Winter roads and climate adaptation: Prospective solutions through R&D

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Abstract

In Canada, the total length of the winter road network is estimated at 10,000 km. These are roads that are usable only in the winter. Nature controls the state of a winter road's foundation – natural ground and ice surfaces – which needs to be trafficable and able to support the vehicles' weight. These surfaces are particularly sensitive to climate change. A large number of adaptation measures were developed over the years, which can be applied at the planning, construction and maintenance stages, and for traffic management. We have reached a stage where increasing our fundamental knowledge base is required. This can be done through research and development (R&D). Avenues of investigation include a field tool to characterize winter roads in a more systematic fashion, by combining physical information (e.g. road grades, cross-slopes, width, over-land vs over-water ratio) with all operational and logistical data (e.g. opening and closure dates, nature of goods transported) into an interactive database. This could be used for capacity and multimodal planning, as well as to guide priorities on road realignment and incremental replacement (partial or complete) by all-weather road segments. Several outstanding questions regarding the bearing capacity and deformational behavior of floating ice roads could also be addressed. Topics that need to be investigated include: ice cover strength, how long a vehicle can be parked on the ice, how cracking patterns affect ice integrity, and the investigation of known procedures, techniques and technologies to reinforce an ice cover.

Introduction

In Canada, there are approximately 10,000 km of winter roads[1]. These are roads that are usable only in the winter – they run over land and across frozen water bodies (lakes, rivers and sea ice along coastlines and in bays). They range in length from a few hundred meters to 100's of kilometers, and are managed either by local communities, provincial/territorial governments or the industrial sector (mines and energy). Winter road users rely on them for their yearly supply of fuel, construction material and other bulk commodities that are too expensive for air transportation. Winter roads are also used extensively for leisure activities such as ice fishing, snowmobiling and participation in sporting events (*e.g.* hockey tournaments, Dene hand games).

Warmer winters cause winter roads to close, leaving communities stranded or mining operations running out of supplies – airlifting is very expensive (Kuryk 2003, Taylor and Parry 2014, Perrin et al. 2015). According to McDonald (2007), "[f]lying supplies to the mines costs four to eight times more per pound than transporting them by road."

Climate change is thought to increase the frequency and extent of warm winters. As such, it affects the safety and effectiveness of this infrastructure and reduces its yearly operational lifespan. A reduction in the number of freezing-degree days (FDD)[2] is the most recognized concern. Both over-land and over-ice segments are affected. Contractors and engineering consultants have a wealth of knowledge and experience, and resort to various corrective measures to address the issues causing these closures. In parallel, as argued in the present paper, there is a need for new Research and Development ('R&D') to improve our basic understanding of ice mechanics and hydraulics, which can be undertaken by research institutions

[1] This is a rough estimate which may be seen as an upper limit – about 8000 km are officially recognized, plus an estimated 2000 km of industrial and community-based operations and sea ice roads.

[2] 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 -5ºC, -8ºC and -12ºC, respectively, the number of FDD for these three days is 25ºC (=5+8+12).

and universities[3]. The outcome of that R&D can then be used for input into manuals, standards and other such guidelines in the planning, design and usage of winter roads.

The purpose of this paper, which draws from a larger document (Barrette 2018), is to present a brief overview of what winter roads are, their challenges in the context of climate change, and prospective R&D toward adaptation strategies – see Golden et al. (2015) for a discussion on climate change 'adaptation' concepts and how they differ from 'mitigation'.

Overview of winter roads

A winter road typically consists of segments that run over land and on floating ice surfaces (Figure 1). Each type comes with its own challenges in terms of planning, construction and safety. The over-land segments are underlain by soil that is frozen to a given depth, itself underlain by bedrock (or directly on the bedrock), or over permafrost at higher latitudes. These foundations can be overlain by snow or artificially-produced ice, used as a supporting surface and as a protection to the underlying vegetation. The ice may be produced with water tankers or from water pulled out directly from a nearby pond or lake (Proskin et al. 2011a). To increase thickness, water can be used to flood ice chips, to help increase ice buildup. The required thickness of that ice/snow layer depends on vehicle weight, weight distribution and frequency of passages.

Segments running on floating ice take advantage of that material, which is naturally-available and, evidently, leaves no environmental footprints. An ice cover is able to support a load because of the ice cover's buoyancy and its resistance to flexure.

Factors controlling the yearly operational lifespan, i.e. the parameters involved in road opening and closure, need to be carefully addressed, especially the weak links.

Road opening and closure

Road opening is usually a function of the time required to grow a safe ice thickness, which itself depends on the maximum expected vehicle mass (e.g. some roads are meant to carry tractor trailers, other to only handle light vehicles). For over-ice segments, this is often achieved in two steps:

- The first step is removing the snow layer from the ice, so as to accelerate ice growth (snow acts as an insulator – e.g. Andres and Van Der Vinne 2001, Ashton 2011). This is done with light vehicles, once a safe thickness for these vehicles is achieved. Note that for over-land segments, the snow is left in place, so as to preserve a high albedo[4] - it is compacted, thereby also reducing its insulating effects, which accelerates ground freezing.
- The second step is flooding the surface with water, or using spray ice[5], to artificially increase the thickness to the required target level.

Understandably, an optimum number of FDD at the beginning of the winter will favor an earlier opening – an example is provided by Hori et al. (2017) for the James Bay Winter Road in Northern Ontario.

[3] The private sector may do its own R&D work, but it is typically for internal use only.
[4] Albedo in this context is the amount of sunlight reflected by the ice/snow. If the ice/snow surface becomes dirty, for instance when it incorporates sand, it absorbs the sunlight, which accelerates melting because of stored heat.
[5] Ice that forms by spaying water in the air as tiny droplets, which fall down onto the target location.

Official road closure occurs when an operation ceases its activities. This varies from year to year (an example is shown in Figure 2). Road closure can due to the deterioration of the over-land segments and its transition to the over-ice segments, for example, where the road is darkened by the soil. Because of the lower albedo, sun rays are absorbed, contributing to the increased melting. Softening of the over-ice surfaces can also be a factor, as it eventually impedes trafficability, i.e. the ability of a vehicle to travel on the ice. Temporary road closure may also happen during the season, when a weak link becomes unusable and a diversion is not possible. Each winter road operation is different and there can be a number of factors contributing to a late opening, mid-season or end-of-season closure. Some operators may close their road because there is no longer a use for it.

Planning the road

A number of factors have to be taken into account when planning a winter road. The following summary is from Proskin et al. (2011a).

Defining general road requirements

These requirements are as follows:

- *Schedule and operating windows*: What are the target road opening and closure dates.
- *Traffic type and volume*: What kind of vehicles (weight, size, axel load distribution) and how many passages are expected.
- *Road right-of-way*: This is the road width – requirements vary with road type, number of lanes, location, type of work involved (servicing communities, mines, seismic program…).
- *Environmental and regulatory requirements*: These address environmental impacts, archeological sites, ecological and cultural sensitivities, etc.

Developing route options

- *Over-land options*: This takes into account topography, water and snow requirements and the nature of the terrain (e.g. dry mineral soil is acceptable, muskeg should be avoided).
- *Over-ice options*: Parameters to be considered include: water currents (if any), bathymetry, availability and nature of portages[6], and water influx from nearby streams. Shallow areas and shoals can be objectionable, for instance, to address issues related with vehicle speed.

Weather parameters

- *Temperature and snow regime for over-land segments*: Historical records of freezing-degree days and snow fall are critical parameters - Proskin et al. (2011a) mention 300^{o}C-days as a minimum for ground freezing, and 5-10 cm of snow to support traffic.
- *Ice conditions*: Similarly, historical ice thickness data should be consulted, along with freeze-up dates and ice cover disintegration/break-up dates.
- *Climate change*: A handle on warming trends is also helpful to try to anticipate the expected number of FDD and changes in precipitation patterns.

[6] A portage is a short over-land segment between two over-ice segments – grade, orientation and the nature of its foundation are important factors.

Challenges with the winter road infrastructure

The winter road infrastructure, like any other infrastructure in Canada, faces its own challenges. Each winter road operation is distinct – usage optimization at the planning stage is envisaged on a case-by-case basis.

Climate change

Climate change is the consequence of global warming, which refers to the progressive rise in temperature of the Earth's atmosphere documented over the last number of decades. At the planetary scale, this temperature rise is only a few degrees. However, this increase has important repercussions on the complex dynamics of the atmosphere and can have a significant impact on local weather patterns, including a significant increase or decrease, depending on geographical location, of the average air temperature. A large number of climatic models have been generated in an attempt to capture these temperature trends.

There is an extensive amount of literature on climate change and its impact on the winter road infrastructure. The following are some recent areas of study:

- How it affects transportation, infrastructures and indigenous lifestyle in the Arctic (Pearce and Smit 2013, Tam et al. 2013).
- How it affects winter road operations (CIER 2006, Rawlings et al. 2009, Knowland et al. 2010, Strandberg et al. 2014).
- How it affects the mining industry in Northern Canada (Hayley and Proskin 2008, Macumber et al. 2012, Perrin et al. 2015, Mullan et al. 2017).
- A projection of operational lifespan in the future (Hori and Gough 2017).
- The establishment of statistical links between FDD and winter roads opening dates (Hori et al. 2017).
- Historical trends and how ice bridges on the St. Lawrence can be used as an index of winter severity (Houle et al. 2007).
- Risk to communities, e.g. ability to resupply and difficulty to plan because of unpredictable seasons conditions (Golden et al. 2015).

Two factors are associated with an increase in temperature:

1. *Safety concerns*: Delays in achieving target ice thickness will increase the likelihood of having users access the over-ice segments earlier than they should, because they are eager to use the ice and do not exercise due caution at that critical time of the year. This results in more frequent breakthroughs.
2. *Operational aspects*: Issues that normally affect winter road operations (e.g. ground thawing, large snow falls, softening of the ice surface) on an occasional basis may recur more frequently because of climate change.

Adaptation measures

Adaptation measures are means of dealing with issues that adversely affect the effectiveness of a winter road operation. Adaptation measures can be reactive – i.e. dealt with as part of maintenance and traffic management strategies, or they can be anticipatory – i.e. planned in advance (Dillon Consulting Limited 2007). Various sources of information discuss adaptation measures (Hayley and Proskin 2008, McGregor et al. 2008, Barrette 2015b, Perrin et al. 2015, Government of Ontario 2016, IBI Group 2016).

Planning, construction and maintenance

The following is a non-comprehensive listing of adaptation measures – as can be seen, most apply to over-ice segments.

- Laying structural bridges to replace river crossings when these become choke points.
- Building all-weather road segments to replace problematic areas.
- Planning route selection over the ice carefully – the shortest option may not be the best, because bathymetry and other factors have to be factored in.
- Re-locating an over-ice segment to the land.
- Building and maintaining multiple routes, in case one becomes unusable, or allowing contingency room for a by-pass, as required (see example in Figure 3).
- Conducting stress analyses to estimate ice bearing capacity under static or dynamic loads[7].
- Including improved standard operating procedures on ice that are embedded in contracts.
- Improving means of monitoring the ice thickness, notably by optimizing ground penetrating radar technology, temperature and strength.
- Limiting the size of windrows[8], which can cause a longitudinal crack to form in the center of the road.
- Periodic monitoring of the ice surface, notably to detect wet cracks[9].
- Maintaining a minimum width for the road so as to allow the traffic to make its way around flooded areas.
- Relying on spray ice at some locations where this method is better than surface flooding to help maintain or increase ice thickness.
- Using 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.
- A high albedo can also be achieved by laying out on the road surface, at vulnerable locations, a light-colored artificial material (mats), or by preventing the accumulation of dirt.
- Covering the ice with a sufficiently thick layer of saw dust to insulate it against warm air temperatures.
- Widening road corners to improve sightlines and increase safety.
- Extending the power grid to remote communities, so as to reduce their reliance on diesel fuel.

Traffic management

- Using the road at night, while the ice is stronger.
- Restricting day time use of roads.
- Enforcing speed limits.
- Driver awareness campaigns.
- Allowing one lane to be faster for empty loads.
- Improving the overall traffic control.

[7] Static loading is when only the vertical action of a vehicle (due to its weight) is taken into account in the anlysis; dynamic loading is when horizontal motion of a moving vehicle is also factored in (especially at high speeds), e.g. Babaei et al. (2016).

[8] Windrows are snow banks on each side of the road.

[9] ‘Wet cracks’ refer to cracks that allow water to seep up onto the ice surface. They indicate the crack has reached the bottom surface of the ice (it spans the full thickness), thereby affecting ice cover integrity. ‘Dry cracks’ are those that do not penetrate the full thickness.

- Proper monitoring of vehicle weight.

Adaptation measures may or may not apply to a given winter operation – it is a case-by-case scenario. None are the Holy Grail. But if any single one works, it can help improve the road's effectiveness considerably. Many measures need to be implemented under the guidance of an experience operator or engineering consultants.

R&D – What it is and how it can help

Adaptation measures such as many of those listed above were learnt from extensive field experience. We may have reached a point, however, where new research and development is required to tackle the challenges that the Canadian winter road infrastructure is facing in the context of climate change. R&D can be based on theory, numerical modeling, laboratory experiments, field tests, analyses of full-scale data, or any combination thereof. Its ultimate outcome is new information, which may then feed into guidelines, standards and working practices. R&D requires time before it bears fruit – several years, depending on its nature. The outcome as planned initially may change in the course of the investigations. That is one of the consequences of dealing with unexplored territory. Overall, R&D is considered an investment, meant to pay off in the medium to long term.

In this section, knowledge gaps are identified – these are topics that, from the authors' perspective, could be good candidates for R&D. They are divided into two avenues of investigations:

1. Road characterization and usage.
2. The integrity of floating ice segments.

Road characterization and usage

From an operational perspective, winter road characterization is the information that one can obtain from a road both over-land and over-ice, in order to know what it is, what it is made of, how trafficable it is, opening and closure dates, the number and types of vehicles, the nature of the goods being hauled, etc. According to Northern Ontario's Multimodal Transportation Strategy[10] "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. The physical parameters are as follows.

For overland segments, they include:

- Foundation – soil, solid rock, gravel, muskeg, icy surface, permafrost.
- Routing characterization – width, itinerary, radius of turns, grade, cross slope, slope direction, vegetation (e.g. shade vs no shade), creeks, obstacles (e.g. boulders, large trees).

For over-ice segments:

- Foundation – Floating or grounded ice, length of segment.
- Hydrological – River versus lake, water currents.

[10] https://nomts.ca/discussion-paper/#C5A [Consulted April 23 2018]

- Ice thickness – This can be done by regular measurements or on continuous mode (profiling).
- Ice cover – Lake ice versus columnar-grained ice, white ice versus blue ice[11], pressure ridges, cracks.
- Routing characterization – Width, radius of turn, angle with shoreline, slope orientation.

For the winter road as a whole:

- Length – Over-land versus over-ice.
- Structural bridges – Number, size, type, capacity.
- Snow coverage – Thickness and extent (including bare segments).
- Usage – One-way versus two-way, nature of traffic, cargo vs people transportation.
- Type of vehicles – Weight, clearance, turning radius.
- Logistics – Weight stations, meteorological instrumentation, rest stations, gas pumps.

A prospective approach would be to leverage the technology already implemented elsewhere. For instance, a ground penetrating radar (GPR) is commonly used to obtain a continuous thickness profile of the frozen ground (Stevens et al. 2009, Campbell et al. 2018) and freshwater ice (Mesher et al. 2008, Proskin et al. 2011b, Fedorov et al. 2016). The package would enclose additional instrumentation, which would increase its capabilities significantly, notably a compass, tilt meters, accelerometers, proximity sensors, cameras, GPS, voice data logger, amongst others. A full 3D representation of routing could be obtained, including some of the parameters listed above: grades, cross-slopes, angles of turn, road width, orientation of slopes on over-land segments, location of ice crossings, ice and snow thickness, etc.

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. This may be technically challenging and would also need to be investigated.

In parallel, operational data for each road – opening/closure dates, number and type of vehicles, number of people traveling, nature and amount of goods (fuel, construction supplies, food supplies) – would be gathered and combined with the information collected by the road characterization system.

A web site could be designed to allow stakeholders (operators, users, analysts in transportation logistics) access to the road characterization data. Such a tool would either apply specifically to the winter road infrastructure, i.e. designed from scratch, or it could be an extension to an existing one – either option would have to be looked into. It would enclose information on parameters such as those listed above, combined with all available information on road usage and transportation logistics. This would be a two-step procedure:

1. Tool design/adaptation.
2. A plan for on-going year-to-year maintenance.

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. However, "[c]ommunities that have more difficult water crossings or other challenges along their route are compensated the same way as those

[11] Or 'black ice' or 'clear ice' – very low in 'air bubbles' compared to white ice.

with fewer challenges" (IBI Group 2016, p. 27). Proper road characterization would alleviate this kind of situations.

Overall, the outcome would be a database that decision makers could use to better visualize transportation of goods and people, as well as for the purpose of multimodal transportation planning. Ultimately, one might envisage availing road users with day-to-day information on road conditions. In the longer term, that database could guide priorities on road realignment, location of new structural bridges, and partial or complete replacement with all-weather roads.

The integrity of the floating ice segments

From a safety perspective, over-ice segments are particularly important, for the following reasons:

- They are very climate-sensitive.
- They are common weak links in an operation, causing later road opening at the beginning of the season, early closure at the end, and temporary closure mid-season.
- The consequences of breakthroughs can be significant – poorly designed or managed over-ice segments are a particular threat to life safety.

There are several outstanding questions regarding the bearing capacity and deformational behavior of floating ice roads. Answers to these questions would contribute to a safer usage of over-ice segments and would feed into guidelines and design codes about winter/ice roads. These questions are discussed below.

Ice bearing capacity – How do ice cover thickness and layering affect bearing capacity?

The ability of a floating ice cover to sustain a given load, has typically been determined using what is traditionally known as the 'Gold' formula (the outcome of R&D in the 1960's). This formula is universally used by engineering consultants as a first approximation to estimate loads, with various values for the 'A' parameter (e.g. Hayley and Proskin 2008). If required, it can be supplemented by a more elaborate stress analyses for critical cases, such as for very heavy vehicles. For local communities, charts based on that formula are the best option because of their simplicity, which is why they are commonly provided in winter road guidelines.

There is a tendency for these guidelines to be conservative, i.e. to underestimate the amount of load an ice cover can sustain, for various reasons. One is the consequence of a breakthrough. As Proskin et al. (2011a) point out, "[the] negative publicity and the reputation for risk of floating ice often makes planners slow to increase loading in their transportation planning." Another reason is the complexity of the ice in nature, and our limited understanding of it. That extra leeway is to cover for the large number of contingencies, inherent to an infrastructure that is not as well-documented, well-regulated and well-controlled as other surface transportation systems in terms of construction, maintenance and usage.

In general, for simplicity sake, an ice cover is viewed as a uniform material of a given thickness, strength properties and elastic behavior. However, in most cases, it is a multi-layered non-uniform material (Figure 4). The layering is mostly due to the existence of clear ice (also called blue or black ice) and white ice. The latter results from water soaking of the snow cover that naturally accumulates on top of floating ice expanses (Röthlisberger 1983, Coutermarsh and Phetteplace 1987). It can also form as a result of maintenance-related surface flooding, typically used to artificially thicken the ice surface or to repair it.

There is currently a lack of agreement as to how to incorporate the thickness of white ice into the Gold formula (Barrette 2015a). Depending on which guidelines one is reading or which operator one is speaking to, the white ice is either left out altogether, it is included, or it is included only if it results from artificial flooding (otherwise it is omitted). There is also a lack of agreement between various sources of information about the value assigned to the 'A' parameter in Gold's formula. All in all, depending on what source of information one might rely on, a different bearing capacity will be prescribed (Figure 5).

A better understanding of how an ice cover reacts to a vertical load can be achieved by combining experimental trials in a large test basin with an instrumented ice sheet of known thickness and a pre-defined layering. Deflection would be recorded under load, and the output of these experiments used to calibrate a numerical model. This would be done by varying the nature of the ice sheet and the applied load. Breakthrough conditions could also be investigated. Testing at a larger scale could be done, such as those of Laidley et al. (1980). Ultimately, deflection could be measured in a real case scenario, on a real ice road. The final outcome would be more reliable recommendations for the 'A' coefficient and how that coefficient might be affected by layering.

Static loading – How long can a load remain stationary on the ice?

Gold's formula is not meant to be used for loads that remain at one location for a certain time period. The reason is that, after a certain amount of time, failure of an ice cover that safely supports a non-static load could occur. That is because, with time, the stresses induce non-elastic deformation in the form of micro-cracks (e.g. Sinha 1989), which develop into large cracks and, ultimately, breakthrough (e.g. Beltaos 2002).

In general, the heavier the load, the less time it should be allowed to remain on the ice. As to what the length of that time period is, different guidelines have different recommendations. Some, for instance, specify that Gold's formula should only be used for moving loads (CSAO 2009, Government of Manitoba 2014). Others specify a two hour limit (CSST 1996, IHSA 2014), which is also what Gold (1971, p. 179) prescribed.

If a load has to remain on the ice, some guidelines advise to monitor the freeboard by drilling a hole through the ice. When the water level reaches the ice surface (i.e. the freeboard reduces to zero), the load has to be removed (N.K. Sinha, pers. comm. 2018). This practice is supported by the analyses of Frederking and Gold (1976) and has been validated by many sources (e.g. CSST 1996, Masterson 2009, IHSA 2014). BMT Fleet Technology (2011) recommends to use a time-dependent reduction factor if the load duration is to exceed 15 minutes – the longer the duration, the lower the allowable load. Proskin et al. (2011a) mention that "if the freeboard is found to be less than 0.04 times the ice thickness, then the ice should be unloaded, repaired or the area closed."

The foregoing demonstrates again a lack of agreement in the recommendations which, as before, stems from an incomplete understanding of how the ice deforms.

In the evaluation of its mechanical response, ice has historically been treated as a perfectly elastic material. That is to say, its response to a load is immediate and the resulting deformation is entirely recoverable upon load removal. In reality, as explained elsewhere (Barrette 2015b), that is not the case, and that there is a difference between the Young's modulus, a material property, and the 'effective' modulus, an artefact that is being used in many analytical treatments.

It would be helpful to implement these concepts into a numerical model, as that would allow a better understanding of ice behavior under a static load. This could be done in parallel with the experimental work described previously, and implemented in the field on a fully instrumented ice cover. Acoustic sensing technology could be used, which would document cracking activity in the ice cover (St. Lawrence and Cole 1982, Langhorne et al. 1990, Li et al. 2015). The relevance of this work can be seen in the context of vehicles parked on the ice while ice fishing, or when estimating the risks of vehicle being forced to stop on the ice, due to a breakdown, a snow storm or any other motive.

Cracks patterns – Do they weaken the ice?

Natural ice covers are always fractured – hairline fissures can be readily seen, provided the ice happens to be transparent (Figure 6, left). These fissures are typically the outcome of air temperature changes, leading to contraction and expansion (Figure 6, right). 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' knowledge. As stated by Proskin et al. (2011a), "[a]ny of the refined analytical methods [to determine bearing capacity] assume 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.

There are a number of ways this topic could be investigated. One is to monitor the development of a crack network over time at a target location, both away and near an operational ice road. Mechanical testing of ice blocks, in the laboratory, with various crack densities (e.g. none, low, high) could be conducted. Cyclic loading of a similar nature as done before (Haynes et al. 1993, Iliescu et al. 2017), specifically designed to address the ice road context, could also be considered. These studies would yield valuable information on to what extent cracking affects ice bearing capacity.

Reinforcement – Can an ice cover be strengthened?

At the road routing stage, it is not always possible to avoid areas known to be vulnerable, e.g. ice exposed to erosion from below by a nearby stream, shoals or just a creek crossing, a perpendicular approach to a shoreline, a river crossing that needs to be accessed early in the winter. In these circumstances, means of reinforcing the road are required. This can be done (and has been done over the last number of decades) in a number of ways. In the context of a warming climate, especially with the support of R&D, this approach is expected to become increasingly instrumental in preserving the yearly operational lifespan of winter roads.

Ice cover reinforcement can be divided into two types: macroscopic and microscopic (Vasiliev et al. 2014).[12]

- Macroscopic reinforcement includes the recourse to wooden logs (Gold 1971, Rhoads 1973, Michel et al. 1974), cables (The Engineer 1964, Ohstrom and DenHartog 1976), geo-fabrics (Jarrett and Biggar 1980, Haynes and Martinson 1989, Haynes et al. 1992) and steel bars (Cederwall 1981).
- For microscopic reinforcement, the ice itself can be produced by mixing water with another material (e.g. wood pulp, fiberglass) before freezing (Perutz 1948, Nixon and Smith 1987, Kuehn and Nixon 1988, Nixon and Weber 1991, Sinha 1992, Gold 1993). Specimens produced from these mixtures are usually tested in the laboratory to assess their strength (Figure 7).

[12] By analogy, this is like using re-bars and microfibers, respectively, to reinforce concrete. Note that both concrete and ice react in a brittle fashion when loaded in tension.

Ice reinforcement involves a number of factors:

- Material availability – the economic aspects of it are discussed elsewhere (Coble and Kingery 1963, Kuehn and Nixon 1988, Vasiliev et al. 2014).
- Extra time needed to build the road (Michel et al. 1974, Ohstrom and DenHartog 1976).
- Darker materials absorb solar radiations and contribute to ice deterioration (Ohstrom and DenHartog 1976, Haynes et al. 1992).
- Depending on the reinforcing material, it may have to be recovered for environmental reasons, which may prove unfeasible (Jarrett and Biggar 1980).
- Material deployment in the field depends on its nature – it may be difficult to position and freeze in the ice cover (Haynes et al. 1992).

Prior to moving forward with the investigation of strengthening methods, it would be desirable to obtain a detailed account of what these methods are. The purpose would be to know if the material has actually been applied on a winter road operation and under what circumstances. Also, information on performance and limitations could be gathered, namely about deployment and retrieval, which are critical considerations. This background work would be used as a stepping stone toward what could be deemed promising avenues, i.e. starting materials, that would be tested in the laboratory, then in the field.

Discussion

Our current knowledge of the Canadian winter road infrastructure, at least on the engineering front, is lagging behind that of other surface transportation infrastructure. This has to do with the complex nature of the foundation (frozen ground and ice covers) and the fact that its condition is mostly controlled by nature. Also, over the last number of decades, there may have been a disconnection between academic circles (universities, research institutes) on the one hand, and the reality of winter road operations on the other.

Conceivable reasons for this state of affairs include the following:

- Stakeholders from R&D organizations investigating cold regions phenomena typically publish their results in the scientific and engineering literature, which is not palatable to stakeholders outside academia.
- R&D results are also presented at conferences, with relatively limited specialist/non-specialist interaction at these meetings.
- Winter roads have historically occupied a relatively small portion of yearly budgets in transportation departments, with relatively (and understandably, based on the two previous bullets) little incentive to integrate new R&D in guidelines.
- R&D is expensive. The limited amount of available funding currently available is channeled instead toward more immediate operational requirements, i.e. to ensure winter road remain safe and effective on a day-to-day basis, at the expense of operational lifespan.

There are three consequences:

1. Our current scientific/engineering knowledge base is not being capitalized on. For instance, our understanding of the physics and deformational mechanics of ice has evolved considerably since the 1970's but it is not being fully applied to guide design.
2. Important knowledge gaps, such as those discussed in this paper, are being overlooked.
3. Long-term provisions for climate change effects are not being addressed.

Conclusion

This paper outlines two main investigation avenues that could be explored through Research and Development (R&D). The first avenue is about data gathering and sharing. It could be of interest to provincial and territorial authorities, as well as to local communities, because it would centralize all relevant information, promote communication between stakeholders, increase user and operator awareness of their operations and guide priorities in the incremental replacement (partial or full) by all-weather roads. The second R&D avenue proposed herein directly addresses knowledge gaps in the mechanical behavior of ice covers under loads. All would work toward increasing the winter roads' safety and effectiveness in spite of climate change.

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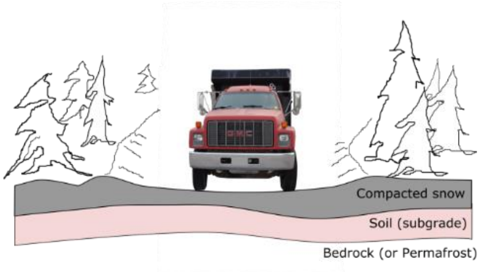
Figures



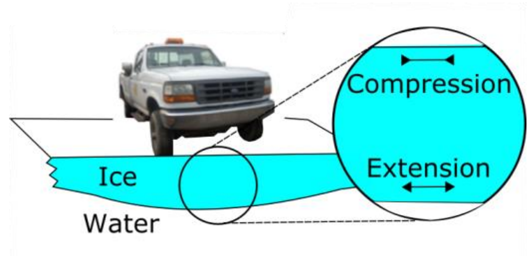


Figure 1: Simplified diagrams of an over-land (left) and over-ice (right) segments of a winter road.

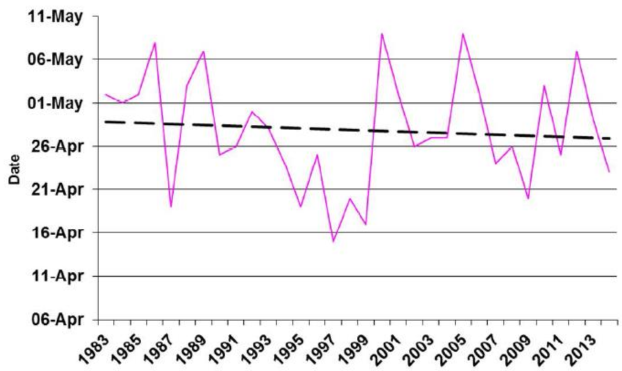


Figure 2: Historical closure dates of the Tuktoyaktuk-Inuvik winter road, showing a slight progression toward an earlier closure (Whalen et al. 2016). Note that this road was replaced with an all-weather road, which officially opened in November 2017.

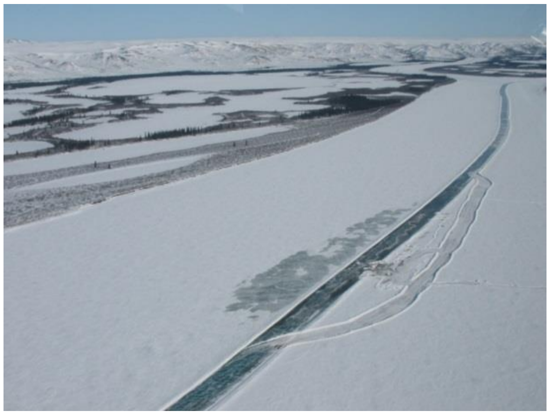


Figure 3: On-ice segment of the Inuvik-Tuktoyaktuk winter road in the NWT (Photo: A. Barker, April 18, 2012) – a by-pass was set up to go around a breakthrough.

Figure 4: A block of ice showing clear ice (bottom of the ice block) and white ice (top of the ice block), the latter with internal layering.

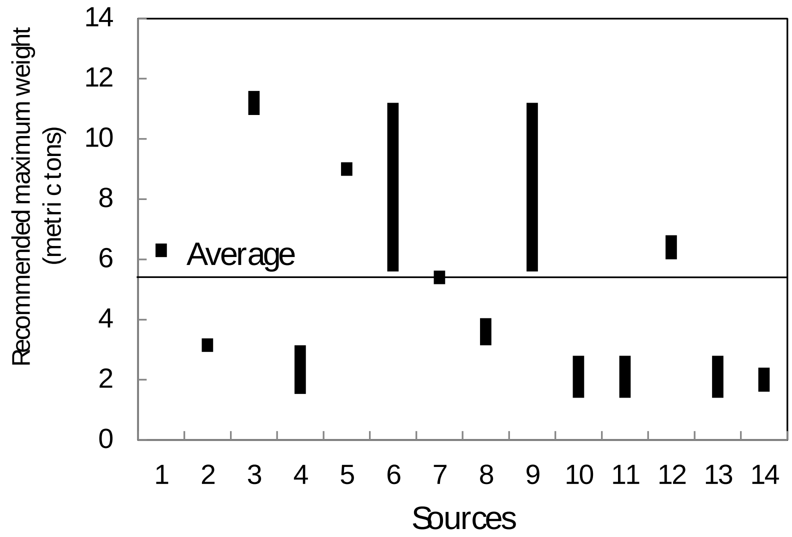


Figure 5: Recommendations from 14 sources, assuming a total ice thickness of 40 cm made of clear ice and natural white ice in equal proportion and of questionable quality (Barrette 2015a).

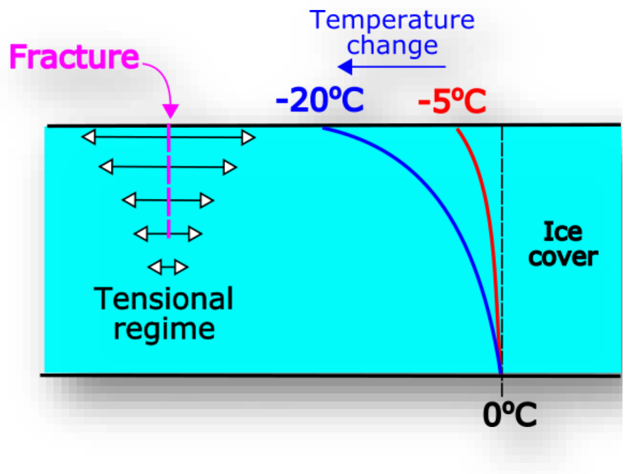


Figure 6: Left) Crack network inside an ice cover (boot for scale) - the crack surfaces are generally vertical, albeit with various orientations. Right) An overnight decrease in air temperature, for instance from -5°C to -20°C as shown here, will induce a tensional regime in the upper part of the ice cover, and result in cracking.

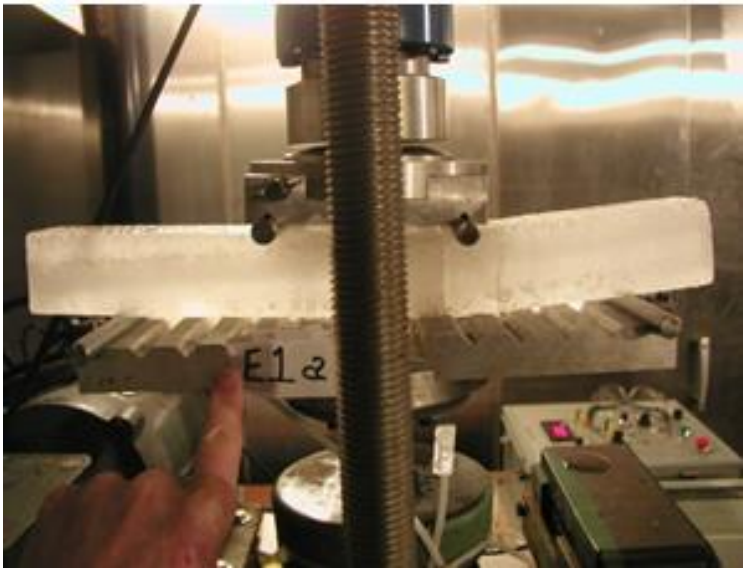


Figure 7: Example of beam bending test set-up used to measure ice strength (Barrette 2011).