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REVIEW ARTICLE

The Canadian winter road infrastructure in a warming climate: Toward resiliency assessment and resource prioritization

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ABSTRACT
Winter roads are seasonal roads thatonly exist during the winter – they run over frozen land and frozenlakes and rivers. Many northern communities in Canada rely onthem for their yearly supplies of bulk goods, including fuel andbuilding supplies, which are too costly to ship by air. Because of awarming climate, a progressive shortening of the operational timewindows is observed, and is predicted to continue based on climatemodel projections. Compared to all-season roads, winter roadsare less well understood; they are also unevenly managed acrossCanada. This state of affairs represents a liability for Northernersand could be addressed via the systematic characterization ofindividual roads. This would help the assessment of communityvulnerability and costs for remediation measures. It would alsoguide decision-making and prioritization.

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1. Introduction

Northern communities in Canada depend on winter roads. Since these seasonal structures rely on a frozen foundation, they are trafficable only in the coldest months of the year (Hori et al., 2017; Kuryk, 2003; Proskin et al., 2011a). They are constructed over land and also run across frozen water bodies (lakes and rivers, sea ice along coastlines and in bays) – these segments are referred to as ice roads, bridges or crossings (Figure 1). An example of each is shown in Figures 2 and 3, respectively. Each comes with its own requirements in terms of planning, construction and safety, and is able to accommodate a wide range of vehicles, including automobiles and pick-up trucks with standard winter tires.

Any given winter road operation ranges in length from a few hundred meters to hundreds of kilometers. They are managed either by local communities, provincial/territorial governments or the private sector, e.g. mining, oil & gas, pulp & paper and hydro-electric companies (Centre d'enseignement et de recherche forestière, 1998; Kuloglu et al., 2019; Perrin et al., 2015). Communities and resource extraction sites rely on them for their yearly supplies of fuel, construction material and other bulk commodities that are too expensive for air transportation. Winter roads also allow people to travel between towns, communities and resource extraction sites, to access health services, education, employment and retail opportunities, as well as to connect with the all-season road networks in the south. Winter roads are also used extensively for leisure activities such as ice fishing, snowmobiling and participation in sporting and cultural events (e.g. hockey tournaments, traditional indigenous festivities and games). The annual construction and maintenance of the winter roads themselves provide employment opportunities for northern residents, particularly given the specialized expertise and local knowledge required to perform that work.

Unlike all-season roads, which are fully engineered structures, winter roads, as they currently exist, are *mostly a product of nature* (although, as stated later, some adaptation strategies would move them away from this natural state). That is why they are particularly vulnerable to a changing climate (e.g. Barrette & Charlebois, 2018; Gädeke et al., 2021; Hori et al., 2017, 2018b; Kiani et al., 2018; Knoll et al., 2019; Mullan et al., 2021, 2017; Prowse et al., 2009; Stephenson et al., 2011). It is generally agreed that, amongst the various factors resulting from climate change, air temperature is the most influential. Warmer temperatures have a number of adverse consequences – the prevalent one is to slow down ground freezing and the growth of ice covers, the latter being crucial due to safety concerns, e.g. breakthroughs. That, in turn, translates into

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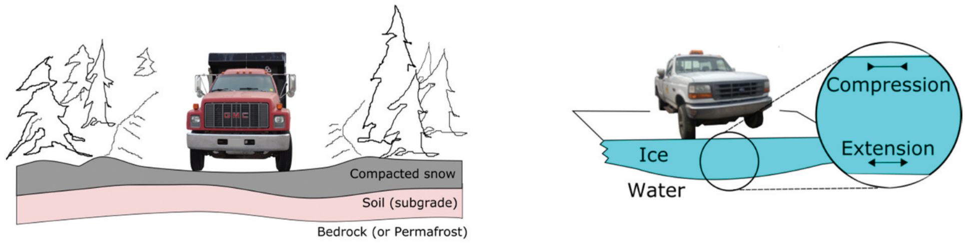

Figure 1. Simplified diagrams of an over-land (left) and over-ice (right) segments of a winter road.

Figure 2. Over-land segment of a winter road, NWT. Source: NRC.

a reduction in the yearly operational lifespan. In addition, mid-season warm spells can cause the roads to close (until the air temperature decreases again). Winter roads are a significant structural component in Northern Canada – they serve a large number of locations, including Indigenous communities.

2. Objectives

In this article, we review the existing literature on winter roads in Canada, and consider the impact of a warming climate on these facilities. Three general questions will be covered: 1) What gaps for further research exist with respect to the resilience of winter roads, particularly with respect to the shifting of key parameters due to climate change? The term 'resilience' (or 'resiliency') is here used as defined by Rosowsky (2020), i.e. the ability of a system to return to its functional state. For winter roads, as will be discussed, this is made possible via a variety of adaptation measures. 2) What information is currently lacking with regards to the unique needs of these networks? 3) What are the necessary and sufficient conditions for an 'infrastructure' to be designated as such?

Figure 3. Top) Winter road in the Northwest Territories, on the Mackenzie River. Bottom) Crack patterns in an ice cover (boot at lower left for scale) – its thickness is about one meter. Source: NRC.

2.1. *Winter road networks in* Canada

Canada is divided into ten provinces to the south, and three territories to the north (Figure 4). Surface transportation infrastructures – railways, highways, residential streets – are mainly the responsibility of individual provinces, territories and municipalities. The federal government (i.e. Canada) provides regulatory and safety oversight on modes regarding interprovincial movement as well as some key facilities

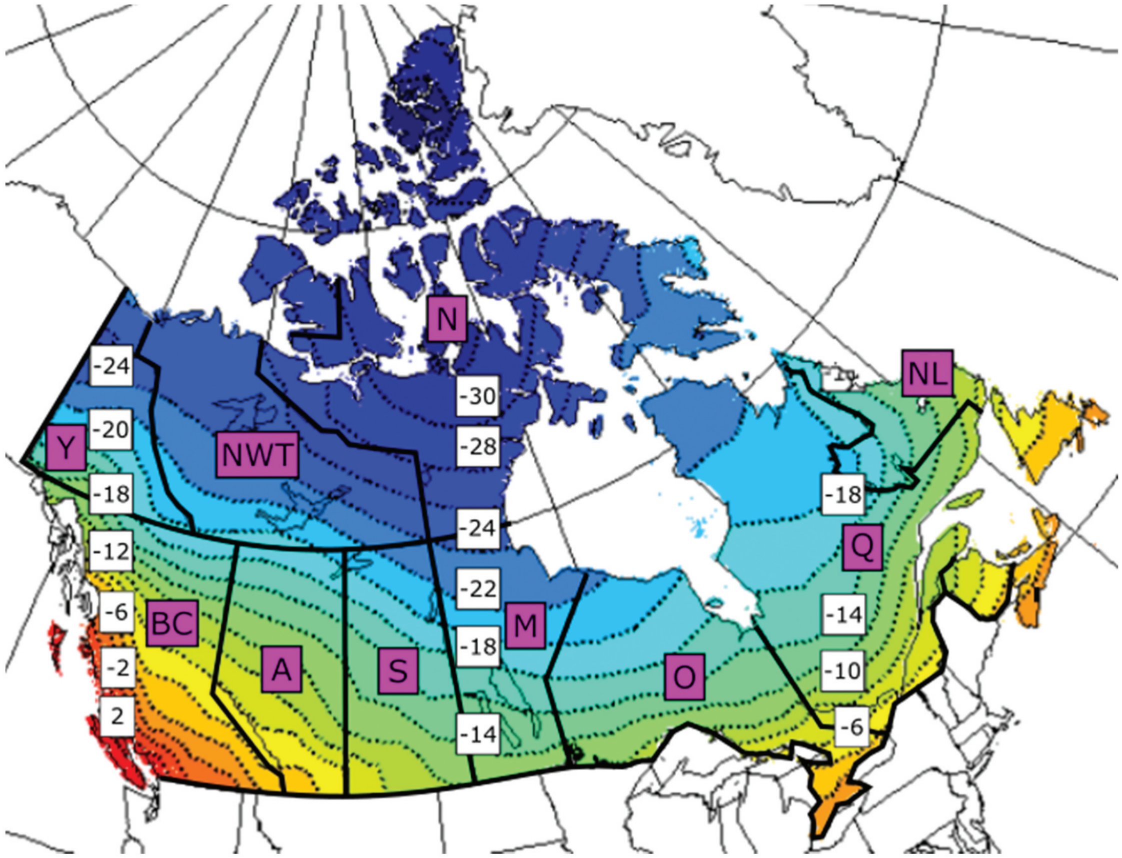

Figure 4. Map of Canada with average air temperatures (in deg. C), December-January-February, 1981–2010. Provinces, from west to east: British Columbia (BC), Alberta (A), Saskatchewan (S), Manitoba (M), Ontario (O), Quebec (Q), Newfoundland and Labrador (NL). Territories, from west to east: Yukon (Y), Northwest Territories (NWT), Nunavut (N). Source: Environment Canada.

deemed to be of importance/concern at a national level. As for the winter road networks, they exist across the country. They service wide areas with a low density population (< 0.5 inhabitant per km^2) and where all-season roads are difficult to construct. They are mostly found in the NWT (~2000 km),[1] Alberta (~250 km),[2] Saskatchewan (~350 km),[3] Manitoba (~2500 km),[4] and Ontario (~3000 km).[5] The extent of these networks elsewhere is uncertain, as they are not systematically monitored or officially recognized by their respective government jurisdiction. The cumulative length of the official winter roads in Canada is roughly 8000 km. These are recurrent, i.e. their surface is re-built and used every year. Winter roads for which no consistent records (or any usage data) are available may be operated by communities or the private sector – they may be recurrent or on a year-to-year basis, depending on supply requirements. As an example, Michel et al. (1974) describes a 600 km road in Northern Quebec, to supply the construction of hydro-electric dams – it was used over two winters. Another example are winter roads reported at a forestry workshop in Quebec, which amounted to about 3600 km (Centre d'enseignement et de recherche forestière, 1998). Recurrent winter roads in, for example, the Mackenzie River Corridor in the Northwest Territories, serve communities that would otherwise have no transport connections except by air (which is all year round, but by far the costliest transport option) and possibly river barge (in the summer ice-free months). Other than what each province and territory produces for its own purposes, there is currently no winter road map available at the national scale.

2.2. *The nature of winter roads*

2.2.1. *Over-land segments*

The foundation for over-land winter road segments is the native ground surface (known as the sub-grade). This means it is typically not engineered or modified to any great extent – in places, this may comprise ground striping and grubbing, although that could be only for the first season (i.e. for a new road). The foundation can consist of rock, frozen soil, with or without permafrost depending on latitude. The natural snow cover, which affords a protection for the underlying vegetation, is compacted to smoothen the surface, for instance with a tracked vehicle. It may be overlain with additional snow, or even with artificially-produced ice brought on site with water tankers or from water pulled out directly from a nearby stream or lake. Ice chips can be used and flooded, to help increase ice build-up and thickness. A well-planned route will consider many factors. For example, zones of muskeg, south-facing slopes (more prone to melting due to sun exposure), stream crossings and the presence of boulders can all be a source of problems. For more information, the reader is referred to a number of sources (Adam, 1978; Centre d'enseignement et de recherche forestière, 1998; Duckert et al., 2020; Government of the NWT, 2015; Hori et al., 2018b; Kuloglu et al., 2019; Proskin et al., 2011a).

The construction of over-land segments takes into account several parameters. The road should include an appropriate right-of-way (road width) and curvature radius. It should have low enough grades (i.e. slope) and cross-slopes, to accommodate the limited traction of standard winter tires. Its surfaces have to be smooth enough to accommodate the limited clearance below standard road vehicles. Road maintenance may include snow compaction after a snowfall, surface watering to increase its bearing capacity or level the surface, and clearing of fallen trees and branches.

2.2.2. Over-ice segments

Segments running on floating ice (frozen lakes or rivers) take advantage of that flat, solid ice surface, which is naturally available, with an environmental footprint that is smaller than other road types. An ice cover is able to support a load because of its buoyancy and resistance to flexure – provincial and territorial guidelines are available for determining a safe ice thickness (e.g. Government of Alberta, 2013; Government of Saskatchewan, 2010; Government of the NWT, 2015; Infrastructure Health and Safety Association, 2014; Proskin et al., 2011a).

A target thickness has to be achieved for all over-ice segments along the roadway alignment before the full road can be formally opened. The time required to reach that thickness is often the limiting factor for road opening – the colder the temperature, the faster the ice growth. Roads that are meant to carry tractor trailers (e.g. 20 tonnes and above) will require thicker ice than those that only handle light vehicles. Over-ice segments are typically prepared in two steps:

- Initial removal of the snow layer from the ice surface, to accelerate ice growth (snow acts as an insulator – see Andres & Van Der Vinne, 2001; Ashton, 2011), (Figure 5). This is done with lighter plows or tractors. Only once a sufficient thickness is achieved can heavier vehicles be used. Ice thickness has to be carefully monitored, either by measuring it in drill holes, on ice cores, or using a standard device meant for that purpose, namely a ground penetrating radar (GPR).
- Flooding the surface with water pumps, or using spray ice at some locations (Figure 6). The latter refers to ice that forms by spraying water in the air as tiny droplets, which fall down onto the target location. These techniques will artificially increase the thickness to the required target level. Artificial ice thickening is also used during the operational season, on an as-needed basis and for maintenance purposes (e.g. to repair overly cracked surfaces).

Figure 5. Snow cat plowing machines are preparing a winter road operation for opening.[6]

2.3. Winter road management

There is a considerable difference between the planning, design, construction and maintenance of all-season roads (e.g. highways, residential streets) versus winter roads. The former are fully engineered structures that abide by a large number of standards, codes and manuals. For winter roads, such guidance is minimal – it is typically provided, or approved, by provincial and territorial jurisdictions (Government of Saskatchewan, 2010; Government of the NWT, 2015; Infrastructure Health and Safety Association, 2014; Ministère des Forêts, 2021). Guidance is not uniform across provincial and territorial jurisdictions (Barrette, 2015; Proskin et al., 2011a), although there has been some convergence over the years. For example, guidelines in Alberta and Ontario are based on those from the NWT – the latter tend to be at the forefront of best practices in Canada. A significant outcome of this lack of uniformity is that winter roads are

Figure 6. Ice cover thickening may be conducted using a pump to flood the ice (left) or implementing a spray ice system (right). Source: NRC.

substantially different from each other in terms of their physical characteristics. Moreover, there is no systematic and consistent country-wide collection of these characteristics.

Further, winter roads are not as well documented as all-season roads. That information exists within the grey literature, namely company and government reports and workshop proceedings (5658NWT Ltd. & GNWT, 2011; Centre d'enseignement et de recherche forestière, 1998; Centre for Indigenous Environmental Resources, 2006; Duckert et al., 2020; Risk Sciences International, 2014). The academic literature addressing these structures is limited – the impact of climate change is central to these investigations (Furgal & Prowse, 2008; Hori et al., 2018a, 2017; Knowland et al., 2010; McGregor et al., 2008; Mullan et al., 2021, 2017). Planning of winter roads, which are part of multimodal transportation systems in the North, has to address climate change impact on resource exploitation and movements of goods (e.g., Centre d'enseignement et de recherche forestière, 1998; Du et al., 2017; Kuloglu et al., 2019; Perrin et al., 2015). The social repercussions of anomalous winter road seasons include user safety, emergency management, high costs of living, general consequences on well-being and reduced opportunities for cultural and social activities (Blair & Sauchyn, 2010; Furgal & Seguin, 2006; Golden et al., 2015; Hori et al., 2018b; Tam et al., 2013).

2.4. Yearly operational lifespan

The challenges of road opening and closure of these roads belong to two main classes:

- *Bearing capacity of over-ice segments*: A sufficient ice thickness should be achieved and ice integrity must be maintained. Both are to avoid the mechanical failure of the ice cover under loading.
- *Trafficability*: Irregular ground and soft surfaces can impede vehicle mobility. This can happen for various reasons. For example, the amount of loose snow is excessive, the over-ice surfaces get too soft (e.g. those surfaces more exposed to solar radiations), there is not sufficient snow to flatten and level overland surfaces or dark surfaces due to sand (used to improve traction in slippery conditions, as is done with salt and sand on city streets) promotes melting, typically at shore crossings. Some events can also prevent a vehicle from traveling, such as stream reactivation or the failure of a culvert.

Air temperature and natural snow accumulation dictate whether soil freezes to an adequate depth and ice reaches a safe thickness at the beginning of winter. Temporary road closures may also happen during the season because of a major winter storm or a warm spell (e.g. Malbeuf, 2021). Each winter road is different, and there are a number of factors contributing to a late opening, temporary mid-season closures, or earlier end-of-season closures.

Official road closure is when a facility ceases its activities for the season, and this varies from year to year. Factors such as softening of over-ice surfaces (which impedes trafficability, as mentioned above), due to warmer air temperatures and sun radiations, and reactivation of streams are two significant contributing factors. But there can be a number of others, including socio-economic factors, such as insurance policies. In some cases, early completion of annual shipping and community replenishment needs allow operators to close their roads because there is no longer a use for them (Perrin et al., 2015).

3. Transportation and goods movement in the North

In the North, winter roads provide the sole overland connection for many small remote communities to the all-season road network, which in turn connects to larger communities and the rest of Canada. As such, much passenger and freight movements for these remote communities occur during the winter road season. Although air transportation is available year-round, the comparatively enormous costs prohibit all but passenger travel (often necessary medical and other travel) and limited freight transport (such as perishable food items). Freight transport by air is also used when and where there have been shortfalls in essential goods delivery by winter roads – an undesirable outcome given the high costs. Although records on the nature of these goods and their movements may exist, they are not compiled systematically or completely by public agencies, due to the fact that the air transportation and logistics industries are privatized.

Winter roads can provide the cheapest means of shipping goods and services (Centre d'enseignement et de recherche forestière, 1998; Centre for Indigenous Environmental Resources, 2006; Hori et al., 2018b). They are also critical to support natural resource exploration, development, and extraction. The Tibbitt-Contwoyto Winter Road (TCWR) in the Northwest Territories (NWT) is a well-known example (Barrette, 2011; Braden, 2012; Mesher et al., 2008; Mullan et al., 2021, 2017). This a private consortium-owned facility used to supply open-pit diamond mines in the Slave Region. It connects to the all-season road and air networks to the south, and thus to the rest of the country via Yellowknife. The winter road season must provide enough capacity to accommodate all resupply needs to the mines served. In years with winter road capacity shortfalls, i.e. when the road is not able to fulfill its mandate, airlift has been used (but, here again, at a high cost).

Given the heavy reliance of winter roads on climatic conditions, there are growing concerns regarding the future viability of such facilities with respect to goods movement capacity and travel safety. Climate change is impacting season lengths as well as ice thickness and surface quality, affecting the types of trucks used and the amount of goods transported. A concern is that the customary resilience of winter roads, defined as the probability that they remain operative (Faturechi & Miller-Hooks, 2015), is decreasing from year to year. This creates growing challenges for freight logistics as well as personal trip planning, increased freight transport costs, and increased construction, monitoring, and maintenance costs. Increasing uncertainties in transportation costs – already much higher in the North – also impacts exploration and natural resource development. This uncertainty plays a major role in driving territorial and federal government investments (with support from local governments) for construction of all-season roads, to replace major winter road corridors. In the NWT, the Mackenzie Valley Highway (MVH) would replace many communities' reliance on winter roads in winter, river barging in the summer, and airlift in the shoulder seasons. The MVH has been under consideration and planning for decades (5658NWT Ltd. & GNWT, 2011). The northernmost portion of the MVH – the Inuvik-Tuktoyaktuk Highway (ITH) – opened in October 2017, replacing a long-existing winter road. Other corridors currently in planning and construction include the Slave Geological Province Corridor (which would replace the TCWR and is in planning stages), the Tłı̨chǫ All-Season Road (TASR – under construction), and the East Side Road (along the east side of Lake Winnipeg in northern Manitoba).

There have been efforts to understand how uncertainty may be considered within quantitative decision models to replace winter roads with all-season roads in major corridors (Kim & Li, 2020; Sturm et al., 2017). Specifically, these authors look not only at how major infrastructure investment decisions are made under uncertainty, but how these decisions can be flexible to changing and less predictable conditions. Attempts to estimate costs of constructing an all-season road have also been made (Dore & Burton, 2001).

4. Impact of a warming climate

Here, we look at the existing evidence regarding what appears to be a reduced operational time window, and review studies that addressed potential scenarios for winter roads in the future.

4.1. Shortening of winter road seasons

A number of studies show that the climate is changing in the northern hemisphere. Climate in the Arctic, in particular, has been warming at more than twice the global rate since 1900 (Knoll et al., 2019; Arctic Monitoring and Assessment Programme, 2017). The highest increase of a global surface temperature is projected at about three times the rate of global warming in the Arctic regions relative to 1850–1900, with a very high confidence (IPCC, 2021). The impact of climate change on the cryosphere, including sea ice thickness, snow cover, lake and river ice duration, and permafrost have increased in significance, with adverse consequences on northern transportation infrastructures (Knoll et al., 2019; Palko & Lemmen, 2017).

Over the years, there has been a small body of literature documenting the reduction in the average time window and in the overall quality of winter roads when in operation (Blair & Sauchyn, 2010; Centre for Indigenous Environmental Resources, 2006; Furgal & Prowse, 2008; Hori et al., 2017; Knowland et al., 2010; Mullan et al., 2021, 2017; Provencher, 2005). For example, in the NWT, later ice freeze-ups and earlier spring thaws are already affecting the duration of the Mackenzie Valley winter road season. The average opening date has been delayed by more than three weeks since 1996 (Furgal & Prowse, 2008). In northern Ontario, during the 2005/2006 operating season, there were delays of up to 10 days in opening several sections of the winter road networks, and many winter roads could not carry full freight loads due to thin ice conditions later in the season (Centre for Indigenous Environmental Resources, 2006). Also, the construction of winter roads in northern Manitoba and Saskatchewan was delayed that year due to the warmer weather conditions. The 2016/2017 operating season was one of the shortest winter road seasons across northern Canada, and was highlighted in the news media (e.g. Levin, 2017).

A trend analysis of the historical opening and closing dates for winter travel on the Alaskan North Slope was performed by Hinzman et al. (2005).[7] Opening dates were delayed from early November in the 1970s to early January in the 2000s, and closing dates have also moved to approximately three weeks earlier in May, resulting in winter travel duration decreasing from over 200 days in the 1970s to only 100 days in the 2000s.

Hori et al. (2017) examined climatological trends associated with winter road operational lengths in the western James Bay region of northern Ontario. They analyzed the relationship between the number of freezing-degree days (FDD)[8] and the opening and closing dates of the James Bay Winter Road (JBWR) from 2005 – 2015. Results showed that the decreasing trends in FDD are statistically significant, along with increasing trends of monthly averages of both minimum and mean air temperatures during the winter months. Results also indicated the opening dates were more closely linked to the FDD during the preceding months of October through December (herein referred to as winter roads' 'preconditioning' period), than the calculated FDD until the opening dates in January. The time-series of their work were extended by Knoll et al. (2019) with the recent years of data (2016–2018). They identified that the relationship between opening dates and FDD during the preconditioning period of the winter roads was statistically significant for the last 13 years. Hori et al. (2017) estimated the minimum number of FDD required for road opening at about 380.

4.2. *Projections into the future*

There is limited research using climate model projections to address the physical and socio-economic implications in Canada. Table 1 provides a listing. Lonergan et al. (1993) first applied three Global Circulation Models (GCMs) to examine the implications of climate change on the winter roads in the Mackenzie Valley, NWT. The three GCMs predict a decrease in the duration of the winter roads and an increase in the duration of open water conditions. The climate models project a shorter winter road season concurrent with a longer barge season (done in the ice-free summer months) which, in turn, will improve transportation and freight movement in the region. Hence, the regional economic impacts caused by these changes are expected to be relatively minor for inland communities that benefit from barge shipping (compared to the communities that do not), because this has historically been less expensive on a per-ton basis than transportation by truck or air. In northern Ontario and Manitoba, on the other hand, winter roads remain the cheapest means of shipping goods and services (Centre for Indigenous Environmental Resources, 2006; Hori et al., 2018b) as well as for communities throughout Northern Canada without marine access.

Mullan et al. (2017) used a set of three Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models driven by four Representative Concentration Pathways (RCPs) to project future changes on the TCWR. Results of the projected changes in ice thickness showed a trend towards thinner lake ice and a reduced operational time window for the TCWR. Almost all future scenarios indicated no operational dates for heavy vehicles by the end of the century, i.e. all winter roads in the region would no longer be viable. Mullan et al. (2021) further simulated lake ice thickness with a warming rate of 1.5°C, 2°C and 4°C above pre-industrial temperatures using the FLake freshwater lake model. Their results suggested that 2°C warming could

Table 1. Winter road networks that were addressed using climate model projections.

Region	Winter road network	Station	Data	Climate model projection	Source
Northwest Territories	Mackenzie River Valley	Norman Wells from 1994–75	• Air temperature • Precipitation	3 GCMs (2 x CO_2 scenarios) • Oregon State University (OSU) • Goddard Institute for Space Studies (GISS) • Geophysical Fluid Dynamics Lab (GFDL)	Lonergan et al. (1993)
Northwest Territories	Tibbitt to Contwoyto Winter Road (TCWR)	Yellowknife Airport from 1942–2010	• Air temperature (Tmean, FDDs, MDDs) • Precipitation • TCWR operational data from 1994–2013	Baseline period: 1981–2010 Projection periods: 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100) 41 GCMs in CMIP5 (RCP4.5, 8.5)	Perrin et al. (2015)
Northwest Territories	Tibbitt to Contwoyto Winter Road (TCWR)	• Hay River from 1894–2012 (air temperature), 1910–2012 (precipitation) • Yellowknife from 1943–2012 • Lupin, Nunavut, from 1959–2012	• Air temperature (Tmax, Tmin) • Precipitation • Ice thickness data in Yellowknife from 1958–2012 • TCWR operational data from 2002–2012	Baseline period: 1986–2005 Projection period: 1861–2100 3 GCMs in CMIP5 (RCP2.6, 4.5, 6.0, and 8.5) • Geophysical Fluid Dynamics Laboratory (GFDL-CM3) • UK Met Office Hadley Centre (HadGEM2-AO) • Model for Interdisciplinary Research on Climate (MIROC5) CLIGEN (CLImate GENerator) for temporal downscaling	Mullan et al. (2017)
Northwest Territories	Tibbitt to Contwoyto Winter Road (TCWR)	0.5° x 0.5° grid square around Tibbitt Lake	• Air temperature (Tmean), relative humidity, solar radiation, wind speed, and cloud cover • Ice thickness data for four lakes >10 years between 1981–2000 • TCWR operational data from 2001–2020	Baseline period: 1986–2005 Projection period: 20-year future time periods for 1.5°C, 2°C and 4°C FLake freshwater lake model All available CMIP5 models (RCP8.5)	Mullan et al. (2021)
Manitoba	Berens River region	Berens River from 1986–2001	• Air temperature • Winter road operational data in the Berens River region	Baseline period: 1961–1990 Several GCMs and scenarios	Babb and Blair (2005)
Ontario	31 winter road network areas in Ontario's Far North	Northern Ontario (not specified locations)	• Air temperature • Surface soil temperature • Northern Ontario winter road network data from 2009–2013 • Modern Era Retrospective Analysis for Research and Applications (MERRA TSOIL1) dataset	Baseline period: 1981–2010 Projection periods: by 2050 (2020–2049) and by 2100 (2070–2099) 25 GCMs in CMIP5 (RCP2.6, 4.5, 6.0, and 8.5)	Deloitte (2014)
Ontario	5 winter road network areas in Ontario's Far North	• Big Trout Lake • Lansdown House • Moosonee • Red Lake • Kapuskasing	• Air temperature (Tmean, FDDs) • James Bay Winter Road (JBWR) operational data from 2005–2015	Baseline period: 1981–2010 Projection period: 2011–2100 29 GCMs in CMIP5 (RCP8.5, 4.5, and 2.6) 2 RCMs – Canadian Regional Climate Model (CanRCM4) (RCP8.5 and 4.5), Reginal Climate Model (RegCM4) (RCP8.5) Statistical DownScaling Model Decision Centric (SDSM-DC) for statistical downscaling	Hori et al. (2018a)

be a tipping point for the future viability of the TCWR. The operational season length of the TCWR has also been studied by Perrin et al. (2015). They projected the FDD accumulations using the CMIP5 ensemble models under two RCPs (RCP4.5, 8.5). Under present climate conditions (1981–2010), the average operating season was 65 days. The length of the season, however, gradually decreased due to a warming trend. By the 2020s, a reduction in average operating season duration to approximately 60 days under both RCPs is expected. By the 2050s, the average length of the season will reduce to 55 (RCP4.5) and 50 days (RCP8.5), and by the 2080s the projections are between 52 (RCP4.5) and 38 days (RCP8.5).

In Manitoba, several GCM projections by Babb and Blair (2005) indicate the winter road seasons will become shorter throughout this century. The GCMs project that the average winter road season in the Berens River region (Manitoba) will likely continue to shorten by five days in the 2020s, 10 days in the 2050s, and 14 days in the 2080s, relative to 1961–1990. In northern Ontario, a winter road study by Deloitte (2014) applied the Temperature at the Top of Permafrost (TOPP) ground temperature model, using the Modern-Era Retrospective analysis for Research and Applications (MERRA) of topmost soil temperature layer (TSOIL 1) data. Their study used a subset of 25 CMIP5 models driven by four RCPs (RCP2.6, 4.5, 6.0, 8.5) for two future periods (2050 and 2100). The operating window for winter roads was defined by dates of freeze and thaw of the MERRA TSOIL1 layer. This window serves as a proxy for the real operational suitability of the roads. Results of the model projections (75^{th} percentile) indicated that by the 2050s, the operating window will decrease by 12 – 20% from the current window, and by 20 – 40% by the end of 2100.

Another study by Hori et al. (2018a) for Ontario applied the lowest threshold of 380 FDD alluded to earlier, derived from the relationship between the FDD and the JBWR, to examine the effects of climate change on the winter road construction in a future period. Their study used five locations in northern Ontario and examined the future FDD accumulations from October to December in the preceding year of road openings for the three time periods: 2011 – 2040, 2041 – 2070, and 2071 – 2100. The 29 CMIP5 models and two Regional Climate Models (RCMs) were used to compare the potential impact of future climate change estimated from different spatial resolutions. Under RCP4.5 and RCP8.5 in both the CMIP5 ensemble and CanRCM4 projections, the projected FDD for Big Trout Lake suggests that climate conditions would be favorable for winter road construction through to the end of 2100. This means that the FDD will be sufficient (above the lowest threshold) during the winter road construction period. However, under RCP8.5, both climate model projections for Moosonee and Kapuskasing indicated unfavorable climate conditions (below the lowest threshold with the mean FDD at 353 and 336, respectively) within the mid-century (2041–2070), and for Red Lake by the end of the century (2071–2100) at 340 FDD.

These climate model studies rely mostly on air temperatures, not only because it is an important parameter, but also because there is more information on it. There is a need for a more in-depth approach using other climate and environmental indicators, such as snow fall, wind as well as permafrost and soil temperatures. Long-term monitoring of all parameters is necessary.

4.3. Consequences for northern communities

A shorter winter road season with less reliable road conditions has a substantial socio-economic impact on remote Indigenous communities. During the warm winter of 1997/1998, $15-18 million was spent to airlift essential supplies such as food and fuel to a number of remote communities in northern Manitoba and Ontario (Centre for Indigenous Environmental Resources, 2006). In December 2012, Kashechewan First Nation in northern Ontario declared a state of emergency due to a lack of fuel, caused by a short winter road season in the previous year that limited the amount of diesel fuel delivered (The Canadian Press, 2012a). Some First Nations communities in northern Manitoba also declared a state of emergency in the winter of 2010 due to warm weather, as fuel trucks were getting stranded in a muddy road (The Canadian Press, 2012b). The lack of winter access for these remote communities has important consequences from an economic perspective, for example, an increase in price of goods and services, which are already expensive. For example, according to Prentice and Adaman (2017), " . . . the cost of food in the remote communities is 2.5–3 times higher than the cost of food in the urban areas of Canada". Consequences of a psychological (e.g. feeling of isolation) and cultural (e.g. no access to traditional hunting and festivals) nature must also be considered (Golden et al., 2015; Hori et al., 2018b).

Manitoba Infrastructure and the NWT Department of Infrastructure play a direct role for all aspects of winter roads, including contracting work to local and/or First Nations companies (IBI Group, 2016). This system can reduce the financial burden for these groups who hire contractors, and also allocate resources based on the needs of the difficult road segments (IBI Group, 2016). In comparison, most winter road corridors in northern Ontario are managed by nearby First Nations organizations, which allows them a direct role in winter road governance. However, due to a lack of a formal system to report how winter roads are used, winter road usage data – including the operating dates in northern Ontario – are under-reported and/or less accurate (IBI Group, 2016). Such jurisdictional differences, and resulting inconsistencies, hinder the collection of usage data, which in turn are inputs towards funding mechanisms and guidelines. These differences also create a gap in regional initiatives on adaptation priority and scientific study regarding the impact of climate change on winter road networks across Canada.

4.4. Adaptation measures

Adaptation measures are means of dealing with issues that adversely affect the effectiveness of a winter road operation. Various sources of information discuss these measures (e.g. Dillon Consulting Limited, 2007; Hayley & Proskin, 2008; McGregor et al., 2008; Perrin et al., 2015; Government of Ontario, 2016, IBI Group, 2016). A large number of options exist, effective in the immediate to long-term – they are implemented on a case-by-case basis. Following are some examples:

- Extending the power grid to remote communities, so as to reduce their reliance on diesel fuel.
- Laying structural bridges and culverts at river and stream crossings.
- Strategic relocation of over-ice segments on land.
- Installation of a remote weather monitoring device along winter road corridors that are located far from meteorological stations.
- Improving means of monitoring the ice thickness, notably by optimizing GPR technology.
- Laying snow on the ice surface to maintain a high albedo – that stored in snow banks can be used for that purpose, or from snow cache constructed and maintained for that purpose.

Traffic management is an important mitigating tool. Examples include: using the road at night (while the surfaces are harder), enforcing speed limits (travelling velocity has an impact on ice deflection, e.g. Babaei et al., 2016), allowing one lane to be faster for empty loads, conducting driver awareness campaigns, and the implementation of an automated passive traffic data collection system.

4.5. Costs and benefits of adaptation

To date, little attention has been paid to the socio-economic costs and benefits of adaptation for the remote communities in response to climate impact on winter roads. Several feasibility studies of the Slave Geological Province Corridor have conducted a cost-benefit analysis for the TCWR and compared it with the proposed all-season road systems (Andersen et al., 1999; CBC, 2001). However, these studies did not factor in the impact of climate change. Perrin et al. (2015) evaluated the climate-related vulnerabilities and estimated the growing costs of winter road construction, maintenance, and shipping scheduling for the TCWR. The yearly operational lifespan was seen as the most important cost driver for the future, i.e. the shorter that lifespan, the more significant the risks from an economics perspective. What is required to conduct these analyses is a better understanding of what these facilities are, what can be envisaged to make them more resilient to a changing climate, and what should guide prioritization. These aspects are discussed next.

5. Discussion

5.1. A physical characterization tool for winter roads

To guide a prioritization exercise and inform what the requirements are on the engineering front, there is a need for an adequate understanding of the physical nature of these networks, i.e. the 'Winter road characteristics' component in Figure 9.

Compared to all-season roads, as mentioned earlier, winter roads are not well documented. According to Northern Ontario's Multimodal Transportation Strategy[9] 'Mobility on the roads is challenged by [. . .] limited real-time information on road quality, as there is currently no central source of information on the winter road network'. Lack of uniformity in road signage has also been raised (IBI Group, 2016). These shortfalls could be addressed with a tool designed to collect information on the roads' physical parameters, which would then be combined with all operational and logistical data (e.g. opening and closure dates, nature of goods transported, size of communities, links with air strips) in an interactive database.

This tool could take the form of a field instrumentation package, an example of which is shown in Figure 7, to collect equivalent sets of information on each facility inside a given provincial or territorial network. By analogy, one might think of the currently employed GPR systems, used to obtain a continuous thickness profile of

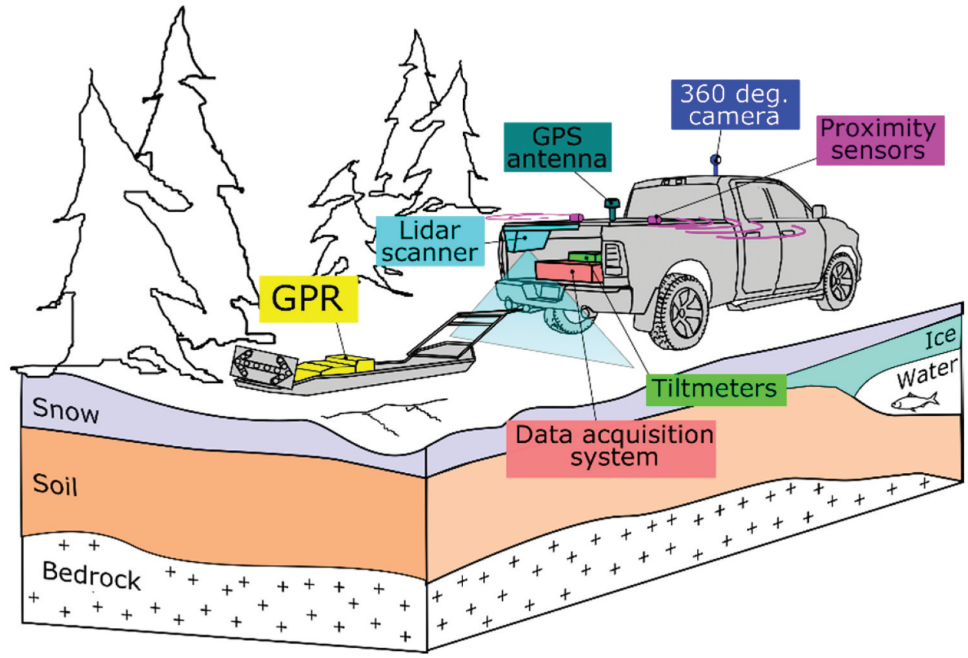

Figure 7. Deployment of a system, such as the concept shown here, would allow a systematic characterization of winter roads in Canada. GPS: Global Positioning System; GPR: Ground penetrating radar; Lidar: Light Detection and Ranging (for detection of trees, boulders and other features).

the frozen ground (Campbell et al., 2018; Stevens et al., 2009) and freshwater ice (Fedorov et al., 2016; Mesher et al., 2008; Proskin et al., 2011b), combined to a package analogous to Google Street View (Biljecki & Ito, 2021). Its conception could draw from an elaborate imaging system such as that shown in Roghani et al. (2022) to monitor water expanses along railroad tracks. The package would enclose additional instrumentation, which would increase its capabilities significantly, notably a compass, tilt meters, accelerometers, proximity sensors, GPS, voice data logger, amongst others. Data output would include: itinerary in a 3D space, foundation, width, radius of turns, grade, cross slope, slope direction, vegetation, canopy, stream crossings, obstacles (e.g. boulders, large trees). Such a system could thus be an extended version of a model that is already being used by Northerners (Bell et al., 2015; Safer, 2016). Real-time access via satellite linking could provide short-term information, accessible to users on a weekly or even daily basis. Yearly databases would be available for extensive analyses by stakeholders.

The outcome would provide a fundamental basis for gauging each facility's resilience. Community involvement in the deployment of the data gathering tool could help ensure data acquisition is done on a regular basis. It could also facilitate on-going communication between communities and the governmental organizations. For instance, in Northern Ontario, the operations are funded on a per-kilometre basis. An issue that was raised is that '[c]ommunities that have more difficult water crossings or other challenges along their route are compensated the same way as those with fewer challenges' (IBI Group, 2016, p. 27). Proper road characterization would alleviate this kind of situations Figure 7.

5.2. Knowledge gaps in engineering

Adaptation measures such as those listed above were learned from extensive operator experience. In the context of a changing climate, however, we have reached a point where research is required to help address stakeholder needs. Areas of investigations have already been discussed elsewhere (Barrette & Charlebois, 2018). A better understanding of the integrity of the over-ice segments is seen as a priority – they are very climate-sensitive, they are commonly weak links in an operation, and the consequences of a breakthrough, or what that perspective entails at a psychological level, are significant.

Ice covers are not uniform in internal structure or thickness. They are also thoroughly fractured (as shown in Figure 3), which is the outcome of air temperature changes, leading to contraction and expansion. They can also be a result of repetitive loading due to vehicle traffic. Fractures may be seen as structural flaws, but their influence on the integrity of a floating ice cover has never been investigated so far, to the authors'

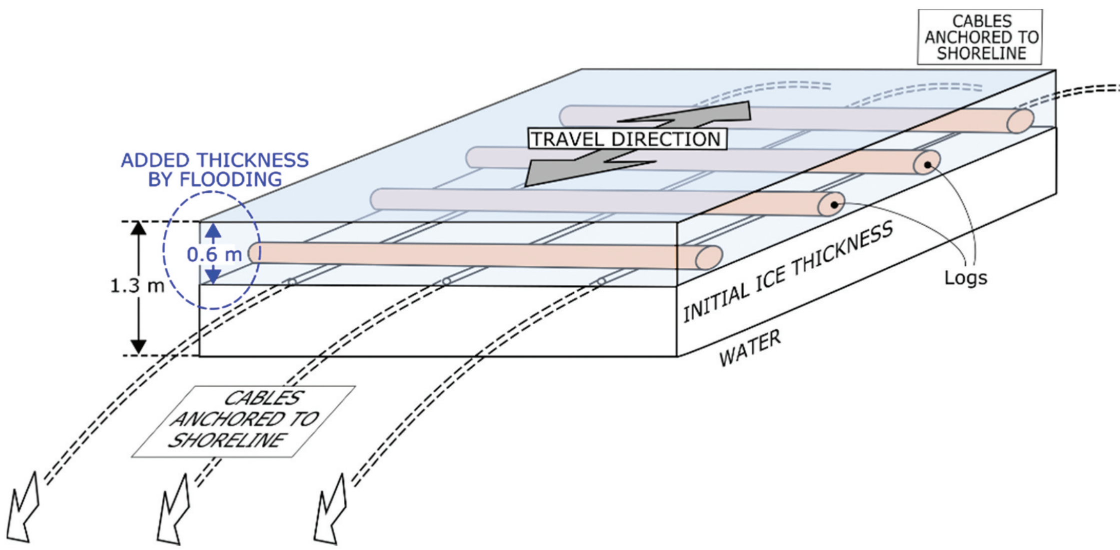

Figure 8. Example of a reinforced ice cover (from Barrette, 2021). Three cables were laid on the surface of the ice and anchored on the shorelines. Logs were placed on top them, then flooded, yielding a total thickness of 1.3 m.

knowledge. As stated by Proskin et al. (2011a), '[a]ny of the refined analytical methods [to determine bearing capacity] assumes the ice sheet acts as an elastic, homogeneous, isotropic plate on an elastic foundation. This assumption is sufficiently accurate for the purpose of designing ice roads, despite the fact that cracks are normally present within ice cover' (p. 64). In other words, these types of flaws are typically overlooked.

Another prospective research avenue is a means to reinforce ice covers at problematic locations, e.g. a river crossing or a shoreline approach, with the aim of increasing their strength while also preventing breakthroughs. This has been done over the last number of decades, with various methods (Barrette, 2021; Barrette & Babaei, 2021; Vasiliev et al., 2015), (Figure 8 is an example). In the context of a warming climate, this approach is expected to become increasingly instrumental in preserving the yearly operational lifespan of winter roads.

Improved understanding should also be sought with regards to static loading, i.e. the maximum amount of time an ice cover can safely support a given load, and dynamic loading, the development of 'waves' in the ice cover under the action of a traveling vehicle (Babaei & Barrette, 2020; Barrette & Babaei, 2021; Barrette & Charlebois, 2018).

5.3. Prioritization of resources

Although adaptation measures may be effective means of maintaining the operational lifespan of any given operation, they imply costs that often cannot be covered by the available resources. Ultimately, decision-makers may choose to replace a more critical winter road facility, or part thereof, with an all-season road – less expensive options would be used for other facilities. Implementation would reside within a decision-support framework aligned with the tenets of co-production, namely the need to involve winter road operators and end-users (Palutikof et al., 2019; Prokopy et al., 2017). Local community representatives would play a key role, so as to ensure adaptation to stakeholder needs, i.e. winter road environment, management and usage between locations, First Nations activities and requirements. Adequate interaction and knowledge exchange between decision-makers (e.g. government officials) and scientists and engineers involved in building that framework would also be desirable (Cvitanovic et al., 2016; Palutikof et al., 2019). This would ultimately provide guidance to the prioritization of resources: how to make the best usage of the available funds, for which facilities and for what purposes.

Figure 9 summarizes the components that are involved in this process. Winter roads inherently vary in characteristics. Hence, irrespective of climate change (i.e. even if it were not occurring), they would also vary in resilience. But these differences are exacerbated by an evolving climate. Community vulnerability takes into account socio-economic factors and the needs that would not be met in the eventuality of road closure. This constitutes the risks, e.g. cost of air lifting for a medical emergency if a health center is no longer accessible, or that incurred by a mine site if it cannot be supplied. Adaptation measures and costs can be established on the basis of road characteristics,

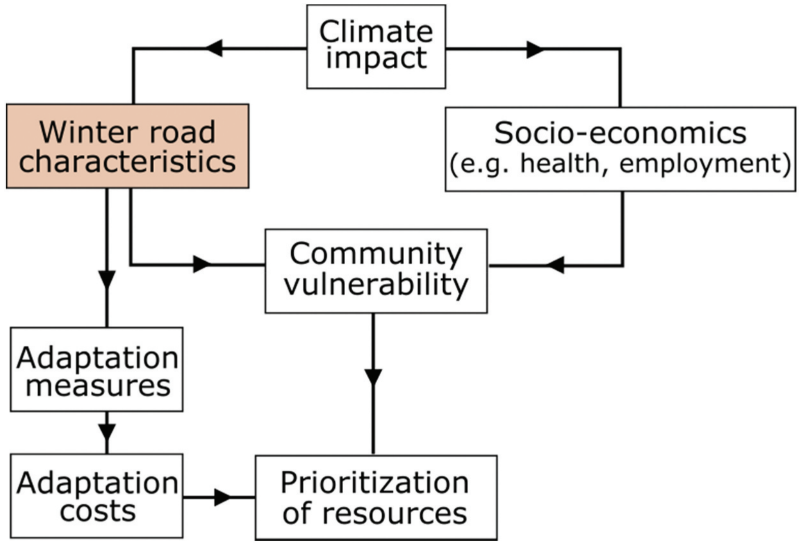

Figure 9. A changing climate has an impact on winter roads, but also on socio-economic development – together, they define community vulnerability. Prioritization of resources takes into account both vulnerability and adaptation costs.

and would feed into the prioritization exercise. The latter would involve monetizing the value of these risks, assessing benefit to cost ratio as it relates to the risks and analysing the return-on-investment on a given road network.

5.4. An infrastructure in its own right

An 'infrastructure' is defined in English dictionaries (Oxford, Cambridge, Collins, Merriam-Webster) in a similar fashion: the basic facilities, systems of services that are required by a society or an organization to run effectively. Examples of infrastructures and the services they address are shown in Table 2.

In the specialized languages, the usage of that term 'varies widely across multiple disciplines' (Aleksandrova et al., 2019, p. 4). Infrastructures are classified as green (nature-based) or grey (engineered), either competing for or seeking access to land use and public funding (Aleksandrova et al., 2019; Choi et al., 2021; Tjallingii, 2003; Wise, 2008). There are also infrastructures that are also labelled as red – housing, commercial developments and public buildings (e.g. Tjallingii, 2003). The concept of a blue infrastructure, or urban blue space – ponds, lakes and rivers – is also known (Deak & Bucht, 2011; Wu et al., 2019).

Table 2. Services and associated infrastructure (from Prud'homme, 2005).

Service	Infrastructures
Transportation	Road, bridges, tunnels, railroads, airports, harbors, ...
Water supply	Dams, reservoirs, pipes, treatment plants, ...
Garbage disposal	Sewers, used water treatment plants, ...
District heating	Heating plants, pipe networks
Telecommunication	Telephone lines, satellite dishes, antennas
Power	Power plants, transmission and distribution lines, ...

Infrastructures are also classified as either 'hard' (physical) and 'soft' (organizational/relational)(Dyer et al., 2019). The former includes utilities (e.g. transportation, water, waste, communication), urban space (e.g. streets, plazas, playgrounds) and buildings (single or grouped). The services provided by a hard infrastructure are mainly from the facility itself, e.g. a power generating station provides electricity to consumers. Prud'homme (2005) suggests the following common attributes for hard infrastructures.

- They are capital goods, as opposed to consumer goods, i.e. fixed assets, used in the production of consumer goods.
- They are tied to lumpy (as opposed to incremental) costs, e.g. a bridge has to be fully built before it can start to provide services. If the demand exceeds capacity, a major addition, such as retrofitting, is required, following the same principle.
- They are usually long lasting – their serviceable lifespan typically lasts decades.
- They are site-specific. A sewer is designed and built for one location, and is not expected to service any other. This is also valid at the network level, i.e. a sewer system is unique to a city.
- The service they provide is used by the public and the private sectors.

Within the surface transportation sector, i.e. considered hard infrastructures, one may speak of a highway infrastructure (e.g. Alderson et al., 2018), a highway bridge infrastructure (e.g. Siddiquee & Alam, 2017) and a residential street infrastructure (e.g. Aleksandrova et al., 2019).

Soft infrastructures include institutional (e.g. government, health care, educational), communal (e.g. community networks such as neighboring watch groups, business associations), and personal (employment, family)(Dyer et al., 2019). Services delivered by these infrastructures result from the interaction between humans, e.g. an elementary school is a building, but the services delivered to the consumers are by teachers (or more generally, by its staff).

What characterizes winter roads? Following are some commonalities:

- The services to users (the consumers) are delivered by the road itself, not by its staff.
- They can be considered capital goods – fixed assets include culverts, structural bridges, vehicles, machinery and other equipment that are used on a year-to-year basis, and without which the road could not become operational.
- A winter road cannot open until the full road has been constructed. As such, it is tied to lumpy costs.
- Winter roads are seasonal operations, i.e. although their location and routing does not change year to year (or minimally), their surfaces are re-built every year. However, most facilities have been operating over a number of decades, mainly in a consistent fashion year to year.
- They are site-specific – every road is custom-designed to suit the terrain and the route along which it is expected to deliver its services.
- They provide services to the public – community members travel on the roads to get to their work, to visit relatives, to access traditional fishing and hunting grounds, etc. Services are also used by the private sector – merchants and contractors depend on it to reach their client base, which includes communities and resource extractions sites (e.g. mines, forestry).

On the basis of the cursory evaluation presented above, winter road networks may arguably be seen as a hard infrastructure. Also, and although they are not usually part of an urban environment (there are exceptions, as some ice bridges are inside communities, e.g. Barrette et al., 2018), they are akin to a green infrastructure, in the sense that they are built on a natural foundation and with natural materials, i.e. frozen ground, snow and ice expanses. Corridors have to be established, involving tree clearing and ground leveling, but these constitute a very small portion of the human input. In a way, winter roads epitomize the integration of a (mostly) non-engineered structure – a road – into a natural environment, with minimal environmental impact.

Irrespective of how and in what classification these facilities may be fitted into, there is no tangible reason why they should not be collectively deemed a stand-alone infrastructure. Acknowledging this would help mobilize the transportation engineering community in addressing the challenges these unique transportation networks are facing. In a country like Canada, it would also be an incentive to centralize information on these structures and to approach their design, construction, usage and maintenance in a coherent fashion, which would be in the mutual interest of all jurisdictions – provincial, territorial and community-based – and of the private sector.

6. Conclusions

Any given road or highway may be conceived as a series of segments in series, analogous to 'links' in a chain. These may vary in 'strength', i.e. some more or less vulnerable than others. The difference in resilience between the various segments is more substantial for winter roads than it is for all-season roads. The main reason is that these facilities are mostly a product of nature. Also, there are fewer guidelines for winter road construction and maintenance compared to those for all-season roads, and they can vary significantly across the various jurisdictions (provinces, territories, communities).

As with all-season road networks, these seasonal roads also support supply lines, services and the mobility of people (albeit in regions with low density populations). A warming climate threatens the effectiveness of these networks and increases the vulnerability of the remote communities that depend on it. This is primarily a consequence of an increase in air temperature, leading to a reduction in the yearly operational lifespan of the roads. Climate models predict further deterioration in the medium- to long-term. Clearly, this does not bode well for the Canadian winter road networks as a whole, and for their serviceability in sustaining healthy Northern communities. Given this state of affairs, decision-makers will benefit from a better understanding of these networks so as to optimize the resources available to support them. The systematic physical characterization of these roads is deemed an important step in that direction. The reason is it would bring together a consistent dataset that could be used to assess adaptation costs, to address the weak links and to guide the evaluation of community vulnerability.

This article's intent was to contribute in raising awareness of the existence of winter road networks, drawing on the Canadian experience. It is also to underscore the need for a structured approach to investigate these networks. This should be dealt with in a holistic fashion, via a coordinated approach, preferably at a federal level, with strong input from other jurisdictions, local communities and stakeholders from the private sector.

Notes

1. Public roads: https://www.inf.gov.nt.ca/sites/inf/files/resources/nwt_highway_facilites_february_2018_0.pdf, Tibbitt-to-Contwoyto Winter Road: https://jvtcwinterroad.ca/about/#facts
2. https://www.rmwb.ca/en/roads-and-construction/resources/Documents/winter-roads-map.PDF
3. https://www.saskatchewan.ca/government/news-and-media/2007/february/08/ice-road-construction-underway-in-far-north
4. https://www.gov.mb.ca/mit/winter/reports.html
5. https://www.mndm.gov.on.ca/sites/default/files/en_-_northern_ontario_winter_roads_map_2019.pdf
6. http://www.cbc.ca/news/canada/north/tibbittroad-opens-2018-1.4515200?cmp=rss
7. Since this article focuses on Canada, information on Alaskan winter road operations is not included.
8. This is the average number of degrees below freezing point summed over the total number of days in a given time period. For instance, if the average air temperature on day 1, 2 and 3 was −5°C, −8°C and −12°C, respectively, the number of FDD for these three days is 25°C (5 + 8 + 12). Days when the temperature is zero or above are not considered.
9. https://nomts.ca/discussion-paper/#C5A [Consulted 23 April 2018]

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