CLIMATE CHANGE IMPACTS AND ADAPTATION:
CASE STUDIES OF ROADS IN NORTHERN CANADA

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ABSTRACT

Access to communities and resource developments in northern Canada often relies on a single all-weather or winter road. Warming trends in recent years can put these indispensable access routes at risk by impacting road structures that overlie permafrost, and by shortening the duration of winter roads built on ice or seasonally frozen ground.

This paper presents two case studies of all-weather and winter roads in northern Canada to describe the issues pertaining to the impacts of climate change and the adaptation strategies that have been or are being implemented to cope with the impacts.

1. The Yellowknife Highway (NWT Highway 3) reconstruction. 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:
    a. The core of the embankment comprises a minimum of 2 metres of quarried rockfill, providing internal strength to even out future settlements;
    b. 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;
    c. A snow management system was adopted to encourage removal of snow from the sideslopes wherever practical;
    d. 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
    e. A ground temperature monitoring system was implemented to track permafrost response.

2. The Tibbitt to Contwoyto Winter Road serving the diamond mines. The development of new technologies and strategies to optimize the shortening operating season are described.

The paper also discusses the aspects of seasonal truck weight limits that are vulnerable to climate change and possible adaptation strategies.

1. INTRODUCTION

It is self-evident that, no matter what the causes, extent and rate of climate change and global warming are, we must plan and implement actions in all spheres of human activity to adapt to the changes.

Reliable and efficient transportation of people and goods is generally recognized as the lifeline of modern economies like Canada’s. Understandably therefore the adaptation of the transportation infrastructure to forestall, mitigate and cope with the adverse impacts of climate change has caught the attention of researchers and transportation infrastructure engineers and managers (1, 2).

Ironically, the northern and arctic regions of the world which are most susceptible to the adverse impacts of climate change are also the ones most reliant on transportation infrastructure. For example, the majority of Northwest Territories (NWT) communities and all of its mines are dependent on a single all-weather or winter road (see Figure 1).

In northern regions, all weather roads are susceptible to permafrost thawing. The seasonal roads that take advantage of ice on frozen lakes and frozen ground are particularly sensitive to effects of climatic warming. These effects are now beginning to surface as limitations that require adaptation strategies. For such situations therefore cost-effective, affordable and proactive adaptation is a matter of necessity, not choice.

There are three categories of road type where even small changes in climate are now influencing decisions on future transportation strategies in northern Canada.

- All weather 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 describes case studies of all-weather and winter roads in the NWT where initiatives to mitigate or adapt to changing climate have been taken. Reference is also made to road structures where freezing and thawing determines seasonal weight limits. Most of the case studies are based on projects that EBA Engineering Consultants Ltd. has undertaken. Other case studies the authors are familiar with are mentioned as appropriate.

2. ROAD STRUCTURES ON PERMAFROST

2.1 General Challenges with 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.

2.2 Case Study: Yellowknife Highway Reconstruction

2.2.1 The Problem

The Yellowknife Highway (NWT Highway 3) extends from the Mackenzie River around the north shore of Great Slave Lake to Yellowknife, a distance of 340 km. This highway is located near the southern fringe of the permafrost zone, where permafrost soils are warm and discontinuous. It was constructed by the Federal Government in the 1960’s and has been reconstructed to modern standards by the Territorial Government over the past 15 years.

The reconstruction of the 100 km west of Yellowknife has been particularly challenging and costly. The original road geometry was poor as it wound around frequent outcroppings of granite rock common to the Canadian Shield. The reconstructed straighter alignment (Figure 2) traverses the rock outcrops interspersed with crossings of poorly drained lowlands where

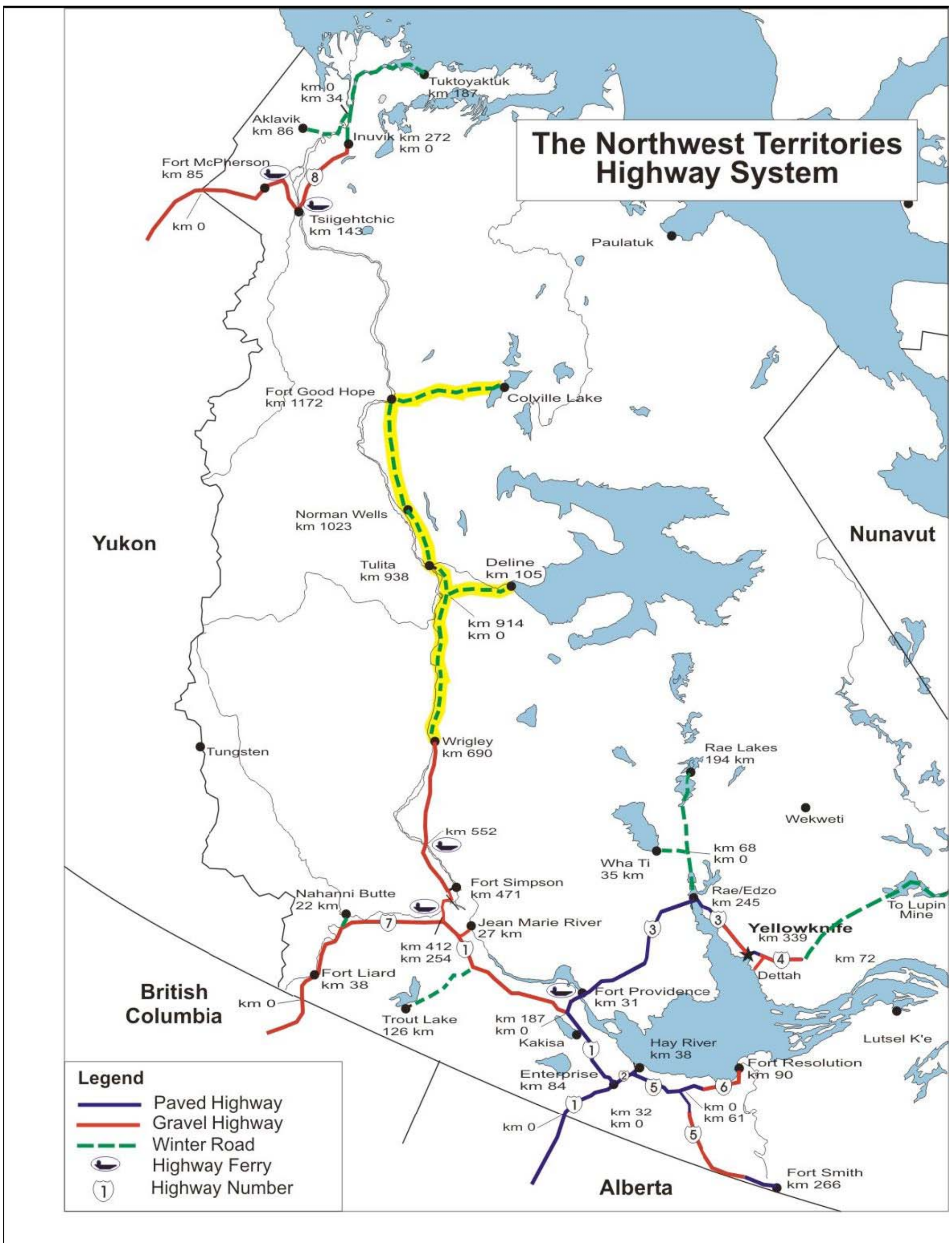

Figure 1 – Northwest Territories Highway System (circa 2004)
(Note: Paving of Highway 3 to Yellowknife was completed in 2007.)

warm permafrost soils comprise 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. This road reconstruction could not practically follow either practice 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 than -1°C.

Figure 2 - Yellowknife Highway After Reconstruction

2.2.2 Adaptation Strategy

Experiences from two major northern highways in Canada; the Dempster Highway (NWT Highway 8) and the Yellowknife Highway (NWT Highway 3), were discussed by Hayley (3) at a specialty conference on Northern Transportation. The climate change effects observed on the road system within the Northwest Territories were discussed by LeBouthillier (4).

The design features applied to the Yellowknife Highway have been described in detail by Hoeve, et al (5). 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 km/h.

2.3 General 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.

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 (6) and subsiding road embankments in Alaska (7).
- 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 (8).

- Selective use of insulation within the embankment.
- Use of surface treatment that reflects solar radiation such as white textured aggregate.
- The combination of subgrade warming and ice-rich soils can also result in catastrophic failure of the roadbed in continuous permafrost regions. Such a failure occurred in late fall of 1985 on NWT Highway 8 (Dempster Highway), 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.

It should be noted that site-specific adaptation strategies generally have limited application along a long linear corridor. They are more useful in limited locations where severe instability has caused a chronic maintenance problem.

3 WINTER ROADS: THE TIBBITT TO CONTWOYTO WINTER ROAD CASE STUDY

3.1 The Problem

Winter roads constructed each season with compacted snow and ice have provided infrastructure to access remote regions of northern Canada since the 1940's. As shown in Figure 1, even in 2008 winter roads are the only surface access available for one-third of all NWT communities and all of three of its producing mines.

The operating season for roads over ice and compacted snow is sensitive to the severity of the winter. Kuryk (9) 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.

The Tibbitt to Contwoyto Winter Road (Figure 3) 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 winter road is operated by a joint venture of EKATI Diamond Mine and Diavik Diamond Mine. 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. 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.

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 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.

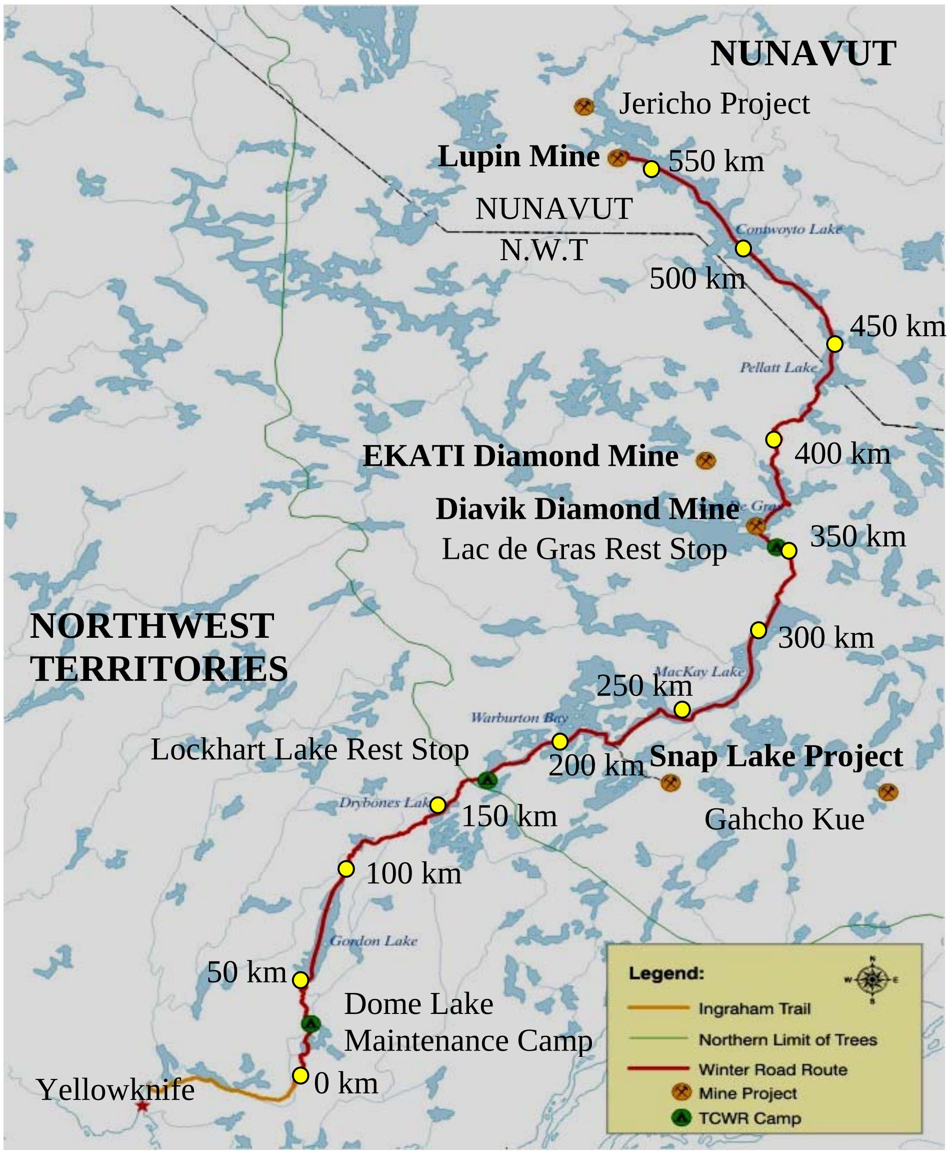

Figure 3 – Tibbitt to Contwoyto Winter Road

Yellowknife, Northwest Territories, the centre of the Canada's northern mining activities, experienced the two warmest winters during 1999 and 2006 in 65 years of record. 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.

A study by EBA Engineering Consultants Ltd. (10) 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 4. 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 5 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.

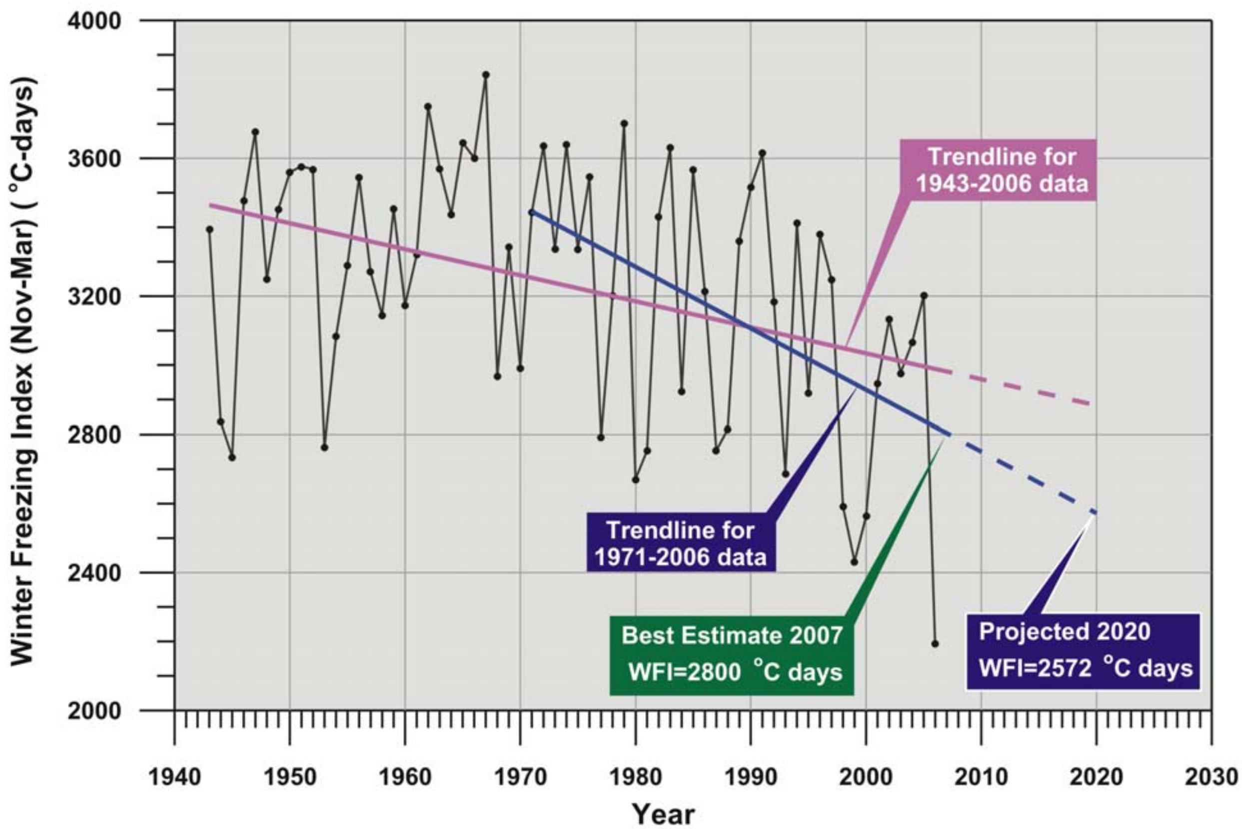

Figure 4 **-** Freezing Index Variability for Southern Route Segment

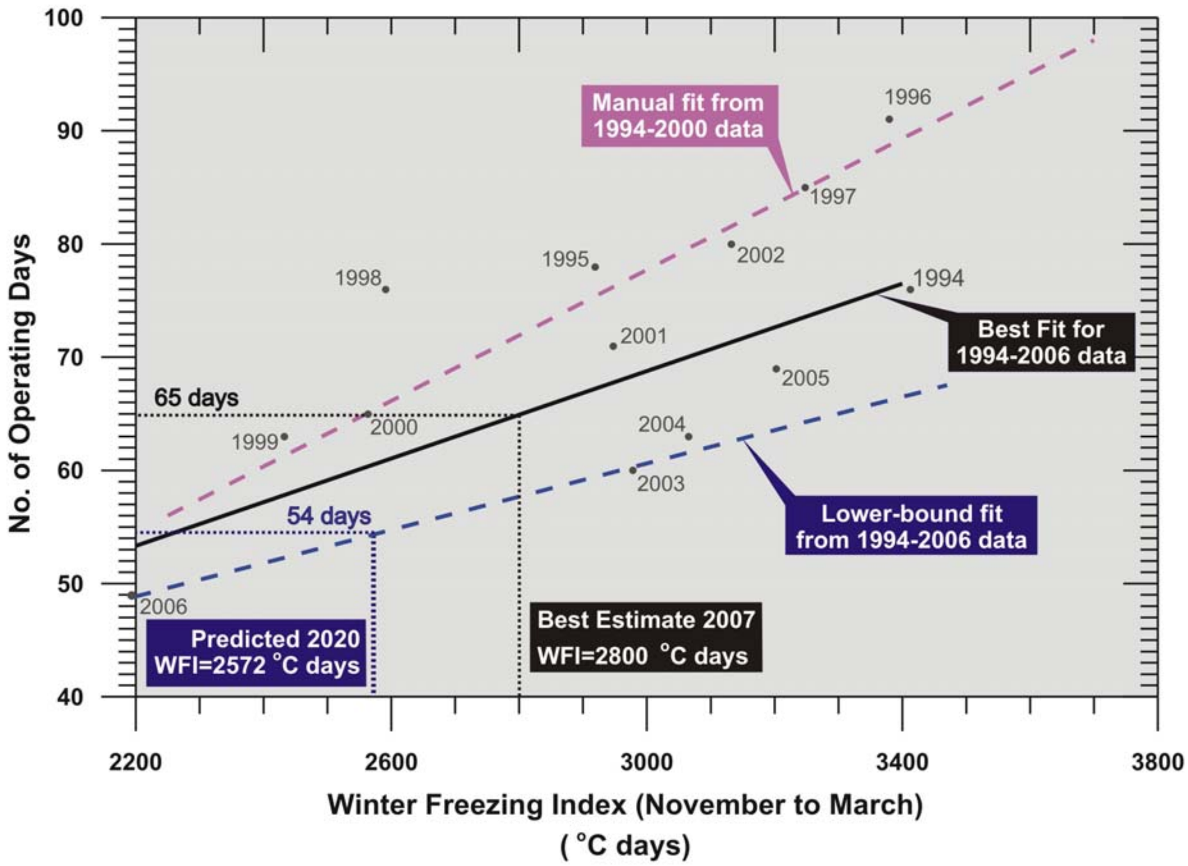

Figure 5 – Freezing Index Correlated with Historical Operating Season

3.2 Adaptation Strategies

General adaptation strategies for winter roads 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.

The operators of the Tibbitt to Contwoyto Winter Road 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.

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 6)
- 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 6 – Optimization of Travel Lanes for Effective Traffic Management

The medium term adaptation strategy that is being considered 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 may also be the first step toward a potential all-weather road to the diamond mines.

The long term options being considered consist of a combination of all weather and winter roads connecting the NWT diamond mines and potential mines in western Nunavut /or to a port on the Arctic Ocean (on Coronation Gulf or Bathurst Inlet). It should be noted that diamond and gold mines can operate effectively with winter roads, but base metal mines, which annually export hundreds of thousands of ore concentrate to overseas customers, require all-weather roads. These options are being evaluated by the various mines 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 socio-economic impacts on the local population who use the land.

4. ROAD SUBJECT TO SEASONAL TRUCK WEIGHT LIMITS

4.1 The Problem

Truck transport across the prairie regions of Canada and the US 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 (11). In addition to basic weight regulations, seasonal weight limits are applied throughout the year at various levels in the different jurisdictions in the following two forms:

- Winter Weight Premiums (WWP) are increases in the basic weight limits that are applied during the period or season when the pavement and subgrade of the road structure is deemed to be frozen. The aim is to increase truck productivity.
- Spring Weight Restrictions (SWR) are decreases in the basic weight limits 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. The aim is to protect the road infrastructure from damage.

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. (The adaptation strategies discussed below should also serve the harmonization of regulations within the prairie region.)

The lack of harmonization can amount to seasonal weight limits for seven months on one or more segments of a truck route through the prairies. 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 (11).

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. (12) 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 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.

4.2 Adaptation Strategies 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 developed 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. CONCLUDING COMMENTS

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.

This paper has presented two case studies of all-weather and winter roads in northern Canada to describe the issues pertaining to the impacts of climate change and the adaptation strategies that have been or are being implemented to cope with the impacts.

For the Yellowknife Highway (NWT Highway 3) reconstruction, 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:

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In the case of the Tibbitt to Contwoyto Winter Road serving the diamond mines, the development of new technologies and strategies to optimize the shortening operating season was described.

The paper also discussed the aspects of seasonal truck weight limits that are vulnerable to climate change and possible adaptation strategies.

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