Economics of Making Roadway Pavements Resilient to Climate Change: Use of Discounted Cash Flow and Real Options Analysis

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Abstract: An increase in the number of extreme weather events and gradual shifts in climate parameters due to a changing climate pose a serious threat to the nation's roadway infrastructure. A systematic approach is needed to define risks and assess consequences of climate change, consider the uncertainties, rank priorities, and initiate an adaptation strategy in a cost-effective manner. The objective of this study is to develop a framework that could be used to assess the impact of climate change on pavements in a rational way using either the net present value (NPV) or the real option (RO) approach to compare several options and to make the most prudent decision regarding selecting an option and the time of adopting that option. The NPV approach will generally go against an investment in cases with high uncertainty, even if they are very promising, and does not take into account the flexibility or decisions that could be implemented on the basis of changing conditions. In contrast, the RO method offers a flexible deferment option when the uncertainties regarding outcomes are resolved to a certain extent. A framework with a step-by-step method for evaluating the feasibility of building roads that are resilient to a changing climate is presented, along with an example. The worked-out example shows that there could be considerable value in using RO analysis, and this value can be leveraged to develop better economic policies for building roads that are resilient to a changing climate. **DOI: 10.1061/(ASCE)IS.1943-555X.0000494.** *© 2019 American Society of Civil Engineers.*

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Introduction

Disruptions in the transportation system in the form of deteriorated roads and resulting construction work have a major negative impact on the nation's economy and productivity. Climate change, as evident from numerous research studies and predictions, pose a serious threat to the nation's roadway infrastructure. The impact of climate change involves a range of factors (PIARC 2012; Brinckerhoff and ICF International 2014; Douglas and Merrill 2016) that are related to climate science, roadway infrastructure/engineering, and economics. The overall effect of climate change will be to increase the cost of maintenance and rehabilitation to keep the pavements at their current serviceability levels. For example, a recent EPA report (EPA 2015) mentions the adaptation costs for roads due to climate change in 2100 as ranging from \$5.8–\$10 billion. To counter this problem, a systematic approach is needed to define risks and assess consequences, rank priorities, and initiate an adaptation strategy to mitigate risks in a cost-effective manner. However, one of the biggest challenges in the assessment of the impact of climate change is that the different climate change factors have different levels of uncertainties (Potential Impacts of Climate Change on US Transportation 2008). This makes it difficult for agencies to adopt a specific plan of action for comparing different options to counter the impacts of climate change on pavements. Therefore, a framework is needed to consider these uncertainties, develop and compare different options, and then select the most desirable option and the time for its adoption for designing and building roads that are resilient to changing climate.

Existing and New Approach

The general approach to evaluating project feasibility or comparing alternatives is to estimate the discounted cash flow (DCF) for different years and compute a net present value (NPV) (Walls and Michael 1998). The NPV is the discounted monetary value of expected net benefits (benefits minus costs). In DCF, a single discount rate is used to capture all future cash flows, even though a sensitivity analysis and a simulation based on high impact factors such as the discount rate could be carried out to obtain a probabilistic value. The three improvements from the deterministic DCF method are sensitivity analysis, scenario analysis, and Monte Carlo (MC) simulation, which depends on the use of an accurate distribution of the input variables. The scenario analyses give the best, worst, and base cases—the results are dependent on the probabilities of each scenario selected by users. In the DCF and NPV approaches, an investment is made if the NPV comes out positive or higher than that of a competing alternative. This approach will generally recommend against investment in cases with high uncertainty, even if they are very promising. It also does not take into account the flexibility or decisions that could be implemented on the basis of changing conditions.

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The real option (RO) method (Dixit and Pindyck 1994; Amram and Kulatilaka 1999; Mun 2016; Kodukula and Papudesu 2006) offers a much more flexible approach to projecting valuation. It offers an abandonment or termination option or a deferment option when the uncertainties regarding outcomes are resolved to a certain extent. The agency can retain the right to expand (but no obligation), and if, within a certain time, the "conditions" turn out to be favorable, the agency will exercise the option, otherwise it will not. And if a project has the option to expand (or contract), then its value is greater than a project that does not have this option. In typical budgeting operations based on DCF and NPV, the assumption is that the agency will go ahead with the implementation *right* now (or at a certain start period) and will not have the flexibility to wait and decide to implement only if conditions are favorable. A RO analysis gives not only an alternative project value (as distinct from traditional NPV) but also a way to select the optimum timing of implementation. RO utilizes DCF along with a decision tree approach to overcome the limitations of the traditional approach. A RO is a right, not an obligation, to take an action on an underlying nonfinancial real asset (Kodukula and Papudesu 2006). The action can be abandoning, expanding, contracting, or deferring a decision to a later date. RO is particularly relevant for resilience against climate change because of the uncertainty in changes in climate-related factors that affect the performance of infrastructure and because, over time, due to progress in modeling capabilities, the uncertainty in prediction is being reduced rapidly. This means that instead of committing to build "thicker" or "stronger" infrastructure components at this time, it is better, wherever possible, to build in stages and wait for the extra investment required for resiliency, for a certain period of time, by which the uncertainty will be greatly reduced.

Recently, RO has been used on infrastructure projects on the recommendation of several researchers. Ford et al. (2002) demonstrated the use of RO for the evaluation and selection of strategies for a toll road project in the face of dynamic uncertainties. De Neufville (2002) and Tao and de Neufville (2005) have introduced and discussed RO *on* and *in* projects—RO *on* projects treats technology as a black box, whereas RO *in* projects seeks to create value by actually improving technology. Kumbaroglu et al. (2008) presented a study on integrating learning curve information into a RO model for investment in renewable power generation technologies. Tan et al. (2009) discussed the use of a systems dynamics approach and RO for the wind power industry in the face of uncertainties and issues related to managerial flexibility. Mittal (2004) discussed the effectiveness of RO analysis for capacity planning decisions in the face of uncertainty. Hassan et al. (2005) provided a RO valuation methodology for complex engineered systems. Johnson et al. (2006) described applications of system dynamics and RO in the oil industry. Kashani (2012) provided a RO model for the valuation of a build–operate–transfer (BOT) project under traffic demand uncertainty. Chiara et al. (2007) presented a multi-least-squares Monte Carlo technique for valuing RO for infrastructure projects. Menassa and Mora (2009) proposed a hybrid model consisting of RO and system dynamics as a means of resolving disputes involving the valuation of investments. Ammerlaan (2010) investigated the implementation of RO in engineering projects and proposed a conceptual design for the adoption of RO by organizations managing engineering projects. Geltner and Neufville (2012) identified RO as one of the best "tools" in the 21st century for the effective development of infrastructure and real estate in the face of uncertainty. Athigakunagorn (2015) proposed a methodology of using RO for scheduling maintenance and rehabilitation work by agencies for managing highway assets. No RO-related work has been reported so far that has considered the subject of pavement rehabilitation with a consideration of climate change.

Objective

The objective of this study is to develop a framework that could be used to assess the impact of climate change on pavements in a rational way using either NPV or RO, to compare several options, and to make the most prudent decision regarding selecting an option and the time of adopting that specific option. The framework is illustrated with an example that includes a comparison between the NPV and RO approaches.

Framework

The proposed framework consists of several sequential steps, which are explained in what follows.

Identify and Quantify Key Climate Change Parameters That Have the Most Significant Impacts on Pavement Properties and Performance

Though the key climate change parameters and their magnitude differ by region, European and North American studies have identified many common parameters and potential impacts (PIARC 2012). Increased precipitation can lead to intensified flooding, increase landslide-related road closures, and impact the structural integrity of pavements. Decreased precipitation can dry out subgrades and impact the durability of pavements. Coastal countries will be impacted by rising sea water levels combined with storm surges that will flood roads. In northern regions, changing winter conditions may increase the frequency of freeze-thaw cycles, causing cracking related frost heave and potholes. Increased temperatures may increase rutting and bleeding in asphalt pavement layers and deformation in rigid pavements.

Identify Pavement Adaptation Options

The options available to pavement designers in building pavements that are resistant to key climate change parameters generally relate to materials or thickness: provide more resistant materials, make pavements thicker, or both (with a corresponding increase in the costs of construction). For example, appropriate polymer modifications to asphalt binder can make it less sensitive to changes in temperature and, hence, make pavement more resistant to rutting failure under high-temperature conditions. Similarly, an increase in thickness can make pavement resistant to premature failure, for example by lowering the stresses at the subgrade level, thereby offsetting the reduction of the modulus in that layer due to an increase in precipitation.

Determining Pavement Life and Mileage of Roads That Will Need Rehabilitation

Researchers have used mechanistic-empirical (NCHRP 2004) (Mechanistic Empirical Design Guide, MEPDG) methods to demonstrate the impact of climate change on pavement performance. For example, Meagher et al. (2012) modified climate data files generated from the Integrated Climate Model (ICM) to show that climate change impacts could reduce pavement lives significantly. Mallick et al (2014, 2016) presented a system dynamics model in which the climate change parameters were related to pavement life using regression equations from data generated from repeated runs of the MEPDG and, finally, to the mileage of roads that will require rehabilitation in any year (object function). The utility of this approach is that the cumulative impact of the progressively shortened life of pavement (due to the impact of climate change) can be demonstrated very clearly in terms of its economic impact. The results of this work clearly showed a significant upward swing of roads that need rehabilitation (and, hence, cost of rehabilitation) as a result of climate change.

Economic Analysis

For each potential option (for resilience against climate change), the cost changes in different years based on reductions in the mileage that requires rehabilitation compared to the base case. Cost recovery will occur over time due to the reduction in rehabilitation costs. Providing better materials or thicker layers (options) can be used as measures to provide added resistance to deteriorating climate conditions. These measures involve higher levels of spending compared to those required for conventional pavements (Chinowsky et al. 2013). However, if the designer does adopt one of these options, then the pavements will not deteriorate as fast as they would under the climate change and conventional pavement scenario. As a result, the life of the pavement will not shorten, or shorten significantly less (depending on the option), so the rate of deterioration of pavements will not increase or increase as rapidly as a result of climate change. This means that at any point in time, the mileage of roads requiring rehabilitation will be lower than that under a scenario of climate change and conventional pavement. The difference in projected costs of rehabilitation of pavements built with one of the options and without, at any specific time, can be considered savings or payback as a result of adopting the specific option (Mallick and Nazarian 2018). However, because the option involves spending extra funds initially, in justifying the use of that option one must conduct an economic analysis. Therefore, the NPVs of several options for making pavements resistant to climate change effects need to be determined and compared against each other, and the option that shows the highest positive value can be explored further as the most suitable one.

Uncertainty Analysis

Climate parameters are uncertain, and that uncertainty may propagate nonlinearly through prior analyses. A deterministic evaluation of NPV cannot provide insight as to the impact of potential parameter variability. Scenario analysis and Monte Carlo simulations are tools that can capture the resultant uncertainty. First, a sensitivity analysis needs to be conducted to determine the parameters that have the most effect on NPV by varying the inputs by a fixed percentage in either direction, calculating the corresponding changes in NPV, and then ranking the variables according to their impacts from high to low. Next, a scenario analysis can be conducted by considering worst-, base-, and best-case scenarios by changing the paybacks to a minimum, base case, and a maximum, calculating the NPVs for each case, assigning probabilities to each case, and then calculating an expected NPV. The drawback of this method is that the probabilities are arbitrarily selected. Next, Monte Carlo simulations of NPVs can be conducted by considering appropriate distributions of the most significant variables and simultaneously varying all of them. This results in the estimation of a confidence interval for the NPV instead of a single value. Now what happens if the confidence interval is large and includes a small negative value? Is that option discarded? This is where RO analysis comes in.

Using Real Option Analysis to Determine Option Feasibility

In this method, an agency can consider the uncertainty in payback, retain the flexibility of making decisions at certain points in the future, and then use a decision tree approach to project the NPVs for different courses of action over a given time period. The end result of this analysis will be the option value, which tells the agency whether it is worth waiting and then making a decision at some future time when the uncertainty will be reduced or resolved. The results will also be in the form of a NPV that will need to be compared against any upfront fees the agency might have to pay to avail itself of the RO option. In RO analysis, the asset value at any specific time in the future is determined through the use of a volatility factor. This factor is calculated from future discounted cash flows. The RO value can then be calculated using either a closed-form solution, an analytical formula, or a decision-tree-like diagram, such as a lattice diagram, typically a binomial lattice diagram. In reality, there is a range of outcomes from a specific project, and the uncertainty of those outcomes increases over time (imagine a "cone of uncertainty" over time). The RO analysis takes into account all of these uncertainties over a time period and calculates a composite value of the outcome, assuming that the whole time the project manager will make the right decision at any given point—the value-maximizing decision. If the value of the option is found to be significant (such as a highly positive number and much greater than the traditional NPV based on discounted cash flow), then it would make sense to actually go with that option (Kodukula and Papudesu 2006).

Volatility is the standard deviation of the probability distribution of the potential changes in the asset's value. It is a function of uncertainties of the different variables used in RO analysis. It is relatively easily estimated for financial options, such as stock options, from historical information on the value of the underlying stock. However, in the case of RO, the volatility factor is usually estimated from the projected returns on an asset in the future, based on a current understanding of the problem or important issues (e.g., in this case, the impact of climate change). Volatility indicates how much of a gap in understanding there is at the current time—for example, low volatility in this case would mean a high confidence in climate change predictions.

Identify the Most Prudent Course of Action

The NPV results from the RO analysis and that from conventional DCF analysis should be compared. If the RO NPV is significantly positive and greater than that from the DCF analysis, then the RO analysis results should be given consideration. The concept of RO is relevant, for two reasons. First, the pavement agency, which may very well be a private organization in the future, may need to borrow money from a bank to finance its projects, and second, it may be able to secure the option (but not take on any obligation) to take out a loan within a certain period of time for a relatively low upfront fee. Within that time, if project conditions become favorable, that is, if the projected discounted cash flows are such that the NPV is very attractive, then the agency will take out the loan and complete the project; if the conditions are unfavorable, then it will decline that option, will not take out the loan, and will not implement the project. In the first case, the agency will be able to secure the loan at a decent rate of interest for the small upfront fee and thus expect a good return on the project. In the second case, the agency will lose the small upfront fee but not lose a larger amount by NOT implementing the project. The value added by the option to defer a project is the NPV of that option minus the option of investing in it at present. The essential difference between the discounted cash flow (and traditional NPV) calculation and the RO approach is that the former takes into account only negative predictions, as of now, whereas the latter takes into account both negative and positive predictions in the future and gives the agency the flexibility to wait before making a decision. That is, the DCF/NPV approach takes into consideration the downside of risk only—it ignores the rewards of risk.

Example

With the framework and steps now laid out, the process can now be illustrated with an example, through Steps 1–6. The problem is as follows. A DOT needs to rehabilitate an asphalt pavement. The road under consideration has 200 mm hot mix asphalt (HMA) over a 600 mm thick granular base course with an effective resilient modulus value of 133 MPa and a subgrade, two-way annual average daily truck traffic (AADTT) of 2,500, and traffic growth of 4% per year. Each lane-km consists of a 3.6 m (12 ft) wide main lane and a 1.8 m (6 ft) wide shoulder. The rehabilitation work conventionally uses a 75 mm thick HMA (binder + surface) layer with a conventional mix. The DOT needs to decide whether or not to account for climate change.

Identify and Quantify Key Climate Change Parameters

For this example, the climate change parameters of interest are increased precipitation and air temperature. The most significant impact of higher precipitation is on the subgrade that suffers a major reduction in stiffness as a result of an increase in saturation, and increased precipitation increases the period for which the subgrade can be expected to be saturated. Air temperature has the most significant effect on the properties of the HMA. The stiffness of the asphalt binder is very sensitive to temperature, and an increase in temperature leads to a decrease in the stiffness of the mix and in the structural capacity of the pavement. Example values of change in maximum air temperature and annual precipitation are selected from a previous study for several cities across the United States (Mallick et al. 2016) that used Coupled Model Intercomparison Project Phase 5 and climate change projections from nine global climate models (GCMs). The selected rates of change values for this example are 0.063°C per year (mean) and 0.013°C (standard deviation) for maximum air temperature and 1.406 mm per year (mean) and 0.45 mm per year (standard deviation) for mean annual rainfall.

Identify Pavement Adaptation Options

Five options are identified as follows:

Case 1: Conventional approach: 75 mm HMA with PG 64-28 binder.

Case 2: 75 mm + 25 mm (total, 100 mm) HMA with PG 64-28.

Case 3: 75 mm + 75 mm (total 150 mm) HMA with PG 64-28.

Case 4: 75 mm layer with PG $64-28+25$ mm HMA with PG 70-28.

Case 5: 75 mm layer with PG $64-28+75$ mm HMA with PG 70-28.

Determine Pavement Life and Mileage of Roads That Will Need Rehabilitation

System dynamics (SD) is used to accomplish this objective by tying changes in climatic conditions to the life of pavements and the mileage of pavements that will require rehabilitation at any given time (Mallick et al. 2016). The change in climatic conditions affects the pavement layer stiffness (moduli), which in turn affects the average pavement life and, hence, the mileage of roads that need rehabilitation at any specific time. The linkages between the different parameters are obtained from regression equations that are generated through repeated running of the MEPDG analysis (NCHRP 2004). The runs are repeated for different options, and the mileages of roads that need rehabilitation are estimated in different years. The differences between each of the different cases and the conventional case in the different years were treated as payback or DCFs for each case.

Series of analyses were carried out to estimate pavement life (critical distress, total rutting). From the analyses four key parameters were extracted and listed along with the rutting life—two controllable parameters, HMA layer thickness, and PG grade—and two that are affected by changes in maximum air temperature and precipitation, the minimum HMA modulus, and the subgrade modulus. Using the analysis output, the following regression equation was developed:

$$\begin{aligned}\text{Pavement life (years)}\\ &= -28.57 + 0.10 \times \text{Resilient modulus of subgrade soil (MPa)}\\ &\quad + 0.001 \times \text{Minimum HMA dynamic modulus (MPa)}\\ &\quad + 0.199 \times \text{HMA layer thickness (mm)}\\ R^2 &= 0.95 \qquad (1)\end{aligned}$$

The regression models that relate pavement life to the four influencing factors were developed from repeated runs of the MEPDG with the pavement structure that was considered in this study. The SD model was developed by considering maximum air temperature and average annual rainfall as two climate change–related relevant factors, relating them to maximum asphalt layer temperature and saturation, and hence asphalt mix and soil resilient modulus, respectively, linking the life of the pavement with the temperature and modulus through regression equations that were developed from repeated runs of the MEPDG and finally using the life to determine the average annual deterioration and, hence, the mileage of road that would require rehabilitation at any given time. In the overall model, a link was thus established between the first considered factors, that is, the maximum air temperature and average annual rainfall, and the parameter of interest, the mileage of roads requiring rehabilitation at any time.

In the next step, the SD model (Mallick et al. 2016) was used to link the changes in climate change–related factors to pavement life and, hence, road mileage requiring rehabilitation at any given time. The mileage of roads was selected since ultimately an economic analysis is desired. The total length of the road network was assumed to be 100 km, so that the values of the mileage of roads requiring rehabilitation could be considered directly as a percentage of the total roadway network. The SD model was simulated for different options that could be considered for rehabilitation.

Using the data obtained from these simulations, equations were developed that relate the percentage of roads requiring rehabilitation in any given year for four different years (8, 16, 24, and 32) to the rate of change in rainfall and maximum air temperature, as shown in Table 1. Note that for better materials and thicker structure, the sensitivity of the pavement decreases, both with respect to time and climate change stressors.

Economic Analysis

Next, considering a roadway network of 10,000 km, for three percentiles of rates of change in maximum air temperature and average

Table 1. Equations from analyses of data from system dynamics simulations

Case	Year			
	8	16	24	32
1	$Y = 31.47 + 2.30 \times X_1 + 0.15 \times X_2$	$Y = 43.34 + 6.39 \times X_1 + 0.41 \times X_2$	$48.41 + 10.48 \times X_1 + 0.69 \times X_2$	$50.58 + 14.70 \times X_1 + 0.97 \times X_2$
2	$15.17 + 1.15 \times X_1 + 0.08 \times X_2$	$Y = 20.30 + 4.21 \times X_1 + 0.27 \times X_2$	$23.26 + 7.67 \times X_1 + 0.52 \times X_2$	$24.94 + 11.89 \times X_1 + 0.79 \times X_2$
3	$7.46 + 0.25 \times X_1 + 0.01 \times X_2$	$Y = 7.52 + 0.51 \times X_1 + 0.03 \times X_2$	$7.53 + 0.76 \times X_1 + 0.04 \times X_2$	$7.53 + 1.02 \times X_1 + 0.06 \times X_2$
4	$14.37 + 1.15 \times X_1 + 0.07 \times X_2$	$18.98 + 3.96 \times X_1 + 0.26 \times X_2$	$21.65 + 7.67 \times X_1 + 0.50 \times X_2$	$23.20 + 11.63 \times X_1 + 0.77 \times X_2$
5	$7.25 + 0.12 \times X_1 + 0.01 \times X_2$	$7.32 + 0.51 \times X_1 + 0.02 \times X_2$	$7.32 + 0.76 \times X_1 + 0.04 \times X_2$	$7.32 + 1.02 \times X_1 + 0.06 \times X_2$

Note: Equation: percentage of roads requiring rehabilitation (Y) = Constant + Coefficient × (Rate of change in maximum air temperature, X_1) + Coefficient × (Rate of change in annual average rainfall, X_2).

Table 2. Difference in cost for different cases

Case	Percentile rate of change in climate change stressors	Difference in cost of rehabilitation from that of Case 1 ($ million)			
		Year			
		8	16	24	32
2	5	118	170	181	179
	50	118	170	181	179
	95	119	171	181	177
3	5	174	299	355	381
	50	175	301	357	384
	95	177	307	369	400
4	5	121	179	192	191
	50	122	179	192	191
	95	122	180	192	189
5	5	167	292	348	374
	50	168	293	350	377
	95	170	300	361	392

Table 3. Direct cash flow, discounted cash flow, and NPV calculations considering 50th percentile of climate change–related stressors

Case	Extra investment ($ million)	Year (n)	Direct cash flow ($ million)	Discounted cash flow ($ million)	NPV ($ million)
2	347	32	179	38	−95
		24	181	56	
		16	170	78	
		8	118	80	
3	1,041	32	384	81	−593
		24	357	111	
		16	301	138	
		8	175	119	
4	399	32	191	40	−135
		24	192	60	
		16	179	82	
		8	122	82	
5	1,197	32	377	79	−761
		24	350	109	
		16	293	134	
		8	168	114	

Note: Direct cash flow = Difference in cost between case in consideration and Case 1; Discounted cash flow $= \frac{\text{Direct cash flow}}{(1+i)^n}$, where i = discount rate, n = number of years; and NPV = (Total discounted cash flow)—Investment. Increase in cost of mix with PG 70-28 binder (considered to be modified binder) compared to mix with PG 64-28 binder assumed to be 15%, after Roque et al. (2005).

annual rainfall (5th, 50th, and 95th), the costs for rehabilitation of the different cases were determined, and the differences in the cost of rehabilitation between a conventional layer and an improved layer in different years were determined, as shown in Table 2.

Considering a normal distribution of climate change factors, the 5th, 50th, and 95th are the different percentiles for those changes at any given time.

Next, NPV was calculated for the different cases. For these calculations, the 50th percentile values of change in the maximum air temperature and average annual rainfall were considered. For the different cases indicated in Table 1, the parameters included the extra investment (compared to Case 1) and cash flows, as presented in Table 3. A review of the results (Table 3) shows that the NPVs of all the cases are negative numbers; Case 2 has the highest NPV, while Case 5 has the lowest NPV. Typically, projects with negative NPVs are not considered for implementation. Therefore, one may infer from Table 3 that all of the cases are unworthy of further consideration. However, while those with higher negative numbers are definitely not worthy of consideration, it may be worthwhile studying further the one with the lowest negative number. Therefore, from this point, Case 2 is considered for further study.

Uncertainty Analysis

A sensitivity analysis was conducted using the NPV of Case 2 to evaluate the effect of the variables by increasing the investment cost, the direct cash flows, and the discount rate by 10% at a time. The results are shown in Table 4. It can be observed that the investment cost and the discount rate are the two high-impact parameters that produce the highest and second highest range in the NPV, respectively. These two parameters can then be selected for further analysis.

Scenario Analysis

In the next step, three scenarios were created, and a subjective estimate (depending on the experience of the agency) of the probabilities of each scenario occurring was considered to calculate the NPV for each of these three cases. The worst case is where all cash flows are half the base case, and the best case is where all cash flows are double the base-case scenario. The probabilities of occurrence are 20%, 50%, and 30% for worst, base, and best cases, respectively. The results of the scenario analysis are shown in Table 5.

The expected NPV from the scenario analyses, shown at the bottom of Table 5, comes out to be −$44.6 million. At this point, the following questions arise:

1. Which figure should be believed, the NPV of the nominal case or the expected NPV?
2. What are the chances that the upside or downside risks will emerge?
3. What confidence can one place in the results?

Table 4. Results of sensitivity analysis

	Expected NPV			Input		
Variable	Downside	Upside	Range	Downside	Upside	Base case
Investment cost	−130	−60	70	381.7	312.3	347
Discount rate	−73	−115	42	4.5	5.5	5
Cash Flow 8th Year	−103	−87	16	106.2	129.8	118
Cash Flow 16th Year	−103	−88	15	153	187	170
Cash Flow 24th Year	−101	−90	11	162.9	199.1	181
Cash Flow 32nd Year	−99	−92	7	161.1	196.9	179

Note: Arranged in decreasing order of range of expected NPV.

Table 5. Scenario analyses

		Time (8 year segments)				
Scenario	Parameter	0 year	1 (8 years)	2 (16 years)	3 (24 years)	4 (32 years)
Scenario 1: Worst case: 20%	Investment	347				
probability of occurrence	Revenue (discounted)		40	39	28	19
			Calculated $\text{NPV}_{\text{worstcase}} = -221$			
Scenario 2: Nominal case: 50%	Investment	347				
probability of occurrence	Revenue (discounted)		80	78	56	38
			Calculated $\text{NPV}_{\text{nominalcase}} = -95$			
Scenario 3: Best case: 30%	Investment	252				
probability of occurrence	Revenue (discounted)		160	156	112	75
			Calculated $\text{NPV}_{\text{bestcase}} = 157$			

Note: For all scenarios, the discount rate is 5. Expected NPV $= 0.2 \times (-221) + 0.5 \times (-95) + 0.3 \times (157)_{\text{bestcase}} = -\$44.6$ million.

Monte Carlo Simulations

A triangular distribution of NPVs with the worst-case, nominal-case, and best-case scenarios was used as input parameters to the simulation model. The results [Fig. 1(a)] show that there is a 25% probability that the NPV will be positive and that the 90% confidence interval will be quite large: it spans from −$172.2 million to $88.0 million.

In the next step, the base (nominal) case in the scenario analysis is considered and MC simulations were conducted by assuming distributions of the two high-impact inputs: discount rate (normal distribution with a mean and a standard deviation) and initial cost (uniform distribution, with a minimum and maximum). The discount rate was considered with a mean of 5% and a standard deviation of 0.5%, while the investment was varied from 10% to 20% in excess of the conventional cost. The results [Fig. 1(b)] show a range of NPV from approximately −$400 million to $100 million, a chance of 10.8% that the NPV will be positive, and another very large confidence interval of 90%—from −$354 million to $25 million. At this point, on the basis of just the NPV analysis, the most likely decision will be to drop Case 2 since the chance of obtaining a positive NPV is relatively small and there is a very large, 90%, confidence interval with most of it in the negative range.

Conduct Real Options Analysis to Determine Option Feasibility

What happens if the agency decides to build a 75 mm thick layer now and waits a certain amount of time and then decides whether or not it will install the extra 25 mm layer? The agency will wait for the uncertainty to be resolved and then decide on its next course of action. The agency will make the investment only if conditions indicate a “good scenario” and abandon the project if the condition is similar to the nominal or worst-case scenario because they both carry a negative NPV.

This approach makes two important assumptions. First, the additional layer must be installed before a significant portion of the life of the existing pavement is used up (note the principles of staged construction), and second, the uncertainty regarding climate change is resolved or a better estimate of these factors is obtained within the time frame being considered for deferring the option.

Against this background, the use of RO allows the agency to estimate the value of the option to wait. If this value turns out to be a significantly positive number (and >NPV from DCF), then the agency can keep open the option of putting down another 25 mm thick layer for a certain period of time and will not need to invest in the additional 25 mm thick layer right now. Consider this period of time to be 5 years.

The analysis begins with a calculation of the volatility of returns. Volatility is defined as a measure of the variability of the total value of the underlying asset over its lifetime (Kodukula and Papudesu 2006). It is calculated from the standard deviation of the natural logarithm of cash flow returns. The return for a specific time period is calculated as the ratio of the current time period’s cash flow to the preceding one’s (Table 6).

Black–Scholes Equation

$\sigma = 0.163$; $S0 = 252$; $X = 347$; $r = 0.05$; $T = 5$; $d1 = -0.01053$; $d2 = -0.3756$; $N(d1) = 0.495799$; $N(d2) = 0.353608$; and C, million $= 29.3$

Note:

$$C = N(d1)S_0 - N(d2)Xe^{-rT} \tag{2}$$

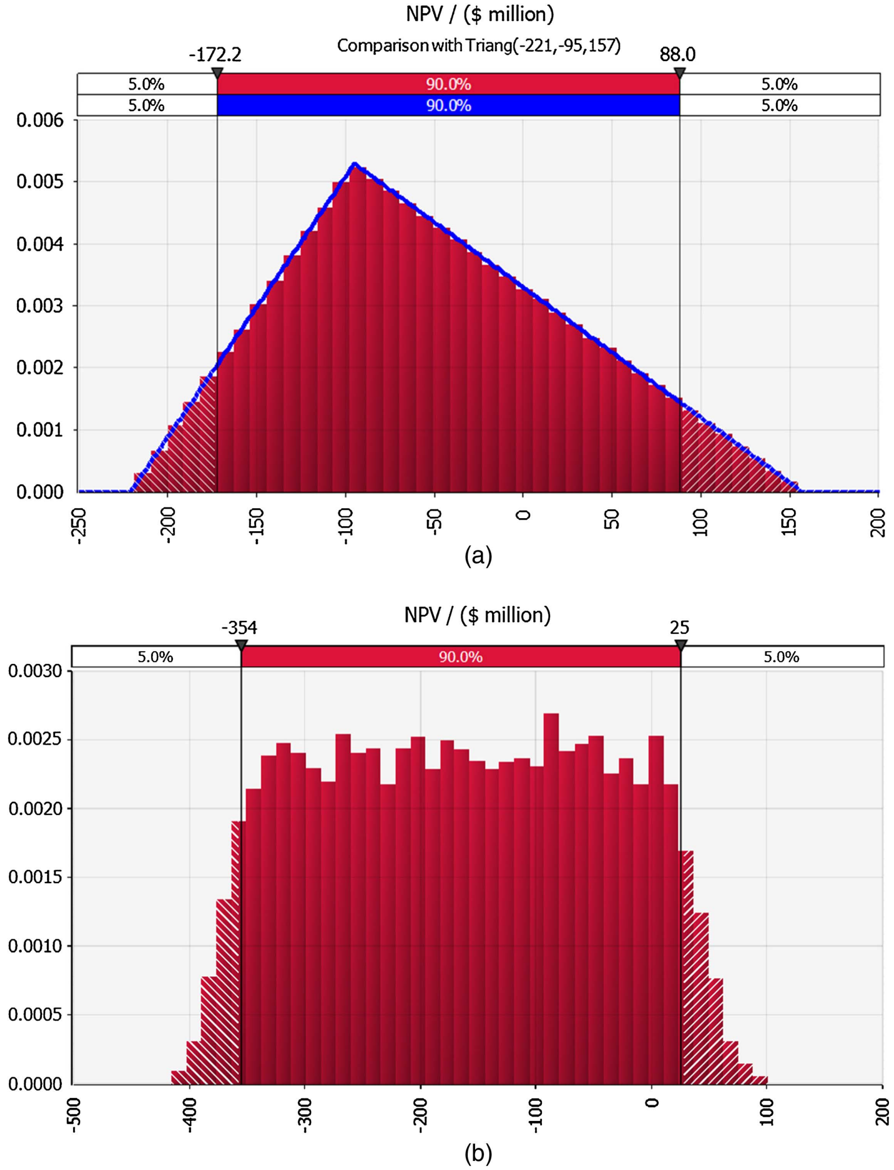

Fig. 1. Results of Monte Carlo analyses: (a) simulation with scenario analyses NPV; and (b) simulation with two highest impact factors.

Table 6. Calculation of volatility and use of Black–Scholes equation

Year	Cash flow St ($ million)	Return Rt $Rt = St/St-1$	ln Rt	Deviation (ln Rt–Average ln R)	Square of deviation $(\ln Rt - \text{Average} \ln R)^2$
32	179	0.98735	−0.012725	−0.15115148	0.022846772
24	181	1.06486	0.0628501	−0.075575508	0.005711657
16	170	1.44073	0.3651526	0.226726996	0.051405131
8	118	—	—	—	—
Average ln R	—	—	0.1384256	—	—
Total of square of deviation	—	—	—	—	0.079963561
n = total number of years	—	—	—	—	4
Volatility = sqrt (total square of deviation/$n-1$)	—	—	—	—	0.163262121
Volatility (%)	—	—	—	—	16

where C = value of call option; $N(d1)$ = cumulative probability p for a z score of d_1; $N(d2)$ = cumulative probability p for a z score of d_2; S_0 = current value of underlying asset (total discounted cash flow); X = cost of investment or strike price; r = risk-free rate of return, considered as 5%; and T = time to expiration.

$$d1 = \frac{\left[ln\frac{S_0}{X} + (r + 0.5\sigma^2)T\right]}{\sigma\sqrt{T}} \qquad (3)$$

where $d2 = d1 - \sigma\sqrt{T}$; and σ = annual volatility of future cash flows of underlying asset.

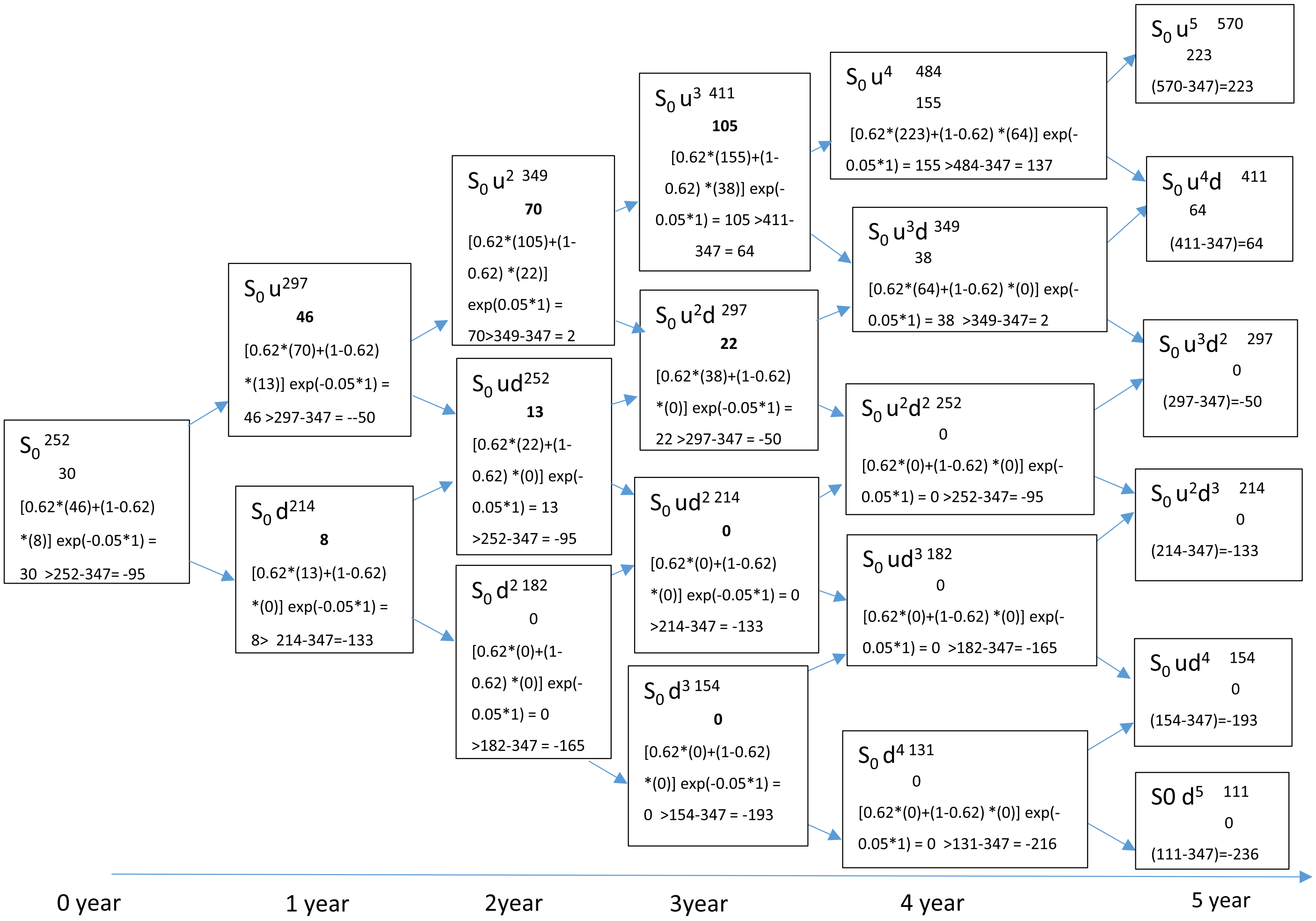

Fig. 2. Real option calculation using binomial lattice.

Next, using the calculated volatility, the RO value is calculated (Table 6) using the Black–Scholes equation (Black and Scholes 1973). The value of the option to wait is \$29.3 million. It is not only greater than the calculated NPV from the DCF but also a very high positive number—indicating that in this case the option is worth pursuing. The value also gives a benchmark against which the agency can justify spending money to "hold" that option, such as to secure the option to take out a loan at a certain percentage rate against the payment of an upfront fee at this time.

Fig. 2 shows the more intuitive way of calculating the RO value, using a binomial lattice diagram, which yields an value approximately similar to that from the Black–Sholes equation (\$30 million). The parameters used in the construction of the binomial lattice are as follows:

σ, volatility = 0.16
S_0, total DCF, \$ = 252 million
X, investment, \$ = 347 million
r, risk-free interest rate, % = 5
T, time to expiration of option, year = 5
δt, interval, year = 1
u, up factor = 1.18
d, down factor = 0.85
p, risk-neutral probability = 0.62

The diagram is constructed as follows:

1. Calculate the asset values for each year (numerator) using the current estimated total DCF and the u and d factors.
2. For the terminal year, subtract the investment from the asset value and, if positive, take it as the option value, and write it in the denominator; if the value is negative, take zero as the denominator.
3. For the years other than the terminal years, start from the $(n-1)$ year as follows: Calculate two values and put the greater one [between results from Eqs. (2) and (3), as shown in what follows] in the denominator. First calculate the expected asset value for keeping the option open and accounting for the downstream optimal decision. This is the discounted (at the risk-free rate) weighted average of potential future option values (upstream and downstream) using the risk-neutral probability:

$$[p(\text{upstream option value}) + (1\text{-}p)(\text{downstream option value})] * \exp(\text{-}r\,\delta t)$$
$$(\text{Note:option value means the denominator}) \tag{4}$$

Next, calculate the value if the expansion option is exercised as follows:

$$(\text{asset value of this step})\text{–investment cost} \tag{5}$$

4. Fill in all the denominators in the preceding years up to year zero.
5. The value of the option (denominator) in year zero is the RO value for this project.

Hence, for the example presented in this paper, the option of waiting to install an additional layer has value, and it can be considered by the agency. The results of a conventional DCF and NPV approach lead to a recommendation against installing the additional layer at this time.

6. Identify the most prudent course of action.

Therefore, the net value that is added by considering the RO analysis approach in this example is $\$30\,\text{million} - (-\$95\,\text{million}) = \$125\,\text{million}$, where −$95 million is the NPV from the conventional DCF approach. On the basis of the DCF-based NPV value of −$95 million, the decision would have been NOT to consider any option to install a resilient pavement. However, the project for implementing one option (in this case, installing another layer) has a value of $125 million, and based on this number the agency may want to keep the option open at this time and wait a few years until the uncertainty is reduced. The process could be repeated at any point in the future to reestimate the RO value based on the new uncertainties (volatility). The RO value is a quantification of the value of waiting and helps the agency to plan for future actions in a rational way. Note that the RO analysis does not change the agency's decision to NOT pave the second layer at this time. However, it is acknowledged that the overall policy of the agency regarding when to rehabilitate or repair a pavement (in terms of its remaining life) will affect the overall budgetary considerations, and this policy should be taken into account during the RO analysis.

Summary

Highway agencies face a challenging task today—in the face of uncertainty in climate change and budget cuts, how do they build roadway systems that are resilient to climate change? Although there are several options that design methods can suggest, how does one justify an investment when its payback is seen to be questionable, specifically because of the considerable uncertainty in predictions of climate change-related factors? This paper presents and suggests the use of a set of traditional direct cash flow (DCF) and net present value (NPV) analyses and nontraditional real option analysis to explore several options. Several cases, consisting of thicker layers and thicker layers with better materials, are explored in terms of their NPVs, through the use of a system dynamics model, which was built on the basis of the results of MEPDG simulations. Sensitivity analyses and Monte Carlo simulations showed that all options had negative NPVs and so were not recommended. However, there was a range of NPVs, and while those with high negative values were not feasible, the one with a relatively low negative number deserved further consideration. This consideration was made with the help of RO analysis, which evaluates the value of the deferment option: Is there any value in waiting and then making a decision regarding the additional layer? The worked-out example showed that there could be considerable value in such an option, and this value could be leveraged by highway agencies to develop better economic policies for designing and building roads that are resilient to a changing climate. The waiting time given by the RO is expected to clarify the scenario—hopefully the projection will be more accurate after a certain period of time than at this time. If the probability of climate change decreases in the future, then this analysis could be conducted again to determine another waiting period.

There are a few important considerations for the successful application of this method. First, to estimate volatility, the cash flows estimated on the basis of savings from not having to pay for rehabilitation work need to be assessed properly. Second, the time frame for the RO analysis should be long enough to justify the applicability of climate change uncertainties and short enough within which the time for having an option will expire. Furthermore, if the option consists in installing an additional layer, it must be done on the existing layer before the existing pavement has used up a considerable portion of its life (e.g., damage <30%). Finally, the time frame should be relevant and pertinent to the pavement design period. The RO concept is appropriate for long-life pavements, such as perpetual pavements, which are supposed to last more than 50 years without undergoing any major structural rehabilitation, and the last payback period should be well within its design life. The concept is also recommended for other long life infrastructure assets that could be built in stages.

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