Maximizing Return on Investment Utilizing a Bridge Depreciation Model

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ABSTRACT: The challenge facing bridge managers is how to optimize investment in their infrastructure given very limited budgets. There are few tools available to demonstrate that scarce monetary resources are effectively utilized. Basic accounting principles offer a relatively straight-forward method to test the efficacy of investment of bridge rehabilitation and renewal. The first accounting principle applied to bridge asset management characterizes bridges in terms of their component depreciation. Each component of a bridge is valuated and has a service life. The value of a bridge depreciates in accordance with a straight-line or parabolic decay function applied to its components. Capital investment in a bridge either renews a component or extends the life of a component. When a component is renewed, its depreciated value is reset to the new value. If a component is rehabilitated, the original service life of the component is extended. The efficacy of investment is measured as the ratio of improvement of the depreciated value of the bridge to the amount of capital investment required.

1 INTRODUCTION

The principal challenge of bridge management is to select the most cost-effective strategies to maintain a bridge population in the best possible overall condition. This paper presents a straight-forward approach to optimizing bridge investment. Central to this approach is the concept of treating bridges as depreciating assets. Kleywegt (2008) introduced the concept of treating bridge structures as depreciating assets. Measuring depreciation is a simple deterministic exercise that very reliably states the overall condition of a bridge network.

Fundamental to the approach described in this paper is basic accounting principles. The first principle, already referred to, is that of depreciation. The depreciated value of the bridge inventory is required. To accomplish this, the primary components of each bridge are described, quantified, valuated, and then depreciated, similar to depreciation of capital assets for tax purposes. This exercise yields a depreciated value of the entire bridge inventory at a point in time.

The second accounting principle is maintaining the asset side of the ledger at the highest possible value. This invokes the third accounting principle, which is to minimize expenses. The business and engineering challenge is to demonstrate which expenditures yield the best return so that the asset values are maximized.

2 CALCULATING DEPRECIATION

Determining the depreciated value of bridge assets is made much easier with spreadsheets and database systems. Most modern bridge management systems already have each bridge discretized into its various components. These components will have material and geometric properties. All that is needed is a realistic new unit value, a realistic life span, and a suitable depreciation function for each component.

Bridge owners that analyze their bid data for new bridge construction will have the best available information for evaluating the cost of individual bridge components. Bridge decks in new construction will generally cost anywhere from $400 to $700 per square metre. New expansion joints will cost about $3,500 per lineal metre. Substructures may cost $1,000 per cubic metre. Prestressed girders may cost $300 per metre.

Estimating the life of components requires significant local experience. It is usually reasonable to think of substructures lasting 80 to 120 years. Bridge decks may last 30 to 60 years depending on traffic demands and deck protection measures. Expansion joints seldom are effective after 30 years. Railing and barrier systems will often last 40 to 60 years.

2.1 *Depreciation functions*

The choice of depreciation function is very important, as it can significantly skew the results, and must be carefully understood and appreciated. Two depreciation functions that work well in this exercise are straight-line and parabolic depreciation. These are illustrated in Figure 1.

With straight-line depreciation, an asset devalues an equal amount each year until the end of its deemed service life.

An interesting observation of parabolic depreciation is that only 25% of total depreciation occurs in the first half of a component's life. Thereafter, the depreciation accelerates so that 75% of the depreciation takes place in the second half of the component's life.

There is good reason to consider parabolic depreciation as a legitimate depreciation function. Very often when describing deterioration or aging of public assets, such as highway asphalt, the aging or deterioration process is shown as accelerating towards the end of the asset's life. A parabolic function is a relatively simple model that duplicates this behavior.

The two depreciation functions are mathematically expressed as follows:

Straight-Line:

$$V_t = V_0 *[1- t/L] \quad \text{(not less than zero)} \tag{1}$$

Parabolic:

$$V_t = V_0 * [1- (t^2/L^2)] \quad \text{(not less than zero)} \tag{2}$$

where V_t is the depreciated value; V_0 is the original value; t = time in years; and L = the deemed life of the component in years.

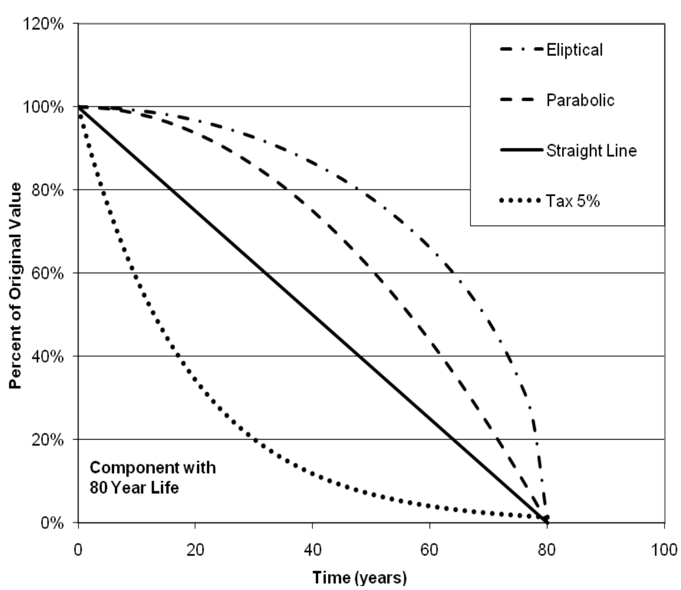

Figure 1. Four possible component depreciation functions.

2.2 *Example*

An example is illustrated in Table 1. The example is a very typical 50 m long by 10 m wide two span bridge with five lines of prestressed girders. The bridge was originally constructed in 1950, and the deck, barriers and expansion joints were renewed in 1990.

The deemed life of each component and its respective age are indicated in Table 1. The basic geometric data and unit costs in the example are extended to produce the new value of the component. The resulting total new value of the structure is \$791,000. The present depreciated value of the structure is \$363,790 or \$539,192 assuming straight-line or parabolic depreciation respectively. With straight-line depreciation the structure value has declined to 46% of its original worth. Correspondingly, with parabolic depreciation the structure retains 68.2% of its original worth.

An entire bridge population's new and depreciated values may be calculated to determine the new worth and depreciated worth of all structures.

2.3 *Application of depreciation to a large inventory*

A very hypothetical scenario is useful to help illustrate the significance of calculating the depreciation of the entire bridge inventory. With apologies to the poet Oliver Wendell Holmes (1858), imagine a bridge owner that constructs one identical bridge a year for 100 years, and each bridge has properties identical to "the wonderful one-hoss shay", that is each bridge lasts exactly 100 years before disintegrating to dust. It is easy to do the arithmetic and realize that at the 100 year anniversary, the straight-line depreciated value of the 100 bridges is 50% of the new value.

It can be demonstrated that following the parabolic approach, the 100 bridges would retain two-thirds of their value.

One can extend the above logic to a well age-distributed and diverse bridge population and conclude that a healthy bridge inventory should retain about 50% of its value after depreciation, if straight-line depreciation is assumed. By contrast, if a parabolic depreciation model is adopted, a healthy bridge population should retain at least 67% of its original value. Realistically and practically, it is simple to test a bridge population's depreciation utilizing both straight-line and parabolic measures. Some interpretation will of course be required based on the actual age and size distribution of the structures.

A bridge population with depreciation figures substantially higher than those above could be interpreted as a very young bridge cohort, or possibly but highly unlikely, an indication of over-investment in the bridges. Similarly, where depreciation figures

Table 1. Example calculation of depreciated value for a bridge constructed in 1950 and rehabilitated in 1990.

50 m x 10 m Bridge Constructed in 1950												Depreciated Value	
Component	Year	Count	Length	Width	Height	Qty	Unit	Unit Cost ($)	New Value (V_0) ($)	Life (L)	Age (t)	Straight-Line (V_t) ($)	Parabolic (V_t) ($)
Deck	*1990	1	50	10	-	500	m^2	500	250,000	50	20	150,000	210,000
Barriers	*1990	2	60	-	-	120	m	800	96,000	50	20	57,600	80,640
Expansion Joints	*1990	2	10	-	-	20	m	3500	70,000	30	20	23,333	38,889
Girders	1950	5	50	-	-	250	m	500	125,000	70	60	17,857	33,163
Abutments	1950	2	10	1	2	40	m^3	2500	100,000	100	60	40,000	64,000
Pier	1950	1	10	0.6	5	30	m^3	2000	60,000	120	60	30,000	45,000
Foundations	1950	3				3	LS	30,000	90,000	120	60	45,000	67,500
								Totals	$791,000			$363,790	$539,192

Legend:

Year = Year of original construction or replacement
* indicates component renewal
Qty = Quantity (Count * Length * Width * Height) as applicable
Unit Cost = Base Line unit cost
New Value = Qty * Unit Cost
Life = Deemed service life in years over which component is depreciated
Age = Age of component in years, present year being 2010

are substantially lower, this would be an indicator of a very aged bridge population, and a strong signal that significant investment will be required.

3 OPTIMIZING INVESTMENT

Think of a bridge population as a small taxi fleet of ten vehicles, all from one to ten years of age. It is not hard to postulate that the wisest investment strategy to maintain the asset value of the fleet is to surplus the oldest vehicle and buy a new replacement. Similar but more complex decisions are required to manage a bridge fleet.

Referring back to the accounting principles, the business objective is to maintain the asset value of the bridge fleet within a "comfort zone."

For a uniformly age and size distributed bridge fleet, it has been proposed that 50% depreciation is a rational target where straight-line depreciation is assumed. One might establish the comfort zone as +/- 5% of the target.

Obviously a bridge population will continue to depreciate without investment. The challenge is to determine which investments yield the highest return so the value of the entire asset inventory is maintained or improved. The most obvious approach may be to construct numerous new bridges, thereby improving the average depreciation of the fleet. However, this is neither sustainable nor practical. Clearly a mechanism is required to determine appropriate investment strategies in the existing bridge stock.

3.1 *Car ownership example*

Car ownership is the best example to explain the fundamental differences between the asset value of a bridge and the impact of investment to maintain the asset. A personal vehicle may be purchased new for a price ranging from $20,000 to $50,000 depending on the make and model. However, if we attempted to purchase the same vehicle as parts such as brake cylinders, windshields, and shock absorbers, and then assemble the vehicle, the car would be easily ten times more expensive. Replacing a wheel disc brake is considerably more costly at the local car dealer than when it was installed at the factory.

Similarly, those bridges that were constructed in a green field in the 1950's are substantially more costly to rehabilitate or replace once they are operational.

3.2 *Standardizing the approach*

A standardized basis is required to assess the undepreciated value of a bridge. A suitable starting point is green-field construction costs. Inflation of course greatly impacts those green-field costs. Hence a suitable fixed time must be adopted. To carry on the discussion, assume that an extensive database of green-field bridge construction costs exists for all new structures built in North America in the year 2000. From this imaginary wealth of data, it would be a relatively simple matter to deduce the average unit costs of all bridge components for the 2000 base year.

By adopting the above or any similar approach, it is possible to calculate the undepreciated and depreciated value of every bridge component for the entire bridge inventory, analogous to the manner described at the beginning of this paper.

3.3 *Impact of investment*

Investment to increase asset value will always cost substantially more than the net increase in value of the assets as a result of the investment. Stated more simply, it may take $2 to increase the value of the asset by $1. The car example best explains this. It may cost $750 to replace a cracked windshield on a vehicle. However, the resulting resale value of the car will only increase by a fraction of the $750 investment.

Similarly with bridge rehabilitation there are substantial overhead burdens that are not recouped in the asset value of the bridge. The overhead costs are typically investigation, design, construction administration, and contractor mobilization, to mention a few. Recall that it is more economical to purchase the car from the factory then it is to assemble it from new parts at the local garage.

So what is the impact of investment in a bridge? Utilizing the advocated approach, replacing a bridge component resets the depreciated value of the component to brand new. For example, an existing 500 square metre bridge deck with a base value of $400 per square metre would have a new value of $200,000. If the deemed life of the bridge deck is 40 years, and it is presently 30 years old, the straight-line depreciated value of the bridge deck is $50,000. Replacing the deck now would restore the value of the deck to $200,000 irrespective of what it actually costs to achieve this. The efficacy of investment is the increase in value of the deck (in this case $150,000) divided by the actual cost to achieve the improvement.

CALCULATING EFFICACY

The calculation of efficacy of investment is illustrated in Table 2. The bridge is very similar to that of Table 1 and follows the same nomenclature.

Table 2. Example calculation of efficacy of investment for bridge constructed in 1960 and rehabilitated in 2010.

Present (2010) asset value of 50 m x 10 m bridge constructed in 1960														Depreciated value		
Component	Year	Count	Length	Width	Height	Qty	Unit	Unit Cost		New Value	Life	Age		Straight-Line		Parabolic
Deck	1960	1	50	10	-	500	m^2	500		250,000	50	50		0		0
Barriers	1960	2	60	-	-	120	m	800		96,000	50	50		0		0
Expansion Joints	1960	2	10	-	-	20	m	3500		70,000	30	50		0		0
Girders	1960	5	50	-	-	250	m	500		125,000	70	50		35,714		61,224
Abutments	1960	2	10	1	2	40	m^3	2500		100,000	100	50		50,000		75,000
Pier	1960	1	10	0.6	5	30	m^3	2000		60,000	120	50		35,000		49,583
Foundations	1960	3	-	-	-	3	LS	30,000		90,000	120	50		52,500		74,375
								Totals		$791,000			*A*	$173,214	*A*	$260,183
Asset value of above bridge after partial renewal in 2010																
Deck	*2010	1	50	10	-	500	m^2	500		250,000	50	0		250,000		250,000
Barriers	*2010	2	60	-	-	120	m	800		96,000	50	0		96,000		96,000
Expansion Joints	*2010	2	10	-	-	20	m	3500		70,000	30	0		70,000		70,000
Girders	1960	5	50	-	-	250	m	500		125,000	70	50		35,714		61,224
Abutments	1960	2	10	1	2	40	m^3	2500		100,000	100	50		50,000		75,000
Pier	1960	1	10	0.6	5	30	m^3	2000		60,000	120	50		35,000		49,583
Foundations	1960	3	-	-	-	3	LS	30,000		90,000	120	50		52,500		74,375
								Totals		791,000			*B*	$589,214	*B*	$676,183
												Improvement to asset value: (B-A)	*C*	$416,000	*C*	$416,000
Cost of improvements																
Deck	2010	1	50	10	-	500	m^2	700		350,000						
Barriers	2010	2	60	-	-	120	m	1,000		120,000						
Expansion Joints	2010	2	10	-	-	20	m	4,000		80,000						
Traffic Control	2010						LS			100,000						
								Sub Total		$650,000						
Design						10	%			65,000						
Contract Administration & Contingencies						20	%			130,000						
								Total cost of improvements	*D*	$845,000				Efficacy: (*C*/*D*)		49.2%

In this instance the bridge was constructed in 1960 and has never been rehabilitated. The new and depreciated values of the bridge components are calculated in the upper part of the Table. The new value or undepreciated value of the bridge is $791,000. The straight-line and parabolic depreciation values of the bridge are $173,214 and $260,183 respectively. In this example the deck, barriers and expansion joints have all out-lived their deemed service lives and are thus fully depreciated.

The middle portion of Table 2 calculates the new depreciated value of the bridge after replacement of the deck, barriers and expansion joints. The respective upgraded asset values of the renewed structure are $589,214 and $676,183 for straight-line and parabolic depreciation.

Since the three renewed bridge components were all fully depreciated to begin with, the improvement to the bridge asset value is identically $416,000.

The bottom part of the Table calculates the actual cost to improve the bridge. It is important to observe that the unit costs for the improvements are substantially higher than that utilized in assessing the value of the structure

Recall that it is more costly to replace parts on a vehicle than it is to install them at the factory.

When a bridge is rehabilitated it is usually required to stage the rehabilitation so that traffic may be accommodated. Hence there is a traffic control cost that is not normally associated with new bridge construction. In this example $100,000 is shown as the traffic control cost.

Additional overheads must also be considered. In the example a 10% allowance is included for design, and a further 20% allowance is included for contract administration and contingencies.

In this example the total cost to replace the deck, barriers and expansion joints is $845,000. However, the net improvement to the asset value of the bridge is only $416,000. The efficacy of the investment then is the ratio of the improvement of asset value to the total cost to achieve the improvement. In the example the efficacy is 49.2%.

3.4 *Additional examples of efficacy*

If the example in Table 2 is changed slightly so that the same bridge is lengthened by 50 m and now includes three piers, the efficacy of investment improves to 52.2%. The improvement in efficacy in this instance is mainly attributable to the overhead cost of traffic control. The cost of traffic control is assumed to be fixed and hence the relative cost of traffic control per unit of renewed bridge is halved.

Had the 100m long version of the bridge been constructed in 1975 and only the barriers and expansion joints replaced, the efficacy of investment would be 20.8% and 8.9% for straight-line and parabolic depreciation respectively. The loss of efficacy is again largely attributable to the traffic control overhead cost. The fixed cost of traffic management is a larger burden when applied to a relatively smaller amount of rehabilitation effort.

3.5 *Repair vs. renewal*

The discussion thus far has centered on complete replacement of bridge components. In some instances it is not practical or possible to replace a component. For example, the deck cannot be replaced on a rigid frame bridge. How is this dilemma resolved?

There are two equally valid approaches to describing the depreciated value of a bridge component that has been repaired instead of replaced. The first approach is to simply extend the life of the component. For example, a rigid frame with a deemed 80 year life has its life extended by 40 years by the application of a concrete overlay at the 60 year mark. The depreciation of the rigid frame is now based on the deemed life having changed from 80 years to 120 years.

The second approach is to break the component into old and new on a prorated basis. An example of this approach is a concrete overlay on an existing deck. The concrete overlay is separately evaluated as a new component of the bridge in the proportion of overlay thickness to overall deck thickness. The overlay may have a different deemed life than that of the deck, but would be valued at the same unit rate as the deck.

3.6 *Bridge replacement vs. rehabilitation*

Analyzing the efficacy of investment for a complete bridge replacement is entirely analogous to that of replacing only components of a bridge. Typically, when a bridge is replaced it is not often replaced exactly in-kind. Replacement bridges are typically larger, better detailed, and constructed with improved materials.

Valuing a new bridge is based on the value of the bridge after the construction dust settles. It is based only on the deemed value of the constituent parts of the new bridge, their geometry and base value. For example, if the deemed base value of substructures is $1,200 per cubic metre of reinforced concrete, and the deemed life is 80 years, then this is applied to value the new bridge's asset value in the overall asset mix. Only the deemed hard asset value of the new bridge is included in the numerator of the efficacy calculation.

The overhead costs associated with demolition of the original structure, traffic control, design, contract administration, contingencies and environmental burdens are included in the denominator of the efficacy equation, together with the estimated costs to rehabilitate or renew the bridge components.

3.7 *Selecting the optimal investment strategy*

The efficacy of investment as explained in the preceding sections is really a measure of “bang for your buck.” Those investments that yield the highest return are clearly those that will most improve the asset value of the entire bridge population.

Where there are numerous competing projects, each project can be tested to determine the efficacy of investment for each project. All else being equal, those projects that yield the highest return in terms of increase of the overall asset value as measured against their cost, represent the optimal investment strategy.

4 CONCLUSIONS

Responsible stewardship of bridge assets involves a careful balancing of many considerations. Ensuring that the money expended on maintaining the bridge fleet is wisely invested is of course a paramount consideration.

There are complex black-box solutions available that utilize multi-objective optimization engines that rely on probabilistic approximations of bridge behavior. They attempt to identify those bridge expenditures that represent the best investment given limited budgets. It is the author’s experience that such solutions are not reliable.

The approach advocated in this paper is straightforward, and follows very understandable accounting principles. The approach is readily adaptable to information technology software such as spreadsheets and databases.

There are significant overhead burdens that amplify the capital cost of bridge rehabilitation or renewal. These overheads are real but do not contribute to improving the asset value of the bridge fleet. Hence the model gives credence to the notion of “Get in, get out, and stay out.”

Calculating the efficacy of investment provides a rational basis for optimizing investment in bridges where all other considerations are relatively equal.

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