mainly composed of regional road networks servicing specific corridors of economic activity. Some parts of the Trans-Canada Highway even have traffic lights, despite its purpose being national connectivity through a highway corridor. The Quebec-Windsor corridor represents the most salient road density articulated by a continuous system of highways and their connectors. Most of the road infrastructure is below the permafrost line and reflects the distribution of main Canadian settlements. It is highly expensive to expand the network outside high-density areas. Distances are vast, markets are limited and generally, no backhaul options are available, which means that trucks undertaking long-distance deliveries must come back empty.

The landscape over which road and rail infrastructure is built includes muskeg (swamp areas covered with water and dead vegetation), rock outcrops, poor drainage, permafrost and many water crossings. Northern territories rely on ice roads that are only operational during the winter season, linking communities that otherwise are not accessible by land transportation. When ice roads are closed, essential supplies can only be delivered by air cargo and at a high cost. Another important dimension concerns the load factor that roads can support, since northern communities often generate heavy and oversized loads related to resource extraction (lumber, minerals, energy) and project cargo (e.g., mining equipment). Due to the long distances involved and empty backloads, truckloads tend to be maximized, which can exceed weight limits and damage road infrastructure. Therefore, roads in northern regions suffer the double stress of environmental (permafrost) damage and heavy loads.

Figure 6. The Canadian Road Transport System



The Rail System

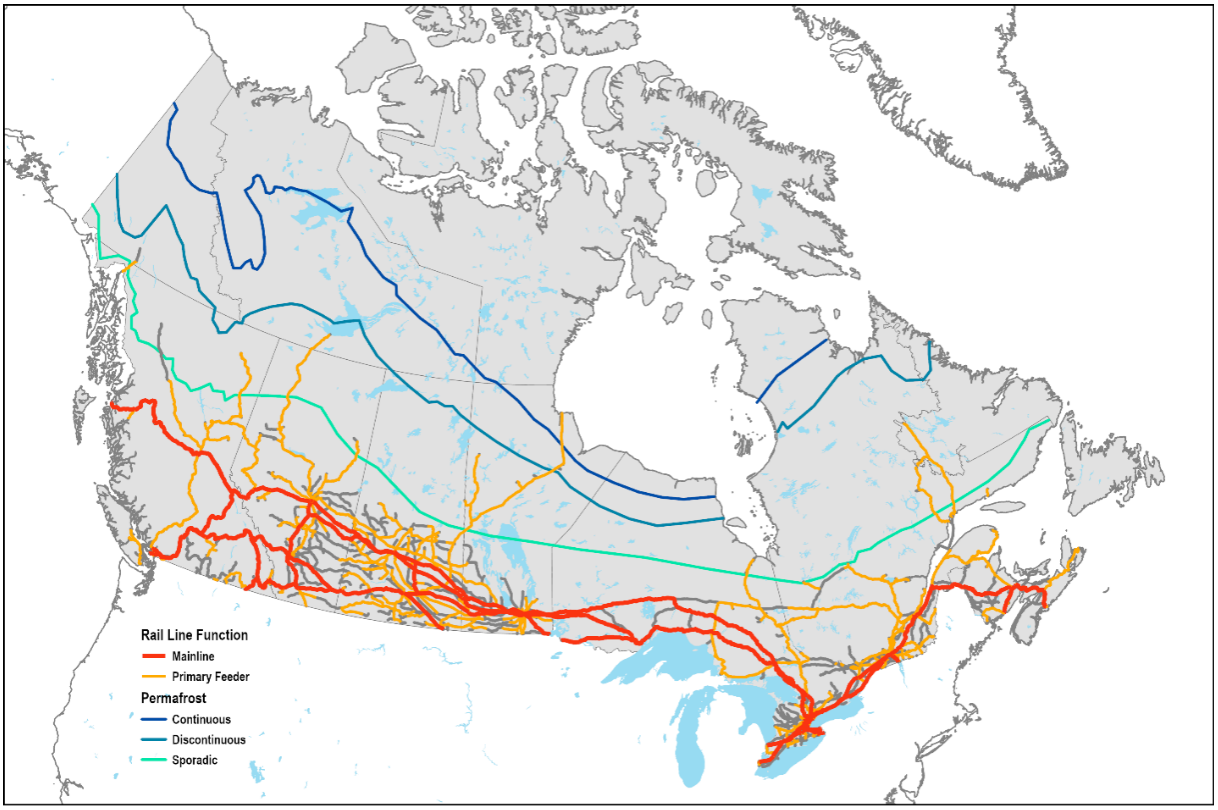
The Canadian rail system is longitudinally served by CN and CP, which are the primary owners and operators of rail infrastructure. They both compete in almost every major regional market, but CP does not own rails east of Montreal. The Canadian and American rail system is highly integrated with the same gauge and even equipment pools[7] made available to operators. A large number of trains enter the United States through southern Saskatchewan, Manitoba and eastern Ontario, underlining the rail corridor's continuity and its integration into the North American economy. Both CN

[7] TTX is an example of a railcar equipment pool company.

and CP own and operate substantial rail assets in the United States, allowing them to connect to the Chicago rail hub, which is the most important nexus in North America.

The Canadian rail system, like its American counterpart, is divided into several segmented markets that share the same tracks but rely on different equipment and loading techniques. Each market usually does not share the same origins and destinations and has its own dedicated trains and railcars. The most important market in terms of total carloads transported is intermodal, accounting for 35 per cent of the carloads. It mainly connects major container ports such as Vancouver, Montreal, Halifax and Prince Rupert, with inland consumption markets being supplied with commercial goods. Most of the intermodal corridors are the mainlines identified in Figure 7. The second market concerns minerals (21 per cent of carloads) moving ores via large-unit trains from remote mining areas (e.g., Labrador) to ports and reprocessing plants. The third market (12 per cent) involves agricultural goods that conventionally involve moving grain from the Prairies towards consumption markets and ports on the Pacific and Atlantic coasts for exports. A fourth market, which includes fuels and chemicals (12 per cent), has experienced fast growth in recent years (see Figure 9) and is particularly related to the oil export sector.

Figure 7. The Canadian Rail Transport System



Mostly because of the gradient, there are energy consumption differences between long-distance rail corridors, which can be used for competitive advantage. For instance, the Prince Rupert-to-Chicago intermodal corridor, which CN established in 2007 after the container port was opened, has a notable fuel efficiency advantage over other West Coast long-distance intermodal corridors. It consumes 15 per cent less energy per tonne-mile than the Seattle-to-Chicago and Los Angeles-to-Chicago corridors. This cost and time advantage has fostered the synergistic growth between the Port of Prince Rupert and the corridor.

The Pipeline System

The Canadian pipeline system tends to link isolated areas of production to primary refining and manufacturing centres in the case of oil, or major populated areas in the case of natural gas. Collecting and feeder pipelines are particularly prevalent in Alberta as the province is the primary producer of oil and natural gas (Figure 8).

Figure 8. Canadian Pipeline Network

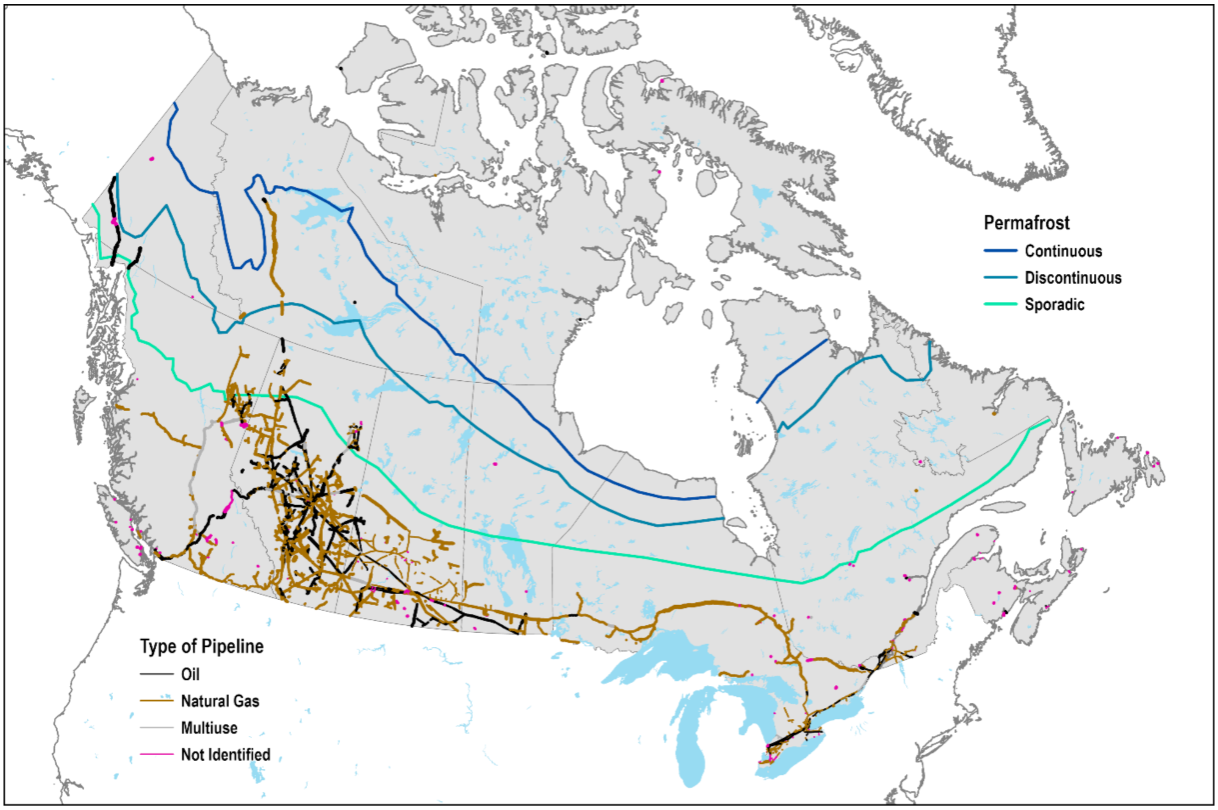


Table 2 represents the most significant Canadian oil and gas pipelines. Their capacity determines Canada's energy distribution and export potential.

Table 2. Canadian Major Oil and Gas Pipelines

Pipeline	Type	Route	Capacity
Enbridge Mainline	Oil	Alberta > Wisconsin	2.5 Mb/day
TC Energy Keystone	Oil	Alberta > Illinois	0.6 Mb/day
Trans Mountain Pipeline	Oil	Alberta > British Columbia	0.3 Mb/day
Enbridge Line 9	Oil	Sarnia > Montreal	0.3 Mb/day
Spectra Express	Oil	Alberta > Wyoming	0.28 Mb/day
Nova Gas Transmission	Gas	Alberta	475 Mcm/day
TC Energy Mainline	Gas	Alberta > Quebec	445 Mcm/day
Alliance Pipeline	Gas	British Columbia > Saskatchewan	48 Mcm/day
Westcoast Pipeline	Gas	Northwest Territories > British Columbia	45 Mcm/day
Maritimes and Northeast Pipeline	Gas	New Brunswick > Nova Scotia	15 Mcm/day

The Canada Energy Regulator manages the pipelines that cross provincial and international boundaries, which includes most of the transmission pipelines. Canada's oldest pipeline, the TransCanada, was developed in the 1950s to allow Alberta natural gas to be exported to the Ontario and Quebec energy markets. At that time, massive extraction began of oil and natural gas reserves in Western Canada, requiring the establishment of energy export corridors to external markets. The most significant energy corridor, the Enbridge pipeline, serves the primary purpose of allowing Alberta oil to be exported to the American Midwest. With a capacity of 2.5 Mb/day, it exceeds the combined capacity of all major Canadian oil pipelines.

The Trans Mountain oil pipeline is the only pipeline that links Alberta to British Columbia and represents the sole energy corridor to the Pacific market. Its capacity is one of the most significant impediments to the growth of Alberta's energy exports to international markets other than the United States. In 2019, approval was granted to build a second pipeline parallel to the existing one, with the goal of doubling the capacity from 0.3 Mb/day to 0.89 Mb/day. This will significantly improve the market potential of Canada's energy exports. Meanwhile, the lack of pipeline capacity and the growth of oilsands production have created a greater reliance on rail to move petroleum products over long distances.

Bottlenecks

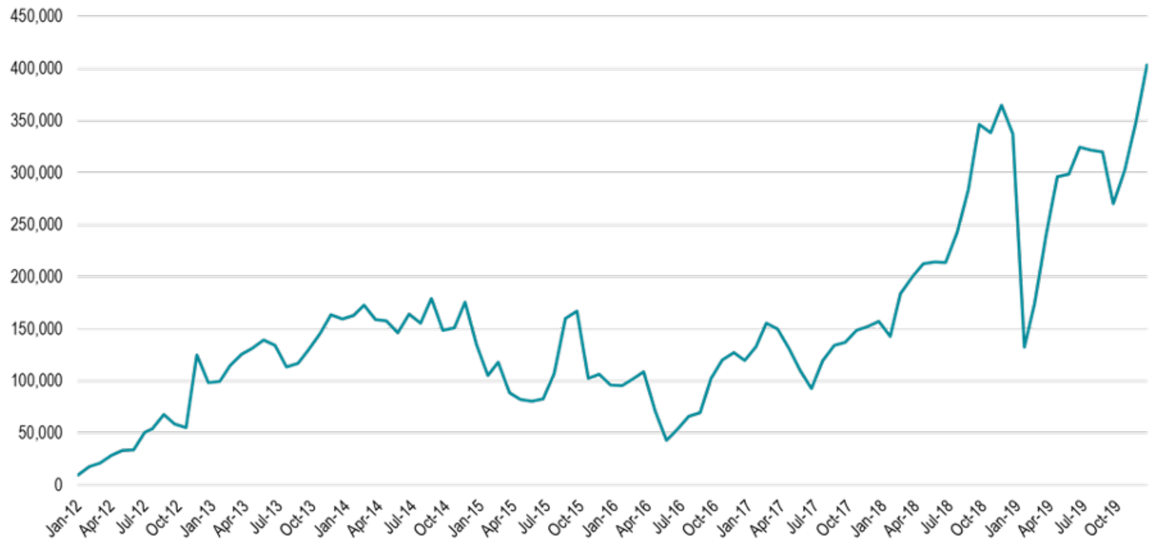
The length of Canadian highway and rail systems and low population densities characterizing most of the landscape underscore the challenge for the availability of construction and maintenance equipment and materials. Outside high-density areas and their corridors, allocating equipment for repairs and maintenance is cost prohibitive, particularly in northern regions. Equipment and construction materials need to be carried over long distances, so more equipment is needed to sustain a similar level of maintenance. Therefore, maintenance is undertaken only to support critical communities and economic activities, with latitudinal flows dominating. The few rail spurs that were constructed northward were built at a high cost and for specific purposes (e.g., Winnipeg-Churchill, which now only involves passenger service or the Quebec North Shore and Labrador Railway carrying iron ore).

Permafrost remains a severe impediment to the construction and maintenance of road, rail and pipeline infrastructure. The more northern the infrastructure, the higher the construction and maintenance costs, and therefore the more economically attractive the infrastructure project needs to be to justify the investment. Differences in road construction costs are staggering as a conventional double-lane gravel road that costs half a million dollars per kilometre to build in southern Canada can average $3 million per kilometre in the North. This excludes additional maintenance costs. The more northern the location, the less its economic potential, except for occasional mining and energy-generation projects. Long distances and high construction and maintenance costs mean that higher economies of scale must be achieved to justify services. Rail corridors servicing mining activities are commonly the only situation that makes economies of scale permissible. For instance, the economics of grain exports did not enable support of the Winnipeg-Churchill rail corridor commercially. Commercial forest areas that are mostly serviced by roads rarely expand beyond the sporadic permafrost line, further emphasizing the limited incentives to build roads in northern areas.

The lack of pipeline capacity to the West Coast and the United States is a major impediment to Canada's energy exports, and expanding this capacity remains controversial. For instance, the Keystone XL project was proposed in 2008, to link Alberta to Illinois, granting additional access for Alberta's energy exports to the American market. The Obama administration rejected the project in 2015 but the Trump administration re-approved it in 2017. Newly elected U.S. President Joe Biden has rejected it. The Enbridge Northern Gateway project is another strategic energy corridor for a diluted bitumen pipeline between central Alberta to the Port of Kitimat in British Columbia. Indigenous and environmental groups oppose the project, which was proposed in 2008.

The lack of pipeline capacity also has some unintended consequences. First, it restricts exports and the revenue potential of energy producers, including taxation revenue. With more limited market options, oil producers have less pricing power and fewer opportunities to sell their energy resources on external markets. Second, it forces a share of the oil to be carried by other modes, namely by rail, which undermines the competitiveness of Canadian energy production and exports as well as creating safety issues. The Lac-Mégantic accident in 2013 was related to pipeline capacity, the lack of which has seen more oil products transported by rail. Since 2017, crude oil exports by rail have surged, driven by limited pipeline capacity and oilsands-related production in Alberta (Figure 9). Rail transportation remains the only option available to handle additional capacity for crude oil exports. New opportunities are being considered, such as carrying bitumen and oil products by rail between northern Alberta and the Port of Valdez in Alaska, which would create a new energy corridor.

Figure 9. Canadian Crude Oil Exports by Rail, 2012-2020 (in barrels per day)[8]



Winter impairment of road and rail operations remains a constant issue in northern areas. Unlike in metropolitan areas, these events require the positioning of equipment and crews over long distances. Most of northern Canada receives between one and three metres of snow per year, with most areas receiving between two and three metres. The situation is particularly salient in the Rockies, where many areas receive more than four metres of snow per year. Strategic rail corridors face challenges in the Rocky Mountain passes where winter avalanches caused by annual snowfalls above eight metres per year can close rail trunks for days.

C. ANCILLARY INFRASTRUCTURE: POWER TRANSMISSION AND TELECOMMUNICATIONS

The Power Generation System

An overview of the Canadian system of power stations and its power grid reveals two subsystems (Figure 10). The first concerns power generation near major consumption markets. This system usually relies on fossil fuels and involves smaller power plants with short-distance power grids.

The second subsystem involves large hydro-power generation projects in remote areas such as James Bay (La Grande), the British Columbian Rockies (Churchill Falls, Mica, Revelstoke), Nelson River (Limestone, Kettle) and Manicouagan (Manic). These mega-power plants require long-distance and redundant high-voltage power lines to main urban and industrial markets, which demonstrates the latitudinal orientation of most power lines in Canada. Some of the surplus power these plants generate is exported to the United States. Northern Canada is energy-rich but generates little demand, suggesting that most of the electric power generated is transported to lower latitudes.

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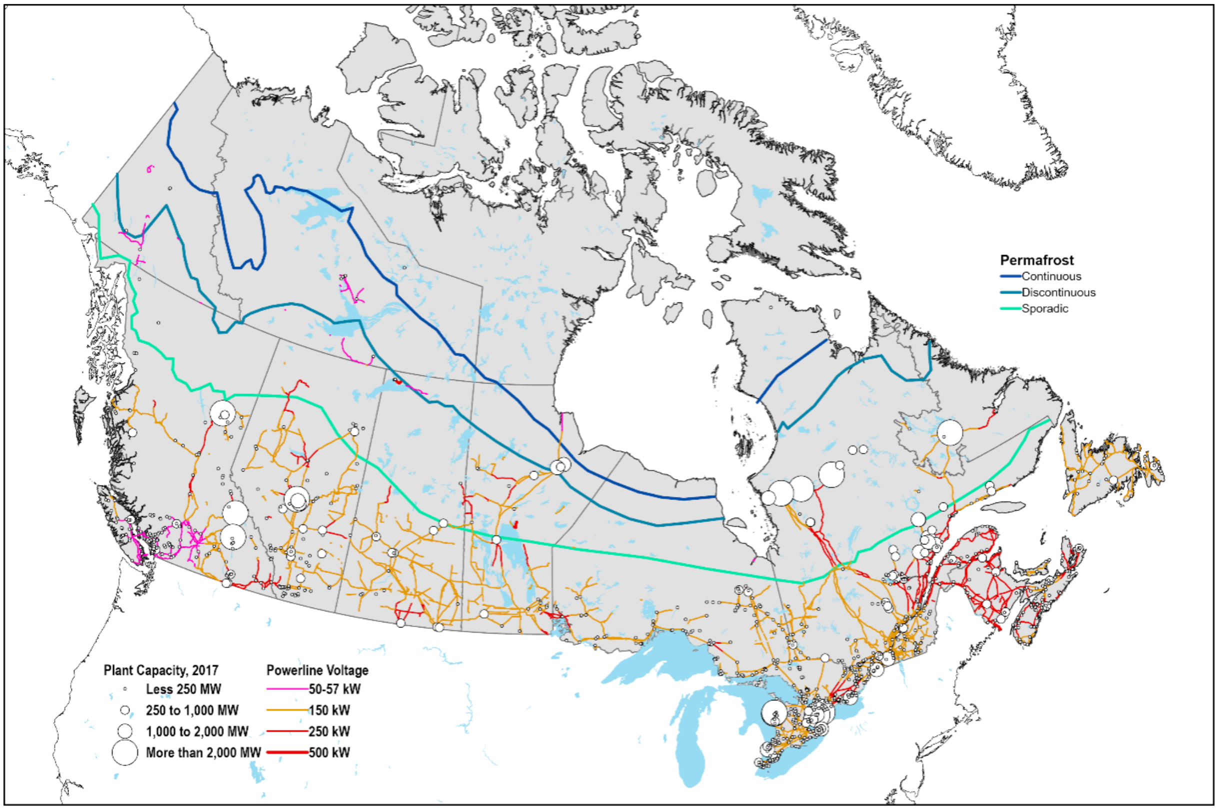
8 Source: Integrated Energy Information and Analysis, Canada Energy Regulator.

A third system concerns large power generators in southern Ontario, which are mainly nuclear power plants. Ontario accounts for the majority of nuclear power generation (New Brunswick has one nuclear power plant while Quebec closed its sole nuclear power plant in 2012).

Figure 10. Canadian Electric Power Network



Further, the regional Canadian power grids are integrated with those of the United States into power-sharing agreements. Under the North American Electric Reliability Corporation (NERC), Canada is part of two major electric interconnections:

- **Eastern Interconnection**. This interconnection includes the eastern part of North America and extends from Saskatchewan to the eastern seaboard, excluding most of Texas. It is linked to the western interconnection through high-voltage DC transmission facilities. Quebec, as Canada's leading electric power generator, is considered to be a sub-element of this interconnection.

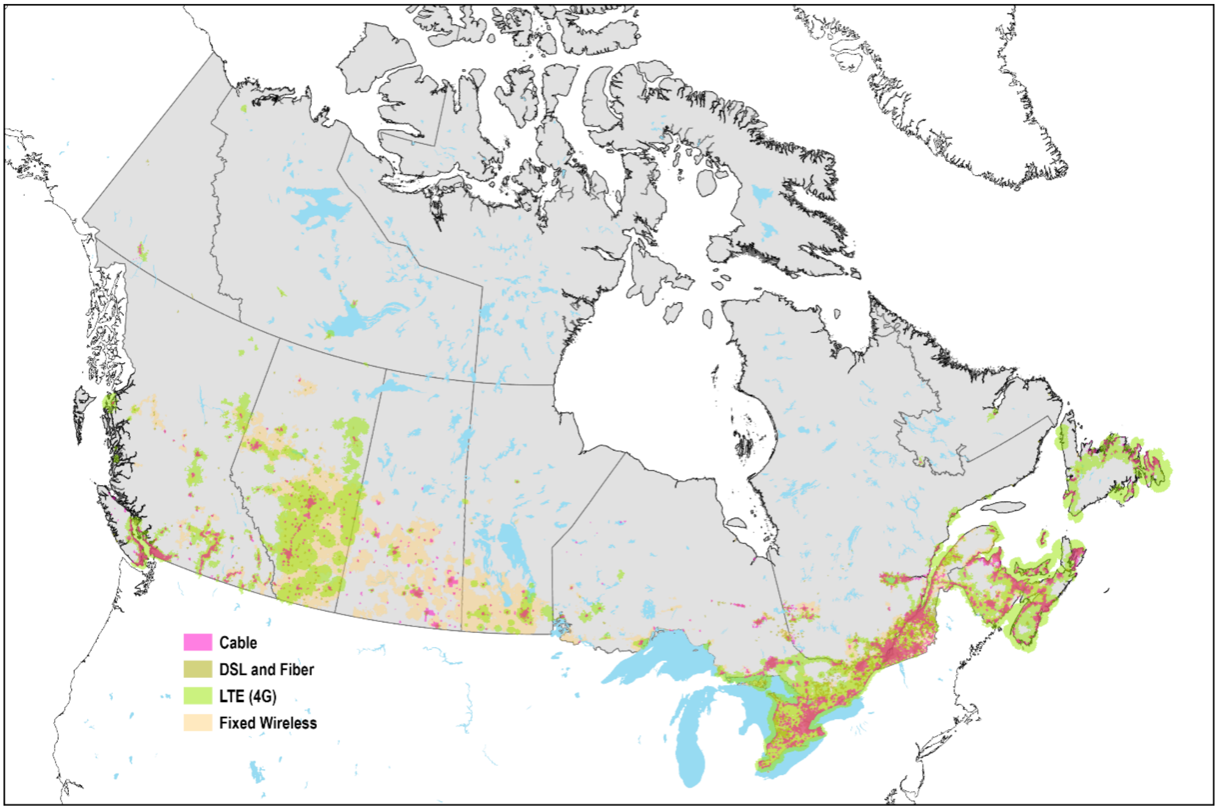
- **Western Interconnection**. This interconnection includes most of western North America, including Alberta and British Columbia. It is linked to the eastern interconnection at six locations.

The primary purpose of these interconnections is to ensure the stability of the North American electric power system by transferring electrical power between regions that have a surplus and those that have a deficit. This is particularly important when a grid is facing overload due to high demand or regional shortages in power generation. This allows for a better distribution of electricity given seasonal fluctuations in demand and to accommodate unforeseen events.

The Telecommunications System

Telecommunications infrastructure is increasingly perceived as being of strategic importance in supporting commercial and social interactions. It is composed of local and long-distance telephony, internet (cable), wireless voice and data. Internet and wireless have become the two most used telecommunications services because of the flexibility of access they offer. The structure of telecommunications networks and the availability of telecommunications services, particularly high-bandwidth services, are direct functions of population density since covering areas, even with wireless service, comes at a considerable cost.

Figure 11. Canadian Broadband Internet Service Coverage, 2014



All major cities and metropolitan areas are served with cable DSL and fibre-optic networks, which are high-bandwidth services (Figure 11). Mid-density settled areas are covered by wireless services, including an expanding LTE (4G) protocol supporting at least 100 Mbit per second. Low-density areas, which include northern Canada, cannot be adequately serviced by wireless services with only punctual coverage corresponding to settlements (CRTC 2019).

Bottlenecks

The Canadian power grid is managed by provincial power companies that are granted monopolistic control. Because of its high reliance on hydro power, Canada requires long-distance, high-voltage electric power lines. This system has some vulnerability to geomagnetic storms, such as in 1989 when a severe geomagnetic storm caused the collapse of Quebec's power grid, leaving six million people without power for nine hours. Since then, no similar incident has taken place, but the risk remains. Hydroelectric plants in northern Quebec (mostly around James Bay) are at the threshold of the highest electromagnetic storm probability area.

At the regional level, power distribution lines are vulnerable to freezing rain and in extreme cases this can affect regional power systems, such as during the 1998 ice storm that struck Quebec, Ontario and New York and left more than four million people without electricity up to several weeks. With climate change, such a risk remains difficult to assess but could increase. People's growing reliance on limited-charge devices such as smartphones creates a new form of vulnerability to disruption in the power supply.

The availability of telecommunications services is bound to population density, particularly for wireless services. While northern communities have access to telecommunications services, they are generally of lower bandwidth and limited spatial coverage. About half of northern communities rely on low-bandwidth and expensive satellite internet coverage instead of land connections by fibre-optic cable and microwave transmission towers. This suggests that the development of any corridor would require the establishment of supporting telecommunications infrastructure.

III. MITIGATING INFRASTRUCTURE BOTTLENECKS

This report helped identify key existing and expected constraints in road, rail, pipeline, power transmission and communications infrastructure which lead to loss of economic opportunities, impede trade and generate indirect costs. Several of the leading causes were discussed, mainly around physical, environmental, demand patterns, financial considerations and regulatory bottlenecks (see Section I.A).

After more than 30 years of free trade (1988 Canada-United States Free Trade Agreement; 1992 North American Free Trade Agreement), the level of integration between Canadian and American transport systems has been reinforced. Because of a strong north/south pull, the Canadian North remains a peripheral component of the Canadian economy. The marginalization of the northern corridor concept must be considered within the broader Canadian infrastructure grid context where terminals, connectors and ancillary infrastructure face specific constraints and bottlenecks (Table 3).

Table 3. Overview of Major Bottlenecks in the Canadian Infrastructure Grid

Mode	Bottlenecks (Cause)
Terminals	
Ports	Draft limitations on the East Coast (physical). Limited additional container capacity on the West Coast (demand and regulations). Challenges in securing funds for infrastructure investment (financial). Winter impacts on port operations (environmental). Closure of the St. Lawrence Seaway December to April (environmental). Ice jams on the St Lawrence (physical). Limited three months' operational window for Arctic ports (environmental).
Airports	Latitudinal connections to the United States prioritized over longitudinal connections (demand). High taxes and fees on airfares (regulatory). High air travel costs to northern communities (demand). Runway constraints in northern communities; surface and length (construction and maintenance). Limited connectivity between northern communities (demand). Winter impacts on air operations; plowing, de-icing (environmental). Disruptions from snowstorms; delays and cancellations (environmental). Challenging hub connectivity for international flights (demand).
Connectors	
Roads	Unintegrated system composed of regional networks (demand and regulations). Many northern communities dependent on ice roads (physical, environmental, demand). Permafrost imposing high construction and maintenance costs (construction and maintenance). Low density prevents efficiency outside major metropolitan areas (demand). Long distances to carry construction and maintenance equipment (demand). Snowstorm disruptions (environmental). Size and load limitations (regulatory).
Railways	Priority on longitudinal services (demand). High-priority intermodal rail corridors between ports and inland markets (demand). Permafrost imposing high construction and maintenance costs (physical). Snowstorm disruptions; major Rockies passes (environmental). Limited latitudinal rail spurs; mining; failure of Churchill rail corridor (demand).
Ancillary Infrastructure	
Pipelines	Permafrost imposing high construction and maintenance costs (construction and maintenance). Lack of capacity to the West Coast and the United States (demand and regulatory). Lack of capacity limiting market opportunities and pricing (demand). Regular public opposition to expansion projects (regulatory).
Power transmission	Two supply systems; close to market and long distance (demand). Large hydroelectric supply in the North (physical). Vulnerability to geomagnetic storms (physical). Vulnerability to freezing rain (environmental).
Telecommunications	Services constrained by density (demand). Lower coverage and bandwidth in northern communities (demand).

Source: Author's calculation.

The most recurring constraints to Canadian infrastructure relate to demand factors, which are either not high enough or not of sufficient density. Physical and environmental factors are prevalent as well, with usually a latitudinal gradation of the constraints northward. The combination of the stated economic, physical and environmental constraints in northern Canada seriously undermines economic opportunities. Each of the constraints identified in Table 3 can be addressed independently as they concern different locations and stakeholders. Corridor development represents an opportunity to co-ordinate the resolution of some of these constraints in a more comprehensive strategy where priorities, locations and segments are ranked.

THE CORRIDOR AS A BOTTLENECK CO-ORDINATION MECHANISM

The key basis of corridor development is to maximize the density of flows along an axis. Canadian transport infrastructure grids are not a fully integrated system because of Canada's inherent geographical and economic characteristics. While rail and air transport systems are the most interconnected since they support longitudinal interactions, other infrastructure systems are regional in scope. The Canadian economy is composed of regional markets, which over short distances interact more latitudinally and with the United States than longitudinally.

The Gateways and Corridor initiative initiated by the Canadian government from 2007 had positive consequences as a co-ordination mechanism, particularly for the Pacific corridor, where the major actors involved agreed upon a prioritization of investments, especially around grade crossings in the Vancouver metropolitan area (Transport Canada 2007). For other Canadian corridors, such as the Atlantic one, the strategy was less successful mainly because core actors could not converge around common investment strategies across several provinces. Other corridor initiatives in North America, such as the I-95 Corridor Coalition,[9] have undertaken long-term efforts to co-ordinate infrastructure investments, assess the needs of passengers and freight transport systems and even plan the infrastructure needed to support vehicle automation. Still, these co-ordination strategies are challenging to implement because of the economic and jurisdictional complexity of the corridors they try to manage. Because of the acute bottlenecks that have been identified, the co-ordination of potential northern corridors is a fundamental pre-condition.

LIMITED LATENT DEMAND OF NORTHERN CORRIDORS

The Canadian government's strategy in recent decades has been to ensure the economy's ongoing competitiveness, for which corridor development was preconized. The focus is obviously to support infrastructure proven to have noticeable commercial benefits, linking Canada's main gateways to large population concentrations, including in the United States (Blank 2008; Rodrigue, Slack and Blank 2020). Evidence shows that developing and operating a transport corridor in a northern area is more costly and tends to have much more limited commercial opportunities than a similar corridor in lower latitudes. It is fundamentally an issue around population and economic density, which are unavoidable constraints. Further, transport infrastructure is cost prohibitive to construct and maintain in a sub-arctic setting, requiring even higher economic value to justify investments. An important question entails assessing the latent demand that any corridor development could reveal.

- **Additional Demand**. Due to low population density and low development levels in northern communities, there is limited latent demand for a northern corridor to unlock. A marginal benefit would be cheaper and more diverse goods available for local consumption and better supply chain management (fewer inventories).

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9 The I-95 Corridor Coalition became the Eastern Transportation Coalition: https://tetcoalition.org/.

- **Connectivity**. The most successful corridors usually improve long-distance connectivity between large terminal nodes and centres of economic activity. This improved connectivity allows for commercial and trade benefits to emerge as comparative advantages are articulated across a wide geographical area, including access to international trade. Long-distance connectivity exists already in southern Canada, linking the Atlantic and Pacific coasts to major inland population centres as well as to the American Midwest. A longitudinal northern corridor would not likely provide any significant long-distance connectivity benefits for the Canadian economy.
- **Resource Development**. Corridor development in northern Canada was conventionally undertaken to access resources such as minerals and energy. These latitudinal road and rail corridors made available resources such as iron ore and supported their use over decades. Making an additional pool of resources available on national and international markets remains one of the core benefits of such corridors. Resource-based latent demand is expected to remain a core driver of corridor development in northern Canada in the foreseeable future. However, this latent demand is subject to the price of resources on global markets, which are prone to the risks of fluctuations.

DEVELOPMENT OF LATITUDINAL CORRIDORS IN THE MEDIUM TERM AND LONGITUDINAL CORRIDORS IN THE LONG TERM

Canadian rail and air transport systems are the only ones that are longitudinally integrated since they were constructed along with national unity imperatives. Developing a northern corridor, therefore, goes against the pattern of existing transportation infrastructure and latent demand benefits appear marginal. There are no apparent commercial incentives to build a northern corridor, but segments can be considered on a case-by-case basis. In the short and medium terms (fewer than 10 years), only political imperatives could justify the establishment of corridors in northern Canada. In the long term (20 years horizon), demographic growth, resource development and even climate change could cause a reconsideration in developing a comprehensive northern corridor. Meanwhile, only specific opportunities should be considered, which mainly involve improving latitudinal connectivity.

Developing latitudinal corridors that would eventually be reinforced by longitudinal corridors appears to be a more effective strategy. If a latitudinal corridor linking a part of northern Canada to southern markets is not viable, then a longitudinal corridor will be even less so. Finding the multimodal potential of corridor development remains a core challenge as corridors tend to be more effective if they are supported by more than one mode. However, the development of both latitudinal and longitudinal segments remains a possibility in the short term. In the long term, the challenge remains in integrating each segment as part of a national corridor strategy.

Connecting small northern settlements remains a challenge as infrastructure costs to access them are prohibitive. The development of dirigible services has been suggested as a cost-effective strategy to deliver payloads of around 50 tonnes. If some of these potential services become effective, it would free up resources used to maintain marginal connectivity and allow the focus to be placed on the development of connectivity, with a better potential to be massified.

ENDURING OPPOSITION AND GOVERNANCE ISSUES TO CORRIDOR DEVELOPMENT

Whenever the development of new transportation infrastructure has revealed a latent demand, the public and private sectors have responded by announcing projects and complying with regulations, such as environmental impact assessments. While conventionally, opposition to infrastructure development projects was grounded in environmental, community disruption and land ownership claims, opposition has become pervasive and a de facto stance. Paradoxically, Indigenous communities depend on critical transportation infrastructure such as ports and airports for resupply and economic development, as the provision of the most basic infrastructure provides significant benefits to under-served communities (National Aboriginal Economic Development Board 2016). The different levels of opposition and delays that infrastructure projects generate undermine the potential for co-ordinating their development, which plays against corridor development.

The risks and high cost considerations for a northern corridor mean that standard governance models may be inadequate. Outside specific northern connectors to resources such as mining, energy and logging, the private sector has limited incentives to provide infrastructure or services to low-density areas. Sole private ownership and operation of infrastructure in such a context is unlikely unless supported by massive subsidies. Public ownership appears one of the limited options, since much of the infrastructure provision would be for political purposes and possible long-term strategic goals. The question remains if northern corridors offer limited economic benefits, to what extent could long-term strategic considerations justify their establishment?

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APPENDIX

DATASETS

The project identified and collected datasets about Canadian transport infrastructure into geodatabases. These geodatabases can be used to produce thematic maps underlining the spatial distribution of key transport infrastructure in Canada. Many of these datasets are already publicly available on sites such as the Open Data portal: https://open.canada.ca/en/open-maps.

The datasets were compiled and organized by Ryan Leighton and Raymond Ram of the Department of Global Studies and Geography at Hofstra University, New York.

Mines, Energy and Communication Networks in Canada

Features power lines, communication lines, pipelines, valves, petroleum wells, wind-operated devices, transformer stations, ore extraction sites, aggregate extraction sites, peat extraction sites and oil and gas sites.

- Power Plant: Station containing prime movers, electric generators and auxiliary equipment for converting mechanical, chemical or fission energy into electrical energy.
- Pipeline: One or more cylindrical conduits used to convey liquids or gases.
- Power Line: One or more cables used for power transmission.

Available at: https://open.canada.ca/data/en/dataset/92dbea79-f644-4a62-b25e-8eb993ca0264.

Transport Networks in Canada

Transport Features is composed of the National Road Network (NRN) and the National Railway Network (NRWN).

- AC_1M_Railways: Portion of a railway track with uniform characteristics.
- AC_1M_Roads: A road is a linear section of the Earth designed for, or the result of, vehicular movement. A road segment is the specific representation of a portion of a road with uniform characteristics. The specific representation of a portion of a road with uniform characteristics.

Location: https://open.canada.ca/data/en/dataset/2dac78ba-8543-48a6-8f07-faeef56f9895.

Port and Airport Facilities

Port information mostly derived from the American Association of Port Authorities that releases key traffic figures about North American ports:

https://www.aapa-ports.org/unifying/content.aspx?ItemNumber=21048.

Broadband Internet Service Coverage in Canada in 2014

Availability of broadband internet access service at or above the target speeds of five megabits per second download and one megabit per second upload within hexagon areas of 25 square kilometres.

- Cable: A communications technology that provides data transmission over coaxial cable.
- Digital subscriber line (DSL): A data communications technology that provides data transmission over a copper local loop.
- Fibre: A technology that uses glass threads or plastic fibres to transmit data using pulses of light.
- Fixed wireless: A wireless network that uses either licensed or unlicensed spectrum to provide communications services (voice and/or data) where the service is intended to be used in a fixed location.
- Long-Term Evolution (LTE) Mobile: A protocol or standard used for communications between a mobile phone and cell towers in mobile networks. LTE is also referred to as 4G (fourth generation) cellular technology.

Location: https://crtc.gc.ca/eng/internet/internetcanada.htm.

About the Author

Jean-Paul Rodrigue received a Ph.D. in Transport Geography from the Université de Montréal (1994) and has been a professor at Hofstra University since 1999. Dr. Rodrigue's research interests mainly cover the fields of transportation and economics as they relate to logistics and global freight distribution. Specific topics over which he has published extensively cover maritime transport systems and logistics, global supply chains, gateways, and transport corridors. He has authored six books, 32 book chapters, more than 50 peer-reviewed papers, numerous reports, and delivered more than 150 conferences and seminar presentations, mostly at the international level. His co-authored paper (with Theo Notteboom) about port regionalization and the development of port/hinterland supply chains became one of the world's most cited paper on maritime transport.

Dr. Rodrigue developed a widely used online reference source about transportation, which became a textbook, *The Geography of Transport Systems*, now in its fifth edition. He is also on the international editorial board of the Journal of Transport Geography, the Journal of Shipping and Trade, and the Cahiers Scientifiques du Transport. He is a lead member of the PortEconomics.eu initiative regrouping the world's leading maritime transport academics and performs advisory and consulting assignments for international organizations and corporations. Between 2011 and 2016, Dr. Rodrigue sat on the World Economic Forum Global Agenda Council on the Future of Manufacturing. In 2013, the US Secretary of Transportation appointed Dr. Rodrigue to sit on the Advisory Board of the US Merchant Marine Academy at Kings Point, a position he held until 2018. In 2019, he was the recipient of the Edward L. Ullman Award for outstanding contribution to the field of transport geography by the Association of American Geographers.

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906 8th Avenue S.W., 5th Floor
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