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Transportation Infrastructure Decision Flexibility in Response to Climate Change and Demand Uncertainties: The Mackenzie Valley Highway in Canada's Northwest Territories

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Abstract

Barge transport operations on the Mackenzie River, a major transportation corridor in the Northwest Territories, are impacted by multiple sources of uncertainties. In particular, the impacts of climate change on this important corridor have led to summer shipping seasons that are growing more volatile in terms of length and quality. This can lead to a growing reliance on costly airlifts for delivering essential freight that cannot be delivered by barge during seasons that end early due to low water. The Government of Northwest Territories has been planning the construction of the Mackenzie Valley Highway (MVH) for decades, in order to provide cheaper, more reliable transportation for communities. However, the costs of constructing the MVH are prohibitive, and traditional benefit-cost analyses are unable to consider flexible investment actions in response to uncertainties. Thus, we apply a real options modeling framework to determine if and when to construct the different segments of the MVH, considering climate change and freight demand uncertainties. We first model climate and freight demand uncertainties as Geometric Brownian Motion processes. Then, a benefit-cost model is developed. Finally, we use the Least Squares Monte Carlo method to solve for extended project values and optimal investment times for each segment. The results indicate that Segment 2 has the largest value with an optimal seven-year delay in investment time, followed by Segment 1, Segment 3, and finally Segment 4 in the last year of the planning period (or possibly beyond). Freight demand volatility appears to have the greatest impact on project values and investment years. The results show that although the benefits of construction may not outweigh the costs now, they may at some future date; in between, decision-makers have opportunities to change their minds as conditions change. This is particularly important in northern Canada, where highly costly infrastructure investment decisions are subject to massive uncertainties. Overall, we see such an approach as a tool to communicate the value of uncertainty in infrastructure benefit-cost analyses, and as one tool in a larger decision-support toolbox that is required for major transportation investments in northern Canada.

Keywords: Real options model; Transportation investment decision analysis; Climate change; Northern Canada; All-weather road project staging; River barge transport.

Introduction

This paper explores the use of real options analysis (ROA) to support large-scale, all-weather roadway infrastructure planning decisions in Canada's North. Specifically, our modeling framework is designed to support flexible decision-making in the face of climate change-impacted conditions and freight demand, both of which are highly uncertain but critically important to these enormous investment decisions.

The Mackenzie River in Canada's Northwest Territories is Canada's longest river system, connecting many remote communities. It remains an important transportation route for freight barging services during the ice-free summer season, to communities along its course as well as coastal communities in the Beaufort Sea. However, over the last two decades, summer water conditions and thus, sailing conditions, have grown increasingly variable. Unserved freight at the end of the season must either be transshipped for airlift, transshipped and stored until the winter roads season, or wait until the following summer season, all of which are undesirable due to delays and costs. To provide more reliable transportation (and encourage economic sustainability and growth) within the Mackenzie corridor, the Government of the Northwest Territories is constructing the Mackenzie Valley Highway (MVH). Although the MVH has been discussed since the 1950s (5658NWT Ltd. & GNWT, 2011), commitments have been slow due to the enormous costs of constructing and maintaining an all-weather roadway, balanced against uncertain (and relatively small) volumes, and more recently, climate change impacts. Although federal and territorial governments have been working to incorporate climate change impacts and adaptation needs in infrastructure decisions (GNWT, 2008), there has been little use of quantitative tools to incorporate uncertainties in supporting these large-scale investment decisions. Moreover, it would be more useful to decision-makers to have decision results that support flexibility in planning and investment actions.

We present a methodological framework that uses ROA for understanding whether and when to construct stages of the MVH, to replace river freight barging services made increasingly uncertain by the impacts of climate change and demand. Our work contributes to the existing literature in that it combines Benefit-Cost Analysis with ROA in the construction of a framework that allows for the multimodal assessment of such an infrastructure project, considering the operations of multiple modes and incorporating the significant uncertainties presented by climate change (and demand) on both transportation infrastructure and operations. We develop and apply this framework within the unique context of a northern transportation system. There has been very little previous application of option-type models to model northern transportation infrastructure decisions. However, in a broader context, it has become critical to explicitly and quantitatively consider the impacts of climate change on infrastructure decisions. Our work provides a decision-support methodology for planners and policy-makers handling large-scale northern infrastructure investment decisions, and more broadly, any transportation infrastructure projects impacted by climate change uncertainty.

Background

The Mackenzie Valley Corridor Transportation System

Access and mobility in Canada's Northwest Territories (NWT) is provided by a sparse transportation system covering a vast northern geography with significant environmental challenges. Most communities cannot be accessed by all-weather roads, and instead rely on a combination of air and winter roads (and for some, marine transport) to move people and goods (Figure 1).

For decades, marine transport has been a dominant re-supply mode to marine-accessible communities along the Mackenzie River and into the Beaufort Sea (GNWT, 2018). Freight is transshipped from rail or truck at Hay River (at the mouth of the river to Great Slave Lake) onto river barge. Freight destined for communities along the Beaufort Sea are further transshipped to ocean barge at Tuktoyaktuk. The dominant river barging system, as well as 20+ airports and airstrips, are operated by the Government of Northwest Territories (GNWT Department of Transportation, 2016; 2018).

Private companies alone historically provided barging services on the Mackenzie River and Great Slave Lake (Zheng & Kim, 2017). Since the late 2000s, uncertainties from climate change and other sources (e.g., freight demand) significantly impact freight transportation operations (and thus, profitability). The Mackenzie River's navigable season has generally grown shorter and more variable due to climate change impacting precipitation, temperatures (air and water), and water volumes and depths (Sung, Burn, & Soulis, 2006; Woo, Thorne, Szeto, & Yang, 2008; Yang, Shi, & Marsh, 2015). Data from the Canadian Coast Guard (CCG) on navigational buoy placement dates at Rader Island (near Norman Wells) shows that the number of navigable, open season days (OSD) decreased from 121 days in 1997 to 110 days in 2017, with a low of 87 days in 2014. Thus, because the unit cost of airlift is reported to be roughly 10 times higher than barge (GNWT Department of Transportation, 2011), transport costs in the Mackenzie River corridor have increased (Pendakur, 2017). Demand uncertainty is another key factor impacting transportation in this region. Barge freight volumes of the Northern Transportation Company Limited (NTCL, by far the largest and oldest barge transport company operating on the Mackenzie River until its bankruptcy in 2016) were observed to decrease at an average rate of 5.7% from 2003 through 2014 (Zheng, Kim, Du, & S.A., 2016), with significant fluctuations. Amidst these challenges, the Government of the Northwest Territories looks for strategies to reduce transportation costs for communities and encourage natural resource development and tourism. Although the Northwest Territories holds significant mineral resources, one of the largest barriers to development is transportation costs. The GNWT supports transportation infrastructure investments to encourage targeted development, and the anticipated movement of ore, supplies, and people (GNWT Department of Infrastructure, 2019).

The GNWT has been planning the all-weather MVH from Wrigley to Tuktoyaktuk since the 1950s (5658NWT Ltd. & GNWT, 2011). Like many other massive and costly transportation projects, the MVH is being constructed in stages. The Inuvik–Tuktoyaktuk Highway (the northernmost section of the MVH, shown in Figure 1) opened to the public on November 15, 2017, followed by the Canyon Creek All-Season Access Road (connecting Norman Wells to Canyon Creek) on November 13, 2018 (GNWT Department of Infrastructure, 2019; 2019a). The GNWT has, to this date, identified five projects on the MVH: Great Bear River Bridge; Canyon Creek to Tulita section; Wrigley to Mount Gaudet access road section, Tulita to Sahtu-Dehcho border section, and Sahtu-Dehcho border to Mount Gaudet access road section (GNWT Infrastructure, 2019). These projects are largely considered to be independent of one another given the economic benefits they bring to individual communities.

Figure 1 identifies four segments of the future MVH. Segment 1 (246 km) consists of the first two projects while Segment 2 (75 km) consists of the final three; Segments 3 and 4 are not yet funded. If the construction of these four segments is independent of one another, should each one be constructed or not? If so, when? In order to answer these questions while considering the effects of climate change and freight demand uncertainties, we apply ROA using the following process. First, simulate the climate impacts (river open season days, or OSD) and freight demands as two stochastic processes. Second, using forecasts of these inputs, calculate project values at different investment times in a benefit-cost analysis. Third, develop a real options model to determine whether to construct, and when, these four roadway segments.

Literature Review

There is a long history of techniques developed to conduct transportation infrastructure project appraisals. Methodologies differ for different project types and countries, but most employ benefit-cost analysis (Jones, Moura, & Domingos, 2014; Mackie, Worsley, & Eliasson, 2014). Other approaches include multi-criteria analysis (Lee Jr., 2000), activity-based costing (Feng & Ho, 2015), and combinations of these methods and others. Even if they account for uncertainties, traditional methods usually follow a static approach to evaluate investment decisions, ignoring the possibility for management to react to future events (Grayburn, 2012). This leads to a systematic underestimation of investment values since they are not able to consider flexible actions such as expanding, deferring, contracting, and abandoning a project (as well as exchanging it with another) as possibilities (Grayburn, 2012). Real options analysis (ROA) provides a means to take such actions into account in maximizing investment value.

ROA is based on a financial option valuation technique applied to “real” (i.e., physical) infrastructure investment decisions, that accounts for flexibility (or rather, actions demonstrating flexibility) in investment valuation (Trigeorgis, 1999). The term was defined formally by Myers (1977), who identified real assets as analogous to financial stock options. ROA assigns values to uncertainty as it changes over time, which in turn changes the value of investments over time. It is thus suitable for determining valuations of infrastructure investment actions under high uncertainties (Dixit & Pindyck, 1994; Schwartz & Trigeorgis, 2001).

de Neufvillle and Scholes (2011) define real options to be potential sources of flexibility both “on” and “in” systems, which are pursued to maximize investment value in light of changing conditions. Real options as sources of flexibility “on” systems involve major strategic project management decisions – for example, all-weather roadway project phasing as per this paper. Flexibility “in” systems is options that can be created within the design of the system or projects (Martins, Marques, & Cruz, 2013), such as choices of construction technology and road foundation materials. Both classes of decisions are, of course, in response to identified uncertainties of critical importance to such decisions.

There are four types of real options “on” systems. To *delay* is the most common of the four options, providing a decision-maker the exclusive right to delay a project investment until a later date. The implicit assumption in benefit-cost analysis is that a project should be canceled if its net present value (NPV) is negative, not accounting for the possibility that its NPV could change if it were delayed to a later time. In practice, the option to delay an investment is sometimes overlooked in project evaluation (Dewar & Wachs, 2006). Other possible actions include *expanding* a project at a future time (Copeland, Koller, & Murrin, 2000), *switching* a project into different modes of operation (including shut down) (Kensinger, 1987; Kulatilaka, 1993), and *abandoning* or quitting at a future date (Damaraju, Barney, & Makhija, 2015; Cruz Rambaud & Sánchez Pérez, 2016). For the MVH, the question is mainly *when* it will be constructed, given how critical it is to regional development; thus, it is an example of a delay option.

To solve real option values, three numerical methods have primarily been used: finite difference (Brennan & Schwartz, 1997), binomial lattice (Cox, Ross, & Rubinstein, 1979), and

Monte Carlo simulation. Neither the finite difference nor binomial lattice methods are suitable for valuating real options with multiple uncertainties (Abadie & Chamorro, 2013). The Monte Carlo simulation method can be used to accommodate multiple and complex uncertainty processes; however, calculating the expected returns of delaying or executing an option at each time interval grows increasingly computationally expensive through the backwards solution process. To address this, Longstaff & Schwartz (2001) developed the Least Squares Monte Carlo (LSM) method, which involves applying least-squares regression to fit expected returns along all simulation paths. LSM is used to identify good decision rules, by comparing the expected returns on waiting versus exercising for each decision time point. Because LSM is simple to implement and understand, accurate, and effectively reduces computational costs, it has become the standard method for simulating options prices. Thus, we have adopted it for this research for the same reasons. However, other similar Monte Carlo methods have also been proposed (Barraquand & Martineau, 2007), including the use of simulation and dynamic programming to value American options (Ju, 1998; Tung, 2016). For example, Del Moral, Remillard, and Rubenthaler (2012) proposed a forward Monte Carlo valuation method.

ROA has been applied to assess a wide variety of infrastructure investment decisions including locating manufacturing sites (Kogut & Kulatilaka, 1994), choosing irrigation dam improvements (Michailidis & Mattas, 2007), upgrading power plant technology (Kato & Zhou, 2011), and choosing designs for drainage systems in floods (Park, Kim, & Kim, 2014). ROA has also been applied to transportation infrastructure problems that require decision flexibility under uncertainty. Applications include parking garage design height under parking demand uncertainty (de Neufville, Scholtes, & Wang, Real Options by Spreadsheet: Parking Garage, 2006; Zhao & Tseng, 2003) and highway expansion accounting for uncertainties in travel demand, land prices, and pavement deterioration (Zhao, Sundararajan, & Tseng, 2004); solutions were generated using dynamic programming. An 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; Smith, 2005; Michailidis & Mattas, 2007). Huang and Chou (2006) used a compound pricing approach to evaluate the Taiwan high-speed rail project, considering minimum revenue guarantee uncertainty. ROA has also been applied to the transportation network design problem considering demand uncertainty (Chow & Regan, 2011a; Chow & Regan, 2011b).

Infrastructure investments in the far north are defined by complex and specific challenges arising from the extremely high costs of construction in remote and vast regions, and the difficulties of engineering in harsh but ecologically and socially fragile terrain (Conrad & Kotani, 2005) made further complex by the effects of climate change and adaptation needs. These conditions call for a flexible infrastructure investment approach. Sturm et al. (2016) used a basic options-type model to evaluate the decision (which must be repeated annually) of whether or not to construct an ice road, while Kim & Li (2020) applied the binomial lattice approach to evaluate the decision of when (i.e., what future year) to construct the MVH to replace the marine barging system. This paper expands on the aforementioned work by using LSM to determine MVH construction staging (when or if at all to construct each segment between Wrigley and Inuvik), considering uncertainty from two sources: climate change impacts and freight demand.

Methodology

Modeling Framework

Three stages are identified for our model: (i) representing uncertain inputs, (ii) benefit-cost analysis, and (iii) applying ROA (Figure 2).

We represent the impacts of climate change and freight demand uncertainties on the MVH all-weather roadway investment decisions using marine OSD (Kim & Li, 2020) and historical barge freight volumes. In Part 1, we describe how we model climate change proxy (OSD) and freight demands as stochastic processes, obtaining 10,000 forecast paths for each in a 38-year planning, construction, and operations horizon. In Part 2, we identify all the paths of the project's NPVs at different investment times and forecasted OSD and freight demand paths. In Part 3, the LSM approach is used to compute the extended NPV (NPV^e) and optimal investment time for each construction project.

Representing Uncertainties (Part 1)

Geometric Brownian Motion (GBM), a continuous-time stochastic process in which the logarithm of the variable follows a Brownian motion (Ross, 2014), is commonly used to model stock prices (Ozorio, Bastian-Pinto, & Brandão, 2018). Most real options literatures also use GBM to model the underlying uncertainty of a project (Bøckman, Fleten, Juliussen, Langhammer, & Revdal, 2008). The Mackenzie River OSD looks like a random walk with negative drift similar to a GBM process, and was thus modeled as such in Kim & Li (2020) and in this paper. A GBM process was used to represent rainfall intensity (Gersonius, Ashley, Pathirana, & Zevenbergen, 2013) and catastrophic climatic event occurrences (e.g., bushfires) (Truong, Stefan, & Mathew, 2018). GBM has also been used to model travel demand and volumes; Chow & Regan (2011a) and Zhao et al.

(2004) applied it for vehicular demand, while Couto et al. (2015) modeled high-speed rail passenger demands as such. In this paper, we represent freight demands on our four MVH segments ($h = 1,2,3,4$) as GBM processes.

A GBM process can be represented as follows (Dixit & Pindyck, 1994):

$$dX_t = \mu X_t dt + \theta X_t dW_t \tag{1}$$

Where X_t is the value of the stochastic process at t; W_t is a Brownian motion, which is a continuous-time stochastic process; μ is the drift, indicating the change rate of the mean of a stochastic process; and θ is the volatility of the stochastic process. The solution for X_t is (Dixit & Pindyck, 1994):

$$X_t = X_0 e^{\left(\mu - \frac{1}{2}\theta^2\right)t + \theta dW_t} \tag{2}$$

Where X_0 is the initial value at $t = 0$. Historical data can be used to calculate μ and θ (Yang & Blyth, 2007):

$$\mu = \frac{1}{n}\sum_{t=1}^{n} ln\left(\frac{X_t}{X_{t-1}}\right) \tag{3}$$

$$\theta = \sqrt{\frac{1}{n-1}\sum\nolimits_{t=1}^{n}\left[ln\left(\frac{X_t}{X_{t-1}}\right) - \overline{ln\left(\frac{X_t}{X_{t-1}}\right)}\right]^2} \tag{4}$$

Based on the above, we model our two uncertainty variables as follows:

$$S_t = S_0 e^{\left(\eta - \frac{1}{2}\theta^2\right)t + \theta dW} \tag{5}$$

$$Q_{h,t} = Q_{h,0} e^{\left(\eta_h - \frac{1}{2}\theta_h^2\right)t + \theta_h dW} \tag{6}$$

Where S_t represents OSD in year t, η is the average growth rate of S_t, and θ is the average annual volatility of OSD. $Q_{h,t}$ represents freight demand on segment h in year t; $Q_{h,0}$ is the initial freight demand on h; η_h and θ_h are drift and volatility of freight demand on h, respectively.

We designate T as the planning horizon of the MVH, with T_1 and T_2 as project construction and operation periods, respectively; $T_2 > T_1 > 0$. All values are in years. We use Monte Carlo simulation to generate 10,000 numerical solutions for S_t and $Q_{h,t}$ $(t = 1,2, \dots, T + T_1 + T_2)$, by generating random numbers in a Wiener process that follows a standard normal distribution:

$$dW_t = \varepsilon dt \tag{7}$$

Where ε is distributed standard normal $N \sim (0,1)$.

Benefit-Cost Analysis (Part 2)

Consider the NPV of segment h, when invested in year τ, is the difference between project benefits $B_{h,\tau}$ and project investment costs (I_h):

$$NPV_{h,\tau} = B_{h,\tau} - I_h \tag{8}$$

τ is the investment year (or, the number of years the project is delayed within the planning horizon T), $0 < \tau < T$. If we invest in the last year of the planning horizon T, then $\tau = T - 1$. In this paper, planning, construction, and operations periods are $t = T + T_1 + T_2 = 15 + 3 + 20 = 38$ (more description in *Other Cost Components and Parameters*). We use Eqns. (5) and (6) to determine OSD and freight demand forecasts for $t = 1 \dots 38$ years. Then, we calculate all the NPVs for different investment times (τ), using our OSD and freight demand forecasts for each year in the 38-year plan, construction, and operations period. By definition, the NPV of building a segment in 2020 (one-year delay) will differ from that of building in, say, 2025 (six-year delay).

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

$$B_{h,\tau} = \pi_{h,\tau}^{dn} - \pi_{h,\tau}^{co} \tag{9}$$

Where $\pi_{h,\tau}^{dn}$ and $\pi_{h,\tau}^{co}$ are the total present (i.e., discounted) costs of the *do-nothing* and *construct* scenarios respectively. The operating cost of the do-nothing scenario, or $\pi_{h,\tau}^{dn}$, is a function of: barge volumes and airlift volumes; unit barge transport costs and unit airlift transport costs; maintenance costs; and the discount rate. The operating cost of the construct scenario, or $\pi_{h,\tau}^{co}$, include all the same elements of the do-nothing scenario until the year when construction ends, at which point it is a function of truck volumes, unit truck transport costs, and logistics and maintenance costs of the all-weather road. Thus, we have Eqns. (10) and (11) to represent these two scenarios.

$$\pi_{h,\tau}^{dn} = \sum_{t=1}^{\tau+T_1+T_2} \left(Q_{b,h,t}P_b + Q_{a,h,t}P_a\right)(1+o_b)e^{-rt} \tag{10}$$

$$\pi_{h,\tau}^{co} = \sum_{t=1}^{\tau+T_1} \left(Q_{b,h,t}P_b + Q_{a,h,t}P_a\right)(1+o_b)e^{-rt} + \sum_{t=\tau+T_1+1}^{\tau+T_1+T_2} Q_{h,t}P_h(1+o_h)e^{-rt} \tag{11}$$

$Q_{b,h,t}$ and $Q_{a,h,t}$ are freight (in tonnes) delivered by barge and airlift respectively in year t, such that total freight is $Q_{h,t} = Q_{b,h,t} + Q_{a,h,t}$. Parameters P_b, P_a, P_h are unit freight transport prices via barge, airlift, and truck (via all-weather road), respectively (\$/tonne); o_b, o_h represent maintenance costs for barging and trucking, respectively, and are calculated as a proportion of the total transport costs; r is the annual discount rate. In the *construct* scenario, freight is transported by barge (and airlift, when necessary) until the all-weather roadway segment is built, after which all freight is transported via trucks.

Now, to determine $Q_{b,h,t}$ and $Q_{a,h,t}$ for the current barge-airlift service, we make the following assumptions:

1. If the predicted freight demand $Q_{h,t}$ is greater than the total barging capacity ($S_t N$, where N is the historical average freight volume per day on the Mackenzie River) in year t, the remaining freight exceeding the barging capacity will be airlifted, 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., if $Q_{h,t} < S_t N, Q_{a,h,t} = 0$.

For each Monte Carlo simulation of the two stochastic processes ($\omega, 0 < \omega \leq K$, where $K = 10{,}000$) from which we obtain the predicted paths for OSD, S_t, as well as freight demand for each segment h, $Q_{h,t}$, we calculate an NPV path for segment h, $\boldsymbol{NPV_{h,\omega}}$, for all possible investment times $\tau = 1,2,\dots,T-1$) using Eqns. (8)-(11):

$$\boldsymbol{NPV_{h,\omega}} = \left[NPV_{h,\tau=1,\omega}, NPV_{h,2,\omega}, \dots, NPV_{h,T-1,\omega}\right] \qquad (12)$$

Real Options Analysis (Part 3)

Using our real options approach, we can now determine when to start construction on the four MVH segments from Wrigley to Inuvik. To calculate final option values ϕ_h, we use the LSM approach developed by Longstaff and Schwartz (2001). This simulation-based approach is simple and widely used for obtaining final option values, particularly when multiple uncertainties must be accounted for in doing so.

We have already found paths $\boldsymbol{NPV_{h,\omega}}$ using the simulations for OSD $\left(S_{t,\omega}\right)$ and segment h freight volumes $\left(Q_{h,t,\omega}\right)$ using Eqn. (12). The final option value of segment h for the ωth simulation $\left(\phi_{h,\omega}\right)$ is obtained as follows. Suppose we consider the construction of h at τ; if $NPV_{h,\tau,\omega} > 0$, then we further compare $NPV_{h,\tau,\omega}$ with the expected return on investment of delaying, $\psi_{h,\tau+1,\omega}$. This value $\psi_{h,\tau+1,\omega}$ can also be described as the discounted cash flow in year τ if the investment is delayed to year $\tau+1$, instead of the traditional ROI (return on investment) which is usually computed as the ratio of net profit to investment. If $NPV_{h,\tau,\omega} \geq \psi_{h,\tau+1,\omega}$, this means the optimal investment time for ω is τ and the segment should be constructed in τ. Otherwise, if $NPV_{h,\tau,\omega} < \psi_{h,\tau+1,\omega}$, project construction should be considered for the following year $\tau+1$:

$$\phi_{h,\tau,\omega} = \max\left\{NPV_{h,\tau,\omega}, \psi_{h,\tau+1,\omega}\right\} = \max\left\{NPV_{h,\tau,\omega}, e^{-r} E\left[\phi_{h,\tau+1,\omega}\right]\right\} \tag{13}$$

Where $\phi_{h,\tau,\omega}$ is the option value of segment h for the ωth simulation when investing in year τ. We use a backward calculation to find the final option values. Starting from the last year of the planning horizon T (which corresponds to construct year $\tau = T-1$), the expected return of delaying segment h construction is 0 (because this is the last year in the planning horizon, an investor must decide whether to invest or not). If $NPV_{h,\tau=T-1,\omega} > 0$, then we should construct segment h in this final planning year, and the optimal investment time is $\tau = T-1$ for simulation ω. Continuing backwards, in year $T-1$ (corresponding to $\tau = T-2$), if $NPV_{h,\tau=T-2,\omega} \geq \psi_{h,\tau+1,\omega}$, we construct. Continuing this process until $\tau = 1$, we can obtain the optimal investment time for segment h on simulation ω, $\tau^*_{h,\omega}$, and the corresponding (optimal) option value, $\phi^*_{h,\omega}$.

Now, in the LSM approach, least squares regression is used to find $E\left[\phi_{h,\tau+1,\omega}\right]$. We take the immediate returns of investing at τ (i.e., $NPV_{h,\tau,\omega}$) as X values, and take the final option value of delaying the investment at time $\tau + 1$ (i.e., $\phi_{h,\tau+1,\omega}$) as Y. By applying least squares regression, we estimate the regression coefficients such that we calculate $\hat{Y} = E[\phi_{h,\tau+1,\omega}]$. For the functional form of $Y = f(x)$, many polynomial forms have been used including a basic polynomial (power series) (Zhao, Sundararajan, & Tseng, 2004), Hermite polynomial (Chow & Regan, 2011a), Laguerre polynomial (Gustafsson, 2015), and the weighted Laguerre polynomial used in the original LSM approach (Longstaff & Schwartz, 2001). Moreno & Navas (2003) showed that the options results achieved by using different polynomials for a given degree are similar. However, we tested the applicability of these polynomials because NPVs, and thus, X are enormous in comparison to stock values. Our tests showed that applying basic or Hermite polynomials did not yield significantly different results, while the Laguerre and weighted Laguerre polynomials were problematic. Thus, we chose basic polynomials with degree 5, which adequately approximated the continuous values:

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \beta_3 X^3 + \beta_4 X^4 + \beta_5 X^5 \tag{14}$$

Given $NPV_{h,\omega}$, the path of NPV given construction decisions at each τ (Eqn. (12)), $E[\phi_{h,\tau+1,\omega}]$ can be estimated using Eqn. (15):

$$E[\phi_{h,\tau+1,\omega}] = \sum_{j=0}^{q} \beta_j \left(NPV_{h,\tau,\omega}\right)^j \tag{15}$$

Where q is the polynomial degree ($q = 5$ for our case) and β_j are the estimated coefficients using least squares regression.

Finally, with the final (optimal) project option value $\phi^*_{h,\omega}$ and investment time $\tau^*_{h,\omega}$ for each segment h and simulation ω, the final project option value, also called the extended NPV (NPV^e), of segment h is obtained:

$$\phi_h^* = \frac{1}{K}\sum_{\omega=1}^{K} e^{-r\tau_{h,\omega}^*}\phi_{h,\omega}^* \tag{16}$$

The LSM method provides the final option value based on the optimal investment times determined for each ω $\left(\tau_{h,\omega}^*\right)$ as shown in Eqn. (16). The final optimal investment time for segment h (τ_h^*, which could also be called delay years) is chosen as the investment year $\tau_{h,\omega}^*$ of greatest frequency among all ω simulations:

$$\tau_h = mode\left(\tau_{h,\omega}^*; \omega \in [1, K]\right) \tag{17}$$

To clarify, what we call the optimal investment time is the most likely (or expected) best time to invest given the existence of American options.

Here we summarize the LSM method. It starts with a forward (in time) calculation of NPVs for investment in year τ (Eqns. (9)-(11)). It then requires a backward calculation where one compares the NPV at τ (the cost of investing) against the expected value of deferring further, discounted to present values (Eqn. (13)). It is essentially a process where we "check," for each year of the planning period going backward, whether to "strike" (i.e., construct) that year or further defer the decision for another year (based on the expected value of deferring), to see how early we should invest. To calculate the final project option value (ϕ_h^*, also called NPV^e), we take the discounted average over all simulations (ω) (Eqn. (16)). The deferral year showing up with maximum frequency over the simulations is our final deferral year (Eqn. (17)) – or as stated above, the most likely best time to invest.

Data and Modeling Inputs

Data was gathered from the Northern Transportation Company Limited (NTCL), BBE Expediting (a northern logistics company based in Edmonton, Canada), Statistics Canada (2019), Canadian

Coast Guard (CCG), and various literature available online. Key modeling input parameters are listed in Table 1 and further discussed in this section.

Freight Demand

In order to model freight demand as a stochastic process, we calculate the volatility and drift of historical freight demands on the four adjacent segments of the Mackenzie River shown in Figure 1. Because freight demand data is not available, we used freight volumes provided by NTCL, the largest and oldest barge transport company operating on the Mackenzie River (until its bankruptcy in 2016) (Zheng, Kim, Du, & S.A., 2016). Until 2016 when its assets and operations were taken over by the GNWT, NTCL estimated that it carried about 80% of marine freight on Great Slave Lake; certainly, NTCL was the only marine freight operator to service the entire length of the Mackenzie River, from Great Slave Lake to the mouth of the Beaufort Sea (and beyond). NTCL provided tow letters from 2002-2015, which provided detailed information about their barging operations (dates; tug and barge configurations; freight type, volume, and origins and destinations). A comprehensive description of the data is documented in a Transport Canada report (Zheng, Kim, Atley, & Du, 2016). We thus (as per Figure 3) estimated freight volumes (based on the assumption that NTCL volumes are 80% of the total) originating from, delivered to, and traversing through each of the four Mackenzie Valley segments (Figure 1). To be conservative, we excluded consideration of potential future road use related to economic growth. Thus, the historical freight volumes delivered through the four adjacent segments on the Mackenzie River were obtained (Figure 3). Next, the volatility of historical freight volumes was calculated as per Eqn. (4). We also obtained the GDP data of all industries in the NWT during the last decade (2009-2018) (NWT Bureau of Statistics, 2019), to further calculate the volatility of this GDP. The volatility of historical freight volumes was computed as the average of the volatility of the historic freight volume and that of the historical NWT GDP. Finally, we calculated the drift (Eqn. (3)) of the NWT GDP data to represent a trend in freight demands on the four segments (as specified earlier).

The average daily freight volume is used for calculating the future barging capacity. Based on the annual freight volume data gathered from NTCL and OSD data gathered from the CCG, we first calculate the average daily freight volume for 2002 and 2014. Furthermore, as NTCL carried approximately 80% of the total freight transported on the Mackenzie River, we divide the NTCL volumes by 80% to represent the total Mackenzie River freight volumes.

Open Season Days (OSD)

The length of the Mackenzie River's summer shipping season, or OSD, is dictated by the dates the CCG installs and removes navigational buoys. We use it as the climate proxy because OSD is a human decision significantly impacted by environmental factors including air and water temperature (and thus, ice breakup, freeze-up, and floating ice), precipitation, water levels, and water volumes. These factors are all, in turn, impacted by climate change. Although these environmental factors could be directly used in our model instead of OSD, they are very location specific and we do not understand how they combine to result in the CCG decisions. To model the impact of different climate factors (and more importantly, how they combine to determine the shipping capabilities of the Mackenzie River) is beyond the scope of this work (and more in the purview of hydrological and environmental engineers). Overall, the OSD is the final manifestation of the CCG's decisions of when to place and remove buoys, which ultimately determines whether barge operations happen or not.

The CCG provided placement and removal dates of three buoys by Rader Island (near Norman Wells, about the halfway point of the Mackenzie River) from 1997-2017, from which OSD was calculated.

Freight Transport Costs by Mode

Approximate freight transport costs by mode (barge, truck, and airlift) in the NWT were obtained from BBE Expediting Ltd., a provider of expediting, supply chain logistics, and cargo handling services in the Canadian North. BBE suggested delivery costs from Edmonton to Inuvik are, in Canadian dollars, \$680-730/tonne by barge, and \$580-610/tonne by truck. Based on these numbers, we assumed the following. 1) Shipping costs between Wrigley and Inuvik are proportional by distance and are the average of the resulting range; 2) freight delivery by air is about 10 times that of barge per unit tonne (GNWT Department of Transportation, 2011); 3) these transportation costs hold over the entire study period and 4) the shipping costs to all communities were constant at the estimated rate from Wrigley to Inuvik. Thus, the costs of transport from Wrigley to Inuvik were calculated to be as follows: \$260/tonne by barge, \$225/tonne by truck, and \$2,600/tonne by air.

Other Cost Components and Parameters

In addition to the freight transport costs (by mode) introduced in the previous section, we also consider roadway construction costs (which implicitly includes the costs of supporting infrastructures like bridges and culverts) and road maintenance costs. Other indirect benefits and external costs were not considered due to the complexities in defining these costs and lack of data to quantify them. The construction and maintenance cost components, as well as other important parameters, are described below.

Construction Costs

The total construction cost of the all-weather road from Wrigley to Inuvik is reported to be $1.67 billion (Tetra Tech EBA, 2011; CBC News, 2013). For the purposes of this paper, we assume that the cost to construct each of the four segments is proportional to the planned distances of each segment (Tetra Tech EBA, 2011), as shown in Table 2.

Maintenance Costs

Maintenance costs are accepted to be a significant and thus, important cost element for transportation infrastructures, to ensure the long-term physical and functional integrity of the infrastructure over an expected lifespan (Schroten, et al., 2019). However, data on maintenance costs are often unavailable. In this paper, we assumed maintenance costs for both the planned all-weather highway and the barging-airlift system are 5% of total freight movement costs, and later show the results of a sensitivity analysis of the maintenance cost.

Discount Rate

The discount rate is required to convert future monetary values to a present value in a benefit-cost analysis (García-Gusano, Espegren, Lind, & Kirkengen, 2016). We estimate the discount rate as the mean of the average inflation for Canada between 2009 and 2018 (Bank of Canada, 2019), which is 1.59%.

Inflation increases the prices of materials and labor, such that the initial and final costs of a construction project can differ (Musarat, Alaloul, & Liew, 2020). This is called "construction inflation." The level of construction activity also has a direct influence on construction inflation (Zarenski, 2020). With construction actively progressing, the growth in total construction costs will generally outpace the net cost of labor and materials. Thus, to capture this, we applied inflation to the labor and materials costs. Although the discount rate is also impacted by many other factors besides inflation, we have focused on using the inflation rate in this paper for simplicity.

Planning Horizon

The planning horizon is the time within which investment decisions are assessed (Cortazar, Gravet, & Urzua, 2008). There are few explanations on how and why specific planning horizon lengths are chosen in the real options literature. Considering that the GNWT has started to build some portions of the MVH, and plan to continue working on the Environmental Assessment in the next step (GNWT, 2019), we assumed the planning period for the four segments is 15 years (2019-2033).

In addition, the construction time and the highway life of building an all-weather highway in Northern Canada are dictated by many factors, such as geometric and structural design details, labor and equipment availability, site conditions (including permafrost conditions), and weather. In this paper, we assume the construction time and life of all the four segments to be 3 and 20 years respectively.

Results

We present numerical results for each segment's final project option value (NPV^e) and optimal investment times. We also explore the sensitivity of NPV^e results to the key parameters and inputs: OSD volatility, freight demands volatility, and segment construction costs.

Project Value and Investment Year

Following the methodology and input data and assumptions (Data and Modeling Inputs), we obtained the NPV^e and optimal investment (i.e., delay) year for each of the four segments of the

MVH (Table 3). The calculations were run 100 times to obtain 100 NPV^e values for each segment, and averages are reported.

Segment 2 has the largest value ($917M) at an optimal 7-year delay investment time, followed by Segment 1 (9-year delay), Segment 3 (12-year delay), and Segment 4 (14-year delay). Note that Segment 4 is not recommended to be constructed until the end of the planning period; however, given that this analysis only considers a delay option, the greatest value may be obtained by delaying this segment even further or not constructing it at all. The average deterministic NPV, when investing at the calculated construction year, is the average of all deterministic NPVs calculated for each pair of OSD and freight demand simulated paths. We observe that this value is significantly smaller than the NPV^es of all segments, supporting the decisions to delay project investments that would result from the application of our method.

Stentoft (2004) showed that project valuations obtained using the LSM approach will converge to their true values (Figure 4). We further illustrate the results of Figure 4 by plotting the CDFs (cumulative distribution functions) in Figure 5. Figure 5 also shows the 100 run results for each segment NPV^es divided into seven equal bins as per the x-axis. The primary y-axis indicates the number of NPV^e results in each bin, while the secondary y-axis represents the cumulative proportion of results. Figure 5 shows that most NPV^e results (i.e., over half, or 50%) are in the first two bins (shown as dark grey bars). We also note that all NPV^es for all segments are greater than the average deterministic NPV reported in Table 3.

Given project costs and both climate and demand uncertainties, the optimal action for each segment is to delay construction in a "wait and see" approach. In terms of segment construction ordering, Segment 2 should be initiated first in Year 7, followed by Segment 1 in Year 9, Segment 3 in Year 12, and Segment 4 in Year 14 (or beyond, given that the maximum delay allowed is until the last year of the planning horizon, and the optimal time to invest could possibly be beyond this horizon or maybe indefinite). We expected our results to support the construction of Segments 1 or 4 first, followed by the inner segments (adjacent to the segment that was built first), given the limited means to reach the inner segments (i.e., marine in the summer, winter roads in winter, airlift all year round). However, the results can be attributed to several key factors. First, investment costs for Segment 2 are smaller than those of the other segments, given they are proportional to their distances (246, 75, 149, and 348 km, respectively). However, we can also observe that investment cost alone is not the sole driver of segment construction order, given that Segment 1 is to be constructed before Segment 3 despite its much higher price tag. The impacts of demand magnitudes and uncertainties, and other inputs described in *Data and Modeling Inputs*, vary across segments and may have disproportionate impacts. Second, segments costs do not account for the dependencies introduced in construction ordering – meaning, the implications of, for example, Segment 2 being constructed first are not accounted for when looking at the costs of constructing the other segments. To account for this in a "brute force" manner would mean simulating every permutation of segment ordering and resulting costs, and the problem would grow rapidly in size with more and more segments or network size. Thus, further methodological work is required to account for these dependencies.

Interestingly, our results with respect to MVH segment construction order are consistent with the GNWT's current construction plan, which includes building the infrastructures along Segment 2 first, followed by Segment 1; no funding commitments or plans have yet been made to constructing Segments 3 and 4 (GNWT Department of Infrastructure, 2019). The GNWT has already secured funding for Segments 1 and 2, and started construction on Segment 2 with Segment

1 to follow immediately afterwards, different from our analysis recommending that they delay until year 7 for Segment 2 and year 9 for Segment 1.

It is notable that despite high investment costs, the costs of uncertainty within this freight system are significant enough to justify the investment – particularly that the costly Segment 1 should still be constructed before the less costly Segment 3. Overall, investment costs have been a major barrier to the construction of the MVH. Secured funds currently total approximately $160 million (CBC, 2016; GNWT Department of Infrastructure, 2019); the federal government did not include funding for the MVH projects in its 2019 budget (CBC, 2019).

Sensitivity of Results

We explored the sensitivity of the segments' project values (NPV^e) to various inputs, starting with OSD volatility. Figure 6 shows that the project option values increase with increasing OSD volatility (each point represents the average of 100 runs). As OSD volatility grows, the potential cost of airlift in bad seasons increases significantly, and thus, the value of each investment increases.

We then explored the impact of OSD drift. Figure 7 shows that project values increase with increasing % changes to OSD drift (which refers to a decrease in OSD drift – as the drift is negative, % change increase means more negative drift). Each point on the figure represents the average of 100 runs. As OSD drift decreases (% change increase), the potential airlift costs in poor shipping seasons increase significantly, and thus, the value of each investment increases.

Table 4 shows the change in optimal delay years against OSD volatility. As NPV^e increases with OSD volatility, recommended investment delay also decreases. Also, we observe that over all OSD volatility values, the order of segment construction does not change. Overall, the results are rather robust to changes in OSD volatilities, which is largely driven by the relatively high investment costs: Segment 2 is the smallest at \$153M, while Segment 4 is the largest at \$710M. Smaller OSD volatilities (i.e., a negative % change) mean less expected airlift needs and thus lower freight costs on the current barge/airlift delivery paradigm, and thus, smaller roadway project benefits and longer project deferral. However, Segments 1-3 are still recommended for construction within the planning period, although Segment 3 is very close to the end. Segment 4 construction should be delayed to the very end of the planning period (and possibly beyond), except when OSD volatilities grow to extremes at 40-50%.

Figure 8 shows that project values also increase steadily with increasing freight demand volatility. Greater uncertainty in freight volumes means there is greater uncertainty in airlift costs (particularly when freight volumes are close to or exceed river freight capacities based on OSD). However, proportional changes in freight demand volatility appear to have a much larger impact on NPV^e compared with OSD volatility.

Table 5 shows the change in optimal delay years against freight demand volatility. Again, greater volatility in freight demands results in higher NPV^e and decreased project deferral periods. When freight demand volatilities are reduced by 40%, none of the segments of this roadway construction project are recommended for construction during the planning period (if not in the last year, then beyond the planning period). However, the results change as freight demands increase, with Segment 2 construction deferral decreasing most rapidly towards the Segment 2, 1, 3, 4 project ordering. When freight demand volatility is high, the resulting volatility in potential airlift costs is also high, which makes roadway construction more attractive – higher values and thus, lower deferral times.

As previously discussed, construction costs are a major barrier to building all-weather roadways in the north. We further examine the resulting project values by segment investment costs (Figure 9). Generally, smaller investment costs lead to higher NPV^e values. However, there are some outliers. The points shaded in red suggest that increasing investment costs will result in increased rather than decreasing NPV^e, while the blue point suggests that the decrease in NPV^e is higher than expected. These anomalies are simply due to the fact that the LSM method approximates true NPV^e values, and they can be addressed by increasing the number of simulated paths (ω) and/or increasing the number of polynomials. However, both come at the expense of computational efficiency.

Table 6 shows the change in optimal years of delay against changing investment costs. The results again show that Segment 2 should always be constructed first with a 7- or 8-year delay, while Segment 4 should always be delayed to the last year of the planning period (and possibly further). The results again suggest that the results are fairly robust to even large investment cost differences (with ±10% being quite extreme) in terms of delay years and project sequencing. Also, Segment 2 has the second largest initial freight demand at about 58,000 tonnes, while Segment 4 has the smallest at about 45,000 tonnes. The benefits of building Segment 2 to alleviate the uncertainties of the barging system continue to outweigh costs most significantly compared to the other segments.

Finally, we also explored the sensitivity of project values to maintenance costs (Figure 10). The maintenance costs of both the barge-airlift and highway systems increase and decrease, respectively, at the same rate. As maintenance costs increase (i.e., by 50%, from 5% to 7.5%), the increase in potential airlift costs in poor shipping seasons exceeds the increase in highway maintenance costs alone – thus, the value of each investment increases. At a 50% (or 2.5%)

increase to 7.5% maintenance costs, the total investment value increases at approximately the same value, between 2-4%. When maintenance costs are decreased by 50%, we observe a similar proportional decrease in the total systems costs.

Verification of Results

We test the LSM methodology by applying the decision rules (generated in a learning environment) in a non-learning environment. The major decision rules obtained from LSM are encapsulated in each segment's coefficient matrix of Eqn. (14), which contain estimates for $\beta_0 \ldots \beta_5$ for each year of the planning horizon (year $T-1$ to 1). To test our method, we apply these coefficients to newly simulated values of OSD and freight demand, and find the resulting project values (NPV^e). The previous project values generated in the learning environment (first shown in Table 3) and the new project values resulting from a non-learning environment are shown in Table 7 for comparison. We observe that two sets are within 0.33-1.09%. The NPV^e results in the learning environment (Figure 4) converge to their true values; the NPV^e results from the non-learning environment also converge to those values, supporting the validity of our method.

Conclusions

This paper demonstrates the use of ROA to account for uncertainties like climate change and freight demand to support flexible transportation infrastructure investment decisions. We apply ROA to assess decisions about constructing the Mackenzie Valley Highway (MVH) in Canada's Northwest Territories, to replace marine shipping. We demonstrate that construction decisions difficult to support using traditional benefit-cost analysis are in fact justified due to uncertainties significantly impacting project valuations and the allowance of project deferral (or "wait and see") options.

After choosing marine OSD as a proxy for climate change impacts on barging operations, OSD and freight demand were modeled as Geometric Brownian Motions. Next, we developed a benefit-cost model to quantify the value of constructing the four segments of the MVH from Wrigley to Inuvik at different times during the planning horizon. Finally, we implemented ROA using the LSM approach to calculate individual project values and optimal investment times. The results indicate that Segment 2 (Tulita–Norman Wells) should be constructed first after a seven-year delay, followed by Segment 1 (Wrigley–Tulita) with a nine-year delay, while Segment 3 (Norman Wells–Fort Good Hope) and Segment 4 (Fort Good Hope–Inuvik) should wait until the last few years of the planning period. All in all, the results recommend that decision-makers take more time in their decisions, in order to gain more opportunities to changes these costly decisions as conditions change.

Our research offers the following contributions. We combine Benefit-Cost Analysis with ROA in the construction of a framework that allows for the assessment of a major transportation infrastructure project, considering the costs of coordinated operations of multiple modes (marine, air, ground), and incorporating the significant uncertainties presented by climate change (and demand) on both transportation infrastructure and operations. Our framework provides quantitative support for flexibility in infrastructure investment decisions, supporting decision-makers in taking a “wait and see” approach to massive investments subject to massive uncertainties. This is particularly important in northern Canada, where infrastructure investment decisions are dominated by the need for climate change adaptation; however, with this need growing ever more critical throughout the world, our method can be broadly applied to assess any major transportation infrastructure investment considerations. Our framework provides a means to quantify and clearly communicate how uncertainties can be included in benefit-cost analyses, to support flexibility in investment decisions – stakeholders in northern Canada include Indigenous governments, federal and territorial governments, resource companies, and others. In this paper, we focused solely on transportation infrastructure and freight operations costs, and did not consider other indirect benefits and external costs that are often difficult to quantify and also, debated (e.g., benefits from more employment and tourism, profits from more natural resource exploration, and Arctic sovereignty (Mackenzie Aboriginal Corporation, 2007)). These considerations can add significantly to project benefits. Overall, we see our framework as one tool in a larger decision-support toolbox for transportation investments in northern Canada.

There are many opportunities to improve and build on this work. First, it is important to consider winter roads in capturing a comprehensive picture of the entire transportation system. Second, although GBM is the most common process used to represent uncertain inputs in ROA, these inputs may not follow the assumptions of GBM. Third, as mentioned earlier, the methodology should be improved to account for project interdependencies and interdependent outcomes. Fourth, both construction and maintenance costs should be considered as important sources of uncertainty in such models of infrastructure decision-making. However, because the focus of this research was to consider how climate change uncertainties could be quantitatively incorporated into infrastructure decisions in northern Canada, we did not consider other uncertainty sources besides climate change and freight demand for the sake of model complexity and tractability. In future research, we aim to include more sources of uncertainty (potentially leading to real options both “on” and “in” system), with contributions towards developing more a computationally efficient solution method that allows for this.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon request. Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. The NTCL tow letters data is confidential. Available data includes Canadian Coast Guard buoy placement and removal dates. Maps and model code can also be made available upon request.

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Table 1 Model Data Sources

Input	**Unit**	**Source**	**Application**
Freight demand	Tonne	NTCL	Benefit-Cost Analysis; stochastic (GBM) model
Historical open season days (OSD)	Days/year	Canadian Coast Guard	Climate proxy; stochastic (GBM) model
Freight transport costs			
· Barge	$/tonne	BBE Expediting	Benefit-Cost Analysis
· 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	
· Variable cost	$/tonne	*Assumption*	
· Plan period	Years	*Assumption*	
· Average daily freight volumes	Tonne/day	NTCL, CCG	

Table 2 Segment Lengths and Construction Costs

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

Table 3 Final Project Values (NPV^e), Optimal Investment Time, and Average Deterministic NPV

MVH Segment	NPV^e ($M)	Delay years from 2019 (construction year)	Average Deterministic NPV ($M)
1	784	9 (2028)	278
2	917	7 (2026)	463
3	590	12 (2031)	157
4	457	14+ (2033+)	69

Table 4 Optimal Delay Years by OSD Volatility

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

Table 5 Optimal Delay Years by Freight Demand Volatility

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

Table 6 Optimal Delay Years by Investment Cost

% change	Segment 1	Segment 2	Segment 3	Segment 4
-10	9	7	12	14
-8	9	7	12	14
-6	9	8	11	14
-4	9	7	12	14
-2	9	8	11	14
0	9	7	12	14
2	10	7	12	14
4	10	7	12	14
6	10	7	12	14
8	10	7	12	14
10	10	8	12	14

Table 7 Comparison of NPV^es in Learning and Non-learning Environments

MVH Segment	NPV^e in learning environment ($M) (average of 100 runs)	NPV^e in non-learning environment ($M) (average of 100 runs)	Percentage difference (%)	Acceptable? (Y/N) [1]
1	784	781	-0.38	Y
2	917	920	0.33	Y
3	590	588	-0.34	Y
4	457	452	-1.09	Y

[1] If NPV^e results in the non-learning environment converge to the true values in Figure 4, they are considered acceptable.

Figure 1 NWT transportation network and planned Mackenzie Valley Highway (in four segments, from Wrigley to Inuvik) [Adapted from the Government of the Northwest Territories (2018a) and Kim & Li (2020)].

Figure 2 Infrastructure decision modeling process.

Figure 3 Freight volumes delivered on the four segments of the Mackenzie River, 2002-2014.

Figure 4 MVH project NPV^e results (each segment's box-and-whiskers represents 100 runs each).

Figure 5 MVH project NPV^e results (each segment's CDF represents 100 runs each).

Figure 6 Sensitivity of NPV^e to OSD volatility (each point represents average of 100 runs).

Figure 7 Sensitivity of NPV^e to OSD drift (each point represents average of 100 runs).

Figure 8 Sensitivity of NPV^e to freight demand volatility (each point represents average of 100 runs).

Figure 9 Sensitivity of NPV^e to segment investment cost (each point represents average of 100 runs).

Figure 10 Sensitivity of NPV^e to maintenance cost (each point represents average of 100 runs).

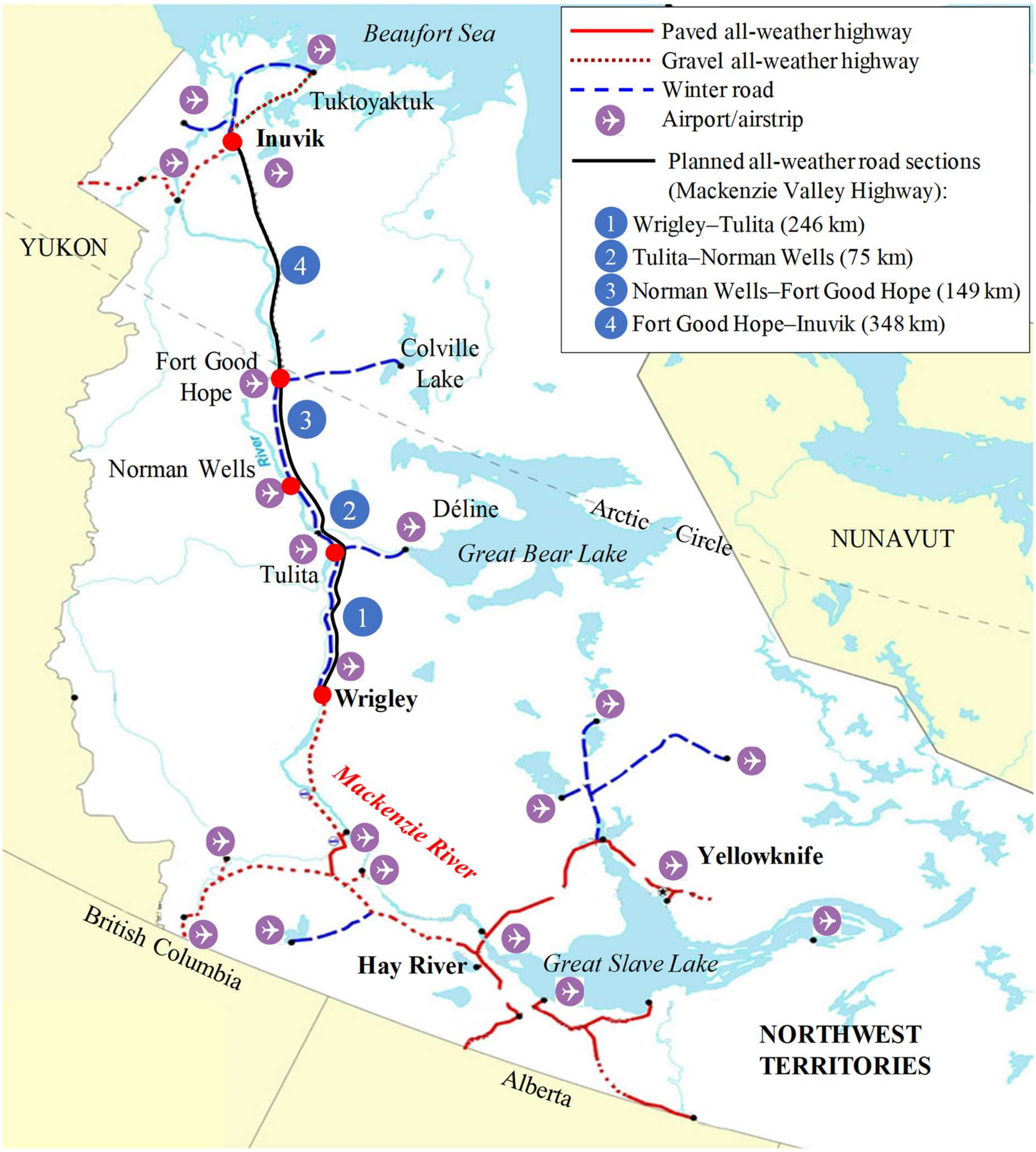

Paved all-weather highway
Gravel all-weather highway
Winter road
Airport/airstrip
Planned all-weather road sections (Mackenzie Valley Highway):
1 Wrigley–Tulita (246 km)
2 Tulita–Norman Wells (75 km)
3 Norman Wells–Fort Good Hope (149 km)
4 Fort Good Hope–Inuvik (348 km)
Beaufort Sea
Tuktoyaktuk
Inuvik
YUKON
4
Colville Lake
Fort Good Hope
3
River
Norman Wells
2
Déline
Arctic Circle
Great Bear Lake
Tulita
NUNAVUT
1
Wrigley
Mackenzie River
Yellowknife
British Columbia
Hay River
Great Slave Lake
NORTHWEST TERRITORIES
Alberta

Fig. 1

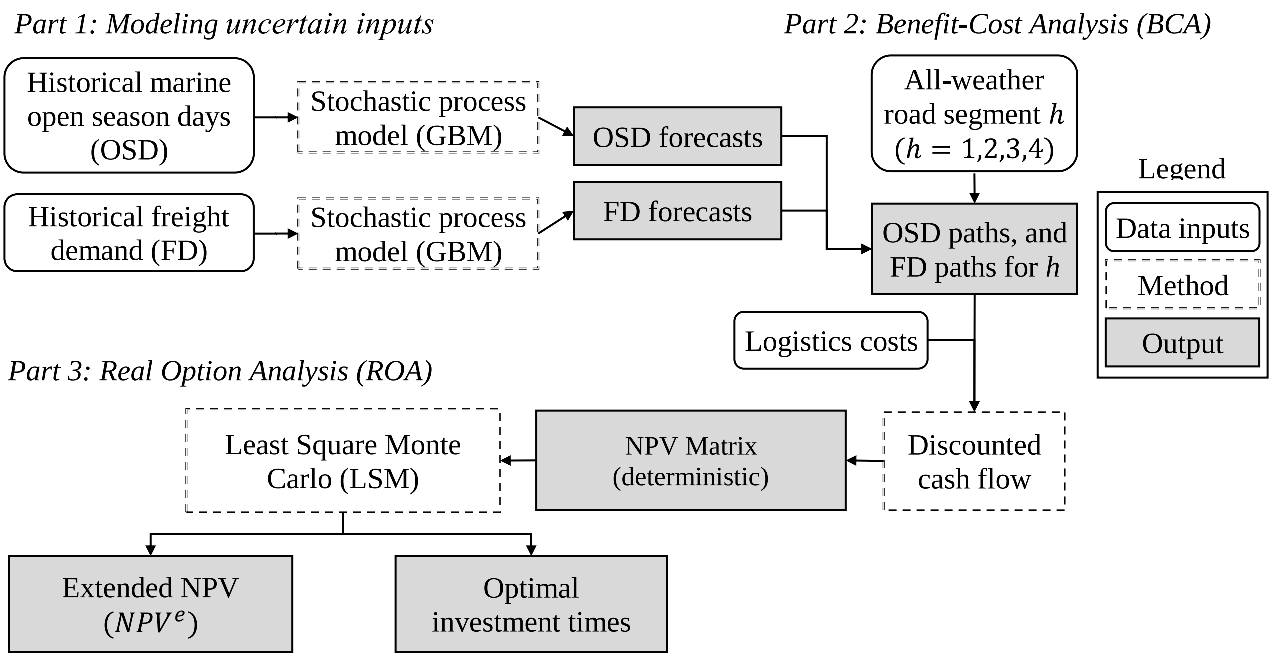

Part 1: Modeling uncertain inputs
Part 2: Benefit-Cost Analysis (BCA)
Historical marine open season days (OSD)
Stochastic process model (GBM)
OSD forecasts
Historical freight demand (FD)
Stochastic process model (GBM)
FD forecasts
All-weather road segment h ($h = 1,2,3,4$)
OSD paths, and FD paths for h
Legend
Data inputs
Method
Output
Logistics costs
Part 3: Real Option Analysis (ROA)
Least Square Monte Carlo (LSM)
NPV Matrix (deterministic)
Discounted cash flow
Extended NPV (NPV^e)
Optimal investment times

Fig. 2

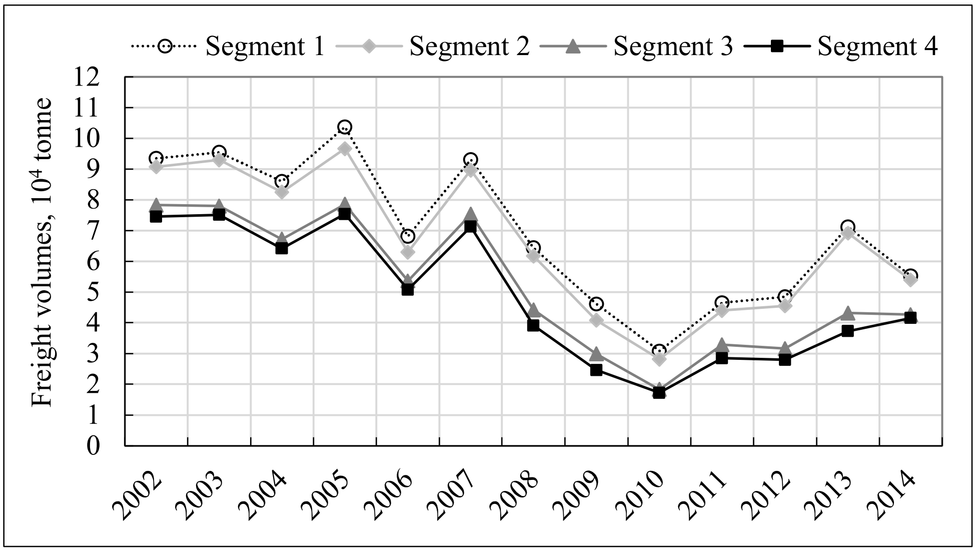

Segment 1
Segment 2
Segment 3
Segment 4
Freight volumes, 10^4 tonne
0
1
2
3
4
5
6
7
8
9
10
11
12
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

Fig. 3

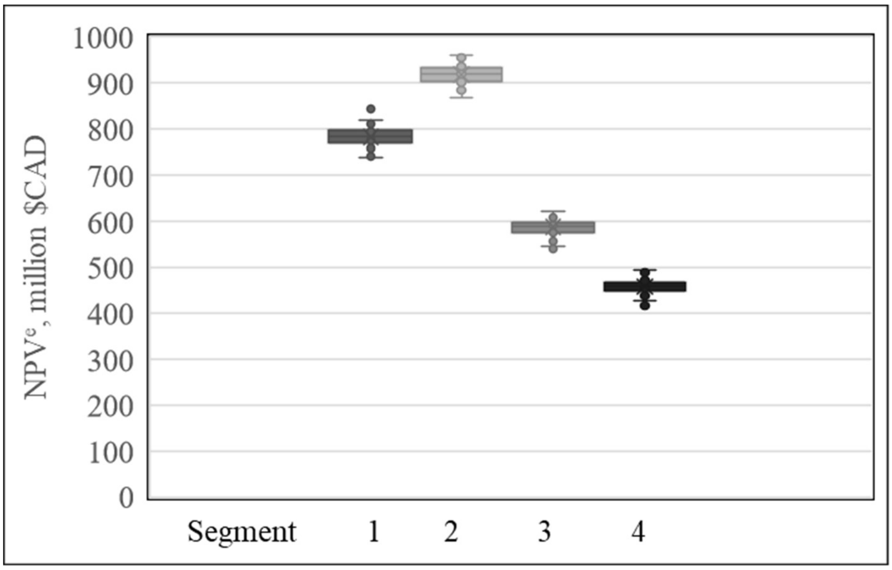
 NPV^e, million $CAD
1000
900
800
700
600
500
400
300
200
100
0
Segment
1
2
3
4

Fig. 4

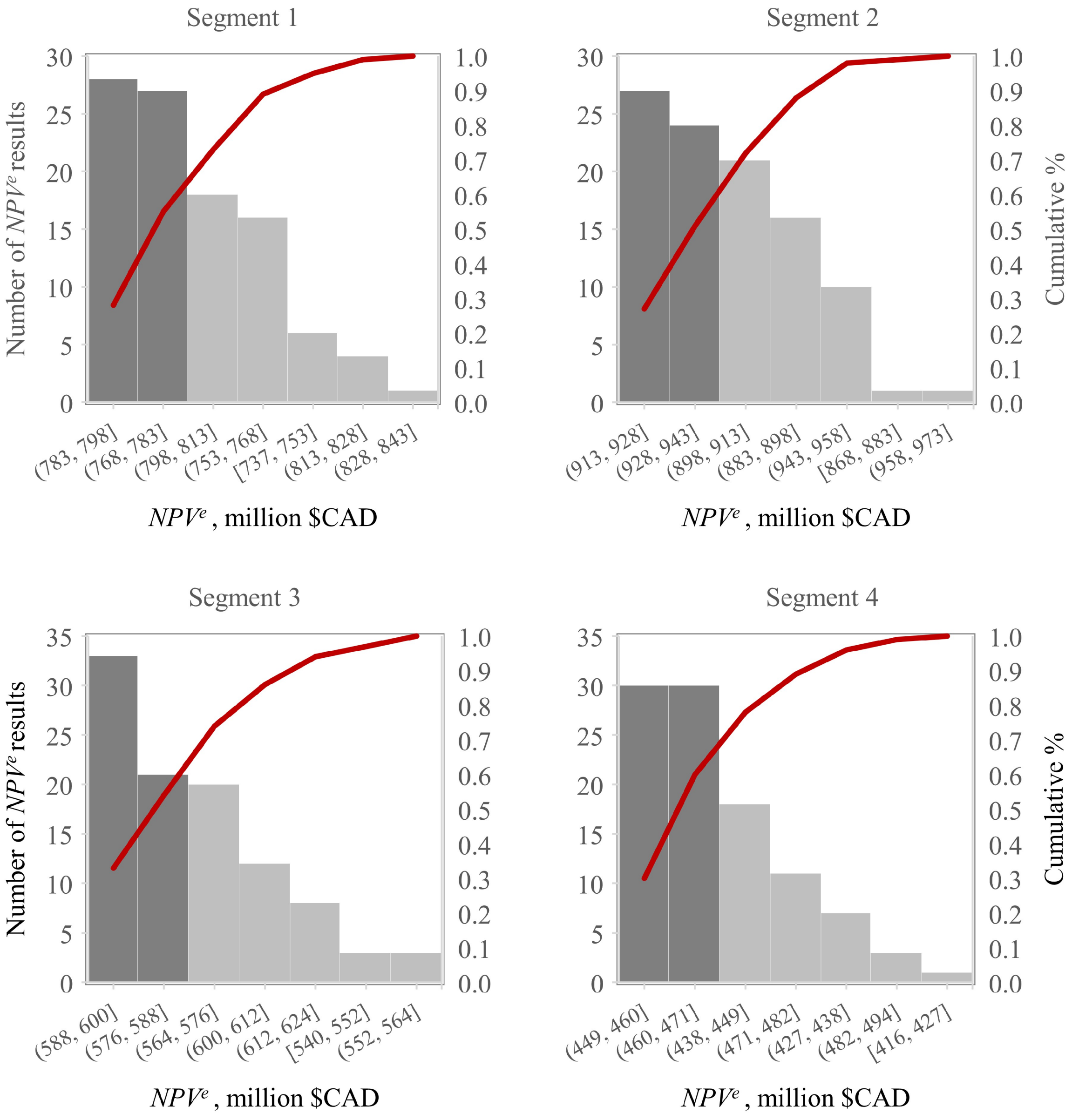

Segment 1
Number of NPV^e results
30
25
20
15
10
5
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
(783, 798]
(768, 783]
(798, 813]
(753, 768]
[737, 753]
(813, 828]
(828, 843]
NPV^e, million \$CAD
Segment 2
30
25
20
15
10
5
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative %
(913, 928]
(928, 943]
(898, 913]
(883, 898]
(943, 958]
[868, 883]
(958, 973]
NPV^e, million \$CAD
Segment 3
Number of NPV^e results
35
30
25
20
15
10
5
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
(588, 600]
(576, 588]
(564, 576]
(600, 612]
(612, 624]
[540, 552]
(552, 564]
NPV^e, million \$CAD
Segment 4
35
30
25
20
15
10
5
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Cumulative %
(449, 460]
(460, 471]
(438, 449]
(471, 482]
(427, 438]
(482, 494]
[416, 427]
NPV^e, million \$CAD

Fig. 5

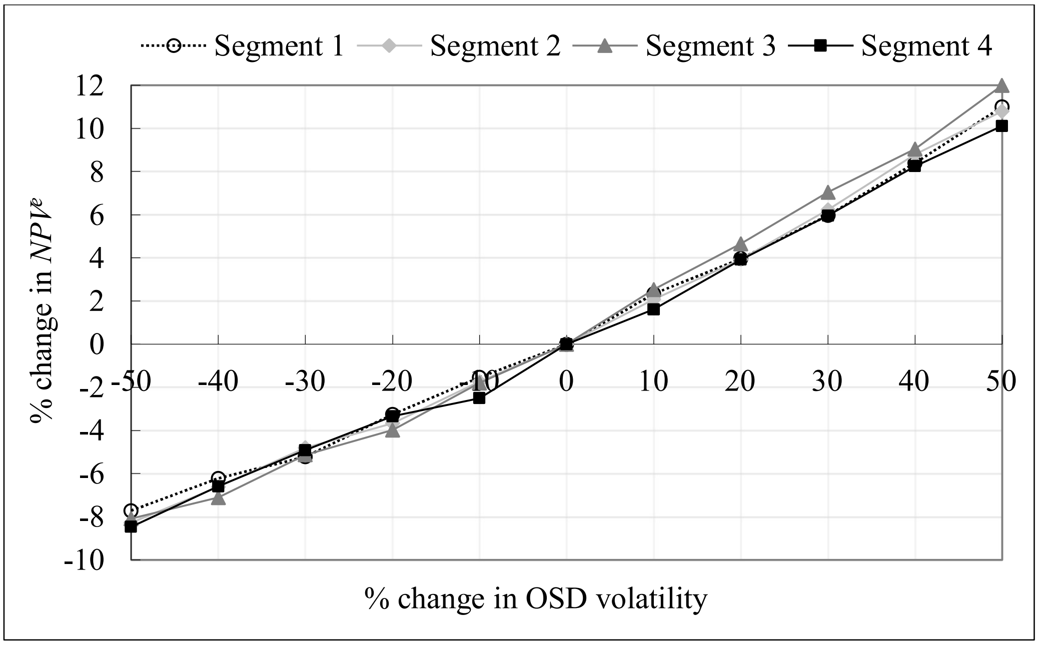
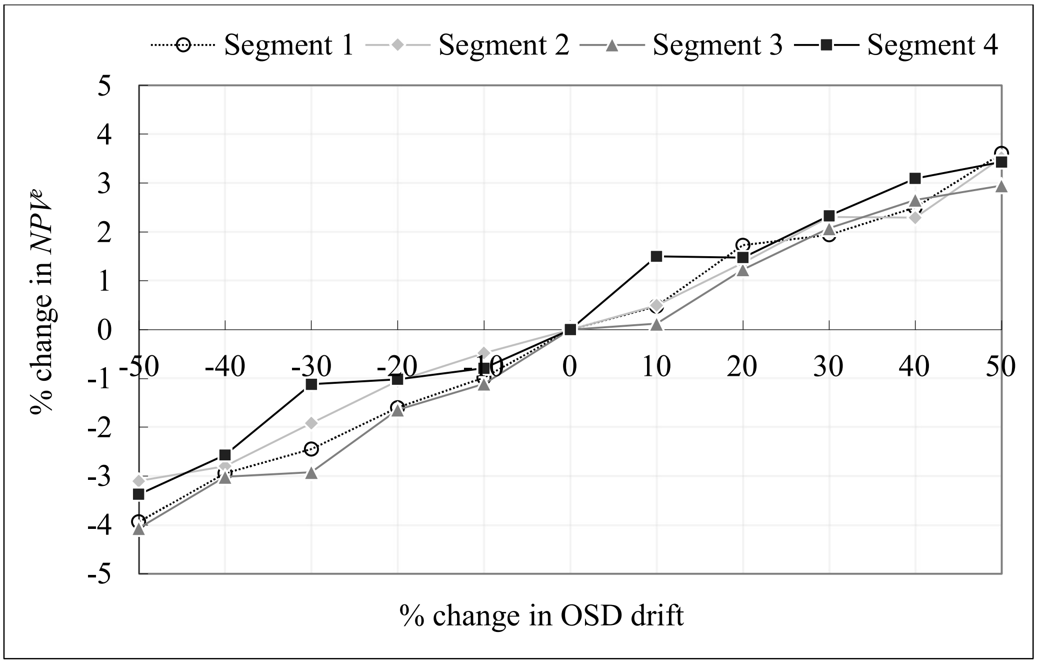

Segment 1
Segment 2
Segment 3
Segment 4
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
% change in NPV^e
-50
-40
-30
-20
-10
0
10
20
30
40
50
% change in OSD volatility

Fig. 6



Segment 1
Segment 2
Segment 3
Segment 4
% change in NPV^e
5
4
3
2
1
0
-1
-2
-3
-4
-5
-50
-40
-30
-20
-10
0
10
20
30
40
50
% change in OSD drift

Fig. 7

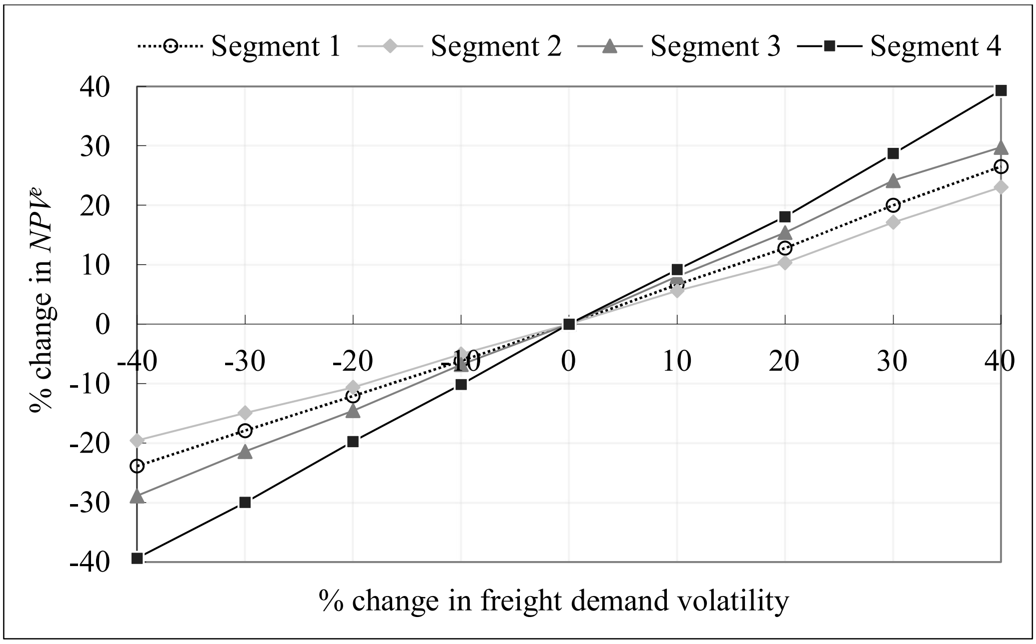

Segment 1
Segment 2
Segment 3
Segment 4
% change in NPV^e
40
30
20
10
0
-10
-20
-30
-40
-40
-30
-20
-10
0
10
20
30
40
% change in freight demand volatility

Fig. 8

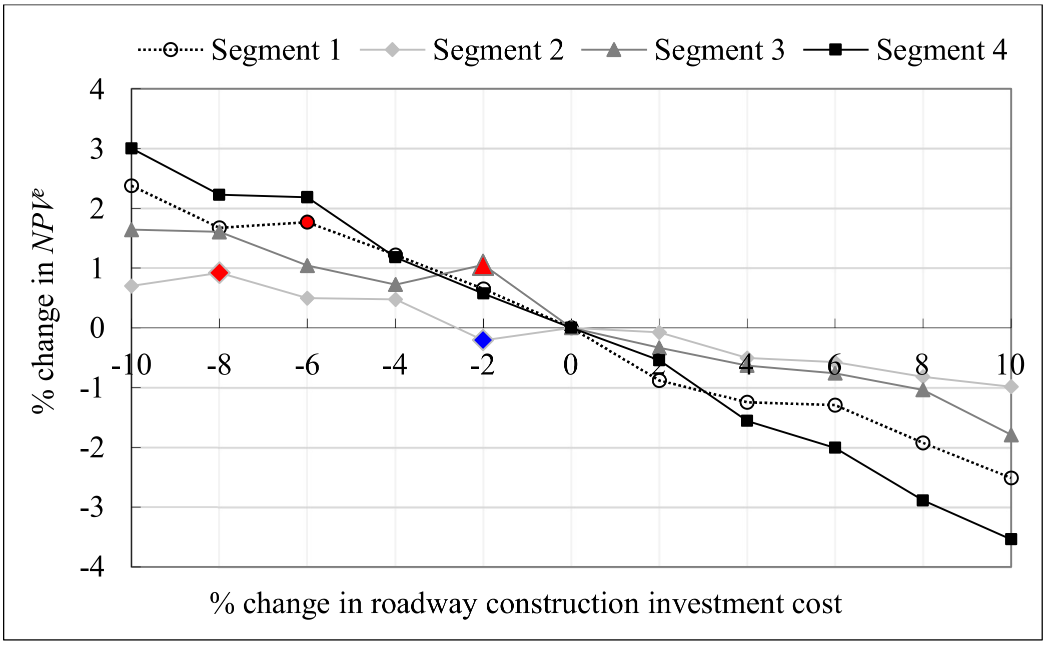

Segment 1
Segment 2
Segment 3
Segment 4
% change in NPV^e
4
3
2
1
0
-1
-2
-3
-4
-10
-8
-6
-4
-2
0
2
4
6
8
10
% change in roadway construction investment cost

Fig. 9

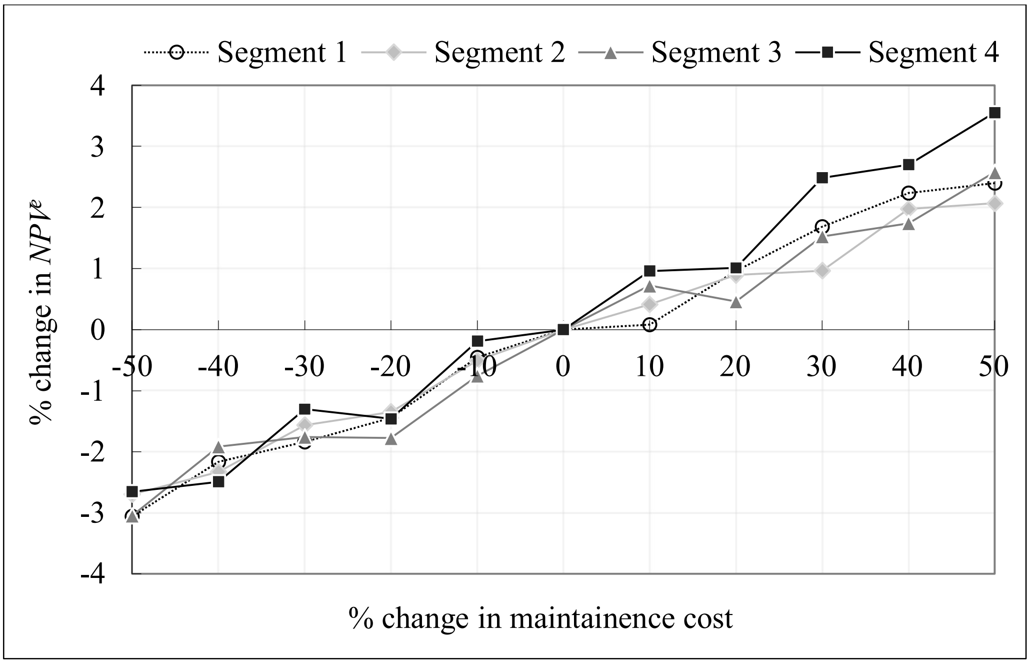

Segment 1
Segment 2
Segment 3
Segment 4
% change in NPV^e
4
3
2
1
0
-1
-2
-3
-4
-50
-40
-30
-20
-10
0
10
20
30
40
50
% change in maintainence cost

Fig. 10