Incorporating climate change uncertainty into transportation infrastructure investment decisions

by

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Abstract

The Mackenzie River is a historically important transportation corridor of the Northwest Territories, allowing for barge freight transport to remote communities throughout its length. However, more recently, climate change has affected the duration of the Mackenzie River's navigational season, making it both shorter and more uncertain. Thus, communities increasingly rely on winter roads and airlift, leading to higher overall freight costs. Using options approaches, this thesis presents an analysis of the decisions of whether to continue barging on the Mackenzie River each year or when (and how) to connect the entire corridor by extending the all-weather Mackenzie Valley Highway, explicitly considering multiple uncertainties (e.g. climate, freight demand) challenging decision-makers and operators. We develop a comprehensive methodological framework that supports flexibility in infrastructure investment decisions.

The proposed methodological framework includes three parts: Modeling of uncertain inputs, cost-benefit analysis, and real options analysis. We apply it to two investment decision scenarios for the all-weather Mackenzie Valley Highway from Wrigley to Inuvik: 1) The entire road as a single construction project under future climate uncertainty, and 2) The roadway as four separate construction projects to be built in stages, considering multiple future climate and freight demand uncertainties.

For the first scenario, we first model river open season days as a stochastic process; barging is dependent on the number of open season days, which in turn is affected by climate change. Then, we evaluate the decision to continue barging and airlift service each year using a modified Black-Scholes model. Finally, we use real options to determine how long construction of the all-weather highway may be deferred. The results indicate that it is advisable to defer construction nearly a decade, in balancing the costs of construction against climate change uncertainty. We

also perform a sensitivity analysis of key inputs and parameters; highway project valuation is quite sensitive to highway investment cost, climate proxy volatility, and airlift costs while less so to freight volumes.

For the second scenario, we model climate uncertainty and freight demand uncertainties as stochastic processes similar to the previous model. Then, a cost-benefit analysis of building different all-weather segments at different times is discussed. Finally, we apply a Least Squares Monte Carlo (LSM) method to solve the extended project value, optimal investment times and investment priorities. The results indicate that Segment 2 (Tulita – Norman Wells) has the largest value ($819M), with a recommended deferral of one year. The resulting sequence of construction is Segment 2 (Tulita – Norman Wells, one-year deferral), Segment 1 (Wrigley – Tulita, six-year deferral), Segment 3 (Norman Wells–Fort Good Hope, 13-year deferral), and Segment 4 (Fort Good Hope – Inuvik, 14-year deferral).

This research also demonstrates that when we explicitly incorporate the impact of climate change on project valuations, particularly those in Northern Canada and the Arctic where these impacts are considerable, project valuations can change significantly such that all-weather road construction is supported, even if it is deferred to future years. This study can assist federal and territorial governments in understanding the growing criticality of accounting for and adapting to uncertainties arising from climate change and other sources in infrastructure planning, and provide another tool to support multi-layered, complex transportation infrastructure investment decisions that address these rapidly changing environments.

Preface

This thesis is an original work by Huanan Li under the supervision of Dr. Amy Kim. A paper titled by *Incorporating the impacts of climate change in transportation infrastructure decision models* based on Chapter 3 and Chapter 4 has been submitted to *Transportation Research Part A: Policy and Practice*, and is currently under review. Another paper will be developed based on Chapter 5 and Chapter 6 work in the near future. No other parts of this thesis have been previously published.

Acknowledgements

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Great thanks to my colleagues: Naomi Li, Laura Cabral, Kaleab Yirgu, Bryan Tran, Sabrena Jahan Ohi, Kasturi Mahajan, Matthew Woo, Gloria Duran Castillo, for helping me adapt to this new study environment and sharing with me their wonderful life. In addition, I would like to thank Rachelle Foss for her proofreading support.

Finally, I would like to express my deepest thanks to my wife, my parents, and my parents in-law for always supporting me with all their love.

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S_t	=	OSD in year t
S_0	=	Initial OSD at t=0
η	=	Average annual growth rate of S_t
θ	=	Average annual volatility of OSD
W_t	=	Wiener process, also called Brownian motion
ε	=	Standard normal distribution N~(0,1).
$P(S_t,t)$	=	Expected airlift cost at time t
$N(\cdot)$	=	Standard normal cumulative distribution function
T	=	Time at which a decision must be made about whether to barge that year or forego it and build a road instead
$T\text{-}t$	=	Time remaining to make the decision
K	=	Minimum required OSD to ship all freight demand by barge
r	=	Annual discount rate
σ	=	Adjusted standard deviation of the OSD
σ'	=	Standard deviation of the OSD
$P(S_t,t)$	=	Additional barging days required to fully serve freight demand in year t
$C_{(B,P,t)}$	=	Airlift cost incurred due to insufficient OSD
NPV	=	Project's net present value
B	=	Present total project benefits
I	=	Project investment cost
π^D	=	Total present (i.e., discounted) costs of the *do nothing* scenario
π^C	=	Total present (i.e., discounted) costs of the *construct* scenario
T_1	=	Project construction period
T_2	=	Project operation period
X_t	=	Total freight delivered in year t (tonnes)
$X_{(b,t)}$	=	Total freight delivered by barge in year t (tonnes)
$X_{(a,t)}$	=	Total freight delivered by airlift in year t (tonnes)
P_b	=	Prices for transporting a unit of freight by barge ($/tonne)
P_a	=	Prices for transporting a unit of freight by airlift ($/tonne)
P_h	=	Prices for transporting a unit of freight by highway (truck) ($/tonne)
N	=	Average volume of freight transported per day under optimal barging conditions
b_{ob}	=	Other logistics and maintenance cost components for barging
b_{oh}	=	Other logistics and maintenance cost components for highway trucking
S	=	The project's value
u,d	=	Multiplicative factor
p	=	Probability
$\triangle t$	=	Time step size

NPV^e	=	Extended project value
s	=	Probability of increase to the next node
$p_{i,j}$	=	Probability of deferring the investment at node *i*, when considering year *j*
$Q_{h,t}$	=	Predicted freight demands for segment *h* in future year *t*
η_h	=	Drift of freight demand of segment *h*
θ_h	=	Volatility of freight demand of segment *h*
$Q_{h,0}$	=	Initial freight demand of segment *h*
$B_{(h,\tau)}$	=	Benefits of segment *h* when invested at time τ
I_h	=	Investment cost of segment *h*
T_p	=	Plan period
$\pi_{(D,h,\tau)}$	=	Total present (i.e., discounted) costs of the *do nothing* scenario for segment *h* when invested at time τ
$\pi_{(C,h,\tau)}$	=	Total present (i.e., discounted) costs of the *construct* scenario for segment *h* when invested at time τ
$Q_{(b,h,t)}$	=	Total freight delivered by barge for segment *h* in year *t* (tonnes)
$Q_{(a,h,t)}$	=	Total freight delivered by airlift for segment *h* in year *t* (tonnes)
ω	=	The ω th Monte Carlo simulation
W	=	Total simulation times
$\boldsymbol{NPV_{(h,\omega)}}$	=	The path of NPV of segment *h* on the ω th simulation
$NPV_{(h,\tau,\omega)}$	=	NPV of segment *h* when invested at time τ on the ω th simulation
$\phi_{(h,\omega)}$	=	Final option value of segment based on the ω th simulation
τ_ω	=	Optimal investment time on the ω th simulation
$\varphi_{(h,\tau+1,\omega)}$	=	Expected return of delayed investment for segment *h* when invested at time τ on the ω th simulation
ϕ_h	=	Final options value of segment *h*
τ_h	=	Final optimal investment time of segment *h*

Chapter 1. Introduction

1.1 Background and Motivation

The Mackenzie River is the longest river system in Northern Canada and a historically significant transportation corridor. It provides the primary mode for essential freight transport via tug and barge to remote communities in the Northwest Territories (NWT) and Nunavut, during the summer open water season from mid-June to late September or early October each year (Zheng & Kim, 2017). Over the last four decades, however, maximum spring flows on the Mackenzie River have generally decreased (Yang, Shi, & Marsh, 2015) due to climate change impacts as well as human-controlled factors upstream of the watershed, contributing to lower water levels. In more recent years, low water levels have caused operational disruptions and early season terminations, resulting in freight delivery delays and cancelations (CBC News, 2014; Bird, 2018). This uncertainty has forced an increased reliance on costly air transport for necessary supplies (Pendakur, 2017; Millerd, 2005). Additionally, other uncertainties like freight demand uncertainty also impact the mode choice and cost for freight transportation. In light of this need for adaptation, the Government of the Northwest Territories (GNWT) has been in support of constructing the all-weather Mackenzie Valley Highway (MVH) (Government of the Northwest Territories, 2018). However, the enormous cost of this highway has been a major barrier. This is at least in part because the impacts of uncertainties from climate change and other sources like freight demand, as well as options for flexibility in infrastructure investment decisions, have not been clearly quantified as assets against this cost. Decision makers in northern governments (and private companies working in the north) understand the growing criticality of both accounting for and adapting to uncertainties arising from climate change and other sources like traffic demand in infrastructure planning but have not yet done so quantitatively. Therefore, incorporating the above uncertainties into these sorts of decisions on transportation infrastructure investment is necessary for the rational decision-making of transportation engineers, government planners, and local companies.

1.2 Objectives

The purpose of the thesis is to explore appropriate methods to support flexible infrastructure decision-making in accounting for the impacts of growing environmental and other uncertainties in transportation service provision and infrastructure investment decisions. We target the Mackenzie River corridor in Northern Canada – specifically, (1) the decision to continue barging services each year, and when to construct an all-weather highway, and (2) if this all-weather highway is divided into four segments to be built in stages, when to invest and how to prioritize the constructions. We present a methodological framework based on options approaches, to explicitly consider how uncertainties from climate change and freight demand impact transportation operations and infrastructure investment decisions. The specific research objectives of this thesis are:

i. Investment decision assessment of transportation infrastructure that considers one uncertainty: Develop quantitative methods that incorporate climate change uncertainty into transportation infrastructure decisions about if and when to construct this project.

ii. Investment decision assessment of multiple transportation infrastructure that considers multiple uncertainties: Develop quantitative methods to optimally decide the construction times of different segments of a transportation infrastructure, incorporating uncertainties from climate change and freight demand.

iii. Comprehensive overview of frameworks: Provide an overview of the methodological framework developed in the previous two objectives to support investment decision-making for transportation infrastructure.

Figure 1-1 shows the connection between these objectives. Two scenarios are considered to achieve the first and second objectives. In scenario one, we treat the Mackenzie Valley Highway from Wrigley to Inuvik as a whole project, and only climate change uncertainty is incorporated into the evaluation model. In scenario two, the Mackenzie Valley Highway from Wrigley to Inuvik is divided into four segments and built in stages. The four segments connect five major communities along the Mackenzie River: Wrigley, Tulita, Norman Wells, Fort Good Hope, and

Inuvik. Additionally, climate change uncertainty and freight demand uncertainties are considered in our model.

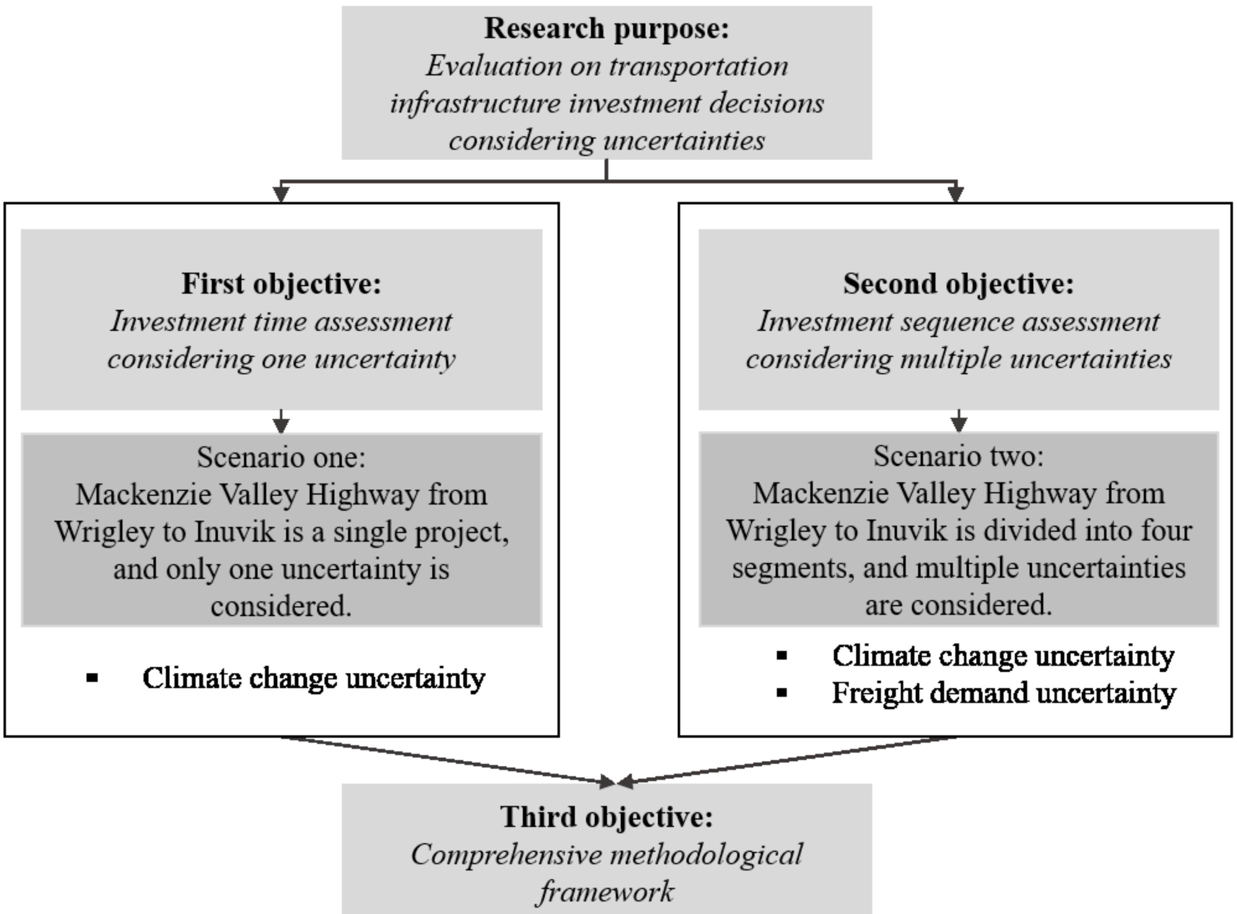

Figure 1-1 Connection of three research objectives

1.3 Research Approach

To attain the first objective, a simple real options method based on binomial lattice is proposed for calculating the extended project value when considering the uncertainty of climate impact. Climate uncertainty is presented by the water open season days of the Mackenzie River, which will be simulated using a stochastic process. For the second objective, a real options framework based on Least Squares Monte Carlo (LSM) is developed to calculate the different projects' value and optimal investment times. Uncertainties from climate change and freight demands are considered in this model, and simulated by stochastic processes. To attain the third objective, the developed methodological frameworks are discussed based on the previous case studies.

1.4 Thesis Organization

This thesis is composed of seven chapters. Chapter 2 describes the background of the Northwest Territories (NWT), including the transportation network, as well as the impacts of climate change (e.g., fluctuating water levels, permafrost degradation) on local marine and road transportation. Chapter 3 includes brief literature reviews of studies on treating climate change uncertainty, real options approaches, and transportation infrastructure investment decisions considering uncertainties. Chapter 4 analyzes the real options model with one uncertainty (climate change) for the scenario of regarding the whole all-weather road as an entire project; further, a real options model with multiple uncertainties (climate change uncertainty and traffic demand uncertainties) are proposed for the scenario of dividing the whole all-weather road into four separate segments in Chapter 5. Chapter 7 provides an overview of previous methodological frameworks and Chapter 7 discusses the conclusions and contributions of this research.

Chapter 2. Background

The Northwest Territories (NWT) is a vast region, covering almost 1.35 million square kilometers—over 10 percent of Canada's land mass. It has a population of 43,000 located in 33 communities, and contains abundant mineral resources including world-class diamond mines and large oil and gas reserves (Government of Canada, 2015). There are significant challenges in providing transportation services in the Northwest Territories (NWT) due to its highly remote communities, incredibly harsh climates, and rough but fragile terrain (Statistics Canada, 2015). The impacts of climate change, which are far more severe in the north, add to these already difficult conditions through permafrost degradation, water level fluctuations, and sea ice melt (Northwest Territories, 2008). The Mackenzie River, flowing from Great Slave Lake into the Beaufort Sea, is a historical transportation corridor in the Northwest Territories (NWT) on which supplies are transported to adjacent communities, as well as those beyond Tuktoyaktuk on the coasts of the Beaufort Sea (Figure 2-1). The Mackenzie River allows for barge service in the summer months, during a limited navigational window that depends on water levels and ice conditions (Mariport Group Ltd., 2011). Isolated communities and minimal road access mean that aside from barging, there are few alternative transportation options in this region (Department of Transportation, GNWT, 2011a). Some communities are connected by all-weather roads (towards the south and north ends of the river), while more communities connect via seasonal winter roads in winter and marine services in summer (Prolog Canada Inc., 2010). Other communities can only be reached via air.

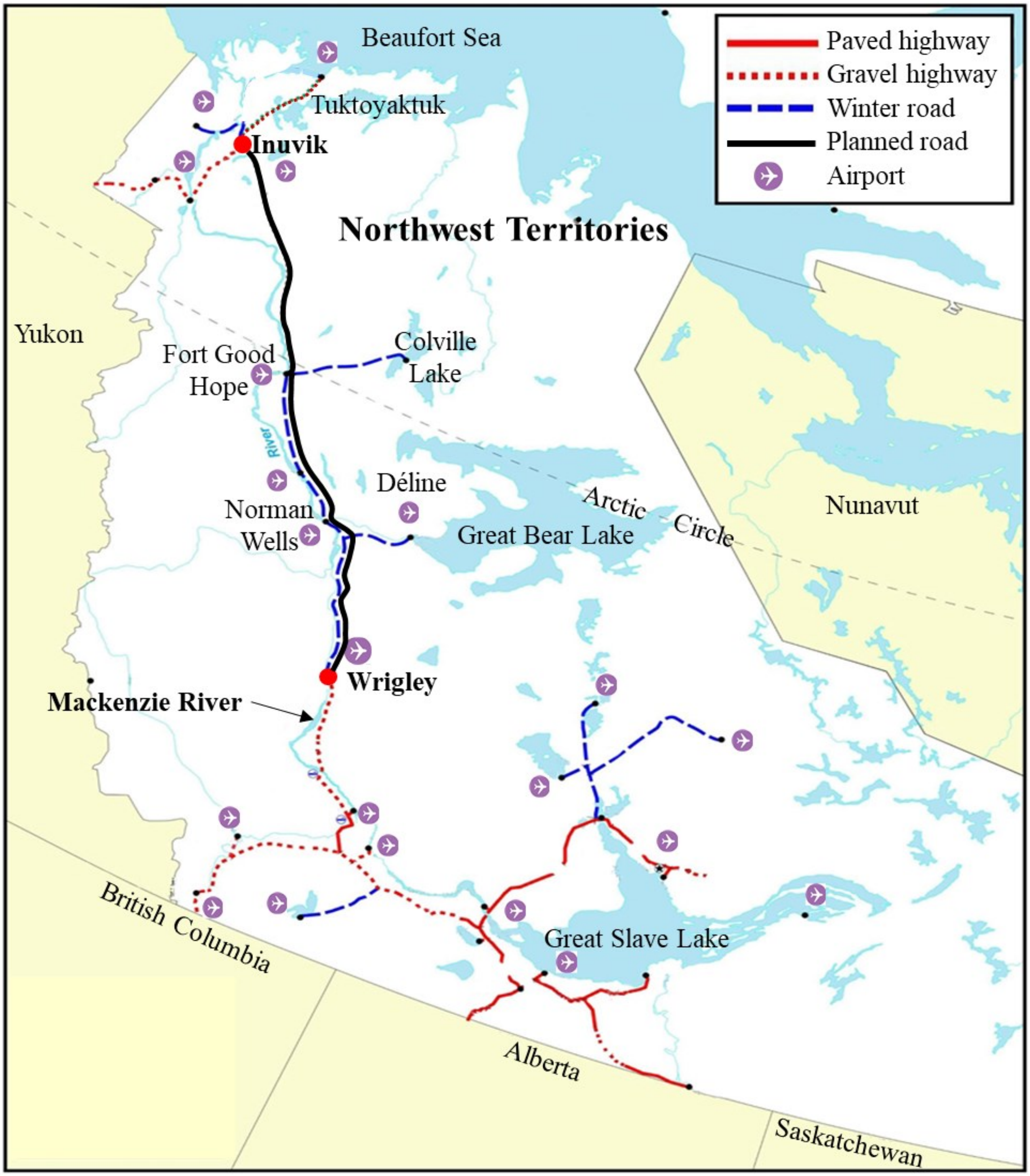

Figure 2-1 Transportation network along the Mackenzie Valley Corridor in the NWT[1]

The transportation system in the Mackenzie River corridor is described in Section 2.1, followed by presenting the impacts of climate change on local transportation along the Mackenzie River

[1] Adapted from the Government of the Northwest Territories (2019).

corridor in the NWT in Section 2.2. In Section 2.3, the problem of operational disruption of barging service due to climate uncertainty faced by the Government of the Northwest Territories (GNWT) is reviewed.

2.1 Transportation Infrastructure along the Mackenzie River Corridor

The Northwest Territories has considerable transportation needs, but access and mobility are restricted due to its relatively sparse transportation system (Government of Yukon, 2008). Except for the Mackenzie Northern Railway running from Edmonton, Alberta to Hay River, most transportation infrastructures in the NWT are located along the Mackenzie River corridor, consisting mainly of three modes: marine, roads (all-weather road and winter road), and aviation, to move people and goods (Figure 2-1). Currently, the transportation system along the Mackenzie River corridor includes 10 all-weather highways and 12 winter roads, four ferries and ice crossings, over 300 bridges and major structures, and an extensive network of airports consisting of 20 more government-operated airports (Department of Transportation, GNWT, 2016; 2018). More transportation infrastructure is highly needed by local communities and companies. The following sections introduce the three transportation modes in detail.

2.1.1 Marine

Marine transportation is the dominant re-supply mode to serve communities and industry along the Mackenzie River corridor, the Mackenzie Delta, the coast of the Beaufort Sea, and the interior of the Canadian Arctic Archipelago (Stantec, 2013). There are three main marine routes: one connects rail/trucks to barge facilities in Hay River, another one extends trucks to barge facilities in Fort Simpson, through Great Slave Lake, up the Mackenzie Valley and into the high Arctic, and the last route extends south through the Athabasca river to the Alberta oil sands (Government of Yukon, 2008). Essential goods are delivered by tug and barge freight companies (both publicly and privately owned) to marine-accessible communities in the NWT (Government of Northwest Territories, 2018). Private companies alone have historically provided barging services on the Mackenzie River and Great Slave Lake (Zheng, Kim, Du, & S.A., 2016). However, the largest of these companies – the Northern Transportation Company Limited

(NTCL), based out of Hay River –filed for bankruptcy in late 2016. The Government of the Northwest Territories (GNWT) subsequently purchased NTCL’s remaining assets in order to continue providing essential barging services as of summer 2017. Other companies include Cooper Barging in Fort Simpson and Horizon North. Some communities like Lutsel’ke, Paulatuk, Sachs Harbour, and Ulukhaktok depend exclusively on this marine re-supply of bulk commodities (Government of Yukon, 2008). Beyond this, another two sea routes across the Ocean Pacific and Atlantic Ocean mainly serve Eastern Arctic communities from Eastern Canada and the east coast of the U.S., and serve Europe and Western Arctic communities from British Columbia, the west coast of the U.S., and Asia (Zheng, 2016).

2.1.2 Roads

Roadway infrastructure provides another vital and effective transportation mode in the NWT, consisting of all-weather roads and winter roads. An all-weather road is useable in all weather conditions, meaning that it can provide year-round transportation access. All-weather highway facilities in the Mackenzie River corridor are highly limited (Figure 2-1). At present, the NWT has 10 all-weather (gravel and paved) roads, a total of 3,835 kilometers (Department of Transportation, GNWT, 2018). Inuvik is connected via the Dempster Highway through Yukon; furthermore, Tuktoyaktuk can be reached from Inuvik via the Inuvik – Tuktoyaktuk Highway, which opened in November 2017. However, the Mackenzie Highway (Highway 1) ends at Wrigley, and there is currently no additional overland access from Wrigley to Inuvik during spring, summer, and fall. In summer months, freight flights are the only other transportation option that prevents communities from experiencing shortfalls in essential supplies (such as fuel) if low water levels and other problems hinder barge operations (Bird, 2018). Communities typically have limited to no storage to accommodate extra supply deliveries in good shipping years.

A winter road is built upon compacted snow or frozen water as a seasonal solution for meeting transportation needs. Currently, Wrigley can be accessed via the Mackenzie Highway, but access beyond Wrigley to Fort Good Hope is dependent on winter roads built annually by the GNWT, which are typically operated from mid- or late December to early or mid-April (Department of Transportation, GNWT , 2016a), and summer barging. The GNWT builds the winter roads to deliver supplies and connect small remote communities with other communities (Zheng, 2016).

At present, 12 winter roads in the Mackenzie Corridor total 1,450 kilometers in length (Department of Transportation, GNWT, 2018; Department of Infrastructure, GNWT, 2018). The heavy reliance of communities on highly climate-dependent transport modes leads to significantly higher prices for both residents and industry (Meyers Norris Penny LLP, 2007).

2.1.3 Aviation

Communities throughout the NWT rely heavily on the aviation system, particularly for mobility of its citizens and fresh food re-supply. There are in total 27 community-based airports (21 of them are located along the Mackenzie River corridor) publicly operated by GNWT, as well as numerous privately owned and operated air strips for resource development, such as those of the Diavik and Ekati diamond mines in eastern NWT, in the Slave Geological Province (Government of Yukon, 2008). Many commercial airlines provide regularly scheduled air service to these airports, including Air North, Air Tindi, Buffalo Airways, Canadian North, First Air, Northwestern Air Lease, Northwright Air, Summit Air, etc. (Government of Northwest Territories, 2019), while remote areas not accessible by road or scheduled airlines are served by charter services (Meyers Norris Penny LLP, 2007). Multiple charter services can be obtained for different purposes, including float plane charter flights, NWT sport fishing & hunting charter flights, business and corporate charter flights, NWT helicopter charter flights, and group charter flights (Charter Flight Network, 2019). Three larger airports (Inuvik, Norman Wells, and Yellowknife) with greater traffic volume constitute the main transportation hubs in the NWT, serving for various human activities, such as natural resource exploration, mine development, tourism, and others (Government of Yukon, 2008; Environmental and Natural Resource, GNWT, 2015).

2.2 Impacts of Climate Change on Transportation System along the Mackenzie River Corridor

The Mackenzie River Corridor has experienced significant climate change impacts over the last several decades. The average annual temperature in the Mackenzie Valley has increased 2.6°C since the 1940s when the first records were collected; temperatures in Inuvik, located at the mouth of the Mackenzie River, have increased by 3°C (Northwest Territories, 2008; Government of Canada, Natural Resources Canada, 2016). Permafrost temperatures in the southern and central Mackenzie Valley indicate warming of between 0.2˚C per decade to 1.2˚C per decade according to multi-decadal trends (Government of Canada, Natural Resources Canada, 2016).

A warming climate has caused fluctuating water levels, permafrost degradation, and more, having a continued and considerable impact on the transportation systems of the NWT. Climate change can influence precipitation and temperature, which in turn impact river streamflow (Sung, Burn, & Soulis, 2006; Woo, Thorne, Szeto, & Yang, 2008). Maximum spring flows on the Mackenzie River have generally decreased over the last four decades (Yang, Shi, & Marsh, 2015) due to climate change impacts as well as human-controlled factors upstream of the watershed, contributing to lower water levels. This has, in turn, contributed heavily to the shortening of a once reliable navigational season (Northwest Territories, 2008). For example, shipment of goods to communities has been delayed because of low water levels on the Mackenzie River in recent years, leading to local residents relying on more costly alternative modes (such as airlift) to ship necessary goods and materials (CBC News, 2014a; 2015; 2015a). This leads to the governments vacillating on new transportation infrastructure investments, since they are not sure if it is worthy to invest considering the impact of climate uncertainty, or when is an optimal investment time.

Roads constructed on permafrost, as well as winter roads, are sensitive to climate change in Northern Canada (Northern Climate ExChange, 2014). Thawing of ice-rich permafrost can lead to ground settlement, slope instability, drainage issues, and road cracking (Government of Canada, Natural Resources Canada, 2016). For instance, an assessment report of climate change vulnerability on Highway 3 in the NWT says that sections of the highway built on "ice-rich permafrost" with soil containing over 20% visible ice were at greatest risk to fail due to climate change effects (Department of Transportation, GNWT, 2011). Thus, it is difficult to make road maintenance decisions about when and how since the impacts of climate change are uncertain. Furthermore, there are significant challenges to the construction and operation of winter roads due to the harsh environmental conditions of the north, such as increased instances of storm weather occurring early in the winter, disrupting the formation of ice (AQTr, 2013). The Inuvik-Tuktoyaktuk Highway was heavily supported by the fact that the operational season length of the winter road was growing shorter due to the continuing trend of warmer weather (CBC News, 2017).

Climate change also has significant impacts on other transport modes in the NWT, including melting permafrost under airport runways and aprons. More details can be found in related reports (Government of Canada, Natural Resources Canada, 2016; Boyle, Cunningham, & Dekens, 2013).

2.3 Problem Overview

It was mentioned in Section 2.2 that the duration of the Mackenzie River's navigable season has generally grown shorter and more variable, resulting in more delays and costs incurred from the use of alternate delivery modes. Data from the Canadian Coast Guard on navigational buoy placement dates at Rader Island (near Norman Wells) indicates that the number of navigable, open season days decreased from 121 days in 1997 to 110 days in 2017, with a low of 87 days in 2014. Because the unit cost of airlift is reported to be roughly about 10 times higher than barge (Department of Transportation, GNWT , 2011b), transport costs in the Mackenzie River corridor have increased (Pendakur, 2017).

To improve transportation reliability and accessibility to remote communities, and thus provide more opportunities for economic development, the GNWT has been considering an all-weather road from Wrigley to Tuktoyaktuk since the 1950s, called the Mackenzie Valley Highway (5658NWT Ltd. & Government of Northwest Territories, 2011). However, the investment has not been completed yet. One of the key reasons for this is because climate change uncertainty makes the decisions about if it is worthy to invest, when and how to invest full of controversy, Currently, the portions from Inuvik to Tuktoyaktuk (the ITH) and from Norman Wells to Canyon Creek (Canyon Creek All-Season Access Road) opened on November 15, 2017 and November 13, 2018 separately (Department of Infrastructure, GNWT, 2019; 2019a). Although plans to construct the rest of the highway have been stalled due to lack of funding commitments (projected costs are $1.67 billion), the GNWT has identified several project phases, including constructions of the Great Bear River Bridge at Tulita (Phase One), Wrigley to Mount Gaudet access road (Phase Two), Canyon Creek to Tulita section (Phase Three), Tulita to the Sahtu-

Dehcho boundary (Phase Four), and Sahtu-Dehcho boundary to Mount Gaudet access road (Phase Five) (Government of Northwest Territories, 2019).

Federal and territorial governments have been working to understand the impacts of climate change on existing infrastructure, how to adapt to it (Northwest Territories, 2008), and how to incorporate climate change considerations into infrastructure decisions. However, there are little to no formal tools or processes currently in place to guide the latter (Auditor General of Canada, 2017). There has been no application of quantitative tools that explicitly incorporate environmental variability into infrastructure decision-making structures. Northern territorial governments have expressed their need for such tools, given the number of major infrastructure projects currently under consideration.

2.4 Summary

There are significant challenges to providing transportation in Northern Canada. Except for a small section of railway extending Alberta to the Hay River, there are mainly three modes of transportation local communities and industry can rely on to deliver necessary re-supply in the NWT: road (including all-weather road and winter road), marine, and aviation. However, in recent years, climate change has significantly affected these transportation infrastructures through fluctuating water levels, permafrost degradation, and more, leaving the GNWT considering whether to build an all-weather road from Wrigley to Tuktoyaktuk. Thus, the study on quantitative tools that explicitly incorporate environmental variabilities into infrastructure decision-making structures is necessary to local government and investment companies.

Chapter 3. Literature Review

In this chapter, we first provide literature reviews on how climate change uncertainties have been handled in the research literature, and analyze the limitations of different methods. Then real options approaches used in this thesis are introduced as a potential tool to consider climate uncertainty, finally we illustrate some researches on incorporating uncertainty in transportation infrastructure investment decisions. The flow of this chapter is shown in Figure 3-1.

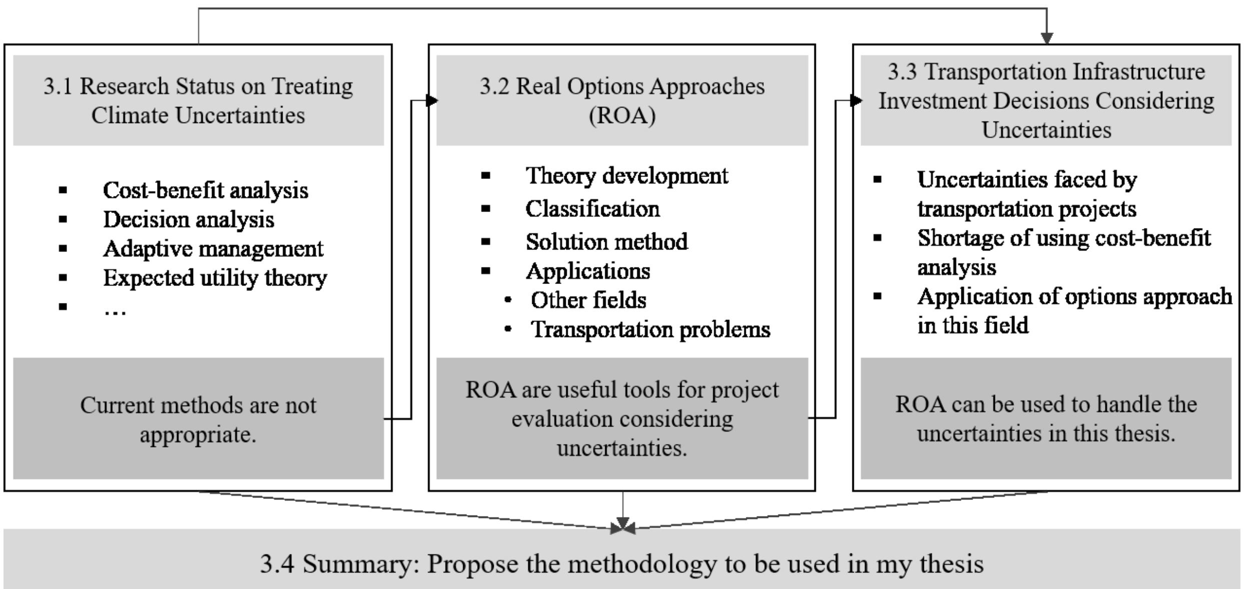

Figure 3-1 Flow of this chapter

3.1 Research Status on Treating Climate Uncertainties

The climate change has profound and increasing impacts on both the natural environment and human society. For instance, an assessment of climate change risks indicates that the impacts of climate change on roads, bridges, coastal development, and urban drainage in the US could be greater in later of this century, because sea-level rises, temperature increases, and precipitation patterns become more extreme and affect the sustainability of long-lived infrastructure (Neumann, et al., 2015). However, due to the obvious limitations to performing scientific experiments on the global climate system, people's understanding on climate change is incomplete, leaving individuals confronting various uncertainties when making decisions that affect, or are affected by, climate change (Malik, Rothbaum, & Smith, 2010). Thus, quantitative tools on treating climate uncertainties is critical for climate related decision-making.

To date, the uncertainty of climate change has been widely considered in climate policy related studies. As the leading governments' organization for assessing the science related to climate change, Intergovernmental Panel on Climate Change (IPCC) has done a great deal of work about knowledge on climate change, its causes, potential impacts and response options (IPCC, 2018). They categorized uncertainties in the climate system into four groups: climate observation, drivers of climate change, understanding recent changes in the climate system, and projection methods and results (Stocker, Qin, & Plattner, 2013). However, most uncertainties are difficult to quantify, relying on experts' judgement and the model type used to generate future scenarios (Drouet, Bosetti, & Tavoni, 2015). The challenges to representing uncertainty in climate models lies in the infeasibility of generating all possible future scenarios and the difficulty in produces a objective probability distribution over the possible states of nature (e.g., cost of mitigation, or temperature increase) (Heal & Millner, 2013; Drouet, Bosetti, & Tavoni, 2015). Many quantitative and qualitative methods can treat uncertainty in model building, including currently used methods such as cost-benefit analysis (Gaspars-Wieloch, 2019), decision analysis (Scholten, Schuwirth, Reichert, & Lienert, 2015), adaptive management (Prato, 2017), structured expert judgment methods (Zickfeld, Morgan, Frame, & Keith, 2010), uncertainty analysis techniques (Burke, Dykema, Lobell, Miguel, & Satyanath, 2015), and the outdated methods like expected utility theory (Savage, 1954). When these methods incorporate climate change uncertainties, climate variables (e.g., climate catastrophe frequency, climate sensitivity[2], and temperature increase) are commonly represented by an assumed probability (Tol, 2003; Malik, Rothbaum, & Smith, 2010), or an estimated distribution (Heal & Millner, 2013). However, most of the current theories considering climate uncertainties are applied to climate impact assessment and climate policy assessment from a global, regional perspective, such as the works of IPCC (2018). None of them can be used in the decision evaluation of an actual infrastructure project investment. Although cost-benefit analysis can evaluate investment decisions on projects, it has never considered climate uncertainty in its applications. Therefore, more appropriate approaches for

[2] Sensitivity of global average temperature to changes in CO_2 concentration (Heal & Millner, 2013).

addressing climate uncertainty in evaluation of infrastructure investment decisions should be investigated.

3.2 Real Options Approaches

Real options are the rights without obligations to delay, abandon, expand, switch or other ways in response to the evolution of uncertainty in investments (Trigeorgis & Reuer, 2017). It is derived from the financial options concept being applied to real operational processes, activities, or investment opportunities (Myers, 1977). It gives decision makers the flexibility to take an action to maximize their value (Zhao, Sundararajan, & Tseng, 2004). Real option theory is a series of evaluation approaches developed from financial options pricing methods, with the feature of quantifying the value of flexibility in a real option (Chow & Regan, 2011).

There are four basic types of real options: delay option, expand option, switch option, and abandon option. Delay option is the most commonly used option, and it gives an investor the exclusive right to delay a project investment until a later date. Traditional evaluation methods, like cost-benefit analysis, indicate that the project should be cancelled if its net present value is negative. However, that does not mean the value would also be negative if the investment is delayed until a later time. In practice, the management flexibility of allowing for the option to delay investment is often overlooked in a project evaluation (Dewar & Wachs, 2006; Zhao, Sundararajan, & Tseng, 2004). Expand option gives investors the option to expand their investment in a future date at a little cost. It offers the possibility of increasing the investment scale of the project by making an additional investment (Copeland, Koller, & Murrin, 2000). Due to the flexibility of increasing investment in future, the expansion option has a high strategic value (Calle Fernández & Tamayo Bustamante, 2009). Third, switch option indicate the investor has the rights to switch between possible outputs or inputs in order to maximize project value (Kensinger, 1987; Kulatilaka, 1993). This type of option is complicated since a decision needs to be taken among multiple interdependent choices that are all facing lots of uncertainties. Finally, abandonment option provides the investor with the opportunity to quit the investment at a future date when the project proves to be inefficient (Damaraju, Barney, & Makhija, 2015). This kind of option will increase the project value by reducing the possibility of the investment turning out to be bad (Rambaud & Pérez, 2016), which is important in long-term investments where capital output may be staged (Trigeorgis, 1999). The questions about *if, when and how* to invest in the Mackenzie Valley Highway from Wrigley and Inuvik is essentially an issue of investing immediately or later, thus, the delay options are applied in this thesis.

There are three classes of numerical methods used to solve for the value of different real options: finite difference (Brennan & Schwartz, 1997), binomial lattice (Cox, Ross, & Rubinstein, 1979), and Monte Carlo simulation (Boyle P. , 1977). The key barrier for application of finite difference methods lies in the difficulty to specify differential equations, and neither finite difference method nor binomial lattice method is suitable for dealing with option pricing issues with multiple underlying assets (Chow & Regan, 2011; Abadie & Chamorro, 2013). Unlike these two methods, the Monte Carlo simulation method has obvious advantages for dealing with multiple or complicated uncertainty processes (Zhao & Tseng, 2003). However, since the Monte Carlo uses a backward dynamic solution and stochastic process, the calculation for the expected return when continuing to delay the option at each time note turns very computationally expensive (Chow & Regan, 2011a). Thus, it is not possible to decide whether to execute the option immediately or continue to hold the option. In recent years, more cost-effective methods are proposed for targeting these new problems, including the Least Squares Monte Carlo (LSM) method (Longstaff & Schwartz, 2001). LSM applies the least squares regression method to fit the expected returns along all simulation paths, effectively reducing the computational cost (Chow & Regan, 2011a). This approach has currently become the standard method for simulating American option pricing.

The applications of real options approaches have grown since Black and Scholes (1973) and Merton (1973) first proposed financial options valuation models. Pindyck (1979) studied the impacts of two sources of uncertainty on non-renewable resource markets. Tourinho (1979) looked at the valuation of a natural resource when the price of the resource followed a stochastic process. Since the 1970s, real options models have been applied to many different types of infrastructure decisions, including manufacturing site location choice (Kogut & Kulatilaka, 1994), IT network expansion (Benaroch & Kauffman, 2000), oilfield development in Alaska (Conrad & Kotani, 2005), power plant construction timelines (Kato & Zhou, 2011), and parking garage sizing decisions (Zhao & Tseng, 2003). Uncertainties (sometimes from multiple sources) often end up being the key decision drivers in these models (Bräutigam, Esche, & Mehler, 2003).

Kim et al. (2017) applied a real options framework to assess renewable energy investments in developing countries, accounting for uncertainties due to rapidly changing technologies and host government conditions. A real options model was used to evaluate NASA technology investments based on development and programmatic risks (Shishko, Ebbeler, & Fox, 2004). The feasibility of privatized infrastructure projects was assessed using an option pricing-based model, with uncertainties, such as bankruptcy risk, accounted for (Ho & Liu, 2002).

There have been relatively few applications of real options models specific to transportation infrastructure decision problems. However, it has been identified as an appropriate approach for handling issues of uncertainties when evaluating transportation projects. Applications include the aforementioned parking garage with future parking demand uncertainty (Zhao & Tseng, 2003) and highway expansion accounting for uncertainties in travel demand, land prices, and pavement deterioration (Zhao, Sundararajan, & Tseng, 2004). These two papers applied dynamic programming to generate solutions. The analysis of a tolled highway extension project used a binomial tree model (Garvin & Cheah, 2004), a popular and easy-to-implement class of approaches that include the binomial lattice method (Kato & Zhou, 2011; Brandão, Dyer, & Hahn, 2005; Smith, 2005; Michailidis & Mattas, 2007). Considering the uncertainty of minimum revenue guarantee, Huang and Chou (2006) evaluated the Taiwan High-Speed Rail Project using a compound option pricing approach. Real options has also been applied to network design and expansion decisions considering the uncertainty of demand (Chow & Regan, 2011; Chow & Regan, 2011a). Stochastic variables have been represented as a Geometric Brownian Motion (GBM) process in real options models applied to transportation. Chow and Regan (2011a) modeled traffic demand as a GBM process, while Couto et al. (2015) modeled high speed rail demand as a GBM process. Zhao et al. (2004) represented both traffic demand and land price as GBM processes in their highway infrastructure decision model.

3.3 Transportation Infrastructure Investment Decisions Considering Uncertainties

Infrastructure projects like highway construction are subject to significant uncertainties from multiple sources, including demand, changing weather, and political and social environments (Zhao, Sundararajan, & Tseng, 2004). For transportation infrastructure projects in Northern

Canada, one of the greatest sources of uncertainty is the varied and long-term impacts of climate change (as discussed in Chapter 2). Beyond that, freight demand uncertainty is another key factor impacting the investment of transportation infrastructure projects. Due to the unavailability of the freight demand data, we analyzed the historical barging freight volume data of the NTLC on the Mackenzie River, finding that it fluctuated with an average annual decrease rate of 5.7% (Zheng, Kim, Du, & S.A., 2016). This reflects the freight demand along the Mackenzie Valley corridor is uncertain to some extent. In addition to holding significant mineral resources and potential tourism opportunities, the Mackenzie Valley in Northern Canada requires significant transportation demands to export its large volumes of ore and transport visitors (Department of Infrastructure, GNWT, 2019). This further increases the uncertainty of freight demand. Traditional evaluation methods, like cost-benefit analysis (CBA), account for valuations of future uncertainties through approaches such as sensitivity analysis and simulation of expected cash flow through random sampling of (stochastic) variables (Asplund & Eliasson, 2016; Gaspars-Wieloch, 2019). However, the main shortcoming of CBA, even when accounting for uncertainties, is that it does not produce results that directly support managerial flexibility in the face of uncertainty (Yeo & Qiu, 2003), ignoring growth opportunities or strategic alternatives in project investment (Dixit & Pindyck, 1994; Michailidis & Mattas, 2007). Real options models, based in financial options theory, were developed and applied in response to this shortcoming over the last two decades (Herder, de Joode, Ligtvoet, Schenk, & Taneja, 2011; Galera & Sánchez, 2010). Real options models are distinguished from conventional CBA in that the flexibility of delaying a project under uncertainties can be considered an asset (Michailidis & Mattas, 2007), and thus an additional source of value in a project investment decision (Bodie & Merton, 2000).

In previous literature, some studies already incorporated freight demand uncertainty into transportation investment decision making using real options analysis; notably, Chow and Regan (2011a) analyzed the value of flexibility for deferral and design strategies in transportation investments considering traffic demand based on a real option method. Considering demand uncertainty, Zhan and Tseng (2003) modeled the flexibility value in the transportation infrastructure facilities investment using a binominal lattice real options model, and further presented a Monte Carlo real options method for decision making in highway development (2004). Couto et al. (2015) searched for the optimal investment policy in a high-speed rail transport (HSR) project by applying a real options. However, only more recently has climate change uncertainty been accounted for using an option-type model. Sturm et al. (2016) presented a modified Black-Scholes model application to the annual decision of whether to construct an ice road in the Northwest Territories of Canada, given varying temperature conditions. They used the ice road season length as their climate input, as it is dependent on ice thickness and quality, which in turn is impacted by climate change. The annual decision of constructing the ice road for another winter season or not is analogous to a European-style option (represented by the Black-Scholes model) where the decision to buy/sell is made at a single pre-defined time (i.e., in the winter before barging season begins). Sturm, Goldstein, and Parr (2017) assessed the impacts of snowfall on various facilities using the same model. However, only more recently has climate change uncertainty been accounted for using an option-type model. Sturm et al. (2016) presented a modified Black-Scholes model application to the annual decision of whether to construct an ice road in the Northwest Territories of Canada, given varying temperature conditions. They used the ice road season length as their climate input, as it is dependent on ice thickness and quality, which in turn is impacted by climate change. The annual decision of constructing the ice road for another winter season or not is analogous to a European-style option (represented by the Black-Scholes model) where the decision to buy/sell is made at a single pre-defined time (i.e., in the winter before barging season begins). Sturm, Goldstein, and Parr (2017) assessed the impacts of snowfall on various facilities using the same model. These are the only works that apply options theory to evaluate infrastructure investments considering climate change uncertainty. These are the only works that apply options theory to evaluate infrastructure investments considering climate change uncertainty. However, the Black-Scholes model alone is limited in its capability to model these decisions, because it can only represent the decision to continue barging or not for a given season, taking into account the number of open season days (the length of the summer shipping season, or OSD) projected for that year alone. The decision to build a road does not only include expected transport costs for one year but rather, many future years, as future uncertainties also impact that decision of *if* and *when* to build.

Overall, real options approaches can be powerful tools to incorporate uncertainties from climate change and freight demand to the evaluation of transportation infrastructure investment decisions.

3.4 Summary

Considering the literature presented above on the research status of treating climate uncertainties, real options approaches, and transportation infrastructure investment decisions considering climate uncertainty, some of the findings are as follows: 1) few current theories considering climate uncertainties are appropriate for transportation infrastructure investment decision problems, thus, more applicable approaches should be investigated; Further, 2) real options approaches have been identified as appropriate methods for handling issues of uncertainties when evaluating transportation projects; and therefor, 3) incorporating uncertainties like climate change into the evaluation of transportation infrastructure investment decisions in regions like Northern Canada is necessary, and real options approaches are powerful tools to handle it.

In this research we apply two different real options modeling approaches to evaluate decisions around (1) whether to continue barging operations each summer or invest in an all-weather road (and when), and (2) how to determine construction sequencing and timing if the all-weather road is to be built in sections. For the first question, we first apply the Black-Scholes model to evaluate decisions around continuing barging operations each year; this is a European-style option where the decision can only be made at a single pre-defined time (i.e., in the winter before barging season begins). We also apply the binomial lattice method to provide valuations of if and to when to defer the all-weather highway construction in the Mackenzie River corridor. We then use the Least Squares Monte Carlo (LSM) method (Longstaff & Schwartz, 2001) to address the second question of road project sequencing. Both climate uncertainties as well as freight demand uncertainties are considered in this model. Finally, we provide an overview of the methodological framework developed to better represent and support the transportation infrastructure investment decisions by accounting for uncertain climate impacts and other uncertainties in Northern Canada.

Chapter 4. Real Options Model with One Uncertainty

As mentioned in Chapter 2, low water levels have caused operational disruptions and early season terminations, resulting in freight delivery delays and cancelations in the Mackenzie River corridor in recent years (CBC News, 2014; Bird, 2018). This uncertainty has forced an increased reliance on costly air transport for receiving necessary supplies (Pendakur, 2017; Millerd, 2005). In light of this need for adaptation, the Government of the Northwest Territories has been considering constructing the all-weather Mackenzie Valley Highway (Government of the Northwest Territories, 2018). In this chapter, the whole all-weather road is regarded as a single infrastructure project, and the climate change uncertainty is considered as the only factor impacting the project value with other parameters predetermined (scenario one). How the climate uncertainty will influence the project value, and when should the GNWT start to build the road? With these purposes, we first model river open season days as a stochastic process as river barging is dependent on these days, which in turn is affected by climate change. Second, we evaluate the decision to continue barging and airlift service each year using a modified Black-Scholes model. Finally, we use real options to determine how long construction of the all-weather highway may be deferred.

4.1 Model Framework

The impacts of climate change uncertainty on this infrastructure investment decision are represented in the variability of marine open season days (OSD) on the Mackenzie River. To model decisions regarding whether barging operations should continue, and when it should be replaced entirely with truck delivery via a new all-weather Mackenzie Valley Highway, we use an options approach. The modeling framework is shown in Figure 4-1.

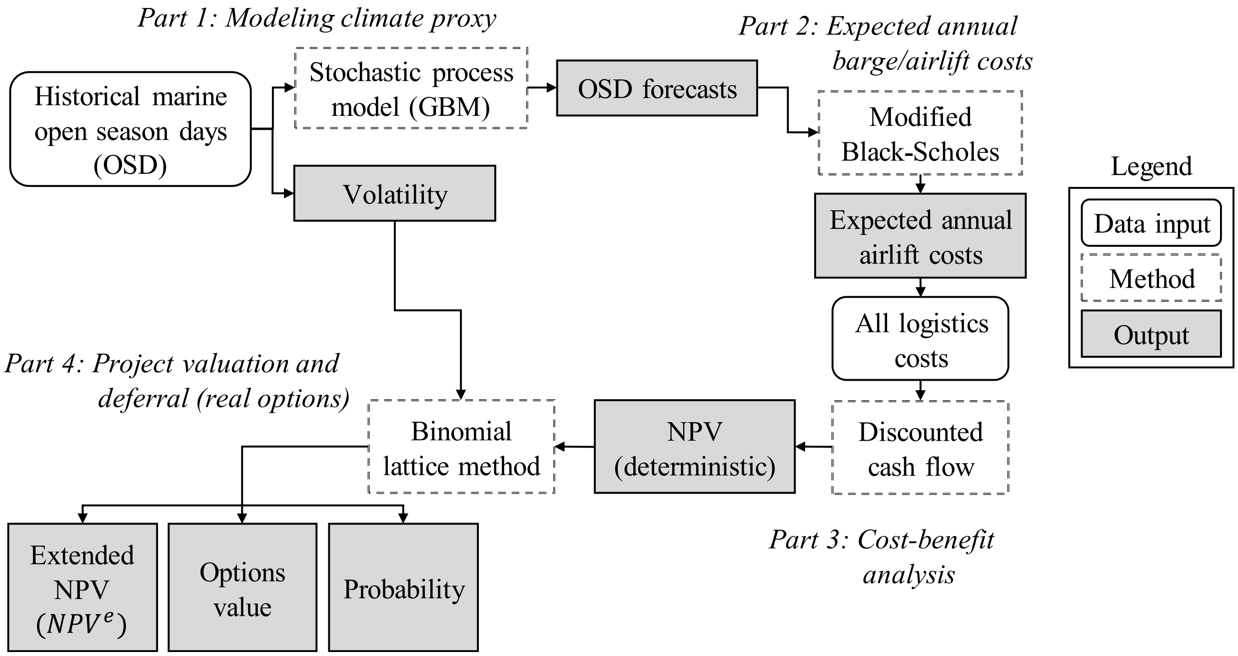

Figure 4-1 Modeling framework for scenario one

Our framework for incorporating environmental uncertainties into transportation investment decisions includes four parts. First, we use historical environmental conditions data that serves as a proxy for climate change (impacting the transportation service and infrastructure investment problem in question), and model it as a stochastic process (Section 4.3.1). Specifically, we model river open season days (OSD) as a geometric Brownian motion (GBM), and obtain OSD forecasts for a 20-year horizon. In Part 2 (Section 4.3.2), we use historical and forecast OSDs in a modified Black-Scholes model (Sturm, Goldstein, Huntington, & Douglas, 2016), which outputs the expected airlift costs for each year barging operations are continued. These expected costs are meant to represent the risk, as observed by the barge operator, in the choice of continuing barging operations for another summer season instead of diverting those operational costs towards other means of delivery (and possibly, delays). In Part 3 (Section 4.3.3) we use these expected costs to calculate the highway construction project NPV, which, with OSD volatility, are input to the model in Part 4 (Section 4.3.4). We determine whether Mackenzie Valley Highway construction between Wrigley and Inuvik (and therefore, replacement of barge shipping with trucks) is justified when we incorporate OSD uncertainty into the project NPV using the binomial lattice method. This results in project valuations (extended NPV, or NPV^e) that can help planners determine if and how long the construction project should be deferred. The most notable outcome is how much transportation project valuations change when climate change impacts are accounted for, specifically in the north where these impacts are among the most severe in the world.

4.2 Data and Modeling Inputs

Data and information used for this research was gathered from Statistics Canada (2019), the Canadian Coast Guard (CCG), NTCL, BBE Expediting (a northern logistics company based in Edmonton, Canada), and various reports and other literature both provided by the GNWT and found online. The key inputs required for our models, including the data and assumptions required to populate those inputs and build our model application, are listed in Table 4-1 and further discussed in this section.

Table 4-1 Model Data Sources

Input		Unit	Source	Application
Freight volumes		Tonne	NTCL	Cost-benefit analysis
Historical open season days (OSD)		Days/year	CCG	Climate uncertainty
Minimum open season days (OSD)		Days/year	NTCL	Cost-benefit analysis
Freight transport costs	Barge	$/tonne	BBE Expediting	
	Truck	$/tonne	BBE Expediting	
	Air	$/tonne	BBE Expediting	
Construction timeline		Years	GNWT	
Life of all-weather road		Years	GNWT	
Other parameters	Discount rate	%	Bank of Canada	
	Investment cost	$	GNWT report (Tetra Tech EBA, 2011)	
	Variable cost	$/tonne	Assumption	

4.2.1 Freight Volumes

Estimates of future freight volumes barged to communities between Wrigley and Inuvik are required for the cost-benefit analysis (Section 4.3.3). In the absence of an all-weather highway, these volumes consist entirely of freight that is ideally delivered by summer barging when possible. In barge capacity shortfalls (due to shortened seasons), the remaining freight is assumed to be delivered by airlift. If the all-weather highway were constructed, barge services would discontinue and all freight would be delivered by trucks.

Barge freight volumes from 2002-2014 were obtained from NTCL, the largest and oldest barging company on the Mackenzie River (Zheng, Kim, Du, & S.A., 2016). We make two assumptions to generate future freight volume estimates. First, NTCL provided, by far, the most barging service on the Mackenzie, carrying the greatest volumes and providing the largest geographic coverage (in fact, the only company to provide service to the Mackenzie River Delta at Tuktoyaktuk, and into the Beaufort Sea), we assumed that NTCL's freight volumes accounted for 80% of the total freight volumes carried on the Mackenzie. Second, we assume that future freight volumes will increase at the rate of GDP growth in the Northwest Territories from 2013-2017 (Statistics Canada, 2019). To obtain a forecast for 2015, we simply took the average barge freight volumes from 2002-2014 and applied the GDP growth rate, and assumed the growth will continue at that rate until 2037. This is one approach, but freight volume forecasts can be obtained from any number of methods including time series analysis, and this may be updated as better data becomes available.

Another parameter is the average volume of freight transported per day under optimal barging conditions. Based on the annual freight volume data gathered from NTCL and OSD data gathered from the Canadian Coast Guard (CCG), we first calculate the average daily freight volume of NTCL per year during 2002 and 2014. Then, we take the average as the average daily freight volume of NTCL. Furthermore, as we assumed that NTCL carried 80% of the total freight transported on the Mackenzie River, we divide the value of NTCL by 80% to be used as the average volume of freight transported per day under optimal barging conditions on the Mackenzie River.

4.2.2 Open Season Days (OSD)

The Mackenzie River is only navigable between the dates that the Canadian Coast Guard (CCG) installs and removes navigational buoys for the summer season. Open season days (OSD) indicate the length of this shipping season; in this work we use it as our climate proxy, modeled as a stochastic process in Section 4.3.1, for the following reasons. Mackenzie River OSD are determined by a complex combination of factors. Environmental factors include air and water temperature (and thus, ice breakup, freeze-up, and floating ice), precipitation, water levels, and water volumes. These are all impacted by climate change. Human factors include watershed management upstream in British Columbia throughout the season (thereby impacting volumes) as well as buoy placement by the Canadian Coast Guard (which is impacted not only by river conditions but also, labor availability). These factors can have conflicting impacts on the season length. For example, warming temperatures may lead to earlier spring ice breakup and in turn lead to earlier buoy placement and thus a longer season. However, less water flow towards the middle to end of the season (possibly due to less precipitation and watershed management practices) can result in an earlier end to the season. Because modeling the impacts of each factor that influences shipping capabilities on this 1700 km river is out of the scope of this work, we use the OSD, the final manifestation of these stochastic factors that directly impacts shipping.

Based on data (provided by the CCG, Appendix B) from 1997-2017 regarding dates of placement and removal of three buoys near Rader Island, we calculate the average historical OSD as the average number of days between buoys placement and removal each season.

We define minimum OSD as the minimum days in a shipping season required to transport all freight (the volumes that are forecasted as per Section 4.2.1) by barge. We first calculate the average freight volumes shipped by NTCL per day during open season, from 2002-2014. If we divide average total annual freight volume by the average daily freight volume, we calculate a minimum OSD of 107 days.

4.2.3 Freight Transport Costs by Mode

We obtained estimates of unit freight transport cost by barge, truck, and air from BBE Expediting Ltd., a provider of expediting, supply chain logistics, and freight handling services in the Canadian Arctic. They suggested that shipping costs from Edmonton to Inuvik were, in 2018, in the order of $680-730/tonne by barge, and $580-610/tonne by truck. In the absence of further information, we assumed that shipping costs between Wrigley and Inuvik are proportional by distance and are the average of the resulting range, such that barging cost is $260/tonne and trucking cost is $225/tonne. As mentioned in Section 2.2, delivering heavy freight (ideally delivered by barge or truck) by air is estimated to cost, roughly and conservatively, about 10 times that of barge delivery (Department of Transportation, GNWT , 2011b), such that the benefits of faster delivery times by air are entirely outweighed by the costs. Thus, we assume that the unit cost of air freight delivery is \$2600/tonne. Note that 1) we also assumed that these transportation costs hold over the entire study period, and 2) we considered average shipping costs from Wrigley to Inuvik, rather than considering each individual community in the corridor.

4.2.4 All-weather Highway Construction Time and Life

The time and cost of construction for an all-weather highway in Northern Canada, and the highway life, depends on many factors including: planning, data collection, and design; subsurface conditions (particularly considering permafrost); labor, supply, and equipment costs (including costs for transporting all the above); weather conditions, and many others. The construction of a new highway can take anywhere from five to ten years, from the time the project is designed to the time it is built (Government of Nova Scotia, 2018). Political consideration, concept planning, and design of this all-weather highway has been ongoing since the late 1950s (5658NWT Ltd. & Government of Northwest Territories, 2011). Given that the (gravel) Inuvik-Tuktoyaktuk Highway (ITH) construction project lasted four years, we will assume the same timeframe for construction of this gravel highway. Also, in the north, gravel roads and runways are less costly to maintain than paved surfaces, which can be subject to significant cracking and sinking. According to discussions with GNWT Infrastructure, the ITH was built with a planned lifespan of 75 years; with new gravel application required every five years, and major bridge rehabilitation (i.e., replacing bridge decks) required in 20 years. As a result, we will assume the lifespan to be 20 years for this stretch of the Mackenzie Valley Highway between Wrigley and Inuvik.

4.2.5 Other Parameters

We require assumptions for several other modeling parameters:

- The annual discount rate converts future monetary values to a present value (García-Gusano, Espegren, Lind, & Kirkengen, 2016), and is required for a multi-year cost-benefit analysis. The discount rate is estimated as the mean of the average inflation for Canada during 2009 and 2018 (Bank of Canada, 2019), which is 1.59%.

- The total construction cost of the all-weather road from Wrigley to Inuvik is reported to be $1.67 billion, according to a project description report prepared for the GNWT (Tetra Tech EBA, 2011; CBC News, 2013).
- Maintenance costs for both the barging-airlift system and the planned all-weather highway are assumed to be 5% of total freight costs.

4.3 Model and Results

We introduce the models we use to assess the Wrigley-Inuvik all-weather highway decision.

4.3.1 Representing Climate Change Uncertainty

The volatility parameter is a commonly used expression of uncertainty in the real options literature (Dixit & Pindyck, 1994). We assume that climate change uncertainty – open season days (OSD) being our proxy for climate change impacts on this barging system – is a stochastic process, and may have a trend and certainly some level of volatility. OSD forecasts may be obtained by modeling OSD as a stochastic process (as done by Sturm et al. (2016) for winter road open season days) or using time series analysis methods. Our rationale for using Geometric Brownian Motion (GBM), a continuous-time stochastic process in which the logarithm of the variable follows a Brownian motion with drift (Ross, 2014), to represent OSD is that OSD looks much like a random walk with drift and is always positive. Also, GBM has been used to model other variables related to climate uncertainty; notably, Gersonius et al. (2013) modeled rainfall intensity as a GBM, while Truong et al. (2018) modeled the count of climate-related catastrophic events as a GBM. We obtain simulated forecasts and descriptive parameters for use in the models of Sections 4.3.2 and 4.3.4.

In the options literature, GBM has often been used to model stock prices (Ozorio, Bastian-Pinto, & Brandão, 2018). A stochastic process S_t following a GBM is represented as follows (Dixit & Pindyck, 1994):

$$dS_t = \eta S_t d_t + \theta S_t dW_t \tag{4-1}$$

Where W_t is a Wiener process, also called Brownian motion, which is a continuous-time stochastic process; η is the drift, or the change rate of the mean of a stochastic process; and θ is the volatility of the stochastic process. The solution for S_t is found by applying Ito's Lemma; the derivation is widely available (Dixit & Pindyck, 1994; Ross, 2014):

$$S_t = S_0 e^{\left(\eta - \frac{1}{2}\theta^2\right)t + \theta dW} \tag{4-2}$$

In this paper, S_t represents OSD in year t; S_0 is the initial value at $t = 0$; η is the average growth rate of S_t; and θ is the average annual volatility of OSD. We can calculate η and θ using historical data (Yang & Blyth, 2007; Dmouj, 2006):

$$\eta = \frac{1}{n}\sum_{t=1}^{n} ln\left(\frac{S_t}{S_{t-1}}\right) \tag{4-3}$$

$$\theta = \sqrt{\frac{1}{n-1}\sum_{t=1}^{n}\left[ln\left(\frac{S_t}{S_{t-1}}\right) - \overline{ln\left(\frac{S_t}{S_{t-1}}\right)}\right]^2} \tag{4-4}$$

We use Monte Carlo simulation to generate 1,000 numerical solutions for S_t. Specifically, we generate random numbers in a Wiener process that follow a standard normal distribution:

$$dW_t = \varepsilon\, dt \tag{4-5}$$

Where ε is distributed standard normal $N\sim(0,1)$. Figure 4-2 shows historical OSDs (1997-2017) and 1,000 simulated forecasts for 2018-2041 based on Equations (4-2)-(4-5).

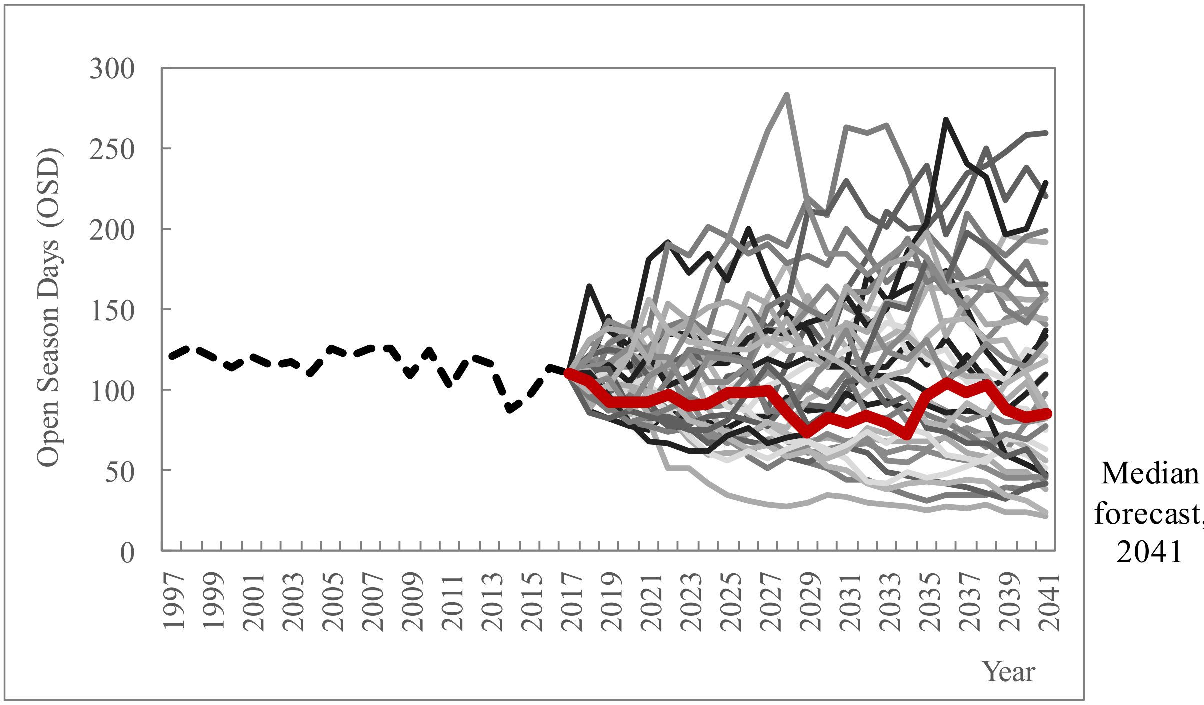

Figure 4-2 Forecasted OSD and its volatility

The 24-year OSD forecast (2018-2041) considers a construction time of three years and highway life of 20 years starting in 2019. The thick red line represents one OSD forecast whose 2041 OSD is the median of all forecasts. We chose this forecast to calculate deterministic future airlift costs and expected future airlift costs using the modified Black-Scholes model, and our NPV from the cost-benefit analysis, because it exhibits the same trend as the historical data and the Black-Scholes expected cost results end up being very close to deterministic values. In the end, any of the other forecasts could be chosen. Also, we use the historical OSD volatility (which is a representation of future OSD uncertainty) for input to our real options model (Section 4.3.4).

4.3.2 Expected Annual Barge/Airlift Costs

We want to determine the costs of airlifting freight in years with barging capacity shortfalls. Capacity shortfalls occur when the number of open season days (OSD) on the Mackenzie River is not sufficient to transport all expected freight (in addition to other logistics and operational problems, which we do not consider in this paper). As mentioned in Section 2.2, OSD is a result of both climate change impacts and human-driven decisions. Our socio-climatic problem is similar to options in a financial market that are assessed by an options approach, used for reducing investment risk (the corollary here is that we want to reduce airlift cost risks). An option is the right to buy or sell an asset at an agreed price at a specific time (Hull, 2005), and the option value is the price paid or received for purchasing or selling the options. We adopt Sturm et al.'s (2016) modified Black-Scholes option pricing formula to determine the annual expected costs of continuing barging, prior to the barging season when the decision to continue or plan other logistics must be made. In Black-Scholes, if a buyer or seller believes the real price of the underlying asset will be lower or higher, respectively, than the agreed price before the specific date, they may not "exercise" the option. This is analogous to the situation where the GNWT barging operations team decides, at a certain time between winter and the start of the barge season, to abandon barge operations altogether that summer in favor of other transport options (we also discussed this in Section 3.3). In this case, the calculated expected airlift costs due to barging shortfalls that summer, caused by uncertain OSD, is too high to tolerate.

The "additional" cost of shipping undelivered freight by airlift is determined using the modified Black-Scholes model (Sturm, Goldstein, Huntington, & Douglas, 2016):

$$P(S_t, t) = N(-d_2)Ke^{-r(T-t)} - N(-d_1)S_t$$

$$d_1 = \frac{1}{\sigma\sqrt{T-t}}\left[ln\left(\frac{S_t}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)(T-t)\right], d_2 = d_1 - \sigma\sqrt{T-t} \qquad (4\text{-}6)$$

where:

$P(S_t, t)$ is the expected airlift cost at time t;

$N(\cdot)$ is the standard normal cumulative distribution function;

T represents the time at which a decision must be made about whether to barge that year or forego it and build a road instead, t is current time, and $T - t$ is the time remaining to make the decision;

S_t is the actual OSD at t;

K is the minimum required OSD to ship all freight demand by barge;

r is the annual discount rate; and

σ is the adjusted standard deviation of the OSD.

When $S_t < K$, airlift costs are incurred. We view this problem as one where the operational team at GNWT faces the choice to barge or not barge each year, at some time before the barging season is expected to begin, such that $T - t = 6$ months. If the OSD was distributed lognormal, its standard deviation would be σ. The Mackenzie River OSD does not follow a lognormal distribution, much like the ice road OSD in Sturm et al. (2016) does not. Thus, we also adopt an adjusted value as per Sturm et al. (2016), which they found to work with reasonable accuracy. We randomly generate 10,000 numbers whose logarithm follows a normal distribution $N(\mu, \sigma)$, and using Eq. (4-9), vary f such that the mean value of OSD is equal to that of the randomly generated numbers (Sturm, Goldstein, Huntington, & Douglas, 2016):

$$\mu = ln\left(\frac{S_t}{\sqrt{1 + \frac{v}{S_t^2}}}\right) \tag{4-7}$$

$$\sigma = \sqrt{ln\left(1 + \frac{v}{S_t^2}\right)} \tag{4-8}$$

$$v = (f \cdot \sigma')^2 \tag{4-9}$$

Where σ' is the standard deviation of OSD. Using the above, we obtain the additional barging days $P(S_t, t)$ required to fully serve freight demand in the season. If N is the average volume of freight transported per day under optimal barging conditions, and P_a is the unit cost of airlifting freight, then the airlift cost incurred due to insufficient OSD $\left(C_{B,P,t}\right)$ can be determined using Equation (4-10).

$$C_{B,P,t} = P(S_t, t) \cdot N \cdot P_a \tag{4-10}$$

Figure 4-3 shows the expected airlift costs (due to insufficient OSD) versus OSD for historical (1997-2017) and forecast (2018-2041) years. The forecast airlift costs are based on the one OSD forecast chosen from the results in Section 4.3.1 – the forecast expected costs are from the Black-Scholes formula, while the deterministic forecast costs are calculated directly from the OSD forecast process.

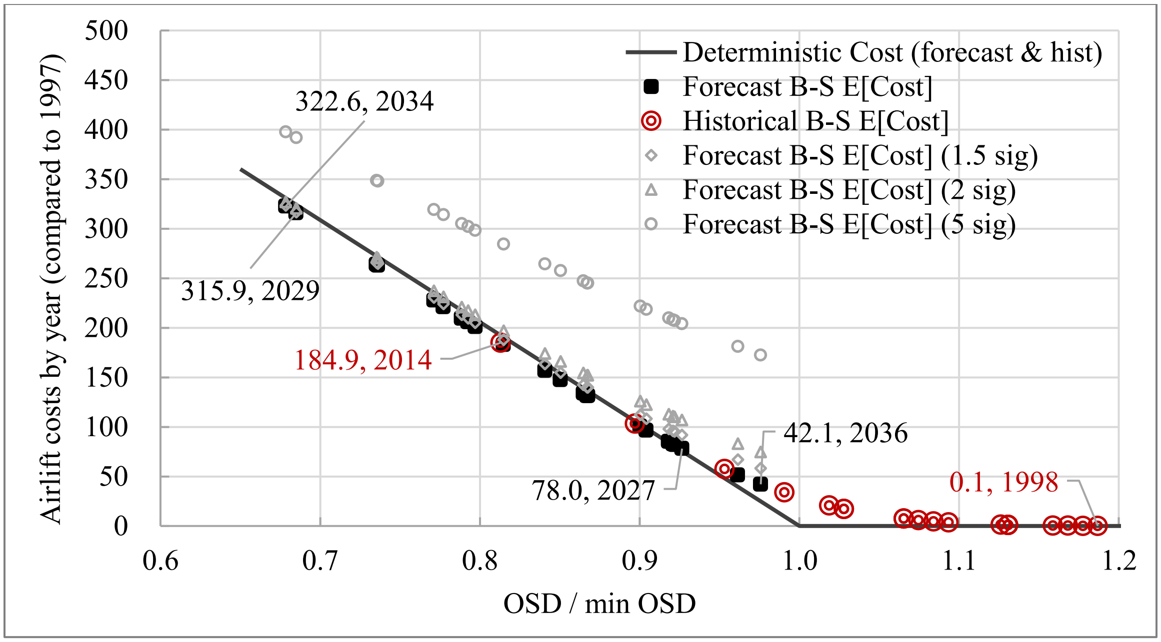

Figure 4-3 Airlift costs (normalized to 1997) versus OSD ratios for one forecast OSD time series

The x-axis is the ratio of OSD and the minimum OSD (107 days) for each year; (OSD/min OSD)>1 indicates that there is enough OSD in the season to transport everything by barge; the opposite is true when (OSD/minOSD)<1. The y-axis is the annual airlift cost normalized to that of 1997 (the first year of study).

The above figure can be used to understand the risk of barging as observed by the GNWT barge operations planner six months before barging season begins (December). Even in historical years when it came to pass that OSD/minOSD>1 and no airlift costs were incurred, the operator would have gone into the season expecting some airlift costs. According to the results of Figure 4-3, expected airlift costs increased between 1997 and 2017 at an average annual growth rate of 15.3%, peaking in 2014[3]. In fact, the largest difference in historical airlift cost ratios is 184.8, with the minimum occurring in 1998 and maximum in 2014. The risks of continuing barging increase significantly with the OSD forecast used; forecast airlift costs are significantly higher than in historic years, with a greater spread (the maximum difference in forecast airlift cost ratios is 280.5, with the minimum expected in 2036 and maximum in 2034). When OSD/minOSD)<1,

[3] 2014 was one of the worst barging seasons in recent history, due to water levels deteriorating rapidly through July and August. In fact, NTCL suspended their services in mid-August (they typically expect to run into late September or early October), leaving much freight undelivered.

the B-S forecast expected costs are close to the forecasted deterministic costs due to the forecast having a relatively low standard deviation. If the standard deviation should grow larger in the future, barge operations planners would also observe higher expected costs.

These results suggest that we could expect significantly larger freight airlift costs to deliver to the Mackenzie River communities into the future, due to growing climate uncertainty (represented as OSD volatility) causing barging capacity issues. However, the results do not suggest that the barge operator will discontinue barging operations in a given year; as long as the costs involved in setting up another barging season (barge and tug preparation, hiring of personnel, etc.) are less than the cost difference between delivering some amount of freight by barge and air (which is likely to be true), the GNWT will continue barging, albeit under more financially risky circumstances. However, the situation could encourage the GNWT to invest in all-weather highway construction.

We plot expected airlift costs for the entire set of 1,000 OSD forecasts from Section 4.3.1 in Figure 4-4. The variations in results are due to both the yearly forecasted OSD time series values as well as each time series' standard deviation.

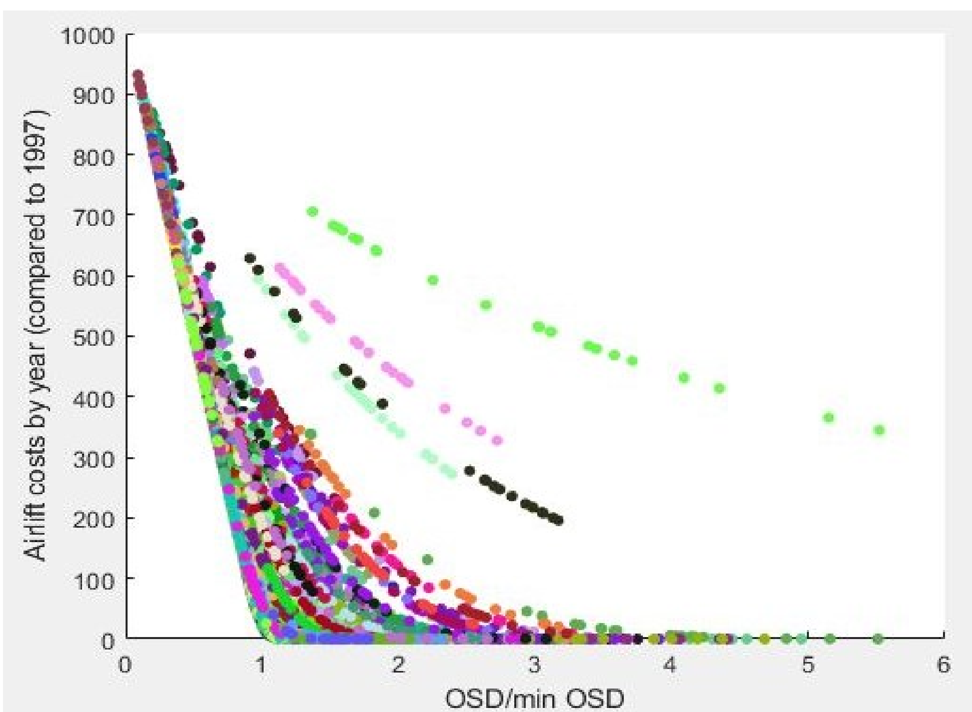

Figure 4-4 Airlift costs (normalized to 1997) versus OSD ratios for all forecast OSD time series

4.3.3 Cost-benefit Analysis

Let us say that the highway project's net present value (NPV) is the difference between the present total project benefits (B) and project investment costs (I).

$$NPV = B - I \tag{4-11}$$

It does not include valuations of uncertainty for the elements considered. A real options value (the extended NPV, or NPV^e) is composed of the project's NPV and the value of the embedded options due to uncertainty (Andoseh, Bahn, & Gu, 2014).

Let us define present project benefits B as the cost savings of building the highway (thus, using truck transport after the highway is constructed, also called the *construct* scenario) versus not building the highway (continuing use of barge and airlift, called the *do nothing* scenario):

$$B = \pi^D - \pi^C \tag{4-12}$$

Where π^D and π^C are the total present (i.e., discounted) costs of the *do nothing* and *construct* scenarios, respectively, and consist of the following:

$$\pi^D = \sum_{t=1}^{T_1+T_2} \left(X_{b,t}P_b + X_{a,t}P_a\right)(1 + b_{ob})\, e^{-rt} \tag{4-13}$$

$$\pi^C = \sum_{t=1}^{T_1} \left(X_{b,t}P_b + X_{a,t}P_a\right)(1 + b_{ob})\, e^{-rt} + \sum_{t=T_1+1}^{T_1+T_2} X_t P_h (1 + b_{oh}) e^{-rt} \tag{4-14}$$

where:

T_1, T_2 are project construction and operation periods, respectively, in years; $T_2 > T_1 > 0$;

$X_{b,t}, X_{a,t}$ are total freight delivered by barge and airlift, respectively, in year t (tonnes), where $X_{b,t} + X_{a,t} = X_t$;

P_b, P_a, P_h are prices for transporting a unit of freight by barge, airlift, and highway (truck) via all-weather highway, respectively ($/tonne);

b_{ob}, b_{oh} represent the other logistics and maintenance cost components for barging and highway trucking, respectively, and are calculated as a proportion of total costs, and

r is the annual discount rate.

In the *construct* scenario, freight is transported by barge (and airlift, when necessary) until T_1, when the all-weather highway is built. After it is built, all freight is transported via trucks. In the *do nothing* scenario, all freight continues to be delivered by barge and airlift only. The amount of freight transported by barge and airlift are taken from the results of Section 4.3.2. Given how similar the deterministic and expected forecast annual airlift costs are, we can use either for our NPV calculations. Note here that the costs and benefits included in this NPV only include those directly related to freight transport cost. There are many other cost and benefit elements that should be included in an analysis by the GNWT.

If the highway were to be constructed immediately, the NPV of the project, calculated with parameter values introduced in Section 4.2, is -\$1.08B. The enormous cost of building this highway (\$1.67B) far exceeds the costs saved in freight delivery by truck compared to the barge/airlift system (\$0.59B). This all-weather highway construction project would never be justified using such a cost-benefit analysis. In the following section, we show how the project NPV changes when we consider the option of project deferral due to environmental uncertainty.

4.3.4 Real Options Analysis

Our results suggest that climate change impacts on the Mackenzie River may result in increased future freight delivery costs to communities, due to greater use of airlifts to make up barge capacity shortfalls. Here we build on the previous sections to present a real options model that determines *if* and *when* an all-weather highway should be constructed.

4.3.4.1 Binomial lattice method

A project's value, when subject to an uncertain input, can be determined using a binomial lattice model developed by Cox et al. (1979), a simple and widely-used method for options valuation. We divide the time period between the current and options exercise time into n intervals, assuming that the project's value S can either increase or decrease within each time interval (Brandão, Dyer, & Hahn, 2005). Given its initial value at the beginning of a time interval t (where $t = 0 \dots n$), S may increase by multiplicative factor u with probability p to uS, or decrease by multiplicative factor d with probability $(1 - p)$ to dS over time step size Δt. These values are calculated as follows (Michailidis & Mattas, 2007):

$$u = e^{\theta\sqrt{\Delta t}} \tag{4-15}$$

$$d = e^{-\theta\sqrt{\Delta t}} \tag{4-16}$$

$$p = \frac{e^{r\Delta t} - d}{u - d} \tag{4-17}$$

Where r is the annual discount rate (Section 4.3.2), and θ is the OSD volatility (4.3.1).

As the number of time steps approaches infinity, it is a necessary condition that $ud = 1$, as proposed by Cox, Ross, and Rubinstein (1979). Figure 4-5 illustrates the real options calculation process using the binomial lattice method. The method requires a forward calculation, starting at $t = 0$, of all possible paths that the underlying project value S could take over time intervals $t = 0 \ldots n$. Project value S either increases by factor u or decreases by factor d for each time step as per Equations (4-15)-(4-17). Then, it requires a backwards calculation to determine options values.

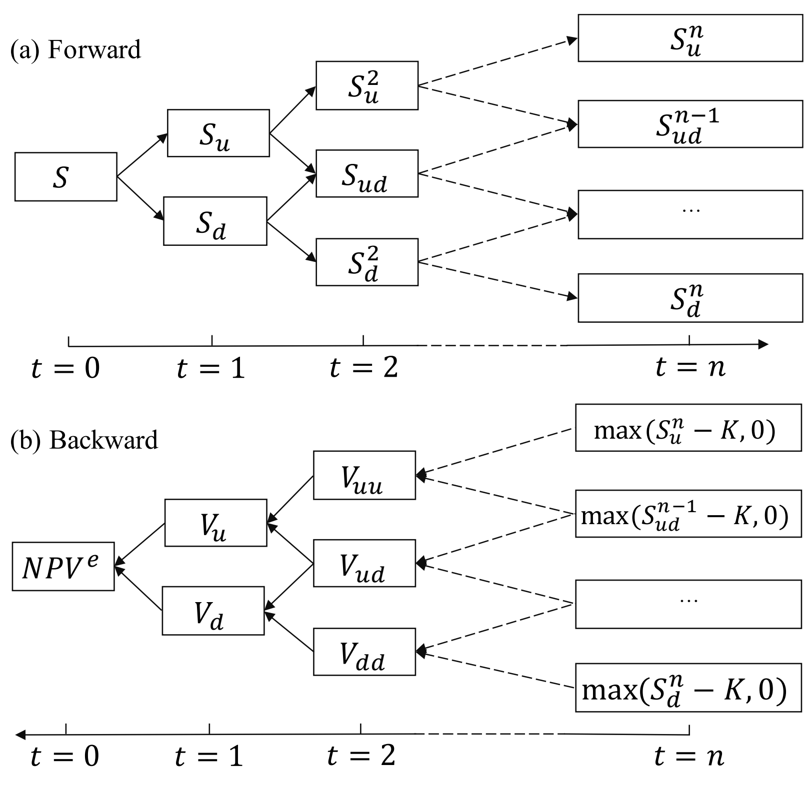

Figure 4-5 Calculating options values using the binomial lattice method

For the backward calculation, starting at final time step $t = n$, options values are calculated backwards in t for each node using Equation (4-18), until at $t = 0$ we obtain the extended project value (the NPV^e of the project).

$$V_{ud} = e^{-rt}(pV_{uud} + (1-p)V_{udd}) \tag{4-18}$$

The option value is calculated as the difference between NPV^e and NPV. The above process is done for each year we are interested in obtaining NPV^e.

Decision-makers may defer construction of the all-weather road when there is no positive net benefit from investment, accounting for the likelihood that continued reliance on barging will result in growing airlift costs. To this end, the optimal year for highway investment can be selected. In the literature, this decision to invest or not invest has been based on two criteria: the NPV^e (i.e., considering the benefits of deferral) of the project is positive (profitable), and the probability of benefit exceeding some predetermined threshold β (Yang & Blyth, 2007; Kato & Zhou, 2011). We will investigate the results of the first criteria below.

4.3.4.2 Results: Project value and investment year

Figure 4-6 shows the highway project's extended NPV (NPV^e) and options value by construction deferral year.

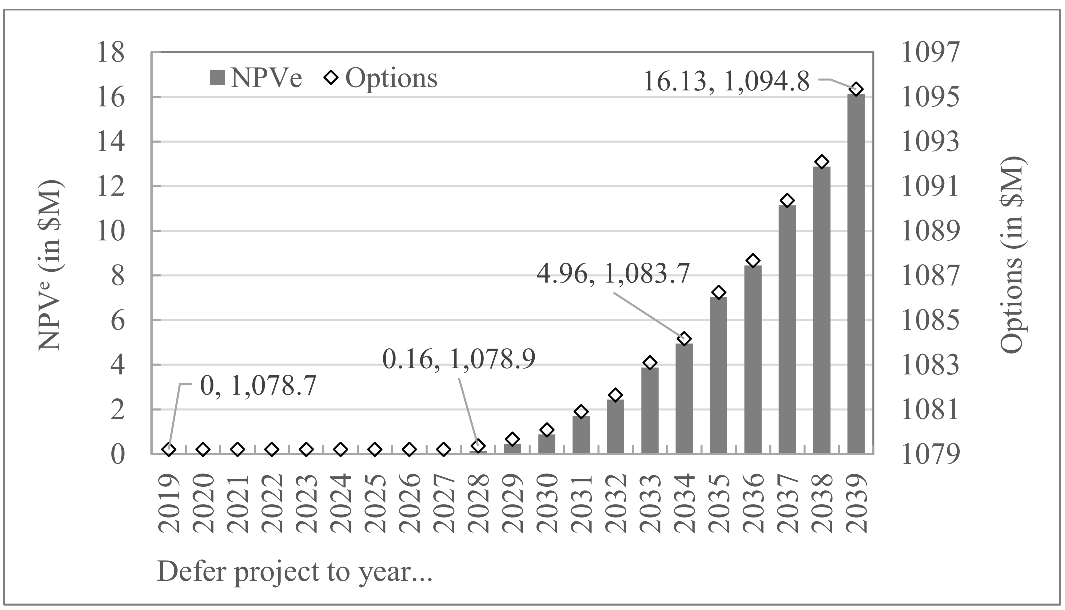

Figure 4-6 Project NPV^e and options values ($M) by construction year

The NPV^e is determined from application of the binomial lattice method in Section 4.3.4.1. The options value is calculated directly from the NPV^e and the project NPV from Section 4.3.3; as the NPV is constant, the options value simply follows the NPV^e. A positive NPV^e indicates an overall project benefit [with respect to the elements we included in the cost-benefit analysis (Section 4.3.3) and OSD uncertainty (Section 4.3.1)].

We do not observe a positive net benefit (NPV^e) from constructing this highway immediately (i.e., in 2019), which we already know from the negative project NPV reported in Section 4.3.3. Construction in 2019 does not allow us to account for OSD uncertainty through a project delay strategy. By considering the project for a future year, we are allowing the possibility of gaining benefit from the additional time we are not obligated to build the project, captured in the options value. However, even with the option to defer, we must do so by at least nine years (to 2028) to observe a positive NPV^e (\$0.16M), which grows significantly to the last deferral year considered (2039, or 20 years deferral). Continued reductions in OSD from year to year result in increasing airlift costs; by delaying construction at least nine years, we increase the probability of obtaining benefits from the all-weather highway through its 20-year lifespan. By exercising the deferral option, planners can take a "wait and see" approach, allowing for the possibility of good years to occur.

Decision makers and planners may choose any criteria for triggering an investment decision. They may decide that construction should begin the first year a positive NPV^e is observed [they may also combine this with threshold probabilities as per Section 4.3.4.4 (Kato & Zhou, 2011)]. In addition, although the NPV^e will continue to grow past 2039, we only consider deferral to that year as it grows increasingly difficult to do investment planning beyond a 20-year timeframe. Because political and economic situations can change quickly, infrastructure investment decisions should be made as soon as possible. Overall, it is clear that OSD uncertainty, combined with the option of deferring construction, significantly increases the project's value.

Finally, we emphasize that our case study results in a 9-year deferral because the enormous costs of road building outweigh the cost effects of OSD uncertainty. If road building costs were lower or uncertainty effects were greater, our results would support a decision towards shorter deferral, or even immediate construction. As we anticipate future changes to the features of climate change uncertainty itself, the managerially flexible results offered by the real options methods becomes increasingly valuable against the binary results (defer or build) of CBA methods. With results indicating that investment should be deferred for nine years (instead of, for instance, 5, or

15, or 0), decision makers should not entirely abandon the idea of the project, as results support future feasibility.

4.3.4.3 Sensitivity analysis

Considering the susceptibility of a highway project's valuation to the inputs, we conducted a sensitivity analysis of the key parameters and inputs on the NPV^e results – future freight volumes, total all-weather highway investment cost, OSD volatility, air-to-barge and truck-to-barge cost ratios, and highway lifespan. All results are based on the previous section's finding that the optimal investment strategy is to defer highway construction for nine years (to 2028).

Freight volumes, project investment cost, and OSD volatility

Figure 4-7 shows how the NPV^e of the decision to defer to 2028 is impacted by future freight volumes, project investment cost, and OSD volatility.

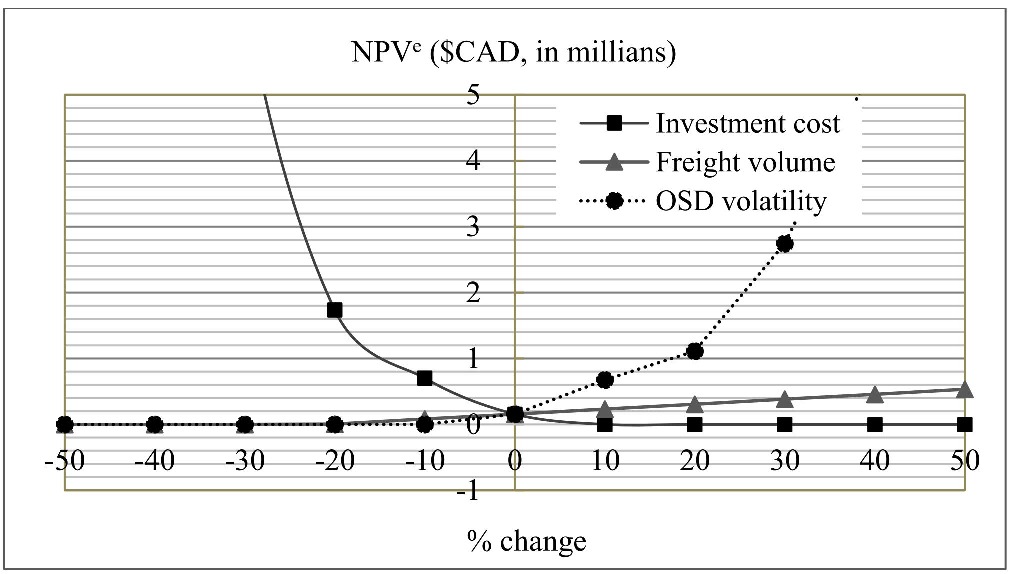

Figure 4-7 Sensitivity of freight volumes, investment cost, and OSD volatility on 9-year project deferral (2028) NPV^e

In Figure 4-7, the x-axis represents the percentage change in total freight volume, investment cost, and OSD volatility from the (benchmark) values used to generate the results in Section 4.3.4.2. The y-axis shows the percentage change in the NPV^e. Increases in freight volumes and OSD volatility result in higher 2028 NPV^e values; larger freight volumes and OSD volatility increase the probability of incurring airlift costs each year. The NPV^e appears to be more sensitive to OSD volatility than freight volumes, suggesting that with a higher OSD volatility, it is highly likely that the project deferral recommendation would be less than nine years.

The results show that the NPV^e is highly sensitive to changes in project investment costs, but this is not surprising given its enormous value ($1.67B). The NPV^e increases with decreases in investment cost, which will result in a recommendation to build earlier. For instance, a 10% lower investment cost results in a recommendation to build in 2027 (eight years deferral). When the investment cost increases more than 3%, the NPV^e falls below zero in 2028 such that deferral may be pushed to a year beyond 2028. On-going research indicates that consideration of staged road-building can yield different results.

Unit freight delivery costs

Given that this work considers a $1.67B all-weather highway investment to avoid the high costs of freight airlift, we also look at how the NPV^e of the decision to defer to 2028 is impacted by barge, airlift, and trucking unit cost parameters (Figure 4-8). Benchmark cost ratios as introduced in Section 4.2.3 and used in the NPV and NPV^e calculations are represented by the vertical lines.

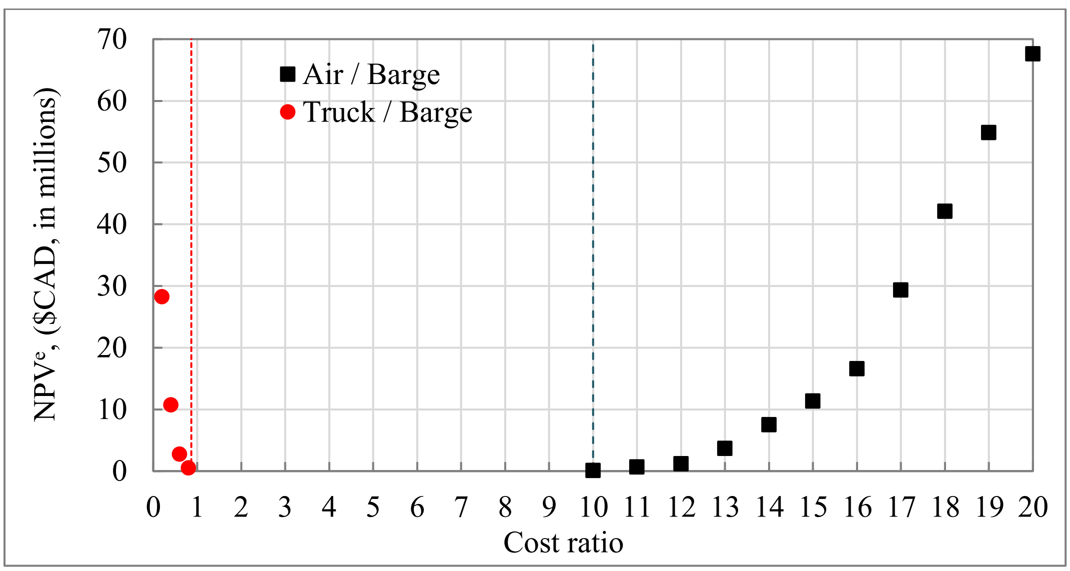

Figure 4-8 Sensitivity of cost parameters on 9-year project deferral (2028) NPV^e

Figure 4-8 shows that the NPV^e grows with the unit airlift/barge cost ratio, such that project deferral could be significantly less than the benchmark nine years. Figure 4-8 also shows that the NPV^e grows with a decreasing truck/barge cost ratio, meaning that as trucking costs decrease, the total cost of building and delivering freight via an all-weather highway also decreases, making it a more attractive option.

Project lifespan

We also investigate how the all-weather highway lifespan impacts project valuation (Table 4-2). When the lifespan is shorter than the previously assumed 20 years, the NPV^e at nine years project deferral decreases significantly, such that a positive NPV^e will not be observed unless the project is deferred even longer.

Table 4-2 Project Values at Nine Years Deferral, by Lifespan

Lifespan (years)	NPV (% change)	NPV^e (\$M)
5	-44	0
10	-26	0
15	-11	0
20	-	0.16

These results also indicate that longer highway lifespans will result in deferral recommendations shorter than the nine years recommended for a highway with a 20-year lifespan, suggesting that the GNWT should extend the all-weather highway's lifespan through major rehabilitation work.

4.3.4.4 Probability of net benefit

We can also calculate the probability of a net benefit ($NPV^e > 0$) from the investment, using a binomial decision tree calculation for the option valuation. At each node of the decision tree one can either choose to invest or defer, moving forward from the current year. The probability of the up-move s is shown in Equation (4-19), while the probability of gaining a net benefit from all-weather road investment is given by Equations (4-20) and (4-21).

$$s = \frac{1}{2}\left(1 - \frac{\eta}{\theta} - \frac{\theta}{2}\right)\sqrt{\Delta t} \tag{4-19}$$

$$p_{i,j} = \begin{cases} sp_{i,j-1} + (1-s)p_{i-1,j-1}, p_{1,1} = 1, if\ when(i,j) \neq investment \\ p_{i,j} = 0, if\ (i,j) = investment \end{cases} \tag{4-20}$$

$$P_j = 1 - \sum_{i=0}^{j} p_{i,j} \tag{4-21}$$

where

s is the probability of increase to the next node (and $1 - s$ is probability of decrease);

η is the drift of OSD (4.3.1);

θ is the historical OSD volatility (as per 4.3.1);

$p_{i,j}$ is the probability of deferring the investment at node i, when considering year j;

P_j is the probability of a net benefit by making the investment in year j, and

Δt is the time interval (one year).

Figure 4-9 shows the probabilities of obtaining a net benefit (i.e., $NPV^e > 0$) with different project investment costs.

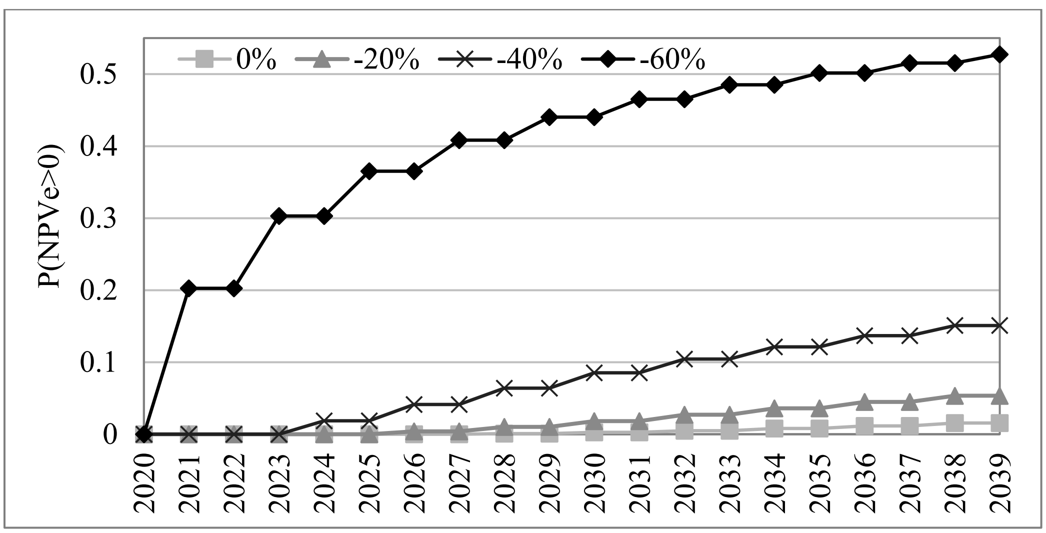

Figure 4-9 Probabilities of net benefits with reduction in investment costs

It can be observed that the probability of obtaining a net benefit under the benchmark investment costs (\$1.67B, represented by the 0% curve) is very low, remaining under 2% even with project deferral to 2039. These low values are due to the relatively low project NPV^e values calculated; probabilities are highly sensitive to NPV^e and therefore, inputs. In the literature, recommendations to construct are given despite that these probabilities are often quite low (Yang & Blyth, 2007). The probability of a positive NPV^e (and the NPV^e value itself, as shown previously) increases with decreasing investment costs. There is a significant difference between a 40% and 60% reduction.

Figure 4-10 shows the probabilities of obtaining a positive NPV^e with different OSD volatility values and freight volumes, expressed as a percentage of the benchmark values used in Section 4.3.4.2.

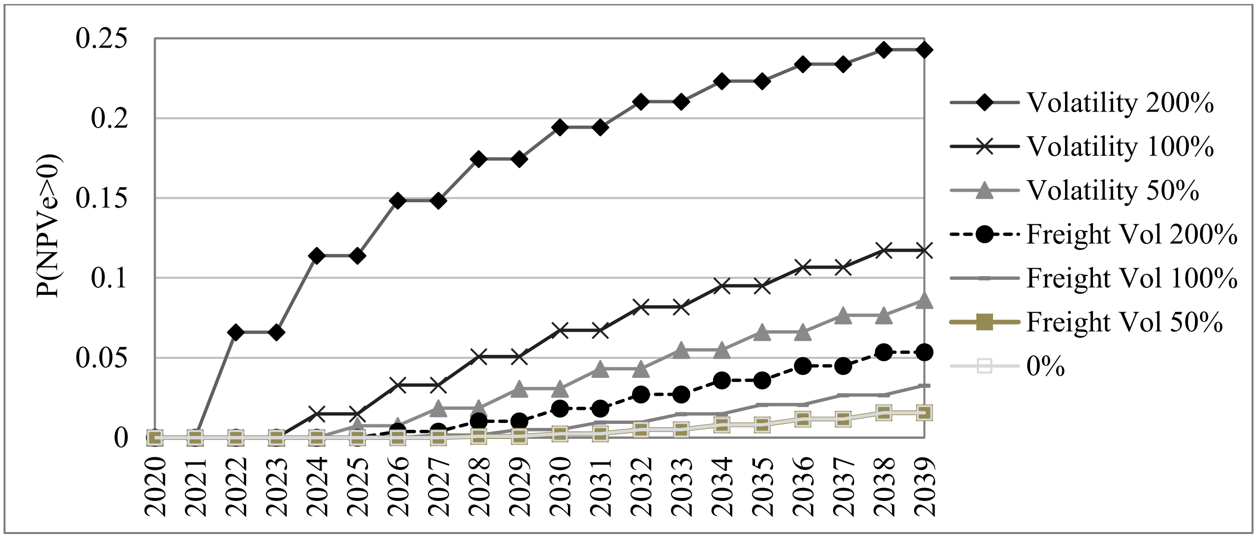

Figure 4-10 Probability of net benefit with different volatilities and freight volumes

Again, Figure 4-10 is consistent with previous results showing that greater OSD volatility and future freight volumes will increase the probability of a positive NPV^e (with corresponding increases in NPV^e and options values). However, it can also be observed that a 50% increase in freight volumes does not impact the probability of net benefit (consistent with Figure 4-7) showing freight volumes to have a relatively small impact on NPV^e. Also consistent is that per cent increases in OSD volatility have a much greater impact than equivalent per cent increases in freight volumes.

We have observed that probabilities increase with longer deferral and higher OSD volatilities, similar to NPV^e values. This is because we prefer to invest later (i.e., hold the option) to wait for a greater chance of having a higher return on investment when OSDs grow more uncertain.

4.4 Conclusions

This chapter proposes using an options approach for assessing the decisions to barge on the Mackenzie River each year, as well as to construct the all-weather Mackenzie Valley Highway, considering ever-increasing uncertainty in river barge freight delivery conditions (and thus, growing freight airlift costs) resulting from climate change impacts. The number of open season days (OSD) is a strong indicator of freight delivery capacity by barge, and shortfalls in capacity must be accommodated through costly airlift, thus OSD was chosen as our environmental proxy impacting barge delivery capacity. We modeled OSD, which is affected by climate change as well as upstream human activity, as a geometric Brownian motion. Next, we evaluate the decision to operate barge services each year using a modified Black-Scholes model. The results indicate that the decision to continue barging grew riskier (i.e., expected airlift costs have increased) from 1997-2017, and that this trend will continue for the next two decades based on the simulated future OSD time series. Finally, we use real options (the binomial lattice method) to determine how long construction of the all-weather highway should be deferred due to OSD (and therefore, airlift cost) uncertainty. As the NPV of the project is negative due to the enormous highway construction cost, the model results show that the project should be deferred at least nine years (to 2028) to achieve a positive extended NPV (NPV^e, which accounts for future uncertainties in the decision to defer investment). To emphasize that when climate uncertainty is considered, a road project's benefit-cost ratio increases significantly towards feasibility, and the option to delay allows for this future feasibility to be considered. Sensitivity analyses show that the project's NPV^e results, and therefore, project deferral time, are most heavily dependent on the all-weather highway construction cost and comparative airlift costs.

4.5 Summary

In this chapter, an options approach combining the Black-Sholes model and binominal lattice method is explored in a scenario regarding the all-weather highway construction from Wrigley to Inuvik as a whole project. This model section only considers the uncertainty from climate change. We first model river open season days as a stochastic process; as river barging is dependent on the number of open season days, which in turn is affected by climate change. Then, we evaluate the decision to continue barging and airlift service each year using a modified Black-Scholes model. Finally, we use real options to determine how long construction of the all-weather highway should be deferred.

Chapter 5. Real Options Model with Multiple Uncertainties

The Mackenzie Valley Highway, like many other massive transportation infrastructure projects, is being constructed in stages. There are many reasons to stage the Mackenzie Valley Highway from Wrigley to Inuvik: 1) The enormous cost of a single construction project, which is a major barrier given the difficulty of procuring investment funds; 2) Provide construction experience for the subsequent projects and cost control benefits (considering in Northern Canada construction is difficult due to harsh conditions); and 3) staged construction will first connect some parts of the territory, and stimulate these local economies. In fact, the GNWT has planned to build the rest of the Mackenzie Valley Highway in consecutive phases. For instance, the Inuvik–Tuktoyaktuk Highway (ITH, the northernmost section of the Mackenzie Valley Highway) opened to the public on November 15, 2017, followed by the Canyon Creek All-Season Access Road (connecting Norman Wells to Canyon Creek) in November 13, 2018 (Department of Infrastructure, GNWT, 2019; 2019a). Additionally, the GNWT has already identified several project phases, including constructions of the Great Bear River Bridge (Phase One), Wrigley to Mount Gaudet access road (Phase Two), Canyon Creek to Tulita section (Phase Three), Tulita to the Sahtu-Dehcho boundary (Phase Four), and Sahtu-Dehcho boundary to Mount Gaudet access road (Phase Five) (Government of Northwest Territories, 2019). In this chapter, the Mackenzie Valley Highway section connecting Wrigley to Inuvik (and thus, connecting the entire Mackenzie Valley Corridor by all-weather road) is divided into four segments (Figure 5-1).

As we discussed in Section 3.3, freight demand is another uncertainty which impacts the investment of transportation infrastructure. Therefore, in addition to climate change uncertainty, freight demand uncertainty is also considered in this model (scenario two, as described in Section 1.2). The discussion in Section 1.1 raises the question that if we build the four segments of the Mackenzie Valley Highway in stages, how should we structure the construction stage, and when should each of the segments be built to maximize the benefits? With this in mind, a real options model has been developed based on the Least Squares Monte Carlo (LSM) method. Herein, the process follows the following framework: Simulate the climate proxy (river open season days, OSD) and traffic demands as two stochastic processes. Then, based on the forecasts of these uncertain variables, calculate the different projects' value at different investment times and with different forecasts in a cost-benefit analysis. Finally, set up a real options model to determine the construction times of these all-weather road segments.

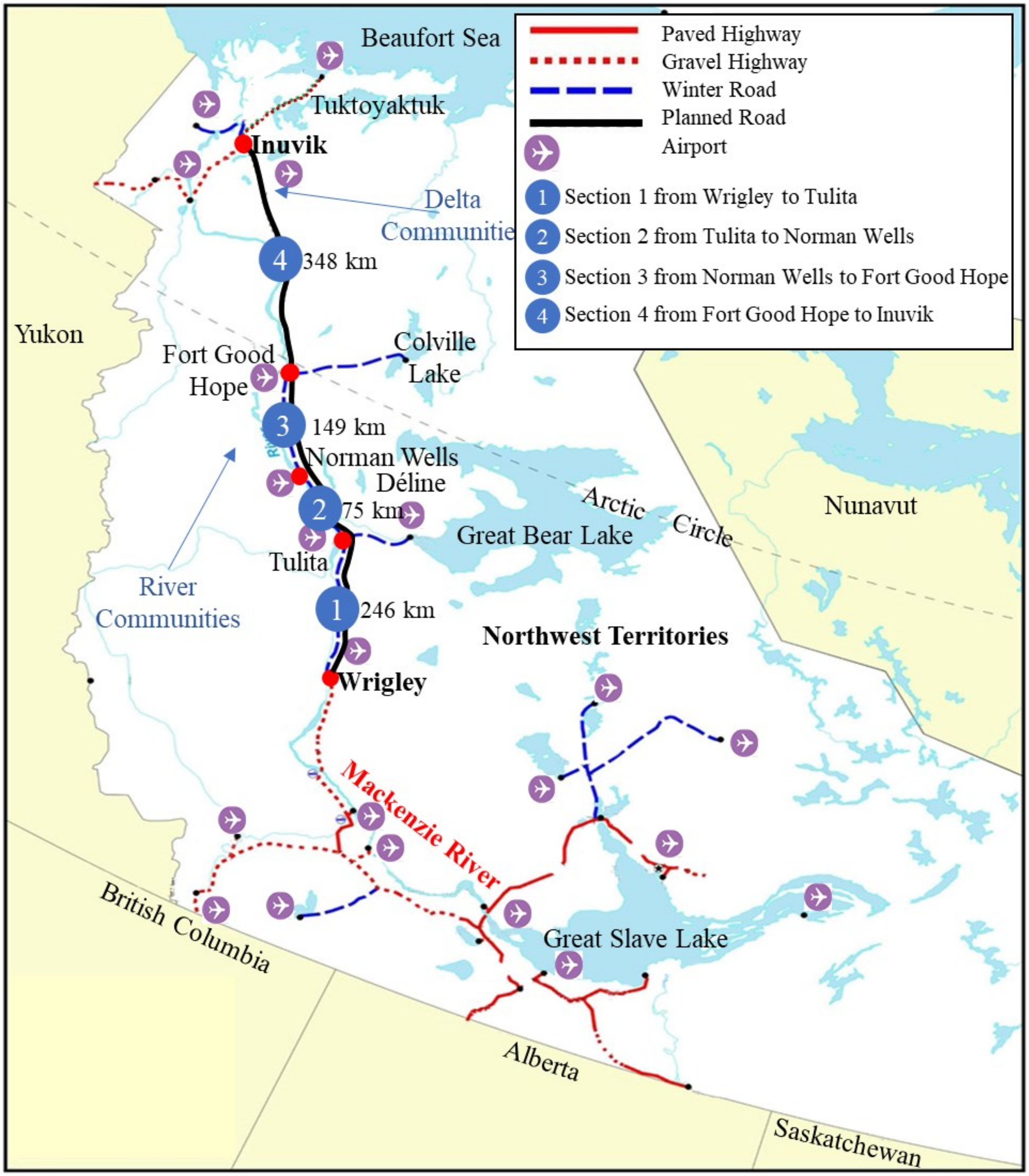

Figure 5-1 Four construction phases of the Mackenzie Valley Highway from Wrigley to Inuvik

5.1 Model Framework

In order to model the decision of when each of the four segments of the all-weather Mackenzie Valley Highway should be constructed, the Least Squares Monte Carlo (LSM) approach for real options modeling was used. The impacts of climate change and freight demand uncertainties on these all-weather roadway investment decisions have been represented in the variability of marine open season days (OSD) and historical barge freight volumes (Section 5.3.1). The modeling framework is shown in Figure 5-2.

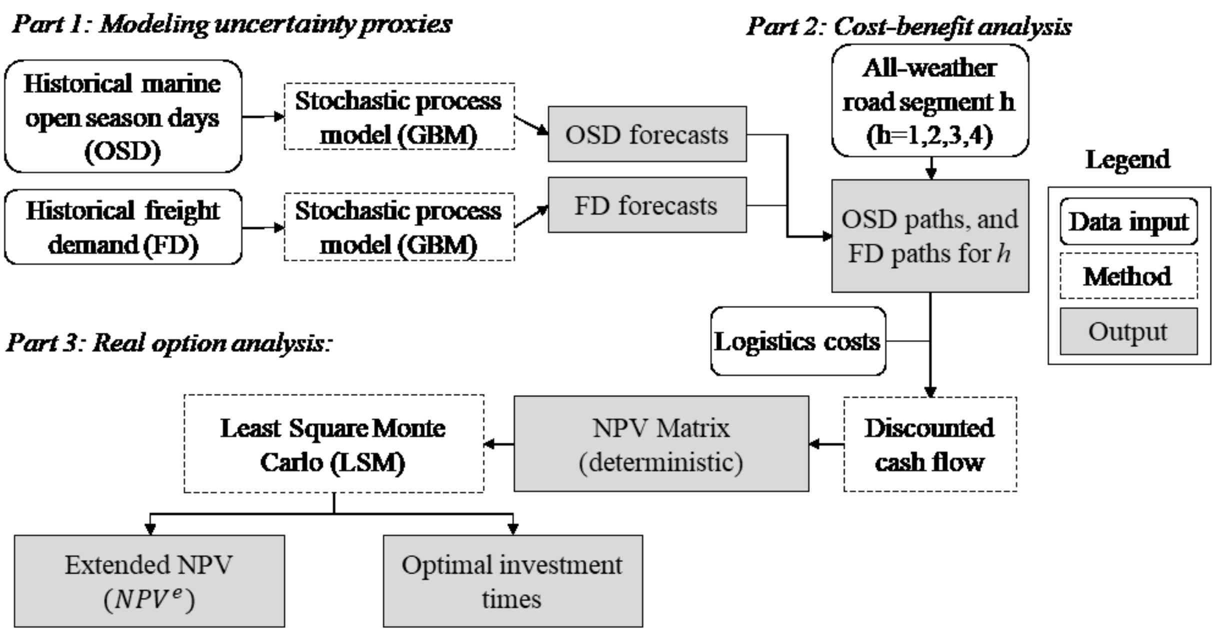

Figure 5-2 Modeling framework for scenario two

Our framework for incorporating climate change and freight demand uncertainties into transportation investment decisions includes three parts. Beginning with Part 1 (Section 5.3.1), our climate change proxy (OSD) and freight demands are modeled as stochastic processes – specifically, geometric Brownian motion (GBM), obtaining 10,000 forecast paths for both OSD and freight demands in a 40-year horizon. In Part 2 (Section 5.3.2), we identify all the paths of the project's NPVs at different investment times and with different paths of predicted OSD and freight demand. In Part 3 (Section 5.3.3), the LSM approach has been used to compute the extended NPV (NPV^e) and optimal investment time for each construction project.

5.2 Data and Modeling Inputs

In this model, some parameters remain the same as those mentioned in Section 4.2, including OSD, freight transport costs by mode, discount rate, as well as maintenance costs for both barging-airlift system and the planned all-weather highway. Thus, in this section, only new parameters are described.

5.2.1 Freight Demands

In order to model freight demand as a stochastic process (Section 5.3.1), we must calculate the volatility and drift of historical freight demands of the four Mackenzie Valley Highway segments shown in Figure 5-1. However, because historical freight demand data is not available, the following alternative approach was used. First, information (Appendix A) containing barge freight volumes and other relevant data from 2002-2014 was provided by Northern Transportation Company Limited (NTCL), the largest and oldest barge transport company operating on the Mackenzie River (until its bankruptcy in 2016) (Zheng, Kim, Du, & S.A., 2016). The key information includes the details on origin, destination, barge number, goods type, and freight volume. A more detailed description of the data was documented in a Transport Canada report by Zheng & Kim (2017). Second, we calculated the historical freight volumes originating from, delivered to, and traversing through each of the four Mackenzie River sections connecting Wrigley, Tulita, Norman Wells, Fort Good Hope, and Inuvik. We tabulated the NTCL freight volumes for each section. For simplicity, we assume that the freight transported to communities located partially along one river section was considered to have traveled the entire section. To manage the scope of our work, we exclude the potential future road use related to possible economic growth. Consistent with Section 4.2.1, we assumed that NTCL carried 80% of the total freight transported on the Mackenzie River during 2002 and 2014, by volume. Thus, the historical freight volumes delivered through the four sections on the Mackenzie River were obtained (Figure 5-3). Third, the volatility of historical freight volume data (Appendix C) was calculated (refer to Equation (4-4)). We also obtained the GDP data of all industries of the NWT during the last decade (2009-2018) (Bureau of Statistics, NWT, 2019), to further calculate the volatility of this GDP. In the uncertainty modeling section (Section 5.3.1), the volatility of historical freight demand has been computed as the average of the volatility of the historic freight volume and that of the historical GDP in the NWT. Fourth, we used the drift (calculated by Eq.(4-3)) of the GDP data of the NWT during the last decade (2009-2018) (Bureau of Statistics, NWT, 2019) to represent the changing trend of freight demands on the four segments (as specified earlier).

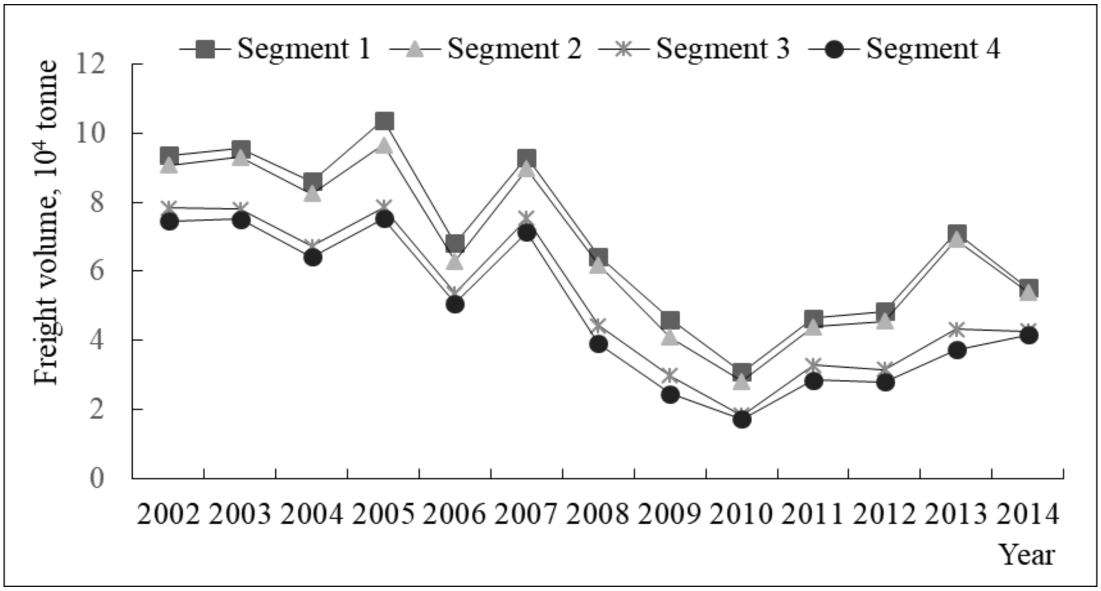

Figure 5-3 Historical freight volumes delivered through the four segments on the Mackenzie River during 2002 and 2014

Another input used in our uncertainty modeling (Section 5.3.1) is the 2018 barge freight demand. For its calculation, due to the availability of barge freight volume data from 2002-2014, we multiplied a simple growth rate derived from the NWT GDP from 2012-2018 to the barge freight volumes from 2014 to estimate the barge freight volume for 2018. The purpose was to project the freight demand, which is otherwise unavailable.

5.2.2 Investment Costs

Recall that the total investment cost of the all-weather road from Wrigley to Inuvik is reported to be \$1.67 billion (Section 4.2.5). We make the simplifying assumption that the costs to construct the four segments are proportional to the planned distances of each segment, found in the Project Description Report for Construction of the Mackenzie Valley Highway (Tetra Tech EBA, 2011).

Table **5-1** provides the specific distances and investment costs of the four segments.

Table 5-1 Investment Costs and Distances of the Four Segments

Segment	Investment Cost ($B)	Distance (Km)
1	0.50	246
2	0.15	75
3	0.30	149
4	0.71	348
Total	1.67	818

5.2.3 Plan Period

The plan period is the time within which investment decisions must be made. This parameter has to be made in accordance with the different research questions. Some literature refers to this as "time horizon" (Cortazar, Gravet, & Urzua, 2008; Chow & Regan, 2011a), and some call it "operation time span" (Sick & Gamba, 2010), while others some term it a "given observation period" (Zhu & Fan, 2011). However, there are no explanations provided on how and why they choose this number. Considering the situation that the GNWT has started to build some portions of the Mackenzie Valley Highway, and plan to continue working on the Environmental Assessment in the next step (Government of Northwest Territories, 2019), we assume the plan period of the four segments as 15 years (2019-2033).

5.2.4 The Construction Time and Highway Life

The construction time and highway life of building an all-weather highway in Northern Canada are decided by many factors, such as design, site conditions, labor, supply, weather conditions. In Chapter 4, we set the construction time and highway life for the Mackenzie Valley Highway (MVH) from Wrigley to Inuvik as 4 and 20 years. Because there are no relevant documents clarifying the construction time and life of the four road segments of the MVH from Wrigley to Inuvik, and the distances are shorter for the four segments than the whole project, to be simply, we assume the construction time and life of the four segments to be 3 and 17 years in this chapter.

5.3 Model Description

In order to determine construction times (and thus, sequencing) for the four segments of the Mackenzie Valley Highway from Wrigley to Inuvik, we developed a real options model based on the LSM method proposed by Longstaff and Schwartz (2001). There are three stages to this modeling framework: (i) modeling uncertain inputs, (ii) cost-benefit analysis, and (iii) the real options method using the LSM approach.

5.3.1 Modeling Uncertainties

We again model our uncertainty inputs as stochastic processes according to geometric Brownian motion (GBM). For climate proxy (OSD), we used the same modeling process described in Section 4.3.1. For freight demand, previous studies have used GBM to model it in real options analysis; notably, Chow and Regan (2011a) modeled vehicular traffic demand as a GBM, Zhao et al. (2004) modeled traffic demand and land price as GBM processes, and Couto et al. (2015) modeled passenger demands for a high-speed rail project as a GBM process. In line with these authors, we modeled freight demands on the four segments ($h = 1,2,3,4$) as GBM processes. The method described for GBM is the same as that in Section 4.3.1. The predicted freight demands for segment h in future year t can be obtained using Equation (5-1):

$$Q_{h,t} = Q_{h,0}e^{\left(\eta_h - \frac{1}{2}\theta_h{}^2\right)t + \theta_h dW} \tag{5-1}$$

Where η_h and θ_h are the drift and volatility of freight demand of segment h, which is represented by Equations (4-3) and (4-4). $Q_{h,0}$ is the initial freight demand of segment h. Other parameters have the same definitions as in Section 4.3.1.

5.3.2 Cost-benefit Analysis

Consider that the net present value (NPV) of segment h, when invested at time τ, is the difference between the project benefits $B_{h,\boldsymbol{\tau}}$ and project investment cost (I_h).

$$NPV_{h,\tau} = B_{h,\tau} - I_h \tag{5-2}$$

Notably, τ is the investment time (indicating delay years), $0 < \tau < T_p$. If we invest at the last year of plan period T_p, the corresponding $\tau = T_p - 1$. τ is different from the general time t, $1 \leq$

$t \leq (T_p + T_1 + T_2)$[4]. In this chapter, $T_p + T_1 + T_2 = 15 + 3 + 17 = 35$, which means t starts from 1 (2019) and goes to 35 (2053). We use Equations (4-2) and (5-1) to calculate the forecasts of OSD and freight demands between 2019 and 2053 based on t. Then, we calculate all the *NPV*s for different investment times (τ), based on the forecast results of the OSD and freight demands. To be clear, using the above forecasts, when we invest in the road in 2020 (delay 1 year), the NPV will be different from the *NPV* if we invest in the road in 2025 (delay 6 years).

Let us define present project benefits $B_{h,\tau}$ as the cost savings of building the highway (thus, replacing river barge transport with truck transport after the highway is constructed, also called the *construct* scenario (C)) versus not building the highway (continuing the use of barge and airlift, called the *do nothing* scenario (D)):

$$B_{h,\tau} = \pi_{D,h,\tau} - \pi_{C,h,\tau} \tag{5-3}$$

Where $\pi_{D,h,\tau}$ and $\pi_{C,h,\tau}$ are the total present (i.e., discounted) costs of the *do nothing* and *construct* scenarios respectively, and consist of the following:

$$\pi_{D,h,\tau} = \sum_{t=1}^{\tau+T_1+T_2} (Q_{b,h,t}P_b + Q_{a,h,t}P_a)(1 + b_{ob})e^{-rt} \tag{5-4}$$

$$\pi_{C,h,\tau} = \sum_{t=1}^{\tau+T_1} \big(Q_{b,h,t}P_b + Q_{a,h,t}P_a\big)(1 + b_{ob})e^{-rt} + \sum_{t=\tau+T_1+1}^{\tau+T_1+T_2} Q_t P_h (1 + b_{oh})e^{-rt} \tag{5-5}$$

Where $Q_{b,h,t}, Q_{a,h,t}$ are the total freight delivered by barge and airlift, respectively, in year t (tonnes), where $Q_{b,h,t} + Q_{a,h,t} = Q_{h,t}$. For determining $Q_{a,h,t}$ and $Q_{b,h,t}$ when using the current barge-airlift service, we set the following standards:

(1) If the predicted freight demand $Q_{h,t}$ is greater than barging capacity ($S_t N$) at year t, the remaining freight exceeding the barging capacity will be transported by airlift, i.e.,

$$If\ Q_{h,t} \geq S_t N, Q_{a,h,t} = Q_{h,t} - S_t N$$

(2) If the predicted freight demand $Q_{h,t}$ is less than barging capacity ($S_t N$) at year t, all the freight will be transported by barge, i.e.,

---

[4] T_1 and T_2 are the construction time and lifespan respectively.

$$If\ Q_{h,t} < S_t N, Q_{a,h,t} = 0$$

The remaining parameters have been introduced in Equations (4-10), (4-11), (5-2), and (5-3). For each Monte Carlo simulation (represented by ω, $0 < \omega \leq W$, where W is the total simulation times) in Section 5.3.1, we can calculate a path of NPV of segment h with different investment time τ ($\tau = 1,2,\dots,T_p - 1$), shown as below,

$$\boldsymbol{NPV_{h,\omega}} = [NPV_{h,1,\omega}, NPV_{h,2,\omega}, \dots, NPV_{h,T_p-1,\omega}] \tag{5-6}$$

Following is the calculation process:

(1) For each Monte Carlo simulation (ω), we can get a predicted path for OSD ($\mathrm{S_t}$), and a predicted path of freight demand of segment h ($Q_{h,t}$).

(2) Using Equations (5-2)-(5-5), we can calculate the *NPV* of segment h when invested at time $\tau = 1$ (i.e., $NPV_{h,1}$).

(3) Increasing τ from 1 to $T_p - 1$, we can get a path of the NPV of segment h from simulation ω, and denote the results as $\boldsymbol{NPV_{h,\omega}}$ (Equation (5-6)).

The process by which the equations are used will be shown later.

5.3.3 Real Options Analysis

In this section, we build on the previous sections to present a real options model that determines when to commence with the construction of the four Mackenzie Valley Highway segments from Wrigley to Inuvik. To solve this question, we calculate the final options value (or say, the NPV^e) of each segment, denoted by ϕ_h. The Least Squares Monte Carlo (LSM) method proposed by Longstaff and Schwartz (2001) is widely used for obtaining the final option value ϕ_h, especially when considering multiple uncertainties in the project value (Chow & Regan, 2011a). To apply the technique, we first need to (1) generate predicted paths of uncertainty variables ($\mathrm{S_t}$ and $Q_{h,t}$) for each Monte Carlo simulation (ω) in order to calculate the value of segment h ($NPV_{h,\omega}$) (this step has been done in Sections 5.3.1 and 5.3.2). Then (2) we calculate the final option value based on the ω th simulation, represented by $\phi_{h,\omega}$; (3) we discount these values ($\phi_{h,\omega}$) to today, and take the average. This is the final option value of segment h, ϕ_h. We give a detailed description of the calculation process in three steps.

Step (1): After running Equations (4-2) and (5-1) each time (ω), we get a predicted path for OSD ($\mathrm{S_t}$), and a predicted path for the freight demand of segment h ($Q_{h,t}$). Then, changing τ from 1 to

$T - 1$ and using Equations (5-2)-(5-5), we calculated a path for the NPV of segment h based on the above predicted results, denoted by $NPV_{h,\omega}$ (Equation (5-6)).

Step (2): The final option value of segment h based on the ω th simulation ($\phi_{h,\omega}$) has been obtained by the following: Supposing the segment h is invested at time τ, if the segment value $NPV_{h,\tau,\omega}$is greater than 0, then we should further compare $NPV_{h,\tau,\omega}$ with the expected return of delay investment $\varphi_{h,\tau+1,\omega}$. If $NPV_{h,\tau,\omega} \geq \varphi_{h,\tau+1,\omega}$, the investment for the segment should be made at τ, and the optimal investment time is $\tau_{\omega} = \tau$, otherwise the project would be delayed and be considered in the next time point $\tau + 1$. This problem is represented as per Chow and Regan (2011):

$$\phi_{h,\tau,\omega} = max\{NPV_{h,\tau,\omega}, \varphi_{h,\tau+1,\omega}\} = max\{NPV_{h,\tau,\omega}, e^{-r}E[\phi_{h,\tau+1,\omega}]\} \quad (5\text{-}7)$$

This requires a backward calculation to determine the final option values. Starting from the last year in the plan period T (corresponding to invest at time $\tau = T_p - 1$), the expected return of delay investment of segment h is 0 (since this is the last year in the plan period, an investor must decide whether to invest or not). Then if the $NPV_{h,\tau=T-1,\omega}$ of segment h is greater than 0, then we should consider constructing segment h immediately, and the optimal investment time is $\tau_{\omega} = T_p - 1$. Continuing and backward, at the $T_p - 1$ year (corresponding to invest at time $\tau = T_p - 2$), to determine if we should invest, we have to compare $NPV_{h,\tau=T-2,\omega}$and$e^{-r}E[\phi_{h,\tau+1,\omega}]$. In case, $NPV_{h,\tau=T-2,\omega} \geq e^{-r}E[\phi_{h,\tau+1,\omega}]$, we should invest it at $T_p - 2$. Then, τ_{ω} is updated to $T_p - 2$. Continuing the calculation until $\tau = 1$, we can obtain the optimal investment time τ_{ω} based on the current simulation ω. Then, the final option value corresponding to τ_{ω} can be calculated using Equation (5-8).

$$\phi_{h,\omega} = max\{NPV_{h,\tau_{\omega},\omega}, \varphi_{h,\tau_{\omega}+1,\omega}\} = max\{NPV_{h,\tau_{\omega},\omega}, e^{-r}E[\phi_{h,\tau_{\omega}+1,\omega}]\} \quad (5\text{-}8)$$

Here, the least squares regression method is used to calculate $E[\phi_{h,\tau+1,\omega}]$. We take the immediate returns of segment h when we invest at τ (i.e., $NPV_{h,\tau,\omega}$) based on all simulations ($\omega = 1,2, \dots, K$) as the X value, and take the final option value of delaying the investment at time

$\tau + 1$ (i.e., $\phi_{h,\tau+1,\omega}$) based on all simulations as the Y value. Through applying the least squares regression, we can find the regression coefficients. Finally, $E[\phi_{h,\tau+1,\omega}]$is the result of the fitted model using each X. To estimate $E[\phi_{h,\tau+1,\omega}]$ using least squares regression, many polynomial forms have been used, such as the Hermite polynomial (Chow & Regan, 2011a), Laguerre polynomial (Gustafsson, 2015), and the weighted Laguerre polynomial (Longstaff & Schwartz, 2001). It has been proven that the options results achieved by using different polynomials for a given degree are similar (Moreno & Navas, 2003). For our model, we chose weighted Laguerre polynomials which was used in the original LSM approach proposed by Longstaff & Schwartz (2001):

$$L_0(X) = exp\,(-X/2) \tag{5-9}$$

$$L_1(X) = exp\,(-X/2)(1 - X) \tag{5-10}$$

$$L_2(X) = \frac{1}{2} exp\,(-X/2)(2 - 4X + X^2) \tag{5-11}$$

$$\vdots$$

$$L_s(X) = exp\,(-X/2)\frac{e^X}{s!}\frac{d^s}{dX^s}(X^s e^{-X}) \tag{5-12}$$

Given a set of realized paths of $NPV_{h,\omega}$ the value $E[\phi_{h,\tau+1,\omega}]$ can be estimated by Equation (5-13),

$$E[\phi_{h,\tau+1,\omega}] = \sum_{j=0}^{q-1} \beta_j L_j(NPV_{h,\tau,\omega}) \tag{5-13}$$

Where L_j are the first q Laguerre polynomials and β_j are the estimated coefficients using least squares regression. The choice of Laguerre polynomials is essential for the estimation of $E[\phi_{h,\tau+1,\omega}]$. As discussed in the reference (Longstaff & Schwartz, 2001), we only need a few

Laguerre polynomials to closely approximate the continuation value, and thus, used the first three.

Step (3): After solving the optimal investment time τ_ω and the corresponding project's final option value for each simulation ω by applying the above method and proceeding backward from last year of the plan period T_p, the final options value of the segment h is estimated by Equation (5-14),

$$\phi_h = \frac{1}{W} = \sum_{\omega=1}^{W} e^{-r\tau_\omega}\phi_{h,\omega} \tag{5-14}$$

The LSM method does not provide the optimal investment time from the theory (Notably, the above calculated τ_ω is the optimal investment time based on each simulation ω, which is not the final optimal investment time for segment h). The final optimal investment time for segment h (or say, delay years, denoted by τ_h) is the year showing up with the greatest frequency among all optimal investment times (τ_ω) solved above, as shown in Equation (5-15).

$$\tau_h = maxfrequency(\tau_\omega = 1, \tau_\omega = 2, \dots, \tau_\omega = T_p - 1) \tag{5-15}$$

5.4 Results

We present numerical results for the extended project value (NPV^e) of each segment and optimal investment times. We have also presented the results of a sensitivity analysis of the key parameters and inputs on the NPV^e results – OSD volatility, freight demands volatility, and investment costs of four segments.

5.4.1 Project Value and Investment Year

We set $K = 10{,}000$ simulation paths for each uncertainty variable (i.e., OSD, freight demands for four roads). Then, we obtained the following results after running the model (Section 5.3). Table 5-2 shows extended project net present values (NPV^e) and optimal investment times (delay years) for the four segments. Given the inputs (Section 5.2), the result shows that Segment 2 has the largest value ($819.32M) with an optimal investment time of a one-year delay, followed by Segment 1 (six-year delay), Segment 3 (13-year delay), and Segment 4 (14-year delay).

Table 5-2 Extended projects' value (NPV^e) and optimal investment time

Segment	NPV^e (Million \$)	Delay years
1	656.8	6
2	819.32	1
3	429.65	13
4	322.52	14

As mentioned earlier, the obtained result is consistent with the current construction plan for the Mackenzie Valley Highway. Specifically, Segment 1 and 2 in this chapter are exactly the same sections described in the construction plan for the GNWT, and they plan to build Segment 2 first followed by Segment 1 (Department of Infrastructure, GNWT, 2019). Segment 3 and 4 are not currently mentioned by the GNWT. We suppose this is not a coincidence. From our model, considering the input data, the key reason for building Segment 2 first might be because its investment cost is relatively small compared to that of other segments (the ratio of investment cost among Segment 1, 2, 3 and 4 is 246:75:149:348, which is same as their distance ratio). The cost of investment is a major barrier to the construction of the Mackenzie Valley Highway. The current stipulated funds for the Mackenzie Valley Highway only include a \$140 million investment (for Great Bear River Bridge, Mount Gaudet Access Road and Mackenzie Valley Highway Environmental Assessment and Engineering [Wrigley to Norman Wells]) and about another \$20 million investment (for Oscar Creek Bridge and Hodgson Creek Bridge) (CBC, 2016; Department of Infrastructure, GNWT, 2019). More seriously, a lack of funding for the Mackenzie Valley Highway was announced in the federal latest budget (CBC, 2019). Therefore, under the current funding situation, constructing Segment 2 first can earlier connect two (Tulita and Norman Wells) of the five major communities (another three are Wrigley, Fort Good Hope, and Inuvik) along the Mackenzie Valley Highway from Wrigley to Inuvik. It is noteworthy to mention that investment cost is not the only parameter affecting the construction sequence in our model. Although the investment cost of Segment 1 is greater than that of Segment 3, our results suggest Segment 1 should be built ahead of Segment 3. Additionally, other parameters such as volatilities of uncertainty variables (i.e., OSD, freight demands) also play key roles in the results of our model. In addition, if the results suggest the same investment time for different roads, we can refer to the order of the projects' value to determine the construction sequence (greater value, earlier investment).

The LSM method used in this chapter relies on Monte Carlo simulation, and as such, the results vary from run to run. Previous research has proven the projects' value will converge to the true value (Stentoft, 2004), and, we can also test it from our results (Figure 5-4), which show the projects' value (NPV^e) falls in a small range (We run our model 50 times, getting 50 NPV^e for each segment.

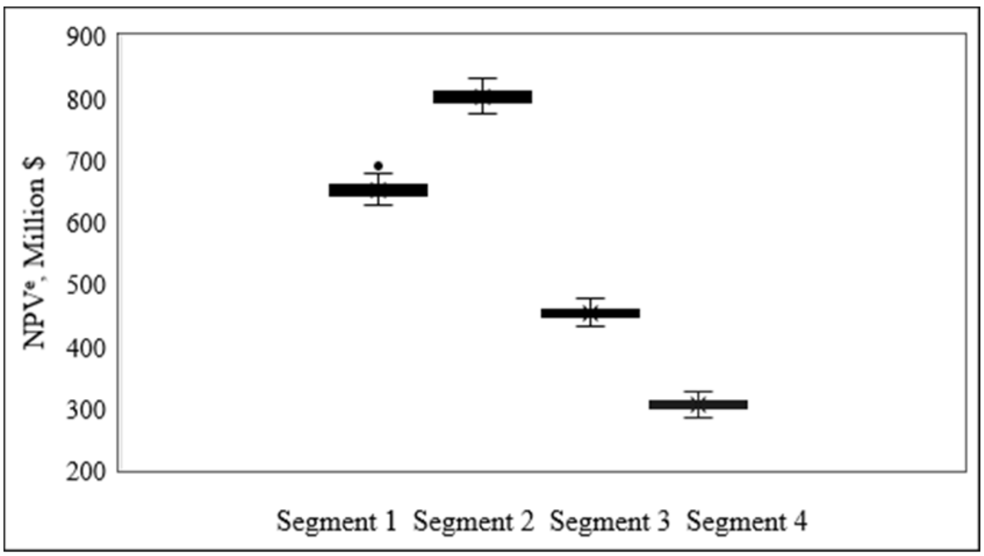

Figure 5-4 Convergence of the results

5.4.2 Sensitivity Analysis

Sensitivity analyses were performed to further explore the impacts of change in OSD volatility on project values, as shown in Figure 5-5. With the increase of OSD volatility, all projects' value will grow gradually, despite fluctuation. The reason is that with greater OSD volatility, the value of deferring investing increases, which in turn provides the decision-makers with more time to decide what to do, in order to maximize their project value. However, since the LSM method can only provide a solution close to the actual project value (due to Monte Carlo simulation), we may get a value less than the actual. This can be attributed to the fluctuating trends for different segments, as shown in Figure 5-5.

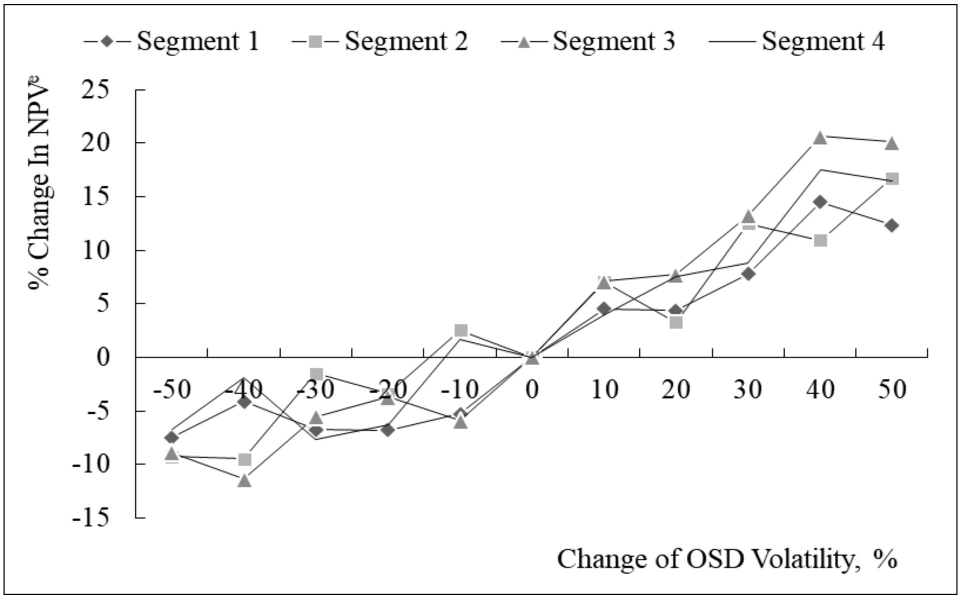

Figure 5-5 Sensitivity of volatility of OSD

Table 5-3 illustrates the change of optimal delay years with the change of OSD volatility. We can assess that Segment 2 should receive the first construction priority in all situations, with a delay of one year, while Segment 4 should be delayed by 14 years and given least priority in all situations except for that with a 40% change rate. The key reason for driving Segment 2 and 4 to be built first and last is their investment costs: Segment 2 has the least investment cost ($153M), while Segment 4 has the greatest ($710M). Even though the decreasing volatility of OSD means lower freight cost using the current barge-airlift service, which, in turn, decreases the project's benefit, the overall project benefit can still exceed its relatively low investment cost for Segment 2. This results in the earlier construction of Segment 2. However, the opposite situation is true for Segment 4. Even though increasing volatility for OSD means more freight costs using the current barge-airlift service, which, in turn, increases the project's benefit, the overall project benefits are still far less than the high investment cost for Segment 4. This results in the later construction of Segment 4. In addition, investment times for Segment 1 and 3 greatly fluctuate based on our results. Different from the previously discussed reason for building Segment 2 and 4, this is because the volatility of both uncertainty variables (i.e., OSD and freight demands) and investment costs play keys roles in the final results. The impacts of freight demand uncertainty are not always less than the impact of investment costs. Thus, the optimal investment time fluctuates with different volatilities.

Table 5-3 Optimal Delay Years with Different Volatility of OSD

Change rate, %	Segment 1	Segment 2	Segment 3	Segment 4
-50	5	2	13	14
-40	9	1	9	13
-30	9	1	14	14
-20	5	1	11	14
-10	3	1	10	14
0	6	1	13	14
10	7	1	14	14
20	10	1	8	13
30	10	1	7	14
40	6	1	14	13
50	11	1	10	12

The sensitivities of the volatility of freight demands are analyzed, as shown in Figure 5-6. When increasing the volatilities of freight demands proportionally, all projects' value grow gradually, with a greater rate than that with changed OSD volatility. Similar to the analysis for Figure 5-5, freight demands with greater volatility provide the decision maker with more time to make their decision, simultaneously increasing the project's value.

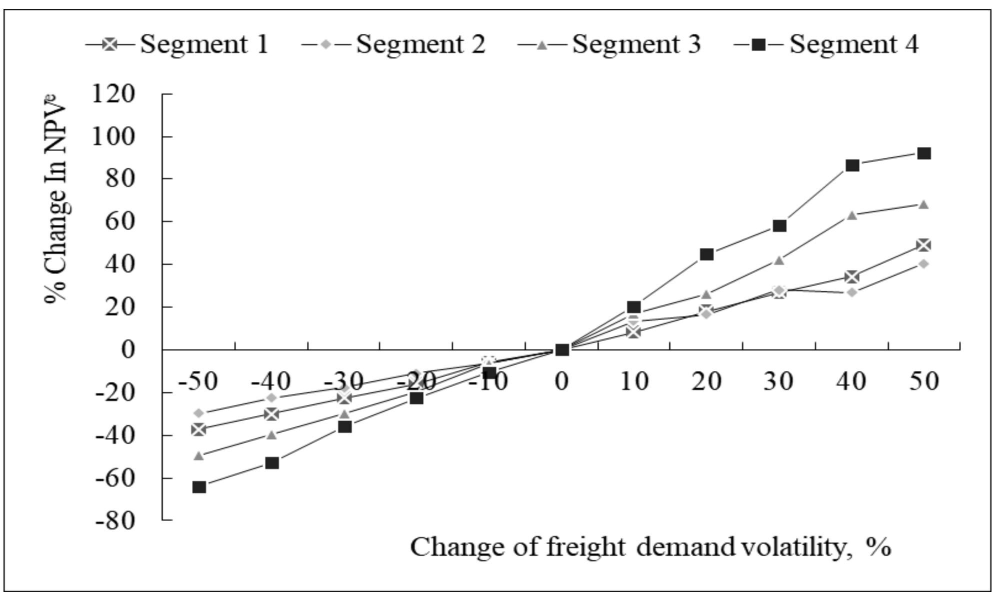

Figure 5-6 Sensitivity of volatility of freight demands

Table 5-4 illustrates the change of optimal delay years with the change of freight demand volatility. We can see that most segments should be delayed by 14 years when freight demand volatilities are reduced while Segment 1 and 2 should be built in the next year (with a one-year delay) except for result in the 20% change rate when the volatilities are increased, and the investment time for Segment 3 and 4 are also much earlier. Notably, these results are similar to the results in Figure 5-6. That is to say, increased volatility in freight demand will not only increase the project's value but also simultaneously reduce the investment waiting time.

Table 5-4 Optimal Delay Years with Different Volatilities of Freight Demands

Change rate, %	Segment 1	Segment 2	Segment 3	Segment 4
-50	14	14	14	14
-40	14	14	14	14
-30	14	14	14	14
-20	14	1	14	14
-10	12	1	14	14
0	6	1	13	14
10	1	1	10	10
20	2	1	3	7
30	1	1	3	9
40	1	1	1	5
50	1	1	2	4

As evident from the discussion about Table 5-2, the cost of investment is a major barrier to the construction of the entire Mackenzie Valley Highway. We conduct a sensitivity analysis of the investment costs of the four road segments on their project value (Figure 5-7). Most results indicate that a decrease in investment costs will lead to an increase in NPV^e. However, some outliers fall in the red background area, indicating that increasing investment costs will increase the projects' value (NPV^e). This is clearly incorrect, and the reason is that the NPV^e from LSM method can only be close to the true value. When we use the Monte Carlo method to simulate uncertainty variables, different results are obtained with each simulation, which further affect the projects' values. Two possible ways to solve this problem are to increase the simulation times and/or to increase the number of Laguerre polynomials at the expense of computational efficiency.

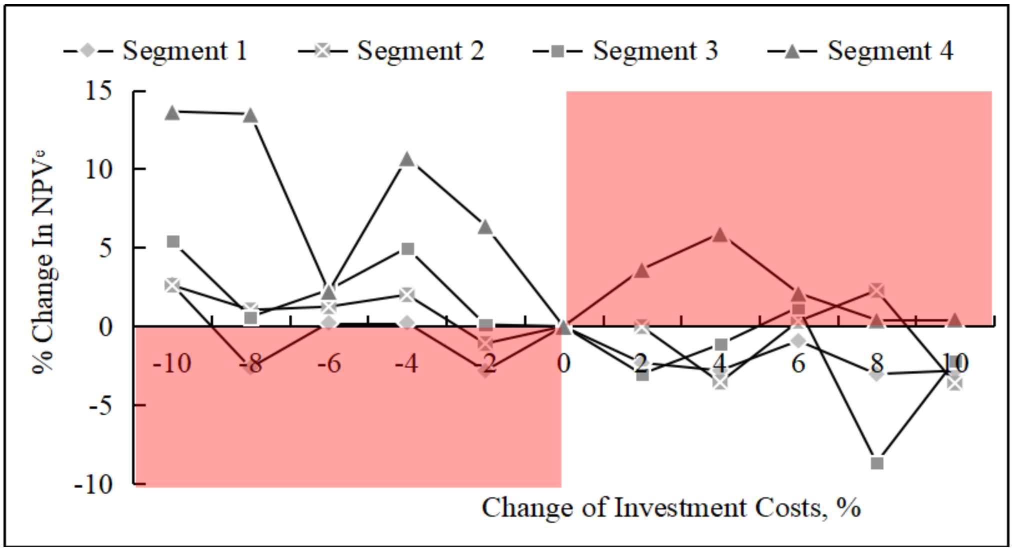

Figure 5-7 Sensitivity of investment costs

Table 5-5 illustrates the change of optimal delay years with the change in investment costs. The results indicate that Segment 2 should be invested first with a one-year delay in all situations, while Segment 4 should be delayed to the last year (i.e., 14-year delay) in most cases. The main reasons for this are: 1) Segment 2 has the least investment cost ($153M), while Segment 4 has the greatest ($710M). This implies that even with the extreme ±10% change rate, their relative value will not change significantly. 2) Segment 2 has the second greatest model input value (initial freight demand, 58,395 tonnes) while Segment 4 has the least (45,016 tonnes). This means their predicted freights demands are relatively high and low, respectively. Combined with the prediction results of OSD, the benefits of building Segment 2 will easily outweigh the cost, but it is opposite for Segment 4. Except that when the change rate is 10%, investment time for Segment 1 varies from a four-year delay to a nine-year delay, while that for Segment 3 varies from 9-year delay to 14-year delay. This means Segment 1 should be built before Segment 3. From Table 5-4, we find the investment sequence of the four segments in most cases are same as the results in Table 5-2 (i.e., Segment 2, 1, 3, and 4). That is to say, synchronous changes in investment costs will not influence the optimal investment sequence.

Table 5-5 Optimal Delay Years with Different Investment Costs

Change rate, %	Segment 1	Segment 2	Segment 3	Segment 4
-10	4	1	12	13
-8	8	1	9	14
-6	6	1	14	13
-4	7	1	10	14
-2	7	1	11	14
0	6	1	13	14
2	9	1	12	14
4	4	1	13	14
6	6	1	9	14
8	8	1	12	14
10	12	1	7	14

5.5 Summary

This chapter describes a real options model for determining construction sequencing and optimal investment times for the four all-weather road segments from Wrigley to Inuvik. An LSM method is used for model building. Based on the data and modeling assumptions, our results suggest that Segment 2 should be built first with a one-year delay, followed by Segment 1 with a six-year delay, while from our results, the suggested build times for Segment 3 and 4 are toward the end of the plan. Furthermore, in this chapter, we conduct a sensitivity analysis of key variables in the projects' value.

Chapter 6. Methodological Framework Overview

Based on the methodologies explored in Chapter 4 and Chapter 5, we provide an overview of the methodological framework developed to support investment decision-making for transportation infrastructure, particular in geographies that face challenges due to uncertainties from climate change and other sources. The framework generally includes three parts (Figure 6-1): modeling uncertainties, cost-benefit analysis and real options analysis. Under each part, different methods can be used according to specific problems. The following sections provide a detailed illustration about each part, including specific inputs and methods.

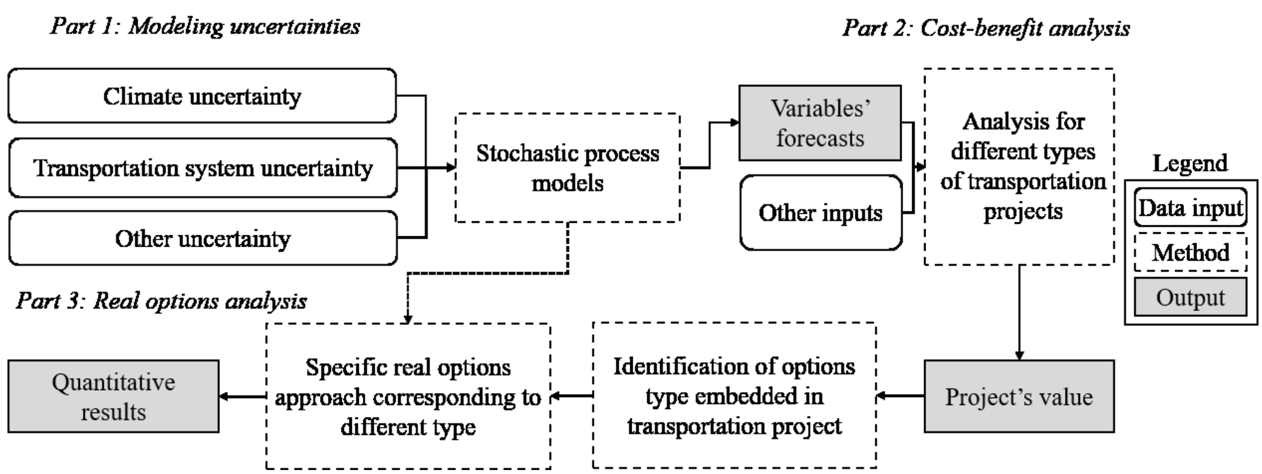

Figure 6-1 General methodological framework

6.1 Part One: Modeling Uncertainties

In this part, uncertainty parameters relating to transportation infrastructure investment should be identified first. Three sources of uncertainties are considered, including climate change, transportation system, and others. Not only OSD but also other indicators like temperature, water level, rainfall intensity, and precipitation can be used to represent climate change uncertainty (Gersonius, Ashley, Pathirana, & Zevenbergen, 2013; Chang, Wang, & Wang, 2015; Truong, Stefan, & Mathew, 2018). Freight demand uncertainty, considered in Chapter 5, is included in the transportation system uncertainty that also contains transportation unit cost, highway service quality, etc. (Zhao, Sundararajan, & Tseng, 2004). Except for the previous two, many other uncertainties may also play an important role in the evaluation model, i.e., land price (Zhao, Sundararajan, & Tseng, 2004). Then, based on the features of different uncertainty parameters, such as distribution, trend, and variance, we can use different stochastic methods to forecast them. Aside from GBM, some other methods can be chosen such as the multiplicative model (Zhao & Tseng, 2003). Finally, the forecasted results will be used in the following parts.

6.2 Part Two: Cost-benefit Analysis

In this part, based on the results of part one (Section 6.1), a cost-benefit analysis of the planned transportation infrastructure project can be made to take uncertainties into account to find an expected project value. In fact, the cost-benefit analysis when making a transportation infrastructure-building decision not only contains the direct costs and operation revenue, but also includes many external and, often, intangible considerations. In Northern Canada, these significant considerations include: cheaper, more reliable passenger travel and thus, more opportunities for employment and tourism; medical transport, which provides more opportunities and cost-sharing for natural resource exploration and development (Mackenzie Aboriginal Corporation, 2007); Arctic sovereignty; and climate change impacts. Indigenous communities are usually highly in favor of these infrastructures. These elements are considered qualitatively and used heavily politically to support infrastructure-building. Given the difficulty of estimating dollars to these opportunities, one can only choose to demonstrate the model on direct costs and operation revenue alone. Future interdisciplinary work should consider these cost elements. Another reason why one can choose to focus on direct costs and operation revenue is that these elements, much like the considerations previously listed, are not quantitatively considered in large-scale infrastructure decisions.

The direct costs can be divided into construction cost (material cost, labour cost, equipment cost, etc.) and operation cost (maintenance cost, etc.). Because most transportation infrastructure is non-profit as public assets, the project's revenue can be defined as the transportation cost savings using the planned infrastructure compared to using the previous transportation facilities. The results of part one (Section 6.1) should be involved in the specific cost-benefit formula built on the actual situation. In addition, other parameter inputs in the cost-benefit formula, such as transportation unit costs by different transport modes, should be determined externally.

Two points need to be clarified here. 1) The results of part one (Section 6.1) may be used not only in part two (Section 6.2), but also in part three (Section 6.3) (e.g., model in Chapter 4). This is dependent on the real options method that one uses in the framework. 2) The modeling framework for scenario one in Chapter 4 has four parts, while the comprehensive methodological framework reviewed in this chapter only includes three parts. We delete part two in the model of Chapter 4 given the following reasons. First, the reason of calculating the expected barge/airlift cost using the revised Black-Scholes model in Chapter 4 is that we consider the decision of building winter roads every year in the model. In fact, even though we do not consider building the winter roads, the expected costs still exist. Second, the expected annual barge/airlift costs calculated using the revised Black-Scholes model are similar to these from the direct calculation using forecasted results of part one (Line of forecast B-S E(Cost) and line of deterministic cost (forecast & hist), as shown in Figure 4-3). Thus, we appropriately simplify the model framework.

6.3 Part Three: Real Options Analysis

In part three, we should first identify the types of strategic management implied in the project investment, i.e., the option type (delay option, expand option, switch option, abandon option, etc.). Then, the specific real options approach can be selected to calculate the extended project's value, including finite difference, binominal lattice, Monte Carlo simulation, LSM, multi-option LSM, etc. Finally, we can obtain the quantitative results: the extended project's value and optimal investment time.

6.4 Summary

In this chapter, we have provided an overview of a modeling framework for supporting decision-making for transportation infrastructure investment. This framework is a useful decision-support tool for managing various uncertainties, and it can be further applied to multimodal systems that are heavily impacted by climate and other uncertain sources (e.g., freight demand), in addition to the transportation system.

Chapter 7. Conclusions

This chapter provides a thesis overview (Section 7.1), and summarizes the major findings and conclusions of this research (Section 7.2), then states the research contributions (Section 7.3), finally discusses the research limitations and future work (Section 7.4).

7.1 Overview

In this thesis, we explore the appropriate methods to support flexible infrastructure decision-making in accounting for uncertainties from climate change and freight demand in transportation infrastructure investment decisions. Targeting the Mackenzie River corridor in Northern Canada – specifically, we ask: (1) if and when to construct the all-weather Mackenzie Valley Highway, considering ever-increasing uncertainty in river barge freight delivery conditions (and thus, growing freight airlift costs) resulting from climate change impacts; (2) if this all-weather highway is built in stages, how should we prioritize the constructions of different segments, considering both climate change and freight demand uncertainties. We presented the following:

1. We apply a real options framework combining the Black-Sholes model and binominal lattice method to the scenario regarding the all-weather highway construction from Wrigley to Inuvik as a whole project. This model section only considers the uncertainty of climate change. We first model the open season days of the river as a stochastic process because river barging is dependent on the number of open season days, which in turn is affected by climate change. Then, using a modified Black-Scholes model, we evaluate the decision to continue both barging and airlift services each year. Finally, we use a real options model to determine how long it is beneficial to defer construction of the all-weather highway.

2. We develop a real options framework based on the Least Squares Monte Carlo method, to divide the all-weather highway from Wrigley to Inuvik into four project segments to be built in stages. We consider both climate change and freight demand uncertainties in this model section. Analogously, climate proxy – river open season days – is simulated as a stochastic process, as well as freight demands. Then, cost-benefit modelling is presented to identify all the paths of projects' NPVs at different investment times and with different paths of

predicted OSD and freight demand. After that, a real options model based on the LSM method is built to evaluate when to construct the segments.

3. Finally, based on the above case studies, we provide an overview of a modeling framework for supporting flexible infrastructure decision making that accounts for climate impact and other uncertainties in geographies like Northern Canada.

The results of this research demonstrate that when we explicitly incorporate uncertainties into cost-benefit analyses through simple real options model applications, project valuations can change significantly. Such tools can help northern governments and communities clearly communicate the severity of climate change impacts and the need for infrastructure investments that address the rapidly changing northern environment.

7.2 Findings

If we build the Mackenzie Valley Highway from Wrigley to Inuvik as a single construction project and only consider climate change uncertainty, the results demonstrate that when uncertainties (e.g. climate change, and freight demands) are considered, a road project's benefit-cost ratio increases significantly towards feasibility, and the option to delay allows for this future feasibility to be considered. The project should be deferred at least nine years (to 2028) to achieve a positive extended NPV (NPV^e, which accounts for future uncertainties in the decision to defer investment). In this situation, sensitivity analyses show that the project's NPV^e results, and therefore, project deferral time, are most heavily dependent on the all-weather highway construction costs and comparative airlift costs.

If we divide this all-weather road into four segments to be built in stages and consider both climate change uncertainty and freight demand uncertainty, the results indicate that Segment 2 (Tulita – Norman Wells segment) should be built first with a one-year delay, followed by the Segment 1 (Wrigley – Tulita segment) with a six-year delay, while Segment 3 (Norman Wells – Fort Good Hope segment) and Segment 4 (Fort Good Hope – Inuvik segment) are suggested to be built close to the end of the plan period. Finally, we review the comprehensive methodological framework that better represents and supports the transportation infrastructure investment decision process by accounting for climate impacts and other uncertainties in areas like Northern Canada.

7.3 Contributions

7.3.1 Research Contributions

We establish a comprehensive methodological framework, using real options approaches, to manage climate uncertainty in transportation infrastructure investment decisions. In addition, we attempt to incorporate two kinds of uncertainties (i.e., climate change uncertainty and freight demand uncertainties) into the evaluation of transportation infrastructure investment decisions. Furthermore, the methodological framework developed in this thesis can be applied to other multimodal systems that are heavily impacted by climate and other uncertainties, and offers opportunities to improve and build on this work.

7.3.2 Practical Contributions

The current transportation infrastructure investment decisions in the Northern Canada do not consider the uncertainties from climate change and other sources such as freight demand. By exploring appropriate methods for incorporating uncertainties into evaluating transportation infrastructure investment decisions, we demonstrate how project valuations can be seriously impacted and change greatly when we consider climate change uncertainty and freight demand uncertainty. We also demonstrate how these results can be used to communicate this to government and communities, to raise awareness of how these challenges that they are facing can be incorporated into decision models – these models should be one tool in a larger set to help guide infrastructure decisions.

7.4 Limitations and Future Work

This research has some limitations that may be addressed in future studies.

1. Although GBM is the most common process used to represent uncertain inputs for the real options approach, the climate proxy (OSD) and other uncertain inputs such as freight demand may not follow the statistical distribution assumptions of GBM.

2. We did not consider some indirect benefits and external costs. In Northern Canada, there are other significant social considerations in road-building decisions, some of which are difficult to quantify, including: opportunities to grow employment and tourism, and medical transport, for historic Indigenous communities (in essence, providing greater connectivity and the benefits this brings to Northerners (Transport Canada, 2017)); more opportunities and cost-sharing for natural resource exploration and development (Mackenzie Aboriginal Corporation, 2007), and to promote Canadian Arctic sovereignty. Some of these benefits, if tangible, are highly debated. Thus, for this research we chose to demonstrate our model focusing on transportation infrastructure and operations costs, and climate change impacts to them. Future interdisciplinary extensions should consider these elements. However, we also reiterate that this analysis method should be considered one tool of many tools and considerations that inform complex transportation infrastructure investment decisions.

3. Finally, to be more comprehensive, the modeling context should also include winter roads construction and delivery costs, such that they are included in the cost-benefit analysis, and winter road open season days also included as a stochastic environmental input variable.

We identify several key ways by which this work can be expanded and improved in the future. First, other real options methods can be considered to replace binominal lattices and the LSM method according to specific features of the research questions. Second, more uncertainty modeling methods targeting specific problems should be proposed, besides GBM. Furthermore, other ways that uncertainty enters into the decision process should be explored. For instance, in addition to uncertain input variables, we may consider the models themselves, project costs, etc. Third, more sources of uncertainty for different projects should be incorporated into the evaluation models of transportation infrastructure investment because many other factors would have a key impact on the investment, which needs to be identified. Fourth, for different transportation infrastructure projects, the decision makers have different flexibility on investment strategies. Therefore, more decision tactics such as expanding or abandoning the investment can be considered in the evaluation model. Finally, transportation infrastructure investments actually face a complex situation and need comprehensive consideration; hence, evaluation on these investments may be explored in a complex transport network.

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Appendix A A Sample of Tow Letter

TO: DATE: June 20, 2004

FROM: SUBJECT:

The following is your northbound tow ex: Hay River Unit: Tonne

Barge	Manifest #	Destination	Description	Subtotal	Total
1509	Load 971	Norman Wells	Deck	143.52	
	Load 956	Norman Wells	P50 (IOL)	1153.63	1297.15
1518	Load 965	Norman Wells	Deck	220.03	
	Load 957	Norman Wells	P50 (IOL)	1118.08	1338.11
1528	Load 955	Norman Wells	Anchors	7.50	
	Load 958	Inuvik	Jet A1 (IOL)	1327.26	1334.76
1504	Load 959	Norman Wells	Jet A1 (IOL)	911.11	
	Load 962	Norman Wells	AvGas (IOL)	96.00	
	P/T's	4721 & 4731			
	Load 961	Norman Wells	PT's/pump	30.20	1037.31
1001	Load 954	Norman Wells	NTCL Equipment	26.05	
	Load 960	Norman Wells	P50 (IOL)	753.72	
		Dory Point	Anchors	5.00	784.77
1032	Load 963	Norman Wells	Midgrade Gas (IOL)	788.92	788.92
				TOTAL	6581.02

Appendix B Data of Three Buoys on the Mackenzie River

Buoy Number	3833		3834		3835	
Year	Start Date	End Date	Start Date	End Date	Start Date	End Date
1997	1997-06-13	1997-10-13	1997-06-13	1997-10-12	1997-06-13	1997-10-12
1998	1998-05-31	1998-10-05	1998-05-31	1998-10-05	1998-05-31	1998-10-05
2000	2000-06-19	2000-10-11	2000-06-19	2000-10-11	2000-06-19	2000-10-11
2001	2001-06-13	2001-10-12	2001-06-13	2001-10-13	2001-06-13	2001-10-12
2002	2002-06-16	2002-10-09	2002-06-16	2002-10-09	2002-06-16	2002-10-09
2003	2003-06-15	2003-10-10	2003-06-15	2003-10-10	2003-06-15	2003-10-10
2004	2004-06-07	2004-09-25	2004-06-07	2004-09-25	2004-06-07	2004-09-25
2005	2005-06-10	2005-10-13	2005-06-10	2005-10-13	2005-06-10	2005-10-13
2006	2006-06-10	2006-10-09	2006-06-10	2006-10-09	2006-06-10	2006-10-09
2007	2007-07-10	2007-10-24	2007-06-10	2007-10-24	2007-06-10	2007-10-24
2008	2008-06-13	2008-10-17	2008-06-13	2008-10-17	2008-06-13	2008-10-17
2009	/	/	2009-06-28	2009-10-15	2009-06-28	2009-10-15
2010	2010-06-15	2010-10-17	2010-06-15	2010-10-17	2010-06-15	2010-10-17
2011	2011-07-02	2011-10-12	2011-07-02	2011-10-12	2011-07-02	2011-10-12
2012	2012-06-21	2012-10-20	2012-06-21	2012-10-20	2012-06-21	2012-10-20
2013	/	/	2013-06-26	2013-10-20	2013-06-26	2013-10-20
2014	2014-06-28	2014-09-23	2014-06-28	2014-09-23	2014-06-28	2014-09-23
2015	2015-06-20	2015-09-24	2015-06-20	2015-09-24	2015-06-20	2015-09-24
2016	2016-06-14	2016-10-06	2016-06-14	2016-10-06	2016-06-14	2016-10-06
2017	2017-06-17	2017-10-05	2017-06-17	2017-10-05	2017-06-17	2017-10-05

Map information of different buoys, 3833 (65º 18' 13.26", 127º 8' 45.66"), 3834 (65º 18' 10.86", 127º 9' 1.32"), 3835 (65º 18' 50", 127º 9' 48").

Appendix C Freight Volume Data

Year	Chapter 4	Chapter 5			
	Total	Segment 1	Segment 2	Segment 3	Segment 4
2002	91033	93527	90785	78283	74513
2003	97020	95457	93031	77921	75105
2004	80585	86030	82502	67236	64143
2005	92538	103706	96673	78548	75367
2006	66702	68126	62951	53634	50736
2007	88031	93034	89600	75296	71292
2008	57365	64374	61787	44226	39147
2009	42423	46108	40853	29840	24636
2010	31697	30838	28189	18303	17214
2011	38784	46489	43959	32849	28469
2012	40240	48437	45485	31603	27919
2013	58147	71129	69120	43193	37247
2014	45021	55281	53916	42716	41563

Unit: Tonne.