Building Bridges:
Treating a New Transport Link as a Real Option

Presented to European Regional Science Association Congress, Barcelona, Sept 2011.

Arthur Grimes [a]

Abstract

A transportation investment that materially improves links between centres opens up previously unavailable options for new activities. Traditional cost-benefit analysis, that focuses on computing benefits such as reduced travel time and safety improvements, does not adequately take account of the value of the option that such an investment creates for new activities. Real options theory must be added to the analysis to evaluate the full benefits of the new link. Two inter-related problems with real options analysis for practical use are that: (a) the nature of the options potentially being created are difficult to value, and (b) the standard mathematics of real options analysis is complex. Nevertheless, the intuition behind the role of real options analysis is straight-forward. This paper uses a specific example – Auckland's Harbour Bridge and the Northern Motorway that stretches beyond it – to motivate the importance of real options analysis. It develops illustrative, multi-period models of the real options problem, that clearly identify the option value created by a major new transport investment. The illustrative models highlight that inclusion of real options factors may either increase or decrease the attractiveness of a proposed investment. The models identify situations in which it is optimal to invest even where a standard benefit-cost ratio is less than one.

[a] Motu Economic and Public Policy Research, PO Box 24390 Wellington 6142, New Zealand. Email: arthur.grimes@motu.org.nz.

1. Introduction

Cost benefit analysis (CBA) is an approach that authorities employ to assess major transport and other infrastructure developments. In the standard CBA approach, discounted benefits are expressed as a ratio of discounted costs to form a benefit cost ratio (BCR) and projects are ranked according to their ratio. In a world of certainty, or one where a certainty equivalence approach is warranted, traditional CBA represents a reasonable methodology. Specific aspects, such as valuing costs and benefits and specifying the discount rate, of course remain contentious.

A more significant problem for CBA arises where the world is uncertain and multi-stage investments are being considered. In practice, as argued below, these conditions exist for virtually all major investments. In these circumstances, if new information arrives after the initial stage of a project has begun and before decisions on latter stages are finalised, a certainty equivalent methodology mis-represents the value of initial investments. Instead, a methodology is required that incorporates the value of the "real option" that is created by an initial stage investment within a multi-stage investment programme.

This paper examines the nature of decision-making and analysis in these circumstances, using transport infrastructure investments as a focus. A specific example – development of the Auckland Harbour Bridge and its motorway extensions – is used to illustrate the issues, but the methods are general. A problem with real options analysis, based as it is on financial options theory (Black and Scholes 1973), is that the methodology for solving the value of the option can become highly complex. The approach here is to concentrate on the concepts involved in valuing the option, building on the decision-tree methodology outlined by Guthrie (2009) which in turn builds on Cox, Ross and Rubinstein (1979) and Dixit and Pindyck (1994). The paper complements the conceptual treatment in Miller and Lessard (2008) and demonstrates the nature of option values through simple examples using the decision-tree approach. The purpose is to ensure that decision-makers have the conceptual tools to incorporate the existence of a real option into their analysis, even if judgement will inevitably be involved in calculating its value.

2. Multi-Stage Investments and Options

It is common-place within CBA analysis to include all costs and benefits accruing to the public as a result of a proposed investment. The public may be defined across a particular region, country or globally. For instance, a rail project may include benefits accruing to existing residents who never use the train but who gain through reduced road congestion, rather than confining the analysis solely to benefits for the rail company and/or rail users.

Typically, a CBA analysis treats a new or upgraded transport link as a single stage project. Such analysis typically considers benefits such as: travel time cost savings, vehicle operating cost savings, accident cost savings, seal extension benefits, driver frustration reduction benefits and vehicle emission reduction benefits (New Zealand Transport Agency, 2010; see also HM Treasury, 2010).

However, deeper analysis suggests that many of the benefits of a new transport link take place via relocation of new activity to the area serviced by the project following improvements in connectivity of that area to other locations. Given national and international mobility of resources, this new activity is not sourced solely from within the regional or national entity, but may arise from external sources. These additional resources add to local taxation revenues and may have other benefits such as increased productivity due to agglomeration benefits (Duranton & Puga, 2004; Rosenthal & Strange, 2004; Maré & Graham, 2009), and so represent genuine additions to local wealth.

The timing of location decisions by agents does not need to coincide with the decision of the infrastructure investor. Agents may observe the progress of the infrastructure project and assess changing valuations of the benefits arising from the new infrastructure prior to making their own location decisions and consequent investments. Thus a new transport link tends to service a growing population of people and firms over time. The value of these subsequent location and investment decisions form part of the ambit of the analysis. Thus even a single-stage infrastructure investment forms part of a multi-stage investment programme: the infrastructure investment is the initial stage and the multitude of subsequent investments form the latter stages. For convenience, we will refer to these subsequent investments as private investments in the remainder of the paper, but additional public investments are also relevant.

The subsequent private investments will only be undertaken if, *at the time of the private investment decision*, the net benefit to the investor of investing is positive. The private investment decision may be taken only after the infrastructure investment has already been completed and after new information has arrived about the value to be gained from using the new infrastructure. The new information may be obtainable only by virtue of having the infrastructure in place and operational. In the following, we assume that the private investment would not occur in the absence of the infrastructure investment. Nor will it occur if the new information about the payoffs to the private investor reveal that a potential private investment yields a net cost rather than a net benefit.

Thus creation of the infrastructure, being irrevocable once built, creates an asymmetric payoff: the private investment can only be considered if the infrastructure is built, and cannot be considered otherwise. However, the staged nature of decision-making means that the private investment is not committed to prior to completion of the new project. This sequencing allows new information to arrive between the time of the infrastructure project decision and the private investment decision. The asymmetry and the sequential decision-making process together give rise to the creation of the real option through the initial infrastructure investment.

3. Examples

Auckland, New Zealand's largest city with an urban area population in 2011 of over 1.3 million, is situated on two harbours. The CBD is situated on the southern side of one of these harbours (the Waitemata Harbour) with only a short stretch of water (less than one kilometre) between it and the harbour's northern shore. McLauchlan (1989; pp. 81-84) documents that a 1946 *Royal Commission on Trans-Harbour Facilities* examined whether a bridge should be built to connect the southern and northern shores.

The Royal Commission report to Parliament "was very conservative in its estimates of traffic build-up and population growth on the North Shore." McLauchlan comments: "A truly accurate estimate was difficult because a bridge itself would be the biggest incentive for population growth on the North Shore, but no one could be certain how much of an incentive." Nevertheless, in 1953, Government approved construction of the bridge provided that it cost no more than five million pounds; eventually costs climbed by 50% relative to this figure.

The (tolled) bridge opened in May 1959 and its effects were immediate. McLauchlan documents: "The rate of traffic vastly exceeded forecasts. In the first ten months, 4,092,307 vehicles used the bridge. The total was 5,543,973 in the year to 31 March 1961, 15,153,659 in the year to 31 March 1970 and exceeded 32 million by the mid-1980s. … The bridge triggered an explosion of development on the North Shore and the early traffic growth at more than 13 per cent a year led to the decision in 1964 to add two more lanes on each side of the bridge."

A map of the Proposed Auckland Harbour Bridge, produced in the late 1940s or early 1950s, shows a combined "North Side" population at that time of 26,820 (Alexander Turnbull Library, 2006, Plate 87). By 2006, the population of North Shore City alone had reached 217,000, and the combined population of North Shore City and Rodney District (further north but also connected to Auckland CBD by the bridge) was 309,000. The population of areas serviced by the bridge therefore increased approximately tenfold over 60 years. This compared with a 2.4-fold increase in New Zealand's population over the same time.

A short motorway, the Northern Motorway, was built soon after the bridge, extending six kilometres northwards from the bridge. Starting from the early 1990s, this motorway was extended substantially (from Albany through to Silverdale), an 18 kilometre extension northwards that was completed in 2000. Grimes and Liang (2010) examined effects of this extension on population, employment and land values in areas to the north of the bridge. Population in North Shore City that were within three kilometres of a newly opened motorway exit increased by 57% in the 15 years to 2006, compared with an increase of just 21% for the rest of North Shore. Similarly, employment within three kilometres of a new exit increased by 67% compared with an increase of 34% in the remainder of North Shore. In each case, the population and employment increases for areas close to a new exit considerably exceeded the increases for Auckland Region as a whole (38% and 55% respectively). Population and employment effects of the motorway extension in Rodney District were even more material. In the area closest to the northern-most exit of the motorway extension, population rose by 80% and employment rose by 120% in the 15 years to 2006.

Using relative land value increases as a measure of the present discounted value of the benefits of the motorway extension, Grimes and Liang calculated a benefit-cost ratio for the motorway extensions of at least 6.3, and possibly as high as 21.9. *Ex post* estimates of benefits using this method were approximately double the *ex ante* estimates of benefit for the project. The benefit calculations formulated using relative land value increases incorporate the value of the real option which is embedded in land values of the newly serviced area. This inclusion of option values can explaining the jump in *ex post* measured benefits relative to *ex ante* expected benefits, where the latter do not incorporate the value of the real option. The approximate doubling in calculated benefits indicates that the value of the real option was approximately equivalent to the combined value of all other benefits calculated using the standard CBA approach.

These two related examples illustrate the importance of understanding the nature and value of the real option created by a major infrastructure development. The Harbour Bridge case highlights the difficulties involved in estimating future demand for a transport link that potentially transforms the attractiveness of a newly serviced area for urban expansion. The Northern motorway case provides a quantitative estimate of the value of the real option created by a new transport link, in this case being approximately equal to the combined value of all other conventionally calculated benefits.

The nature of an option means that not all such major developments, even if chosen optimally *ex ante*, will be successful *ex post*. The reasoning for this is best illustrated by a financial option. A financial option may be purchased to give the opportunity to obtain a return (or protect against risk) in certain circumstances (e.g. if the exchange rate rises) but will not be exercised in other circumstances (e.g. if the exchange rate falls). In this latter case, the option will have zero value on expiry. However, this does not imply that initial purchase of the option was sub-optimal, since purchase was undertaken in a climate of uncertainty with respect to future outcomes and purchase may have been optimal to obtain the best *ex ante* risk-adjusted outcome for the investor.

This logic needs to be incorporated into the analysis when interpreting unsuccessful historical infrastructure investments. One New Zealand road bridge investment, across the Mangapurua Stream near the Whanganui River, was completed in June 1936. It was built to open up a new area of farmland that had hitherto been unserviced by road access. However the farmland (and thence the bridge) proved to be uneconomic and access was closed entirely in 1942.[1] This bridge has since been dubbed the *Bridge to Nowhere*.

Belich (2009) documents a range of unsuccessful transport investments throughout the settler colonies in the 1800s. Canada, for instance, experienced 'Canal fever' in the 1820s and 1830s whereby it sought to emulate the success of New York's Erie Canal in opening up new territory for development. Its per capita expenditure on canals at that time was above that even of Ohio and Indiana (two prominent US canal building states). The Canadian canals proved to be financial failures, and Belich (page 286) comments: "Contemporaries and historians alike were bewildered by the level of waste."

Subsequently, in the 1850s, 'Railroad fever' took over from canals as the major transport development in Canada, with construction of the Grand Trunk Line (primarily servicing Ontario plus Montreal). Belich notes that the Grand Trunk Line was never profitable in itself. However other parts of the economy that used the rail line did boom: "Between 1844 and 1866, pine exports doubled, oak exports tripled and elm exports increased over

[1] Information taken from the Department of Conservation sign situated at the bridge.

fourfold." (page 288). No modern study has been undertaken to assess whether, *ex post*, the rail investments were economically worthwhile once these broader economic benefits are assessed. But even if such an analysis were undertaken and showed that realised (discounted) benefits fell short of (discounted) costs, this would not be conclusive evidence that the investment was *ex ante* sub-optimal. The *ex ante* option value must also be incorporated into the analysis. Methods for doing so are detailed below.

4. Analysis of Option Value

The binomial approach to option valuation, outlined by Guthrie (2009), can be used conceptually to assess the value of a real option created by an infrastructure project. We consider two separate cases relating to a major bridge (or other transport) project. The examples have been chosen to show that consideration of option values can either decrease or increase the likelihood of current investment in the project relative to a decision based on standard CBA criteria. The standard CBA criterion in a capital-unconstrained world is to invest if the BCR > 1, and not otherwise. (In a capital-constrained world, the criterion is to invest in projects with the highest BCRs.) The criterion to invest if BCR > 1 is identical to a criterion to invest if the sum of discounted cash flows (ΣDCF) > 0.

4.1 Option Value of Waiting for New Information

A classic result of the investment under uncertainty literature (Dixit & Pindyck, 1994) is that investment may be sub-optimal even where BCR > 1. This can occur when: (a) an investment decision can be taken either in the current period or in the future; and (b) new information becomes available after the end of the current decision period. We outline a simple example of how this can occur.

Consider a three-period model (t=0,1,2) in which the decision to build a bridge can be taken either at the start of t=0 or t=1. The (discounted) cost of the bridge is 1 if built in either of these periods.[2] If the bridge is built at t=0 there are positive payoffs in each of

[2] Thus, if the discount rate is x%, the dollar cost of the bridge is 1+x if built in t=1 and is 1 if built in t=0. The example does not rely on choice of discount rate or cost differences of the bridge between periods.

t=1 and t=2; if built in t=1, the payoffs occur in t=2 only. Payoffs are state-dependent, where the state of the world in t is summarised by i, the number of 'bad' news events that have occurred prior to t. News in each period can be either "good" or "bad". At t=0, i=0 since there have been no prior news events. At t=1, i can take the value of 0 (no bad news event during t=0) or 1 (one bad news event). At t=2, i can be 0, 1 or 2. The payoffs to the bridge in each period decline as the state of the world worsens (i.e. number of prior bad news events increases) for that period.

The payoff matrix, with elements Y(i,t), is given in Table 1A for the case where the bridge investment is undertaken in t=0. In this case, Y(0,0) = -1, the construction cost of the bridge in t=0. If no bad news events occur, the payoff stream is Y(0,1) = 0.4 and Y(0,2) = 2 in t=1 and t=2 respectively. If a bad news event occurs during t=0, then the payoff in t=1 is Y(1,1) = 0.2. If no further bad news event occurs during t=1 then the payoff in t=2 is Y(1,2) = 0.5; this is also the payoff if a single bad news event occurs during t=1 but not during t=0. If a bad news event occurs during t=0 and t=1, the payoff in t=2 is Y(2,2) = 0.2.

For the calculations that follow we assume that good and bad news events are equally likely, so the probability of a bad news event, p, is 0.5 in each period. (The method does not hinge on this particular choice of p.) If we treat the payoffs in Table 1 as discounted cash flows,[3] we can calculate their sum for the project as viewed from the outset of period 0; this value is 0.1 (noting that the probability that i=2 and i=0 in t=2 are each 0.25 while i=1 has probability 0.5).[4] Thus, according to the conventional CBA approach, the project should proceed since ΣDCF > 0 (i.e. BCR > 1).

Consider, however, if the potential investor waits until t=1 to make a decision regarding the project. If i=0 at t=1, the investor knows that good news occurred at t=0 although there is still a risk of bad news during t=1 (after the investment choice has been made). The investor faces the payoffs shown in Table 1B. The investment cost is now incurred at

[3] In the next example, we analyse the method used to discount cash flows in more detail.
[4] ΣDCF = -1+0.5(0.4)+0.5(0.2)+0.25(2)+0.5(0.5)+0.25(0.2) = 0.1.

t=1 and the positive payoffs for that period are lost (due to construction only being completed at the end of the period). However the possibility of two bad news events has been averted, and so the potential payoffs in period t are either Y(0,2) or Y(1,2) from Table 1A. If the investor is in this state, the investment should proceed in t=1 since ΣDCF = 0.25 > 0.[5]

If, at t=1, the investor had instead observed a bad news event at t=0, she will face the payoffs shown in Table 1C if she decides to invest. Again the construction cost must be borne in t=1, while the potential payoffs in t=2 are now either Y(1,2) or Y(2,2) from Table 1A. If the investor is in this state, the investment should not proceed since ΣDCF = -0.65 < 0.[6] Since the investment will not proceed in this case, the actual ΣDCF = 0; i.e. no investment occurs and hence no cash-flows take place.

[Table 1 about here]

Since a good and a bad news event are equally likely in t=0, the expected ΣDCF (at t=0) if the investor chooses to wait until t=1 to make her investment decision is 0.125 (i.e. an equal weight on each of ΣDCF = 0.25 and ΣDCF = 0). This value is greater than that obtained by investing at t=0. Hence waiting is preferred to investing immediately, even though the conventional CBA approach recommends investing at t=0 given the positive ΣDCF calculated for an investment in that period.

The key to this result is that under conditions of uncertainty where (a) valuable new information is obtained over time, and (b) there is a choice of period in which the project can be constructed, there is a positive option value attributable to waiting. This does not always favour waiting, since the value of the option will be payoff dependent. For example, if Y(0,1) = 0.6 instead of 0.4 in Table 1, it would be optimal to build the bridge in t=0 rather than t=1. Thus, while the option is a contributor to overall value, it is not necessarily the dominant component. Its presence, however, can change the decision of

[5] ΣDCF = -1+0.5(2)+0.5(0.5) = 0.25.
[6] ΣDCF = -1+0.5(0.5)+0.5(0.2) = -0.65.

whether or not to invest immediately relative to a CBA approach that does not incorporate the explicit option value of waiting and learning.

4.2 Creation of Private Sector Option Value

The previous example showed how consideration of option value can lead to a more conservative approach to investment than would be recommended by a standard CBA approach. That result is the most well-known result of the investment under uncertainty literature. However, for the purposes of a major infrastructure investment that opens up the opportunity to develop new territory (as with the Auckland Harbour Bridge), a less conservative approach to investment relative to a standard CBA recommendation may be warranted. This result derives from an alternative set of assumptions as follows.

Consider a public sector infrastructure provider that has the opportunity to build a bridge which opens up a new area for development. We consider a three-period model (t=0,1,2) in which the bridge can be built in t=0, or not at all. This restriction means that we do not have to consider the potential option of waiting, discussed above, although the generality of the issues considered here transfers to a model where timing of the infrastructure project is also a choice variable.

In each period there is uncertainty about future states of the world, but learning occurs as time proceeds. If the bridge is not built, the payoff in each of t=0,1,2 is set at 0. The cost of the bridge is 1, and hence the net payoff in t=0 is -1 if the bridge is built. Henceforth (unless otherwise stated) we consider payoffs on the assumption that the bridge is built. The private sector can develop the new area at t=1 if and only if the bridge is built.

Private sector development leads to growth in the population and employment of the city. We assume that this growth is sourced from outside the region of analysis and so represents new resources for the relevant region. Private sector development only occurs in t=1 if it is expected to be profitable over the life of the development (i.e. over t=1,2).

News about the state of the world in t=1 can again be either "good" or "bad". This news is only revealed during t=0, and so is not known at the time the bridge investment decision has to be made. The private sector development choice occurs at the start of t=1. Table 2 shows two payoff matrices; Table 2A shows payoffs if the private sector chooses to develop, and Table 2B shows payoffs if the private sector does not develop. [B,G] indicates that decisions to build the bridge [B] and to develop (grow) the area [G] are both taken; [B,N] indicates that a decision to build the bridge was taken but that the private sector decided not to further develop the area [N]; [D,N] denotes the case where the initial decision was "do not" build the bridge (and hence do not develop the area).

Each payoff is again denoted Y(i,t). For each of the [B,G] and the [B,N] cases, the initial period payoff is given as Y(0,0) = -1 (being the cost of the bridge project). For the [B,N] case (the bridge is built but no development takes place), Y(0,1) = 2 and Y(1,1) = 0, as shown in Table 2B. If private sector development occurs in t=1, i.e. [B,G], we assume that this private development cost is 1. Thus the net payoffs in t=1 if new development occurs are -1 (=0-1) in the bad state and 1 (=2-1) in the good state, as shown in Table 2A.

[Table 2 about here]

After t=1 (i.e. after the private sector development decision has occurred), further news is revealed. Thus, in t=2, there are again three potential states of the world (i=0,1,2). If no private sector development has occurred, i.e. [B,N], the payoffs in t=2 corresponding to i=0,1,2 are 1, -1 and -5 respectively. If private sector development has occurred, i.e. [B,G], the respective payoffs in t=2 are 25, -5 and -12 respectively. The more pronounced negative outcomes with poor states of the world (i=1,2) reflect the extra costs involved in expanding the city boundaries when it would have been preferable to remain within the original boundaries. The large benefit when two good states have occurred (i=0) reflects the positive returns to expansion when that expansion is supported by a sequence of good news events. The payoffs in each case are shown in column t=2.

A brief note is in order here about the specification of the payoffs. Each payoff is deterministic once the (i,t) combination is revealed. Thus the payoff for [B,N] with two bad outcomes is known to be Y(2,2) = -5. This payoff is the utility payoff at t=2 in state of the world i=2; it is not the dollar return. At an aggregate level, the consumption capital asset pricing model (Breeden, 1979) can be used to assess the utility payoff for any dollar return. For instance, a one dollar return in bad times will have a higher utility payoff than a one dollar return in good times.

A corollary of measuring the payoffs in utility terms, where each payoff is deterministic once the (i,t) combination is known, is that the real risk free rate is the appropriate discount rate to use to discount future payoffs to the present (Guthrie, 2009). In our example, we use a real risk free rate of 4% per annum (i.e. a discount factor of 1.04).

The payoff matrices from Table 2 can be used to perform a discounted cash flow analysis[7] as would typically be done for a cost-benefit analysis. Table 3 shows the net DCFs (discounted to t=0) corresponding to Table 2, using a 4% p.a. discount rate. In order to arrive at an expected value, we must specify the probability (p) of each news event (i.e. each state transition) being bad; we again adopt p=0.5 for convenience.

[Table 3 about here]

The sum of *ex ante* discounted cash flows (ΣDCF) for each case is shown beneath each portion of Table 3. Typically, a CBA considers whether either of these totals is positive. In the first case, if both the bridge and private developments proceed, the *ex ante* discounted cashflow is negative (-0.31); thus, *ex ante*, a two-stage development is not warranted according to the conventional CBA criterion. In the second case (the bridge is built but no further development proceeds), the *ex ante* discounted cashflow is again negative (-1.43) and so a single stage bridge development is also unwarranted using the conventional CBA criterion. Thus a standard CBA will reject the bridge project because

[7] Strictly speaking, this is a discounted utility analysis, but we will retain the usual nomenclature.

it yields a negative ΣDCF (i.e. BCR < 1) and the negative ΣDCF holds whether or not the subsequent private development is undertaken.

However, conventional CBA analysis, as above, misses the value of the option that the bridge creates. An option provides the opportunity, but not the obligation, to exercise an investment choice in a future period. In our bridge example, the private developers, having observed the value of i at t=1, have the option at t=1 of choosing whether or not to invest in developing the area opened up by the bridge, but not the obligation to do so.

To examine the worth of the option, we adopt a value function approach, as displayed in Table 4. Each cell shows the forward-looking value of being in that position, given the existing value for i, at time t. In t=2, the value in each cell, V(i,t), is therefore identical to the equivalent payoff, Y(i,t), in Table 2.

The value for V(0,1) equals the payoff at that time, Y(0,1), plus the discounted worth of the probability-weighted potential values in t=2 [V(0,2) and V(1,2)].[8] The same approach is adopted for each other cell at t=1 in the two matrices. Similarly, V(0,0) is calculated as the payoff at that time, Y(0,0), plus the discounted worth of the two probability-weighted potential value functions in t=1 [V(0,1) and V(1,1)].[9]

The resulting V(0,0) corresponds exactly to the sum of the discounted cash flows presented in Table 3 in each case, so for both the [B,G] and [B,N] cases, V(0,0) < 0. Again, consistent with the DCF approach, a conventional CBA would conclude that the bridge should not be built since the value of the multi-stage project is negative whether or not private development subsequently occurs. However, these values are still calculated prior to taking the option into account and would only be an appropriate valuation of net benefit if the choice between private development (G) or none (N) were irrevocably committed to at t=0. In fact, that choice is made only at t=1.

[8] Thus, in the [B,G] case, 10.62 = 1+ (0.5*25-0.5*5)/1.04.
[9] Thus, in the [B,G] case, -0.31 = -1+ (0.5*10.62-0.5*9.17)/1.04.

To see how this choice affects the analysis, consider the nature of the private development decision at t=1 if the bridge had been built at t=0. If i=0, the developer has V(0,1) = 10.62 if the development proceeds, i.e. [B,G], while V(0,1) = 2.00 if there is no development, i.e. [B,N]. Thus if i=0 at t=1, the developer will maximise value by developing since 10.62 > 2.00.

If i=1 at t=1, the developer has V(1,1) = -9.17 if development proceeds, i.e. [B,G], while V(1,1) = -2.88 if there is no development, i.e. [B,N]. Thus if i=1 at t=1, the developer will maximise value by choosing not to develop since -2.88 > -9.17.

Viewed from t=0, the bridge investor will optimally recognise that the decision tree will diverge depending on the value of i at t=1. If good news occurs after the bridge is built, the private development will take place, but no further development will be undertaken if bad news occurs at that time. The two relevant values in t=1 are therefore shown in bold, one in each of the [B,G] and [B,N] cases. The actual value of the project at t=0 if the bridge is built, **V(0,0)**, will then be equal to the payoff in t=0, Y(0,0), plus the discounted worth of the two probability-weighted (bolded) potential value functions in t=1 being **V(0,1)**, from the [B,G] case, and **V(1,1)** from the [B,N] case. In our example, this yields **V(0,0)** = 2.72.[10]

The resulting project value prior to any investments occurring, **V(0,0)**, is positive and thus the project should proceed. The choice to build the bridge is optimal, but is contrary to the conclusion derived from a standard CBA that recommends against the bridge project since BCR < 1 either with or without the subsequent private development. The optimal approach incorporates the value of the option whereas the standard CBA approach ignores its value. With multi-stage decision-making, coupled with the ability to update information and alter decisions between stages, a conventional CBA therefore fails to incorporate all benefits of a project. Specifically, it fails to incorporate the option benefit related to future investment decisions made by other investing parties that can

[10] I.e. 2.72 = -1 + (0.5*10.62-0.5*2.88)/1.04.

only be taken conditional on the infrastructure investment being undertaken in the initial period.

[Table 4 about here]

The results derived from this example are instructive for interpreting the merits of actual historical decisions. In some circumstances, an investment may have been optimal to proceed with *ex ante* when viewed from t=0 where the option value is included in that assessment but, *ex post*, subsequent information may lead to a [B,N] outcome rather than a [B,G] outcome. If the [B,N] outcome occurs, the project will not be viable either with or without subsequent private sector development. Thus one may be left with a "white elephant" such as an unprofitable canal or railroad or a "bridge to nowhere". A simple historical *ex post* analysis, undertaken with the benefit of hindsight, might conclude that the investment was foolhardy or poorly researched (and of course this might be the case for some projects). However, the investment decision to build may nevertheless have been optimal *ex ante* even though the subsequent information made the investment unprofitable.

One implication of the inevitable *ex post* failure of some transport projects – that were optimally chosen to proceed – is that a portfolio approach to infrastructure investment, as in standard finance applications, should be considered. Each investment can be considered as part of a portfolio of investments. It is the return (and risk) on the total portfolio which is of importance, not the outcome for any single investment. Thus, rather than considering whether each project turned out to be warranted *ex post*, a more comprehensive and appropriate assessment would examine whether the portfolio of transport investments added value given that each project was assessed legitimately *ex ante* inclusive of option value.

5. Conclusions

This paper demonstrates two key implications of incorporating option values into the analysis of major transport (and other infrastructure) projects where information is uncertain and can be updated over time. First, where timing of the infrastructure investment itself is a choice variable, the option to delay construction has value and this raises the hurdle rate for the project relative to a situation where (a) the investment cannot be delayed (i.e. must be undertaken now or never), or (b) new information regarding the benefits or costs of the project are not expected to arrive within the time horizon for decision-making. Most projects will have some elements of (a) or (b), so there is a case to apply some premium to the discount rate in order to account for this aspect of option value.

Second, where additional private (or public) sector decisions are taken subsequent to the infrastructure project's construction, the project can create a valuable option for other investors that provides them with the opportunity, but not the obligation, to invest in ways that utilise the new project. The key requirements for a project to create positive option value in this way are: (a) project decisions are made sequentially; (b) there exists uncertainty concerning the value of future stages of a project; and (c) flexibility is retained about whether successive projects are undertaken or not, with decisions on those projects reflecting new information that comes to hand after completion of earlier projects in the sequence. Under these circumstances, the *ex ante* economic value of a sequence of projects can be greater than the discounted present value of the expected future cash flows. The reason for this result is that value is increased through the creation of options for subsequent sequential choices through the completion of initial projects.

The potential for projects to "fail" *ex post*, even when proceeded with optimally *ex ante*, implies that public sector investors should treat infrastructure projects as part of a portfolio of projects. Provided that each project is optimally assessed *ex ante*, it is the return and risk on the portfolio of projects that should be the focus for accountability rather than the *ex post* outcome on any one project.

In the case of a major new transport link, such as a major bridge, the range of subsequent investors may be very wide. It includes every potential firm and household that could locate in the newly serviced region, and most of these potential investors will be unknown at the time of initial construction. Thus it is impossible to contract *ex ante* with those who may gain as a result of the infrastructure investment. *Ex post*, however, if the project proves to be worthwhile, standard spatial equilibrium arguments (e.g. Roback, 1982; Haughwout, 2002; Glaeser and Gottlieb, 2009) imply that land values will rise subsequent to the project's announcement.

A range of land value capture mechanisms can then be used to extract some or all of the proven benefits of the project (Coleman and Grimes, 2011). Thus public sector investors can seek to extract the value of the option that they create through imposition of financing techniques such as betterment taxes or tax increment financing. Whether or not these financing alternatives are available should not, however, detract from the over-arching result that project assessment of a multi-stage infrastructure project needs to incorporate the value of the option created for other potential investors.

One extension for the use of this method of analysis is worth noting. Howell and Grimes (2010) discuss considerations that should be borne in mind when considering the merits of (costly) large-scale investments in fast fibre for broadband purposes, as is currently being proposed by public bodies in many countries. The fibre investment creates the option for firms and households to utilise fast broadband services that would be unavailable without the fibre availability. Availability of fast broadband through the fibre investment can spur innovations by potential users that use the new network. In the absence of the fibre investment, the innovation could be stifled since there would be no way of applying such an innovation domestically. However, the infrastructure provider cannot know which firms will choose to innovate and so cannot capture the full benefits of such innovation. Furthermore, the fibre investor cannot be sure that innovations using the network will ultimately occur, since the infrastructure only provides the opportunity, not the obligation, for such innovation to occur. The analytical properties of this issue are identical to the bridge example, and so the same techniques can be applied to the fibre decision as outlined here for a new transport link.

References

Alexander Turnbull Library. 2006. *Map New Zealand: 100 Magnificent Maps from the Collection of the Alexander Turnbull Library*. Godwit, Random House, Auckland.

Belich, James. 2009. *Replenishing the Earth: The Settler Revolution and the Rise of the Anglo-World, 1783-1939*. Oxford: Oxford University Press.

Black, Fischer & Myron Scholes. 1973. "The Pricing of Options and Corporate Liabilities", *Journal of Political Economy* 81, 637-654.

Breeden, Douglas. 1979. "An Intertemporal Asset Pricing Model with Stochastic Consumption and Investment Opportunities", *Journal of Financial Economics* 7, 265-296.

Coleman, Andrew & Arthur Grimes. 2010. "Betterment Taxes, Capital Gains and Benefit Cost Ratios", *Economics Letters* 109, 54-56.

Cox, John, Stephen Ross & Mark Rubinstein. 1979. "Option Pricing: A Simplified Approach", *Journal of Financial Economics* 7, 229-263.

Dixit, Avinash & Robert Pindyck. 1994. *Investment Under Uncertainty*, Princeton NJ: Princeton University Press.

Duranton, Gilles & Diego Puga. 2004. 'Micro-Foundations of Urban Agglomeration Economies' in: V. Henderson & J. Thisse (eds), *Handbook of Regional and Urban Economics Vol 4*, Amsterdam: North-Holland.

Glaeser, Edward & Joshua Gottlieb. 2009. "The Wealth of Cities: Agglomeration Economies and Spatial Equilibrium in the United States", *Journal of Economic Literature* 47, 983-1028.

Grimes, Arthur & Yun Liang. 2010. "Bridge to Somewhere: Valuing Auckland's Northern Motorway Extensions", *Journal of Transport Economics and Policy* 44, 287-315.

Guthrie, Graeme. 2009. *Real Options in Theory and Practice*. Oxford: Oxford University Press.

Haughwout, Andrew. 2002. "Public Infrastructure Investments, Productivity and Welfare in Fixed Geographic Areas", *Journal of Public Economics* 83, 405-428.

HM Treasury (accessed 2010) *The Green Book: Appraisal and Evaluation in Central Government*, London: TSO; http://www.hm-treasury.gov.uk/d/green_book_complete.pdf.

Howell, Bronwyn & Arthur Grimes. 2010. "Productivity Questions for Public Sector Fast Fibre Network Financiers", *Communications and Strategies* 78(2), 127-145.

Maré, David C. & Daniel J. Graham. 2009. *Agglomeration Elasticities in New Zealand*. Motu Working Paper 09-06, Wellington: Motu.

McLauchlan, Gordon (editor). 1989. *The Illustrated Encyclopedia of New Zealand*. Auckland: Bateman.

Miller, Roger & Donald Lessard. 2008. "Evolving Strategy: Risk Management and the Shaping of Mega-Projects", Chapter 8 in: H. Priemus, B. Flyvbjerg & B. van Wee (eds), *Decision-Making on Mega-Projects: Cost–Benefit Analysis, Planning and Innovation*, 145-172, Cheltenham, UK: Edward Elgar.

New Zealand Transport Agency. 2010. *Economic Evaluation Manual Volume 1*, Wellington.

Roback, Janet. 1982. "Wages, Rents and the Quality of Life", *Journal of Political Economy* 90, 1257-1278.

Rosenthal, Stuart and William Strange. 2004. "Evidence on the Nature and Sources of Agglomeration Economies" in: V. Henderson & J. Thisse (eds), *Handbook of Regional and Urban Economics Vol 4*, Amsterdam: North-Holland.

Table 1: Payoffs with Single Investment Opportunity

Table 1A: Payoffs Y(i,t) at period 0

	t (period)		
i	0	1	2
0	-1.0	0.4	2.0
1		0.2	0.5
2			0.2

ΣDCF = 0.1.

Table 1B: Payoffs Y(i,t) at period 1 with i=0

	t (period)		
i	0	1	2
0		-1.0	2.0
1			0.5
2			

ΣDCF = 0.25.

Table 1C: Payoffs Y(i,t) at period 1 with i=1

	t (period)		
i	0	1	2
0			
1		-1	0.5
2			0.2

ΣDCF = -0.65.

Table 2: Payoff Matrices for Multi-stage Investment

Table 2A: Payoffs Y(i,t) for [B,G]

i	t (period)		
	0	1	2
0	-1	1	25
1		-1	-5
2			-12

Table 2B: Payoffs Y(i,t) for [B,N]

i	t (period)		
	0	1	2
0	-1	2	1
1		0	-1
2			-5

Table 3: Discounted Cash Flows

Table 3A: DCFs for [B,G]

i	t (period)		
	0	1	2
0	-1.00	0.96	23.11
1		-0.96	-4.62
2			-11.09

ΣDCF = -0.31

Table 3B: DCFs for [B,N]

i	t (period)		
	0	1	2
0	-1.00	1.92	0.92
1		0.00	-0.92
2			-4.62

ΣDCF = -1.43

Table 4: Value Function Matrices

Table 4A: Value functions V(i,t) for [B,G]

i	t (period) 0	1	2
0	-0.31	**10.62**	25
1		-9.17	-5
2			-12

Table 4B: Value functions V(i,t) for [B,N]

i	t (period) 0	1	2
0	-1.43	2.00	1
1		**-2.88**	-1
2			-5