THE IMPORTANCE OF PERMAFROST, ICE AND SEASONALLY FROZEN GROUND TO ROAD SYSTEMS IN CANADA

D. Hayley, and R. McGregor
EBA Engineering Consultants Ltd., Canada
dhayley@eba.ca & rmcgregor@eba.ca

ABSTRACT

Transportation in support of natural resource development and agriculture in Canada's cold regions utilizes a roadway system that can be reliant upon permafrost, ice and/or seasonally frozen ground.

Road structures on permafrost are discussed and include specific aspects of performance that can be linked to climate change. Selected case studies in Canada's north are presented to describe the issues and adaptations.

Winter and Ice Roads are used extensively in Canada to resupply remote communities and to support resource development. The Tibbitt to Contwoyto Winter Road is infrastructure that supports the diamond mining industry in the Northwest Territories. This case study is used to demonstrate how climate change has impacted the operation and initiated the development of new technologies to optimize the shortening operating season.

Seasonal weight limits play a significant role in the economy of the prairie region of Canada. It is important to consider potential changes in seasonal weight limits as a result of climate change. The aspects of seasonal weight limits that are vulnerable to climate change and possible adaptation strategies are discussed.

The paper concludes by making some summary statements on what this means in terms of reshaping the Canadian approach to transportation infrastructure management in Canada's cold regions.

1. INTRODUCTION

The geographic expanse between resources and markets in Canada (both national and international) requires much of our transportation system to be road based. Our northern latitude makes those roads particularly vulnerable to effects that climatic warming trends could have on this critical infrastructure. Much of the shipping and transport requirements for the natural resource and agricultural industries utilizes a roadway system that has been designed to function through four distinct seasons. The winter season produces frozen ground, ice and snow that is used to advantage in many parts of the country to supplement the road system. Roads that take advantage of ice and frozen ground are particularly sensitive to effects of climatic warming. These effects are now beginning to surface as limitations that require adaptation strategies.

This paper examines the effects of climate change on road structures that are reliant on freezing and thawing conditions. There are three categories of road type where even small changes in climate are now influencing decisions on future transportation strategies in Canada.

- Roads constructed on permafrost soils;
- Winter roads over ice or compacted snow ; and
- Road structures where freezing and thawing determines seasonal weight limits.

This paper examines certain effects that can be related to climatic warming that is currently influencing decision making in Canada. Initiatives that are taken or being considered to mitigate or adapt to changing weather patterns are also described.

2. ROAD STRUCTURES ON PERMAFROST

2.1 Roads Over Permafrost Terrain

Permafrost terrain is ground that remains below 0°C year around. The definition is based on the thermal state of the soil or rock. Permafrost occurs in Canada in northern regions where the mean annual air temperature is below 0°C. Permafrost ground can be considered perennially frozen with a thin surface "active" layer that thaws each summer. The frozen ground has variable proportions of ground ice commonly well in excess of the water retained in the soil following first-time thaw. When thaw does occur, the excess water is expelled and consolidation produces substantial settlements. The thermal stability of the frozen ground is sensitive to minor changes in heat transfer at the ground surface. Changes in surface properties such as stripping vegetation or changes to moisture retention capacity of the soil can alter the surface heat balance, initiating thaw and increased active layer thickness. These conditions are challenging for highway engineers particularly in the southern fringe of permafrost where the ground temperature is between -1°C and 0°C. Any change in ground-air heat flux can initiate retrogressive thaw that can result in large embankment settlements. These conditions are exacerbated by uncertainties related to climatic warming trends. The Highway Engineer is often faced with a difficult compromise between control of capital cost and long term maintenance of embankments that are anticipated to experience highly variable settlements at a rate and magnitude that are difficult to predict.

Experience from two major northern highways in Canada; the Dempster Highway (NWT Highway 8) and the Yellowknife Highway (NWT Highway 3), were discussed by Hayley (1) at a specialty conference on Northern Transportation. The climate change effects observed on the road system within the Northwest Territories were discussed by LeBouthillier (2). The Dempster Highway provides the only road route to the arctic, terminating at Inuvik near the mouth of the Mackenzie River. The highway, constructed in the 1970's, provided important base line information for future road design and construction management on permafrost terrain in Canada. The design principles adopted at that time have been described by Huculac, et al (3). The 85 km segment of route on the eastern slopes of the Richardson Mountains where it extends down into the Mackenzie Valley crosses residual and colluvial soils that are particularly rich in excess ground ice. The natural permafrost temperatures are -7°C to -9°C, well within the region where permafrost is considered continuous. The sloping terrain and large volumes of ground ice make this terrain particularly sensitive to thaw-related disturbance followed by erosion on the slopes. Thaw-flow slides are common within several hundred metres of the road embankment.

Figure 1 – Dempster Highway, km 8.5 Near Rat Pass

The Dempster Highway in this region, generally has an east-west alignment. The prevailing wind from the north causes deep snow drifts to form on the southern, lea sideslope. Snow several metres thick, insulates the permafrost below the sideslope, gradually raising its temperature. These conditions continue until longitudinal cracking is observed on the crest of higher sideslopes become unstable as the thaw weakens the foundation soils below the embankment slopes and they creep outward. These conditions are not unusual but demonstrate that it is not possible to construct a road embankment over permafrost terrain without affecting the underlying thaw-sensitive foundation soils, even in regions of seemingly cold continuous permafrost.

The combination of subgrade warming and ice-rich soils can also result in catastrophic failure of the roadbed. Such a failure occurred in late fall of 1985, when water percolated under the embankment, thermally eroding a wedge of ground ice. The embankment collapsed into the void causing a roadbed failure that resulted in a fatal collision. Such occurrences may be more frequent in periods of climatic warming coupled with greater snow cover. These risks must be managed with increased vigilance by maintenance personnel and by non-destructive testing of embankment integrity using technology such ground penetrating radar.

Figure 2 – Ground Penetrating Radar Survey, Dempster Highway

2.2 Yellowknife Highway Upgrade

The Yellowknife Highway (Highway 3) extends from the Mackenzie River around the north shore of Great Slave Lake to Yellowknife, a distance of 340 km. Unlike the Dempster, Highway this location is near the southern fringe of the permafrost zone, where permafrost soils are warm and discontinuous. It was constructed initially by the Federal Government in the 1960's and has been upgraded to modern standards by the Territorial Government over the past 10 years. The upgrade has been both challenging and costly. The original road geometry was poor as it wound around frequent outcroppings of granite rock common to the Canadian Shield. The upgrade improved sight distances by reconstruction through the rock outcrops interspersed with crossings of poorly drained lowlands where warm permafrost soils comprise at least half of the terrain.

Common highway design practice over permafrost has been to either protect the permafrost by design that will configure the embankment to maintain frozen foundation conditions or to recognize the permafrost will recede with time and adopt a maintenance program to deal with it. The design features applied to the Yellowknife Highway have been described by Hoeve, et al (4). This road reconstruction could not practically follow either objective because local warming trends, estimated to be 0.5 C° per decade, prohibit cost effective retention of permafrost when the initial ground temperatures are warmer then -1°C. The alternative approach was one of risk mitigation. The design addressed those features of embankment performance over the long term that represent the greatest risk of uncontrolled maintenance and safety. The following features were adopted to mitigate climate change effects and retard the rate of thaw for a scenario that includes climate warming:

- The core of the embankment comprises a minimum of 2 metres of quarried rockfill, providing internal strength to even out future settlements;
- A sacrificial shoulder and flat sideslopes were provided on the embankment as it was recognized that the permafrost soils supporting the slopes would be the first to thaw;
- A snow management system was adopted to encourage removal of snow from the sideslopes wherever practical;
- Sideslopes as gentle as 4 or 6 horizontal to 1 vertical were adopted for low fills to push standing water away from the toe and reduce snow drifting; and
- A ground temperature monitoring system was implemented to track permafrost response.

The ground temperatures within and below the embankment have been monitored at several locations characteristic of the permafrost terrain over the past 4 years. In all cases there has been slow and predictable regression of the permafrost. In some cases the permafrost has been retained but the temperature is increasing. In every case, the sideslopes usually experienced some distress as a result of permafrost thaw after the first year. The soils below the core of the embankment have retained permafrost for 3 to 5 years. The reduced rate of thaw and settlements have retained embankment integrity sufficiently well that the road can be comfortably driven at 90 kph.

2.3 Climate Change Adaptation Strategies for Roads on Permafrost

Climatic warming is affecting performance of many roads constructed on permafrost terrain in northern Canada. New road construction in the southern fringe of permafrost, such as the Highway 3 example, must be designed to balance the capital cost against the risks that permafrost regression poses on long term performance. It is not going to be practical to design most future projects in anticipation that the foundation soils will remain in a permafrost condition. The strategy is shifting toward a risk-based design that includes prediction of the rate of thaw and adoption of techniques to mitigate the effects of thaw-settlement.

Figure 3 - Yellowknife Highway After Reconstruction

There are site-specific processes that have been used to offset increased heat absorbed by the subgrade from exceptional air temperature increases. These can be considered when permafrost thaw results in predicted settlements that cannot be managed using common design principles. These techniques include:

- Use of thermosyphons to enhance winter heat extraction from the ground. These devices have been used to stabilize railway embankments on thawing permafrost in Manitoba (5) and subsiding road embankments in Alaska (6).
- Design that uses open-graded rock embankment materials to mobilize convective heat transfer within the embankment materials. Natural air convection within a dry rockfill embankment is an effective supplementary heat removal mechanism in winter (7).
- Selective use of insulation within the embankment.
- Use of surface treatment that reflects solar radiation such as white textured aggregate.

Site-specific adaptation strategies generally have limited application along a long linear corridor. They have been used in the past to focus on limited regions where severe instability has caused a chronic maintenance problem.

3. WINTER ROADS

3.1 Winter Roads Over Land and Ice

Winter roads constructed each season with compacted snow and ice have provided infrastructure to access remote regions of northern Canada since the 1940's. Their purpose is often to connect isolated communities of First Nations people scattered throughout northern Ontario and Manitoba. These provinces together with Saskatchewan and Northwest Territories still maintain an extensive network of public winter roads for the primary purpose of resupplying remote northern communities. The winter road systems found alternative uses to support harvesting of northern resources, including fish in Northern Manitoba and timber in Ontario and Manitoba. (8)

Winter Roads took on a new meaning in Canada in the 1960's when they were extended many hundreds of kilometers north to the Arctic Circle in support of the mining industry. These roads were more aptly called "ice roads" as they connected long chains of lakes to capitalize on the use of ice covers for transportation. (9) Today, ice roads are a vital part of Canada's northern transportation infrastructure with roads such as the Tibbitt to Contwoyto Winter road serving a new Diamond Mining industry in Arctic Canada. That road and the mines it serves was estimated to contribute $1.6 billion annually to the gross domestic product (GDP) of Canada in 2001. (10) That number would be even greater today.

The operating season for roads over ice and compacted snow is sensitive to the severity of the winter. Kuryk (11) describes the changes in winter season that have shortened the available operating period for winter roads in Manitoba. In 1998, the Manitoba winter road system failed to perform resulting in a costly airlift to service northern communities. The season shortening not only places the community resupply at risk but puts pressure on ice road contractors to compromise on operator safety. Over the past five years there has been an average of one ice failure each year in Western Canada resulting in a fatality. These risks are clearly unacceptable and have resulted in a sharp focus on adaptation strategies for transportation over ice roads in the current period of climatic warming.

General adaptation strategies have included greater use of bridges to replace ice bridges over fast-flowing streams and rivers and a gradual shift away from lake ice onto frozen ground on the southern route segments, particularly in Manitoba. These changes have been adopted together with a much greater focus on improved technology for judging the capability of an ice sheet to support load. These fundamental improvements are being reflected in better documentation of standard operating procedures on ice covers that now form the core of construction safety plans imbedded in contracts.

3.2 The Tibbitt to Contwoyto Winter Road Case Study

Yellowknife, Northwest Territories, the centre of the Canada's northern mining activities, experienced the two warmest winters in 65 years of record during the past 8 years, (1999 and 2006). The observed range of extremes from "30 year normal" conditions are increasing and the data clearly show a trend in mean annual air temperature warming at an estimated rate of 0.5 C° per decade. The Tibbitt to Contwoyto Winter Road, shown in Figure 4, begins 70 km east of Yellowknife heading north for 600 km with 85 percent of the route over lake ice. It serves as a construction and resupply corridor for Canada's Diamond Mining industry. The traffic frequency has been steadily increasing and at the same time there is a predicted decline in the available safe operating period. Trucks hauling fuel and supplies to the mine operate at normal Gross Vehicle Weights (GVW) of 63,500 kg with maximum loads up to 100,000 kg. The 2007 operating season was the best on record with greater than 10,000 loaded trucks making the trip north during a 72 day operating period. This is in direct contrast with the 2006 operating season, which was the warmest winter on record in the region. The season opened late and the closed early because of unsafe ice conditions after only 49 days of operation. The road failed to deliver the fuel and materials to the mine sites in 2006 requiring a costly supplemental air lift operation at the end of the season.

The road is believed to be the most heavily used transportation system in the world that relies on lake ice cover as a seasonal roadbed. There is more than 20 years of history on the route but the intense use did not begin until the mid 1990's with the construction of EKATI Diamond Mine. The projections are for the traffic frequency to continue to increase until 2013 before it stabilizes and diminishes for the following 14 years of foreseeable utilization. The road exists as an over ice corridor, predominantly because the rugged terrain of the Canadian Shield with exposed bedrock interspersed with permafrost affected lowlands would make all-weather road construction very costly, (Figure 5).

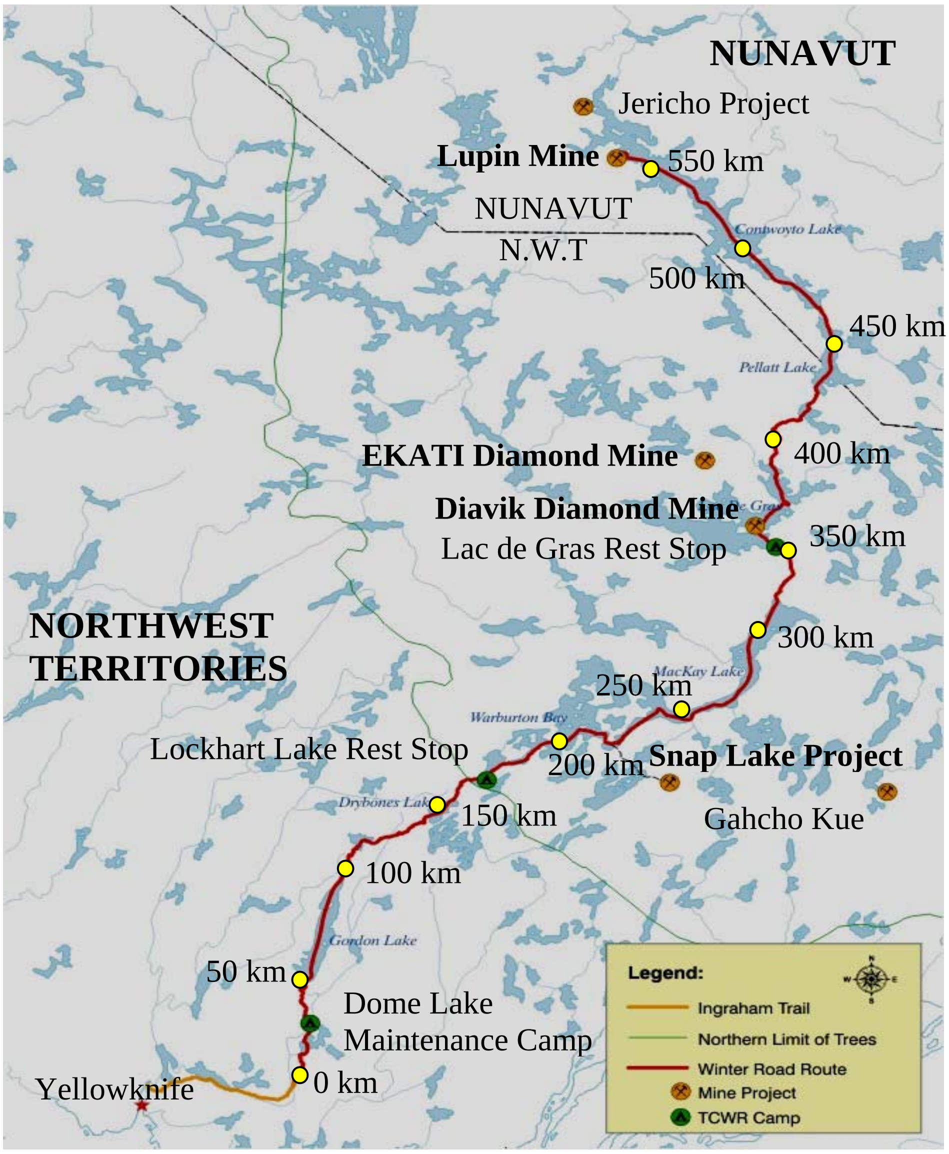

Figure 4 – Tibbitt to Contwoyto Winter Road

Figure 5 – Controlled Operations along the Tibbitt to Contwoyto Winter Road

The winter road is operated by a joint venture of the two largest operating mines, EKATI Diamond Mine and Diavik Diamond Mine. The operators have been examining the risks associated with climate warming on the roads ability to meet future freight demands for the winter season. The objective initially focused on use of technology to optimize a winter-based transportation system that is currently at or near maximum capacity. The realization that technology alone could not achieve satisfactory risk reduction, has shifted the objective to a examination of a wider range of adaptation strategies to supplement or even replace the road as the sole overland supply route.

A study by EBA Engineering Consultants Ltd. (12) examined the risks that climate warming place on future operations by developing a correlation between length of operating season and the cumulative air freezing index for the season. The combination of winter freezing index and snow cover controls the rate of natural ice growth and the ability of the ice sheet to sustain loads late in the season. The freezing index variability for the southern route segment is represented by the historic data from Yellowknife shown in Figure 6. The freezing index is predicted to diminish at a rate of 174 C° days per decade or a loss of about 0.5% of the available freezing capacity every decade. The freezing index has been crudely correlated with the historic operating season in Figure 7 and the conclusion has been that although a normal season is about 65 days now, this could drop to only 54 days by the time the traffic reaches its projected peak and enters a period of significant decline by 2020. These predictions have stimulated a thorough review of adaptation strategies that are most appropriate for the near term, the medium term and the longer term.

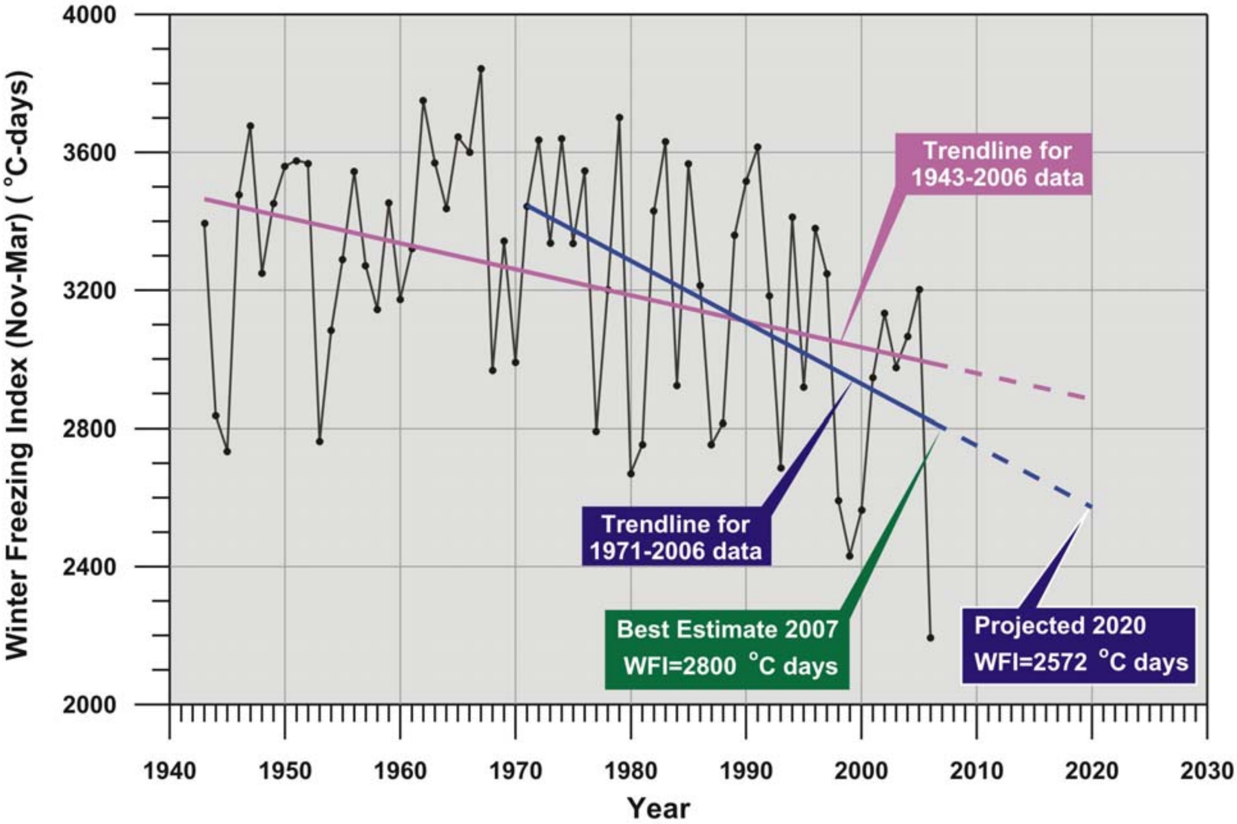

Figure 6 - Freezing Index Variability for Southern Route Segment

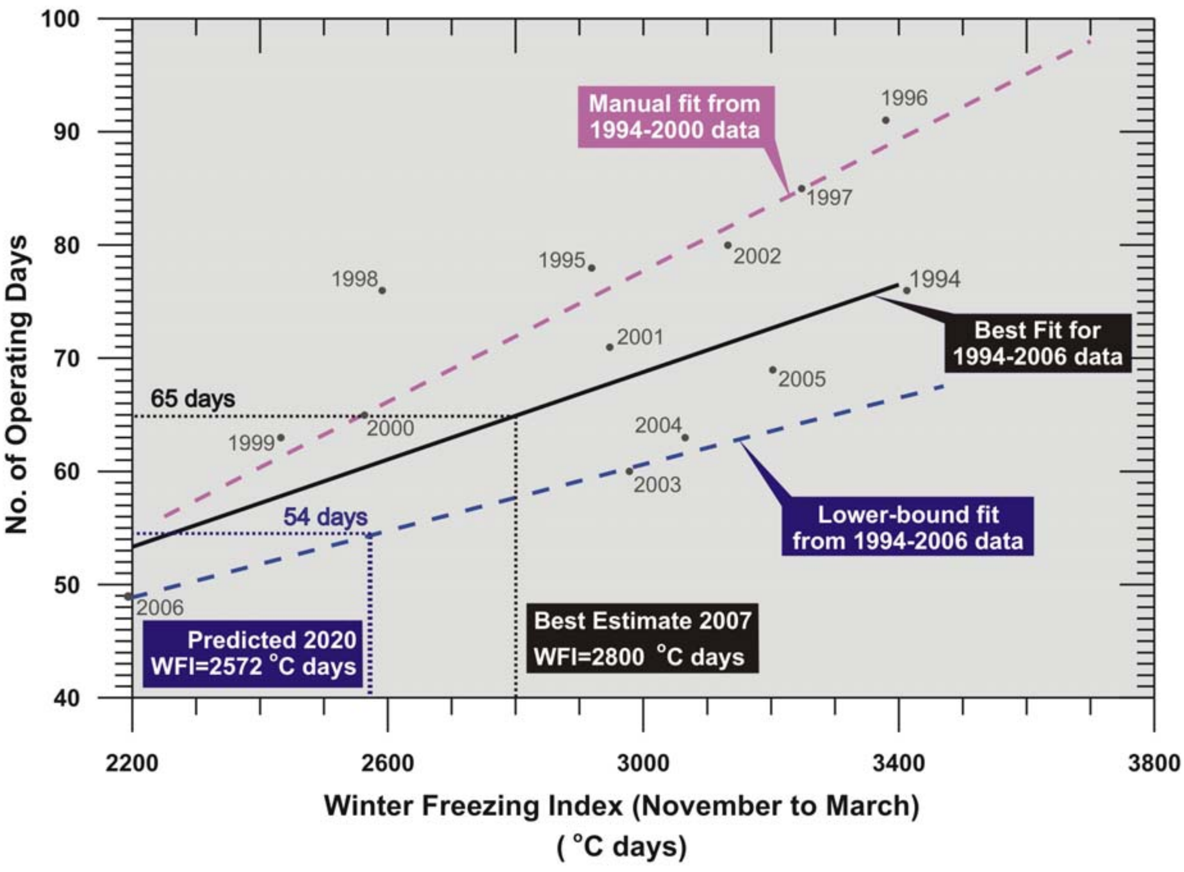

Figure 7 – Freezing Index Correlated with Historical Operating Season

The near term adaptation must recognize that any supplemental option would have a time frame associated with design, environmental studies and permitting before construction could begin. These activities normally require a 5 year planning and implementation window. The short term strategies relate to enhancing the current operations by:

- Technical improvements in ice stress analyses to safely allow greater loads;
- Improved techniques for assessing the ice capacity and locating discontinuity through improved radar systems;
- Traffic management by express lanes to separate loaded trucks from returning trucks allowing the speed restrictions on the returning trucks to be relaxed; (Figure 8)
- Implementation of multiple routes across lakes with known ice instability to allow rapid traffic redirection in the event of ice deterioration; and
- Greater vigilance on speed restrictions together with driver awareness campaigns.

Figure 8 – Optimization of Travel Lanes for Effective Traffic Management

The medium term adaptation strategy that is being pursued is to move the southern 170 km of route off the lake ice and construct a parallel seasonal overland road a distance of 156 km. The resulting road would remain seasonal because the northern half is still on lake ice. With this plan, the southern-most lake system crossed would moved to a more northerly climate where it has been estimated from ice thickness data that about 30 days will be added to the current operating season. This would also be the first step toward a potential all-weather road to the centre of the Diamond Mining industry at Lac de Gras, in the central Northwest Territories. (Figure 9)

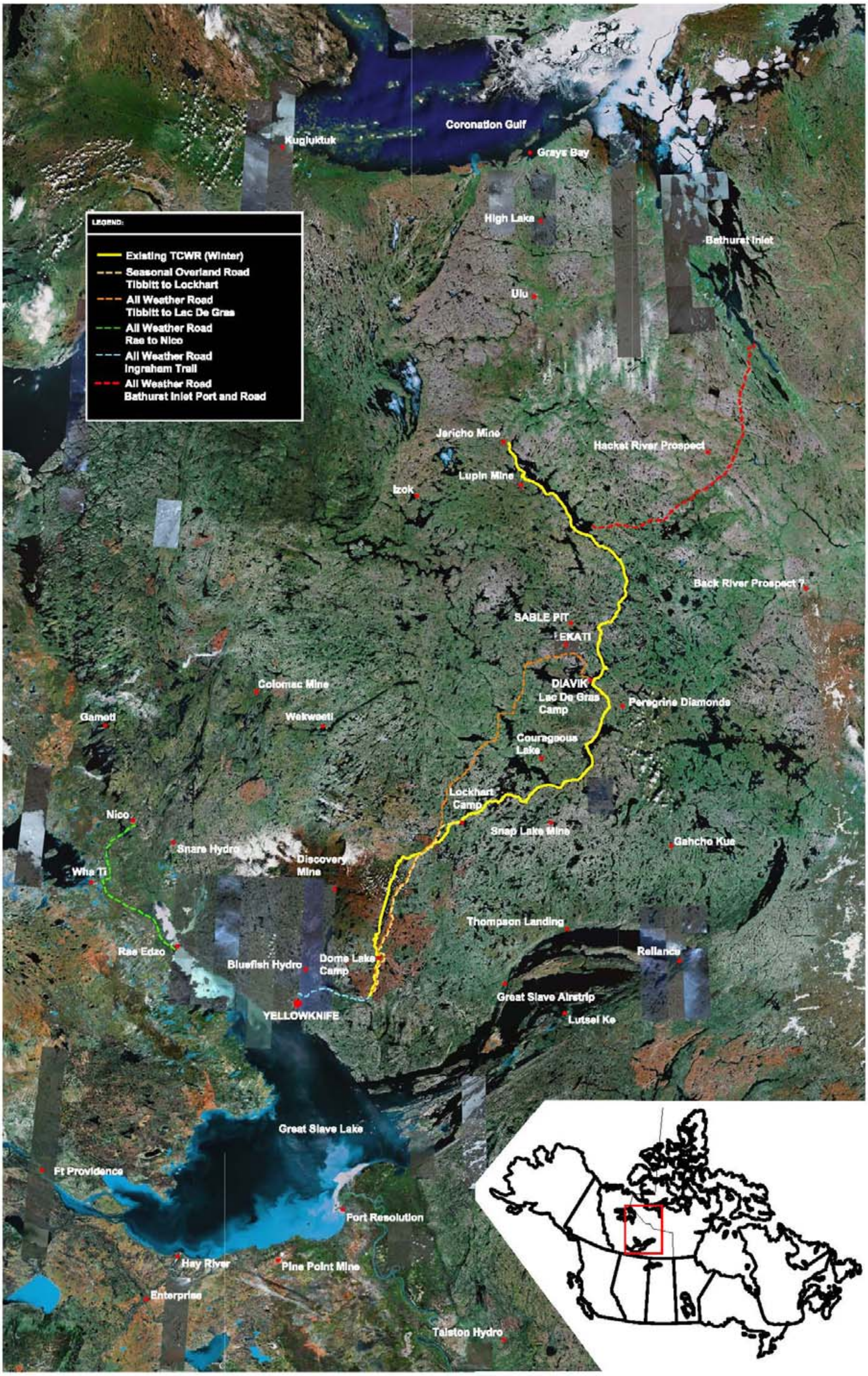

Figure 9- Northern and Southern Transportation Options

The long term option being considered provides a shipping route south from the Arctic Coast for fuel and bulk supplies. This would still rely on a winter road but across arctic tundra rather than boreal forest physiographic units. Both alternatives are being evaluated in order to identify the most appropriate alternative for managing future risk of failure of the supply infrastructure over the next 20 years. The evaluation must consider not only technical feasibility but acceptability of environmental and social impacts on the local population who use the land. (Figure 9)

4. ROAD STRUCTURES THAT ARE SUBJECT TO SEASONAL WEIGHT LIMITS

4.1 Roadway Network in the Prairie Region

The prairie region considers the Canadian provinces of Manitoba, Saskatchewan and Alberta, as well as the northeast portion of the province of British Columbia and the southern portions of the Northwest Territories and the Yukon Territory. South of the Canada/United States border, the U.S. states of Minnesota, North Dakota, and Montana are also considered part of the prairie region. The success of the economy in the prairie region is a large contributing factor to the success of the overall economy in Canada and the economy of the prairie region is dependent upon efficient freight transport by truck. The roadway network in the prairie region is made up of approximately 75,000 kilometres of Canadian provincial highways and 53,000 kilometres of U.S. interstate and state highways. (13)

4.2 Seasonal Weight Limits

Truck transport across the prairie region is operated within laws, regulations and policies specific to the individual jurisdictions or road authorities. Each jurisdiction operates public roadway network under a system of basic weight regulations that define weights and dimensions of commercial vehicles and have a direct impact on the types of trucks that operate on the road network, as well as the operating characteristics (i.e., axle loading) resulting in productivity issues. (14) In addition to basic weight regulations, seasonal weight limits are applied throughout the year at various levels in the different jurisdictions. Seasonal weight limits serve two purposes:

- To provide opportunities in winter to increase truck productivity and lower shipping costs for weight based products given that the pavement and subgrade structure of the roadway is frozen and capable of carrying increased loads (both GVW and axle loads); and
- To protect the roadway infrastructure from damage during the period of spring thaw when the pavement and subgrade structure is at its weakest.

To serve these two purposes, seasonal weight limits are applied in the following two forms:

- Winter Weight Premiums (WWP) are increases in the basic weight limits (as defined by the regulations), that are applied during the period or season when the pavement and subgrade of the road structure is deemed to be frozen.
- Spring Weight Restrictions (SWR) are decreases in the basic weight limits (as defined by the regulations), that are applied during the spring thaw when the road structure is weak due to the upper layer being thawed but still maintaining a high proportion of moisture that has not been allowed to escape due to the fact that the lower layer of the road structure is still frozen.

Across the prairie region, there is currently a large variation in the methods to determine when to apply seasonal weight limits, the magnitude of these weight limits, and which roadways are subject to the seasonal weight limits. In some jurisdictions, timing of the application of seasonal weight limits is based on actual freeze/thaw conditions in the road structure and in others the timing of the application is based on a calendar date fixed by regulation. This “disharmony” in the regulations from jurisdiction to jurisdiction, impacts the efficiency of the trucking industry and therefore has impacts on the economy. Although harmonization of these regulations is not the subject of this paper, it is worthy to note, that the adaptations that are discussed below to serve the impacts of climate change will also serve harmonization of the regulations within the prairie region.

4.3 Climate Change and Seasonal Weight Limits

Although the impression would be that the application of seasonal weight limits across the prairie region are temporary in nature and that the impact on the efficiency of trucking is small, this is, in fact, not the case. Freight is transported by truck across great distances throughout the prairie region and for a period of seven months, a seasonal weight limit is in place on one or more segments of roadway. A study completed between 1998 and 2000 that included monitoring the application and duration of seasonal weight limits throughout the prairie region, showed that WWP are in place as early as December 1 and SWR are in place as late as June 30. (14)

Any change in the average air temperatures from year to year, throughout the region will have an impact on a road network where freight capacity is limited by freezing and thawing effects. The questions are; “How significant is that impact?”, and “Is the impact negative or positive?”.

The issue of climate change and its impact on seasonal weight limits throughout the prairie region was addressed in a study by Montufar, et al in 2005. (15) The study used modeling to account for the application and timing of seasonal weight limits throughout the prairie region given a temperature only climate change scenario over the near term (25 years), the following conclusions were reached:

- The start of winter is likely to be postponed or occur later and the duration of winter is likely to be shorter. Where WWP are applied based on the actual depth of freezing in the road structure (rather than a calendar date fixed by regulation), there will be a negative impact to those trucking activities that are dependent on WWP. For example the shipping of raw forest products is done on the lower or secondary classes of roadways as these are the only roads available to access the source of the resource. Shipping within a shorter WWP period or with lighter loads during other periods will reduce efficiency and increase product costs. For jurisdictions where the WWP are applied based on a calendar date fixed by regulation, damage to the road structure could occur during the early part of the WWP due to heavier loads being hauled on a road structure that is not yet frozen.

- The duration of spring thaw is not likely to change; however, the start of spring thaw as well as its ending is likely to occur earlier in the calendar year. For jurisdictions where SWR are applied on actual conditions, this would appear to only shift the timing of the application and for some weight based products (i.e., fertilizer); there could be a positive impact to the local economy by removing the bans sooner. For jurisdictions where SWR are applied based on a calendar date fixed by regulation, damage to the road structure could occur due to heavier loads being hauled on a road structure that is in the midst of thaw.

In summary, a warming trend in mean annual air temperature in the prairie region could negatively affect freight transport that is dependent on heavier load limits on lower classes of roadways. There could be some positive effects for transport of weight-based products if load restrictions were lifted earlier in the spring. Moreover, there will likely be negative effects in terms of damage to the road structure where seasonal weight limits are applied based on fixed calendar dates.

4.4 Adaptations to Effectively Manage the Climate Change Impacts on Seasonal Weight Limits

Continued advances within the prairie region towards condition based vs calendar based application of seasonal weight limits is needed to mitigate a climatic warming trend in this region. In recent years, advanced technology applications have been development and introduced to monitor the freeze/thaw conditions in the road structure, even in remote locations, and real-time analysis of the road strength under these conditions is being introduced. As the introduction of such applications throughout the prairie region continues, the effective application and removal of seasonal weight limits at the appropriate times will minimize damage to the road structure.

Technology improvements, such as road weather information systems and the associated analytical tools for forecasting, and sharing this information with the trucking industry in a timely manner will assist the trucking industry in managing their operations to take maximum advantage of WWP, alternate routes, or other factors of advanced planning.

Improved road design that eliminates the need for seasonal weight limits on selected portions of the network may also be advantageous. This could be as significant as the introduction of strengthened road or pavement structures that could tolerate heavier loads during vulnerable periods (i.e., spring thaw), or down grading a riding surface for a lower volume roadway from a thin pavement to a gravel surface that is less vulnerable to damage during periods of spring thaw.

5.0 SUMMARY STATEMENTS

The success of the Canadian economy as well as our ability to maintain reasonable lifestyles in our remote communities is largely dependent on an extensive road based transportation system with some of it seasonal in nature. The trade and transportation corridors are east-west between provinces and to our ocean ports, and north-south between territories, provinces, the United States and Mexico. Our northern latitude has created a system that is optimized for four distinct seasons. Winters produce snow, ice and frozen ground that we use to advantage to extend the transportation system. In cold regions the roadway system can be reliant upon and affected by permafrost, ice and seasonally frozen ground.

Unexpected extremes in winter air temperature and warming trends that are now commonplace in Canada’s north are affecting stability of permafrost, seasonal ground freezing and integrity of ice covers that are used for transportation. The consequences of these effects include :

- Increased costs for construction and maintenance of northern roadway systems;

- Reduction in the ability to maintain an acceptable level of service throughout the roadway system;
- Increased vigilance to maintain safe performance of the roadway system; and
- Decreased transportation efficiencies that are reflected in increased costs for goods and services, throughout Canada.

The impacts of climate change on the roadway transportation system cannot be ignored. The effects reported in this paper relate predominantly to observations over the last five years. If climatic warming continues at trends evident in the historic data from northern communities, the effects described in this paper will accelerate. We must reconsider the paradigms that control engineering design of our northern transportation system, adopting risk-based design approaches with climatic variability recognized as one of the least understood uncertainties.

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