Incorporating and assessing travel demand uncertainty in transport investment appraisals

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An important note for the reader

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Executive summary

The key issue of this study was to find ways to improve transport investment decisions in the face of uncertainties about future transport needs.

A literature review was undertaken. Fitting for a study of uncertainty, a broad range of research was canvassed, including uncertainties inherent in traffic modelling, approaches to value real options and processes used to address uncertainty, including, in particular, adaptive management.

The research pointed to the presence of pervasive uncertainty, as opposed to measurable risk facing transport planners. In turn, this highlighted the need for approaches that could take into account all uncertainties, irrespective of whether they could be quantified or not. The research showed how real options could be valued and why conditions for accurate valuation will seldom exist for major transport projects. Nonetheless the valuation models do provide insights into what drives value, value that is easily missed in the standard cost–benefit analysis that typically overlooks adaptation. The research showed several processes being used to address risk and uncertainty but no one elegant universal solution.

A key finding was that value does exist in flexibility and more can be done to ensure flexible solutions, where appropriate, are found. A cross-section of examples illustrates and provides insight into this value creation. Similarly, examples show where adaptive management has been used to apply some of the concepts of real options.

If stochastic models are only of limited use in the face of uncertainty, as opposed to risk, then a broader approach to decision making is required. A multi-faceted approach to uncertainty is recommended, which identifies the uncertainty of relevance to the investment decision, ways the investment may be adapted over time to suit the future that does evolve and ways this learning process might be improved by seeking learning opportunities within the investment. This process was applied to three New Zealand case studies – one ex post and two ex-ante.

The study did not find a single definitive answer on how to reduce or deal with uncertainty. Nevertheless, the study has shown that (a) a thorough process is required in the face of large uncertainties rather than adoption of a single go/no-go benefit–cost ratio; (b) learning and adaptation can be of significant value even if this involves a trade-off between interim costs versus reduced incidence of poor returns; and (c) use of one discounted expected value as the basis for a decision criterion does not transparently capture the risk propensity of decision makers.

In practical terms, the recommended solution entails the use of decision trees and scenario planning. Quantitative analysis is used to provide insights but not necessarily dictate the answer. In short, the key recommendation is that more time is taken by decision makers to understand how uncertainty interacts with decisions, and adaptive solutions which provide flexibility in the face of uncertainty are given more prominence.

Abstract

Uncertainty is pervasive when it comes to transport investment decisions. While it is natural to improve the traffic forecasts that inform such decisions, it is also important to acknowledge fundamental uncertainty exists about the future. Consequently, a process is required that acknowledges and addresses these uncertainties as part of improving investment decisions. This paper explores the uncertainties within transport modelling and the ways flexibility in the face of uncertainty can add value to a transport project. Insight into value is revealed by way of examples of real options. Likewise examples of adaptive management are explored. A process is recommended that explores the nature of the key uncertainties pertaining to a transport investment and actively searches for robust solutions in the face of uncertainties. This process transparently sets the trade-offs inherent in alternative solutions in front of decision makers.

1 Introduction

The topic of this research was making transport investment decisions in the face of uncertainty. There is a well-established procedure to transport appraisal of alternative fixed investment choices but this approach usually ignores management's ability to adapt in the future. The standard approach is based on the net present value of expected benefits and costs to society and provides a consistent and rigorous assessment of the relative benefits and costs when there is certainty about these future outcomes and when there is little ability for management to adapt over time to changing circumstances. In the latter situation, management can not only choose amongst current alternative transport investments but also has the option to change investments over time, such as to increase or decrease scale, delay the timing or switch between alternative investment pathways. These are examples of real options, namely the ability to invest (or divest) in real assets over time. This adaptability is generally not well treated within a standard investment appraisal.

A major source of uncertainty within transport appraisal is future travel demand. Typically, a major investment into transport infrastructure is undertaken to achieve lower travel costs for users over the next few decades. The actual benefits achieved will depend on how demand evolves over a long period of time, and that can be influenced by external events (eg gross domestic product (GDP) and population growth) and by changes to other parts of the transport network (eg introduction of alternative routes or modes). Instead of committing to a fixed transport investment, it may be optimal to adapt the investment over time as certainty about demand increases. Or in other cases, discovery of demand may depend on the provision of some initial infrastructure. Both are examples of real options. There is a possibility these real options are ignored in a standard transport appraisal, either not being quantified or not being acknowledged at all.

An important contribution of this research paper is to consider how the NZ Transport Agency (the Transport Agency) can further build uncertainty and adaptability into current appraisal methods. Major insights into decision making under uncertainty is provided by real options analysis (ROA) and hence consideration of real options is a major part of this research project. It should be noted that while much of the study has been undertaken with travel demand in mind, the methodology extends to consider uncertainties that generally relate to a transport investment.

The research paper is laid out in three parts: (a) literature is reviewed to explore real option definitions, applications and valuation, plus provide an overview of uncertainties around transport demand forecasts and the models that create such forecasts; (b) a methodology is developed from this literature that potentially could be widely used within New Zealand transport appraisal; and (c) this methodology is illustrated – and refined – by way of three brief case studies.

There are two distinctions that require elaboration early.

First, ROA can quickly become mathematically intricate. This will sometimes be the case in this paper but the emphasis of the research is to find a pragmatic way for insights from ROA to be applied in New Zealand transport appraisal. This means the emphasis moves away from the valuation of a real option per se to the identification of real options and the consideration of the potential effects of these real options on benefit and cost assessments.

Second, there is a distinction between uncertainty and risk. Future events with known probability distributions are termed risky. The rest are considered uncertain[1]. The valuation of real options deals primarily with risky events. However, the approach can be generalised to consider how uncertain events might interact with a series of investment decisions and the valuation methods do provide a means to test sensitivity to assumptions about uncertainties.

The key findings are that there are numerous opportunities for a more adaptive approach to project design, even if this provides some challenges in the valuation stage. Valuation models provide insights into when various options might be valuable – and under what conditions. Ensuring these opportunities are explored, or are not extinguished, has been the major focus of the research.

The results for two real options, in particular, are noteworthy. Decision makers will be familiar with projects mooted as transformational – a type of prosperity project where there is the alluring prospect of a very large benefit, but the development response of others is uncertain. Real option analysis can indicate when such a project might offer a high net present value. More importantly, though, a ROA forces a focus on the not-so-prosperous outcomes that might eventuate. In many cases, preference is likely to be for projects with more modest but less sensitive benefit expectations that also do not extinguish the prosperity scenario, rather than the ‘big hit’ project that possibly offers the higher *expected* return.

The second phrase familiar to many is ‘buying time’. Generally this occurs when a large, irreversible cost appears required but the benefit stream is modest. The real option to learn becomes especially valuable in such situations. It can simply entail delay but it can also include actions to reduce uncertainty and possibly changes that enable the large cost to be avoided, or at least delayed.

As it turned out, the research project was conducted in a manner fitting of an analysis in the face of uncertainty: it has entailed weaving together a wide range of issues, it has proceeded in an iterative fashion and it has produced an inelegant solution. A methodology is suggested, and tested by example, that fits closely with the better business case methodology and the cost–benefit analysis (CBA) approach of the Transport Agency. However, by virtue of the presence of uncertainty, it is inevitably imprecise and will need to be adapted to the situation at hand. The key recommendation is simply that time is taken by decision makers to understand how uncertainty interacts with decisions, and that adaptive solutions are given more consideration.

[1] There are also some rare known future events

2 Literature review

2.1 Summary of literature review

People know the future is uncertain and that flexibility is valuable but there remains the difficult balancing of doubt and optimism or of excessive future-proofing and short-term compromising or simply of procrastination and impulsiveness. This study considers ways that help find this balance, enabling the value of flexibility to be identified and measured where appropriate and then informed decisions made as to whether to act now or later, and by how much.

This entails finding technical solutions to measuring value but, more importantly, establishing methods to address uncertainty in decision making. The technical tools considered in this report largely revolve around the field of real options and modelling stochastic processes. The managerial tools revolve around decision making and adaptive management methods.

The second section of the literature review (this being the first section) defines some of the terminology and concepts to be used within the report. An important distinction is between unknowns that pertain to variables with known distribution functions, ie risk, and uncertainty about which we know very little. The former will be examined under the heading stochastic processes.

The third section outlines current approaches to dealing with risk and uncertainty, especially within the widely used CBA approach.

Uncertainty within transport forecasting is pursued in the fourth section. Largely these forecasts are derived from transport models. In turn, these models require data to be gathered, equations to be specified and parameters to be estimated – each brings with it uncertainty. A tentative conclusion at this stage is that subsequent development by the local private sector is a key uncertainty in the short term (this is not usually considered a stochastic process) while larger driving forces such as gross domestic product (GDP) and population growth are pivotal longer term (these may be stochastic but do also face shift changes).

Real options is the topic of chapter 5: what they are, how they are valued and where they have been applied. A key finding is the usefulness of the binomial option pricing model to value a wide range of real – and financial – options. When variables are stochastic the model offers a way to value the option. When dealing with deeper uncertainty, the models can be employed to test sensitivity of value to specific future events of interest. However, a challenge exists when it comes to deriving accurate real option values across a wide range of circumstances.

An ROA provides a concept and valuation method but this still leaves open the choice of objective function. Adaptive management, the topic of the sixth section, complements and extends an ROA by considering more widely the trade-off between risk and return.

Variations or mixes of the approaches discussed in this chapter will be explored in the next phase of the project, as presented in chapter 3.

2.2 Terms and definitions

2.2.1 Risk and uncertainty

There is much uncertainty created by talk of uncertainty itself.

One key distinction is between risk and uncertainty. Knight (1921) proposed: 'It will appear that a measurable uncertainty, or "risk" proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all. We shall accordingly restrict the term "uncertainty" to cases of the non-quantitative type'.

Put more succinctly by Michael Mauboussin[2].

> *Risk: We don't know what is going to happen next, but we do know what the distribution looks like.*
>
> *Uncertainty: We don't know what is going to happen next, and we do not know what the possible distribution looks like.*

Applying this terminology, there are unknowns. Unknowns such as the throw of a die involve risk and it is appropriate to talk in terms of means and variances. Other unknowns like the effect of self-drive vehicles (SDVs) are uncertain. We can make judgements but there is no repeatable event drawn from a perceived probability distribution.

Chapman and Ward (2011) suggest this distinction is at odds with the common vernacular. Typically people connote risk with unfavourable outcomes, whether the probability distribution is known or not. This is not disputed but to maintain consistency with the literature around real options, this report adheres to the Knightian distinction between risk and uncertainty, unless otherwise stated at the time.

2.2.2 Types of risks and uncertainties

There are also other ways to break down risks and uncertainties.

Walker et al (2010) refine the distinction between risk and uncertainty to encompass four types of uncertainty (in the more general sense of uncertainty and risk):

- There are uncertainties that can be described adequately in statistical terms.
- There are situations where a few alternative trend-based futures capture the extent of uncertainty.
- There are other situations where a wide range of plausible scenarios adequately capture the nature of the uncertainty.
- There are those situations where we only know that we do not know, referred to as deep uncertainty.

Chapman and Ward (2011) point to four distinct types of uncertainties that can arise in projects (with uncertainties used in the more general sense that includes risks and uncertainties):

- ambiguity – including about the project objective, project specifications and contractual obligations
- inherent – including ongoing issues such as inflation or GDP growth
- event – including equipment failure or a one-off scenario such as an earthquake
- systemic – including events and responses that feed back, often in a complex manner, to create large effects that may be disproportionate to the original shock.

While these were presented as relating to risks and uncertainties within a project, as opposed to benefit and cost forecasting, the distinction between ongoing, one-off and complex risks and uncertainties is

[2] www.ritholtz.com/blog/2012/12/defining-risk-versus-uncertainty/

useful. As too is the fundamental question of whether any analysis undertaken to address uncertainties and risks is unambiguously pertinent to the project objective.

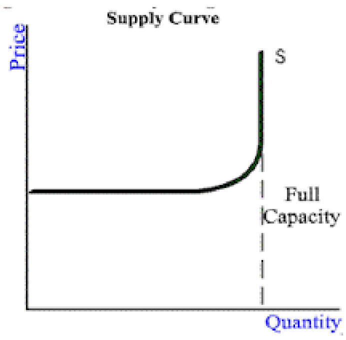
A distinction is also made between risks and uncertainties that are project specific, such as those pertaining to an oil company finding oil or a drug company developing a new drug or the Transport Agency finding that geological conditions for a new highway are adverse, and those that arise due to changes in market forces, such as the price of oil or a drug or the volume of traffic (Guthrie 2009). The former are called 'private' risks and the latter 'market' risks (Kodukula and Papudesu 2006). They are also referred to within finance as idiosyncratic and systemic risks. The relevance of this distinction is that private (or idiosyncratic) risks are potentially diversifiable by the investor while market (or systemic) risks are not.

A similar distinction is between 'collective' risk and 'individual' risk (which can generalise to include uncertainties in the Knightian sense). Boardman et al (2011) define collective risk as events that will affect all people of relevance to the analysis (ie the people of standing), such as a nuclear accident, as opposed to events that will affect some individuals only, such as a road crash.

Before delving further into the unknown, some housekeeping: the rest of the report will largely ignore the variation due to intra-day and seasonal effects. These effects are clearly prominent but they are also generally well understood, so for the sake of brevity the following notes consider variation as if all observations were seasonally adjusted, unless specifically stated at the time.

There is one clear temporal distinction, though, of relevance for transport projects. The supply curve for a road, say, is likely to be shaped as below, where 'price' denotes the generalised cost of travel and 'quantity' denotes vehicles per hour (or some other time interval). The flat section of the curve depicted applies to roads where traffic volume is well below capacity and thus travel times and costs are largely unrelated to volume. The steep section describes situations of congestion, where more traffic volume typically ramps up the travel time and hence the cost of travel. Projects that involve stretches of road where capacity is rarely reached will focus on improved travel time or safety and hence aim to shift the supply curve downwards; seasonal and intra-day effects are likely to be of minor importance. Conversely, intra-day effects will be of primary importance with projects where congestion is the key issue; such projects will aim to increase capacity (ie shift the supply curve to the right).

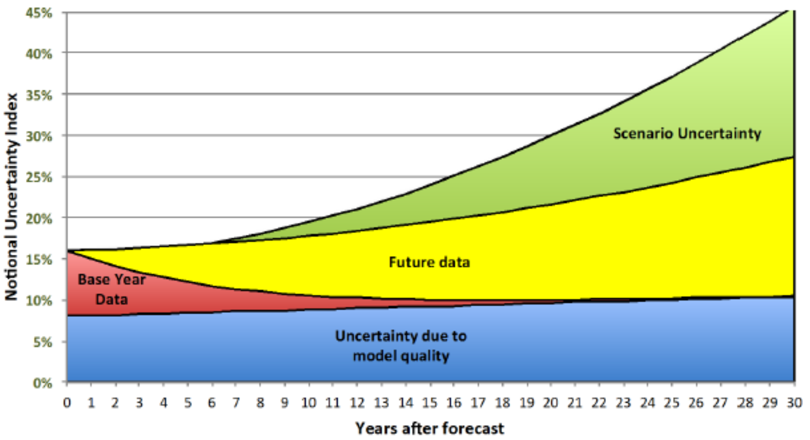
Figure 2.1 Typical transport supply curve



Returning to risk and uncertainty and in particular to travel demand forecasts, there are many unknowns. In general terms these unknowns can be categorised as unknown aspects of current observations, unknown parameters/models that explain what is occurring and an unknown future. To make any decision we generally need to know what is happening, be able to explain why it is happening and predict what will happen if we intervene in some manner. We can further distinguish future events that we have some control over, those that are expected to evolve according to a reasonably well-understood process and those largely one-off events that will occur, either expectedly or unexpectedly.

Willumsen (2014) adopts a similar categorisation of the main sources of uncertainty: base year accuracy; model fit; future data inputs; and future scenarios (eg competition and technology)[3]. He notes the sources of uncertainty will take on more significance over different forecast periods.

Figure 2.2 Notional sources of uncertainty in forecasting



Source: Willumsen (2014, figure 24)

To reinforce the challenge posed in modelling current travel flows, let alone future traffic flows, consider how the vehicle kilometres travelled (vkt) on a major road in Auckland will depend on the following factors:

1. There will be events at global and national levels, be they of a continuous change nature (eg NZ GDP, average vehicle usage per person) or of a discrete technological disruptive nature (eg adoption of SDVs).
2. There will be industry and/or regional occurrences within the macro-economy (eg New Zealand tourist arrivals, freight usage within sector, natural disasters, or changes in local public transport or roading infrastructure).
3. There will be firm or location-specific events (eg development of residential sub-divisions, expansion of industrial sites).
4. There will be random events (ie in practice all the unexplained influences).

Thus we will see Auckland vkt outcomes in recent years affected, for example, by:

- changes in international fuel prices
- ongoing New Zealand population, GDP and employment growth
- at a sectoral level,[4] changes to regulations about vehicle dimensions and weight restrictions
- strong New Zealand tourism arrivals causing an increase in tourist vkt

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[3] The key difference in categorisation is the separation of controllable future events.

[4] See vehicle volumes on selected roads at www.anz.co.nz/about-us/economic-markets-research/truckometer/

- at the regional level, strong population growth in Auckland
- more public transport provision and rising road congestion (in some parts)
- at a local level, residential sub-division and industrial expansion in urban peripheries, particularly around Auckland in places like Pokeno.

The above can be compared with Christchurch where there have also been negative shocks from earthquakes, followed by positive shocks associated with reconstruction.

The point is that local traffic volumes will be influenced by a tier of many factors.

The challenging task for traffic *forecasters* is to accurately predict all these influences on traffic flows that will extend decades into the future, plus correctly predict how any relationship between explanatory variables and traffic flows will change (let alone what they are now), and allow for random variation. Not surprisingly, traffic forecasts do err from the eventual reality. This subject is taken up in section 2.3 and again in section 3.1. The task for traffic *planners* is how to deal with these various sources of uncertainty when designing and choosing projects. This issue is the central focus of this paper.

2.2.3 Risk and uncertainty in valuation models

An adjustment for risk is core to any valuation model.

First risk must be measured. One way to measure risk is to find the stochastic properties of the variable of influence. Market risks and private risks can both result from stochastic processes. A variable is termed stochastic if over time the changes in the variable include random effects. However, there are many ways random effects might occur (eg a variable might transition to only one (unknown) state of two future possible states or it may potentially transition to many future states). There are also many deterministic factors that might affect a stochastic variable. An overview of some terminology used to describe various stochastic processes is provided in appendix A3. For now, it is simply noted that a common stochastic process of interest is one displaying geometric Brownian motion (GBM), which applies when the percentage change between the random variable between any two time periods is a mix of a trend effect (ie a drift parameter multiplied by the time lapsed) and a random amount (that will also increase with the time lapse).

Second, risk is factored into the valuation model. The distinction between 'market' risk and 'private' risk (or more literally, 'risks and uncertainties') is important from a valuation perspective. Market risks are unlikely to be diversifiable, eg national GDP growth will wax and wane and project benefits will do likewise. Conversely the private risks can typically be diversified, eg the risk of a cost over-run on one project could be offset by a cost under-run on other projects within the portfolio of all projects (assuming there is otherwise no bias towards management incompetence across the portfolio). When it comes to valuation, an undiversifiable risk requires inclusion of a risk factor in the valuation, effectively reducing the present value of any expected future benefits. Under certain circumstances, a diversifiable risk does not require a risk factor in the valuation and hence only a risk-free discount rate is applied to calculate present values.

Taken to its extreme, as in the Arrow-Lind theorem (Brent 2006), no risk adjustment is required for all public projects, essentially because any risk is diversified across the population. However, this result does not hold if the project is correlated with national income and/or if the risks are concentrated among a group of the population. It is also possible conditions can exist for a negative risk premium to be applied to public projects.

Putting aside any risk premium, there is also the contention around what inter-temporal risk-free rate should be applied (see, for example, Creedy and Guest 2008).

For now, it is simply noted the Transport Agency prescribes a 6% pa real discount rate to consistently apply and rates of 4% and 8% can be applied as sensitivity tests. We recommend these different discount rates be applied within decision trees to test sensitivity of results.

The common method for factoring a risk premium into a valuation is to add a risk premium onto the discount rate, thus the discount rate is the sum of the risk-free rate and the risk premium. The (gross) discount rate then forms the denominator that discounts future expected cash flows. It is possible to instead apply a risk factor to the expected future cash flow directly and achieve the same result by discounting at the risk-free rate[5]. The numerator used in this case is the (smaller) risk-adjusted expected cash flow and is termed a 'certainty equivalent'. This difference in method is typically of no significance to the standard CBA, as the same net present value is derived. The difference does take on significance in the discussion of real option valuation as different modelling approaches use different risk-adjustment methods[6], and the same net present value is not always derived.

The contention over discount rates is additional reason to prefer an adaptive management approach, as discussed in chapters 3 and 4.

2.3 Overview of approaches to uncertainty

2.3.1 The standard CBA approach

The future is unknown, whether these unknowns are considered risk or uncertainty, and yet we still have to make transport investment decisions in anticipation of the future, even if the decision is to defer any investment.

Before embarking on a discussion of other ways to address uncertainty, it is useful to define how uncertainty is addressed at present. Obviously this leads to generalisations that will not always be the case. This is an issue that Eschanback et al (2007) raise when critiquing the usefulness of real options in engineering projects. There is also the matter of emphasis that may or may not be put on sensitivity testing within the standard CBA (NSW Treasury 2007). We will return to these issues in section 2.4.2 but, to provide context for many of the papers discussing real option applications and real option valuation, it is useful to describe a widely used approach to a CBA for transport investments. This will be sometimes referred to as the 'peak-design' investment within this report.

The key tools in the standard approach in transport appraisal are the transport model and the CBA. Readers are referred to Boardman et al (2011) for an overview of CBA. Transport models are discussed further in section 2.4 and appendix A1.

The difficulty with these combined tools is the transport models do not accurately predict the future and the CBA does not transparently summarise the benefit-cost and risk-reward trade-offs[7]. Both tools are

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[5] In fact, this type of two-step approach is conceptually the correct way to adjust for investment risk and consumption time preference (Boardman et al 2011, p265)

[6] The binomial option pricing model employs the certainty equivalent approach while Monte Carlo models apply a risk premium via the discount rate. See appendix A2 for more detail.

[7] Out of scope for this project, Dorfman and Rothkopf (1996) add a third short-coming, namely the failure to identify those benefiting or to be harmed, although this adjustment is possible in a CBA but is rarely undertaken

likely to provide reasonable approximations in many situations and are suitable for small and repeated projects. But these two tools will not be sufficient when dealing with large future changes, such as might occur due to technological breakthroughs, demographic and economic developments and shifts in activity behaviour. The challenges arise because these potentially large and discrete changes imply a future that cannot be described in probabilistic and symmetric terms and are likely to trigger an adaptive response by decision makers.

In general terms, management addresses uncertainty with the transport model – CBA framework on several levels:

1 Accept some variation is natural. Whatever is done in subsequent steps to reduce uncertainty, there will always be variation, say, in trips along a road. It may be possible to more fully understand (step 2) the underlying causes of observed trips but there remains an element of whim about when someone chooses to move from point A to point B.

2 Improve measurements. Simply observing what is happening involves uncertainty, particularly in a multi-faceted network such as transport. We can improve and/or increase measurement to better understand the cause of any variation that we do observe. This typically involves using unbiased sampling techniques, including stratified and repeated sampling to reduce unexplained variation.

3 Improve estimation of model parameters. Measurement alone cannot help us decide what might happen if we intervene in any system. A model is required for this. We improve our estimation of model parameters by use of unbiased and/or consistent estimation techniques, and generally by disaggregating variables and extending models to improve goodness of fit[8].

4 Improve forecasts. Forecasts by definition involve uncertainty. Techniques used to reduce forecast error include use of multiple models including possibly a time series analysis of average annual daily traffic (AADT) alongside a transport model, scenario creation, close attention to the average forecast of experts (in preference to any one expert's opinion) and a 'reasonableness' test by decisions makers, either explicitly or implicitly[9]. Each technique leads to further probing of the initial forecasts and/or use of averages of multiple forecasts.

5 Test for sensitivity. Given uncertainties about model inputs, model structure and model parameters, it is commonplace to test outcomes for sensitivity to key inputs and/or assumptions. This testing will typically vary depending on the decision at hand.

6 Consider different scenarios. Sensitivity testing can easily miss the cumulative effects of any assumptions. Consideration of outcomes under several scenarios enables greater insights into potential interactions and the range of outcomes.

It is important to note in the situations where decisions are especially sensitive to uncertainties that the usefulness in the standard approach comes from the sensitivity and scenario testing rather than the point estimates of demand, costs and benefits per se. This will always remain an important part of the response to decision making under uncertainty.

[8] It is worthwhile recalling a model might have a poor goodness of fit, as measured by a statistic such as R-square, but the model may still provide unbiased and sometimes even precise estimates of the parameters of relevance to the decision in hand. The uncertainty in this situation is the relevant parameter estimates may be biased due to some omitted variable in the model.

[9] Including the use of heuristics.

But even with all these enhancements, there is likely to remain uncertainty and the ability of management to adapt is typically not well captured by a net present value (NPV) summary.

2.3.2 Wider approach to uncertainty

Methods to address risk and uncertainty have also evolved within other disciplines.

Operations research provides several mathematical methods to consider uncertainty. A commonly used method is a decision tree. Decision tree analysis (DTA) can be employed within a CBA but this does not appear to be common practice.

DTA is a well-known tool that enables the sequence of alternative decisions faced in light of future uncertainties to be laid out in a systematic manner, according to widely used conventions (eg circles for chance nodes, squares for decision nodes). A complementary tool commonly used with DTA is the influence diagram. A standard text is Render et al (2012).

DTA provides a simple way to reduce a lot of information to a small diagram but it does require reducing chance events to discrete outcomes and also having supporting methods to derive the probabilities of each chance event and the ultimate payoffs from each branch. The use of subjective probabilities is common although there is evidence that so-called experts are not necessarily good at forecasting (Harford 2011).

Complexity is also an issue as interdependencies can lead to decision trees becoming very 'bushy' quickly, albeit computer software exists today (eg TreeAge) that improves the tractability of complex decision trees.

A further major challenge with decision trees, when it comes to valuation, is that it is not clear what is (are) the appropriate discount rate(s) to apply.

Finance has also provided techniques and methods for risk and uncertainty. The key insights are the usefulness of portfolios to reduce private risk and the use of a risk-adjusted discount rate to adjust for market risk.

The real options field has emerged from finance as one way to address the valuation challenge, albeit incompletely. Probably more relevant for this research project, ROA also draws attention to the specific types of choices available to decision makers. This is taken up in more detail in section 2.5.

ROA has also gained support from research into institutions and law, where value is perceived in terms of 'rights' and contracts are considered in terms of opportunities to exploit uncertainty (Pennisi and Scandizzo 2006).

Then there is the discipline of risk management. Standards (eg ISO 31000) have been set within the profession for understanding, managing, communicating and monitoring the effect of uncertainty on the objectives of an organisation.

Of particular interest to this project is the field of adaptive management. Aligned to risk management processes, the methods involved – and discussed in section 2.6 – enable real options to be recognised and managed.

A crude synthesis of the approaches to uncertainty is to build uncertainty into the decision making on several levels, as listed below. This is broadly incorporated within the Better Business Case methodology adopted by the Transport Agency.

1 Align projects with strategy[10]

2 Be aware of behavioural biases in decision making

3 Analyse volatility and instability

4 Build risk into the cost of capital

5 Seek mitigation (accept, avoid, minimise, restore, offset, transfer)

6 Monitor and adapt over time.

The standard CBA approach fits within this wider framework but with emphasis on (3) and (4).

The methods researched in this research project also fit within this wider methodology but with the emphasis more on (6), as well as (3) and (5). The key components of the methods investigated are:

- decision tree analysis
- real options analysis
- adaptive management.

The three components do overlap and, as will be seen in the case studies, were used together. Before expanding these components, see section 2.4 for more about travel demand forecasting and existing guidelines on dealing with uncertainty.

2.4 Travel demand uncertainty and management

Prediction has been described as being: '...at least two things: important and hard ' (Stevenson and Cruickshank 1998).

2.4.1 Uncertainty within transport modelling

The transport model is a core part of any transport appraisal. A review of transport modelling, including the widely used four-step model, and the sources of uncertainty in transport models was undertaken within this research project and is summarised in appendix A.1. A summary of uncertainties within the four-step transport model is given in table 2.1.

Table 2.1 Key uncertainties within the four- step transport model

Variable to be estimated	Affects	Uncertainty that may underlie the estimate
The network. Includes description of road links and junctions, public transport (PT) facilities, parking areas. Plus travel times and costs across all parts.	Distribution, choice of route and mode.	Network may not be accurately represented (eg excluded bus lanes may affect travel times). Unknown new infrastructure (ie roads, PT capacity, lanes, speed limits, SDVs) will exist in the future.
Congestion. Modelled as function of free-flow travel time and capacity.	Travel time. And hence choice of route, mode and number of trips.	Interdependent with above to the extent the descriptions of lane width, alignment, gradient etc may not be accurate in the model. Also, congestion around project link can affect use of the link[11].

[10] A project that is insensitive to strategy would be very adaptive, as discussed in section 2.6

Variable to be estimated	Affects	Uncertainty that may underlie the estimate
		Willumsen: equations commonly used 'tend to underestimate delays at junctions' and 'when demand is close or above capacity'. Key actual responses to congestion are (a) change route then (b) change departure time but the latter is often not well modelled.
Generalised travel cost (GTC). Modelled as function of time in-vehicle, waiting, walking and at interchange.	Distribution over: • choice of route • mode • number of trips.	Different time values exist for different individuals but SKM (2009) report limited segmentation used in models. Different and changing out-of-vehicle costs (eg parking, walking) may not be well modelled. Unknown future costs of public transport (including public subsidies).
Use of network at equilibrium.	How trip distribution adjusts to congestion levels.	People are not fully informed and rational so actual trip distribution will vary from 'equilibrium'. Travel will also be affected by unforeseen and not modelled trips due to crashes, mistaken routes, joy riders, weather conditions, local one-off events.
Trip rate per household and activity. Including for trips within, between and through the study area. And reconciliation with (partial) traffic counts.	Number of trips.	Besides macroeconomic influences on trip rates, there is local variation. Typically measured by local surveys, hence subject to sampling error and potentially sampling bias (eg time of day, day of week, weather, base year effects). Trip destinations typically have limited data to establish models, especially for 'other purposes'. Usual uncertainties relating to future estimates. In practice, judgement and/or a model is also required to blend new information with existing estimates of trip matrices, including new traffic counts[12].

Source: Heavily but not exclusively sourced from Willumsen (2014).

Future travel demands form a key input to economic appraisal of transport projects (World Bank 2005). Such appraisals are highly influenced by demand forecasts, for the following reasons:

- A transport investment will alter travel patterns and an understanding of this change (ie a demand forecast) is needed to enable an appraisal to take place.
- Demand forecasts provide estimates of key inputs to the calculation of user benefits. For example traffic flow measures (such as vehicles, passengers, tonnes of freight), as well as travel times and vehicle speeds are required for the calculation of travel time and operating cost benefits.

[11] Eg congestion has altered travel times either side of Brisbane's Clem Jones Tunnel and has reduced the marginal benefit of using the tolled tunnel, leading to traffic in the tunnel well below those initially forecast.

[12] Willumsen (2014) notes a 10% natural variability to traffic counts.

- Economic appraisal occurs over the life of a project. Estimates of the way user benefits vary over time are therefore required[13] and, to determine these, demand forecasts over time are required.

Travel demand estimation (and its associated uncertainty) is thus one of the key challenges of CBA, particularly for transformational transport projects where land uses changes may be induced (Laird et al 2014; NZIER 2013).

General and cautious conclusions from our review of this literature and professional experience are:

- Within the short- to medium-term (0–10 years), key benefit uncertainties for most projects may exist principally through relatively local land use development, some of which may be induced by a transport project or package.
- Within the longer-term (10+ years), potentially more significant uncertainty exists over the principal drivers of overall transport demand, such as GDP and population growth as well as potential change in trip generation and distribution parameters in the face of uncertain social, economic and technology changes.

These reflect an assumption that appropriate steps can be and are taken to minimise errors in measurement and modelling of the existing situation, being the starting point for any projection(s). For different projects it is likely the impact of uncertainty will vary, but it should be helpful for decision-makers considering transport investment to know:

- whether the transport demand (and resulting project benefits and investment scale recommendation) would be similar whatever happens? (some dominant effect)
- whether the forecast transport demand and performance are unstable? (outputs may readily change with small input variations)
- which uncertainties are key to outcomes? Knowing this may provide the potential for hedging risks, if real options and adaption opportunities can be identified and valued.

2.4.2 How do transport models currently deal with uncertainty

Nicolaisen and Driscoll (2014) outline two possible approaches for how planning research and practice can meet the challenge of providing accurate demand forecasts, in an increasingly complex (and inherently uncertain) world:

- One is labelled ‘hubris’, in which attempts are made to substantially improve model-based forecasting by monitoring performance, improving models and modifying institutional arrangements to reduce optimism bias;
- The other is labelled ‘humility’, in which attempts are made to quantify uncertainty, recognise the lack of accuracy and deliberately reduce the impact of forecasts on decision making.

Approaches along both lines are being adopted. Internationally it is apparent that uncertainty in transport modelling is being seen as increasingly important to recognise and address. Examples include the UK Webtag Uncertainty Log and the NZ Transport Agency (2013) *Economic evaluation manual* (EEM) (appendix A13).

Uncertainty within transport models when applied for project evaluation has most often been looked at (where sufficient resources have been made available) by (a) implementing well-founded model

[13] This need may be reduced in with more adaptive solutions

calibration, validation and peer review processes to minimise base model error and potential uncertainty propagation, with feedback derived from ex post studies of project evaluations; and (b) sensitivity testing of future performance, for example through application of:

- alternative (usually 'high' or 'low') population/employment growth forecasts
- alternative spatial distributions of development
- alternative network assumptions (eg do-minimum road improvements, competing public transport services)
- assumed model parameters or methods (eg value of time, perceived future fuel prices, parking costs, tolls, PT fares, assignment algorithms)
- comparing implied elasticities against ex-ante evidence/experience from other projects.

Wangsness et al (2015) in a review of 19 national transport CBA guidelines finds:

- Most guidelines recommend sensitivity analysis and many recommend simple or simulation-based scenario analysis as well.
- Besides construction costs, the variable most often recommended for uncertainty analysis is predicted traffic growth.
- The common way to assess systematic uncertainty is by sensitivity analysis of the discount rate.
- Highlighting uncertainty in a summary table was recommended by 9 of the 19 guidelines.

Although this represents the most common practice, such sensitivity testing may, however, be viewed as a fairly limited and arguably a crude manner of testing uncertainty, with the alternative sensitivity-test scenarios generally developed in a deterministic manner.

Often at the forefront of analysis, DfT (2014) recently outlined the following multi-faceted approach to addressing uncertainty. Before listing these approaches, it is worthwhile noting the more general approach adopted by the DfT (and the Transport Agency) has been to standardise methods and inputs where possible, to ensure the use of reliable forecasts and parameter estimates and to standardise approaches, thus reducing the uncertainty that arises solely due to model/method differences, albeit true underlying uncertainty remains. The DfT provides extensive transport analysis guidance (TAG), including TAG Unit M2 on demand modelling and TAG Unit M4 on uncertainty, and also provides a set of forecasts suitable for traffic modelling in the form of the National Trip End Model (NTEM). Their current approach to uncertainty follows.

1 Continue research into modelling to reduce model error. A key research area is around the changes in urban trip rates for commuting and shopping and reduced car ownership in dense urban areas.

2 Undertake more ex post evaluations to build up a portfolio of evidence. Again the aim is to improve the modelling plus gain better understanding of other pivotal inputs. Note, a US Transportation Project Impact Case Studies (TPICS) database of previous projects is used for different purpose in the US, namely for early stage project assessment.

3 Maintain an uncertainty log and use it as an input in sensitivity testing. TAG M4 requires keeping a log to record the central forecasting assumptions that underpin the core scenario and record the degree of uncertainty around these central assumptions. Uncertainties will include those around: the model, national travel demand, national travel cost, local non-transport developments and local transport developments. Key uncertainties are to be removed from the base case in sensitivity analysis.

4 Analyse benefits beyond the final modelled year where appropriate by, first, including a constant benefit profile and, second, using the best evidence to construct a long-term demand forecast. The HS2 (2013) figure shown below as figure 2.3 illustrates the constant benefit profile (B_2) where in this case the rail scheme was expected to deliver benefits well beyond the model period (Y_2). Alternative scenarios were provided for this project whereby the benefits kept growing for a range of longer periods. In all cases, benefits were subsequently expressed in present value terms.

5 Investigate the appropriateness of a long-term trend model, potentially linked to population and income growth, and the development of guidance on the potential of schemes in the long run.

6 Provide a range of forecasts rather than a point estimate, including probabilistic forecast ranges of outcomes. The calculation of probabilistic forecasts can proceed in various manners. Some transport models allow variances and covariances to be input, then propagated through to the model to provide variances around outcomes, including Timmermans et al (2014). The UK Airports Commission (2014) used this approach with their air passenger demand model, running the model over two thousand times to produce the fan chart in figure 2.4. An alternative method used by HS2 (2013) was to develop a regression model that estimated cumulative rail demand alongside the transport model, and then use this reduced form model to derive a range of outcomes for various levels of probability. These outcomes provided an earlier or later realisation of the benefit levels used in the base case for the start year (Y_1) and the model end year (Y_2). Figure 2.3 shows a case where the base benefits B_1 and B_2 take longer to eventuate (shown as points E_1 and E_2 moving to the right). The profile of benefits is adjusted accordingly for the intervening years and the post-model years (in this case constant benefits are assumed, as per TAG M4). The results were presented as a probability distribution of benefit-cost ratios (BCRs), categorised in line with DfT 'value' settings (shown below). It should be noted, though, irrespective of whether variances are generated within the transport model or contemporaneously, the outcome variances only capture the variance acknowledged in each model and hence provide only an approximate probability distribution, at best; plus the distribution of outcomes does not capture the uncertainties, as opposed to risks, that also exist.

Figure 2.3 HS2 risk analysis for long-term UK rail project

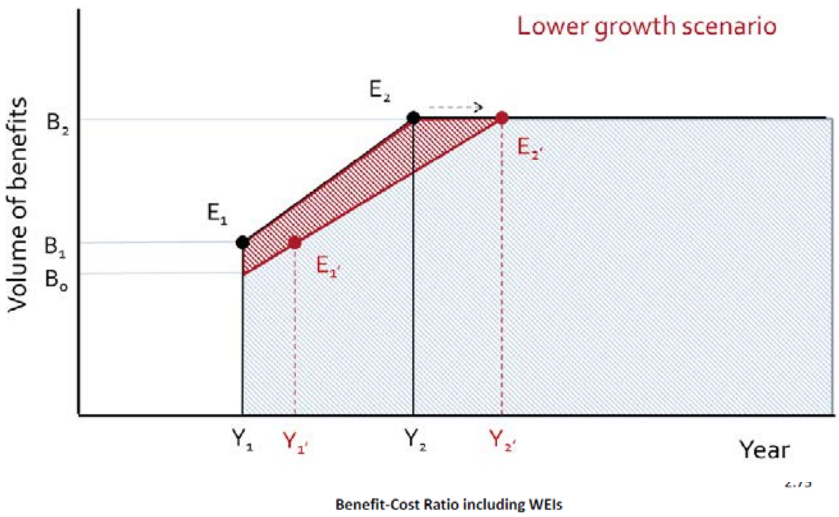
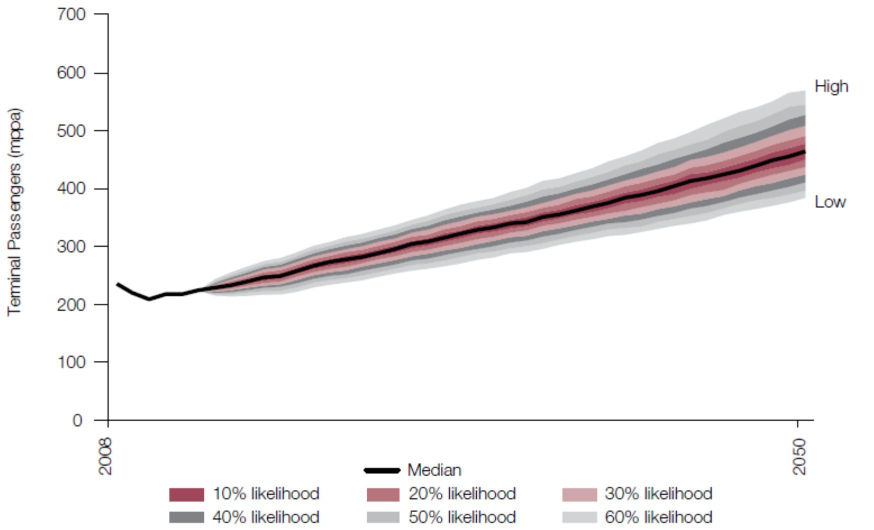


Figure 2.4 Airports Commission (2014) forecasts of UK air terminal passengers



7 Provide scenario testing. In the examples above, HS2 (2013) also provided outputs for six scenarios and the Airports Commission (2014) presented results for five wide-ranging scenarios. More generally, the latest UK National Traffic Forecasts (DfT 2015) have recently applied a scenario approach which seeks to recognise potential uncertainty. Their evidence suggests changes in travel behaviour observed through a decline in the trip rates over the decade before their paper (the extent varying by trip purpose), although they also appreciate the extent to which this will continue into the future is a key uncertainty for the future direction of growth in travel demand, particularly as the period studied includes a recession which may be a causal factor. The volatility in the oil price and the historical difficulties in forecasting GDP has also led them to examine assumptions around the growth in these variables, to take that uncertainty into account. These uncertainties are now reflected in five forecast scenarios which examine uncertainty in (i) peoples' propensity for travel (as reflected in trip rates); (ii) the cost of travel and peoples' ability to pay for it (as reflected in fuel costs and income growth); and (iii) the extent to which rising incomes lead to higher rates of car ownership and car use. Internationally, Wangsness et al (2015) list seven types of uncertainty that would lend themselves to scenario analysis: technological; demographic; relative price; national political; local political; local private sector development; residual value of infrastructure.

8 Generally provide more narrative around scenarios and uncertainty to decision makers. One important component of the communication is to show the outcomes expected from a core scenario, based on published plans and plausible assumptions, and then explicitly show the effect of various uncertainties on these outcomes. This step is considered particularly important where induced traffic, either from diversion or new land use, is considered to form a significant portion of the expected benefits.

Emerging methods

Although there clearly appears to be potential for improving understanding of potential uncertainty through greater application of a probabilistic approach to travel demand forecasting (and that of resulting project benefits), this still may not provide decision makers with an appropriate level of confidence whether and in what form to proceed with a project: It could certainly provide more information, and, setting aside whether decision-makers actually do find this to be helpful, would, essentially, still be heavily-reliant on 'traditional' methods of forecasting (including deterministic assumptions).

Such methods have, however, been criticised for their degree of inaccuracy in estimating both the benefits and costs of transport projects.

'Reference class forecasting' is a project management method that has emerged to address the potential for optimism bias and strategic misrepresentation of both project benefits and costs. Simply put, it is a method of predicting the future by looking at similar past situations and their outcomes, of 'ground-truthing' forecasts.

The method has been developed extensively since, not least by Flyvbjerg (2013) and Flyvbjerg et al (2006) and applied to major projects and programmes in the UK (including the $m London Crossrail project), the Netherlands, Denmark and Switzerland. (Salling and Leleur 2012; Priemus et al 2008).

For a specific project, the process involves the following three steps:

1. Identify a reference class of past, similar projects.
2. Establish a probability distribution for the selected reference class for the parameter that is being forecast.
3. Compare the specific project with the reference class distribution to establish the most likely outcome for the specific project.

2.5 Real options

This section starts with a brief definition of real options and their key features, then considers examples of ROA reported in the literature and proceeds to a more detailed description of option valuation and use of options in decision making.

The natural place to start in terms of describing real options is to liken them to their namesake, financial options. Financial options apply to financial assets; real options apply to real assets. However, that distinction does not do justice to the overlap existing between these two types of options. Nor does it do justice to the fundamentally different properties of those options on real assets that may never have a price, let alone trade in a secondary market, as initially envisaged (Myers 1977).

The sections draw from numerous sources, including reviews by Centinkaya and Thiele (2014); van Geenhuizen and Thissen (2012); Martins et al (2015) and textbooks by Guthrie (2009) and Kodukula and Papudesu (2006). A history of real options is provided by Armstrong et al (2004).

2.5.1 Definition

To use the language of financial markets, a real option gives the right, but not the obligation, to the option holder to invest or divest in an asset. In effect, the option holder can adapt their future investments in light of new information that evolves over time. The essence of option value is learning.

In financial markets, the option holder has the right to buy (if a call option) or to sell (if a put option) an asset by a fixed date at a fixed price. The asset could be a currency, an equity, a bond, gold, a house etc.

With real options the buying and selling could be in the form of building a road (equivalent of buying) or scaling down a road project (equivalent of selling) and the equivalent of the fixed asset price is the cost of construction or research and development or investment more generally. Time is typically measured in years rather than days or months.

However, real options are not necessarily standalone assets. Trigeorgis (1993) refers to the real options embedded in real operational processes, activities, or investment opportunities that are not financial instruments.

2.5.1.1 Property of real options

An inherent property of a real option is having the ability to act in the future (Zhao et al 2004). Thus an investment may evolve over time, with each stage adapted to the new information at hand. The eventual cost of possibly a series of investments and the ultimate value of the benefits derived will be unknown at the start of the investment process.

In contrast, the typical fixed peak-design investment is irreversible as there is little or no ability to alter the investment in the future. In this case the investment cost is largely known but the ultimate value of benefits remains unknown when the investment decision is made.

In general, real options will be of value when (a) the future state of the variable of interest is uncertain (b) the investment involved is irreversible, or at least costly to reverse and (c) the investment to be undertaken can be done sequentially, or deferred in full.

The real option entails the right to invest in (or divest of) an asset at a fixed price within a set period. The value of the option comes in avoiding otherwise loss-making situations. Such losses are potentially large when the investment is irreversible. Such losses are potentially large when the factor(s) that determine success or failure of the investment are uncertain. For example, build a toll bridge and people decide not to use it then the costs of the bridge represent a (large) loss, as opposed to constructing a ferry for a river crossing and people decide not to use it then the costs can be reversed to some extent by the removal and sale of the ferry. In both cases, future demand was uncertain at the time of investment and subsequently proved to be unfavourable. Having the right to defer the bridge construction, while retaining the opportunity to build or not build, creates flexibility around an otherwise irreversible investment and provides real option value if potentially large payoffs exist. Addressing the otherwise irreversible bridge investment by trialing a ferry first also creates flexibility, to the extent that the ferry was designed for general purpose and can be abandoned at a relatively low cost, and hence can also provide real option value (both a learning option and an abandonment option). The real option value in both cases derived from avoidance of a premature irreversible investment in the face of uncertain demand.

The key condition – irreversibility – implies once you act you lose the flexibility to change (Dixit and Pindyck 1994). However, to 'act' may include 'to not act'. That is, failing to act may lead to irreversible investment situations, eg if you do not buy land now for a motorway then other users may undertake investments on this land that makes future use of the land for a road impossible or very costly. In this case, the real option comes from creating flexibility around an otherwise irreversible non-investment situation.

The sequential nature of an investment enables learning and adaption. If there is the ability to learn over time then the real option approach would be expected to generally provide a larger net benefit, except when the future evolves according to the forecasts that formed the basis of the fixed peak-design investment (Zhang and Babovic 2011). If the future is as forecast then the extra costs typically created by a flexible design approach will reduce the net benefit relative to the fixed peak-design approach. Put another way, if there is much uncertainty about the future then an adaptive approach is likely to produce a higher net value; conversely if confident about the future, the probable lower cost of the fixed peak-design investment will be an advantage.

Kodukula and Papudesu (2006, p59) also point out that an ROA, as well as being useful in situations of high uncertainty, is likely to be valuable when the NPV of an existing project is close to zero[14]. That's to say, recognising the value of flexibility may show that an otherwise negative or low NPV project is of net benefit and hence the decision to invest will be altered. This logic would extend to projects with a BCR near any other non-zero number that is chosen as a BCR threshold (eg BCR>4).

2.5.1.2 Types of real options

The choices defined as real options are many but will often fall within several classes. Lists have been provided by various authors including Trigeorgis (1993); Martins et al (2015, table 3) and Kruger (2012, table 2). Types of options and examples relating to transport are tabled below. The grouping is as provided by Guthrie (2009).

Table 2.2 Examples of real options in transport

Real option:	Comment and examples
Timing options	
Option to defer	The option to defer relates to timing. This might be when to develop a property or oil well, or when to expand capacity in a factory? Or to defer a new road investment until high traffic demand materialises. More generally it is the determination of the optimal time to fully invest, such as whether to rehabilitate a road sooner or later.
Option to abandon	Similar but opposite to above would be to cease an existing operation. In this case there is still the investment of some funds to pay the costs of closure but the future benefit will be lower ongoing expected costs, as opposed to higher ongoing expected revenue. Such an option might be having the flexibility to be able to decommission a manufacturing factory, end a pharmaceutical research programme, or have written into the contract the right to cancel a road construction programme if expectations are not met.
Option to scale up or down	More generally both the above options may have the flexibility to scale up or down, The flexibility may result from incurring ongoing costs (eg retain a property for development) or from accepting low- or non-profitable operations such as maintaining a railway track even if usage is low at present in case demand increases in the future.
Compound timing options	
Option to stage	This is having the ability to undertake a sequence of (irreversible) investment decisions, such as stop-starting a construction project or gradually expanding a firm's production capacity or having a gradual programme to work to build a road network. It may be expansion ceases at some point midway through a conceived programme. A specific example might be to build a motorway between cities A and B as, first, a motorway between A and intermediate location X and, second, a motorway between X and B (when and if still of value).

[14] Although this also requires that conditions exist for a real option to be of value.

Real option:	Comment and examples
	A more general form of this option is where each stage in the sequence is not fixed. There may be the flexibility to double, say, the size of the capital expenditure in any stage of a road building programme or change the order that new roads are constructed.
Learning options	
Option to learn	This is a variation of the above options, except now the waiting time is used to actively learn, such as drilling to learn about the underground structure when beginning construction of an oil well or a road tunnel.
Switching options	
Option to switch	The option to switch involves the simultaneous expansion and contraction of activities and hence is a combination of options. The option might be that flexibility exists to switch between road and rail investments depending on relative demand.

The options of interest to a transport project will vary by circumstances but the option to learn can be especially valuable. A special case of this option is an option initially termed the quasi-option. As described by Treager (2014), the quasi-option was derived to determine the value of waiting and learning about the odds of species' extinction before proceeding with a development that may create this risk. Noteworthy about this type of option is the development is irreversible once started.

A second type of option of particular interest to transport projects is the real option that transport infrastructure creates. New infrastructure provides an option for the private sector (or other public bodies) to undertake developments with a higher chance of success than otherwise would have been the case. The value to society of this option comes from the payoff should development proceed that otherwise would not have occurred and the probability of such development.

Further discussion of these two options is taken up in section 3.2, following discussion of real options examples.

2.5.2 Real options sought in project design

It is possible to view real options as an aid to decision making, laying out the decisions and conditions on when to expand, contract, or wait. From this perspective, the importance of real options comes from recognising their existence and incorporating suitable real options into project design. Martins et al (2015) describe the importance of real options for infrastructure project design as being a 'paradigm shift on how infrastructures will be built in the future'. Triantis and Borison (2001) report that simply framing problems in real option terms was helpful. That is, the consideration of real options brings focus on uncertainty and response to resolution of uncertainty, on the sequencing of events and on the inter-dependence of decisions and influences. This in itself aids decision making.

2.5.3 Valuation

Besides providing an aid to decision making, ROA aids the calculation of benefits. This, as can be attested by a scan of a few real option papers, can be very complicated. Before looking at specific methods, some general points may help the intuition when it comes to the mathematical intricacies of option pricing.

First, the valuation of options proceeds like much valuation by linking the asset in question to an asset regularly traded in an open market. A key difference, though, for options is the option value is derived in some fashion from the underlying asset. For example, we might value a house by comparing it to similar houses that have been traded recently. For an option to buy a house, say, we go one step further and use the observed variation on houses sold in the housing market to derive a value for buying the house at a set price by a set date. For financial options, such underlying assets are generally readily available. There are markets for houses, shares, bonds, traded commodities and currencies, to name a few major markets. For real options, such assets generally do not exist, eg bridges and roads are generally not traded. Methods have been devised to get around this short-coming but the valuation of real assets remains a general challenge.

Second, and expanding on the above usefulness of markets, the starting point for valuation by a risk-neutral investor[15] of any asset is to equate current value to the expected return. There is also a reward for risk to add but even that can be broken down into an expected return over a large number of events (eg average return over a large number of successful and unsuccessful new ventures) plus a pure risk premium for taking on this volatility (eg around 4–6% pa for taking on the volatility in share markets). The point is that the major component of most asset pricing is expected return. Options are no different (Tanenbaum 1987). The major component of a fair value for an option will be the amount it is expected to deliver in the future, be that future cash earnings, future capital gains or, for transport, future travel cost savings. This link with expected return can easily be lost amongst the at-times convoluted pricing models. Where markets exist, information about our future expectations can often be discovered, eg we can estimate whether people, on average, expect a recession to occur within the next two years. Without markets, the challenge is to know what benefit people are expecting. This can sometimes be provided by surveys or fundamental models of behavior.

Third, the normal practice in valuation is to take a cash flow perspective. An investment, including an option, is broken down into the cash flows to be expected, and these cash flows are then risk-adjusted and discounted to present values (usually in the one step). In the case of real options, the valuation methods generally consider the value of an asset at any point of time as cash, implicitly assuming that the underlying asset is sold at that stage. This assumption applies in financial options as well (eg exercising the option to buy an equity does not typically coincide with the immediate sale of that equity, although it is possible) but this assumption does present an added complication for many real assets, as they are often not sold, nor can be sold.

With these general comments in mind, three methods are commonly employed for valuation and a fourth is sometimes used to derive approximate values. These methods are:

1 The Black Scholes Option Pricing Model (BSOPM) was the breakthrough method used for pricing financial options. It is not widely used with real options as it only values European options (ie the ability to exercise your option is only at the end of the option period) when one uncertainty exists whereas most real options are usually of the American type (ie exercise any time before expiry) and have multiple uncertainties[16]. Furthermore the valuation is closely linked to prices for market traded financial assets that are often not directly relevant for real options.

2 The Binomial Option Pricing Model (BOPM), also referred to as the binomial lattice[17] method, can be viewed as a more general version of the Black Scholes model in that it also requires close linkage between market-traded financial assets and the real asset from which the real option derives its value. The BOPM can value European options, multiple uncertainties and structural changes in the evolution of the underlying real asset value (eg jumps, changes in volatilities). It has been widely used for real

[15] A risk neutral investor is one who is indifferent between a certain payoff of, say, $50 and the expected value ($50) of gaining $100 with a 0.5 probability or gaining nothing with the same probability

[16] Another type of option is a Bermudan option where rights can be exercised at particular moments.

[17] Also trinomial lattices in some cases

option valuation. One advantage of the BOPM is there is no need to choose a risk premium to apply to any discount rate as risk is encapsulated in the measurement of benefit at any one point in time.

3 A Monte Carlo simulation provides an even more general method to produce likely outcomes of the underlying asset price and optimal strategies. A Monte Carlo simulation allows a wide range of pathways to be modelled but therein lies its disadvantage as sometimes the outcomes will lack transparency. Also there is some contention over the appropriate discount rate to use.

4 DTA will not provide an accurate valuation of a real option but has been used to approximate option values. It requires subjective assessment of the probability of future events and of the discount rate. Martins el at (2015) states the methodology is suited to situations of drastic change but can be difficult to interpret when several branches are developed.

More detail on these methods, including some worked examples, is given in appendix A2.

Borison (2005) provides a comprehensive critique of these various valuation methods, showing the different methods can produce different values and lead to different decisions for essentially the same situation. The conclusion reached was that an integrated approach was to be recommended, whereby the BOPM is employed where risk can be identified as pertaining to markets and decision trees are employed, with subjective probabilities, for private risk. Given that many situations faced in major transport projects will entail uncertainty rather than market risk, this recommendation reduces to heavy use of decision trees within major transport projects.

The potentially inaccurate nature of such valuations raises a large challenge. However, the valuation methods do provide insights into what potentially determines value, which can help with the selection of adaptive solutions. Adaptive management is backgrounded in section 2.6 below.

In the meantime, some perspective on which real options have been considered and how they have been valued is provided by way of some examples by sector in the following sections. In some cases the ROA has been combined with DTA, an issue that will also be discussed further in subsequent sections.

2.5.4 Oil/gas industry

> *Option to defer: Regards profitability on investing. Possible future condition may be preferable compared to the present situation. This option exists when management is able to leave itself open to investment opportunities, for a certain period. (*Martins et al 2015)

One field suited to real options is that of the oil and gas extraction industries. Dixit and Pindyck (1994) used the example of an oil field as an early illustration of real options. The real option exists in the form of being able to leave reserves in the ground until such time extraction is profitable, subject to the term of the lease for the field. The fundamental flexibility is being able to defer the investment. The real option can also be accurately priced as the value of the underlying asset, a developed oil field, is traded and is also linked closely to the widely-traded market for delivered oil.

It should be noted the ‘cost of delay’ is to be included within the pricing of a deferral option, eg delay may mean a revenue stream is forgone as is the case with dividends if deferring the purchase of a listed share in a company. Eschenback et al (2007) warn these waiting costs can be large for real options and are sometimes overlooked in valuations.

> *Option to abandon: Management’s ability to abandon a current operation permanently and recover the salvage value of the asset. Similar to American put options.* (Martins et al 2015)

A real option can also exist at the other end of the oil field life, and in mining industries more generally. Owners hold a real option if they have the flexibility to abandon the oil field, or mine, if market conditions are no longer favourable.

Furthermore, this real option will have value even before the oil field is developed. Having the flexibility to discontinue extraction if unprofitable means an initial investor can now achieve an asset value above the average expected asset price, otherwise typically used in a CBA. As stated by Dixit and Pindyck (1994), the extra value of the real option will depend on the sizes and the probabilities of the losses you can thus avoid.

> *Option to stage: Some investments can be staged in order to create growth and abandonment options. This allows for viewing each stage as an option on the value of subsequent stages (compound options).* (Martins et al 2015)

Bringing the above two simple options together, the oil industry can also create a compound real option by staging development, hence enabling investments to be sequentially undertaken, deferred or abandoned.

A further sophistication is that two uncertainties often exist. The value of a developed oil field will change as oil prices go up and down, and hence the expected benefit from investment is uncertain at any point prior to investment (as in the simple deferral option). The other uncertainty is typically a variation around two themes: also unknown is (a) the volume of oil within the field and/or (b) the time and cost to develop the field. The decisions may be (a) when to drill (ie learn) and/or (b) when to develop (ie expand) or (c) when to simply abandon the field. Each step entails an irreversible investment. Revealed at each step will be information about the underlying asset price and about the quantity or cost of product. New decisions to drill, expand or abandon will be made at each stage and so the process continues.

A real option approach enables framing the decision process and also putting values around learning, deferring or expanding. Whereas similar decisions are faced within transport investments, the key difference to the oil industry is not having widespread availability of market data in transportation.

As an example of the valuation calculation, Guthrie (2009), in valuing a real option to time development of a gas field, could take advantage of the market price of traded energy royalty trusts, dubbed the ‘spanning asset’. These prices provide an estimate of the present value of expected future gas revenue for various fields, enabling a lattice of potential ‘developed gas field’ values to be derived, ie the stochastic properties of the value of the field[18] could be deduced. There was also the ability to model the relationship between this ‘developed gas field’ value and the probable, risk-adjusted, value of the undeveloped, or at times semi-developed, gas field in question.

In this example, there was a private risk that revolved around the cost and timing of the development stages. Gas reserves were known. Decisions were made each year but there existed a multi-year lag before development was complete. The private risk could also be modelled based on a history of field developments. The cost of development can thus be estimated in each of the future years, taking into account uncertainty and the limited remaining lease term. These costs effectively established a threshold each year above which the value of the developed gas field must reach before development is undertaken. Should the price of developed gas fields prove high then development will proceed; conversely lower prices imply waiting.

The combination of the potential asset values and the expected return in face of variable investment costs can be represented as a lattice. At a simple level, this enables a full set of investment outcomes to be

[18] As opposed to the price of gas or the demand for gas

viewed; at the more sophisticated level the value today of proceeding (or not) down individual pathways can be estimated.

It should be noted the calculation of the asset price distribution required not just a market traded asset but adjustments for leverage, taxation, remaining gas reserves and rates of depletion, ie the calculations are not trivial.

The two stand-out differences to a parallel transport investment is (a) there is unlikely to be a history of market valued transport assets that can be used as a spanning asset and (b) there is also no market price to observe while waiting until the optimal time of investment.

Valuation of real options of this nature are generally undertaken using the binomial pricing method as above, including Kalligeros et al (2006), or derived from a Monte Carlo simulation, including Cardin and de Neufville (2008).

This same type of problem and real option approach also exists with mining and with the development of vacant real estate (Damodaran 2007).

2.5.5 Forestry

The forestry sector provides further examples of where timing – and other – options can exist.

The problem of when to harvest trees grown for forestry is a long-standing application of both the present discounted value[19] and ROA (Thomson (1992); Insley and Rollins (2005)). Guthrie (2009) provides a useful discussion of the application of real option valuation techniques to this problem.

Briefly, the issue facing a forestry owner is to decide when is the optimal time to harvest a forest given volatile timber prices and in the face of: (i) ongoing forest management costs, (ii) harvesting costs, and (iii) post-harvest regeneration costs – where each of these costs may themselves be volatile. For instance, should an owner of a radiata pine plantation harvest the trees when they are 25 years old at a time of historically buoyant wood prices while foregoing another 5–10 years' growth of the trees? The problem facing the owner is a classic real option problem, and the value of waiting to harvest versus harvesting now can be valued using standard real option techniques.

In valuing this option, the owner faces both a standard timing problem and a potential switching problem involving land use following harvest, eg whether it should be retained in forestry, regrown with the same type of tree or regrown with a different type of tree. Information required to value this option includes (i) the stochastic properties of the timber price; (ii) forest management costs; (iii) harvest costs; (iv) the appropriate risk parameters (eg from the Capital Asset Pricing Model (CAPM)), and (v) the risk-free interest rate.

The forestry application is not particularly isomorphic to a road investment problem in that the forest has already been planted; it is known it will bring in a point-in-time revenue scheme at some chosen future period and the key decision problem is when to harvest. By contrast, the road investment problem is normally whether to embark on a new road (or on a road upgrade). Furthermore, the forest application can be informed by constantly observed market prices for timber so the stochastic properties of the key state variable (timber prices) can be modelled. Again this is not the case for most road applications. While forestry therefore provides an elegant example of real option valuation in practice, it is not a particularly suitable exemplar for applying real option valuation techniques to the road investment problem. As a result, we do not develop this field further in this review.

[19] Guthrie notes that the first application of the present value approach to forest harvesting dates back to 1849.

2.5.6 Manufacturing

> *Option to alter operating scale: Regards changes in market conditions in order to make the most of them (either increase profits or minimise losses). If market conditions are favourable, the company will want to increase the output level by making an investment to scale up the production plant. On the other hand, if market conditions are unfavourable, the company must have the ability to shut down production. Similar to call options.* (Martins et al 2015)

A very flexible option is the option to choose amongst multiple options to abandon, expand or contract.

Such an option can exist for a manufacturer if they have the ability to alter production levels. The option is relatively simple in that the key uncertainty is market demand. This can often be modelled as a stochastic process. The complication comes in taking into account the choices at each decision node. Using the standard backward induction used with binomial lattice structures, it requires assessing the optimal choice for each possible time and valuation combination. Kodukula and Papudesu (2006) show in a worked example for the production of a drug product that the value of the compound option to choose will likely have a greater value than any of the component simple options to abandon, expand or contract. However the compound option can sometimes be valued at less than the sum of the simple options.

2.5.7 Electricity generation

> *Option to switch: Options that create both process and product flexibility. By combining call and put options, the owner is able to switch between two or more modes of operation.* (Martins et al 2015)

Electricity generation is another sector where real options widely exist.

A real option for some generators is the ability to switch between different energy sources. Trigeorgis (1993) noted that a plant designed with the flexibility to use alternative energy inputs would enable the cheapest form of fuel to be used. There would be the extra design/construction cost of the production facility that would be partly, fully or more than offset by fuel cost savings over time. Trigeorgis noted this 'process flexibility' would also be valuable in other feedstock-dependent facilities and in cropping. A similar real option would exist for 'product flexibility' if there was the ability to switch products such as automobiles, consumer electronics, toys or pharmaceuticals. Dixit and Pindyck (1994) also applied this approach to managerial ability to enter or exit markets.

This real option to switch exists today for some players in the New Zealand electricity sector and is of a twofold nature: to switch inputs such as oil, gas, coal, wind, geothermal or hydro; and/or to switch the level of production, eg operate at 50% capacity or full capacity.

The equivalent real options within transportation would include having the flexibility to switch traffic between routes (as would be required by a resilient network) or having the flexibility to shift passengers across modes. Two of the case studies presented in chapter 4 discuss this latter switching option.

An important parallel situation for electricity generators is the construction of new generation plants.

2.5.8 Research and development

> *Option to grow: Exists when early investments (eg in R&D) create the opportunity for future revenues. Compound options whose value depends on a preexisting option. Similar to European or American call. (*Martins et al 2015).

The above real option examples were largely around observing market conditions, and in some cases some internal uncertainty, and responding accordingly, ie wait, expand, contract, switch or abandon. A more active option is to undertake activity to learn or to position for future growth opportunities. These growth options are prevalent in research and development (R&D) activity and include the option to grow that a patent provides. Hartmann and Hassan (2006), for example, point to real option use in pharmaceutical company clinical trials. More generally, Pennings and Lint (1997) refer to companies' survival depending on turning uncertain future payoffs into opportunities, thus any R&D investments can be thought of as the price of an option on major follow-through investments.

A simple example is presented first. Guthrie (2009, pp135 and 168) sets up the basic R&D timing problem as follows: a firm holds the rights to develop a new product within a fixed number of years; an initial decision is made to either take-up development rights or delay investment until the next period; if taken up, development costs are incurred and a known probability of success is faced; if the development turns out to be successful the product will go to the next stage; otherwise product development is abandoned or the rights sold (if still of value).

The valuation of this analysis can be undertaken by combining decision tree and binomial lattice methods. A worked example is given in appendix A2.

A more sophisticated example is that the probability of development success is unknown and is learnt as development stages progress. Now there are two uncertainties: the market risk as above; and a private risk relating to the probability of research success. Guthrie (2009) poses the problem now as there being an initial estimate of the probability that the development succeeds and this probability is refined after each stage (ie learning). The choice to proceed or abandon is revisited as new information about the product – and coincidentally about the market, as per usual – is gained.

Another sophistication with learning options is to consider the arrival of new information. Pennings and Lint (1997) refer to the discrete nature of the arrival of information that might cause a revision of research project values – the underlying asset in R&D real options – as opposed to the continuous information updates and asset price revisions that occur in financial markets.[20]. Examples of valuation 'jumps' caused by the sudden arrival of significant information include the discovery of new technology or the entrance of a new competitor – both will lead to a quick revaluation of future expected benefits. Using (pre-2000) research into optical tape for data storage, the authors discussed how the future revenue generated by (irreversible) research may be affected, including during the research stage, by (a) competitors' product development, (b) adoption of new technology standards by software producers and (c) changes in technology that may negate the need for optical tapes (as has since largely been the case). A real options value was estimated that took into account the stochastic nature of the information arrival.

Cetinkaya and Thiele (2014) refer to numerous papers on ROA within the R&D sector, including the following that are pertinent to transportation:

- Childs et al (1998) use real options to analyse two parallel development projects with only one to be taken to implementation;
- Bollen (1999) takes a life-cycle approach to product development and considers the possible effects of competing technologies also being introduced;
- Huchzermeier and Loch (2001) categorise five types of operational uncertainties, namely the market pay-off, budget, performance, market requirement and schedule uncertainties, and caution that some

[20] Managerial decision making does not appear to fit with the geometric Brownian motion assumed for financial asset prices.

uncertainty may decrease the value of flexibility by decreasing the probability of real options being exercised.

Transport investment shares some commonalities with R&D: market acceptance is often unknown at the time of initial investment; the eventual assets created (ie product or road) are typically long-lived; and the initial investments are often irreversible. Conversely, Pennings and Lint (1997) suggest irreversible spending in infrastructure markets will not provide as much opportunity for learning as R&D investment in technology markets.

Two aspects of the valuation of learning options are relevant to transport. The distinction between 'market risk' and 'private risk' is important[21]. Market risk usually affects the project as a whole and is outside the influence of management. Market risk cannot be diversified away and hence a risk premium must be included within any valuation in some way. Private risk is within the project itself. It is often an important element of infrastructure investments, eg reserves within an oil field, acceptance of a new product, costs of a bridge. In theory private risk can be diversified. Hence a risk-free discount rate is often assumed for private risk in real option valuation. Such diversification may not be true in practice.

The second aspect is the combined use of decision trees and the binomial option pricing technique to derive the option value, if required. Loch and Bode-Greuel (2001) go further and argue that the project-specific nature of major risks in R&D projects means decision trees alone should be used for project evaluation. Consistent with this argument, Santiago and Vakili (2005) argue that when the source of variability is development uncertainty or market requirement uncertainty then it is not possible to make a general statement about the impact of increased uncertainty on a real option value.

2.5.9 Urban development

One sector where timing and growth options can exist is urban development. The extra issue here, though, is not just responding to market conditions but taking into account actions that you or others may take to affect the market.

Guthrie (2010) analyses how real option value affects the price of houses relative to development costs for a new house. He shows that with demand uncertainty the value of a new house can considerably exceed development costs of new housing. The essential insight of the study is that housing amenity values are location-specific and hence each house differs in some respect to another house, giving the land-owner some monopolistically competitive power in the housing market. Each land-owner can choose when and if to develop their land where their decision is taken both relative to what a competing developer may do and relative to what they themselves may do in the future (if they do not develop today). Provided amenity values are not homogeneous across plots of land (reflecting, for example, different views or differing distances to the CBD) then the competitor is not in an identical position to the developer and so the developer has an option value to delay development, even if development would be profitable at present. In the face of uncertain demand, the developer must weigh current profits from development (where the resulting house price would exceed development costs) against profits from future developments. All potential developers face a similar situation so each developer will delay development until the resulting house price exceeds development costs by a sufficient hurdle to make further delay uneconomic.[22]

[21] Other authors refer to 'on-project' versus 'in-project' risk (Wang and de Neufville 2005)

[22] Building on these insights, Guthrie (2012) further shows how building densities will react to the heterogeneity of amenity values – and also to property taxes – across the city.

The importance of this application of real option values to the road investment problem is the recognition the real option of one agent may depend on the real option value of another agent. If a second (competing) agent also has positive value in delay, then the first agent's value of delay is increased. By contrast, if the competing agent were to have no value in delay (and so, in the housing example, to develop as soon as the housing price exceeds development costs) then the value of delay for the first agent would also fall, possibly to zero where the development plots are close substitutes.

In the transport example, the existence of close substitutes is an empirical matter. In many situations, there will be no close substitutes for a particular road; for example, the highway from Te Anau to Milford faces competition only from air flights which are a highly imperfect substitute for road travel. In other cases, however, the existence of other, perhaps less utilised, roads or passenger rail within a city may result in some degree of competition for a road being considered for an upgrade. The existence of a rail link or coastal shipping link may be relevant in terms of potential substitutes for long-haul freight traffic.

The important insight here for road transport investment is t the value of an option for delay with regards to a particular development cannot be considered in isolation of the decisions that may be taken by competing transport providers in circumstances where the competing provision is a partial substitute for road travel. The greater is the degree of substitutability, the lower is the value of the option to delay. Where there is a low degree of substitutability, on the other hand, the greater is the option for delay and hence the greater is the ratio of required benefits to the costs of the project.[23] before a project should proceed.

2.5.10 Environmental

Another type of real option is that found in climate change analysis. The option does involve a timing issue but here there are two conflicting uncertainties to take into account.

Dixit and Pindyck (1994) discuss the application of real options to environmental policy. They consider the optimal timing of a policy designed to reduce greenhouse gas emissions (eg through levying a carbon tax or imposing an emissions trading scheme).

The interesting feature of this case, which is similar to the transport example, is there are two types of irreversibility to consider. The first type of irreversibility is the investment that will take place by firms to reduce carbon emissions following imposition of a carbon tax (eg new fuel-efficient machines or new electricity generation plants). The second irreversibility is the environmental damage that will occur in the absence of a policy, ie through the additional build-up of carbon in the atmosphere. The key source of uncertainty is the costs imposed on society by the build-up of carbon.

The first type of irreversibility favours delaying introduction of the environmental policy so as to limit the costs of irreversible costly investment by firms if it became known the costs of damage from carbon were less than initially anticipated. The second type of irreversibility favours accelerating introduction of the environmental policy so as to limit the costs imposed by carbon accretion if it became known the costs of damage from carbon were greater than initially anticipated.

As shown in their example, the optimal timing depends on a number of factors including (i) the stochastic properties of the cost function; (ii) the costs associated with each type of damage; (iii) the form of the cost function, eg whether it is linear, concave or convex; and (iv) the discount rate. Differences in these assumptions (especially the functional form for costs) can deliver quite different policy prescriptions. In practice, we cannot know what the exact parameters should be to apply the model, but we can make some

[23] This ratio is analogous to the ratio of the house price to development costs in the Guthrie analysis.

judgements about the shape of the cost functions. For instance, we can use scientific information to make a judgement that the costs of carbon are convex.[24] so an absence of policy action currently or in future is unlikely to be optimal. As in many examples, however, the lack of parameter certainty is likely to make the application of the real option method most useful as a framing device for making policy decisions rather than as an exact guide to which decision should optimally be taken at a certain time.

The carbon problem has similarities to a standard road investment problem. A road investment incurs irreversible costs in the form of the up-front and subsequent maintenance costs of the new road (or the road extension). However, neglecting to build the road has an irreversible cost in that the opportunity to open up a new area for development will be postponed and may even be lost if an investment that would have occurred there is instead undertaken elsewhere (eg in Australia). Both of these irreversibilities must be factored into the road decision – concentration on just one source of irreversibility will bias the decision either in favour or against investment. Again, therefore, the methodology appears most useful in framing the investment problem rather than in providing an exact tool to value the benefit or cost of delaying the road.

2.5.11 Transport

The above examples illustrate how option analysis might be applied to transport and also some of the challenges presented. This section presents a synthesis of some real option applications already undertaken within the transport sector.

An early example of a transport option given by de Neufville (2008) is the Portuguese 25th of April Bridge which initially was reinforced to allow for an unbuilt second road deck and to which a second deck was added decades later, but for rail.

Table 2.3 below lists a range of transport infrastructure ROAs, with attention given to nature of the flexibility, the relevant state variable and the method of valuation. Discussion of some key features of these ROAs follows the table.

Table 2.3 Examples of applications of real option analysis in transportation

Authors	Sector	Stochastic variable(s)	Type of option(s)	Period	Valuation method
Car parks					
Zhao and Tseng (2003)	Transport – car park	Daily demand for parking spaces	To expand car park levels	15 years	Trinomial lattice
Zhao and Fu (2006)	Transport – car park expansion	A variant on Zhao and Tseng (2003) with parking modelled with drift and variance	To expand car park levels	15 years	Binomial lattice, including a risk preference
Bridges, motorways and rail					
Zhao et al (2004)	Transport – motorway extension	Average annual daily traffic (AADT) Land price Road condition index	To expand. To time rehabilitation	25 years	Monte Carlo
Power et al (2015)	Transport – existing	Real GDP, assumed	Time to	100	Monte Carlo

[24] A 1% increase in carbon at already high carbon concentrations has a greater detrimental effect than a 1% increase in carbon at an initially low carbon concentration.

Authors	Sector	Stochastic variable(s)	Type of option(s)	Period	Valuation method
	bridge	stationary	undertake major repair	years	
Brandao et al (2012)	Transport - rail		Guarantees in subway public private partnership (PPP)		
Dong and Chiara (2010)	Transport - highway	Toll revenue	Contractual flexibility in PPP	10 years	Monte Carlo
Airports					
Smit (2003)	Transport – airport expansion	Number of flights pa at an airport	To expand airport	25 years	Binomial lattice
Other					
Cheah and Liu (2006)	Transport - minimum revenue in bridge concession	Traffic volume	Value of concession guarantee	30 years	Median from Monte Carlo of annual cash payment, and Binomial model
Galera and Soliño (2010)	Transport – minimum revenue in highway concession	AADT, modelled as GBM	Put option as floor on revenue	Series of annual options for 25 years	Black Scholes (β=0.15, α=0.035, σ= 0.075)
Saphores and Boarnet (2006)	Transport - congestion	Urban population, modelled as GBM	Time to provide congestion relief	Not defined	Use of Taylor expansion to solve model

The real options that have been applied vary. There are those creating the flexibility within the infrastructure to be expanded at a later date (eg a new car park). In others the flexibility exists to select the timing of expansion or repairs to existing infrastructure, or provide concessionaires a floor (ie minimum) on their revenue.

A common feature is the use of **demand volume** as the source of ‘market risk’. Future volumes are uncertain but it is known the value of the underlying asset, be it a bridge or road or airport or carpark or be it a concession on a bridge or road or carpark, will be affected by different demand forecasts. In turn, the value of the option will be derived from the value of the underlying asset. The challenge is to estimate the stochastic properties of demand volumes that generate the underlying asset value.

In some cases, the assumption has been made that the volumes follow a GBM, ie volumes showed a random variation around a trend. For example, Galera and Soliño (2010) made this assumption for AADT when setting out to calculate the value of a minimum revenue guarantee (ie an option) for a highway toll concession. Galera applied the Dickey-Fuller test to calculate the AADT for 11 Spanish highways between 1974 and 2004 and could not reject the hypothesis that AADT followed GBM. The underlying asset in this case was not the infrastructure itself but the value of the concession to operate the highway. Likewise Zhao and Tseng (2003) assume random variation around a constant growth rate for car parking space and proceed to build a lattice of car park values accordingly, noting a lack of data precluded them from using a more general stochastic model that would allow the constant trend parameter to be replaced by a drift parameter that varied by time and state of car parking demand. Smit (2003) bases a valuation of an option to expand an airport in the face of competitor uncertainty on the assumption the yearly number of flights will vary randomly around a constant trend, and proceeds to construct a lattice of expected values.

Some authors have attempted to dig deeper to find the source of the stochastic demand. Saphores and Boarnet (2006) assumes urban population follows a GBM, subject to a minimum and maximum urban population, and model congestion costs as a function of city population. A timing option is thus explored to determine the optimal time to invest in methods of congestion relief. Incidentally, the effect of uncertainty was ambiguous in this situation because it affects both the benefits and the costs of waiting: 'increasing uncertainty augments the gains from congestion relief, but also the flow of congestion costs during project implementation'. Power et al (2015) assume GDP growth evolves according to random variation around a growth trend, where the growth trend will vary during recession and expansion periods, and that bridge utilisation, and in turn the value of travel time saved, are functions of GDP.

Besides the general stochastic evolution of demand, some studies considered other influences on demand. Smit (2003) models the effect of competitors on the demand for flights at the study airport by considering the optimal competitor response at each decision node (ie if demand was to increase in the next period then all competitors would act in a manner that produced the optimal response across the market for expected increasing demand and if demand was to decrease they likewise would choose the market-optimal response).

One demand issue touched upon by Smit (2003) was the recognition that the provision of infrastructure could induce growth effects and that 'part of the growth option value of these investments does not flow to the investor', although the paper then focuses on shareholder value rather than the wider societal value.

The other side of any ROA is the cost of investment. Power et al (2015) estimate the cost of bridge repair by, first, using a Markov transition matrix to model the condition of the bridge (measured as being in one of six states), and then derive the cost of repair, taking into account also general price inflation and inflation of material and labour prices. Zhao et al (2004) considered land prices and a road condition index.

Having derived models of potential benefits and costs, the next step[25] is to value the option. This is the most contentious issue, as explored in appendix A2, but for now the use of different methods and some of the reasons offered are noted.

Galera (2010) undertook a standard Black Scholes option valuation and relied on the CAPM and the correlation between the return of quoted highway concessionaire firms and the evolution of the whole stock market to derive the volatility for concession value. Key reasoning behind this approach was a GBM for the sample data used could not be statistically rejected and the estimated value of a concession without options, using the CAPM, would substitute as a replicating asset. This was proposed by Copeland and Antikarov (2001) (see Borison (2005) for criticism of this technique).

At the other extreme, Zhao et al (2004) choose the Monte Carlo method for valuation, including the use of a regression technique (as proposed by Longstaff and Schwartz 2001) to reduce compilation, claiming they could not use the risk-neutral assumption implicit in the BSOPM and BOPM as 'there are no traded derivative securities dependent on the values of these uncertainties. Without these derivative securities,

[25] Not always required as simply framing the problem can sometimes reveal the preferred solution

the “dynamic hedging” approach used in the financial options valuations cannot be applied’. Power et al (2015) also employed Monte Carlo simulation.

Smit (2003) argues the stochastic demand variables typically of influence are unlikely to follow GBM, other than for natural resources. Reliance is made on the ‘as if traded’ argument, as presented by Mason and Merton (1985), to use the BOPM for option valuation. It was also noted asymmetries and competitive break points could be examined with the BOPM.

Zhao (2003) also employed the BOPM but does note ‘we are assuming that the demand does not depend on the supply, such as the availability of a new parking garage, which may not be the case in reality’. This serves as a reminder large-scale investments that can affect demand require special consideration.

Last, there is the choice of objective function. Typically it is assumed decision makers will choose the pathway with the highest expected return, including the expected return from real options. Instead, Zhao and Fu (2006) provided a measure resembling a coefficient of variation as a basis for decisions.

2.5.12 Real options and decision making

We come now to how recognition and valuation of real options may be used within decision making.

Myers (1977) originally envisaged real options as part of a growth strategy in that real options opened up opportunities to expand. Inherent in this approach is the need to decide when and how to expand. In other words, options and decision making are inter-related parts of an ongoing advancement.

Just as there are challenges in valuing real options, so too are there challenges in even knowing options exist – or are being taken away. The real options often also interweave so it can be difficult to point out clearly the options involved (Galera and Soliño 2010). Having identified the real options, there are the challenges of knowing how to use this information, not the least being having confidence in any valuations that revolve around dynamic and unknown future events.

Before embarking on a review of ways real options have been or are recommended to be used in decision making, it is worthwhile noting a distinction in the use of real options.

There are some situations where the value of an option is part of a pricing process. For example, a roading authority might be tendering a tollway concession to private operators which includes revenue floors and caps. Accuracy about specific option values is important in this situation.

More often the use of real options is to understand the potential value in flexibility. In particular, ROA is used to extend the information gained in the standard CBA. Typically the ‘straw man’ used for comparison is the fixed peak-design decision making process. The standard CBA for a fixed design typically entails (a) forecasting demand, (b) creating a design for peak load, (c) estimating costs, (d) estimating benefits, (e) comparing the design against a do-minimum scenario, and (f) testing the results via sensitivity and/or scenario analysis. On the basis of these outcomes, the project will receive a ‘go’ or ‘no-go’.

Analysis of real options can be seen as assisting this decision in two ways: it extends the number of alternatives, including recognising management’s ability to adapt; and it encourages more thought to go into the design. Insights into possibilities and designs need not rely on accurate real option valuation (Wang and de Neufville 2005), although wildly inconsistent or poorly applied valuations will not be helpful.

Viewed from this perspective, ROA provides a complement to – not a replacement of – traditional capital budgeting tools such as discounted cash flow (DCF) and decision trees.

It is also appropriate to recall the properties of a real option from section 2.5.1 – these properties dictate when a real option will be of value to a project. The three key properties were that the project revolves around an irreversible investment decision, that the outcome of that decision is significantly affected by some future uncertainty and that there is the ability to delay or adjust the investment in response to any ROA. Methods to judge whether these conditions exist are presented below, after discussion of the associated issue of when real options can be valued.

2.5.13 Conditions required to value real options

There does not appear to be a consensus around when real options can be accurately valued. Borison (2005) warns that approaches differ widely, leaving practitioners 'in troubling circumstances'.

There will be some occasions when an analytical method, such as the BSOPM, can be derived for the situation at hand. These situations will be infrequent for real options.

More frequently, the valuation method will be a numerical method such as the BOPM. This and similar methods rely heavily on pricing information existing for some other asset that is in some way related to the underlying asset of the real option. It is when this related, traded asset does not exist that difficulties arise.

Guthrie (2009) summarises the issue as having to find a price variable that relates to the value of the underlying asset (state variable) within the option. This can proceed in three ways:

- The state variable is a traded asset (eg oil).
- A forward markets exists for the state variable (eg futures market for oil).
- Assume a portfolio of assets that replicates the option cash flow exists and estimate its price using the CAPM and the minimal mean square tracking error.

Guthrie (2009) states the BOPM, as applied in his text, rests on one assumption, namely 'assets are priced in such a way that arbitrage opportunities do not exist' (p28). However this assumption need not imply a BOPM valuation is necessarily accurate should, say, the risks surrounding a real option not be fully understood and/or the real option cannot be traded or, more generally, the costs of any trade are very large. The point is that unless an underlying asset can be linked to the real option then reliance on the CAPM does not necessarily produce an accurate value simply because no arbitrage opportunities exist. As Guthrie warns (p292), 'given its poor empirical performance, it is probably best to use the CAPM only as a last resort'.

Unfortunately, major transport investments cannot usually be linked back to specific traded assets. This leaves CAPM as the only choice for specifying BOPM. Given the shortcomings of CAPM, in practice, valuation of real options is usually left to methods such as decision trees or Monte Carlo simulations where probabilities are subjectively estimated. The role of formal risk-based option pricing models is reduced to providing (a) insights into what drives option values and (b) potential means to at least partially validate subjectively derived real option values.

Formally the requirement is to understand the nature of 'uncertainty', as to whether it results from market risk, private risk or pure uncertainty. Borison (2005) recommends that market risk components are valued by the BOPM, which leaves the rest – most likely the biggest source of uncertainty – valued subjectively.

2.5.14 Incorporating real option analysis into investment decisions

While most of the real option literature is on valuation and to a lesser extent on applications, there are some papers that provide guidance around good real option practice, including methods to be used to recognise the existence of real options.

Zhang and Babovic (2011) synthesise the current real option best practice approach:

1. Identify and understand the impacts of key risk drivers
2. Define major project states
3. Identify possible options to transit among states
4. Select feasible and important options and estimate an exercising threshold
5. Undertake Monte-Carlo simulation of key risk drivers and estimate values.

A more general interpretation of the methodology would be to replace 'risk' with 'risk and uncertainty' in (1) and to use a mix of estimation methods in (5). In broad terms, the five steps entail structure uncertainty, create scenarios, establish pathways, determine triggers and evaluate.

Kodukula and Papudesu (2006, appendix B) offer a two-step method to filter projects to determine those that might benefit from ROA. This entails completing the following questionnaire, scoring responses as indicated.

First, if the answer to any of 1–4 is scored zero then ROA is not necessary or appropriate. This could be interpreted as real options will not help if the project payoff is certain and/or the estimated BCR from a DCF analysis is far below or far above any acceptance threshold and/or there are no contingent decisions within the project and/or there is no flexibility to change the project direction to maximise value.

Second, upon the completion of the rest of the survey, ROA is expected to provide significant value to projects scoring more than 30 across the questions and moderate value for projects scoring between 10 and 30. In other words, ROA is ideally suited to a project that has large growth opportunities but is subject to market risk that can be resolved relatively cheaply over three to five years and private risk that can be diversified across a portfolio of projects and the project can be staged.

Both conclusions appear unnecessarily restrictive. The conditions described are those that would suit inclusion of real options in an analysis. However understanding the real options that may exist within a project can also have value in other situations. This might be because a more adaptable solution is preferred over a fixed design system with the similar BCR or because the fixed design solution unnecessarily extinguishes a growth option.

Table 2.4 Questions to assess ROA usefulness (Source: Kodukula and Papudesu 2006, appendix B)

1 What is level of uncertainty related to the estimated payoff?	High 6	Low 3	None 0
2 What is the investment cost in relation to the DCF-estimated pessimistic, base and optimistic payoffs?	Similar to base 6	Different to base but within range 3	Outside of estimate range 0
3 Do you have contingent decisions in your project definition?	Many 6	Just a few 3	None 0
4 Do you have flexibility in changing project direction to maximise value?	High 6	Low 3	No 0

If any of 1–4 scored 0 then do not proceed with the ROA, otherwise complete questionnaire			
5 What is the potential for this project to create future growth opportunities?	High 6	Moderate 3	None 0
6 Can the project be broken down into a sequence of logical small projects, each requiring its own investment (I_j)?	Yes with initial I_j small 2	Yes with initial I_j large 1	No 0
7 What is the source of your payoff uncertainty?	Mostly market risk 2	Market and private risk 1	Mostly private risk 0
8 How long does it take for the payoff uncertainty to clear?	3–5 years 2	1–2 years 1	Very long* 0
9 What is the investment needed to clear the uncertainty relative to the estimated payoff?	Small 2	Moderate 1	High 0
10 How many other projects is the candidate project being evaluated against for investment as part of the project portfolio?	Many 2	Just a few 1	None 0

* In which case competition will erode the asset value

Cardin and de Neufville (2008) also provide guidance on when to consider real options and also what to do about private risk. Implicit in the Kodukula and Papadesu questionnaire is that project teams recognise the uncertainty and flexibility within the project. Cardin and De Neufville (2008) offer a guide to discovering and assessing flexibility within projects, dubbed flexible design opportunities in their paper. They make the distinction between flexibility related to the whole project, or 'on' systems flexibility, and flexibility within the project, or 'in' flexibility. 'In' systems flexibility systems typically relate to private risk – assumed to be managed by diversification in the standard option valuation models – which can potentially be reduced by technical aspects of the design. 'On' system flexibility typically relates to market risk and offers opportunities for management such as deferral, staging, scaling and abandonment without necessarily modifying the technical design components – this 'on' system risk coming within ROA. A prescriptive framework is offered to look for and exploit flexible design opportunities. Their methodology culminates in a table similar to that below.

Table 2.5 Guide to explore flexible design opportunities arising from 'in- project' uncertainty

Methods		Guidance Criteria				
		Main area of flexibility	Frequency of exercise	Intended audience	Intensity of LCC	Nature of uncertainty
Identify FDOs	Information flow	PS	IF	T	High	DR/PR
	Interview	PS/OP	IF/F	T/NT	High/Low	DR/PR
	Screening	PS (any) OP (approx)	F	T (optim) NT (approx)	High (optim) Low (approx)	PR
Value FDOs	Decision-Tree	PS/OP	IF (DA) F (lattice)	NT (DA) T(lattice)	Low	DR (DA) PR (lattice)
	Design Transition	PS/OP	IF	T	High/Low	PR
	Simulations	PS/OP	F	T, NT	High/Low	PR

Source: Cardin and de Neufville (2008, p14)

The first step suggested is to classify a project according to:

- main area of flexibility is in the physical structure (PS) or in the operations (OP) of the system
- frequency of option exercise is frequent (F) or infrequent (IF)
- intended audience of decision makers is technical (T) or non-technical (NT)
- intensity of the life cycle cost (LCC) is high or low
- the nature of uncertainty progresses (P) over time or is more likely to be sudden, ie drastic (D).

The second step is to use the above classification to select the appropriate tool to identify the flexible design opportunities, including:

- interview subject matter experts to identify how system design may adapt to different scenarios
- a range of information-flow methods to break down and represent the flow of information between different components of the system, eg change propagation analysis, sensitivity design structure matrix, engineering systems matrix
- screening methods

The third step is to appraise the flexible design opportunities, using tools such as:

- decision tree methods such as DTA, binomial lattice (lattice) or enumerative techniques that address path dependency
- a design transitions method, which explores possible design transitions to find those that minimise lifecycle cost
- a simulation method which considers DCF under several scenarios and then uses the distribution of outcomes to select optimal flexibility, using the preferred management rule.

The valuation methodology suggested again fails to take into account the distinction between risk and uncertainty. Being couched in terms of flexible design, the method does focus on looking for design features that can either span or adapt to a range of uncertain outcomes. Also implicit in the methodology is an element of learning, a key part of the process to be discussed under adaptive management in the next section.

Chapman and Ward (2011) acknowledge the fundamental unknown nature of uncertainty. They suggest a process referred to as PUMP (performance uncertainty management process) for project management, including within the concept stage that is pertinent to this report. The process consists of an iterative exploration of uncertainty, its causes and consequences and the possible solutions, split into seven phases:

1. Define the issue – answering the seven Ws (who, why, what, which way, wherewithal, when, where)
2. Focus the process – involves scoping the analysis required
3. Identify all uncertainties and alternative responses
4. Structure all uncertainties – possibly using decision trees
5. Clarify ownership of uncertainties – similar to a benefit analysis
6. Quantify as a first pass some of the uncertainties
7. Evaluate all implications.

Steps 1–3 largely develop the problem, 4–5 provide some qualitative analysis and 6–7 entail quantitative analysis. The end result is not necessarily one number with which to assess go/no-go but rather an insight into the uncertainties and responses most relevant to the opportunity at hand.

Campbell (2016) suggests a similar method. Possibly fitting under the heading of the next section on adaptive management, the framework heavily involves real options and hence provides a useful introduction to the next section.

The framework suggested requires:

1 The project objective is given greater prominence

2 Early identification and characterisation of alternatives, with first principles probing in terms of the criteria favoured by the real option formulation of the question, allowing some culling and the identification of initial information search requirements

3 Development of a well-structured if quite stylised representation of the choices and their essential differences

4 Systematic probing to characterise the strategy-relevant uncertainties and to develop and prioritise potential information-seeking investments.

The framework acknowledges it may not be possible to value real options accurately but seeks to explore what real options are likely to be of value, and then take the next step to learn about the uncertainties that pertain to the real options of interest.

Providing balance to the discussion, the NSW Treasury (2007) recommend caution should be exercised when it comes to inclusion of real option values in an analysis, due to a combination of issues such as optimism bias and contrived risks. Instead a more general guideline is provided to address risk analysis, including:

- requiring consideration of the widest possible range of alternatives to address a clear project objective
- spelling out the range of options that should be considered, including deferral, staging, scaling down, closing, thus indicating an iterative process may be appropriate, and as circumstances change appraisals and decisions should be revisited
- discussing the desirability of maintaining maximum flexibility
- discussing different ways to address risk and uncertainty.

Note the real options and flexibility remain a core part of the recommended analysis.

A further warning about adaptable solutions comes from Harford (2011), who points to research showing people appear to have difficulty abandoning projects. This behavioural tendency does require consideration in the design stages if options to scale down, switch or abandon are to be sought.

2.6 Adaptive management

The practice of adaptive management is one approach (or, more accurately, a set of approaches) that is used to deal with sequential decision making in the presence of uncertainty. As with all applications of real options, this approach is relevant in cases where there are some irreversible (or costly to reverse) components of initial decisions that may subsequently be revealed as being sub-optimal following the receipt of additional information. Adaptive management has been applied most often to questions of environmental management but has also been applied to a range of other applications including water supply, research and development, electricity supply and transport planning.

Chades et al (2015) state: 'Adaptive management was specifically developed to handle decision problems with imperfect knowledge of the dynamics of the system, and is known as "learning by doing".' A sequential decision approach is adopted in which initial decisions are taken so as to leave future flexibility in the knowledge that the relevant system incorporates some form(s) of structural uncertainty about system dynamics for which additional information is learned over time. Structural uncertainties may reflect a number of factors including model uncertainty and parameter uncertainty. Model uncertainty occurs when the decision maker does not know the 'true' model that determines future events, while parameter uncertainty occurs when the true model is known but the size of effects within the model is not known.

Although the adaptive management approach has only been formalised in recent decades, some traditional environmental and farming practices have long embodied the approach. Dobes (2012) shows how a dryland pastoralist created flexibility by purchasing chains of properties along stock routes and water courses around the dead heart of Australia where rainfall is entirely unpredictable, a situation of uncertainty rather than risk. During severe regional droughts, he was able to move stock to markets through his own properties while others' cattle perished due to lack of available feed on the stock routes. Hoekstra and De Kok (2008) show how a traditional decision-making system for establishing the height of dikes in the Netherlands (called the 'self-learning dike'[26]) outperforms modern probabilistic approaches to determining dike heights.

One way of characterising the difference in emphasis between the adaptive management literature and the real option literature is the former often allows for only a small number of alternatives whereas options approaches allow for probability distributions over future variables (Chades et al 2015). The distributions over future variables reflect the law of large numbers in relation to a multitude of factors that may affect relevant outcome variables. This distinction may, however, be more apparent than real, since ROA can be applied to cases with a small number of alternatives. A more apposite way of characterising the difference between approaches is that a management technique such as adaptive management is best applied in a focused way (hence the concentration on a few alternatives) whereas real options can be applied at a number of levels of complexity.

Another contrast can be drawn between two types of adaptive management: active and passive (Chades et al 2015). An active adaptive management approach incorporates the potential for active learning over time where the active learning enables future decisions to incorporate newly acquired information; the passive approach does not explicitly account for future learning opportunities. Henceforth, in discussion of adaptive management, we consider the active variant since passive adaptive management involves an

[26] In the self-learning dike system, a dike is raised by 0.5 metres above the highest previously observed flood level, so enabling the dike's height to react to observed water flow patterns that change over time.

explicit decision not to undertake an optimal approach (ie it does not explicitly incorporate the forward-looking benefits of learning by doing).

When the ROA is applied in a focused way (with a limited number of alternatives) it becomes very similar, but not necessarily identical, to active adaptive management. The reason they may not be identical is one of practical application. Adaptive management stresses the importance of maximising opportunities for learning by doing whereas, in some applications, real options may just incorporate a given set of opportunities to learn in the future. Thus (active) adaptive management may structure the learning and decision-making process so as to incorporate additional nodes at which information is obtained and so actively induce the production of new information that would not be gained through a more passive approach. At the most basic level, for instance, an adaptive management approach might increase the frequency of traffic counts for a specific road (relative to some institutional norm) in cases where parameter uncertainty is high for that road and where a subsequent decision could be made to alter the road's capacity. The cost of the additional information gathering then has to be balanced against potential benefits through better informed and faster future decisions.

ACIL Allen (2014) applies insights from the adaptive management (real options) approach to transport planning. They emphasise that, in practice, mathematical ROAs are often not suited to the types of decisions made by transport planners. Planners are normally faced with choosing amongst a few alternatives (eg a limited number of road designs) based on limited information.

Faced with this set of circumstances, ACIL Allen – along with other studies that analyse the usefulness of these approaches for practical policy-making (eg Grimes 2014) – recommend the use of decision trees that emphasise the importance of incorporating flexibility into a sequence of decisions. Incorporating flexibility within a series of sequential decisions can create value relative to a peak design (or other single) decision even if the latter were based on best available current information. Note for flexibility to have value, the otherwise single decision must incorporate some degree of irreversibility (which may include costly reversibility).

Consistent with the broader adaptive management literature, ACIL Allen emphasise the ability to structure (sequential) decisions in such a way to enhance the gathering of information prior to future decision nodes:

> *… some uncertainty, even uncertainty external to the project, can sometimes be reduced dramatically as a result of information that the project will itself generate. For example, the first stage of a proposed road system, one designed with options to later broaden the road to accommodate higher demands, will itself start to deliver real data on service demands and trends in demand. The data emerging from the first stage of the project – including resultant changes in residential and commercial land use patterns that will feed later demand – can all contribute to a much sounder assessment of likely forward demand than can modelling …*
> (ACIL Allen 2014, p6).

The importance of managing decisions to include the possible effects of induced demand – discussed in the quotation above – is highlighted in Grimes (2011). That analysis shows how the building of a new infrastructure asset (eg a bridge) creates the opportunity (but not the guarantee) for induced development that would not arise in the absence of the initial development. If the induced demand occurs, the consequence may be the need for both further public investment (eg in new roads and schools) and private investment (eg in houses and commercial buildings). An important insight here is that the adaptive management (real option) approach, when applied in the context of a social CBA, must include consideration of all potential investment stages whether they be public or private. The adaptive management approach highlights that the building of the initial bridge may be the catalyst that generates the extra information on induced demand, and hence on the required scale of further investment. Without the initial catalyst, information about the opportunities created may be too nebulous to build satisfactorily into a conventional CBA.

A practical example of this adaptive management approach is discussed in Grimes (2011). The Auckland Harbour Bridge (AHB) was built at a time (1959) when there was little demand for transport links on Auckland's North Shore given its then small population. The building of the bridge generated the information that enabled policy-makers to gauge the extent of incipient demand for access to, and development of, the North Shore. Actual demand greatly exceeded expected demand at the time of planning the bridge. The revealed demand following this first stage investment led to subsequent building of highways and other roads on the North Shore (Grimes and Liang 2010) plus expansion of the Harbour Bridge's capacity from four to eight lanes[27]. While not anticipated at the time of the bridge's planning, the bridge's doubling in size based around the initial structure, is a good example of adaptive management in action.

A caveat highlighted both in the ACIL Allen and Grimes analyses is included here: an adaptive management approach may result in extra costs that would not be borne if a conventional CBA of a complete programme of works (ie all stages of a project) were undertaken. There are cases where a conventional CBA (relying on expected values of benefits and costs) would not yield the green light for a project but where an adaptive management response nevertheless would indicate an initial small investment, which may generate new information and/or be capable of being scaled up in future, is warranted. Grimes (2011) discusses the case of the Bridge to Nowhere in the Whanganui catchment. While no formal analysis was conducted at the time, one can retrospectively (and charitably!) characterise the bridge as an avenue to gain information regarding induced demand consequent on the bridge's building. The outturn was that induced demand was close to zero, so further expansion was not warranted. (A more flexible approach, however, would have been to prepare to build the bridge, but temporarily to use a ferry, and then wait to see if private sector development occurred.)

The two bridge examples above highlight situations where the initial phase within a sequential project involved large up-front outlays. An adaptive management approach may, however, often favour a small initial investment that generates information as to whether a larger investment is warranted. The second decision can be taken subsequent to the initial information being revealed. This management approach may entail three different types of decision: (i) delay the investment and gain additional information from existing information sources (eg traffic counts) regarding changing demands for the infrastructure [this type of decision essentially reduces parameter uncertainty]; (ii) invest in additional information gathering (eg comprehensive choice surveys) prior to making a decision [this type of decision again reduces parameter uncertainty but potentially also provides some information on model uncertainty]; and (iii) invest in the first stage of a scalable activity (eg the initial AHB without the clip-on lanes) while leaving open the potential to build a subsequent phase of a broader potential programme [this type of decision reduces both parameter and model uncertainty].

ACIL Allen highlight another benefit of the adaptive management approach. As discussed in our section on valuing real options, all multi-period projects require some assessment of the appropriate price of risk to include in a project's discount rate. Their analysis leads them to the following conclusion:

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[27] Of course, we cannot know what the counterfactual development path for Auckland would have been had the Harbour Bridge not been built, and hence cannot make conclusive judgements as to whether the bridge enhanced efficiency or not.

> *The major benefit of real options analysis lies in its ability to structure the way in which risk is handled; in other words it is often more about managing the risks than valuing the project. Nonetheless, projects will still require the choice of an appropriate cost of capital if the project is to be subject to assessment criteria, and/or if it is to be compared with other projects. In that case, one possibility would be to use the standard risk rate used for government projects. Alternatively the discount rate could be adjusted downwards, if the real options approach succeeds in reducing the project's risk profile significantly, potentially allowing lower cost funding to be accessed.* (ACIL Allen, 2014, p25).

ACIL Allen (p5) emphasise that in implementing adaptive management processes it is important not to confuse ends with means. The potential pitfalls of misusing adaptive management techniques are illustrated in a paper by Marchau et al (2008). As in other papers dealing with adaptive management, Marchau et al emphasise the importance of learning from information generated by early stages of a sequential set of decisions. However their recommended approach fails to deal appropriately with uncertainty across a multi-stage project.

The adaptive approach recommended by Marchau et al 'takes some actions right away and creates a framework for future actions that allow for adaptations over time' (p405). The recommendation to take actions straight away fails to recognise the potential benefits of delaying investment decisions to await further information prior to taking an initial action. Furthermore, the Marchau et al examples of adaptations that might occur are distinctly sub-optimal as their first case study demonstrates.

Marchau et al's first case study, which is applied to improving road safety, involves fitting vehicles with an ISA (an in-vehicle device that warns the driver and/or temporarily controls the car in case of speeding). They state (p408): 'policymaking on ISA implemented (sic) has been limited to funding (further) research on ISA. This limited policymaking is caused by, among others, uncertainty about the real world outcomes of ISA'. The real world uncertainties include effects on driver behaviour once an ISA is installed. In the face of these uncertainties, Marchau et al advocate (p408): 'In order to handle these uncertainties, a policymaking approach is required that does not focus on improved predictions of the outcomes of ISA implementation, but one that starts with the implementation of ISA right away and can be adapted to future events and knowledge that becomes available'. (They recommend starting with implementation for unsafe drivers on unsafe roads). In discussing this recommendation, the authors note necessary conditions for success of this basic policy include a range of factors, for example drivers will follow the system advice and they will not exhibit adverse behaviour. The authors then note that experimental results already indicate drivers with the device exhibit 'riskier gap-acceptance, loss of vigilance, increased frustration and increased impatience'. As a consequence, Marchau et al argue for further policies, such as driver education, exclusion of 'unsafe' drivers or fitting vehicles with black box recorders, to correct for these risks.

The mistake Marchau et al make in their case study is that adaptive management is applied to support the initial policy *action* rather than to structure policy actions to best achieve the desired policy *outcome*. Furthermore, the initial policy action is explicitly implemented prior to resolving some of the uncertainties that could be resolved through delaying the initial policy choice and undertaking more research as the initial step. This error in applying adaptive management falls foul of the warning by ACIL Allen not to confuse ends with means.[28]

[28] Their third case study, dealing with underground freight movement, falls foul of the same issue.

Marchau et al's second case study reveals a different error in potential application of adaptive management techniques. This error again relates to taking policy decisions too early in the process. In this case the key error is in ignoring potential market solutions that would obviate the need for a policy response. Briefly, the authors (in an article published in 2008) argue for a policy that implements 'personal intelligent travel assistants' (PITA; now simply known as 'Do you want GPS with your car?'). The policy is designed to improve travel flows. The authors argue to implement the policy first for business travellers and professional drivers. They recommend (p410): 'If, for instance, the number of travellers following the PITA advice appears to be too low, some corrective action can be undertaken, eg giving some financial incentive to those travellers who do comply with the PITA advice'.

Here policy activism (and hence official resources) is mooted in a case where the private market very soon obviated the need for any policy action. A short wait in policy response to assess the market response to the devices would have saved public resources and so resulted in a less costly outcome. The Marchau et al approach in this case can be contrasted with the approach recommended by Dobes (2008) that the role of government is to steer, not row, the boat. Dobes identifies that government's use of adaptive management is appropriate to address genuine instances of market failure (including where externalities occur), removal of bureaucratic impediments to private sector adaptation, and fostering the identification of potential adaptation strategies and disseminating this information.

The positive features of the Marchau et al analysis are that it focuses on learning over time through policy-makers observing from early stages of multi-stage processes. However the confusion of ends with means, ie of using adaptive management to shore up the initial policy action, rather than to focus on achieving the desired policy outcome, is a fundamental mistake. Adaptive management is instead designed to incorporate flexibility in multi-stage decision making that may involve delaying decisions to await further information, and/or being prepared to abandon or reverse initial policy directions if subsequent information reveals abandonment or reversal becomes an optimal strategy.

Walker et al (2013) provide a more nuanced approach to planning for adaptation, which they apply to conditions of deep uncertainty. They are critical of simple scenario analysis which does not provide a systematic means to deal with future uncertainties or to learn from their implications. They distinguish between adopting an *optimal plan* based on the best (current) response to one or a limited set of scenarios, and a *robust plan* that yields satisfactory outcomes across a wide range of plausible future states of the world. *Dynamic robustness* builds in future flexibility to deal with the (partial) resolution of uncertainties both through *planned adaptation* (eg deliberate decisions taken in future in response to observed triggers) and through *autonomous adaptation* (eg self-regulating responses to developments).

A number of closely-related planning approaches, including *assumption-based planning*, *adaptive policymaking*, *adaptation pathways* and *dynamic adaptive policy pathways*, can be used to enhance dynamic robustness. Key features of these approaches to adaptive management include:

- Identifying (i) key assumptions upon which the success of an initial plan rests, and (ii) identifying assumptions that are most vulnerable to uncertainty; the product of these two aspects identify the most critical assumptions.[29] Signposts (or *triggers*) are created in relation to these assumptions to alert future policy-makers of the need to review the plan; shaping actions may be incorporated into the plan to help influence the future and hedging actions can be incorporated to limit negative responses to a negative surprise.

[29] This approach is akin to that in value-at-risk modelling which identifies key risks according to the product of probability of an event by loss given the event.

- A five-step approach to robust decision making includes: (i) scoping uncertainties and policy options, (ii) simulating outcomes across a wide range of scenarios, (iii) using the scenario outcomes to identify key vulnerabilities, (iv) adaptation through identification of hedging actions and (v) displaying outcomes across the scenarios and choosing a robust plan for implementation.[30]
- Explicit consideration of the timing of actions, based on observed tipping points that may trigger a policy response (eg an extension to the project, or implementation of a new hedging action).

Several computational approaches that may be used to enhance these adaptive management approaches are highlighted by Walker et al.

- Simple policy models can serve as laboratory experiments to produce a wide range of simulations under differing assumptions.[31] The variation in model outcomes across differing assumptions provides information to policy-makers about the robustness of certain policy options.
- A suite of alternative models (using different modelling approaches) can be used to simulate similar scenarios, again providing a range of model outcomes of use to policy-makers wishing to adopt a robust plan.[32]
- Using either of the above methods, policy makers can identify model runs that are of particular interest – most likely those generating outlying predictions about outcomes of interest (eg traffic flows). The modellers then work backwards from these outcomes to identify the factors, or combinations of factors, that are responsible for generating these particular outcomes. This process serves to focus attention on key assumptions and vulnerabilities. We note here this process will be particularly valuable the more non-linearities there are built into a model since it is often difficult ex ante to predict how outcomes will depend on these non-linearities. Traffic flows, in particular, exhibit sizeable non-linearities bordering on chaos, so this approach may be particularly useful in transport planning.
- In implementing any of these approaches, it is useful for policymakers to specify their objective function in the presence of uncertainty.[33] For instance, the maximin criterion chooses the plan that minimises the loss under a worst case scenario, while minimax regret minimises the worst case regret (ie the opportunity loss through having made the wrong decision ex post) which leads to a less pessimistic approach than the maximin criterion. Alternatively, a satisficing approach may be adopted in which policy-makers accept a range of outcomes that meet certain objectives most or all of the time. Note under conditions of deep uncertainty (and hence in the absence of well-defined risk parameters) a more conventional certainty equivalent approach is not an available option.

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[30] Walker et al's approach adopts an engineering-centric approach and does not discuss costs of achieving robust outcomes. A public (and private) policy approach would explicitly incorporate the costs and benefits of alternatives under the conditions of uncertainty that the authors highlight.

[31] Reflecting the insights of Chades et al (2015), the range of assumptions could reflect both model uncertainty (changing the nature of some of the model equations) and parameter uncertainty (changing parameters for a given model structure).

[32] As an example from another field, the Reserve Bank of New Zealand forecasts economic outcomes using a suite of widely varying model types to assess how confident they can be about the evolution of the economy.

[33] In addition, officials may wish to present benefits based on a range of methods both with respect to quantification and with respect to which benefits are included. For instance, benefits may variously include or exclude option and non-use values of services (Laird et al 2009; Wallis and Wignall 2012).

The key to these approaches is a range of alternative policies, including policies that can adapt over time to certain triggers, are modelled and the information from this modelling is used in advance of any initial investment to prioritise project options. The information is used to design projects that are sufficiently flexible to adapt to new information as it occurs and to include potential hedging and shaping strategies to support a plan. This emphasis on information is at odds with the Marchau et al (2008) approach that argues against waiting for such new information to emerge. The Walker et al (2013) approach is more in keeping with approaches based on the real options literature which emphasise the potential value of delay in initial stage investment in order to obtain extra information where the value of this information outweighs the costs incurred by delay.

In one respect, however, the Walker et al approach does not incorporate sufficient breadth. They argue (p961) that a key (desirable) element of the management approaches which they discuss is 'to keep the system headed toward the original goals'. In the face of deep uncertainty, this approach ignores one key uncertainty: the goals themselves may change over time. For instance, a goal of New Zealand transport planning in the 1960s may have been to enhance use of Auckland motorways by private cars commuting to and from the suburbs, whereas this aim may have changed in the early 2000s to reduce urban sprawl and so reduce motorway car travel (in part because of climate change concerns), while the advent of non-fossil fuel electric cars and autonomous vehicles together with skyrocketing house prices and opposition to intensification may in future lead back to a goal of enhancing motorway driving to far-flung suburbs. A flexible application of adaptive management techniques therefore needs to incorporate uncertainty over objectives and not just uncertainties over models and states of the world.

Van Geenhuizen and Thissen (2007) place considerable emphasis on uncertainties in relation to final policy goals which they describe as uncertainties relating to 'valuation of policy results based on a set of values' (p104). As an example, they discuss policies in relation to automated guided vehicles (AGVs), the precursor to the SDV. One of the key uncertainties in this field is the degree of user acceptance of AGVs which will feed through into the valuation of benefits.[34] This uncertainty cannot be known at the outset of a programme that analyses AGVs, and so the goals are themselves subject to a considerable degree of valuation uncertainty.

As well as this important source of uncertainty, van Geenhuizen and Thissen highlight a range of other uncertainties including: (i) defining the boundaries of the system, (ii) future relevant external inputs and (iii) system properties and performance. The latter two mirror the model uncertainties referred to in previously cited studies. The first uncertainty is a crucial one as an incorrectly drawn boundary may lead to analyses that miss important inter-relationships. In the case of AGVs, the study notes that introduction of AGVs may impact, for instance, on people's residential location decisions. To ignore these latter effects – even though they are uncertain – may be to miss a crucial pathway through which the introduction of AGVs will have their effect.

Based on their framework, Van Geenhuizen and Thissen (2007) provide some very useful conclusions for policymaking. First, they stress the importance when taking decisions of not curtailing or ruling out the introduction of new technologies (or other possibilities) as an unintended consequence of current decisions. One crucial aspect of the adaptive management approach is therefore to ensure the widest opportunity set remains (for private and public actors) after current decisions are made. A second set of directions is the authors' emphasis on undertaking detailed research prior to making concrete infrastructure investments. With respect to AGVs, they argue that a reduction in uncertainty can be

[34] The authors state (p112): 'What is evident is that the generally accepted core value of individual freedom to make choices as a driver (traveller) is challenged by particular types of AGV'.

achieved through: additional research and better integration of disparate existing research; additional research on external factors including legal issues; identifying uncertainties in related fields such as spatial planning; increased understanding from the psychological literature about likely AGV acceptance; and the participation of stakeholders in planning and decision-making. This emphasis on up-front research is again at odds with the ‘act now’ emphasis of Marchau et al, and is more in keeping with the application of real option methods to decision making.

2.7 What next?

There are key uncertainties that pertain to transport investment, including those around technology, demographics and private sector development. The analysis and valuation of real options involves making distinctions between market risk and private risk. This distinction is probably of little help in practical terms when it comes to valuation of the sort of real options that pertain to these uncertainties. It is helpful in that it distinguishes risks and uncertainties relating to the transport network (eg the added structures fail or an earthquake occurs) from demand-driven uncertainties (eg more people choose to not travel a route). But these demand-driven uncertainties are the topic of this research and for the most part they are uncertainties that would be market risks if markets existed for transport network infrastructure. Such markets only rarely exist.

A more useful distinction is to differentiate the type of uncertainties that might dominate in a city and those that dominate away from the large urban environments. For example, the macro trends will be important in the large urban environments, as well as issues around changes to the transport network and private sector development, whereas the latter will be the dominant uncertainties for projects in smaller environments. In other words, there is more averaging of local effects in the large environment and hence more focus on macro while little changes may be of more influence in smaller regions, with migration/relocation of people and businesses a major influence.

While valuation of real options is challenging, real options do exist and they can add significant value to a project. Thus real options should not be ignored. There is likely to be value in simply recognising the real options that are, or can be, integrated into a project. This entails understanding real options, including learning and adaption opportunities, understanding the nature of the uncertainties that exist and then combining these insights to provide a project whose quantum of benefits is less sensitive to the uncertain outcomes. This insensitivity can come from building a transport system now that can span a wide range of uncertainties. While possible, it is likely to be costly. The alternative is to create a transport system that can be adapted once uncertainties are either better understood or resolved completely. This is the approach of adaptive management. This type of management puts emphasis on learning, either by simply waiting or by actively seeking information that enables a decision to be made even before the uncertainty is completely resolved.

There are several areas emerging from consideration of this literature review that are likely to be fruitful areas of further research for the Transport Agency:

1 Real options are already being pursued by the Transport Agency. There is the future proofing of new highways for eventual expansion from two to four lanes, say, by initially providing wide shoulders. There is zoning or designation of roads accompanied by the delay of construction until the BCRs improve. There are four ways consideration of options may aid decision making around these situations.

   a It will, in some cases, be helpful to be able to explain the real option and quantify the real option benefit. At present only the cost side of this analysis is being explicitly recognised in BCRs.

- b There may be changes that could be made now to make the option more valuable. For example, in deferring projects with marginal BCRs, it is likely to be of value to explore elements of cost fixing and irreversibility, such as protecting the right to build or the retention of project teams or supply contracts to reduce the risk of cost inflation.
- c It may be that an option to learn is undertaken to resolve uncertain elements of the project, ie use the delay to learn of design and cost elements and/or of likely market demand.
- d Last, the Transport Agency and wider government have the ability to influence future demand, thereby actively changing the demand for transport, eg establish new suburbs or changing other parts of the transport network.

2 Flexibility is also already being considered within infrastructure designs. Some sensitivity testing is being undertaking in the planning stage but it is not obvious that sensitivity tests are being used to fully explore flexible design features. A wider consideration of real options would formalise this process.

3 Decision makers are also taking uncertainty into account when considering investment proposals. However the shift in focus from 'expectation' to 'risk/opportunity' brought about by adaptive management approach is likely to lead to more robust decisions and a more concerted search for adaptive solutions.

4 For both designers and decision makers, there is some advantage in putting the deeper uncertainties into perspective. The modelling features of real options and DTA provide this information. That is, it may not be known just what the effect of SDVs will be, for example, but threshold levels can be estimated which enables judgement about appropriate design and investment to be more anchored, eg there may be no agreement on the level of SDV take-up but current decision makers may be able to form a consensus that the impact on traffic volumes will likely be above (or below) the threshold that makes one investment better (or worse) than alternatives.

A suggested methodology follows in the next chapter, which will then be trialled with three case studies.

3 Suggested methodology

This chapter leads to a suggested methodology to, first, identify the nature of the uncertainty and, second, to define a process that will lead to determination of the appropriate opportunity to pursue. Before presenting this methodology, more detail is explored about uncertainty (section 3.1) and about key option types (section 3.2). An analysis of the stochastic properties of a traffic demand series is undertaken, to illustrate how different forms of uncertainty may affect planning decisions. The decision tree structure for a 'prosperity' option and a learning option are presented.

3.1 Stochastic analysis[35]

The standard Black-Scholes approach to modelling option prices is based on an assumption that, at each instant, the value of the state variable changes from its previous value according to some stable underlying probability distribution (usually a normal distribution) – see discussion in appendix A, section A2.1. The binomial approach to modelling option prices follows the same logic,[36] allowing the state variable to move either up or down in each instant. Any deterministic trend in the variable can be catered for simply in each case.

These approaches are based on the concept of *risk*. For our purposes, the important criteria that must be met for each of these approaches to be considered appropriate for modelling the range of future potential outcomes are the probability distribution governing changes to the state variable: (i) is known, and (ii) does not vary over time.

These risk-based approaches are likely to under-perform, or even fail spectacularly, when the process governing developments in the state variable exhibits *uncertainty*, rather than risk. In modelling the path of a variable over time, uncertainty may reveal itself as a structural break in the movement of the state variable.

Sometimes a situation arises when a time series relationship exhibits apparent instability towards the end of the observation period. In this case, the modeller cannot tell whether: (i) this instability represents a permanent structural break (reflecting uncertainty), or (ii) the time series will revert back to its stable path based on previously estimated relationships, or (iii) the time series will be characterised by a stable long-run relationship that incorporates the new information but differs from the previously estimated relationship. As for case (i), case (iii) represents a situation of ex ante uncertainty the modeller may learn about over time but which cannot be predicted in advance.

In the financial field, the presence of uncertainty was reflected at the time of the global financial crisis beginning in 2007. The most commonly adopted model used to manage financial institutions' portfolio risks was the value at risk model.[37] As with risk-based option pricing models, these value at risk models relied on the assumption of a stable joint probability distribution governing changes in the values of

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35 'The story that I have to tell is marked all the way through by a persistent tension between those who assert that the best decisions are based on quantification and numbers, determined by the patterns of the past, and those who base their decisions on more subjective degrees of belief about the uncertain future. This is a controversy that has never been resolved.' (Bernstein 1996).

36 The limit of a binomial distribution as the number of events approaches infinity is the normal distribution.

37 Value at risk is the assessment of the maximum potential loss in value of a portfolio over a given time horizon at a given confidence level.

financial assets. Furthermore, most modellers relied on (short time horizon) historical data to derive the relevant joint probability distribution. Subsequent work has shown reliance on the historical data was woefully inadequate in dealing with the events of the crisis.[38] What occurred was not a 'draw' from the estimated probability distribution based on historical data, but instead was an event with a probability of occurrence that was unquantifiable but which was nevertheless known to be possible.

The same types of issue that pertain to financial markets pertain to transport. In an historical context, one can cite material structural shifts following which transport demand patterns could not be predicted from the historical data: the advent of the train, the advent of the motor car and the advent of the aeroplane. Closer to home, the change in transport patterns in Auckland following the opening of the AHB in 1959 could not be predicted from prior data.[39] As was the case in the global financial crisis, the implications for future developments that arise out of such uncertain events may dwarf the implications that arise out of known risk-based developments.

These are all examples of uncertainty relating to case (i) above where relationships changed consequent on a certain event. Appendix A4 uses more recent transport data from New Zealand to illustrate another form of uncertainty, reflecting a situation in which the modeller does not have sufficient data to judge whether an unexpected development represents a shift in the estimated relationship or not. In practice this form of uncertainty may occur quite frequently.

An example of how a stochastic analysis might have been used around a hypothetical AHB expansion decision in 2006 is also given in appendix A4. However, given the stochastic properties of the traffic flow on the bridge are uncertain, such an analysis would have been unhelpful in this case.

In the face of these uncertainties, there are a number of alternative policy responses that could be adopted. These include simply delaying any new investment until the model becomes clearer. Alternatively, one may implement new learning strategies in the manner advocated by active adaptive management. One means of doing so is to employ choice modelling in which potential travellers are notionally faced with the costs of using the transport link (in this case the bridge) to obtain a more realistic estimate of intended travel behaviour. Another means is to introduce actual congestion pricing so as to observe travellers' responses to price signals. Each of these approaches provides the modeller with additional information that can be used to improve estimates of travel demand.

3.2 Key options of relevance to transport investment

Two options of importance that emerge from chapter 2 – and in the case studies of chapter 4 – are the written option that facilitates further development and the option to learn. These are explored below.

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[38] Crotty (2009) describes the problems inherent in relying on historically-based estimates of risk probabilities: 'In August 2007, two large hedge funds managed by Goldman Sachs collapsed, forcing Goldman to inject $3 billion into the funds. To explain why Goldman should not be held responsible for their collapse, chief financial officer David Viniar said 'We were seeing things that were 25 standard deviation moves, several days in a row' … The Director for Financial Stability of the Bank of England noted that, under a normal distribution, 'a 25-sigma event would be expected to occur once every $6x10^{124}$ lives of the universe' adding, tongue-in-cheek, that when he tried to calculate the probability of such an event occurring several days in a row, 'the lights visibly dimmed over London'. Even a 7.3 standard deviation event should occur only once every 13 billion years'.

[39] Grimes (2011).

3.2.1 Option to expand written by transport provider

A situation that presents several problems for project evaluation is where the proposed project is claimed to be transformational or at least capable of triggering a sequence of highly beneficial investments by other parties. It is also a situation that lends itself to DTA and to approximation of option values.

Envisaged is a situation where public sector infrastructure is provided, then various economic, political and technological events unfold, followed by the private sector or some other public sector entity(s) undertaking other major investments, again a period of time passes when the general operating environment changes and at some later stage it becomes apparent whether the combined investment projects were successful or not. At the extreme, this situation would describe a 'prosperity' project whereby a large-scale multi-party series of investment holds the promise of substantial prosperity[40].

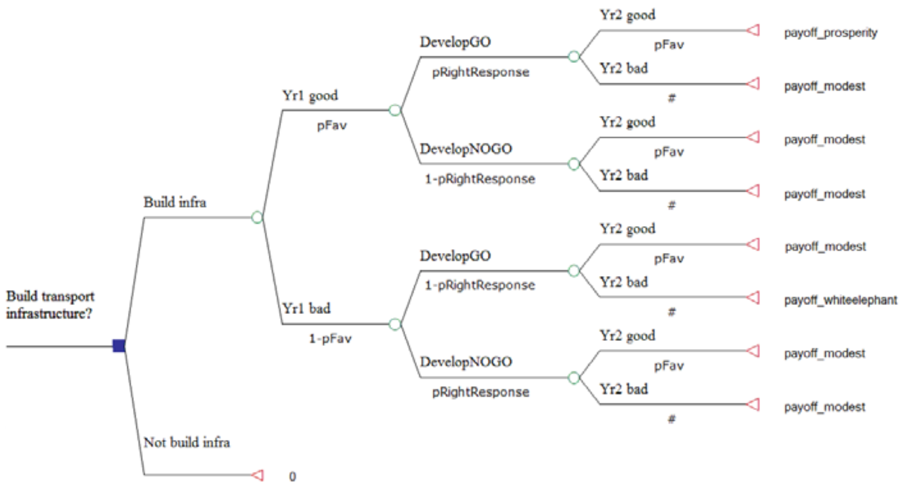
A framework for approaching the evaluation of such projects follows.

The above sequence of investments and events is depicted as a decision tree in figure 3.1 whereby:

- it is assumed probabilities exist around the operating environment being favourable (pFav) and about developers choosing the right response to match operating conditions (pRightResponse) – this assumption is literally unrealistic but does enable insight into what judgements need to be made to justify the initial infrastructure investment
- the period before and after the decision by external developers is denoted here as Yr1 and Yr2 but represents undefined periods of several years
- there is a substantial benefit (payoff_prosperity) under favourable conditions and complementary development (DevelopGO, given probability pRightResponse)
- there is a substantial loss (pay_whiteelephant) under unfavourable conditions if both the initial infrastructure investment and the subsequent development investment(s) also occur (a sequence of events depicted here as having probability (1-pFav)*(1-pRightResponse)*(1-pFav))
- otherwise if the infrastructure is built there is expected to be a modest payoff (payoff_modest) under other operating conditions and development responses
- and no infrastructure investment providing a zero payoff.

[40] See Cicmil and Braddon (2012) for discussion also of glory projects.

Figure 3.1 Decision tree for joint infrastructure and other investment



Using this framework to describe the real option example of Grimes (2011) and treating the payoffs as net present values, payoff_prosperity is assumed to be $25, payoff_whiteelephant is assumed be -$12, payoff_modest varied but is approximated by an average of -$1, pFav would be 0.5 and pRightResponse is 1.0. Thus the expected value of the infrastructure investment is $5.5.

A key feature of this investment situation is the success of the combined projects depends on the interaction of external events (that may be general and/or specific) and the investment response of the other parties. A substantial benefit would eventuate with a favourable operating environment and a third party investment response but there is also the risk that the initial infrastructure investment becomes a 'white elephant' and between these outcomes is a wide range of modest benefit or loss scenarios.

In effect, the infrastructure affords significant local economic development. It creates a real option for the developers by significantly reducing the chances their investment will fail. However the infrastructure investment is not assured to return a large benefit and could return very little marginal benefit in a large number of cases.

The challenge to the infrastructure investor is to invest in a way that not only keeps the local expansion option open but also reduces the downside risk of any initial investment.

The following paragraphs explore this balancing act.

First there is the payoff_prosperity. This will generally have to be high to provide a large option value.

Second there is the probability that favourable conditions emerge. This will also generally have to be high to provide a high option value.

There is also an interaction between these two variables: the same option value could be attained with a lower prosperity payoff and higher probability of favourable conditions.

The third variable is the probability of the developers to make the right response, namely to develop when conditions are favourable and to not develop when conditions are unfavourable. Certainty about this response avoided the white elephant scenario in the Grimes example. However this response is more generally unknown at the start of the investment process.

The fourth factor is payoff_modest. The magnitude of return during the periods when the prosperity and white elephant scenarios do not emerge makes little contribution to the value of the real option in the Grimes example but it is still important. It matters in two ways. First, this is the most likely outcome, occurring 75% of the time in the example, and hence has to be a scenario the infrastructure investors are willing to accept. If the infrastructure investment were an often repeated event then there might be high tolerance for a large number of low-return investments. When the infrastructure investments are large and infrequent it is likely even a few unsuccessful projects will be unacceptable. Thus the maximum expected NPV or BCR are unlikely to be the appropriate criteria to determine the best alternative action within mega projects, even if derived to include option values. Second, if the initial infrastructure investment is a large proportion of the combined investment (ie infrastructure plus development) then payoff_modest will approach payoff_whiteelephant. In other words, a large and irreversible initial cost shifts the situation towards a discrete succeed or fail situation with big gains and big losses to be had.

This summary of influences reinforces that both parts of the challenge to infrastructure investors are important: finding upside benefits is valuable but the potential downside, both in terms of magnitude and frequency, is equally an issue.

Returning to each factor within the decision tree framework, the potential ways to address the uncertainties within an infrastructure project that faces these type of asymmetric uncertainties is as follows.

1 The uncertainty around the response by other major developers could be reduced by seeking contractual commitment to their projects (ie increase pFavResponse)[41]. This would be possible if the number of developers was relatively low but otherwise the costs of coordination and the risk of coordination failure may be too high. Also this approach would be limited to those times when more certainty exists around the 'favourable conditions' as strong commitment in the face of uncertainty risks escalating the costs. In other words, there are times when the two-stage (or multi-stage) phasing[42] of developments provides the appropriate manner to resolve economic, political and/or technological uncertainties ahead of further irreversible investments and thereby reduce the chance of a white elephant scenario.

2 The stage of investments could be preserved but payment extracted for the expansion option created for the developers (ie sell the real option). This approach allows the developers to choose their optimal development response but also enables the associated risks to be passed from the infrastructure investor to the developers (who presumably stand to benefit).

3 Where subsequent development and/or benefit is widely dispersed, (2) may be channelled through the local government body or some other public sector entity.

4 Irrespective of funding, there is at times value in introducing interim measures that enable learning about key uncertainties before committing to an irreversible infrastructure investment and that do not extinguish the development option. This learning can be active, in that the early investment seeks to resolve a particular uncertainty, or passive, whereby time is simply allowed for the uncertainty to

[41] These contractual commitments could be state dependent, allocating risk differently across the parties depending on the state of nature. However this would increase the complexity and costs of contracting which would have to be incorporated into the project appraisal process.

[42] This describes a multistage stochastic programming situation (http://users.iems.northwestern.edu/~jrbirge/html/dholmes/StoProIntro.html)

resolve itself. In terms of the decision tree, a middle branch is introduced which includes different probabilities around future events.

5 A phased infrastructure approach will in part reduce the likelihood of the white elephant scenario but there may exist other means to reduce the consequence of an unfavourable sequence of events (or non-events). Effectively insurance might be sought, thereby increasing payoff_whiteelephant. This includes providing an initial infrastructure solution that can be put to substitute uses[43], should the initially proposed demand not emerge.

6 Of a similar nature, the benefits associated with the infrastructure could be increased if the infrastructure also provided benefits that were complementary to the primary demand. This amounts to raising payoff_modest.

As with dealing with uncertainty in general, the response is to find solutions that can fit multiple outcomes and/or to find ways to resolve some of the key uncertainties.

3.2.2 Option to learn

A core component of adaptive management is the option to learn. More generally this consists of two components: an ability to delay the investment and resolve the uncertainty before investing (a form of passive learning); and the ability to actively learn enough about the uncertainty to be able to make a decision (active learning).

These situations are depicted in the decision tree in figure 3.2, which shows a two-period decision and outcome process.

At the initial decision point, there are three choices:

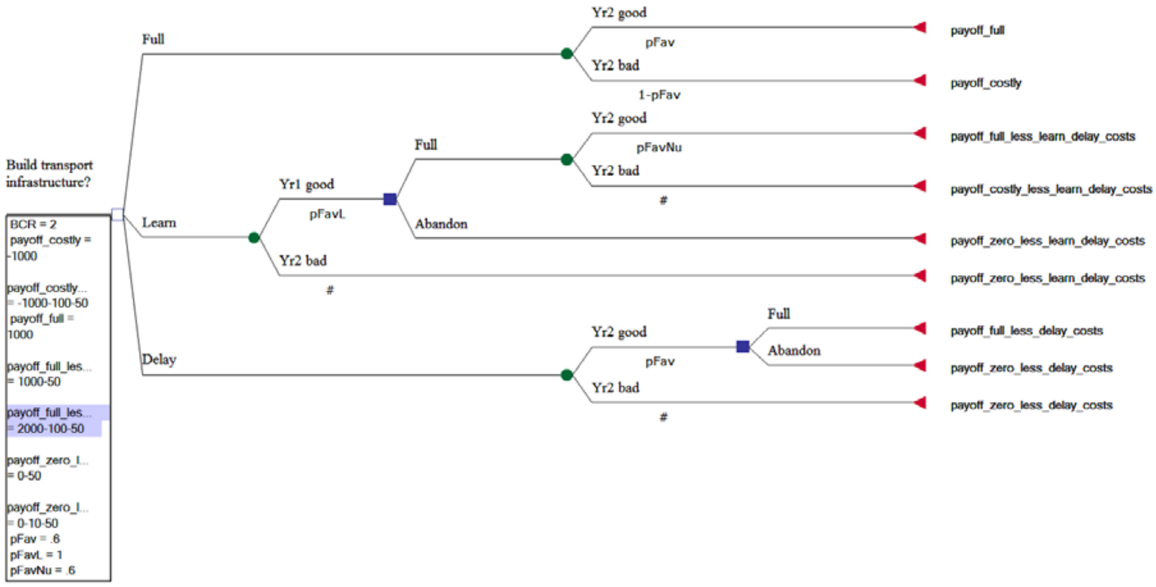
- to fully develop an infrastructure project (full)
- not develop and wait (delay)
- or undertake a smaller development project that enables learning (learn).

Take the top branch first. If the initial decision is to invest in full, the outcome will be known after two periods (denoted Yr1 and Yr2 but could be multi-year periods). If conditions prove favourable then a large positive NPV will eventuate (depicted as *payoff_full*). This is expected to occur with a probability of *pFav*. Conversely if conditions prove unfavourable to the investment then a negative NPV of *payoff_costly* eventuates.

A combination of a high probability of favourable conditions and an associated high payoff is likely to lead to an expected positive NPV and hence a 'go' to full development, eg say payoff_full=$1000, payoff_costly=-$1000 and pFav=0.6 then the expected NPV would be $200 – a 'go' project. But is this the best decision?

[43] This is an example of redundancy incorporated into the design (Giezen et al 2015)

Figure 3.2 Decision tree for 'buying time'



Take the bottom branch next. A decision could be taken to delay full development until such time as the uncertainty is resolved in period 2. In the meantime, a cost of delay will be incurred (eg congestion in an urban transport project). After resolving the uncertainty, a decision to fully develop or to abandon is made, again a dichotomous branching assumption made to simplify illustration as more generally there may also be further opportunities to delay. If conditions prove favourable to the infrastructure investment there is the choice to fully invest or abandon. For the range of values considered within this example, the decision to invest will be the rational response and a NPV will be realised of pay_full_less_delay_costs. The advantage of the initial delay decision comes in not incurring the otherwise poor NPV of payout_costly. Whether there is value in waiting will depend on the mix of factors. Figure 3.3 illustrates the trade-off for a range of situations. The formula for the extra value derived by delay in this example is

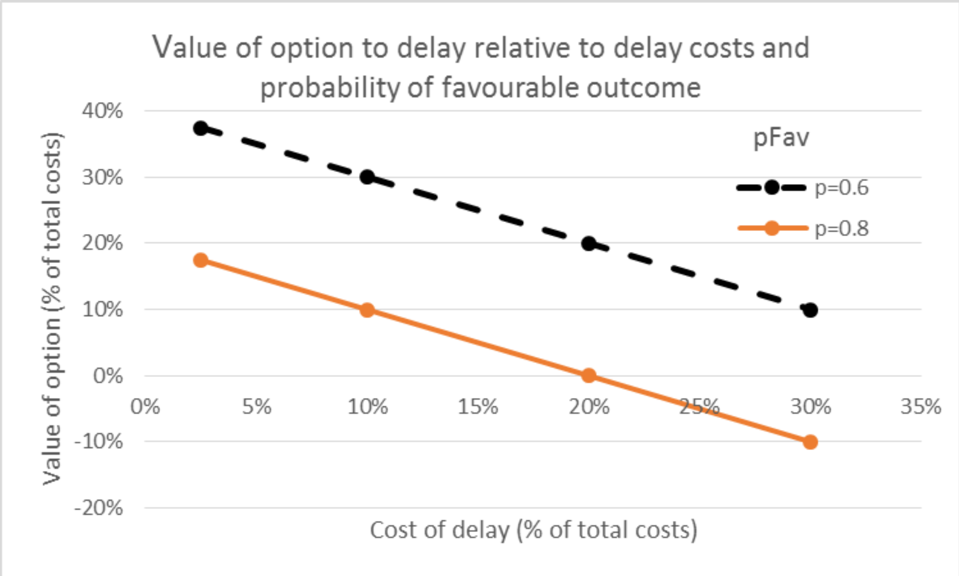
$$-(1-pFav)*payoff\_costly - delay\_costs \qquad \text{(Equation 3.1)}$$

For example:

- if the probability of conditions favourable to the investment were 0.6 (and hence the probability of unfavourable conditions is 0.4)
- the NPV of an unfavourable investment was the cost of the project itself (ie no benefits)
- the cost of delay was around 5% of the full development project costs
- the value of the option to delay would increase the BCR by around 35%.

Using the numbers above, the expected value under the delay scenario is $550 and the expected value of the option to delay is $350 (ie $550 – $200 as the difference in expected values or -(1-0.6)*1000-50 using the formula above). In this example, there is value in delay. However, as illustrated in figure 3.3, the option will not be of value should certainty be high around conditions being favourable and the cost of delay high.

Figure 3.3 Value of option to delay under various circumstances



However, is this the best decision? The third branch shown depicts the learning option. In this case, an intermediate investment is made in an endeavour to learn more about the uncertainty so a decision can proceed (in period 1) before the uncertainty is fully resolved (in period 2). This new knowledge can take the form of an upwardly revised NPV for the full development project or an upwardly revised probability of favourable investment conditions, both of which might tip the expected NPV over some decision threshold. An example of the former revision would be that local employment and hence travel demand was now judged to be higher than previously estimated. An example of a revised probability might be a downward revision given to the chance that technology was about to significantly change the demand for public transport within a public transport project. Conversely, the new knowledge could also lead to downward revisions of both and hence tip the decision to abandonment.

In the decision tree, these changes are equivalent to *pFavNu* being different to the initial *pFav* estimate and to *payoff_fully* being greater within the learn branch (not shown). Also changing will be the cost of delay: the delay cost may be less now than in the delay branch given the quicker decision but there will be the additional cost incurred in the learn investment. Last there will be an expectation as to what chance is given to the learning investment being sufficient to trigger a 'go' decision.

For the numbers used in the example above, incurring a cost of $100 that was believed to have a 90% chance of leading to a 'go' decision that in turn was now expected to deliver benefits twice the previous level would have an expected value of $570. Thus the value of the learning option in this case would be $20 (ie $570 less the expected delay return of $550). The combined value of the learn option, relative to the initial invest or not decision would be $370 (ie $570 – $200).

The value of the learning option will vary for different permutations of probabilities and payoffs. In general the value of the learning option relative to the delay option will increase:

- as the chance of successful learning increases (more chance that learning is useful)
- as the magnitude of possible upward revisions to net benefits increases (more to gain by learning)
- as the cost of delay increases, as would be the case if the period before uncertainty resolution was long (more to gain by learning)
- as the cost of learning decreases (less costly to learn)

- and for lower costs of full infrastructure development (less to lose by committing before uncertainty completely resolved).

The option to delay can be considered as being exogenous learning and the option to learn is endogenous learning. A special case where endogenous learning becomes more valuable is where no exogenous learning opportunity exists, in which case the value of the learning option is equal to the option to delay plus the option to learn. In terms of the decision tree above, there is no ability to choose full development in the lower branch – delay effectively becomes abandon, or more succinctly, 'no-go'.

3.3 Suggested method to address uncertainty

The method suggested below brings together ideas from several sources, including feedback from advisors to the project team. It is not necessarily a large change in current methodology but rather a change in emphasis. The better business case methodology already exists as an investment appraisal process in the New Zealand public sector. It includes steps such as establishing the case for change, for understanding the risks and uncertainties, for finding a wide range of viable solutions and for scenario testing. These are all key parts of an adaptive management approach as well. The standard tools are still required within an adaptive management approach but of particular interest is the search for alternatives that can be adapted once various uncertainties are resolved and/or alternatives which can span conceivable scenarios, and for quantitative analysis that can put choices into perspective and provide insights into thresholds, rather than necessarily provide a precise answer.

All the steps within a better business case[44] appraisal are not listed below; instead the following steps within the better business case methodology are recommended for emphasis. The steps are presented as a sequence of events but in practice there is likely to be substantial iteration between the steps to build insights into opportunities. Workshops are the probable means to provide the answers required in the early steps (as per the better business case).

3.3.1 Define issue

As always, a key step is to understand the issue and what objective – and by when – is sought by any policy intervention, which is potentially either a capital project or changes to prices and/or rules. Note, the issue is often couched as a problem but it is helpful to think in terms of pursuing opportunities.

When taking an adaptive management approach, one particular aspect of interest is the inter-relationship between the opportunity and the system, in part because issues involving other parts of a transport network or economic network are likely to be more complicated and have multiple uncertainties, as well as multiple potential solutions. Note, the system relationship may be that other parts of the system are feeding into the current issue and/or a potential solution may feed through into other parts of the system. That is, the interaction of interest can be both backward and forward.

It is also appropriate at this stage to scope the extent of analysis required in the following steps.

3.3.2 Estimate status quo and BAU scenario

Another universal requirement of any analysis is to measure the status quo. Unfortunately, this is not always simple as the future is uncertain. In practice, this step is likely to merge with the next step below – identify key drivers of uncertainty – but it is important to first know what is happening at present and what

[44] Better business case guidance is available at www.treasury.govt.nz/statesector/investmentmanagement/plan/bbc

would happen if recent trends were simply extrapolated forward. This could include an analysis such as undertaken in appendix A4 to determine key trends and key underlying relationships.

3.3.3 Identify key drivers of uncertainty

At this stage, it is important to understand the key uncertainties.

This information can then be used to proceed down three paths:

1. The future regarding this issue and project are relatively certain and the traditional CBA will be appropriate
2. The uncertainty revolves around market risk and/or diversifiable private risk, in which case the following analysis can draw heavily on option valuation techniques
3. The uncertainties are large and probabilities are simply unknown, in which case emphasis shifts to finding robust, timely and adaptable solutions, with the quantitative analysis used to provide perspective rather than definitive valuations.

The methods of Kodukula and Papudesu (2006) and Cardin and de Neufville (2008), as discussed in section 2.5.14, have been suggested as aids to this classification process. However they do not appear to have been widely adopted.

In the AHB AADT example of appendix A4, the nature of the uncertainty is likely to be (3). It may be possible to describe the current situation and policy framework but it is not possible to be certain about what happens next. There are many ways future demand for the harbour bridge could evolve. Uncertainties pertain to local economic development, migration patterns, oil prices, car technology and public transport capacity to name a few. For the sake of tractability and the subsequent application of a decision tree approach, it is useful to define discrete possible states for the uncertainties that are relevant to the objectives being sought. For example, if SDVs are a relevant uncertainty, then some estimation is helpful as to what travel demands would be under a 'low' or a 'high' SDV uptake scenario, or possibly under a 'medium' uptake as well.

3.3.4 Create short-list of alternatives

Having defined various possible outcomes, the next step is to find alternative solutions or opportunities. The better business case guides already list ways in which various opportunities can be explored. Without being explicitly referred to as such, some of the alternative solutions suggested for consideration are real options. In particular, we recommend actively searching for methods that allow flexibility and adaptability, such as:

- timing of any investment
- staging of the investment
- staging in a manner that enables learning (ie undertake phases that enable some uncertainty to be resolved).

As above, a system-wide perspective is recommended. This may be an alternative solution can provide solutions to other issues within any system, or it could be that changes elsewhere in the system can address the issue at hand.

The intention of sections 3.3.3 and 3.3.4 is to build a matrix of drivers of uncertainty versus alternative solutions (see table 3.1).

Thus starts the filtering process. The better business case process employs critical criteria as one method to strike out alternative solutions. It is also possible some solutions may dominate others.

The quest is for solutions that will be appropriate however the future evolves. Hence solutions that can successfully span uncertainties are valuable. Also solutions that enable major financial commitment to be deferred until key uncertainties are resolved, either partially or fully, are valuable. Delay in this case is not a matter of procrastination but rather a process of probing for adaptable solutions and committing now if appropriate to protect the ability to invest as desired at a later stage. The shift in focus is away from finding a solution with the highest BCR to considering benefits under a range of outcomes, without defining probabilities at this stage.

One way suggested to build understanding of the interaction between uncertainties and alternatives is to consider the preferred solution should the uncertainty be resolved, both in a 'high' and 'low' state. In the trivial example below, alternative C provides a solution that is viable under all states of the key uncertainties (unfortunately such a simple solution is unlikely to exist).

Table 3.1 Viability of alternatives under different future states for key uncertainties

Alternative	SDV		Oil prices		Local development		Public transport	
	Low	High	Low	High	Low	High	Low	High
A	Y		Y	Y				
B					Y			Y
C	Y	Y	Y	Y	Y	Y	Y	Y
D		Y		Y	Y			

It is not envisaged that benefits are quantified at this stage but rather alternatives are explored for suitability under different conditions, to build understanding around the issue and the viable solutions and to remove from the list of alternatives those that are inappropriate in light of the uncertainty being faced.

3.3.5 Draw decision tree for alternatives

The authors believe representing the short-listed alternative solutions as one or more decision trees will improve understanding of the inter-relationship between uncertainty and the solutions under consideration. The challenge is to reduce the many uncertainties and alternatives to a tractable number to represent within a decision tree. Several iterations will typically be required to represent the key choices to be made and build understanding around the inter-relationship between the drivers of uncertainty.

A very simple decision tree might consist of several alternatives including a fixed design build now and a more staged alternative, followed by one or more chance nodes. For the fixed design, there will be no further decisions. For the staged alternatives, there will be more decisions required after resolution of key uncertainties, in particular whether to expand, continue or abandon.

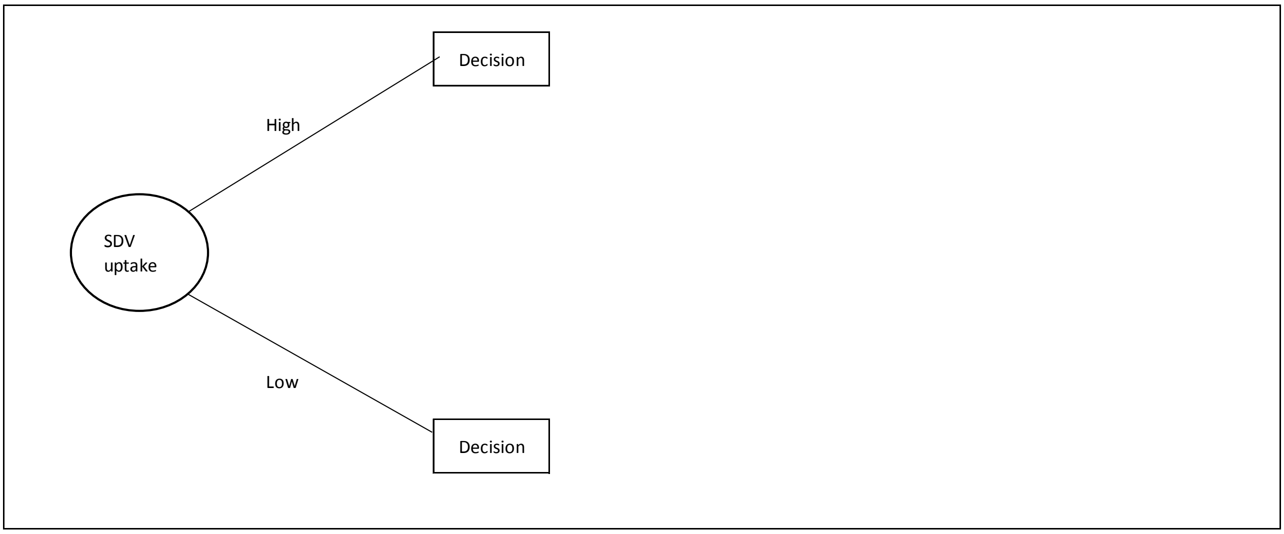
3.3.6 Probe robustness to uncertainties

Both an advantage and disadvantage of a decision tree approach is that it tends to require thinking in terms of discrete events. An advantage is that this does require deep thinking about what are these key event 'chance nodes'. It forces consideration of various scenarios and provides a means to depict these scenarios in a transparent manner (unfortunately it can also risk over-simplification). The process of drawing the decision tree also forces ranking and sequencing of uncertainties.

One way to explore the interaction between uncertainty and the alternatives is to ask two questions, assuming the uncertainty in question is known, as illustrated in figure 3.4:

- What alternative(s) would be preferred?
- What would be the avoidable costs of not anticipating this outcome, including congestion costs?

Figure 3.4 Preferred decision if uncertainty was resolved (with the impact of SDVs used as an example of an uncertainty)



It is also expected that insights into sequencing emerge at this stage, including whether any decisions are urgent, especially around securing rights to future possible investments and/or about committing to initial investments that might help resolve uncertainties quickly.

3.3.7 Crudely estimate indicative payoffs

In an endeavour to provide perspective, and as a means to estimate thresholds, an estimate of an indicative payoff for each short-listed solution under each scenario can be made. To improve transparency and to reduce distraction, it is not expected that payoffs be discounted back to present value today although this could be crudely done using the standard Transport Agency discount rate. Even without discounting of payoffs, there is likely to be some form of discounting implicit in the payoffs as they are reducing some future benefit stream to an asset value at one point in some future period. The emphasis at this stage is on order of magnitude.

It is likely a large element of judgement will be required in forming estimates of payoffs. However, it is also important there is awareness of the sensitivity of the ranking of alternatives to these judgements. Where the ranking of alternatives is considered sensitive to these judgements then more research will be required to improve confidence in the payoff estimates.

3.3.8 Establish threshold that favour one alternative over another

Having derived scenarios and payoffs, it is a matter of calculation to then derive thresholds around the uncertain events that shift preference from one alternative solution to another. In some cases, this alone will be sufficient for reasonable ranking of alternatives. In other cases, it is likely to put focus on where more information is required for a decision. This may entail taking steps to:

- Revisit the steps above to further refine alternatives and system interactions, including reconsidering learning opportunities.

- Develop methods to test the sensitivity of alternatives to plausible chance outcomes.
- Probe stakeholders to assess their degree of regret if costly outcomes were to eventuate.
- Determine how much further analysis of the preferred alternative is required to justify the decision.

The challenge with the above method is that it does force judgements to be made where precise information is not available, and hence well-informed parties are required to be part of the process. It also requires substantial iteration of steps and considerable discussion and debate and hence requires parties to commit to the process. And, given time, there will also be extensive modelling of different scenarios, with the modelling providing inputs to the decision-making process rather than to precise benefit valuation.

4 Case studies

The previous chapter outlined a general approach to evaluating uncertain situations. Taken to completion, the approach will provide additional value to be added in a CBA as outlined by Boardman et al (2011, chapter 7). In many cases, though, definitive probabilities and payoffs will not be known but insight into the uncertainties is likely to assist with resolving which alternative is most appropriate. The three case studies are: the Auckland Northern Busway (NB) introduced in 2005; unplanned changes to passage through the Kaimai ranges between Hamilton and Tauranga; and the Auckland Light Rail proposal under consideration.

4.1 The Auckland Northern Busway

The NB provides an opportunity to explore an historical project that included many adaptive features. The example enables illustration of the recommended methodology plus the nature and value of options to delay, learn, expand and switch.

The NB currently is a 3.2km two-lane section of dedicated busway on the eastern side of Auckland's northern motorway, starting around 1km north of the AHB. Three bus stations, with limited parking, exist along the busway and a fourth exists at Albany, with higher parking capacity, with buses able to use the shoulder of the motorway between the busway and the Albany station. The busway and two stations were partially operational in 2005 and the system became fully operational in 2008. Work to acquire/set aside land for the busway was underway in the early-mid 1990s. Other key dates are tabled below.

Figure 4.1 Key dates associated with Auckland Northern Busway evaluation

Date	Event
Jul 2001	Application for funding for stations to Infrastructure Auckland, including: • Kingett Mitchell evaluation of busway project (vol 1) • Gabites Porter bus rapid transit economic evaluation (vol 3)
2003	Northern Busway construction commences
Apr 2004	Beca North Shore Busway economic evaluation update reported to Transit NZ (now the Transport Agency)
1 Jul 2004	Time zero for 2004 evaluation
Jul 2005	New North Shore bus services commenced
Nov 2005	Albany and Constellation bus stations open and Northern Express dedicated service started, including use of motorway shoulder south of Constellation Drive
Feb 2008	Full busway operational
Feb 2012	BECA scheme assessment report of busway extension to the north

4.1.1 Define issue

As with many large public transport projects, there are several issues that led to the NB. Kingett Mitchell (2001) states the intention of the busway was to:

- provide a cost-effective way to move a large number of people

- provide jobs around universities and information technology incubators in North Shore City[45]
- reduce vehicle operating costs.

The foremost issue was the capacity of the then-existing road network to move people between their residences in the northern suburbs of Auckland to their work and education activities[46] in or near the Auckland CBD during the peak workday travel times. While some ferry services exist[47], the commute between the North Shore and the city primarily entails moving people across the AHB and along the motorway sections immediately to the north and south of the bridge.

While congestion centred on the AHB, Kingett Mitchell (2001) reported extra capacity existed on the AHB but was not being utilised due to queuing on the motorway both north and south of the AHB. The use of moveable lane barriers on the AHB meant the capacity was estimated to be 10,200vph. The southbound morning peak flow over the AHB was around 8,800 vehicles per hour in 2001 and had been since 1987. Meanwhile, however, traffic flows over the AHB were increasing. The net effect was a spreading of traffic over a longer AM peak period.

Transport Agency figures[48] show cars southbound 7–9 am workdays increased 2.6% pa 1990 to 2000 while bus patronage declined by 1.0% pa. This decline in bus usage reversed in 2001. Bus patronage increased at a rate of 6.6% pa 2000 to 2005 and the number of cars slowed to a growth rate of 0.9% pa. Public transport carried around 15% of people crossing the AHB southbound during the AM peak hour in 2001. Wignall (2012, annex p41) reports this ratio to be 22.2% in 2005.

There were (and still are) three key drivers to the pattern of development and travel. First, the city of Auckland was growing rapidly. Second, people had revealed by their home-work choices that (a) high amenity value was placed on living in the northern suburbs, whether for beach access or cultural reasons and (b) high productivity as gained by working in or near the CBD. Third, there was space for further development of residential and commercial development in and around the northern suburbs of Auckland and plans exist for future development. So there were strong reasons to believe the number of people travelling across the AHB would continue to increase.

There are two elements to the congestion issue. First, congestion is costly (in terms of time that could be used for other activities) and people do not like congestion. Savage et al (2002), as commissioners considering the initial business case, went so far as to state 'the limited vehicle carrying capacity of the Harbour Bridge and its approaches, together with significant projected population growth on the North Shore is a recipe for unacceptable traffic congestion in the main corridor between Auckland and the North Shore'. Second, there was a concern that congestion on the northern motorway and the AHB would constrain economic development (Kingett Mitchell 2001). Reference was made to the Auckland Regional Council's 1999 regional growth strategy that had recognised more public transport as being a necessary trigger for the envisaged growth to be realised (p55). The first issue of dislike for, and costs of congestion

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[45] Auckland consisted of seven local authorities at the time including North Shore City and Rodney District north of the AHB

[46] The total number of people in the Auckland CBD from all origins of residence is currently 84,000 for work and 68,000 for education (Auckland Transport 2016, p12), although these numbers will vary depending on how the CBD is defined

[47] 1,300 people travelled by ferry to the CBD daily in 2001 compared with 3,338 bus passengers southbound over the AHB and over 17,000 vehicles (Gabites Porter 2001, table 1)

[48] Personal communication

can be shown by surveys, as was done at the time. Evidence that congestion would in fact impede Auckland growth was not provided in the reports sighted.

This challenge of linking economic growth and congestion is important when it comes to selection of projects. Conceptually there are two major approaches:

1 Define an acceptable level of service in terms of congestion and invest to maintain this level of service with minimal cost, implicitly accepting a one-to-one relationship between the level of service and the economic benefits.

2 Measure the economic effect of changes in congestion and invest to achieve the maximum benefit-cost ratio, including, as Weisbrod et al (2003) suggests, effects beyond direct travel time savings such as through travel time reliability and agglomeration.

The NB assessments did not include a full economic assessment, as per (2) above, and appear to have implicitly put emphasis on the first approach. A post implementation review by Wignall (2012) did include account of wider economic effects.

4.1.2 Estimate status quo and BAU scenario

The key driver was an expectation the northern population would continue to grow rapidly.

Gabites Porter (2001) referred to 82,106 households and 230,627 people in North Shore City and Rodney District in 2001, expected to grow by around 1.5% pa between 2001 and 2011. Employment was 90,539 in the two areas in 2001 (39% of population).

Kingett Mitchell (2001) referred to population growth forecasts of 70% for North Shore City by 2050 (to 292,000) and of 170% for Rodney District (to 177,000 by 2050).

These figures imply an expectation of population growth for the combined area continuing at around 1.5% pa.

The traffic flow and AHB congestion assumptions were not specifically stated in the reports sighted but it is likely models were based around traffic flow growth of around 1% pa and PT passenger growth of around 3% pa. Wignall (2012) refers to reports of ‘stop/start driving conditions’ prior to the busway, a situation that was presumably expected to worsen without intervention.

The effects of congestion can be measured in terms of extra actual travel time and/or the extra travel time allowance required given the distribution of expected travel times, as is done in many transport appraisals.

More difficult to measure is the effect on economic growth that might result from increased congestion. A typical transport appraisal will ignore such ‘land use changes’[49].

4.1.3 Identify key drivers of uncertainty

There are three key levels of uncertainty relating to the major issue of congestion:

- How many people will live in the northern suburbs, in turn affected by issues such as household income growth and the monetary costs of travel?
- How many people will choose to travel to the CBD daily for work or education?
- How many people will choose public transport instead of their car?

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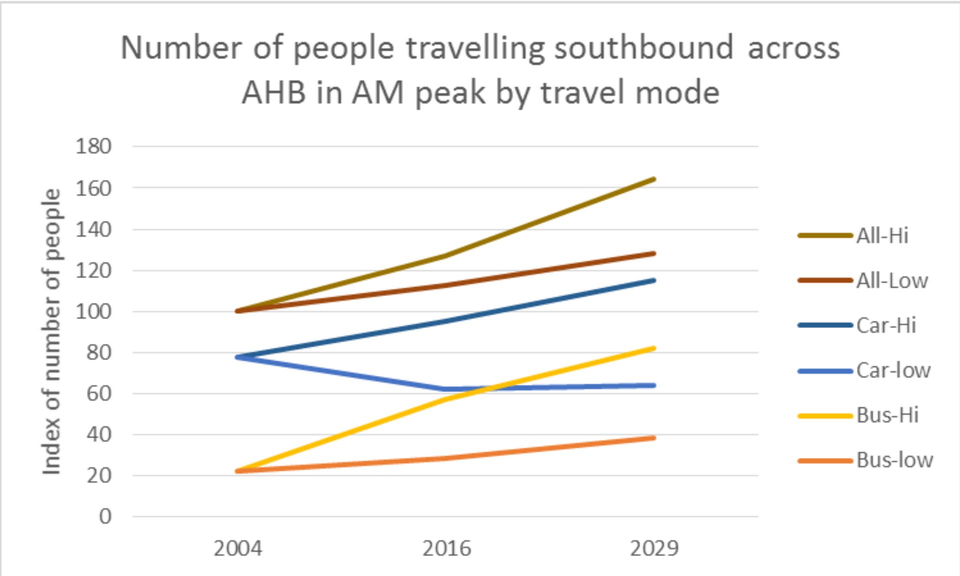
[49] Gabites Porter (2001) report the use of different land use growth in an appraisal scenario was ‘discouraged by Transfund’.

There are other propensities that are also unknown, including the number of people per vehicle, but these are likely to be secondary uncertainties.

In terms of the project undertaken, Kingett Mitchell (2001) listed patronage on the buses as the key risk and Savage et al (2002) acknowledged ‘there was some debate and differences as to the likelihood of the busway project “succeeding”’.

In fact, the uncertainty of bus mode share interacts significantly with uncertainty relating to the number of people wanting to travel across the AHB during peak periods. An illustration of uncertainty pertaining to bus and car patronage is shown in figure 4.2. The figure shows that starting from a set number of people wanting to travel southbound during the AM peak period and the then 22.2% bus mode share, the range of probable people wanting to travel (the top fan) widens with time (low and high growth rates of 1% and 2% shown) but the plausible range of people travelling by bus or car (the lower two fans) is an even wider range (assuming mode share low rising from 22% to 25% to 30% shown, plus high from 22% to 35% to 50%).

Figure 4.2 Number of people travelling southbound across AHB in AM peak by travel mode



Besides the wider plausible range of bus and car passenger outcomes, there is also an interaction between the uncertainties. For example, there is a larger travel time saving effect of a shift to PT when roads are heavy congested, as would occur with a fast growth rate of people wanting to travel at peak times, all else being equal. Conversely, there is a lower incremental time saving from a switch to PT when travel demand is slower and hence traffic is less congested. The net effect is asymmetric uncertainty around the growth rate of persons commuting and PT mode share as described in table 4.1.

Table 4.1 Relative magnitude of travel minutes saved with the Northern Busway

	People travelling growth		
Change in PT share	Low	Medium	High
Low	Very low	Low	Low
Medium	Low	Med	High
High	Med	High	Very high

4.1.4 Create short-list of alternatives

From a general perspective, the policy and investment alternatives are:

1. Use various means, including planning and pricing, to create a larger proportion of work and/or education activities north of the AHB.[50]
2. Use various means to create a larger proportion of residence to the west or south of the AHB
3. Construct more bridge and/or motorway capacity
4. Use various means, including construction, pricing and rules, to create a higher vehicle occupancy on the AHB and northern motorway.

Solutions (1) and (2) are beyond the scope of a transport project in New Zealand. In fact they become further sources of uncertainty to the degree that planning and pricing policies of local and central government can change in some unknown way. Effectively the transport solution sits within the policy and pricing rules of central and local government. It is simply noted here that the NB, a solution of type (4) above, was consistent with aims to expand education activities at Akorangi.[51] and Albany and with more employment in the northern suburbs.[52] (both type (1)) but it was also consistent with plans to continue strong residential development in the northern suburbs.

Choices available of types (3) and (4) above include:

3a) Build another bridge

3b) Build a rail crossing and rail network on the North Shore

3c) Build more approach lanes for all vehicles

4a) Build more approach lanes for dedicated buses and/or high-occupancy vehicles (HOV) use

4b) Use existing approach lanes for dedicated use by buses and/or HOV.[53]

4c) Use motorway shoulders for buses and/or HOV

Each alternative will have different costs, with costs potentially including those associated with any active learning undertaken. Each alternative will also have different benefit streams over time, with alternatives involving delays to investment potentially having smaller near-term benefits.

The Auckland Regional Council assessed various bridge, tunnel, ferry, bus and rail solutions to northern corridor peak traffic flow congestion in the late 1980s (Kingett Mitchell 2001), effectively considering solutions of types 3 and 4 above. The council determined a busway was the best solution and commissioned studies into a North Shore Busway in 1990. Further studies then led to consideration of the proposed busway as a priority lane for buses and HOV (Kingett Mitchell 2001).

[50] Over 75% of employment in Auckland is already outside the Waitemata Board Area, including the CBD (Paling 2014, pp15, 114).

[51] Gabites Porter (2001) report to Auckland University of Technology, Akoranga plans to increase from 2,500 to 10,000 over 10–15 years.

[52] Paling (2014, p106) reports commuting growth from south to north of the AHB increased faster than north to south between 2001 and 2013.

[53] Gabites Porter (2001) report 16% of the morning peak were HOV.

It is important to note the NB was seen within the context of longer-term solutions that were expected to include an additional Waitemata Harbour Crossing (AWHC), at the time estimated to cost $950 million (Auckland Regional Council 1999, p51).

> *The need for a third crossing of the Waitemata Harbour is unlikely until at least 2020 by improving north-south accessibility through the North Shore Bus Rapid Transit System, by introducing traffic demand management measures and improvements to the motorway system, as well as encouraging job growth on the North Shore.*

The business cases sighted focus primarily on (4a). It is stated by Wignall (2012, annex p37) that the use of motorway shoulders immediately before the introduction of the busway was largely ineffectual, implying (4c) was considered but dismissed as a solution.

It is not known why (3a) and (4b) were dismissed but it is likely to have been because they offered limited scope for higher capacity usage. These alternatives are discussed below, as well as the AWHC alternative, to draw out adaptive advantages of the busway solution actually chosen at the time.

The following long-list of options is presented below to reflect the wider set of alternatives that were assessed over several years. A judgement now is provided as to how sensitive the viability (ie NPV) of the alternative project would have seemed (in 2001) to conditions in 2011. This 10-year horizon is chosen as the NB business cases placed emphasis on 10-year forecasts, with benefits for other years generated by extrapolation.

Table 4.2 takes the three key sources of uncertainty listed in section 4.1.3, with each having a high or low outcome attributed to them. We then provide an initial yes/no (Y/N) judgement as to whether the listed investment alternative would have been viable if one of these outcomes occurred, holding all other factors constant.

Table 4.2 Judgement today as to viability of 2001 alternatives to relative levels of key driving forces in 2011

Alternative	North Shore population		CBD commute		Bus mode share		Comment
	Low	High	Low	High	Low	High	
3a) Add bridge	N	N	N	N	N	N	LOW sensitivity but high fixed cost not justified at present
3b) Add rail	N	N	N	N	N	N	LOW sensitivity but high fixed cost not justified at present
3c) Extra approach lanes for all vehicles	Y	N	Y	N	Y	Y	HIGH sensitivity to extra volume. Extra capacity can accommodate extra buses but limited extra capacity if PT share is low and offers limited impetus to PT
4a) Extra approach lanes for buses/HOV	N	Y	N	Y	N	Y	HIGH sensitivity to low uptake of PT, which may affect viability under low total demand growth
4b) Dedicated use of current approach lane(s) for buses/HOV	Y	N	Y	N	N	Y	HIGH sensitivity to extra volume – PT mode combination as extra capacity depends on bus uptake.

The AWHC alternatives are generally insensitive to outcomes in a 10-year horizon as there was likely to be insufficient demand growth over that timeframe to justify the high fixed costs.

It was possible to build new approach lanes to accommodate extra car traffic and more public transport. However, the success of these approaches would have been very sensitive to PT pick-up as otherwise congestion would soon re-emerge unless total traffic demand was to be relatively low. Meanwhile, the chance of high PT pick-up was lessened by the limited potential for faster PT travel times, in turn reducing the ability of the system to cope with any higher travel demands.

Conversely, lanes could be dedicated to buses/HOV – either using existing or new lanes – and the viability of these outcomes would again be sensitive to the change in mode share, except now the bias would be towards accommodation of higher total traffic demand should PT pickup be high. The speed and extent of PT adoption would also affect the extent of congestion relief on the non-dedicated lanes[54].

If instead of taking a 10-year horizon, planners were to have taken (say) a 50-year horizon, the sensitivity to uncertainties could differ, and the interdependency of some solutions would become more apparent.

For instance, the bridge option becomes less sensitive to the likely range of populations (over 50 years) but remains sensitive to commute and mode choices. By 2050, the population is very likely to be large enough to justify another harbour crossing but that need will depend on how, when and where people choose to travel in 2050. People may choose to work more from home, or work at varying locations, or to have more flexible hours of work, or travel by rapid transit or uber-style HOV self-drive vehicles. Each of these uncertainties will influence the need for a high-capacity harbour crossing.

The use of a longer-term horizon highlights an important point with regard to the relationship between length of planning horizon and the value of a real option. Certain alternatives, which may be chosen when only a 10-year planning horizon is used, will have the effect of closing off, or raising the cost of, alternatives for future expansion that may later be required should a range of longer-term outcomes eventuate. In particular, solutions that enable a higher capacity crossing and/or higher vehicle occupancy do offer the advantage of less costly transitions in situations should greater capacity than initially anticipated eventually occur.

4.1.5 Draw decision tree for each alternative

The inter-relationship between the alternatives is apparent once we draw decision trees for each.

The decision tree for an AWHC is relatively straightforward: given current information, do I start construction now or defer? See figure 4.3. This was not an alternative directly applicable to the NB business case but was an alternative from a longer list previously dismissed and it is an alternative that is worthy of consideration when it comes to integrating short-term solutions with long-term solutions[55].

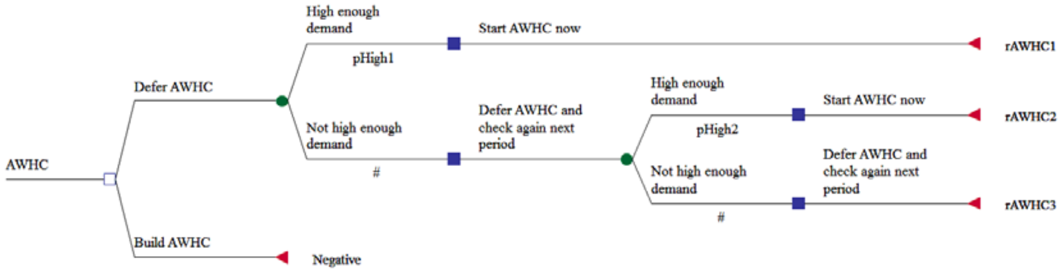
The decision tree shows an initial decision to build the AWHC at the time or to defer the build, with an immediate build producing a negative NPV. The return from deferral depends on action taken in subsequent periods – say each five years – with only two periods shown in the decision tree for simplicity. The range of outcomes is summarised by two discrete events: either travel demand increases sufficiently to justify the immediate construction of the bridge, with probability denoted by pHigh1 in period 1 and pHigh2 in period 2; or demand is not sufficient with probability 1 minus the high scenario probability and denoted as '#'. The NPVs of the project that hypothetically starts after each period 1,2,3 are denoted rAWHC1 (or 2 or 3). Potentially these could be the same benefits and costs relative to each start date but

[54] It is not known why this option was not tried earlier as this would have provided an option to learn about PT uptake, one of the key uncertainties

[55] The NB was also built to enable later conversion to rail, should the AWHC include rail. This option is not expanded upon here as the Transport Agency (2010) put little value on a rail connection

with different discount factors applied to bring back to 2001, but in this case differing congestion levels are likely to mean these payoffs will differ. The wide range of demand outcomes has been reduced to two scenarios to illustrate the key decisions and uncertainties. More likely a wider range of scenarios would be required in practice.

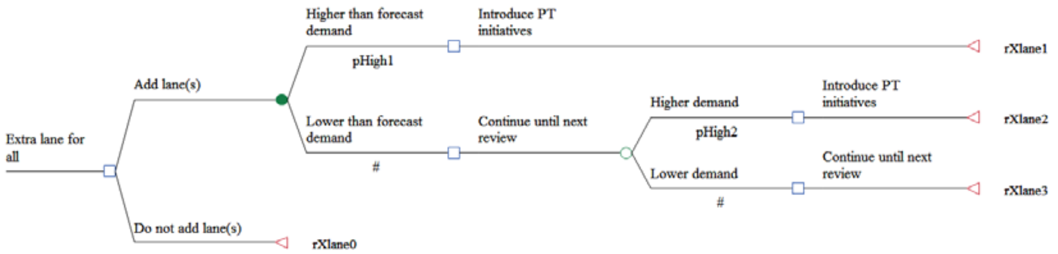
Figure 4.3 Decision tree for the AWHC alternative (truncated after two periods for simplicity)



Turning to the construction of extra non-dedicated lanes, the initial decision to add a lane is likely to have provided a benefit via a travel time saving across all vehicles travelling at peak periods but the decision tree shows this alternative also provides an option to introduce enhanced PT in future. In other words, the extra non-dedicated lane did not close off the option to expand PT. The extra non-dedicated lane solution in 2001 was seen of limited value but should extra non-dedicated lanes have been provided and should traffic demand increase quickly then congestion would re-occur and, at that stage, it was likely other initiatives would still be sought, including use of dedicated PT lanes. The notation in the decision tree is similar to above.

While this alternative includes an option to learn, and hence the ability to switch to PT if required, this option was of limited value as it enabled learning of the general level of transport demand but did not provide learning about the propensity for PT, in spite of this information eventually being required.

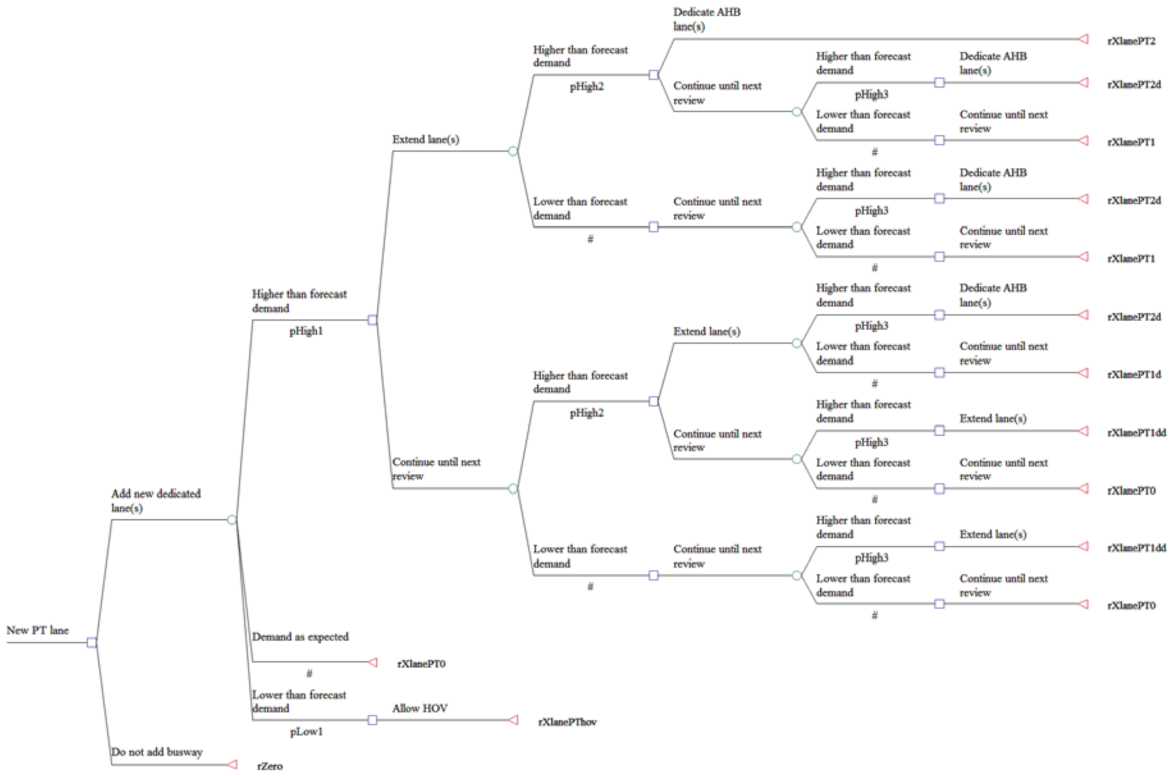
Figure 4.4 Decision tree for expansion beyond extra non- dedicated lanes



The adaptive value of a dedicated busway solution is illustrated in figure 4.5. The figure depicts staged decisions at the end of each of three, say, 10-year periods, with an arbitrary cut-off at year 30 to simplify the diagram. Notation is consistent with the previous decision trees.

Taking the highest branch first, should travel demand for the busway prove stronger than expected in the first 10 years then the busway can be extended. One option is to extend the busway further north (eg to Silverdale) and to enhance the connection to the centre of Albany. These extensions (by themselves) would make little sense if the initial busway was not already in existence, so the busway has effectively created an option to build these extensions. Note the value of learning is higher in this alternative than the preceding alternative (ie additional non-dedicated lanes) due to the knowledge gained about PT mode share in the early years of the busway.

Figure 4.5 Decision tree for dedicated lanes



Furthermore, if demand for the northern motorway increases unexpectedly, then the existence of the busway creates an enhanced opportunity to dedicate AHB lane(s) to PT, thereby effectively increasing the people-movement capacity of the bridge. In turn, this enhancement may enable a delay for another period in the need to start the AWHC, a decision which can subsequently be re-visited.[56]

As it turns out, the pathway being considered at present is similar to this top branch. A proposal exists to extend the busway to the north and Wignall (2012) notes the potential created by the busway for more person-movement growth.

At the other extreme a new busway need not be added. This becomes the do-nothing scenario (see bottom branch).

Above that in the decision tree is the lower busway branch from a 2001 perspective. Should demand for the busway prove weak in the first period then HOVs could be granted access to the busway/priority lane, thereby increasing the value of the lanes even under slow initial PT uptake.

Or, the next branch up, demand could be as expected, in which case the NPV estimated in the initial CBA applies, albeit subject to later upward revision.

An intermediate branch also exists between the busway extremes whereby a delay is possible during a review period, after which the previous decision can be revisited.

[56] Note, this assumes (a) the wider network can accommodate more buses and (b) the AWHC can be deferred without substantial cost.

There are other adaptive features of the dedicated busway solution not shown in the decision tree. Wignall (2012) refers to the added flexibility during times of sharply higher (or lower) fuel prices, the additional modal choice made possible by the more frequent and reliable bus service on offer since 2005 and the ability to switch the busway to a railway if required. These have been excluded here to focus on what are judged to be the key options for higher value (but could be included in a fuller analysis).

4.1.6 Probe uncertainties

The uncertainties largely revolve around population growth, use of the AHB and mode share. Each is discussed below and the combined uncertainty then considered.

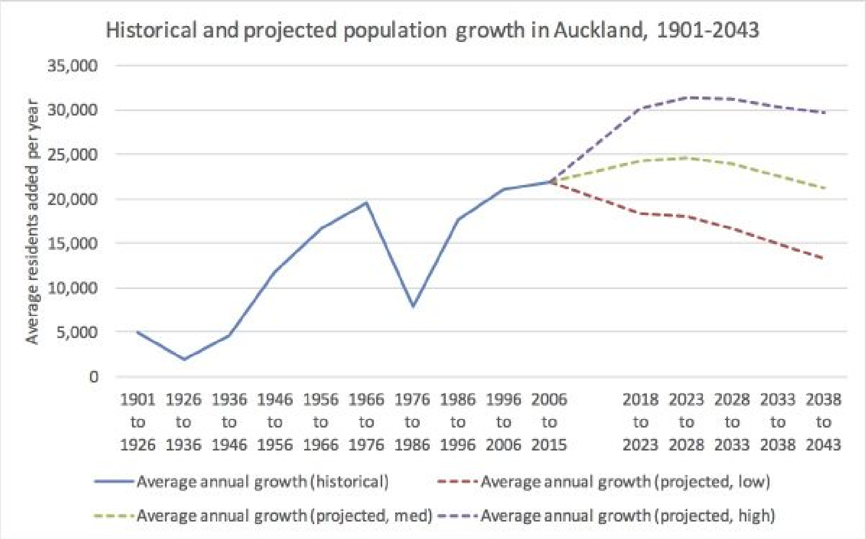
4.1.6.1 Growth of population

A core uncertainty is the growth rate of the population and its spatial distribution.

Auckland had a usually resident population of 1.4 million at the 2013 Census, of which 0.3 million lived in the northern suburbs that previously formed North Shore and Rodney. The population of Auckland increased by an average of 21,273 per year or 1.2% pa between 2006 and 2013. The population in the northern suburbs increased 5,377 or 1.4% pa.

The degree of uncertainty about future population growth is illustrated in figure 4.6, where a range of Statistics NZ projections[57] are imposed on a graph of historic growth rates for Auckland. The average forecast growth rates over any five-year period range from about 0.7% to 1.7% pa. While there are strong reasons to believe Auckland population growth will be above the 'average' forecast,[58] history shows that a period of low growth is also possible, as occurred during a period of low net immigration to Auckland in the late 1970s and early 1980s.

Figure 4.6 Auckland population growth – historic and forecast (source: http://transportblog.co.nz/2016/09/06/aucklands-urban-growth-a-historical-perspective/)

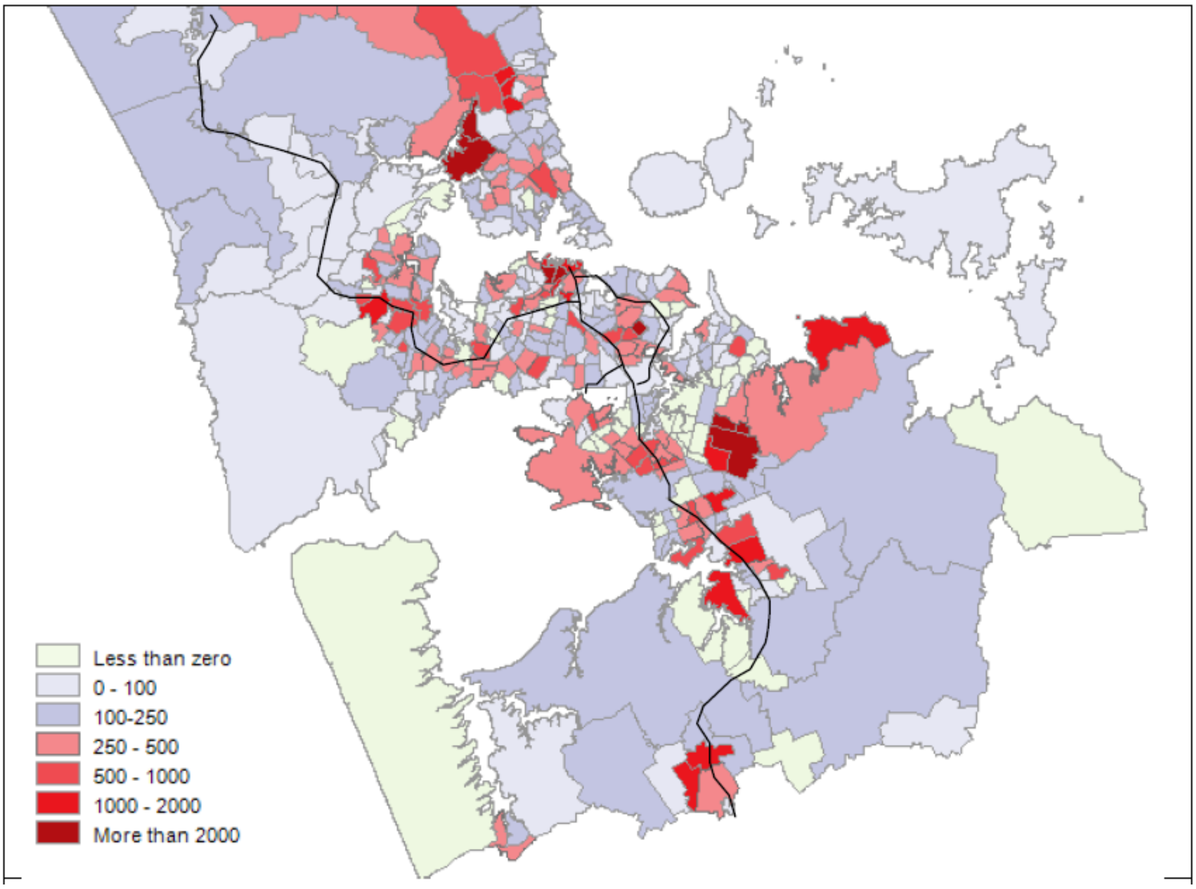


57 www.stats.govt.nz/browse_for_stats/population/estimates_and_projections/SubnationalPopulationProjections_HOTP2013base.aspx

58 Growth estimated for the 12 months to Jun-16 is 44,000 people or 2.8%. See: www.stats.govt.nz/browse_for_stats/population/estimates_and_projections/SubnationalPopulationEstimates_HOTPAtJun16.aspx

Within Auckland's overall population growth rate is the uncertainty pertaining to where growth will occur. In recent years there has been strong population growth near the fringes of the city, as shown in figure 4.7. Recent trends point to this pattern continuing. However, the map also illustrates the wide area of Auckland and the opportunity for more intensive population growth, including around the current rail network (shown as black line on map). The Auckland Unitary Plan[59] recently adopted by Auckland Council increases the number of existing properties that can be used for more intensive housing. However, not only does this change in zoning potentially change the spatial pattern of population growth around Auckland, including within the northern suburbs, the process that led to these zoning changes also raises uncertainties: zoning policies are set through a political process and hence can be subject to further change.

Figure 4.7 Change in Auckland number of residents 2006–2013 (Source: Paling 2014, p125)



Summarising these population uncertainties, there is a strong ongoing force in the form of a substantial natural rate of population growth but there is also uncertainty around the pattern of migration to/from the northern suburbs. There is an element of endogeneity in migration to the extent New Zealand politicians can change national immigration targets and local zoning laws and to the extent local congestion influences locational choices but there remains a fundamental uncertainty. While this population uncertainty is very real, it is its interaction with commuting patterns and with potential PT uptake that makes it particularly relevant to the NB proposal. We examine these factors below.

[59] Some minor changes were made by Auckland Council to the plan recommended and available at www.aucklandcouncil.govt.nz/EN/planspoliciesprojects/plansstrategies/unitaryplan/Pages/ihpreportsrecommendations .aspx

4.1.6.2 Commute north- to- south

Given population forecasts, the issue then arises of how many people choose to commute north to south over the AHB (with or without an AWHC). This propensity does vary with the location of residence and factors such as household formation (age and composition). It can also vary over time, especially should communications technology lead to more working away from one centralised location.

The proportion of residents in the northern suburbs commuting to the south of the AHB is recorded in each census and was summarised recently by Paling (2014). The figures for 2001, 2006 and 2013 show the following patterns:

- 35,523 people reported commuting north-to-south in 2013
- This total had increased at an average rate of 2.1% p. between 2001 and 2006 and again between 2006 and 2013.
- The average increase in 2006 to 2013 was 658 commuters per year.
- 87% of these commutes were to the Auckland CBD or the nearby isthmus.
- Fewer people in 'Rodney' chose to commute to south of the AHB, with AHB commuters 4.5% of the population in Rodney but 13.8% in North Shore in 2013.
- Since population growth was also less in absolute terms in Rodney (2,103 versus 3,274 pa in North Shore), the growth in commuters was less for Rodney residents (160 versus 498 pa.)
- At the margin, the propensity to commute increased across the area, with the increase in commuters being 10.3% of population growth in Rodney and 19.4% or population growth in North Shore, and 15.8% combined.

The results show any increase in commuting north to south will in part depend on whether population growth occurs within the suburbs previously described as Rodney or the North Shore. They also show the propensity to commute does change over time.

Note also, commuting to work is only one of the factors that determine the traffic demand on the AHB. Given the large presence of tertiary education in the CBD and on the north shore, this also will be of significant influence.

Summarising these commuting uncertainties, there have been steady increases in the number of people commuting north to south but this growth rate may decrease as congestion increases (an endogenous response) and as population growth shifts further north.

4.1.6.3 Public transport usage

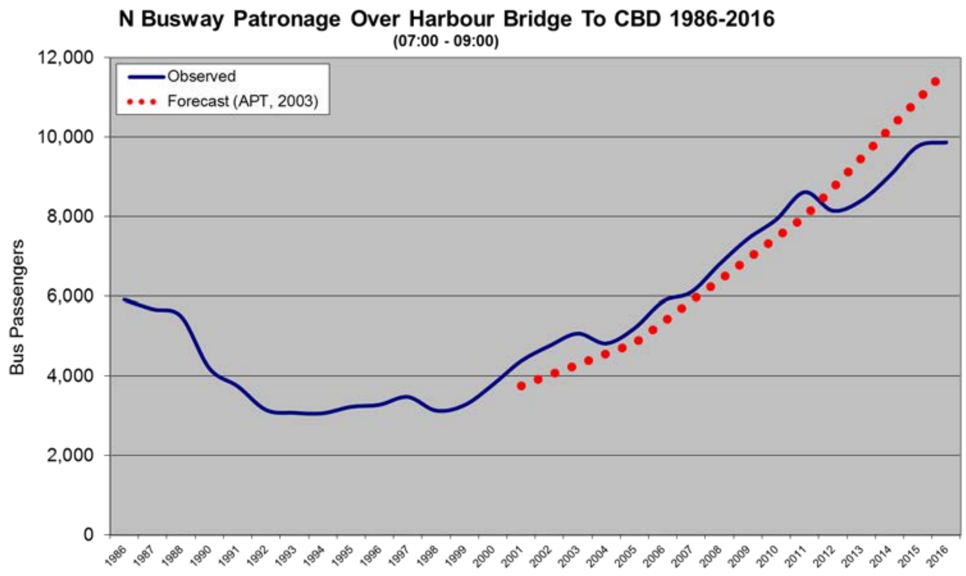
The third key part of the traffic demand equation is the proportional use of PT. This appears to have been the key uncertainty at the time of the project's adoption.[60]

There are three aspects to this uncertainty, as faced in 2001. First, the use of PT in the northern suburbs was relatively low at the time and the motorway bus patronage had been declining during the 1990s (see figure 4.8). Second, in spite of the success of the NB in the 2000s, Transport Agency figures show NB patronage is now below forecasts made in 2003, pointing to the uncertainty that exists over time. Third,

[60] As it turned out, the introduction of the NB led to a significant increase in the proportion of travel across the AHB by bus. Paling (2014) shows the share of north-to-south harbour-crossing commuters that travelled by PT increased from 11% in 2001 to 13% in 2006 and to 18% in 2013.

and one factor behind this general uncertainty, mode share varies as destination varies, hence so too will overall mode share should the mix of destinations change in the future. Paling (2014) reports that within the 18% north-south PT mode share in 2013, the PT share was 34% among those commuters heading for the CBD, 8% for those heading to the isthmus surrounding the CBD and 5% for those heading further afield. Recent Auckland Transport coordination of a rapid transit network may improve PT patronage in trips beyond the CBD but this effect remains uncertain.

Figure 4.8 Northern busway patronage – actual and forecast (source: Clarke, NZ Transport Agency, personal communication)



Summarising these mode share uncertainties, the uptake of buses was a major risk faced by the NB project. This was recognised at the time and steps were taken to reduce the risk. First, there were substantial supporting changes made to stations, buses, scheduling, payment mechanisms and other parts of motorway/local road network to increase the attractiveness of PT. (Costs were incurred to provide these services but there may have been other benefits that helped to offset these costs.) Second, if PT uptake did prove low then the 'option to switch' use of some lane capacity to HOV was created. Third, advantage was taken of a 'learning option' in that a full laneway along the length of the northern motorway was deferred, with the bus lanes created along only a portion of the northern motorway but with plans made to extend the lanes to the north when, or if, required.

Evaluations of the busway have tended to produce the HOV benefits as an alternative scenario, along the lines 'the expected benefit of the busway is $x with buses only and $x+y if HOV are also granted access'. As it turned out, HOV access has not been granted. Whether or not the option to switch to HOV was taken up, the value of this option existed at the time of the original decision and could rightly have been included in the original BCR.

The same applies to the option to extend the busway: this value was not recognised at the time of the initial decision in the benefit calculation; the value of the option to expand rightly could have been added to the BCR, or more transparently added as a higher BCR within a sensitivity analysis.

4.1.6.4 Combined uncertainties

Before looking closer at valuation of the switching and learning options, there is the major issue around the timing of extra harbour crossing capacity, presumably in the form of one of the two AWHCs on the table at present (ie bridge or tunnel). The provision of a busway was expected in 2001 to produce substantial benefits via immediate travel time savings but perhaps a bigger issue was whether (and/or when) an expenditure of around $3.5 to $4.5 billion would be required to provide a step-wise increase in harbour crossing capacity. Evaluation of this issue requires an understanding of the interacting uncertainties around (a) how many people will want to cross the harbour during the AM peak?, and (b) how many will choose to travel by PT?

It is beyond the scope of this project to delve into these issues to provide strong insights into the interplay between the projects and the uncertainties. Rather this research project simply notes that potentially a large benefit could accrue if the NB, including the proposed northern extension, could be used to shift more people by bus over the existing AHB.

At this stage it may be possible in some business cases to provide subjective probabilities (or even model derived probabilities) about the unknown future scenarios. In this case, it was not possible so the next step is to estimate indicative payoffs under the key scenarios and the test the sensitivity of decisions to probability assumptions.

4.1.7 Estimate indicative payoffs

There are three payoffs that are core to the calculation of expected option benefits that can be gained from:

1 Reducing the reliance in the busway on buses by granting access to HOVs

2 Extending the busway to Albany and/or further north to Silverdale

3 Extending the busway south by dedicating part of the AHB to a busway.

Table 4.3 lays out the logic and sources used to provide indicative estimates of the benefits that could be achieved, albeit each benefit requires a sequence of events to occur. By definition, none of these events is certain.

To provide some perspective to the estimated payoffs, and for further use below, the 2004 NB business case estimated the PV of benefits to be $199 million and the costs to be $172 million, giving a BCR of 1.2. This analysis excluded the cost of significant enhancements to the four stations. Wignall (2012) completed a post-implementation review of the initial analysis and concluded the PV of the benefits, in $2004, were more likely to be $685 million and the PV of the costs to be $264 million, giving a revised BCR of 2.6. The revisions largely resulted from applying the current EEM methodology, using a 30-year horizon (instead of 25 years), an 8% real discount rate (10%) and added benefits estimates pertaining to reliability, congestion and agglomeration.

Table 4.3 Estimate of option payoffs

HOV use of lanes	A Beca (2004, pii) evaluation put the extra present value of use of lanes for HOV at $93m versus $199m for the busway only ($2004 at 10% discount rate over 25 years, 2 or more people per vehicle). ESTIMATE USED HERE: Rather than estimate the marginal benefit of HOV under various scenarios, it is noted the ability to add HOVs at any stage puts a floor on the benefits of the initial busway. It is assumed this floor would be set at 10% below the base case busway-alone benefit estimate. Such a floor thus excludes the potential benefit decline that might have accompanied a fall in bus patronage similar to the 48% fall in northern busway patronage between 1986 and 1994.
Northern extension of busway	The Beca (2012) Scheme Assessment Report for extending the current busway estimated the NPV of an extension to Albany to be $127m (PV 2012). Beca also judged a full extension of the busway further north to Silverdale was not of value but allowing buses to use the current motorway shoulder would realise further NPV of $77m.

	ESTIMATE USED HERE: This case study added these two PVs (giving $204m in 2012) and applied an 8% pa discount rate to calculate an NPV as at 2004 of $110 million, this being the payoff should this growth option be exercised. The implied assumption here is the initial busway largely limited the real cost of the extension and any subsequent nominal cost inflation has been matched by nominal benefit inflation.
Higher use of PT on AHB (and effectively the delay of the AWHC).	There is no (known) available estimate of the net benefit of higher PT use over the existing AHB. ESTIMATE USED HERE: A crude approximation is to assume the order of magnitude of the benefit is some proportion (0–100%) of the benefit gained in the first 10 years of the AWHC, as estimated by PWC/NZIER (NZ Transport Agency 2010) (assumes bridge opens 2029, 8% discount rate). Any project that enables the bridge to be delayed 10 years would be expected to provide a proportion of the benefits otherwise expected of the bridge. PWC/NZIER estimated the present value of the total benefits, including agglomeration benefits, to be $600m in 2010 dollars. Approximately 50% of these benefits will result from benefits in the first 10 years of the bridge, implying a $300 million benefit of delaying construction – but maintaining level of service – by 10 years. Applying the 8% discount of the NB study, and assuming a benefit proportion of 100%, this equates to $190m PV of benefits in 2004.

The PV of benefits and costs, as estimated by Wignall (2012), and the estimates of option payoffs from above are combined in table 4.4. The table is largely illustrative as many of the numbers are unknown. Nonetheless the table illustrates where the missing value from the initial NB evaluation occurs, namely in the options to extend and to switch to HOV. To derive this table, it has been assumed there are three states possible: (1) a base case scenario where benefits derived are as expected, (2) a low benefit scenario where benefits are 20% less than in the base case and (3) a high benefit scenario with 20% higher benefits. The assumed probabilities are 20%, 60% and 20%.[61]. These probability assumptions are arbitrary in this research project but conceivably they could have been derived as subjective judgements at the time of the original decision. Importantly, the sensitivity to these probability assumptions will be tested below but for now it is noted that implicit in these arbitrary numbers is an assumption the risk around the outcomes is symmetric. This would also require further research.

Under the low benefit scenario, a floor exists due to the ability to allow HOVs in the busway if bus demand is low. Under the high benefit scenario, extra benefit can be derived by the busway extension to the north and it is further assumed there is a 50/50 chance existing lanes are then dedicated to buses on the AHB. In fact, the probabilities are unknown and the situation may not be adequately described by three scenarios, especially given the interaction between travel demand growth and PT share. Also, an important point about these valuations (raised earlier) is they are sensitive to the chosen discount rate since options are likely to be heavily weighted to future events. These are all areas that would require further research in an applied analysis. For now, a sensitivity test will follow in the next section whereby the fuller decision tree of figure 4.5 will be used.

[61] These probabilities provide a reasonable discrete approximation of a symmetrical continuous distribution of outcomes although Chapman and Ward (2011) suggest using asymmetrical probabilities of 20%, 50% and 30% to counter a typical optimism bias.

Table 4.4 Illustrative simplification of expected benefit calculation with and without options

	Benefits without options included (A)	**Option taken up**	**Additional benefits (B)**	**Illustrative probability of events (C)**	**Benefit contribution (=C*[A+B])**
If 20% higher (high benefit scenario)	$822m	If northern extension and dedicated bridge lanes	$300m = $110+ $190m (see Table)	10%	$112m
		If northern extension	$110m (see table 4.3)	10%	$93m
Base case	$685m	BAU	$0	60%	$411m
If 20% lower (low benefit scenario)	$548m	If allow HOV	$68m (to raise to floor, see table 4.3)	20%	$123m
TOTAL	**$685m (without allowing for options)**			**100%**	**$740m (with option values included)**

4.1.8 Establish thresholds that favour one alternative over another

The preceding calculation is a simplification of the option valuation and in this case is largely illustrative as key payoffs are not known. It is possible to undertake research into parts of the valuation to improve the approximation but, before discussing that possibility, it is helpful to understand the sensitivity of the valuation to some of the key assumptions. This may reveal there is no need for further research because the decision is clear cut, eg the plausible range of assumptions produce a valuation that exceeds any decision threshold and hence supports a 'go' decision.

The two key uncertainties are the value of busway extensions and the probability demand will be sufficient to warrant extensions. The sensitivity to these variables is tested below.

The decision tree of figure 4.5 and the values used within table 4.4 were analysed through the TreeAge decision tree software. The initial run produced an expected value of $744m, slightly above the $740m derived above due to options to delay embedded in figure 4.5. The following table shows the sensitivity of this expected value to the key assumptions around probabilities and payoffs.

Table 4.5 Expected benefit (2004$m) under various payoffs for extensions and probabilities of high demand

	Probability of high demand			
Payoff from northern extension ($m)	0.1	0.2	0.3	0.4
0	692	699	706	712
37.5	700	714	729	743
75	707	729	752	774
110	714	744	773	802
150	723	760	798	835

The figures confirm the following:

- Looking at the second column of the fourth row (ie the initial run), $744m is the expected benefit with a $110m northern extension payoff and a high-demand probability of 0.2 in the first 10 years, and further assuming there is a 50/50 chance that the busway expansion across the AHB also proceeds with a payoff of 1.7 times the northern extension payoff (these relativities derived from the indicative payoff estimates are maintained in all scenarios to reduce the permutations).
- Turning to the fifth row, this value increases to $760m if the payoff from the extensions were 36% higher – this might be the case should further research reveal the current calculations have been conservative or if the expected 2012 extension benefits were discounted back to 2004 at 4% instead of 8% pa (note the discount within the extension project has not been adjusted).
- Now looking at the first row of the second column, a value of $699m is expected if the extensions are of no value, implying a $15m value of the option to switch to HOV under low demand scenarios (ie $699–$685).
- The expected value of the NB would be $835m (fourth column, fifth row) should the value of extensions be higher than the initial assumptions and should there be a high probability of high demand (and, due to the symmetry assumption, an equivalent high probability of low demand but with the effect of low demand capped by the HOV switch option).

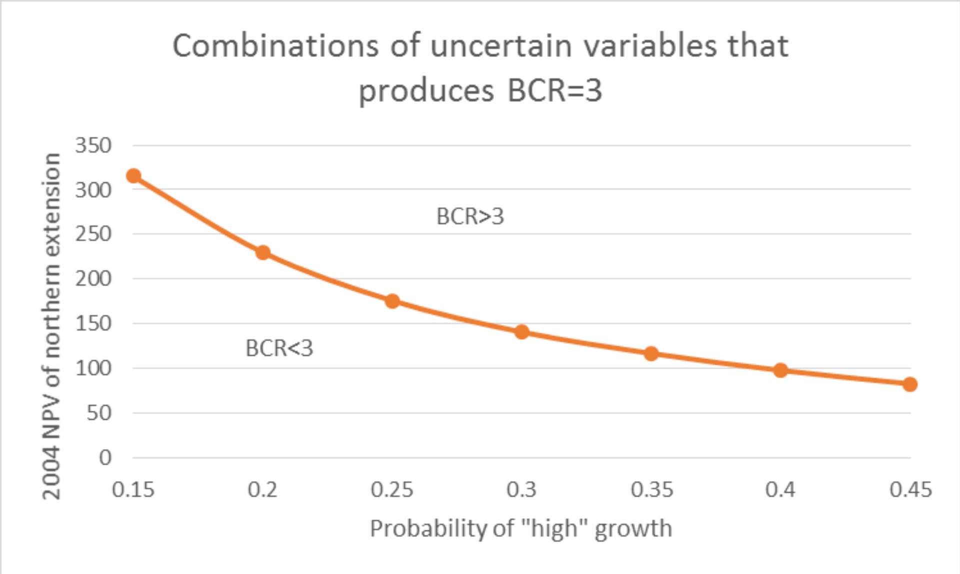
The information can then be used to test the sensitivity of the decision to the assumptions about these uncertain variables. In this case, the BCR was estimated to be 1.2 initially and was revised to 2.5 in the 2012 review. Should, say, a BCR of 3 be required using the revised figures then figure 4.9 shows the combination[62] of probabilities of high growth and NPV of the northern extension that would be required. If such a threshold were required then three situations would exist:

1. It is judged very unlikely these conditions would be met and hence the project would not proceed.
2. It is judged very likely these conditions would be met and hence the project would proceed.
3. It is uncertain whether the conditions would be met and hence more research into the payoffs and probabilities might be required and/or consideration taken as to how to change the project design to improve these payoffs and probabilities.

As it was in the NB business case, the inclusion of option values in the evaluation would have provided greater assurance that the initially estimated BCR was very likely to be greater than 1 (a contentious issue at the time).

[62] Implicit in the calculation is that assumed relativities between these two variables and others remain valid, eg value of busway extension to south is 1.7 times value of northern extension

Figure 4.9 Conditions required for BCR above 3



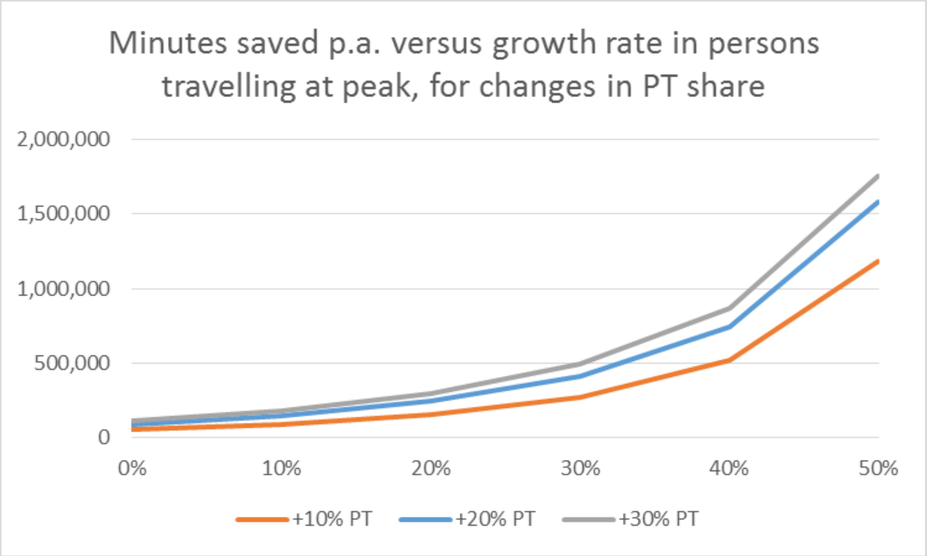
It is possible to improve the precision of the above calculations by building more sophisticated decision trees and by testing more permutations. In general terms, the extra analysis is likely to involve diminishing returns in that extra work produces smaller revisions to initial estimates.

However, there are two improvements to the above model that are likely to materially change the precision of NPV estimates.

First, the decision tree of figure 4.5 only captures some of the adaptability that is available with the NB. There is also the ability to switch back from the use of HOVs in the busway to buses only, plus there is the ability to extend the busway if demand should increase quickly after an initial slow period. Adding these options will increase the original NPV.

Second, an assumption of splitting a continuous range of outcomes into three discrete traffic growth scenarios is the scenarios reasonably represent the wider range of outcomes. This is not necessarily the case when a non-linear relationship exists between the benefits and the uncertain variables that will determine these benefits, as appears to exist with the NB. As illustrated in table 4.1, a brief investigation of the relationship suggests there are at least nine permutations of travel demand growth and PT share that can lead to five different levels of benefits. More precisely, there is a continuous array of states that produce a wide variation of benefits, as depicted in figure 4.10 using a hypothetical relationship between travel speed and people volume and assuming benefits are proportional to travel time saving. It is not known whether this asymmetry was researched in the initial business cases – it would appear not. It was beyond the scope of this research study to delve further into new traffic modelling for the initial project but it is likely the estimation of the expected value requires more than the three scenarios of high, low and medium.

Figure 4.10 Minutes saved in relation to growth in travel demand and change in PT share



4.1.9 Comment on Northern Busway case study

The above case study involved reworking the effect of uncertainty on an historic project. It entailed revisiting (a) the process used to derive the end solution and expected benefits and (b) the valuation of the expected benefits.

It is not known exactly what process led to the initial decision, other than it was over many years and the process did lead to a highly adaptive solution. Rather than make comparisons with the initial process, the following points are reflections about the process undertaken here for the NB.

The following parts of the process in this review led to significant insights into the benefits of the NB project:

1 Considering the interdependence of the busway, including the consideration of the long-term (20–40 years) ramifications of actions taken at project inception.

2 Considering ways the project could be made more adaptable to the unknown contingencies to be faced.

3 Investigating more closely the interaction between uncertainties and benefit outcomes, in this case the uncertainties relating to travel time savings (with other benefits largely correlated to travel time savings).

4 Examining ways the project could provide endogenous learning, in this case learning about bus demand, as well as the more general learning about exogenous factors such as population growth.

As to the valuation, it is clear the original decision makers envisaged value in its various forms but this was not fully captured in the initial benefit estimate. The subsequent 2012 review pointed to ways wider benefits could be incorporated into the excepted benefit estimate. This project points to other ways the estimation could be improved, namely by inclusion of the value offered by the adaptive features of the project design.

Reflections and comments on valuation continue the list from above.

5 The decision tree is a powerful tool to explore the structure of interdependencies and hence its use is recommended but it should be noted that building a decision tree requires substantial assumptions to enable fewer permutations than exist in reality. This requires care and creates the risk of judgement error.

6 The appropriateness of the discount rate used was not explored, other than to test the sensitivity to one discount rate. It is believed the discount rates applied, including in the initial studies, are conservative.

7 The use of the NPV of future projects as the extra payoffs from options was aided in this case by hindsight but does present a challenge to future estimation, as shown by the difficulty deriving an estimate for the benefit of extra lane dedication to PT on the existing AHB.

8 It is also noted that inclusion of an NPV estimated at points such as 10 or 20 years in the future, in turn derived from 40-year forecasts, partially extends the benefit assessment beyond the current 40-year horizon, effectively creating an inconsistency in approach although not necessarily a bias to the estimate of option value.

9 The exercise above did not consider valuation of the growth option written by the Transport Agency and the local authorities for the private sector when transport capacity is increased. To some extent this is captured in the agglomeration benefit measure, as used in the 2012 review of the NB. It is not clear, though, whether the full option value is being captured.

10 The exercise above also did not include the estimate of option value using the binomial option pricing model (see appendix A2, section A2.2 for more on BOPM). The BOPM model is not appropriate in this case given the fundamental nature of the uncertainty that exists. That said, probabilities and distributions are assumed in the DTA and the BOPM valuation would provide a useful validation test, in that a significantly different option value would raise questions as to the appropriateness of the expected benefit estimate otherwise derived.

In sum, the NB team delivered a highly adaptive project, which has subsequently proven its worth. The above methodology shows how the estimate of expected benefits can be improved. In this case, the extra value not measured at the time would probably not have changed the decision but it would have offered more confidence that value would be delivered.

4.2 Less travel time to passage the Kaimai Ranges

The Kaimai Ranges example is a future-looking case study. Changes to both rail and road have been mooted as opportunities to improve economic productivity, both around the Bay of Plenty (BOP) and the Waikato regions and also in Auckland, due to lower than otherwise port-related activity around the Port of Auckland (POAL). The case study shows how one might approach a large transport project that alluringly offers the prospect of large productivity gains outside of the transport sector. In the language of real options, it is an example of the Transport Agency writing an option for others to expand. More generally, it fits with approaches that aim to ‘future proof’.

Again order of magnitude numbers are largely used in the analysis but even these crude estimates, when combined with a real option framework, provide key insights into what would be required to make this project a ‘go’.

4.2.1 Define issue

The Kaimai Ranges separate the BOP, including the major Port of Tauranga (POT), from the Waikato and Auckland regions. When considering any major changes to SH29 over the Kaimai Ranges, there are the usual issues around volume of traffic between major centres, as well as travel safety[63] and resilience.

There is also the rapid growth of freight expected in the next few decades within the combined region, which raises uncertainties about the size of the ports of Auckland and Tauranga and in turn about accompanying private sector developments. These include a proposed major inland port in Hamilton and also alternative potential developments around the Auckland port that are not yet under consideration.

This case study can be considered as an example of the more general case of economic development that might follow an infrastructure investment. With this framework in mind, what are the possibilities for any major Kaimai Range infrastructure investment? This is taken up in the rest of this chapter.

4.2.2 Estimate status quo and BAU scenario

Currently there is AADT of around 10,000 crossing the Kaimai Ranges by road (SH29), of which 15% are heavy vehicles. There is congestion occurring around Tauranga city but none beyond the city.

The current modal split for domestic freight moving through the BOP (not all on SH29) is road (78.3%), rail (19.0%) and coastal shipping (2.7%), with total volumes forecast to increase 35–42% by 2042 (BOP Regional Council 2015, p32).

Within the wider upper North Island, freight volumes are expected to grow by 50–100% over 25 years (Sundakov 2014).

The UNISA (2013) Upper North Island Freight Study (p19) reports the value of freight crossing the Kaimai Ranges by road was $6 billion in 2011 (at 2007$). Also reported is 3.8 million tonnes freighted by rail, with a value of $7 billion.

Table 4.6 Freight volumes (tonnes) through POT, 2010/11 and 2031 (Source BOP regional land transport plan ((RLTP)) (* = includes across Kaimai Range)

Sector	2010/11	To 2031	Inland transport
EXPORTS			
Dairy	588,000	Strong growth if 7000-TEU vessels come to POT	Largely by rail
Kiwifruit	757,000	+250%	All by road, largely from east of Kaimai
Logs	4,400,000	5.5m by 2020	2/1 by rail/road*
Sawn timber	981,000	Strong growth forecast	Mainly by road* and 75% into containers
Pulp and paper	1,337,000		Paper 100% rail, some already in containers
IMPORTS			
Retail and other	3,400,000	50% growth in line with population growth	Mainly by road*

[63] BOP RLTP 2015 reports SH29 from Kaimai Ranges to Tauranga as being ranked 7th amongst road sections with collective risk, where collective risk is a measure of the total number of fatal and serious injury crashes per kilometre over a section of road

Sector	2010/11	To 2031	Inland transport
Oil products	1,200,000	Growth at least in line with GDP growth	Mainly by road*
Grain and stock feed	1,100,000	At the time was growing at 26% pa.	Mainly by road*
Fertiliser bases	530,000	Was also showing strong growth at time of report	Mainly by road*

4.2.3 Identify key drivers of uncertainty

The key uncertainties largely relate to how freight volumes are transported into and out of the upper half of the North Island, and to/from Auckland. At the heart of these issues are constraints near Auckland's port around competing land use, competing road and rail use and harbour depth.

There are uncertainties that also pertain to local population growth and local economic growth but these are assumed to be secondary to the magnitude of the freight issue in this case study. This assumption does require further research.

The uncertainties relating to freight growth via the Kaimai Ranges largely revolve around three unknowns:

- To what extent will freight grow under a BAU scenario?
- To what extent will freight grow should an inland port be created in Hamilton?
- To what extent will future demand for port services be met by POT and POAL?

The economics behind how these uncertainties relate to benefits of a Transport Agency investment are now explored.

The benefit uncertainties pertaining to the BAU freight forecasts are the usual issues of identifying the change in consumer surplus in the transport market, in this case taken to be the road freight market between Tauranga and Auckland (in some cases via Hamilton). Note other freight demand exists and other traffic demand also exists but it is the uncertainty around Auckland–Tauranga freight which is judged to be the major uncertainty in this case study.

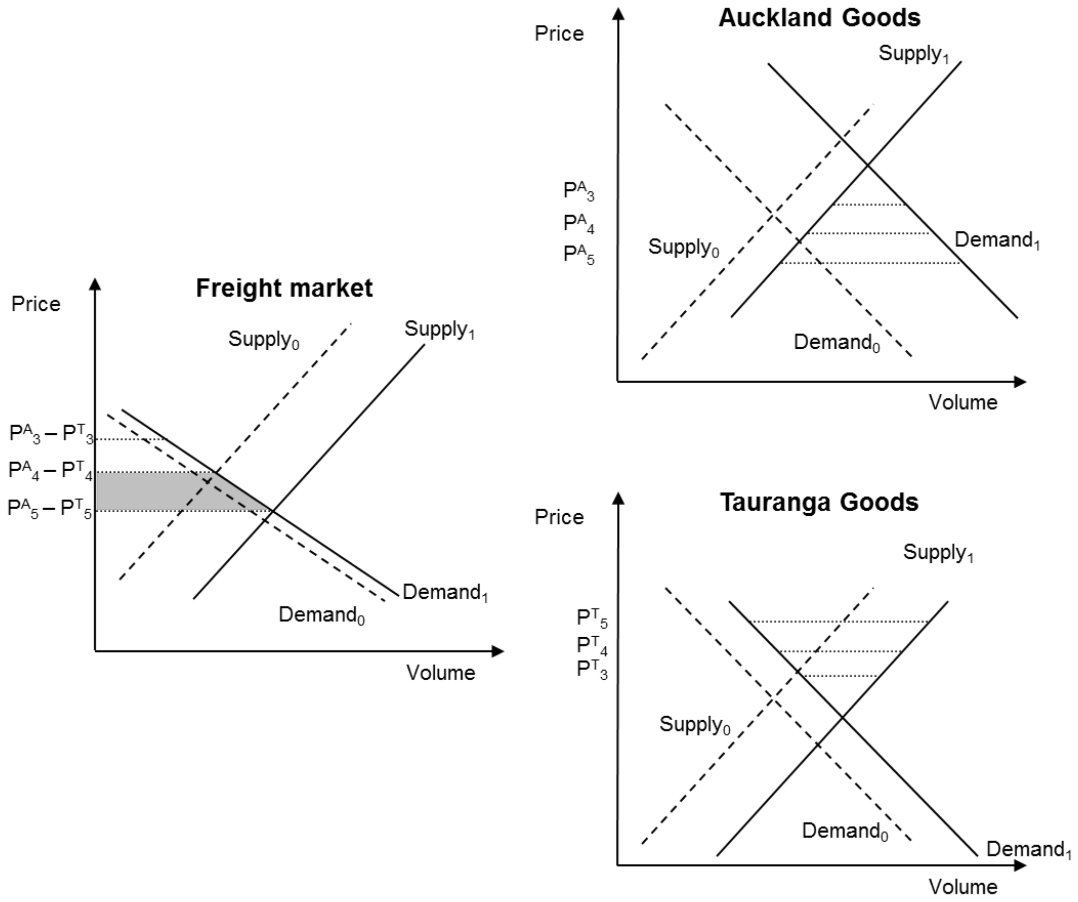
The change in the transport market consumer surplus is illustrated by the shaded area in figure 4.11. That is, demand and supply for goods in general will increase in Auckland and Tauranga between time 0 and time 1 with the assumptions at this stage that:

- both Auckland and Tauranga ports expand
- a combination of faster demand growth in Auckland and faster supply growth in Tauranga (via Port of Tauranga) is expected to create higher demand for freight travel over time
- and any supply-side improvement in the freight market, such as improvements on the Kaimai Ranges (shown as $Supply_0$ to $Supply_1$), will lead to the standard travel cost savings[64].

Seen from this perspective, a key uncertainty derives from the future excess/deficit goods supply in Tauranga and Auckland, including in particular goods passing through the two international seaports.

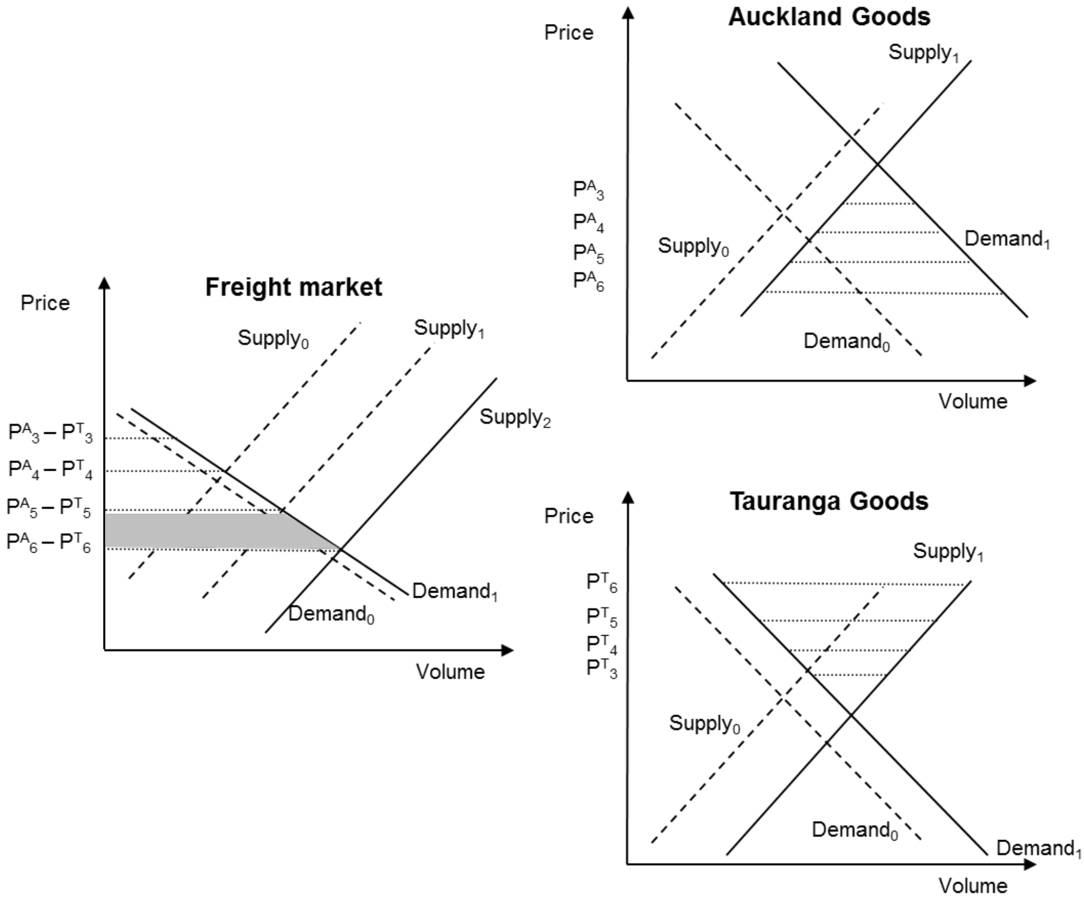
[64] 'Price' in the figures represents 'generalised cost of freight transport'.

Figure 4.11 Benefits under BAU scenario



An inter-related uncertainty pertains to the cost of shifting freight between Tauranga and Auckland. Adding an inland port in Hamilton has the potential to reduce this transport cost. An illustration of the effect of a new inland port is shown in figure 4.12, with the freight transport supply curve moving from $Supply_1$ to $Supply_2$. As above, for each existing trip and for each induced trip between Tauranga and Hamilton/Auckland there will be a travel cost saving, as shown by the shaded area in the Auckland-Tauranga freight market.

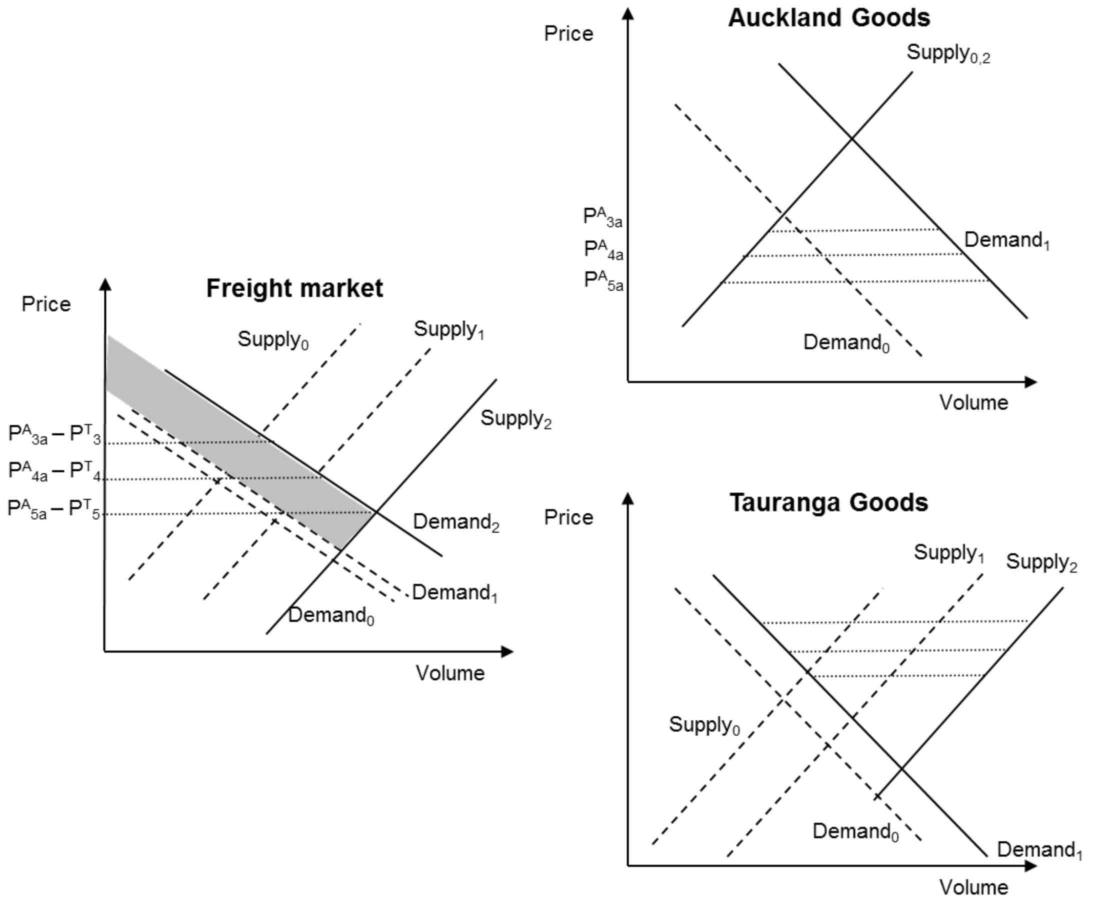
Figure 4.12 Benefits gained by adding a major inland port



Returning to the uncertainty about the Tauranga–Auckland excess-surplus goods balance, the excess in Tauranga can be expected to increase faster than otherwise expected if (a) POT can reduce freight handling and shipping costs relative to POAL and (b) the market enables these cost advantages to be reflected in relative pricing. If POT can be expanded at a lower cost than POAL which, together with economies of scale that will come with POT handling bigger ships, leads to a growing cost advantage to POT then there will be a larger rightward shift in the Tauranga supply in the future and a smaller rightward shift in Auckland, both relative to the market envisaged in figure 4.12. A situation where all port future expansion would occur at POT is illustrated in figure 4.13, showing as freight demand between Tauranga and Auckland moving from Demand_1 to Demand_2, Auckland goods supply reverting to the original Supply_0 and Tauranga goods supply rising further to Supply_2, and extra benefits arising that are equivalent to the shaded area in the Auckland-Tauranga freight market[65].

[65] This illustrates the scenario presented by PwC (2012, section 6.2)

Figure 4.13 Benefits gained by future expansion at POT and not POAL



The above analysis points to where benefits might emerge due to changes in the Tauranga-Auckland freight system. But what these changes might be is unknown. It is likely, though, the major benefits will arise from the addition of a Hamilton inland port and the expansion plans of the ports of Auckland and Tauranga.

Which raises the issue of attributing any change in benefits to any transport improvement. These benefit streams depend on investments by the transport sector and by other parties. Further discussion of this issue follows when each uncertainty is discussed below.

4.2.4 Create short list of alternatives

The next step in the methodology proposed is to consider alternative investment opportunities to the problems and/or opportunities raised. The general choices are:

1. Undertake major road improvements to SH29 now in anticipation of future needs and with the aim of not constraining the wider potential improvements that are possible
2. Do likewise with the rail infrastructure
3. Undertake minor road and rail improvements
4. Delay major works for now but meanwhile actively work with the major investors in the three ports (Auckland seaport, Tauranga seaport and Hamilton inland port) to determine their transport needs and the timing of these needs.

In this case, the solution of type (1) entertained is the construction of a road tunnel through the Kaimai Ranges. This is not necessarily the only or preferred alternative at present but is used instead to illustrate core parts of the decision assessment relating to a large project that has network implications.

This is explored below against an undefined project of type (4), again to largely illustrate features of real options. This project is referred to as the Learn project.

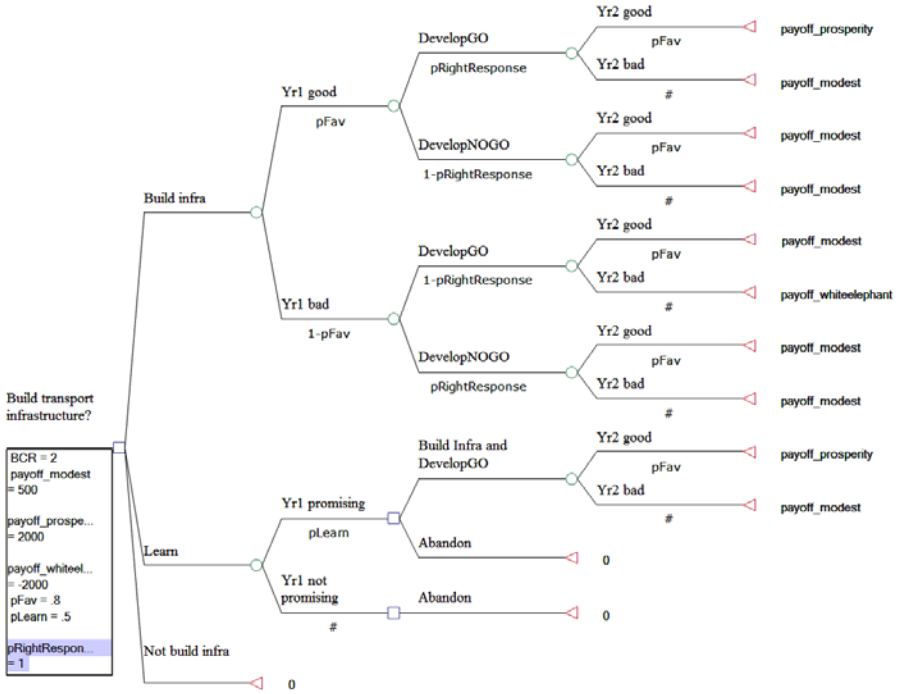
In a more formal analysis, other alternatives would deserve closer attention.

A tunnel is likely to cost in the order of $3 billion. It is assumed that the undefined Learn alternative would cost $100m (ie significantly less).

4.2.5 Draw decision tree for alternatives

The prosperity decision tree introduced in section 3.2 forms the basis for the decision tree framework. Added to this tree is another branch to show the active learning alternative. Thus the choices depicted in figure 4.14 show the initial decision as to (a) undertake a major project (b) undertake a smaller project in the interim that would remove the uncertainty about both the initial demand growth and the actions of the other major investors or (c) do nothing.

Figure 4.14 Decision tree for Kaimai Ranges case study



For simplicity, the Learn branch has been drawn as leading to a discrete expand or abandon decision after period 1 (depicted as Yr1 but possibly a period of several years), when in reality there are likely to be variations of scale up and scale down.

4.2.6 Probe uncertainties

No detailed probing of the uncertainties was undertaken within this case study. Estimates of payoffs are provided below and sensitivity of thresholds are then discussed.

A more extensive analysis would include a large number of alternatives that would likely require more in depth analysis of the key uncertainties.

4.2.7 Estimate indicative payoffs

The payoffs are initially discussed in terms of benefits per annum. The payoffs in the decision tree are calculated as the PV of the benefits in each scenario, net of any subsequent non-Transport Agency capital costs, with the Transport Agency-prescribed real discount rate of 6% pa applied where required.

4.2.7.1 payoff_modest

The benefit under the modest benefit scenario arises from the increased consumer surplus in the standard transport market analysis, as described in section 4.2.3. These savings will depend on the nature of the improvement but an order of magnitude is provided by calculations undertaken for an earlier research project (Byett et al 2017). The AADT across the Kaimai section of SH29 was around 10,000 in 2014, of which 15% were heavy vehicles.

- A tunnel between the western side of the Kaimai ranges and Old Kaimai Road would reduce a 12km trip by 2.5km and reduce the gradient and corners. This is estimated to provide an approximate $20m travel cost saving per annum at present, including a $7m pa freight travel cost saving.
- Other benefits not calculated would include those pertaining to safety improvements, pollution reduction and increased agglomeration.
- In total, the benefits under this scenario would be of order of magnitude $30m pa.

4.2.7.2 payoff_prosperity

There are potentially several steps that could lead to increased benefits above those accounted for above. Two in particular are significant and discussed here, being changes around inland handling of freight and changes around port capacity.

Castalia (2013) provides some detail about the probable effects of a Hamilton inland port.

The addition of an inland port could reduce freight costs for existing Tauranga to Hamilton/Auckland users. This amount is unknown to this study. A figure of $25m pa has been assumed here. This figure does require more research but it is noted here that any decision is relatively insensitive to this number. This is equivalent to the shaded area in figure 4.12.

More significantly, a Hamilton port will also enable trucks that would otherwise travel between the POAL and South Auckland to be fewer than otherwise. Castelia estimate the annual reduction in the resulting congestion on Auckland roads to be around $75m pa.[66]

The combined benefits are approximately $100m pa, with most of the benefit in Auckland.

To realise these benefits requires a substantial capital investment to create the Hamilton inland port. Improvements on the Kaimai Ranges can potentially influence this investment in two ways: it could potentially shift the economics of the inland port above an investment threshold during a window of time that the investment opportunity exists; and/or it could bring forward the time the threshold was reached if the option to invest remained open. Further research would be required to understand whether there was a limited window of opportunity but for this case study the assumption has been made that Kaimai improvements could potentially bring forward the time of the Hamilton inland port investment.

[66] Note, this benefit is not shown in figure 4.12 as it shows in other Auckland freight markets.

Each year the Hamilton inland port can be brought forward as a result of changes to the Hamilton-Tauranga route would create a benefit of magnitude around $100m pa.

The second major change of significance is the relative expansion of POAL and POT. This third step further increases the benefits from the Kaimai Range improvement and the addition of the Hamilton inland port. Again the initial Kaimai improvement cannot be claimed to fully create this benefit but it is worthy of investigation to understand to what extent any inland transport improvements could influence the decisions about port expansion. In this case, the decisions to invest rest with two private sector companies, POAL owned by an Auckland Council holding company and POT owned 54/46 by a BOP Regional Council controlled entity[67] and the public. Should these decisions be taken largely independent of any inland transport plans then the extra benefit shown in figure 4.13 cannot be attributed to any Transport Agency project. However, if the inland transport improvements are influential then, as with the Hamilton inland port, some attribution of the POT-biased expansion scenario could be made to the Transport Agency project and, again as above, the attribution is more likely to be a change in the timing of the benefit realisation. In contrast to the Hamilton inland port situation, though, there is no large marginal cost to be incurred by any third party. The issue instead is where the port expansion capital cost is incurred – Auckland or Tauranga – and by whom?

Further to the above and also part of the network issues that can accompany large scale projects, consideration is also required of any interdependence between rail and road transport investments within the Hamilton to Tauranga corridor. The initial transport improvement above has been couched in terms of an improvement in the road corridor. There also exists a rail corridor that services imports from and exports to POT, initially to Hamilton but also to Auckland, including the POT inland port in South Auckland (Metroport).

This rail service currently has a significant price advantage for freight in large volumes that is travelling to/from POT. In turn, though, the ability of the rail service to price in this manner will depend on maintaining high volumes. An improvement in the road corridor has the potential to shift freight – either existing or at the margin for future freight – from rail to road and potentially undermine the rail service. The economic potential of the Hamilton inland port is closely tied to the current rail service, albeit upgraded over time. For sake of completeness, the inland port is also heavily dependent on the imminent road service between Hamilton and Auckland (when the Waikato Expressway is completed) plus continued access to the Auckland motorway and main trunk line, even at peak times but generally travelling in the counter-peak-direction.

The issue of road-rail interdependency is raised here as a potential consideration but it is also acknowledged it will only sometimes be a relative factor. In those cases, the shaded areas in figure 4.11 would need to be netted off against any benefit loss due to reduced rail demand. This case study proceeds on the assumption the road changes under consideration would not significantly pull existing rail freight to road.

In sum then, the payoff_prosperity could be very large, relative to the payoff_modest. It would include the $30m pa base case benefits, which would increase gradually as traffic volumes increase, plus $100m pa

[67] Auckland Council ownership is via Auckland Council Investments Limited (www.aucklandcouncil.govt.nz/EN/AboutCouncil/representativesbodies/CCO/Pages/council_investments.aspx) and BOP regional council ownership is via Quayside Unit Trust (www.quaysideholdings.co.nz/group/quayside-securities-ltd.aspx)

for each year the Hamilton inland port is brought forward, plus an unknown sum per annum if the project were able to facilitate faster expansion at POT.

There is a fourth potential benefit under the prosperity scenario that could increase the payoff, namely any extra benefit that would arise should the shift towards trade through POT be sufficient to allow POAL to release land for higher productivity use. This is not considered likely given the forecast freight volumes in the upper North Island.

Partially (maybe fully sometimes) offsetting any benefits will be the costs of the subsequent investments.

4.2.7.3 payoff_whiteelephant

The white elephant payoff will reduce to approximately the costs for the two subsequent projects – Hamilton inland port, POT expansion – as any offsetting benefit that might arise due to existing travel trends being preserved would likely be relatively minor. The initial cost of the Transport Agency investment would also add to the true cost of any white elephant situation but has been treated as an initial cost in this analysis against which the other benefits and costs are compared, and so it has not been added to the payoff here.

These included costs are not incurred by the Transport Agency but rather represent the potential loss to society.

The Hamilton inland port costs are likely to be of the order of $1.3 billion (Sundakov (2014) evidence to the Environment Protection Authority, p13).

Should POT expand on the belief it will service more of Auckland's freight needs and POAL does likewise then the over-capitalised costs incurred by POT would also form costs to include within the white elephant payoff. As an indication of order of magnitude cost, the recent five-year POT expansion programme cost $350 million.

Bringing this payoff discussion together with the decision tree in figure 4.14, the numbers provided in table 4.7 are a starting point for considering a Kaimai Range road tunnel. The fourth column provides possible approaches that may address either the size or uncertainty pertaining to each variable.

Table 4.7 Numbers to populate Kaimai decision tree

	Potentially	Relevant numbers for this case study	Approach to consider
Initial Transport Agency cost (excluded from payoffs)	Initial infrastructure costs	~$3b	Explore other possibilities that deliver similar magnitude of benefits for lower cost AND retains POT and inland port growth expansions
payoff_whiteelephant	Subsequent developer costs, including POT and inland ports, plus any (likely low) benefits	Say -$2 billion	Phasing with abandon option Explore projects with substitute uses
payoff_modest	Above payoff_whitelelephant plus marginal benefits arising from: Existing use of new infrastructure Complementary new use of new infrastructure	Say $0.5b Being: EEM benefits ~$0.5b (= $30m pa growing by 2% p.a. over 30 years discounted at 6% pa, ie in real terms and including volume growth) Assume POT and Hamilton inland port recoup costs but	Understand travel cost savings for current travel and potential new non-port travel

	Potentially	Relevant numbers for this case study	Approach to consider
		do not produce extra productivity gains.	
payoff_prosperity	Above payoff_modest plus marginal benefits arising from: • more use of POT and inland port(s) • more freight via Kaimai. • less freight via roads near POAL • economies of scale advantages of Hamilton inland port • lower costs of POT expansion relative to POAL expansion • higher productivity use of existing POAL property.	Say $2b. Being: Above payoff_modest Hamilton port benefits ~ $0.5b (= $100m pa growing by 2% pa over 5 years discounted at 6% pa.) Assume Hamilton inland port recoup costs but do not produce extra productivity gains beyond travel cost savings. Faster POT expansion benefit and costs is unknown. Assume worth $1b as starting point to discussion in above total payoff.	Understand this potential better
pFav	Probability of higher freight volumes is high But benefit of Kaimai improvement also depends on other factors that will shape the decisions of developers (including POT and POAL), including Transport technology Shipping patterns	Say= 0.8 Unknown but likely to be high given expected population and GDP growth in upper North Island and constraints that exist around Auckland.	Coordinate joint understanding of influential factors
pRightResponse	Even if conditions are such that value could be gained from development, such development is not assured due to: • political choices • funding constraints (including level of interest rates) • coordination failure	Say= 0.5 Very uncertain given political involvement and regional loyalities. But an uncertainty that can be resolved.	Coordinate communication of and openness to the strategic pathway proposed.
pLearn	Requires research.	Say 0.5	Research coordination success at other ports.

The core scenario presented above would deliver a Transport Agency project with expected benefits of $0.9 billion, including the real option value written to the private sector. Against the initial $3 billion cost, this represents a BCR of 0.3. While this is the weighted average expected benefit, the high payoff scenario of $2b would only be expected to occur 32% of the time while less appealing payoffs of $0.5b and -$2.0b would be expected 66% and 2% of the time.

Note that the Learn alternative would not be chosen with its expected benefits of $0.8 billion if the sole decision criteria were ‘highest expected BCR’, although this conclusion is sensitive to assumptions about the benefit of deferred costs. This sensitivity is not pursued here as discussions below will show why this alternative would probably be preferred for other reasons (and hence the sensitivity debate is immaterial to the final decision).

Other expected values and BCRs are also tabled for different input assumptions.

Table 4.8 Table of outcomes (billions in NPV terms) and expected incidence of scenarios

Assumption about inputs	Expected value and BCR	payoff _whiteelephant	payoff _modest	payoff _prosperity	pFav	pRight Response
As per table 4.7	+$0.9 BCR=0.3	-$2.0 (2% occurrence)	+$0.5 (66%)	+$2.0 (32%)	0.8	0.5
As above but with lower payoff_prosperity	+$0.6 BCR=0.2	-$2.0 (2%)	+$0.5 (66%)	+$1.0 (32%)	0.8	0.5
As per table 4.7 but with Transport Agency cost of $1b instead (say improvements rather than tunnel)	+$0.9 BCR=0.9	-$2.0 (2%)	+$0.5 (66%)	+$2.0 (32%)	0.8	0.5
As above but improved coordination of decisions	+$1.2 BCR=1.2	-$2.0 (1%)	+$0.5 (48%)	$2.0 (51%)	0.8	0.8
As above but with complete certainty about decisions	+$1.5 BCR=1.5	-$2.0 (0%)	+$0.5 (36%)	$2.0 (64%)	0.8	1.0
As above but with complete certainty about demand	+$2.0 BCR=2.0	-$2.0 (0%)	+$0.5 (0%)	$2.0 (100%)	1.0	1.0

4.2.8 Establish thresholds

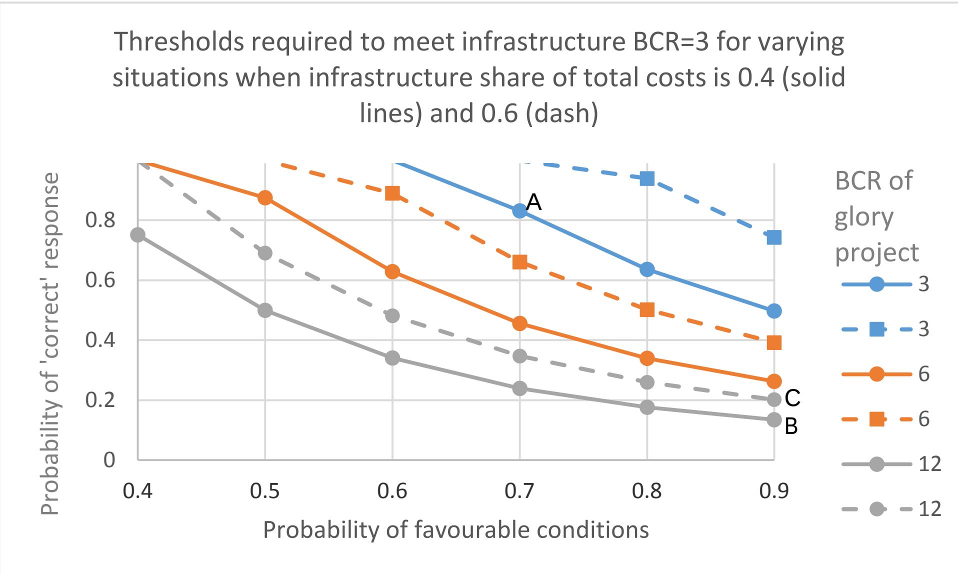
The overall project BCR, including the real option value granted by the Transport Agency, depends significantly on the benefits possible under the prosperity scenario and the probability of this outcome.

Also significant, though, the chance of achieving only a modest benefit, and in this case a benefit less than the initial capital cost, increases sharply as doubts increase about the achievement of favourable conditions for such a prosperity scenario. A reminder at this stage is appropriate: pFav is unknown and is possibly not even knowable, even under the Learn project introduced here. However, framing the decision in probability terms does illustrate the potential effect of the uncertainty. Combined with a likely intolerance for large projects delivering modest (in this case negative) returns on a regular basis, the analysis points to the need to focus on improving the BCR of the modest scenario and/or establish more certainty about the prosperity scenario.

It is possible the likelihood of regular low-returning infrastructure projects would be acceptable should the prosperity payoff be exceptionally large, relative to the original infrastructure cost. Whether this is the situation in this case requires more research. However, even if the prosperity payoff was expected to be huge, it is likely focus will still be required on improving the modest payoff BCR and/or learning more about the chances of the prosperity scenario.

As an insight to the more general issue, the certainty required around favourable conditions being achieved following an infrastructure project increases with the relative size of the initial infrastructure project. This is illustrated in figure 4.15. Putting aside any tolerance for modest scenarios and focusing only on the expected value, including real option value, an expected value sufficient to provide an initial BCR of 3 requires higher probabilities of success when the initial capex is 60% of all capex costs (see dashed orange line below when prosperity projects expected to deliver six times the investment of other parties) rather than 40% (solid orange line for same magnitude of prosperity project)[68]. In other words, as is generally obvious, the Transport Agency is carrying more of the risk with relatively high cost infrastructure investments, even if they offer the prospects of high benefits.

Figure 4.15 Sensitivity of sequential decision making to probabilities, relative costs and benefits



4.2.9 Comment on Kaimai Ranges case study

This case study provided the opportunity to explore the general issue of the Transport Agency writing a real option to other developers. As it turns out, the BCR for a major project such as a tunnel is low. Also low in its current form is the alternative to learn – this is largely due to the extreme limitations imposed on this option. The key point, though, of the analysis was irrespective of a high or low BCR for the major development, alternative projects with positive net benefits over a wider range of outcomes will also appeal to the decision maker.

[68] The BCR threshold for subsequent investments by other parties was also assumed to be 3.

Two general insights emerge from approaching the issue from a decision tree/real option framework:

- Even if it is accepted there is a realistic opportunity for a very large payoff, it is still appropriate to focus on what payoff to expect under a more modest payoff scenario, given the envisaged opportunity will not always eventuate and there is likely to be low tolerance of regular low-returning projects;
- Likewise reducing the risk and/or the consequence of a white elephant scenario will also always be important.

Viewed from this perspective, the investment decision is about accepting the prosperity payoff may be large but also cannot be relied upon so the key requirement is to find ways to add value while keeping the prosperity option open. This may be by way of smaller projects that will be of benefit should the prosperity scenario emerge but are also of substantial benefit now or by undertaking projects – including potentially non-engineering projects – that reduce uncertainty about the decision to expand to a full development. This conclusion is consistent with the current practice of the Transport Agency appraising projects on the basis of BCRs without real option values and then including the BCR with the real option value as a sensitivity.

Returning to this specific case study, the above analysis also accords with the PWC (2012) conclusion that 'In our view, a key role public sector planning role going forward is to ensure flexibility and options are maintained'.

In this case, the very tentative conclusion of this study is that major work of SH29 does not appear warranted but instead better value would be obtained by undertaking higher BCR projects that fit with the strategic objective of facilitating a significantly larger freight flow between Tauranga and Hamilton/ Auckland, by rail and/or road. Such projects are likely to be around:

- improvements on SH29 of a lesser scale
- improvements to the East Coast Main Trunk rail line
- road/rail improvements around the ports of Tauranga and Auckland, which benefit both local people and will enhance freight flows to/from the ports.

4.3 Light rail in Auckland

The Auckland light rail case study is a forward-looking study. A light rail transit (LRT) network has been proposed and many of the alternatives to this costly project are being talked about in terms of 'buying time'. This provides a good opportunity to explore more about learning and delay options.

A light rail network has been investigated by Auckland Transport. The key driving force is a need to shift larger numbers of people in a concentrated area. The proposal follows the construction of light rail networks in Australia at present or in recent years, including in Gold Coast, Sydney and Canberra.

The LRT proposal is one suited to ROA: it entails a large, irreversible capital investment; it potentially creates significant private sector development opportunities; there are uncertainties as to the take-up of the service and of the surrounding development; and there is potential to delay and/or sequence any investments. The project shares some of the real option types that have been explored in the previous two case studies of this report:

1. Option for private sector to expand – as in the Kaimai Ranges example, there is an uncertain but potentially large private sector development benefit from the light rail investment, both in terms of property development along the route and in terms of agglomeration gains in the CBD

2 Option to switch – as in the NB example, there will be value in ensuring the infrastructure can be switched to an alternative use should demand prove insufficient

3 Option to learn – likewise by staging the investment there is the opportunity to learn about demand and about private sector development, either passively or actively

4 Option to expand – and, again similar to the NB, there is the opportunity to expand the light rail network if demand proves to be high enough.

Section 4.3 considers how these options might be explored when developing solutions and when valuing such solutions for the Auckland LRT proposal. While some detail about the issues and alternatives are presented below, the emphasis is on the adaptive management approach to appraisal rather than the LRT project per se.

4.3.1 Define issue

The key driving force for this project is the congestion of buses expected along the key arterials of Dominion Road and Symonds Street, from the south, into the Auckland CBD given the growth in patronage being experienced and the inability of the Auckland heavy rail network to service this area. The congestion occurs both along the routes and at the ends of the routes in the CBD around Britomart and Wellesley Street (Auckland Council 2015, p71). More generally the wider issue is that on current projections around 500 buses per hour will be entering the CBD in the morning peak by 2046 while road and terminal capacity is currently only for 400[69].

More bus congestion will lead to both slower and less reliable travel times for all travellers and to reduced amenity value in the CBD and along the key arterial routes.

Currently Auckland Transport is investigating a proposal to create a light rail system in this area, from just south of the CBD through to the northern end of the CBD, to increase public transport capacity along these key routes. This area sits between suburbs further to the west and south that can be serviced by the existing heavy rail network. The replacement of buses with light rail in this area also frees up some CBD capacity that will enable more buses from the north shore (where rail does not exist and would be expensive to add). However, a light rail system is also expensive to create.

4.3.2 Estimate status quo and BAU scenario

The three Auckland local board areas that include the routes of the proposed LRT network had a population of 237,000 at the 2013 Census (Statistics NZ). However, as alluded to above, the potential number of people who might benefit from less congestion around the corridor, including in the CBD, is much higher. The Waitemata area, which includes the CBD, had a population of 77,000 and had increased at an average rate of 2.9% between the 2006 and 2013 Censuses. Statistics NZ projects an average Auckland 30-year population growth rate ranging from 1.0% (low) to 1.6% (high). The Auckland plan (Auckland Council 2016) includes scope for significant growth within the three local board areas.

The CBD is an employment hub for 84,000 people and 68,000 students, with average growth rates expected to be around 2.1% pa and 0.7% pa respectively by 2046 (Auckland Transport 2016).

Currently there is an average of 130 buses per hour (4,619 passengers) driving along Symonds Street in the AM peak to the CBD – the busiest corridor and the corridor that takes a significant number of buses from the Dominion Road area. Various measures of capacity exist but Auckland Transport reports current

69 https://at.govt.nz/projects-roadworks/light-rail/

usage is 23 buses per hour *above* capacity and forecast a do-minimum scenario of 0.7% pa bus demand growth on this corridor, taking the level of over-use to 48 buses per hour by 2046, even after allowance for some improvements to the bus network (including double decker buses).

The 'wall of buses' and associated noise and fumes are reported to already be of low amenity value, although this is not measured quantitatively, as pointed out by Aurecon (2016, p2).

Specific assumptions within the Auckland Transport (2016) scenario include:

- Auckland growth in general is along the lines of Auckland Transport Alignment Project (ATAP) scenario I9 (which predates the 2016 Auckland plan).
- The Auckland CBD grows along the lines of the city centre masterplan and the waterfront plan.
- Various transport projects are completed, including the city rail link project.
- The bus network operates according to the bus reference case.
- The transport network operates as per predictions from the ART/APT models.

The plan specifically omits an additional harbour crossing and rail to the airport.

4.3.3 Identify key drivers of uncertainty

The key uncertainties are listed in table 4.9. There are the usual uncertainties relating to travel demand growth, plus unknowns to do with the effect of technology on travel demand and the uptake of private sector development in the vicinity of the light rail network.

Some insights into these uncertainties and the interplay with decisions can be provided by the numerous light rail networks created in recent years, including in the US and Australia. However, it needs to be taken into account that US appraisals put emphasis on commercial property development near light rail (eg Dallas) which risks treating a simple business relocation as a net benefit gain to society.

Table 4.9 Key uncertainties pertaining to Auckland light rail proposal

Population growth in origin areas	This uncertainty was illustrated in figures 4.6 and 4.7 for the NB example. Both the two local board areas south of the CBD have experienced relatively low population growth between 2006 and 2013. A key uncertainty is whether this growth rate would accelerate given the presence of light rail access to the CBD and the commercial centres in between.
Work and education numbers in CBD	Besides the general uncertainty about economic growth within the CBD from year to year, especially in light of rising CBD costs, there is the added uncertainty raised by potential technology changes that might change work – and education – location. Conversely, increased provision of public transport and potential improvements in CBD amenity may accelerate the growth of daytime CBD occupancy.
Number of people wanting to travel per day from Dominion Road to the CBD, particularly during the AM peak	The above uncertainties will combine to determine the potential demand for movement to/from the CBD. However technological and other factors such as congestion, other network effects and pricing for travel and parking also have the potential to shift inbound demand away from the AM peak.
Number of people choosing each transport mode	The above factors interact to form the number of people travelling. A major uncertainty is around their uptake of the LRT. Even without major other changes it is not certain how many people will switch from their current mode to light rail – this was the uncertainty explored by staging in the NB example. Even more uncertain at present is the effect of technological changes on all modes of transportation, as mentioned by Aurecon (2016). This later uncertainty has been excluded from the Auckland Transport (2016) programme business case ('outside the

	scope') and instead is to be monitored.
Induced demand on Dominion Road-CBD bus/car routes	Interdependent with all the above issues, there is also likely to be some induced demand movement to/from the CBD by vehicles in general. This creates uncertainty about the travel time cost savings that will be achieved for existing travellers. This also was revealed to some extent in the learning option provided by the staged NB. Bentley et al (2016) warn the PT uptake is likely to be stronger with LRT than bus rapid transit (BRT). Auckland Transport (2016, p70) mentions also the impacts on general traffic on isthmus arterials is not well understood.
Travel demand beyond the 40-year period of analysis	While events beyond 40 years are excluded from the analysis, both due to EEM requirements and a stated uncertainty about events many years ahead, the costly and irreversible nature of the infrastructure investments means that their ultimate benefit will in part depend on events beyond 40 years. In particular in this case, the LRT and associated solutions are expected to 'fix' bus capacity issues for only two decades. Very likely the Auckland CBD will need further infrastructure investment beyond the next 20 years. It is possible that some current solutions create more robust platforms to the next phase investments, eg if ultimately an underground Auckland CBD bus station is likely then moving in this direction now may be of some value (although LRT may still be the best value for money now). This uncertainty was addressed in the Northern Busway by the design taking in account the possibility of another harbour crossing and/or rail on the north shore.
Productivity gain in area	A key benefit claimed for the LRT network is the agglomeration benefits that come from working in close proximity to others, including the ability to walk/rail along and around Queen Street. While there has been much research into what productivity gains to expect from agglomeration, the ex post evidence of these gains is less clear cut, raising uncertainty about whether such productivity gains will indeed eventuate. Again a learning option would be of value (albeit offset to some degree by any options to expand that may be extinguished by delay and/or any interim extra congestion).
Private sector development in area	Not quantified in the indicative BCR but nonetheless claimed to be a key benefit of light rail is a likelihood of increased private sector development in the vicinity of the light rail stations. Citylab[70] reports light rail has proven most successful when public and private sectors work together to develop near stations. The commitment of both private sector and public sector parties is uncertain at present. This is important as current BCR estimates are at best only just above 1, so wider benefits could be an important justification of the project (as too could improved estimates of congestion costs, as stated in Auckland Transport (2016)).

4.3.4 Create shortlist of alternatives

The programme business case (Auckland Transport 2016) considered an extensive list of solutions within workshops and reduced the alternatives down to six:

1 Do regardless – a combination of refinements including double-decker buses on all routes entering the CBD, charging higher peak bus fares and providing more active mode infrastructure (cost estimate $340m)

2 BRT – a combination of double-articulated buses and all-day bus lanes on the Dominion Road and nearby routes, expanded bus terminals in the CBD and, in time, an underground bus multi-station

[70] www.citylab.com/commute/2014/04/have-us-light-rail-systems-been-worth-investment/8838/

facility beneath Wellesley Street in the CBD but it would appear no buses along Queen Street (~$9,500m)

3 LRT network – initial Queen Street-Dominion Road light rail in the middle of existing roads, with another southern arm down Sandringham Road and an extension at the northern end to Wynyard Quarter, and in time further arms added for Symonds Street-Mt Eden Road and Symonds Street-Manukau Road, includes pedestrian and LRT access only on Queen Street north of the Town Hall (~$3,700m)

4 Extend heavy rail line from west to end of Dominion Road – includes new rail spur (some of which may be required for CRL), fewer buses around this vicinity to the CBD and more from east of Dominion Road (~540m)

5 Demand management – including reduced car parks within CBD, more active mode infrastructure, buses only in peak direction along Symonds Street and Wellesley Street and expanded CBD bus terminals (~$540m)

6 Extended bus network – allow Queen Street to take buses from Dominion and Sandringham Roads, remove parking on these two roads, provide a new terminal facility at north end of Queen Street (~$900m).

Only (2) and (3) are considered solutions that extend beyond several years (assuming no radical effect of technology). The trade-off between BRT (ie 2) and LRT (3) are seen as flexibility with buses (up to tunnel station phase) versus lower cost, higher capacity and relatively better amenity with light rail.

The matter of capacity appears to be a contentious issue. Auckland Council (2015, p71) reports a light rail system would allow maximum capacity of 18,000 people per hour, compared with 6,000 people per hour under a priority busway system. Bentley et al (2016) quote other figures which show the capacity limits can overlap between BRT and LRT, depending on configurations, but also concludes that LRT systems 'offer higher capacity once land use impacts are realised and demand paths consolidated to the transit corridor' (implying that LRT has greater ability to draw in more patrons).

Amongst the alternatives discarded, Aurecon (2016, p7) reports any change in land use was ruled out, as Auckland Council already had an established policy framework. Also not considered were any car-based solutions as these were likely to be expensive, harmful to the city character, environmentally damaging and contrary to Auckland Council policy.

4.3.5 Draw decision tree for each alternative

The following paragraphs discuss the four option types (A–D above).

4.3.5.1 A. Option for private sector to expand

Figure 3.1 (chapter 3) provides the decision tree for the private sector development. In the case of light rail, the initial infrastructure build is the provision of the lines, stations and trains. There will then be some demand response, which if favourable will trigger nearby private sector development that potentially is of large benefit. While the uncertainty is such that a probability distribution cannot be attributed to outcomes, if it is possible to judge the chances of favourable demand as high and the chances of adjoining private sector development as high then the expected value of the initial project will tend towards the high 'prosperity' payoff.

The prosperity payoff has not been estimated within the programme business case, largely because it is very difficult to isolate ex post let alone forecast ex ante. In this case, one form this prosperity scenario might take is strong commercial and/or residential development near the light rail network but outside of the CBD. The former would effectively spread the CBD across a wider area and it would be a moot point whether this provided a productivity gain to New Zealand, given it effectively amounts to a de-agglomeration although it may also enable a more efficient spatial distribution of businesses (eg education institutes developed around Dominion Road area, and freeing up capacity in CBD for higher value commerce and tourism, although this begs the question why a transport intervention was required to facilitate this redistribution). The latter – more intense residential development around Dominion Road – would enable a stronger concentration of work in the CBD and hence provide higher agglomeration benefits, plus potentially reduce congestion elsewhere in Auckland (relative to the counterfactual of the same population being more widely dispersed).

While further consideration of the prosperity scenario is required, equally important considerations are the non-prosperity scenarios. As discussed previously, unless the two responses to the initial infrastructure investment are near certain (ie pFav and pRightResponse near 1), there will be a significant number of occasions when only a modest outcome will eventuate. There is also the possibility of a large loss to society – the white elephant scenario. The challenge to the initial infrastructure investor is to find ways to enhance the BCR of the modest alternative projects and reduce the likelihood of a white elephant outcome – in other words, protect the downside.

Before picking up on these points, it is worth repeating the conclusion of the Kaimai Range example, namely that the appropriate reporting of BCRs, assuming the white elephant risk was addressed and society is intolerant of repeated low return outcomes from large infrastructure projects, is to show the BCR for the modest payoff scenarios and to add on an estimate of the real option value of the prosperity scenario to this BCR to show the sensitivity of the BCR to this uncertainty.

4.3.5.2 B. Option to switch

The potential white elephant scenarios here would occur should the uptake of LRT be low or, given a BRT selection, should the use of the CBD bus tunnel be low. The decision tree structure for this switch would be similar to that shown in figure 4.5 for the Auckland Busway, where the option existed to switch in the form of allowance for HOVs within the dedicated lane should bus demand prove weak.

It is not obvious what switch opportunities exist for a LRT system.

However, there appear two switching options in the BRT system: initially there is the ability to simply switch any extra buses that are purchased to other routes and allow other vehicles to return to otherwise dedicated bus lanes; and should the CBD bus tunnel be built then there would appear to be an opportunity to switch its use to buses from northern and eastern routes, should demand for the Dominion Road bus system prove weak. This latter option is discussed further under 'Option to expand'.

4.3.5.3 C. Option to learn

The option to learn is one of several real options that can be used to reduce either the risk of a low-return outcome or adapt the system in ways that reduces the sensitivity of any outcome to specific risk(s). The general form of this option is shown in figure 3.2.

The key choice in this case study is whether to go down the LRT or BRT pathway. Putting aside the prosperity uncertainty discussed above, the other key uncertainties are whether (a) technology will significantly reduce the demand for peak commuter travel between the Dominion Road area and the CBD and (b) what standard of amenity will be tolerated by the community for Queen Street and other CBD areas[71].

The second uncertainty lends itself to a learning option, ie action is taken to actively remove this uncertainty. In this case, a clear understanding is sought of the minimum standards that will be accepted for buses and for trains that use Queen Street. This is likely to involve research into tolerances elsewhere and fundamental marketing research in Auckland. It may also involve testing a bus lane along Queen Street first, although such an experiment would have to be carefully designed to avoid any bias.

The technology uncertainty could also be reduced by learning, although that will be more difficult given some of the perceived technologies are not yet available and, even if they were, it might take an experiment on a grand scale to test public responsiveness in terms of work-residence location, commuting time and commuting mode.

The value of a learning option is best understood by comparison with a ‘wait and see’ approach. In both cases there will be potential costs to delay: there will be costs incurred while waiting, primarily around congestion; the cost of ultimately introducing the preferred solution may increase (or decrease) more than the general inflation rate; and/or the benefits may differ with a later solution (in this case, some opportunities to attract new migrants or businesses may be lost). Taking a ‘wait and see’ approach, time is allowed to elapse to resolve the uncertainty. With the learning option, an attempt is made to resolve the uncertainty quicker.

Addressing each of these potential costs in both situations can also be of value.

The benefit of reducing the interim costs was recognised in the programme business case where some alternatives were reported to be ‘buying time’. It should be noted, though, that to provide a net benefit of delay requires the benefits of any short-term actions to outweigh the costs. Should, say, spending more money on infrastructure now lead to an equivalent reduction in congestion costs (and nothing else) then this represents a shifting of the cost of delay, from the peak users of the route to the general public, rather than a net reduction in the cost of delay. An example where the marginal cost of delay could potentially be reduced is the heavy rail expansion to Dominion Road alternative (4) and the non-financial management alternative (5), to the extent some of these costs may be incurred within other projects.

More generally responses also could take one or more the following forms:

- Create a situation where benefit streams move differently to the uncertainty of interest, thereby reducing the need to wait and resolve the uncertainty (eg should demand of the Dominion Road-CBD route prove low and hence travel time savings are low, are there some other ways people might benefit from the solution provided when commuter demand is low. It seems unlikely with LRT that this is the case but, in the spirit of illustration only, maybe some tourists would pay highly to use freed-up capacity to travel on a novel tram along Dominion Road while for a BRT solution the freed-up capacity in a bus lane could be used by HOVs).
- Create a situation where the solution costs also vary with the uncertainty of interest, effectively shifting the cost from a large upfront irreversible cost to a variable cost (eg phase the solutions, as suggested within the programme business case for both a BRT and LRT solution).

[71] There are also responses to other uncertainties that also create value in an option to learn, including response to congestion charges, if introduced, and to other network changes such as the soon-to-be-completed Waterview connection

- A third alternative is to fix the expected benefits and/or expected costs. This seems unlikely for the benefit stream but fixing some infrastructure costs is possible through planning designations. Such a designation already exists within this case study for the rail corridor between the western rail line and the south end of Dominion Road, an option to expand that may be taken up as one of the project alternatives (4).

More generally these real options require either adjusting the infrastructure design to enable greater benefits across a wide range of scenarios and/or phasing the infrastructure investment in a manner that enables later adaption to the circumstances that may eventuate. The pathways for adaptive solutions appear numerous, although there will be gains and losses with each alternative pathway. Some examples are presented in table 4.10.

Table 4.10 Potential real options within a light rail case study

Option	Potential cost of delay	Potential cost avoided by delay	Possible outcome	Comment on potential outcomes.
Bus only solutions				
Use bigger buses initially or dedicated bus lanes in Dominion Rd and Symonds St.	Congestion in meantime. Lower productivity gain in meantime. Potential loss of key persons/businesses to offshore.	Unnecessary construction costs, including congestion caused by construction. And need to choose between BRT or LRT.	Demand is high so continue to expand. Or demand is low so no BRT/LRT (only likely if technology leads to major change).	Reduce cost of delay. Retains choice of LRT or expand to BRT. Advantage if technology was about to change transport. Disadvantage if interim congestion costs high.
Use Queen St for buses	As above (although have improved intra-CBD connectivity).	As above for routes excluding Queen St.	As above. Plus provides test of Queen St policy, that can be cheaply reversed (however acceptance likely to be tied with level of service).	Reduce cost of delay. Retains choice of LRT or expand to BRT. Learn about use of Queen St. Advantage as above. Disadvantage as above. Potential disadvantage is that it may lead to rejecting PT on Queen St without testing of LRT.
Both above	Congestion around CBD. Lower private sector development.	Unnecessary tunnel station. Or delay to LRT construction costs.	Demand is high so expand BRT. Or build LRT Demand is low so stop.	An advantage if (a) unsure of demand and (b) unsure that LRT fits with longer-term CBD strategy. Disadvantage if does not deliver GTC savings, including because Queen St policy is reversed.
Light rail solutions				
Use Queen Street only for rail	Congestion on corridors in/out of CBD. Lower private sector development (excluding Wynyard if included).	Unnecessary construction costs beyond CBD, including congestion caused by construction.	Demand is high so expand. Likewise productivity response is high so expand. Both are low so	Reduce cost of delay. Retains choice to expand LRT or expand BRT. Learn about use of Queen St. Advantage is learning about PT in Queen St. Disadvantage is does not

Option	Potential cost of delay	Potential cost avoided by delay	Possible outcome	Comment on potential outcomes.
			stop.	resolve immediate congestion issues (may worsen problem by limiting bus movement within CBD).
Add rail to Dominion Rd	Congestion around CBD.	Unnecessary construction costs in CBD, including congestion caused by construction.	As above.	Reduce cost of delay. Retains choice to expand LRT or expand BRT. Learn about use of private sector development around Dominion Rd. Advantage is learning about LRT response, although this may require a lengthy period. Disadvantage is high irreversible cost.
Both above	Congestion on routes not serviced by LRT (eg Manukau Rd)	Unnecessary construction costs on other LRT arms.	As above.	Reduce cost of delay. Retains choice to expand LRT or expand BRT. Learn about use of private sector development around Dominion Rd and PT acceptance on Queen St. Advantage is learning about LRT, although this may require a lengthy period. Disadvantage is high irreversible cost.

4.3.5.4 D. Option to expand

There are also numerous real options within this project relating to expansion. To some extent these are an extension of the learning options but the issue here is more likely to be about timing once it becomes clearer whether a BRT or LRT pathway is appropriate. The structure of the decision tree is the same as within the NB example (see figure 4.4).

The programme business case mentions two key options to expand, namely the option to extend the LRT system to roads parallel to Dominion Road, and in time to the airport if desired, and the option to build a CBD tunnel for the BRT system once bus saturation is approached in the CBD.

Consideration of expansion options also provides a link through to the wider network issues over a period that extends beyond the 40-year horizon. At the core of the current issue is congestion within and near the CBD. The light rail proposal is intended as a part of a wider solution for the next two to three decades that involves extra use of heavy rail for travellers to the CBD from the west and south and extra buses from the north and east. It is possible other solutions reach an inevitable end, such as a bus tunnel in the CBD or rail on the north shore. The former would raise the appeal of a BRT direction for the Dominion Road area while the latter could make the LRT solution more valuable. This is worthy of further investigation.

Likewise probable transport solutions for access to/from Auckland airport potentially integrate with this project. Along with the CBD, the airport is a pivotal point in the transport system, requiring ease of access from the CBD and also the suburbs to the west, north and east of the CBD. It is probable this project may reduce costs or increase benefits associated with future changes to the current airport access, as suggested by the potential extension of the LRT. However, the project does not appear to necessarily link well with north shore access to the airport, unless the LRT were extended to the north shore. This also is worthy of further consideration.

Note the benefit of integration with longer-term requirements is twofold: there is the potential for reduced future spending, albeit any dollar saved in 40 years has only a PV of around 10 cents; plus there are the benefits that are brought forward (eg faster trips to airport if LRT introduced to route or faster trips for all commuters in CBD if bus tunnel created earlier).

4.3.6 Probe uncertainties

No detailed probing of the uncertainties was undertaken within this case study. A more extensive analysis would require more in depth analysis of the key uncertainties that related to each alternative solution.

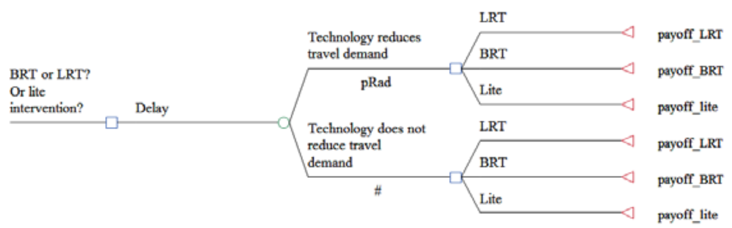
4.3.7 Crudely estimate indicative payoffs

A full threshold analysis was not possible within the case study given the many permutations[72] and the lack of data.

4.3.8 Establish thresholds that favour one alternative over another

Likewise rather than test the many permutations, a subset of the decision tree is shown for illustrative purposes. Under consideration is the decision to commit to LRT or BRT in the light of technology uncertainty.

Figure 4.16 Subset of decision tree pertaining to BRT or LRT in light of technology uncertainty



Hypothetically there may come a stage soon when the effect on travel demand of the current wave of technological innovations is known. If the effect is a radical change to travel demand and in particular a reduction in the demand for PT into the city then both the full BRT and LRT alternatives are likely to provide low payoffs. The full costs of the projects are currently estimated at $9.5b and $3.7b respectively and neither is expected to deliver strong value (ie BCR much greater than 1) under strong demand growth conditions. There is possibly a 'BRT-lite' programme of changes that would produce the highest payoff under a low travel demand scenario.

Conversely if technology innovations did not reduce travel demand significantly relative to current expectations then the LRT programme would offer the highest payoff. The advantage comes from its high capacity and its ability to use Queen Street without the need for a costly CBD tunnel.

[72] Known as the 'curse of dimensionality' whereby the number of stages in decision trees grows exponentially

In other words, LRT would provide a higher payoff than BRT under both extreme scenarios. The conditions required for BRT to rank higher would be (a) the major costs of the BRT programme could be deferred by around 15 years (ie the period required to equate PVs) relative to the LRT costs, which might be the case under the BRT lite alternative above and/or (b) the tunnel costs could be avoided or largely attributed to another project.

This raises the interaction with other parts of the network again. The pre-condition for the BRT alternative (2), including the CBD tunnel, is the tunnel is required to accommodate buses in general and is not exclusively a marginal need of the Dominion Road area network. Conversely, if a CBD tunnel is required for bus access from other routes then the LRT project has value if its benefits exceed the costs (and is NPV positive) of delaying the construction of a CBD tunnel by order of 10 to 20 years. Both situations hinge on whether technology fails to halt the strong growth in peak period travel in and out of the CBD.

4.3.9 Comment on light rail case study

The Auckland light rail case study extends some of the insights gained from the two earlier case studies around the importance of interdependencies and adaptive abilities.

The case study was also another opportunity to explore the ‘prosperity option’. Again it showed the importance of focusing away from the probable but uncertain prosperity promise of large projects to consider complementary value. Or conversely if the prosperity scenario is to be the key driver of value then strong commitment from the other major parties involved is required, eg a large push by Auckland Council and some major property developers to increase housing intensity in the Dominion Road area to justify a local LRT system.

Also apparent is the large number of real options that otherwise do exist and the many permutations the mix of alternatives and uncertainties can create, especially as other parts of the network and a longer period are brought into consideration. There are numerous options to learn that deserve exploration.

At a practical level, a process to reduce these decisions down to key issues is required, and for the sensitivity to this reduction of dimension to be tested. The better business case process introduced into New Zealand in recent years provides such a process although the robustness of scenario testing is yet to be proven.

The presence of many real options also implies the total benefits of a project may consist of many parts. There will be times when a series of relatively small changes provide the best value proposition, each small benefit combining to imply a significant value proposition. The decision tree provides a useful tool to explore these interdependencies.

Again it was not thought necessary to resort to a binomial model to price real options. This valuation tool may be useful in a more comprehensive analysis, especially around the timing of projects, but initially the value in analysis is derived from understanding the inter-relationship between actions and uncertainties. This required a more fundamental – and often iterative – exploration of scenarios.

Last and to repeat, this case study discussion has largely focused on where options may exist and how these options might influence a decision about the light rail proposal. It only touches upon the analysis required, some of which is underway already by others. The intention of this report has certainly not been to prescribe any one solution.

5 Conclusions

Uncertainty is a pervasive feature facing society, and is a feature that must be accounted for properly by planners, investors and policy-makers. Uncertainty differs from risk, to adopt the Knightian nomenclature. Under conditions of risk, a planner can base projections and scenarios on a well-defined probability distribution, so expected values and variation around those expected values can be defined. By contrast, under conditions of uncertainty, the planner cannot rely on a known, well-specified model and probability distribution for determining events that may be material for the planning decision.

Uncertainty may arise from a number of sources. Parameter uncertainty exists when a modeller knows the 'true' form of a model that describes potential outcomes for the variable being modelled, but does not know the 'true' parameters. Model uncertainty arises when the modeller is unsure of the correct variables (and/or their functional form) to include in the model. Fundamental uncertainty arises when unknowable developments may occur for which there is no basis in history or theory to predict their likely impact. Historical examples of the latter include the advent of the train, invention of the telegraph and invention of the car. Current examples include the impacts of electric vehicles on issues of climate change and the impact of autonomous vehicles on transport flows.

Fortunately, planners can use well-established techniques to deal with these various forms of uncertainty, as well as for dealing with risk. In particular, real options or adaptive management techniques should be used where four conditions exist:

1 There is uncertainty or risk

2 Irreversible investments are to be made

3 The investor has flexibility in the timing of at least some investment stages

4 The investor can learn about the nature of risk or uncertainty over the relevant planning horizon.

If risk, but not uncertainty, exists then the planner can use quantitative real option techniques to price the option value of undertaking (or not undertaking) certain investment stages. These techniques are commonly used in markets that face well-defined and deeply traded prices, such as in oil (for example, an oil exploration decision) and forestry (for example, the decision on when to harvest).

If, instead, uncertainty (and especially fundamental uncertainty) exists, then the quantitative real option approach is less useful, or cannot be used at all. This is because well-defined distributions do not exist for the evolution of key variables that affect the investment decision. In this case, the same real option concepts can nevertheless still be used, but in a more qualitative fashion. While definitions in the literature are a little fluid, we adopt the common terminology which labels this approach 'adaptive management'. As we discuss below, active adaptive management is an appropriate method to use in these circumstances to account for the dynamic effects of uncertainty on optimal decision-making.

Faced with the four conditions listed above, which commonly face transport planners, the investor should not treat a (single-stage or multi-stage) investment project as a once-only decision of whether to invest or not. For a multi-stage project, a decision can be made whether or not to invest in the first stage of a project without committing to the entire sequence of potential investments. That first stage may simply be preparation of the project drawings or the obtaining of resource consents. Even in a single-stage project, the investor has the choice of whether to invest immediately or to delay the investment until a future period while more is learned about the environment. As well as taking account of the state of knowledge at each point of the decision process, optimal adaptive management decisions account for the potential future evolution of knowledge about key drivers for the investment decision.

Given the four conditions above, a number of forms of option are available to the investor:

1 An option to defer

2 An option to abandon

3 An option to scale up or down

4 An option to stage (or increase the number of stages of) an investment

5 An option to learn

6 An option to switch.

The nature of each of these options is discussed in section 2.4 and key concepts are illustrated in our case studies.

Our light rail (Dominion Road) case study is one that includes an option to defer ('buying time') plus options to learn. By choosing not to invest immediately and irrevocably in a light rail system, the planner can observe how traffic flows evolve in response to various features such as a new road coming on-stream (Waterview), the potential introduction of congestion charging, and developments in new vehicle technologies (eg electric buses and autonomous vehicles). Other less costly investments, such as introduction of full-time dedicated bus lanes, can be made. These investments keep open the option to invest in light rail and yet still improve transport services while at the same time generating new information about demand for improved public transport.

The Kaimai case study illustrates a 'prosperity' option in which the transport investor can create opportunities to invest so potentially boosting prosperity of a region. As in the Kaimai illustration, such an option may relate to a large project that may have considerable downside ('white elephant') as well as upside ('prosperity') possibilities. Faced with a large potential 'white elephant', a risk-averse investor may choose not to incorporate the expected value of the option in the central estimate of benefits within the BCR of a CBA. Instead we consider it suitable practice to derive the central BCR calculation by including the most likely values of benefits and costs, ie using their mode rather than their mean. The 'prosperity' option can then be incorporated into an asymmetric scenario that demonstrates the potential upside risk that is present as a result of this option. If the project's central BCR is close to, but below, a decision threshold, then the value of this prosperity option (incorporating some heuristically-determined probability) can then be added into the decision process for whether or not to proceed with the project.

The North Shore busway case study uses an actual historical example to illustrate a range of option types. The building of the busway enabled an option to defer other potential investments while generating learning about public transport demand from the North Shore. It also included options to scale the project up and to include additional stages (eg through busway extensions) and an option to switch (eg to use by high occupancy vehicles). We show these were valuable options.

Typically, in circumstances faced by traffic planners, a qualitative decision-tree approach within an adaptive management framework will constitute an appropriate methodology for handling uncertainty. Appendix A4 illustrates, for the case of demand uncertainty (which is a pervasive issue facing planners), how a dynamic decision tree can assist the planner to make appropriate choices.

The pursuit of 'active' adaptive management can be particularly useful. In this approach, the planner actively builds in stages to the investment process to generate learning opportunities. For instance, opportunities may be taken to learn about traffic count responses to initial transport initiatives. One example is to introduce more frequent public transport services on an existing network to gauge potential public transport uptake prior to irreversible investments being made to extend that network.

The Dominion Road case study illustrates the potential for such active investment stages to be introduced into the dynamic decision process. Sometimes, the addition of active learning decision stages will involve a cost that cannot be retrieved, such as the installation of traffic counters on a busy stretch of road. In other circumstances, the cost of an active learning stage may lead to benefits that can be reaped under any conceivable evolution of events; for instance, gaining a resource consent will be valuable for a development that will proceed in some form but where the exact form (as opposed to its occurrence) is still to be determined. Naturally, the latter learning alternative, which will be useful for all potential outcomes, has desirable properties. Nevertheless, the former alternative may also constitute a worthwhile investment in the same way a fire insurance payment on a house (which is irretrievable) is a worthwhile investment.

We have outlined a toolkit for the transport planner/investor who is facing the type of problem in which adaptive management may usefully be implemented. We recommend a multi-stage process that is consistent with the better business case approach to investment within the New Zealand public sector. This approach involves the following steps:

1. Define the issue
2. Estimate the status quo and business and usual (BAU) scenario
3. Identify key drivers of uncertainty
4. Create short-list of alternative investment opportunities[73]
5. Draw decision tree for each alternative
6. Probe uncertainties
7. Crudely estimate indicative payoffs
8. Establish threshold(s) that favour one alternative over another.

This approach is primarily qualitative rather than quantitative in nature. Within this approach, we stress the importance of building in, wherever possible, multiple investment stages that contribute to the ability to learn about the evolving environment over time. Furthermore, we stress the importance of retaining flexibility, wherever possible, to adapt the investment sequence in a dynamic fashion when those learning opportunities yield material new information about the environment.

Our suggested approach is not intended to replace CBA. Indeed, an option is a form of benefit that can, in principle, be taken into account in a comprehensive CBA. As discussed above, however, we consider that the presence, and value, of some options (especially one such as a 'prosperity' option that could have a considerable downside) may be best incorporated within the decision process as an asymmetric scenario relative to the most likely set of benefits or costs (or relative to the benefits and costs that do not incorporate the option value).

Rather than focusing on the **valuation** of the option per se (especially under conditions of uncertainty), our emphasis has been on the **process** for considering the benefit of retaining or creating option value within an investment programme. This concentration on process means that active adaptive management, with its emphasis on incorporating learning stages into a multi-stage investment programme, is well suited to many transport planning problems.

[73] We take it as given that each of these alternative investment opportunities should align with the objectives of the investing agency.

Ultimately, the incorporation of adaptive management techniques into major project planning is as much an attitudinal as a technical matter. A project with the highest ex ante BCR is not necessarily the best option when another project is available that allows more flexibility in decisions over time, even if the latter project has a lower ex ante BCR. Flexibility has value, and that value must be considered through the use of adaptive management (and/or real option) techniques when comparing alternative projects. Adaptive management techniques are applicable where projects exhibit some degree of flexibility, irreversibility and potential learning, in the presence of risk or uncertainty. In these cases (and especially for large scale projects), we recommend the adaptive management process, which we have formulated to be consistent with the better business case process of the New Zealand public sector, be adopted for transport planning.

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Appendix A: Transport modelling

A1 Introduction

This appendix provides an overview of the traditional approach to transport modelling. It is not intended as an extensive survey but rather to draw out where uncertainties can arise within the widely used current approach. It is noted that new models have been developed that enhance, complement or replace the current standard.

This appendix considers the following in turn:

- What are the properties of travel demand?
- How is travel demand forecast?
- What type of errors may travel demand estimates be subject to?
- How uncertain are travel demand forecasts?
- How uncertain are the inputs into a traffic model?

For the purpose of this review:

- A **prediction** is defined as being a statement about the way things *will* happen in the future, an outcome that *is* expected – with the associated certainty this implies.
- A **forecast** is also suggested as implying something specific – but may cover a range of possible outcomes. Willumsen (2014) suggests it is a judgmental statement of what a professional believes to be the 'most likely' future.
- A **projection** is also a statement about the way things will happen in the future, but is explicitly dependent on stated assumptions. It is an estimate of a *potential* outcome. A projection is therefore not a prediction, although it may be misinterpreted as such if distinction is not understood or explicitly acknowledged.
- A **scenario** may be defined as a set of forecasts, under a single set of assumptions.

A1.1 Properties of travel demand

The ultimate purpose of any transport system is to enable connections – transport being almost always a means to this end. In the context of this study, transport is the function which allows movement of goods or people from one physical location to another (SACTRA 1999). Transport demand thus is very largely a derived function arising from other activities and is therefore usually highly-correlated with land use that generates the need for such connections.[74] (NZIER 2013, Grimes). In practice, the two are interrelated, although it is very common practice for (future) transport appraisals to be based upon fixed and exogenous input assumptions, including for (future) land use.

Traffic volumes have generally followed a similar pattern in many places, as illustrated and explored for the Auckland Harbour Bridge (AHB) in section A4. Namely, traffic volume tended to trend higher until

[74] It is acknowledged that technological and/or social change may influence the degree to which physical transport is required and future potential changes (anticipated or not) can affect practical levels of uncertainty in physical transport planning.

around 2004 and then tended to trend sideways. Volumes have since increased again. Various studies have explored this change in trend, usually in terms of a disconnect with wider economic measures such as GDP (eg Agnolucci and Bonilla 2009).

Of more interest at this stage of the project is simply the nature of the variation patterns over a longer term. No time series analysis of New Zealand was found to be reported for New Zealand traffic counts. Simic and Bartels (2013) simply record their preliminary investigations indicate vkt data is volatile.

Kruger (2012) considered the stochastic properties of Sweden national annual passenger km between 1950 and 2010. The series grew at a rate of around 4.8% pa (until recently) with 'a mean deviation of 6%'. He also found evidence that (a) traffic demand deviations from trend coincided with GDP deviations and (b) that the series exhibited long-term memory features. The first finding provides solid ground to model traffic volume as a function of GDP[75]; the second is a warning that shocks to traffic demand may result in higher (or lower) future traffic demand *growth*. This result is also a warning that the option valuation models based on the typical finance assumption of geometric Brownian motion may be inappropriate.

The 6% Swedish mean deviation broadly fits with Willumsen's (2014) repeatedly mentioned observation that volume varies by around 10% per annum. Local measures of annual variation are similar. As an example, the Transport Agency reports[76] annual percentage growth for all vehicles on state highways within six New Zealand regions ranged from -11.9% in November 2008 for region 6 to 10.2% in May 2011 for region 5 between January 2008 and December 2012. Stepping down to individual roads, the range of values is much broader, possibly due to network changes in the vicinity of the measurement site. That said, annual change in traffic volume ranged from 0.8% to 3.9% on the busy AHB right clip-on (telemetry site 55) between 2010 and 2014, with a four-year change of 8.8% while the much quieter Gore telemetry site 45 volume change ranged from -0.3% to 3.3% with a four-year change of 4.3%.

Another traffic measurement of interest is travel time. As an illustration of the variation in travel times, TDG (2015) showed observed travel times on various Waikato routes having a standard deviation of generally less than 10% of average travel time (ie coefficient of variation less than 10%).

75 Note that even where a strong relationship does appear to hold, the traffic variance may be higher than the GDP variance, eg the quarterly variation in the ANZ Heavy Traffic Index is approximately twice that of quarterly variation in national GDP. The growth variation on any one road would be even higher.

76 www.nzta.govt.nz/resources/state-highway-traffic-volumes/?category=67&term=&start=10

Figure A.1 Travel time variation in Waikato

Source: TDG (2015, pp15–19)

A1.2 How is travel demand forecast?

Travel demand is forecast in a variety of ways. Here we provide only a brief overview of methods most commonly adopted to forecast travel demand to set the scene for an unfamiliar reader – it being beyond the scope and unnecessary for this project to provide a full exposition of such techniques. Our overview is intended to assist subsequent consideration of potential methods to acknowledge and mitigate uncertainty within transport investment decision making, potentially through the identification and, if necessary, valuation of real options.

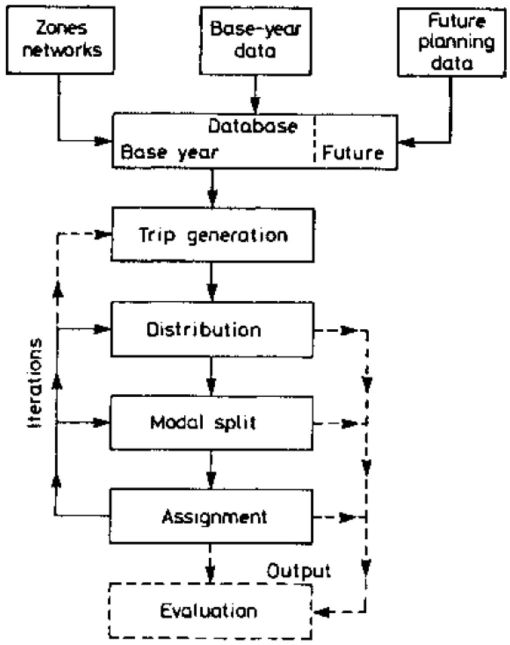
Mathematical transport models attempt to represent complex human behaviour in such a way it is possible to make reasonable and useful predictions of potential behaviour in the future. While all (transport) models are simplifications of reality, such models can still provide a foundation for quantitative estimates of use and benefits that can be helpful for decision makers to justify allocation of the funding required for implementation.

Transport modeling can be conducted at a variety of scales, from national through to local. It is axiomatic that any model study area would have to encompass the (principal) areas of expected policy or infrastructure impact in order to be able to capture the (principal) areas of benefit or dis-benefit. Although relatively simplified models may be appropriately applied for local schemes, for more significant policy and infrastructure appraisals, study areas will typically be defined at a regional or sub-regional scale.

For transport models at this scale, the most commonly applied overall structure is the 'four-step model' (FSM) form, shown in figure A.2). Despite its potential criticisms, it has changed little since the 1960s, although within this framework there have been considerable advances in modelling techniques and approaches (Bolland and Jones 2010; Ortuzar and Willumsen 2011; Transportation Research Board 2012).

Within the study area the transport system is simplified into a series of zones (where trips begin and end) and representations of the various available transport networks.

Figure A.2 A simplified form of the typical four- step model (Ortuzar and Willumsen 2011)



The broad purpose of each step is as follows:

Trip[77] **generation** determines the travel demand frequency (ie the scale of demand), usually by trip purpose: Data on demographic and economic variables is used to estimate a model of the total number of trip productions and attractions[78] for each zone.

Trip distribution determines the travel demand pattern, matching origins and destinations, resulting in an origin-destination (OD) matrix (referred to also as 'trip matrix'). This is most commonly achieved with a 'gravity model' formulation, where the scale of travel between a particular origin and destination is a function of the generalised cost of travel (or other measure of impedance or disutility) between them. Iteration within this step is required to ensure total trip productions, attractions and required balancing factors are consistent.

Modal split determines the mode for each trip (such as car, bus or train). This is usually achieved through application of a simple logit model (eg providing choice between car and PT) or a more complex 'nested-logit' model, where further segmentation and potential modes (or combinations of modes) are considered.

Trip assignment determines the choice of route for each trip**.** The trips are assigned to each or all networks (allowing for multi-mode trips or tours), resulting in a flow along each link. Route choice can be estimated in a wide variety of ways but the most commonly-applied consider the generalised cost

[77] Note that some models may estimate demand based on tours rather than trips

[78] For readers unfamiliar with modelling terminology, it might be noted that the terms 'productions' and 'attractions' should be distinguished from the perhaps more familiar terms origins and destinations – although productions and attractions are used to determine the latter. In terms of definition, a trip production is defined as the home location for all home-based trip purposes, while a trip attraction is defined as the generating trip end – thus the latter might be a school for a home-based education trip, or a shop in the case of a home-based shopping trip. For non-home-based trips (where neither trip end is the home), the site of trip origin is defined as the production end and the site of destination the attraction end.

perceived by one or more market segments and apply one of several methods to estimate a state of equilibrium.

In the first step, future trip productions are usually estimated by application of a trip rate (usually that observed in the base year) to one or more assumed input future variables (such as population, households, income, car availability, residential density and accessibility). Often this step is performed using category analysis or cross-classification of two or more variables (if these are found to be significant to trip generation), applying calibrated trip rates by each market 'segment', which may, for example, reflect persons by age and income or households by 'lifecycle' and car availability classifications. Essentially, however, most model forms boil down to a simple, usually linear relationship being assumed for each segment:

$$Pi = \sum_{1}^{n} f(p) \qquad \text{(Equation A.1)}$$

Where:

Pi = number of trip productions by zone i,

n = trip purpose (eg work, shopping)

$f(p)$ = function of production variables such as population, household types, accessibility

eg:

$$f(p) = \sum_{1}^{l,v} ERP_{lv} \times t_{lv} \qquad \text{(Equation A.2)}$$

Where:

ERP_{lv} = estimated residential population in lifecycle category l and vehicle-availability category v within zone i

t_{lv} = trip rate for lifecycle category l and vehicle-availability category v

Trip attractions for most trip purposes are usually found to be strongly related to a land use variable, such as employment (by type), for example

$$Aj = \sum_{1}^{n} f(a) \qquad \text{(Equation A.3)}$$

Where:

Aj = number of trip attractions by zone j

n = trip purpose (eg work, shopping)

$f(a)$ = function of attraction variables such as jobs, floor space, population, accessibility

eg:

$$f(a) = \sum_{1}^{k} J_k \times t_k + \sum_{1}^{c} S_c \times t_c \qquad \text{(Equation A.4)}$$

Where:

J_k = jobs in industry category k within zone j

t_k = trip rate parameter for industry category k

S_c = school children in age-cohort c within zone j

t_c = trip rate parameter for school age-cohort c

At a high-level, the network representation will seek to represent the *supply* of transport services, while the *demand* (scale and pattern) is represented by the matrix of cells representing all zone pairs and the resulting routing through the network (trip assignment). The geographic-level zonal demand aggregation may, however, be applied within the model with a greater or lesser degree of disaggregation of activity at various steps of the model (eg trip generation by life-cycle category as in the above example, modal-split options by vehicle-availability, route choice by vehicle or person type.)

As noted above, the 'cost' of transport, for the user, is conventionally represented in terms of 'generalised cost,' which includes operating costs, fares or tolls paid, incidental costs, such as parking fees, and the costs of time involved in making the journey. The generalised cost of a journey will depend on, among other things, the amount of congestion on the network and may therefore vary by time of day and location. Demand for transport is usually found to follow an inverse relationship with costs perceived by the users, although this not always the same as the full costs actually paid.

The four-step process would thus usually require iterative feedback *between* at least two steps[79], given the relationships between supply and demand. In its simplest form, the process will adjust the cells within the trip matrix to optimise the number of trips between zones subject to[80] a fixed pool of people leaving a zone, a fixed pool of people arriving at each zone and the cost of zone-to-zone travel. In more complicated processes, the optimisation may occur over modes and times of day. For example, the distribution of trips may usually be found to be a function of generalised cost between potential alternative locations of productions and attractions. However, this utility will be dependent upon the level of service between alternatives – a product of the trip assignment step (which depends upon the interaction of both the scale and pattern of demand *and* the interaction of this with the network supply). Time of travel is commonly and most simply estimated within the trip generation step, with productions and attractions being generated for specific time periods. However, it may also be estimated in a more sophisticated manner at other stage(s) of the FSM; for example, taking account of level of service (sometimes by alternative modes), and thus requiring inclusion within subsequent step feedback loops.

Four-step models used in New Zealand include the TRACKS-based models used in Waikato and Christchurch and the EMME-based models used in Auckland and Wellington.

As an example of the level of disaggregation in models used, SKM (2009) note the following characteristics of transport models[81] in six Australian states:

- zones ranging from 304 (South Australia) to 2715 (NSW)
- time periods per day ranging from 1 (ACT) to 3 or 4 for the rest
- trip purposes generally around 5–8 but 14 for Victoria
- trip assignment taken for cars and commercial vehicles (except cars only ACT and NSW).

[79] Furthermore it should be noted the steps may not always be applied sequentially depending upon context: For example mode split and distribution steps may be combined.

[80] The row and column totals will remain fixed in a 'fixed trip matrix' model run but will change in a 'variable trip matrix' model run.

[81] They also report model run time in 2009 being 1–2 hours (ACT, SA, WA) to 24–30 hours (NSW, QLD, VIC).

Other demand modelling approaches

Despite its longevity in transport planning practice, a number of criticisms may be levelled at the FSM approach, not least the absent or limited consideration of transport/land use interaction. Methods other than the traditional FSM approach (or for its component steps) are therefore emerging (Transportation Research Board 2012). Such developments include increased research and/or application using land-use/transport interaction (LUTI) models, activity and agent-based modelling and micro-simulation assignment modelling.

LUTI models have been implemented internationally although their application to date has primarily been for large-scale policy or 'sketch-planning' appraisals. There is currently a single (Auckland) application within New Zealand, which integrates a DELTA-based land use model (ASP3.3) with an EMME-based transport demand model (ART3). Its principal application to date has been for scenario testing, to inform development of the Auckland Plan, with more limited application for major individual transport projects or programmes (eg AMETI, AWHC).

Rasouli and Timmermans (2012a) review prior work on uncertainty analysis in travel demand forecasting and discuss different sources and other studies of uncertainty. They differentiate between FSM, discrete choice models and activity-based models of travel demand. Gaps in the literature and avenues of future research are systematically discussed, with a particular focus on complex activity-based models. More recently, Rasouli and Timmermans suggest basic assumptions underlying commonly applied transport modelling theory and practice (eg the FSM approach) may not mimic the quintessence of day-to-day activity–travel behaviour and identify avenues of future research.

Despite their apparent potential to address deficiencies within the traditional FSM approach, as yet, LUTI and activity based models in particular have seen relatively-limited uptake, and this may reflect some difficulties in practical application – particularly to examine the potential impacts of input and parameter uncertainty within individual project evaluation.

While methods other than the FSM approach may allow estimates of output measures that can (better) reflect stochastic variability (particularly for example in journey times), we observe that such ability will still be a sum product of models that may, effectively, be founded on assumptions for a great number of parameters. The apparent level of confidence of output distributions would, the authors suggest, therefore have to be treated cautiously.

We also observe that run-times for agent-based and microsimulation (assignment) methods may be a potential barrier to their widespread use in stochastic simulation of *input variability*. Despite gaining increasing prominence (mostly in academia), agent-based models (eg Huynh et al 2015; Zheng et al 2013) appear to be some way off providing practical assistance to risk management.

A1.3 What type of errors may travel demand estimates be subject to?

Mackie et al (2014) surveyed a number of countries where CBA plays a formalised role in decision making and suggest the outcome of a CBA is fraught with many kinds of uncertainties. These include the future scenario assumptions underlying the forecasts; the forecast effects of the project; the final cost of the project and the benefit valuations being methodologically and philosophically contestable. They acknowledge and reference recent progress in quantifying the uncertainties due to uncertain valuations, scenario assumptions, and cost and benefit estimates

The minimisation of demand forecasting errors is clearly important in the delivery of a robust appraisal. There are two principal sources of transport model forecast error: uncertainty in the inputs (such as the scale of development adjacent to or influenced by a transport scheme) and error (uncertainty) arising from model parameters and specification (how these inputs propagate through the model).

Measurement or data errors occur because, while a complete dataset of travel demand patterns, supply conditions and behavioural parameters is fundamental to the accurate description of the existing situation, this may be very costly to obtain and still impossible to guarantee that they will reflect 'the' situation accurately, with absolute certainty – not least because of the likelihood that what constitutes 'the' situation will itself be an estimate: Demands, for example may be expected to vary by time of day, day of the week and seasonally and further, it is common for partial datasets to be used for estimation, eg of travel patterns.

Model specification errors in any of the relationships contained within the demand forecasting model can be expected to lead to errors within demand forecasts. Transport models typically include many such relationships, which approximate complex human behavior. These may be applied at various levels of aggregation and segmentation, be it spatial, population group, temporal, modal, etc, but the approximations adopted may not always be appropriate. Potentially key explanatory variables may sometimes be omitted altogether (eg income or walking time) or misapplied (such as the potential bias introduced when disaggregate data is used for calibration of non-linear functions, but application is undertaken using aggregate data). While significant attention and resource can be applied to minimise such model specification errors when seeking to replicate an *existing* situation, more limited attention can be given to application in *future* environments. For example it is common practice to assume stability over time of trip rates, distribution and assignment parameters, when such assumptions may be uncertain.

External or exogenous errors are associated with the external inputs or assumptions that may underpin the forecasting model. Most travel demand forecasts are heavily dependent upon the forecast of external factors, such as economic activity, income growth, population and car ownership. Errors in such assumptions can therefore have a significant impact on potential changes in transport demand. Differences can also occur between assumed political and planning policy and reality, in terms of the actual scale and distribution of land use development, or in transport system investment and management, particularly between competing projects and modes.

The reader wishing to see a fuller exposition of potential model errors may also refer to Mackie and Preston (1998); Ortuzar and Willumsen (2011) and Willumsen (2014).

A1.4 How uncertain are travel demand forecasts?

This is a question which, by definition, cannot be answered 'accurately'. Over the last few decades however, there has been increasing attention given to the lack of historical forecast accuracy of transport demand. This may be defined as the actual deviation between predicted and observed values. Thus, accuracy (or inaccuracy) is only possible to measure *after* the true value is known. 'Uncertainty' however, may be defined (broadly) in a number of ways, Walker et al (2003) for example suggesting that it is 'any departure from the unachievable ideal of complete determinism'. That said, examination of the scale and potential causes of inaccuracy should be helpful to inform methods to acknowledge, incorporate and reduce where possible, uncertainty about potential travel demand into transport investment decisions.

Nicolaisen and Driscoll (2014) provide a comprehensive literature review of the largest ex-post studies of demand forecast accuracy for transport infrastructure projects across Europe and the US. Their review suggests data availability for comprehensive ex-post appraisals is, however, somewhat problematic and such studies are still relatively rare. Methodological and systemic differences in available studies contribute to difficulties in identifying the causes of inaccuracy. For example, despite having binding archival requirements for ex-ante appraisal documents, they observe that the UK's Highways Agency was unable to supply the necessary documentation to assess demand forecast accuracy in detail for one-third of the projects within its (2011) evaluation of major projects.

Using a measure of 'inaccuracy' equal to the percentage that actual traffic either exceeded or fell below the forecast level, the average inaccuracy for road projects ranged from -23% in one study of toll roads to +19% in another study of roads. The standard deviation of the inaccuracy measure ranged from 21% to 44% across the eight road and toll studies examined.

From the available evidence, they conclude demand forecast inaccuracy is problematic for all project types they examined (road, toll and rail). A tendency to underestimate demand for road projects results in capacity limits being met earlier than anticipated. For fixed links this will typically require an expensive capacity expansion, and for congested networks it means that expected travel time savings will likely be overestimated The authors cite Næss et al (2012), who found just 5% of additional demand could result in more than one third of the expected benefits being lost. For toll and rail projects, the tendency is to overestimate demand, resulting in reduced fare revenue and lower overall user benefits. However, they do suggest there is some indication that forecasts are improving in accuracy, as studies of newer toll and rail projects report both lower bias and standard deviation than those of older projects.

A further issue is that available ex-post studies have tended to be on project-specific links, whereas demand forecasts are typically produced for a full transport network. This means the observed inaccuracies could potentially be the result of failures to accurately assess network distribution[82], rather than the overall demand.

Despite these difficulties, Nicolaisen and Driscoll (2014) observe the most important source of inaccuracy for demand forecasts appears to be auxiliary forecasts of exogenous variables, where inaccurate forecasts of economic growth, car ownership and migration patterns propagate into demand forecasts. They also suggest model specification remains a potentially large source of demand forecast inaccuracy – but acknowledge none of the studies included in their own review have had access to data that allows the impact of this to be evaluated in detail.

As noted above, the UK Highways Agency conduct post opening project evaluation (POPE) studies for Major Schemes[83], these being evaluations one and five years after opening. The Highways Agency also conducts meta-analysis of these studies on a bi-annual basis, in a bid to identify emerging trends of major scheme ex-post impacts and scheme appraisal accuracy.

The latest published meta-analysis (Atkins 2013[84]) confirms a majority (65%) of schemes[85] 'accurately' forecast traffic flows (defined as being to within +/-15%) – but there is much variability in accuracy between schemes – even over the limited post-opening period able to be examined.

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82 We assume Nicolaisen and Driscoll (2014) mean the final network assignment of demand, thus reflecting all steps (including trip distribution) within typical transport models.

83 The Highways Agency suggests major schemes are those costing over £5 million (approx. NZ$11.5m) whereas Nicolaisen and Driscoll (2014) report this as being over £10 million (approx. NZ$23m).

84 Note the 2013 meta-analysis is a more recent version than the 2011 version reviewed by Nicolaisen and Driscoll (2014). While highlights of a subsequent 2015 meta-analysis have been presented at the Transport Modeller's Forum 10 June 2015 (and may be found at https://drive.google.com/file/d/0B-x3iEfB8cU9Q2NZbXBkRXd5T3M/view?usp=sharing), the full report has not (at the time of writing) been published by the Highways Agency.

- Bypass scheme corridors have the highest level of forecasting accuracy with 68% of schemes having observed traffic flows within 15% of predicted. However, the forecasting of traffic flows on the old and new roads, for these bypass schemes, is the least accurate, with only 31% and 43%, respectively being within the threshold. This demonstrates that although the overall level of traffic flow in the *corridor* has been accurately modelled for a high proportion of these schemes, the reassignment of traffic between the old road and the new road has been less accurately modelled.
- Approximately 60% of online widening and junction improvement schemes have been observed with traffic flows within 15% of predicted, demonstrating a large proportion of the forecast traffic flows are *inaccurate.*
- The four 'upgrade to motorway' schemes within the meta-analysis all have observed traffic flows within 15% of predicted, demonstrating a high level of accuracy for this scheme type – albeit for a small sample size.

Where 'accurate' traffic flow predictions have been made, the Highways Agency considers the following factors have played an integral role in achieving that accuracy:

- Proposed major land use changes in the area of the scheme have been taken into account and realised.
- Model scale and complexity was appropriate and sufficient to capture all possible strategic and local reassignment.
- Do-minimum traffic forecasts have generally been broadly in line with observed 'before scheme' traffic flows.
- The growth forecast assumptions used have been broadly in line with observed growth, and local growth estimates have been used where appropriate.

Conversely, the analysis of schemes where *inaccurate* traffic flow forecasts have been made suggests the following may be key factors contributing to the differences

- strategic routing assumptions
- local routing assumptions
- background growth assumptions
- land use issues
- other highway schemes
- do-minimum accuracy issues which may stem from base year or coding errors.

Table A.1 shows the number of schemes influenced by each factor, identified as percentages of the total[86]. This demonstrates the level of importance of each factor for higher or lower forecast flows for each scheme type.

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[85] This figure relates to forecast corridor traffic flows and post removal of outliers (using Devore's 'fourth-spread' method.)

[86] This is the total of schemes influenced by each factor which is greater than the number of schemes as for some schemes more than one reason was identified for the traffic flows being higher or lower than predicted by more than 15%.

Table A.1 Reasons for predicted traffic flows higher or lower than predicted by 15% (including outliers), shown as percentages

Reasons/ outturn flows being > +/- 15% higher or lower than forecast	All scheme types*		Bypass corridor		Online widening		Junction	
	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower
Strategic routing assumptions	42%	3%	33%	8%	50%	0%	100%	0%
Local routing assumptions	26%	3%	25%	8%	33%	0%	0%	0%
Background growth assumptions	11%	50%	8%	42%	17%	63%	0%	50%
Land use issues	16%	17%	25%	0%	0%	25%	0%	30%
Other highway schemes	5%	17%	8%	25%	0%	13%	0%	10%
Do-minimum accuracy	0%	10%	0%	17%	0%	0%	0%	10%

*including upgrade to motorway

The following can be observed from table A.1:

- For bypass schemes, the key reasons for observed traffic flows being higher than predicted are strategic and local routing assumptions, as well as land use issues. In contrast, the key reasons for flows being lower than predicted are background growth assumptions and other highway schemes.
- For online widening schemes, similarly to bypasses, the key reasons for higher observed than predicted flows are strategic and local routing assumptions. Background growth assumptions and land use issues are the key factors in the forecast of higher traffic flows than observed.
- For junction improvement schemes, the majority of schemes have lower observed flows than forecast due predominantly to background assumptions and land use issues.
- The majority of schemes with observed flows outside the ±15% range have observed flows that are lower than forecast.

The Highways Agency suggests the economic downturn in 2008 has been a key factor where observed traffic flows have been lower than forecast, in particular for online widening and junction improvement schemes, as they are generally more recent. Assumptions in relation to specific developments have been overestimated, with less coming to fruition than expected.

The reasons for differences between observed and predicted traffic flows are discussed in more detail within the meta-analysis under the following headings:

- background traffic growth
- land use issues
- base year accuracy
- do-minimum accuracy
- forecast and actual opening year
- model size and detail.

These issues may be reduced in the future, given procedures for transport modelling and appraisal specified by the UK's Department of Transport in the form of their transport analysis guidance ('WebTAG'), and particularly TAG unit M4: Forecasting and uncertainty (see section 2.4.2 of this report).

In New Zealand, Wallis et al (2012) examined five schemes and found transport benefits calculated from travel times, vehicle operating costs and crash costs were within 20% of pre-appraisal estimates.

A1.5 How uncertain are the key inputs to travel demand forecasting?

As mentioned above, models have produced base results that in many cases are near the eventual outcome but in some cases are very different. These ex post studies were typically taken within one or several years of project completion. As Willumsen (2014) suggests unexpected outcomes will become evident quickly and this short-term analysis may be appropriate.

However, this still leaves the issue of, ex ante, is this model run likely to be one that provides a reasonably accurate short-term forecast or is this model one that will produce inaccurate results. Furthermore the assertion of 'success' being evident quickly appears to be only weakly empirically tested (as cited by Parthasarathi and Levinson 2010), with the focus on 'failed' projects remaining 'failed'. It is not clear if the under-estimation of future 'success' has also been considered.

The following section looks more deeply at the sources of potential error in the typical four-step transport model. Table A.2 highlights and categorises some key issues while the remaining part of the section explores some of literature relating to the issues highlighted.

Table A.2 Categorisation of uncertainty in four- step traffic model

Model step	Source of unknown	Current knowledge status	Current model status	Controllable in future	Uncontrollable in future	
					Potentially stochastic[87]	Discrete
1	Population at origin of trip (the trip generation step). Activities at destination.	Known (at least relatively fixed in a short period of time and can be inferred from Census and/or annual Business Directory)[88].	Treated as exogenous known. Analysis at unit of households. Errors within the first step are particularly important as they may be propagated through remaining steps of the model.	Policy changes to create more capacity for residences and/or activities.	Time to take up new capacity • Population growth by age • Household formation • GDP growth	Will the private sector respond at all? Will new competitors emerge for key industries?
1a	Trips per origin population. Trips per activity	Trips per origin are estimated and generally considered fixed.	Disaggregation of trips explains much trip variance but not all. UK trip rates for	Policy changes can encourage or restrict trip generation (eg fuel excise change).	Incremental changes in technology, preferences and costs Income growth	One-off technology changes (eg SDVs)

[87] Larger lists of potential explanatory variables are provided by Stephenson and Zheng (2013); Simic and Bartels (2013).

[88] Even populations outside of study area are generally stable over periods of months.

Model step	Source of unknown	Current knowledge status	Current model status	Controllable in future	Uncontrollable in future	
					Potentially stochastic[87]	Discrete
			shop and commute down in recent years (DfT 2014)		Fuel prices Vehicle prices	
2	Trips between origins and destinations (the trip distribution step)	OD trips only partially recorded.	Gravity model typically used to generate trip matrix, using GTC within assumed deterrence function. Urban travel differs to rural.		Incremental changes in technology, preferences and costs	One-off technology changes (eg SDVs)
3	Mode share of trips (the modal split step)	Surveys used to estimate shares, plus one-off census.	Logit models used to estimate mode choice. Averaging of disaggregated results is sensitive to non-linearities.	Policy changes to create/change non-road capacity[89]	Incremental changes in technology, preferences and costs: • Rail capacity	Disruptive private sector initiatives (eg Uber taxi vans?)
4	Network (the trip assignment step)	Known (although not all parts of network may be accurately recorded)	Treated as exogenous known.	Policy changes to create/change road capacity[2]	Private sector developments will gradually change flow characteristics of network.	Natural events (eg Christchurch)
4a	Trip assignment to network links	Total trips are measured regularly for parts of the network. Totals show moderate variance.	Algorithm used to balance origin/ destination demands and cost of travel.	Model estimation can be improved.	Incremental changes in technology, preferences and costs: • GTC relativities	

Three methods have been employed to assess the determinants of travel demand uncertainty: case studies, meta-studies and simulation. Note the case studies and subsequent meta studies are effectively ex post studies that go into more detail about any forecast error. The simulation studies provide insights

[89] Note policy decisions may rest with same authority in some cases (eg local body changes land use plans to create more residential and commercial capacity and builds new roads at same time) and may rest with more than one authority in other cases (eg local body changes land use plans as above but the Transport Agency builds state highways).

from an ex ante perspective, albeit they are model based and hence are subject to uncertainties about the model itself.

A1.5.1 Meta- analysis and case studies

Flyvbjerg et al (2006) concluded the stated reasons for first year traffic errors were largely related to trip generation, land use development, trip distribution and the forecasting model. In general, they also noted an optimism bias applied in rail forecasts, believed due to the level of contestability in funding.

Parthasarathi and Levinson (2010) analysed traffic forecasting error for 108 Minnesota roading projects and concluded there was a tendency to underestimate traffic volumes on higher volume and higher classification roads and to overestimate demographic growth (especially in the 1970s). Of mixed effect was the tendency to not fully incorporate fundamental shifts (eg security threats) and societal changes (eg internet use).

Many case studies are included in the above meta-analysis. A more recent study of interest is that of Sanko et al (2013), who decomposed a forecast travel demand model for a Japanese rail project and found large forecasting errors could occur from model uncertainties, a warning that not just inputs are a major source of any ultimate forecasting error.

A1.5.2 Simulation studies

A number of researchers (including Manzo et al 2015; De Jong et al 2007) have confirmed model *output* uncertainty results from the inherent uncertainty of the variables included in transport models, including both exogenous *inputs* and model parameter *inputs*.

A commonly applied method to examine the effect of variability is to run a Monte Carlo study with inputs drawn from assumed distributions and their moments. The resulting variability in outputs such as number of trips or vkt provides a measure of sensitivity to input assumptions. These studies show how variance propagates within a model but only represent uncertainty to the extent the initial input distributions are accurate. They generally show uncertainty about inputs to be the key determinant of output uncertainty.

Zhao and Kockelman (2002) provided an early study of stochastic propagation of uncertainty, through a simple (25 zone) four-step travel model in Dallas, TX USA, using a Monte Carlo approach and 100 model runs. They found the demographic inputs and trip generation parameters to be primary contributors to the total vkt output and confirmed uncertainty at early stages of the multi-stage model (eg trip generation) was amplified across later stages[90].

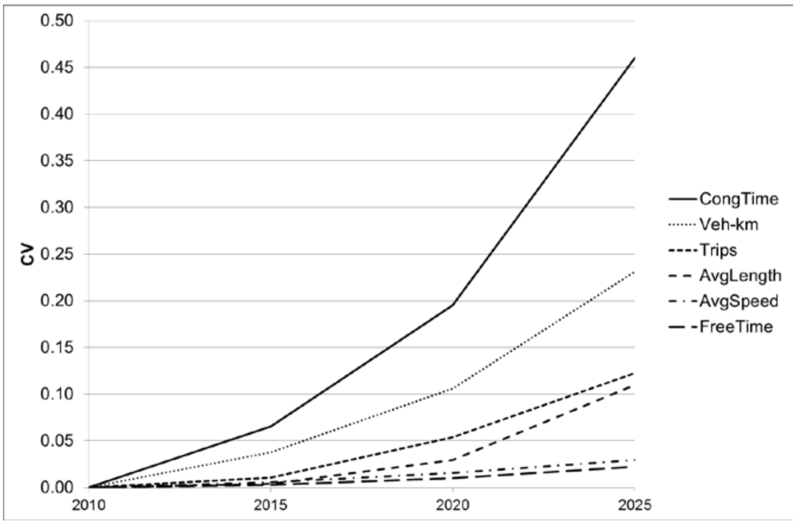
Manzo et al (2015) confirm available literature on uncertainty in transport models investigates both the sources and the effects of uncertainty in transport models – but only a few papers have focused on uncertainty deriving from model inputs alone. The majority of existing literature focuses on both model input and parameters uncertainty and appears highly context-dependent. With the Danish National Transport Model as a case study, they used Monte Carlo simulation[91] to examine the potential propagation of uncertainty in a limited set of socio-economic input variables (population, GDP, employment and fuel prices) and the effects this may have on uncertainty propagation over time for key outputs (such as trip numbers, vehicle kilometres and congested time). They quantified the level of

[90] They also found relatively little sensitivity to the parameters of their trip distribution and trip assignment models; attributing this to the particular forms used within their study model (eg iterative trip-balancing for trip distribution and equilibrium feedbacks used in trip assignment).

[91] Manzo et al acknowledge that the choice of the distribution used in Monte Carlo procedures is of crucial importance to correctly reflect the level of the variables' uncertainty.

uncertainty of output variables, by calculating the coefficient of variation[92] for each of the outputs. An important finding (while accepting the limitations of their study) was that while the uncertainty (and its propagation over time) in some output variables was unlikely to be material, others that may significantly affect potential value and investment decisions (eg congested travel time) exhibited non-linear and more significant uncertainty over time (see figure A.3).

Figure A.3 Propagation of uncertainty over time in Danish National Transport Model (Manzo 2015, figure 4)



Manzo et al (2015) showed in a similar Monte Carlo study that the coefficient of variation of trip number increased throughout the first three model steps, ie trip generation, trip distribution and mode choice, to finally reduce in the assignment model. This reduction of variance in the last step has been found in other studies.

Some of these issues raised are considered in more detail below.

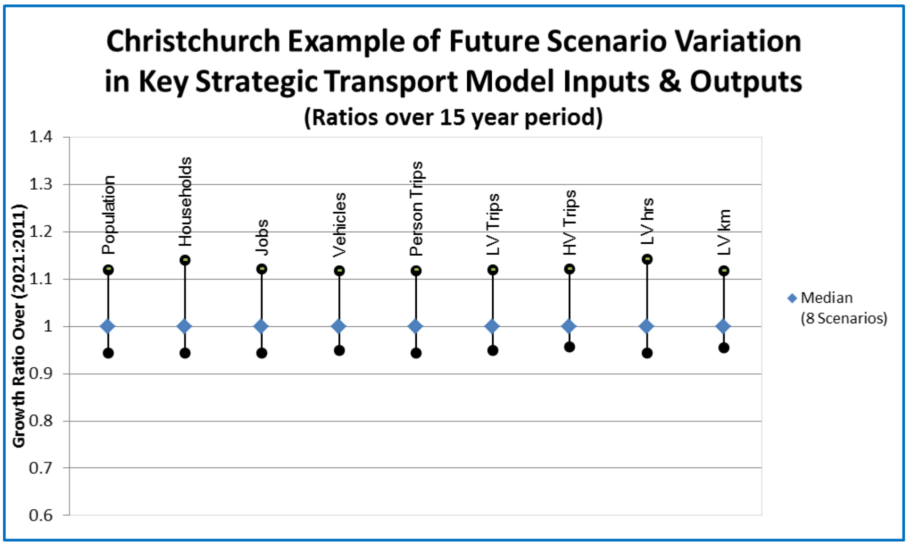
A1.5.3 Input variability – macroeconomic – population, employment and GDP

The trip generation step requires forecasts of population (trip origins) and forecasts of employment and school rolls (trip destinations) and the number of trips. The issues around population forecasts, to take one of the macro inputs, are expanded below to illustrate how uncertainty enters the transport model.

Population has been found to be highly correlated with transport demand and this, in combination with other assumptions currently commonly-applied within strategic transport (demand) models (eg temporal stability of trip rates) is reflected in future trip demand projections (see figure A.4 for an example).

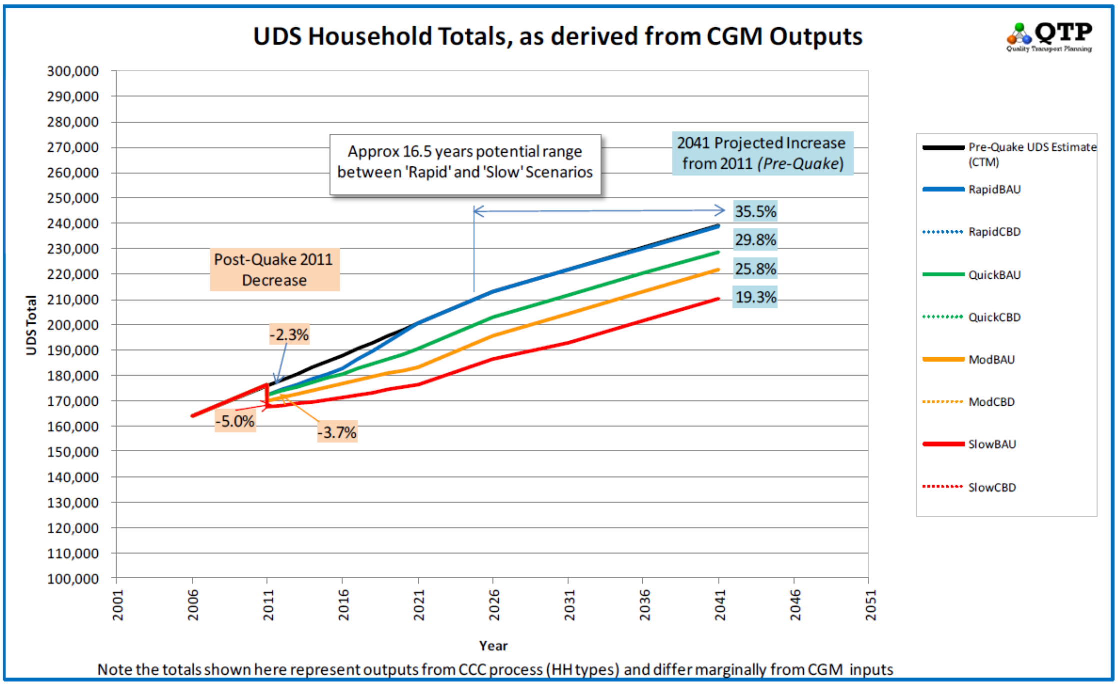
[92] The coefficient of variation corresponds to the standard deviation divided by the mean. Whether a particular coefficient of variation should be considered low or high variance will depend upon the distribution

Figure A.4 Example of strategic transport model potential input and output variance



Future population projections (usually prepared by demographers) are used as a common framework for national and sub-national planning, in a number of key policy areas. They may be used to analyse the determinants of population change, to present alternative scenarios, and to provide a base for other projections (eg of family and household formation, and labour force size).

Figure A.5 Example of strategic transport model scenario inputs for the Greater Christchurch Urban Development Strategy, as derived from the Christchurch Growth Model



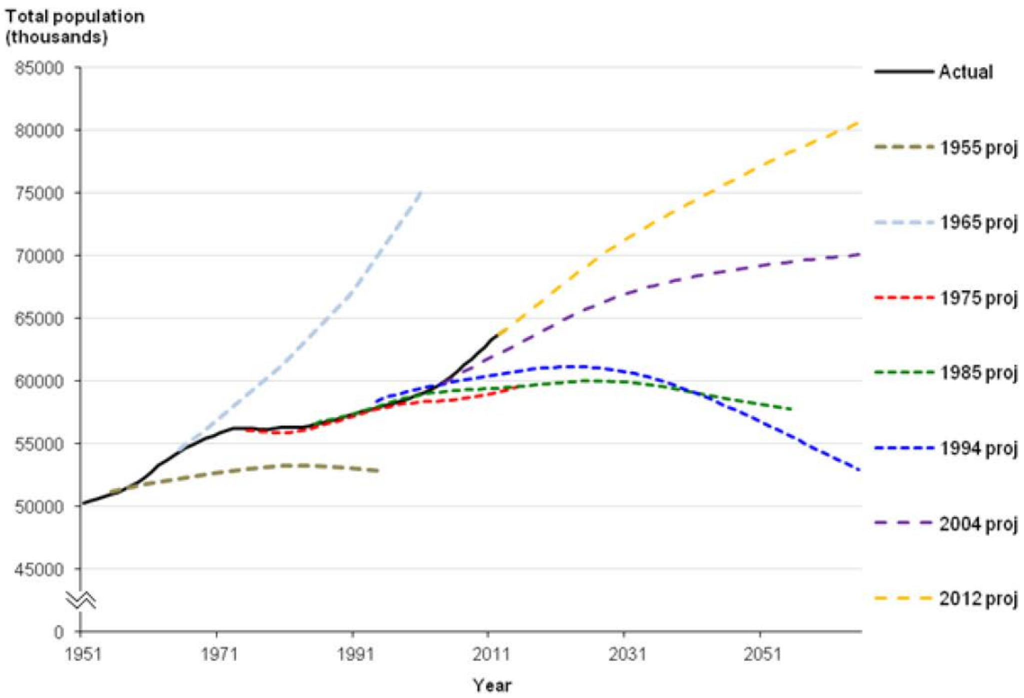
Note: UDS = urban development strategy; CGM = Christchurch growth model

Such projections have traditionally been derived 'deterministically', which simply means they are scenario-based projections, produced using specific assumptions – commonly about future fertility, mortality and migration patterns of the population. These underlying assumptions may be formulated from an assessment of short-term and long-term demographic trends, but there is no implication or *certainty* any of the assumptions or the resulting projections will be realised. The projections are, however, used to indicate possible changes in the future size and structure of the population, and also its finer-grained distribution (in New Zealand, 'sub-national' and 'census area unit' forecasts).

Further, these are often used, explicitly or implicitly, to inform preparation of transport model inputs, particularly for aggregated future scenario data in cross-classification demand models. Authorities producing such population projections (eg within both New Zealand and the UK) stress they are not forecasts. Statistics New Zealand view a forecast as being one prediction of what the population will be at a given date. However, this distinction is not necessarily shared by other demographers (eg Alho, Keilman) who argue a mid-range projection is inevitably used as a forecast. Within New Zealand urban planning and transport modelling in general, the latter does appear to reflect current practice.

The UK's Office for National Statistics (2015) has confirmed the (perhaps obvious) fact that UK population projection accuracy declines as the forecast period increases. Considering projections made at approximately 10-year intervals from 1955 (see figure A.6), the mean absolute percentage error at 20 years ahead was found to be around 2.7%, rising to over 8% at 35 years ahead. Errors in the projections of the total population were found to be mainly due to errors in the projections of the three components of population change (births, deaths and migration), although errors in the base year population estimates may also potentially contribute, because such errors are accumulative.

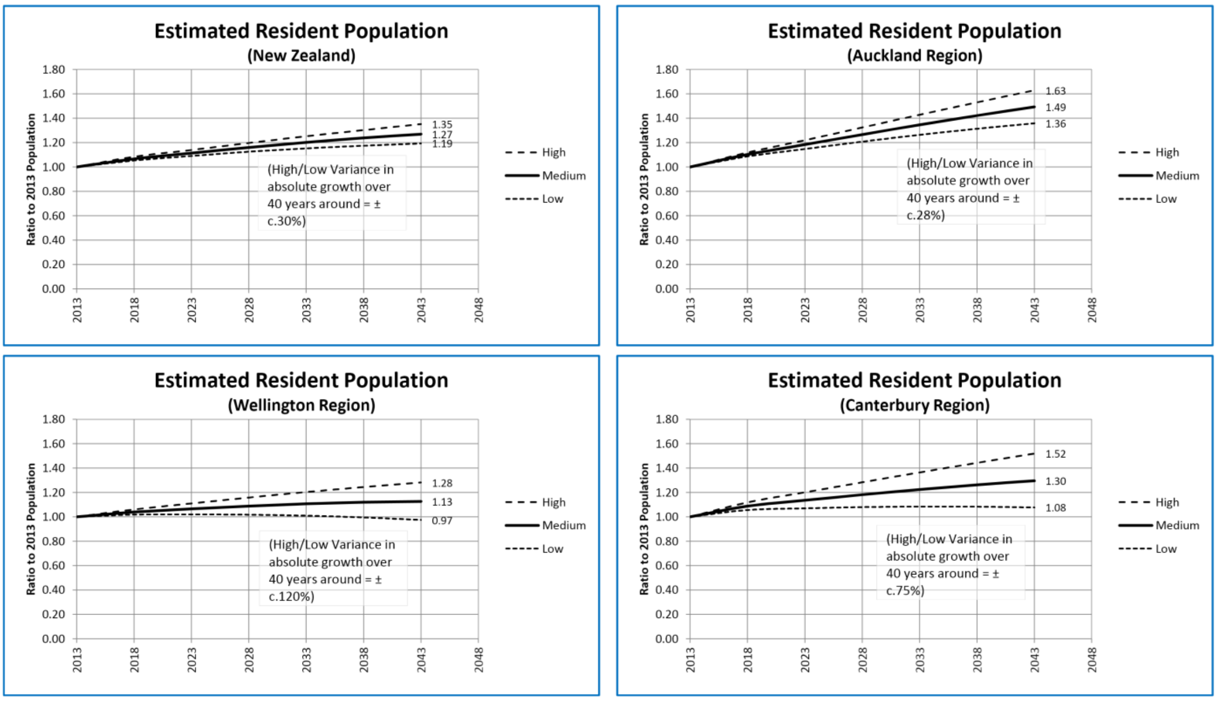
Figure A.6 Actual and projected UK population, 1951 to 2065, selected projections by base year



The actual national population total may be seen to typically depart from each projection within a period of only 5-10 year and this is attributed to a range of factors that were not anticipated (eg 1960's 'baby-boom').

In New Zealand, the potential variation in population growth, implied by the 2013-base New Zealand sub-national population projections, is shown in figure A.7.

Figure A.7 Projected population growth for New Zealand and major regions (2013–2043)



NB Data sourced from StatisticsNZ Subnational population projections, by age and sex, 2013(base)-2043 (released February 2015). The sub-national projections are consistent with the 50th percentile (median) of the National Population Projections 2014(base)-2068 (released 28 November 2014)

While such 'deterministic' approaches to realise alternative projection scenarios do give some indication of possible uncertainty, they do not quantify this uncertainty. To address (in part) this deficiency, the trend in population demography is towards increasing application of stochastic approaches.

In New Zealand, Dunstan (2011) outlined a stochastic method and summarised the results for his experimental projections of the New Zealand population (from a 2009 base). Uncertainty was modelled from historical data for fertility (total fertility rate), mortality (life expectancy at birth), and net migration, as well as for the sex ratio at birth. Uncertainty in the base population was modelled using expert judgement. Simulations of these parameters gives probability distributions around Statistics New Zealand's deterministic mid-range projection. Statistics NZ have recently officially adopted this stochastic (probabilistic) approach, to produce their latest release of *national* population projections (2014-base, released November 2014)[93].

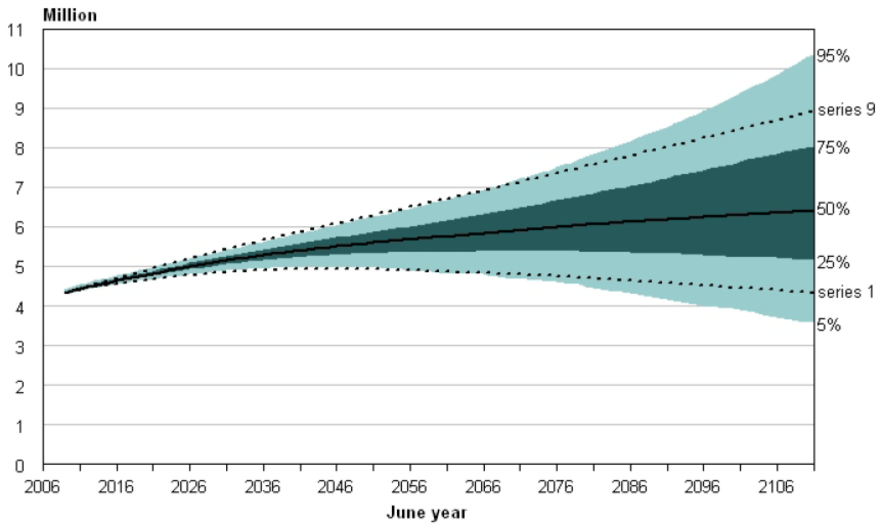
It is important to note the estimates of uncertainty adopted as the basis for most stochastic simulations, including those applied by demographers, are themselves uncertain. By modelling uncertainty, however, estimates of probability and uncertainty are available for each projection result. While no individual simulation is more likely, or more unlikely, than any other, the combined simulation results provide a probability distribution which can be summarised using percentiles. For each assumption, the median (50th percentile) is equivalent to the 'medium' assumption used in previous deterministic population. Similarly, the median stochastic projection is equivalent[94] to the deterministic projection that combined

[93] Consistent sub-national (and area unit) projections using the same stochastic approach, which would be required for application within local transport models or to inform their potential uncertainty, have however, at the time of writing, still to be released.

[94] In sense, if not absolute terms, given that the base estimates differ.

the medium fertility, medium mortality and medium migration assumptions in previous projections (ie series 5 in the 2009-base projections). Figure A.8 indicates the potential distribution provided by Dunstan, from which it may be deduced the 95%ile range at 40 years (the typical evaluation period for transport projects in New Zealand) in his experimental application was around ± 8.2%.

Figure A.8 New Zealand projected population probability distribution, 2009–2111 (Dunstan 2011, figure 16)[95]



More disaggregate projections for age-cohorts exhibit a greater degree of potential variance, and this factor may have some significance for uncertainty of derivative projections, for example when used to inform household formation rates, occupancy etc. based on life-cycle, as is typical in cross-classification transport (trip generation) models.

A1.5.4 Input variability - macroeconomic inputs – trip rates

Typically regression analysis is used to derive trip-to-household ratios, growth rates are applied to external trips and destinations are scaled to match the total of origin trips.

Overall travel demand (in terms of trip productions) is usually estimated as essentially the simple product of a demographic variable multiplied by a trip rate assumed to apply to the relevant variable[96]. Thus not only may potential uncertainty in the demographic variable be important (such as population as described above, or households), but also any uncertainty regarding trip rates and indeed the potential combination or the two. As noted above, one of the key assumptions often made in the application of future demand modeling is that key parameters calibrated to ensure base models reflect an existing situation will remain stable over time into the future – when available evidence that such assumptions are valid remains mixed (DfT 2015; Huntsinger and Rouphail 2013; Ortuzar and Willumsen 2011).

[95] 'Series 1' represents the deterministic 'low' forecast and assumes low fertility, high mortality and low migration; 'Series 9' represents the deterministic 'high' forecast and assumes high fertility, low mortality and high migration.

[96] Often these variables are segmented where significant differences may be identified for each cross-classification and trip rates derived and applied for each of these. Limited research in New Zealand (Falconer 2013) has, however, posited there may be a greater degree of uncertainty introduced by a model framework that requires such disaggregate variable estimates and a simpler approach may be as good or better, not least because it may-potentially free modelling resource to examine a greater number of scenarios for a reduced number of variables and parameters.

Another key macroeconomic influence on transport use is economic growth: it will tend to increase incomes and affect vehicle usage; it will tend to increase activities and raise trip attraction; and growth will alter willingness to pay travel costs and hence affect mode choice. In aggregate, it has been observed that GDP tends to lead to more traffic. The elasticity of traffic growth to GDP growth is widely measured and does differ by country, in part due to local conditions and, according to Ortuzar and Willumsen (2011), in part due to elasticity reducing with the level of GDP. However, a recent review by Dunkerley et al (2014) showed generally mixed results among the wider literature[97] and simply concluded that national passenger vkt elasticity to GDP was between 0.5 and 1.4 and the national freight tonnes elasticity to GDP was around 0.5 to 1.5, with even wider variation between sectors. It is possible the vkt relationship with economic growth is better defined in terms of gross national income or population, instead of GDP; this has not been taken up in this report.

Stephenson and Zheng (2013) report ranges in New Zealand studies of 0.21–0.55 for total car travel and 1.0–1.4 for road freight. They also distinguish between a 0.2% car-to-income short-run elasticity from a 0.5% long-run elasticity. Australian elasticities were recently updated by the Australian Productivity Commission.

A1.5.5 Input variability – regional inputs – urbanisation and other regional influences

As well as potential uncertainty with respect to overall national growth profiles of segments of the population (as they may affect transport demand) it can also be observed projection accuracy is generally proportional to the population size of geographic areas (Keilman 2005; Statistics NZ 2008). That is, demographic uncertainty generally increases as the size of the geographic area decreases. For the 1991-base, 1996-base and 2001-base New Zealand area unit projections (where the 2006 population exceeded 100 people), the absolute relative errors were found to under 5% for 60% of area units after five years. The errors exceeded 10% for 15% of area units after five years.

A major cause of the uncertainty within subregional population forecasts is migration (Cameron and Poot 2011). More generally migrations are seen as the weak link in any demographic study (OECD/ITF 2014).

A1.5.6 Input variability – industry inputs – freight, tourism.

Freight flows are typically handled separately from other vehicle flows in a transport model. Either regressions are run against factors such as GDP to derive elasticities or a proportion of all vehicle traffic might be assumed. One additional source of uncertainty in these models of recent years has been the effect of a shift to larger trucks. An example of a regional freight model is that recently provided by Stephenson and Zheng (2013). Comi et al (2012) provide an overview of urban freight modelling.

Another major sectoral traffic flow is that from tourists. The OECD/ITF (2014) reports tourism is rarely explicitly included in transport models. This provides an uncertainty in many parts of New Zealand where domestic and international tourism provide large traffic flows.

A1.5.7 Input variability – zonal inputs – coinciding development

As previously discussed and shown in table 2.1, the accompanying or subsequent change in land use surrounding a transport project can significantly affect transport usage. This has proven to be challenging for transport appraisal.

The widespread practice is to assume there is no land use change initiated by the transport investment (Willumsen 2014). Thus a forecast of surrounding land use is made and the traffic model is run to test the change in traffic flows generated *given* fixed surrounding activity. The land use forecasts will typically

[97] A range of elasticities are also reported at www.vtpi.org/tdm/tdm11.htm

include anticipated new land use but there is no explicit feedback within the traffic modelling between transport and land use.

It is possible to model the interaction between land uses and transportation. This can be done with various Land Use Transport Interaction (LUTI) models. Here travel costs (including time) cause household and firm changes, including re-location, and changes in property floor space, which in turn feed back into the transport model to affect trips and travel costs. OECD/ITF (2014) reports that such model track spatial redistribution of activity rather than net generative effects.

Willumsen (2014) concludes LUTI models suffer from requiring many assumptions that are difficult to validate. The data requirements also slow the process of model building considerably.

While the consideration of land use within transport models is a highly contested area, there are some factors that are clear.

First, if transport projects are to induce large land use changes then there will be some interdependency with non-transport policy makers and private sector developers (OECD/ITF 2014).

Second, induced land use changes, and hence the uncertainties surrounding them, are likely to be greater over the long-term rather than in the next few years.

Examples of where transport investments have not delivered to expectations due to lack of supporting policies and developments include the UK M65 built on the mistaken assumption that Central Lancashire New Town would be built, the Concorde not being granted inland air space for supersonic flight throughout the world (Mackie and Preston 1998) and New Zealand's Bridge to Nowhere.

An associated issue with local land use is the degree of zonal disaggregation. Small zones will pick up inter-zone traffic that might otherwise be intra-zone with larger zones – these flows are typically important for public transport and toll projects. Larger zones will miss a lot of intra-zone traffic but will be quicker to run and allow a wider area to be included. However, the inter-zone GTC will be less accurate as zone-to-zone travel is modelled from zone centroid to zone centroid.

A1.5.8 Model parameter variability – assumptions around trip generation and trip distribution

The key role of any transport model is to take the information about people and freight at potential origins and destinations and generate trips across the intervening routes. The equations and algorithms determining these trips are also subject to uncertainty, both in terms of the current (base) relationship and in terms of any forecast relationships.

Two major challenges faced within transport models, even given fixed and exogenously provided land use assumptions, are decomposing current trip behavior into repeatable trips and forecasting future relationships.

At the core of any travel model is an assumption that households generate trips to specific activities and that these trips occur regularly. But studies have shown substantial non-repeated trips occur. Clegg (2005) noted low recurrence of travel across Lendall Bridge in the UK. Similarly Rasouli and Timmermans (2012b) note a person's travel time, rather than being fixed, shows substantial variation across the day and between days of the week.

Going forward, there is also evidence of changing relationships. Wallis et al (2012) note the following tendencies in their review of 11 urban road schemes in New Zealand, Australia, UK and Europe, where the focus was primarily on effects within 12 months of scheme opening:

- Some switch from public transport to car will occur with the magnitude observed being around an extra 2–3% corridor traffic, being around half of the 'induced' traffic.

- Some trip retiming will occur whereby people change their time of travel to take advantage of any decongestion that may result from increased road capacity, thereby reducing the decongestion effect – a tendency referred to as 'reversion to the peak'.
- There were only small effects noted in the subset of schemes with 'after' studies of trip end shifting or generation of new trips.

The first issue above leads to consideration of the level of population and trip disaggregation required. If a large portion of current trips are unexplained then maybe further disaggregation of trip generation and distribution is appropriate, eg consider trip rates by time of day for 20–25 year olds with a 15-year-old car carrying two occupants heading to university between 9am and 11am. But this cohort is likely to be very difficult to forecast[98]. And possibly many trips are of a more random nature and these trips would be better forecast using aggregate figures. Associated with this trade-off between disaggregation and potential forecast error, Willumsen (2014) points out some aggregation may be necessary when threshold effects occur (eg income above a set level).

Table 2.1 in chapter 2 of this report summarises some of the key challenges in reducing uncertainty within the four-step transport model.

A1.5.8 Goodness of fit

As in all models, there is a residual or unexplained error with transport models. This in itself is not reason to disbelieve the model outcomes. However, a large unexplained error in a model does leave the potential for bias in the parameter estimates should an important explanatory variable be omitted from the model.

In general terms, transport models are expected to have a high goodness of fit, as measured by measures such as the percentage difference between model counts (M) and observed count (O) for links, correlation coefficients, the percentage of root mean square error and the GEH[99] formula where:

$$GEH = \sqrt{\frac{2(M-O)^2}{M+O}} \qquad \text{(Equation A.5)}$$

Various transport authorities, including the Transport Agency[100], specify acceptable tolerances for different situations. Willumsen (2014) states that in 'general terms between 60% and 85% of the volumes in a traffic model should have a GEH less than 5.0'.

Similarly model travel times can be compared to observed travel times. One requirement specified by the Transport Agency is that modelled travel times for all routes should be within the 95% confidence interval of observed travel times. The New Zealand model users group also recommends travel time for 80% of routes to be within 15% of surveyed times.

As an example of goodness of fit measures, the TDG (2015) validation of the then three-step model shows modelled travel times generally within 15% of average observed times.

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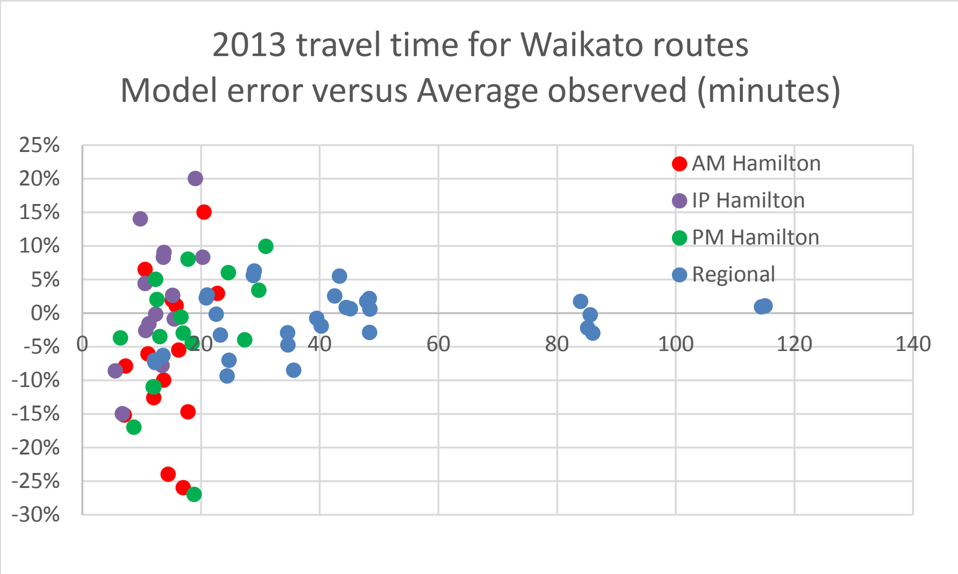
[98] Cameron and Poot (2011) report on the difficulties of making sub-regional population forecasts.

[99] An empirical formula named after London transport planner Geoffrey E Havers and similar to the chi-square statistic (which, unlike the GEH, follows a probability distribution).

[100] www.nzta.govt.nz/resources/transport-model-development-guidelines/index.html

Figure A.9 Forecast error in Waikato traffic model



Source: TDG (2015, pp15–19)

A2 Valuation of options

Three valuation methods and one approximate valuation method were introduced in section 2.5.3. Further detail of these methods is provided below.

Kodukula and Papudesa (2006, p59) point to three methods that are regularly used to value both financial and real options: the Black Scholes model; the Binomial Lattice; and Monte Carlo simulations[101]. Martins et al (2015) add the fourth approximation method, namely decision analysis.

- The Black Scholes Option Pricing Model (BSOPM) effectively assumes the cash to be delivered upon expiry of the option is risk free, because it can equivalently be delivered by a market-traded portfolio, but the amount of that cash will depend on how the underlying asset prices evolve according to an assumed lognormal distribution, ie the probability of future asset prices is known and risk adjustment of expected cash flow is not necessary. Note this formula can only be applied to European options, ie an option that can only be exercised on its expiry date.
- The Binomial Option Pricing Model (BOPM) also takes (a) the known (or assumed) distribution of underlying asset prices and represents possible changes, including potential changes in distribution parameters, as discrete binomial steps from period to period, then (b) dissects an expected underlying asset price for each state into a market risk premium and a remaining value, termed the certainty equivalent expected value, then (c) considers these certainty equivalent expected cash flows as risk-free and hence applies a risk-free discount rate to determine a present value and, finally, (d) derives, working backwards from the option expiry, the optimal strategy by mathematical induction applied to these certainty equivalent values. The method enables pricing of a wide range of future scenarios and choices at one or multiple periods (eg optimality may be in terms of to invest now or wait or expand

[101] Cetinkaya and Thiele (2014) include the BSOPM within a wider set of analytical valuation methods and group the BOPM and MCS within numerical methods (that can also include methods to approximate the partial differential equations used in the analytical methods).

or contract) and hence can price the more common American options (ie exercise can occur any time before expiry) and many compound options. The model also enables options on a wider range of underlying assets to be valued. In both cases, the model is more general than the BSOPM[102] but still requires (a) some knowledge of the distribution of future underlying asset price outcomes and (b) a method to determine the certainty equivalent expected value, with the typical default being the CAPM.

- A Monte Carlo Simulation (MCS) provides an even more general method to produce likely outcomes of the underlying asset price and optimal strategies, and in turn the option expected cash flows, by simply simulating a range of scenarios and decision rules. The method also requires (a) some knowledge, as above, of the distribution of future underlying asset price outcomes and (b) some method to convert the derived future expected cash flows into risk-adjusted present values, with the typical default being via a risk-adjusted discount rate, often derived from the CAPM.
- Decision analysis shows a road map of the key decisions and uncertainties, with costs and payoffs and subjective probabilities. The decision tree depicts the choices ahead and their probable implications while the probability weighted revenues and costs can derive an 'expected value' for the NPV of the project, with the discount rate including a subjective risk premium. NPV sensitivity to the probabilities can be quickly assessed by changing any assumption. Neely and de Neufville (2001) point to the widespread use of decision analysis in operations research but warn the constant discount rate assumption weakens the effectiveness of the approach for long-life projects.

Further detail follows on the three valuation models.

A2.1 Black Scholes Option Pricing Model (BSOPM)

The standard valuation method used with financial options is the Black Scholes model. In essence, the assumption is the option can be traded, without profit, for a portfolio of bonds and equities that have the same risk profile, ie a replicating portfolio exists and there are no arbitrage opportunities. This is a valid assumption for many financial options, especially where trading opportunities for options exist. Eschenback et al (2007) note the importance of trading opportunities for financial options as a method to validate option pricing models and further record that this validation is not possible for real options as trading is generally not undertaken.

The BSOPM is further limited to only valuing European options, ie options with a fixed date of exercise. The more general American option, where exercise can occur any date up to expiration of the option, requires another method.

The formula for the value of a European call option is

Value of option (ie option premium) = $N(d_1)*S_0*exp(-I*t) - N(d_2)*X*exp(-r_f*t)$

Where:

$d_1=(log_e(S_0/X)+(r_f-I+0.5*\sigma^2)*t) / \sigma*\sqrt{t}$

$d_2=d_1 - \sigma*\sqrt{t}$

$N(d_1)$ and $N(d_2)$ are the values of the standard cumulative normal distribution at d_1 and d_2

The variables are shown in table A.2.

[102] The BOPM converges to the BSOPM valuation for simple European options with underlying asset prices that follow Brownian motion.

Table A.2 Variables in Black Scholes equation

Variable	Description	Example
S_0	Current value of underlying asset	$200 million
l	Annual leakage (eg dividend or forgone cash flow) per period	10%
t	Years to expiry	15
X	Strike price (eg cost of investment)	$220 million
r_f.	Risk free interest rate pa.	5%
σ	Volatility (standard deviation) of annual future cash flows of underlying asset.	30%

Applying the numbers presented in table A.2 gives a call option value of $10 million. That is, this is the amount, in present value terms, expected to be gained by having the right to buy an asset at $220m at the end of year 15, given the asset in the meantime is expected to face volatility of 30% pa and incur cash outflows of 10% pa. A real-option interpretation of this example could be a firm waiting 15 years to commercialise a new patent at a fixed cost of $220m which incurs 10% costs pa to retain the patent and which could only create a business worth $200m now if commercialisation occurred today.

The actual value-add gained by owning the option is higher than $10m as currently the investment would be worth -$20 million (being $200m less $220m) whereas having the ability to fix the price of investment for 15 years is currently valued at $30 million more (being $10m less -$20m) – this is the extra value of the call option.

Note the use of the risk-free rate to effectively discount the expected year-15 cash flow. A risk premium is considered inappropriate in this calculation because the replicating portfolio is such that the cash flow to be received is certain once the difference between strike price and future asset price is struck, ie there is no risk around the amount of the cash once it is determined (nor any payment risk).

Kodukula and Papadesu (2006) suggest using the Black Scholes formula as validation of other valuation methods but otherwise the Black Scholes model will not be further considered in this report.

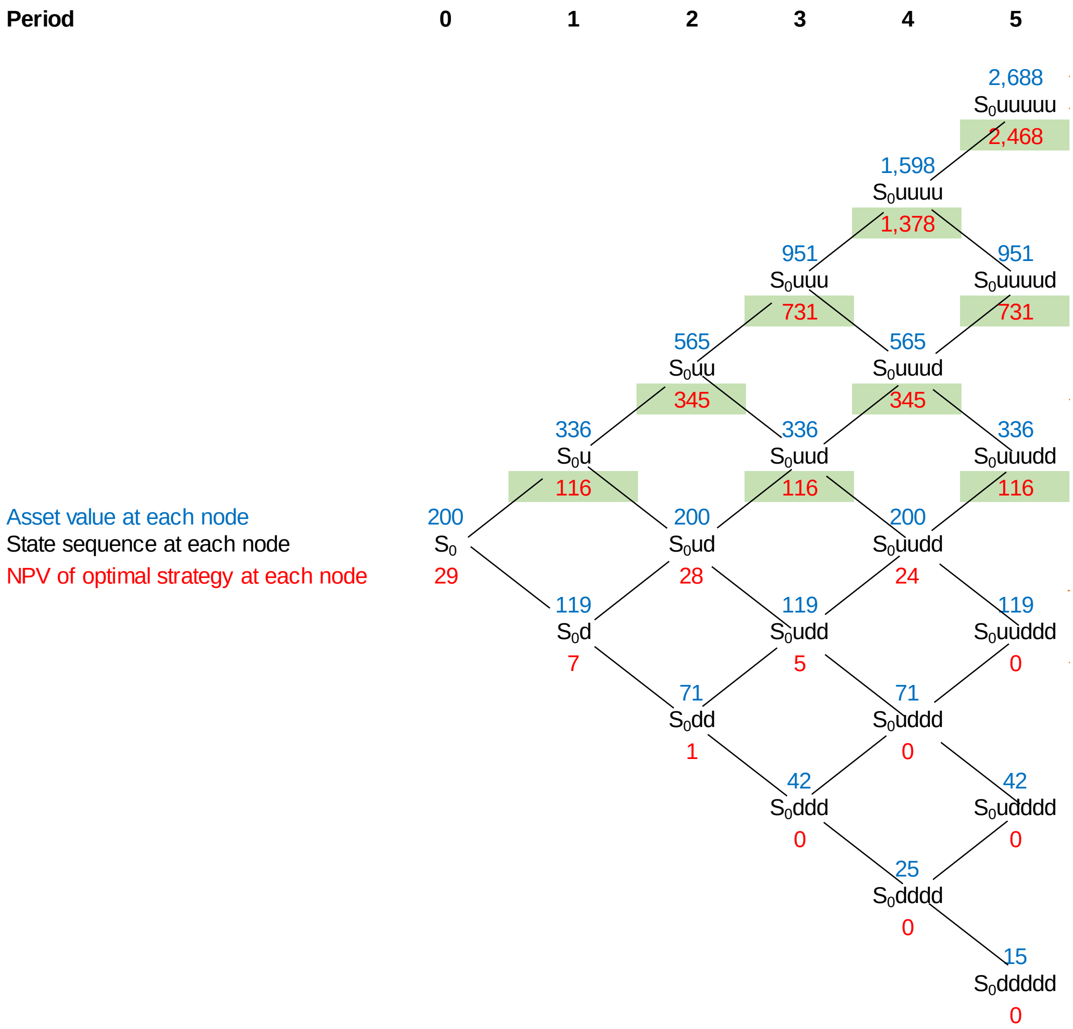
A2.2 Binomial Option Pricing Model (BOPM)

Another widely used model to price financial options is based on a binomial lattice. Rather than considering continuous asset price changes, the BOPM breaks time into discrete periods. The state of an asset, principally the asset price, is assumed to evolve from a starting point (S_0) to one of two states in the next period, typically referred to as the 'up' and 'down' states and denoted at nodes in period 1 as S_0u and S_0d (see figure A.10). The up/down movement from state to state might appear too simple but after many periods the distribution of state outcomes will tend towards the type of lognormal distribution often found in markets. With sufficiently small intervals and a large number of periods, the BOPM valuation will approach the BSOPM valuation (Cardin and de Neufville 2008).

After building a lattice of future states, typically using probabilities derived from past asset price movements, the next step is a backward induction process known as stochastic dynamic programming, starting at the last period, to calculate the optimal decision at each node (ie at each state within a time period). This decision can be to invest or to wait or to abandon, depending on the option being modelled. This flexibility enables American options to be valued, plus others. This stepwise method also allows parameters such as strike price and volatility to change during the option period and/or for discrete jumps in asset prices to be considered (Kodukula and Papudesu 2006).

The third important element of BOPM is the transformation of unadjusted expected asset values into certainty equivalent values. This step, in particular, marks the BOPM apart from decision trees. To paraphrase Schulmerich (2010), the basic idea with DTA is to calculate expected present values with subjective probabilities and a risk-adjusted discount rate whereas, with BOPM, the probabilities are derived from actual volatilities, the expected values converted into certainty equivalents and a constant risk-free discount rate is applied. The risk adjustment depends on the nature of the linkage between the underlying asset and a tradeable risky asset. In the example below the assumption is that the underlying asset is tradeable. More generally, the linkage can be assumed via the CAPM.

Figure A.10 Binomial lattice for call option



Applying the method to the example of table A.2 illustrates the model. The asset values, states and option values at each node are shown in figure A.10. Take the 15-year option period and split into five 3-year periods. The following notes start from period 1. Note the risk-adjustment step is discussed further below these bullet points.

- The current value of the commercialised asset is $200 (with the millions unit dropped), below the $220 million cost of investment.

- One period later (ie three years), the value of the commercialised asset is modelled to be either valued at $336 or $119, depending on how the market for this product evolves over time (the multiplicative factors U and D used to calculate each transition derive from the volatility parameter).
- In period two, the mix of up and down moves leads to possible values of $565, $200 and $71.
- After five periods, the range of values is $15 to $2,688. Clearly being able to commercialise the patent at a cost of $220 when the market value of the business is $2,688 would be very attractive. Conversely, no commercialisation would occur if the state of the world was such that the market value of the business would be $15 (ie creating a loss of $205). The induction process starts at the end period and calculates the NPV of the optimal strategy at each time period. For example, the choice in each state at period 5 is to invest at $220 and receive the asset value associated with that state, thus the NPV value of each optimal decision is the node value less $220 when the node value is greater than $220 (ie invest) and zero otherwise (ie not invest).
- In period 4, the choices are to invest or wait at each node. The value of investing is the node value less $220 (being an immediate return in this example). The value of waiting is the weighted average of the next period expected optimal NPV, eg for the node with asset value of $200 in period 4, the choice would be to not invest but wait another period with the expectation of an NPV of $24, being the discounted weighted average of the $116 if an 'up' state emerges and $0 if a 'down' state emerges.

The net result of this backward induction reasoning, in this case, is the (American) option to wait and commercialise at any 3-year point over the next 15 years is valued at $29m, or $49m higher than the NPV of commercialisation today and $19m higher than the European option value derived with the BSOPM above.

The missing step in the description above is how to estimate the risk-neutral future value at each node. This is where the BOPM diverges from the standard NPV method in that the risk adjustment is to the numerator rather than the denominator. Take again the $S_o$uudd node showing period 4 asset value of $200. The choice is to invest or wait.

- Investment would bring a return of -$20 (ie $200–$220). In this example, the $200 cost and $220 return are immediate so no risk adjustment is required.
- The alternative choice is to wait until period 5. This is expected to deliver one of two risky outcomes, either $116 or $0. These risky outcomes can be converted to a risk-neutral outcome (ie one that delivers a risk-free return) by weighting $116 by 0.2448 and $0 by (1-0.2448), thus giving a certainty equivalent value of $28. Discounted back to period 4 at the risk-free rate, the present value in period 4 is $24, as shown.

The maximum value at this node would be obtained by waiting (ie -$20 versus $24) and hence the optimal value is shown in the lattice at this node as $24.

So where did the risk weightings come from? Termed the risk-neutral up probability, the formula in this case where the state asset is a traded asset is $((1-I/X)*r_f – D)/(U-D)$ (see Guthrie 2009, p31).

To recap, in this example the cash return and cash outlay from any investment was assumed immediate at each point in time and hence required no risk adjustment while the expected next-period return was converted to a certainty equivalent value using a formula that matched the 'immediate cash return' assumption and then discounted at the risk-free rate. The highest net value was chosen at each node as the result of the optimal decision.

Examples of applying the BOPM to other options are provided in section A2.4.

A2.3 Monte Carlo simulation

A Monte Carlo simulation of option values can proceed in various ways.

De Neufville et al (2006) suggested an approach for valuing flexibility based on Monte Carlo simulations that entails three steps, as below.

- First, perform a standard DCF on the inflexible system design using deterministic projections of the exogenous factor(s) affecting value.
- Second, apply a stochastic process to generate a distribution of projections for exogenous factor(s) affecting value. Simulate several stochastic scenarios and perform a DCF analysis on the inflexible system for each scenario. This Monte Carlo approach provides a distribution of possible value outcomes measured using the standard NPV approach.
- Third, repeat step 2 for the designs that incorporate technical flexibility and managerial rules. This third step also creates a distribution of NPV, which is one upon which the designer may act. The goal is to act on desirable properties of the entire distribution to take advantage of upside opportunities and reduce possible downsides.

One appeal of the method is the readily understandable and transparent output in the form of a distribution of NPVs, to which decision makers can then apply their preferred decision rule. This rule may be the traditional 'highest expected value' or it could be to limit alternatives to those with 5% percentile above a threshold (ie a value-at-risk approach).

Another Monte Carlo approach is the least squares Monte Carlo method devised by Longstaff and Schwartz (2001). Power et al (2015) provides the following intuition behind the least squares Monte Carlo method: 'the NPV from investing "today" (exercise value) is compared with the expected NPV from investing "tomorrow" (holding or continuation value) calculated using ordinary least squares regressions across all simulated paths. If the holding value is higher than the exercise value, then it is optimal to delay the investment one period'."

While a Monte Carlo approach offers much flexibility, the method suffers from the need for a very large number of runs when there are multiple decision points (eg an American option with the right to exercise any day in the next year will require 365 runs of 1000, say, simulations) and the need for largely subjective judgements about the distribution of future outcomes and the risk premiums to apply to discount rates (Kodukula and Papadesu 2006).

A2.4 Valuations of option types

The following examples are provided to give some insight into the valuation of real options, as per the BOPM, and some of the assumptions and their practical implications. This BOPM has been used with transport ROA previously and has widespread application. The examples were drawn from textbooks by Guthrie (2009) and Kodukula and Papudesu (2006). The reader is referred to these texts for more examples or more detail about these examples.

The intermediate aim of the BOPM is to build two sets of lattices, one for a state variable and one for the risk-neutral value of the optimal cash flows at each state node. The following steps are taken (a variation of Guthrie 2009, p67):

- Construct a decision tree to illustrate the choice set at each period.
- Specify a state variable and estimate the lattice of values (ie estimate X_0, U and D and derive the lattice).
- Estimate the risk-free rate (r_f).

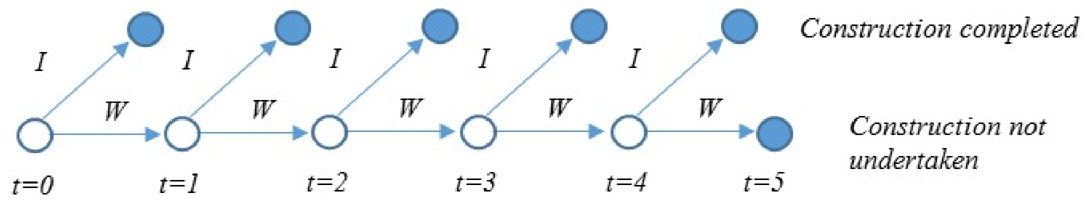
- Calculate the risk-neutral probabilities, using formulas that will depend on whether the state variable is traded on spot markets, on future/forward markets or is not traded. This is probably the step that will require more attention by readers.
- Build a tree of market value, by applying the risk-neutral probabilities to the future period cash flows under the different choices and choosing the highest value (ie the optimal decision).

A2.4.1 Timing options (see section A2.3; Guthrie 2009, p122)

In many cases a key question is whether to invest now or defer investment until some uncertainty is resolved. An example of a timing option is as follows. The workings are now laid out in a stepwise fashion, with more attention than previously given to each step. In this example the manager holds the right for 4 years to construct an asset for an immediate outlay of $102, which will be completed and available for sale in 1 year. Other detail follows in each step of the analysis.

- Step 1. Construct the decision tree. At 5 points in time the manager has the choice as to whether to invest (I) or wait (W). If invest, then the project (and option) will be completed one year later. If invest is never chosen then the option will lapse in year 5.

Figure A.11 Decision tree for a timing option



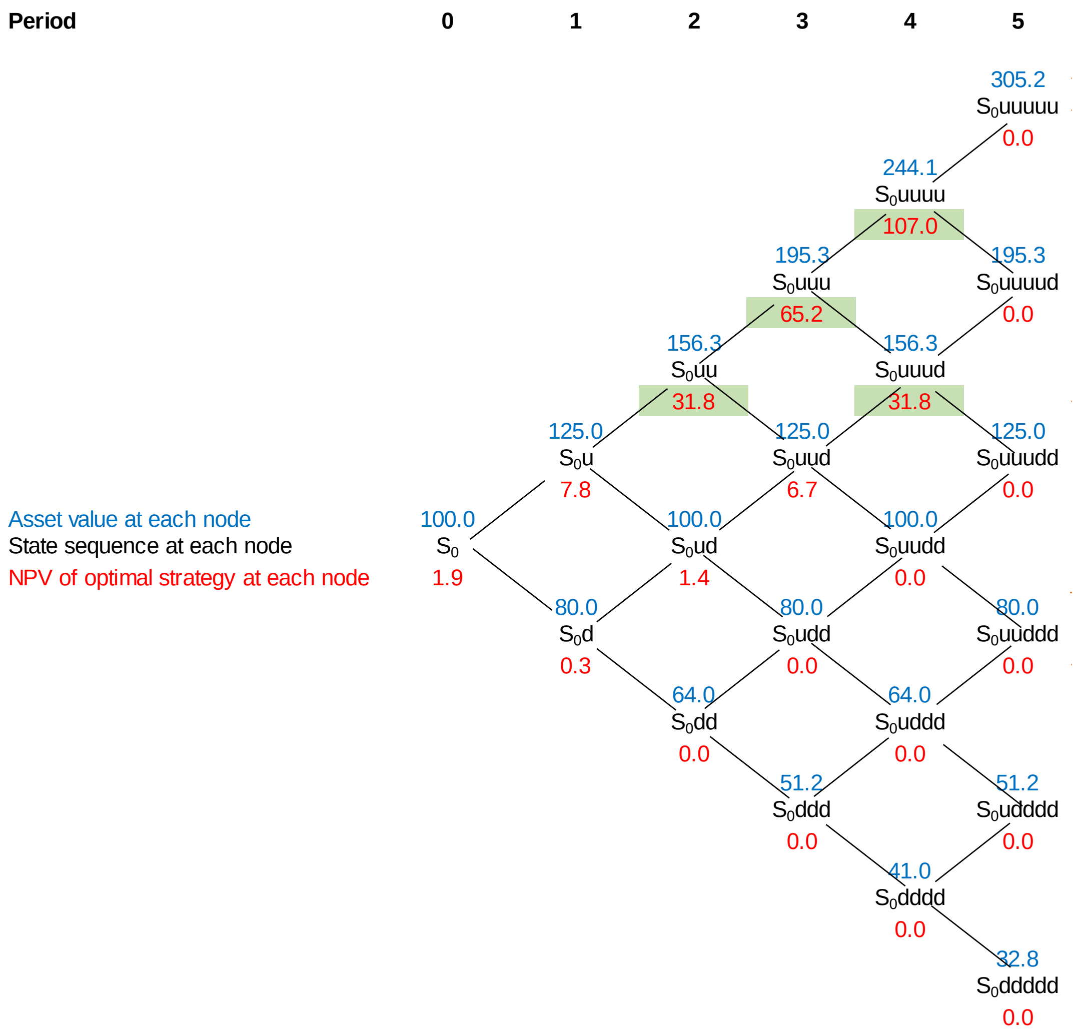
- Step 2. Calculate state variable lattice. The current market value of the underlying asset is given as $100. The underlying asset is not, on average, expected to increase in value but does have underlying volatility (σ) of 23.315% pa, implying U=1.25 (from $U=\exp(\sigma*\sqrt{t})$) and D=0.80 (from D=1/U). Applying the factors to the initial state provides the state variable lattice (ie the X's shown above the node descriptor in figure A.12). Note, these U and D factors assume that the underlying asset value follows a random walk. It is possible to make other assumptions.
- Step 3. Calculate risk-free rate. The risk-free rate is given as 5% pa (based on the market yield for a one-year risk-free bond).
- Step 4. Calculate risk parameters and returns from investment. In this case the project's state variable is not traded but has a correlation with the market of risky assets (β=1.25). This is an application of the CAPM, ie the underlying asset is assumed to go up and down, albeit in an exaggerated fashion, with the major share market index that would have been used for measurement. This has two implications: it will influence the risk-neutral up and down probabilities (as used in the previous example); it will also be used to derive a risk-adjusted value for the return from investment as in this case there is a one-year delay between any cash outlay and any cash inflow, during which time the asset value can change. The key factor in both these calculations is a risk-adjusted growth factor (K) of 0.9, based on r_f=5%, an assumed market risk premium=10% and the derived risk-adjusted growth factor formula (K= asset return (average of U and D) less beta (β=1.25) times the market risk premium (0.1) = 1.025-1.25*0.1= 0.9). The risk-neutral up probability is now 0.2222 (being (K-D)/(U-D)). The calculation of market values from investment at each node is shown by two examples.
  - Take the node S_0uuu. If invest, the current outlay is $102 and the current underlying asset is $244.1 but this could change in the year before construction is completed. The risk-adjusted

present value of the cash inflow is $209.0= (0.9*$244.1/1.05) i.e. the current value is adjusted downwards to take account of the risk during the next year. Deduct the $102 outlay and the market value of investing at this node is $107, as shown.

- Take $S_o$uud. If invest, the current outlay is $102 and the current underlying asset is $125 but this could change in the year before construction is completed. The risk-adjusted present value of the cash inflow is $107.0= (0.9*$125.0/1.05). Deduct the $102 outlay and the market value of investing at this node is $5.0. This value is not shown in the lattice as it was exceeded by a waiting strategy.

- Step 5. Calculate the market value lattice. The value at each node (shown below the node descriptor) is the expected risk-neutral cash flow of the optimal decision. For example, at the top right node the expected cash flow is zero as it is too late to act. Drop back one period and the optimal decision is to invest, as the market value of investing ($107.0, as calculated above) exceeds the $0 return in period 5 from waiting. An example of where it would be optimal to wait is shown at node $S_o$uud. Here the market value from investing was shown above to be $5.0. If the manager were to instead wait then the expected return is the risk-weighted average of the next period optimal values. In this case the calculation is (0.2222*$31.8 + 0.7778*$0)/1.05 = $6.7, as shown. That is, the optimal decision is to wait and hence this value is shown as the expected market value at node $S_o$uud.

Figure A.12 Binomial lattice for timing option



The following points are noted about the calculation.

- The option is valued at $1.9 at time zero, above $0 and above the inflexible NPV which would be negative. The option value was derived from progressively moving leftward through the lattice, calculating the market value of each optimal decision.
- The situations when the manager would choose to invest are shown as the shaded nodes.
- After one period, the optimal decision is to wait irrespective of whether the value of any potential investment went up or down. If asset prices went up, the option would be valued at $7.8 in period 1, or if asset prices went down the option would only be worth $0.3. Either outcome is better than the loss expected by investing immediately.
- After two periods, the investment would be undertaken if asset prices had increased over the first two periods. By then the underlying asset was worth $156.3 and the cost of investment was still $102. Given that there is a one-year delay before the asset value is realised and in that time the value can change again, a risk-adjustment is required to calculate the risk-neutral equivalent in period 2. This amount is (0.9*$156.3/1.05) = $209.0 less the $102, giving $31.8, as shown.
- To put another way, the expected period 2 value (following the two up periods) is not given as the average of next period up ($195.3) and down ($125.0) states, but rather a lower value of $140.67 (=0.9*$156.3), a number that can be interpreted as a 'certainty equivalent' expectation. The period 2 cash flow equivalent is then this number discounted at 5% less the $102 outlay.
- Note, the discounting of this certainty equivalent value is at the risk-free discount rate. Effectively, instead of the more traditional risk adjustment coming through the denominator, the allowance for risk has been undertaken through the numerator.
- Taking another example, if instead of values rising in the first two periods, there was one up and one down transition then the investment would not be undertaken and the option value would by then be worth $1.4.
- Alternatively should the first two movements of asset prices be downward then the option would be worthless. At this stage it would be possible to predict that the option would not be taken up.

The following points are noted about the assumptions within the model.

- Effectively taking up the option at period 2 is assumed to be cash-out of $102 at the end of period 2 and cash-in at the end of period 3 that is indeterminate but is conservatively estimated to be $140.67.
- If the asset is not cashed up in period 3 but instead held for a longer period then any subsequent return would be considered part of a subsequent investment and not part of the real option.
- The valuation assumes the value of the investment asset follows a GBM price trajectory and there exists a portfolio based on traded risky assets that has a correlated cash flow profile. If the asset in question was an oil well then these assumptions are reasonable. Whether the assumption is valid for a road or bridge is unlikely.

The following points are noted about the investment inference.

- The option to time the investment has value (in this case).
- Consideration of the real option value has provided insights into the conditions required for the investment to be value-adding: the value is in waiting until the manager is more certain that

favourable demand conditions will be sustained; and the value is derived from having a fixed cost and being able to choose the time of investment.

- The lattice shown also highlights that the option would be exercised (ie the investment at $102 undertaken) under three other circumstances (see the shaded nodes). This information is largely academic since the option would be expected to be exercised at period 2 (if demand improved in periods 1 and 2). Higher asset values might subsequently occur but so too could situations where the investment proved to be unprofitable.

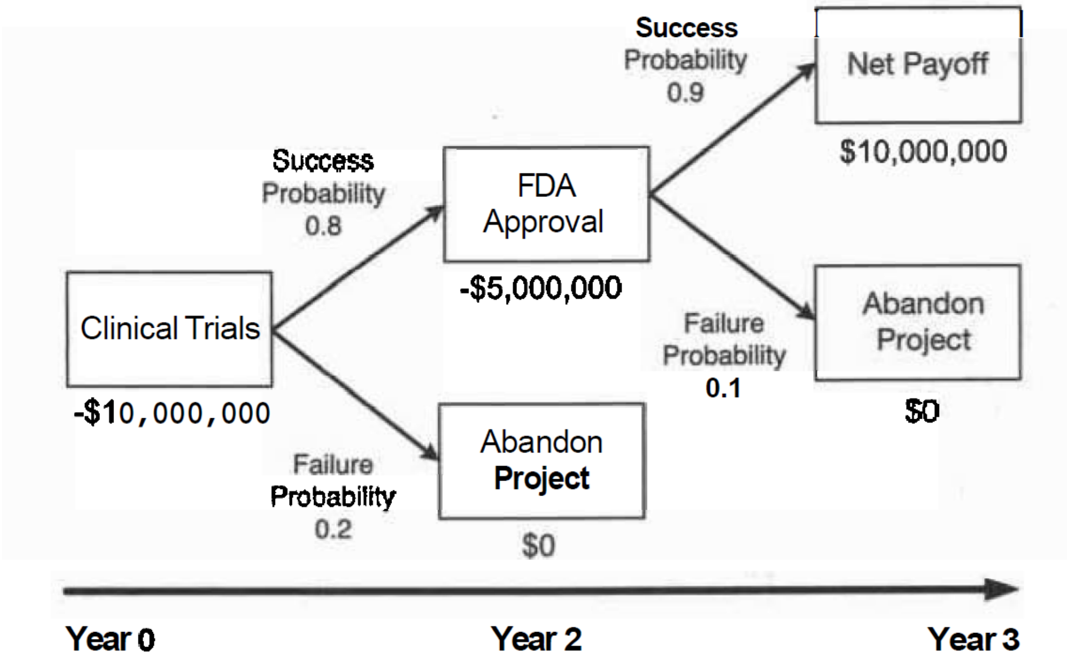
Guthrie (2009, p125) shows the value of timing flexibility in the above option would increase quickly if the term of the option were to increase from one year (ie the traditional now-or-never choice) to five years (as in the example above) but little extra value is added by increasing the term beyond eight years.

A2.4.2 Binomial lattice with DTA (see Kodukula and Papadesu 2006, p174)

One more example is provided. In this case a decision tree is combined with a binomial lattice, thus combining the analysis of market risk and private risk. The situation is that of a drug company undertaking trials and getting Federal Drug Agency (FDA) approval before taking the drug to market. There is private risk in the trials and approval and market risk around product demand.

- Step 1. Construct the decision tree.

Figure A.13 Decision tree for FDA trial

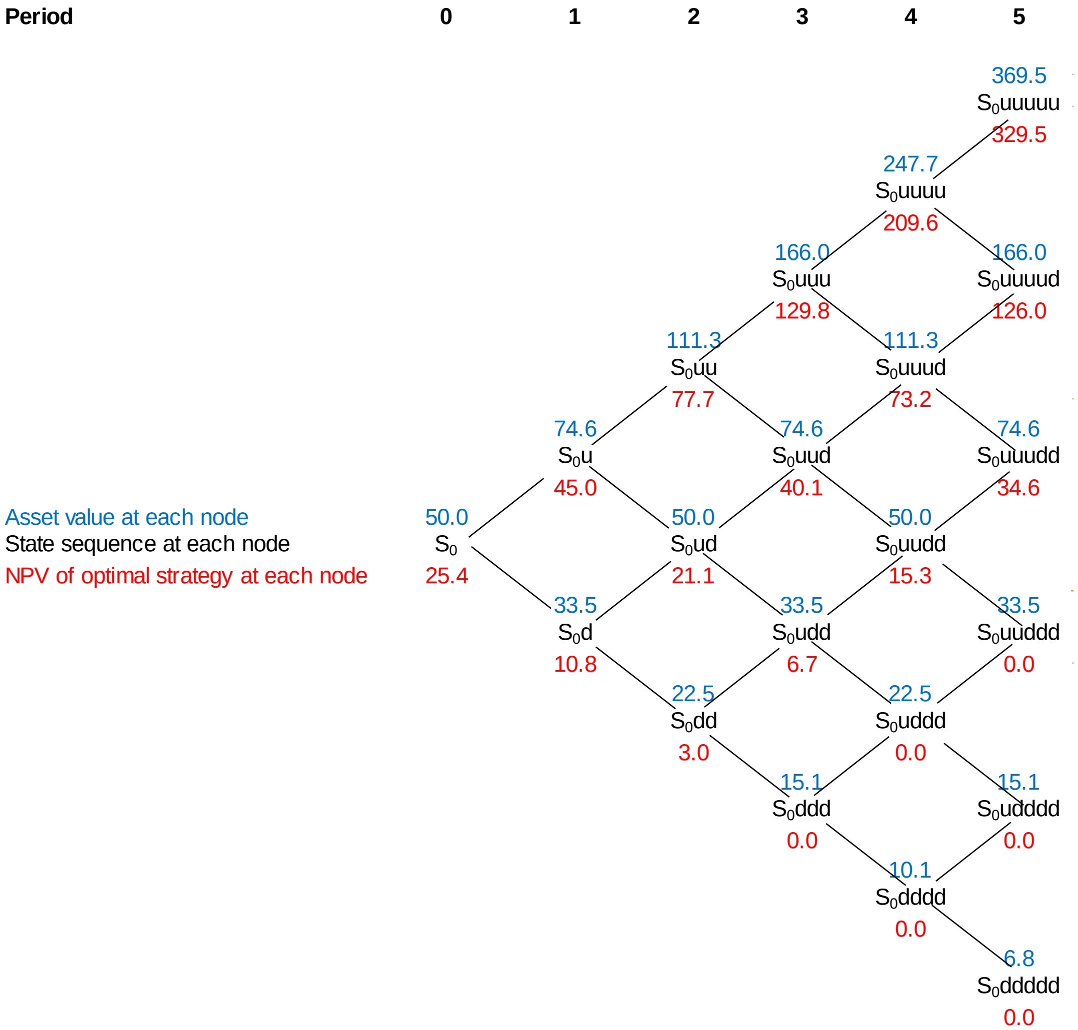


- Step 2. Calculate state variable lattice. Assume the trails and approval are successful and calculate lattice as per previous examples. The current market value of the underlying asset is given as $50. The underlying asset is not, on average, expected to increase in value but does have underlying volatility (σ) of 40% pa, implying U=1.492 (from U=exp(σ*√t)) and D=0.670 (from D=1/U). Hence second period values are $74.6 (=1.491*$50) and $33.5 (=0.670*$50), and so on.

- Step 3. Calculate risk-free rate. The risk-free rate is given as 5% pa.

- Step 4. Calculate risk parameters and returns from investment. Any investment on marketing the drug in this case is expected to deliver an immediate return. This assumption is unlikely in practice but simplifies the calculations. A more realistic assumption would require risk adjustments similar to those of the previous example. In this simpler example, the risk-neutral up probability is given by ((1-I/X)*r_f – D)/(U-D) and equals 0.4637.
- Step 5. Calculate the market value lattice. As in the earlier examples.

Figure A.14 Binomial lattice for FDA trial example



The extra steps here are to integrate the private risk analysis. The cost of clinical trials in period 0 is $10. These trials are judged to have an 80% chance of success. The cost of FDA approval in period 2 is $5. The approval is judged to have a 90% chance of success, given clinical trial success. The discount rate, including risk premium, to apply to the private risk portion of the analysis is 8% pa. The steps are as follows.

- The option to invest $40 and go to market is valued at $25, as derived above.
- Working backwards, the chance of FDA approval is 90% so the expected payoff in year 3 is $22.5 (=0.9*$25 + 0.1*$0).

- The present value in period 2 of this payoff is $20.83 (=$22.5/1.08), less the $5 FDA cost gives $15.83.
- The chance of clinical success in period 2 is 80% and hence the expected payoff in year 2 is $12.67 (=0.8*$15.83 + 0.2*$0)
- The present value in period 0 of this payoff is $10.86 (=$12.67/1.08^2), less the $10 clinical trial cost gives $0.86.

That is, the value of the option in face of market and private risk is $0.86. Kodukula and Papadesu (2006) show that a standard NPV of this scenario would show an expected value of -$7.7. The option to abandon has clearly added value (however it is a moot point whether the company would have continued with a fixed investment strategy given failure at the clinical trial and FDA approval stages, so a fairer representation is that an NPV would be inappropriate).

Guthrie (2009) shows how this type of situation can be modelled when there is learning about the probability of success during the project stages. That is, you may start out with the judgement of a 90% success rate in the FDA stage but refine this judgement to be 95% from information gathered in the clinical trials.

A3 Stochastic variables and Brownian motion

The following definitions were drawn from Blanco et al (2012).

A stochastic process is a series of events which can be described by the change in some random variable over time, which may be discrete or continuous. As stated by Feller (1968), 'in stochastic processes the future is not uniquely determined, but we have at least probability relations enabling us to make predictions'.

Special cases of stochastic processes are defined as below.

- A Markov process is a stochastic process over discrete time intervals or continuous over time which has independent increments from state to state. Thus future values of the random variable of interest do not depend on the manner in which the current value of the random variable has emerged. At each point (or interval), there will be probabilities to move to several new states with these probabilities possibly different for each state (ie the probability of the next move can vary with the current level of the random variable but remains constant over time).
- A Wiener process is a stochastic process which starts at zero and has independent increments that are normally distributed with mean of zero and fixed variance. As above there are more than two next states but, unlike above, the probability of moving to the next state is not precisely defined and the probability is not affected by the current state of the variable, ie the next move is independent of what is the current level of the random variable and of how this level emerged.
- A Random walk is a Markov process over discrete intervals where there are only two next states, determined by a probability of moving up at the next interval of p and a probability of moving down of $(1-p)$. The one-step probability is the same at all times and levels but it need not be 0.5 (ie the series can evolve rather than revert to a mean).
- A Martingale process is a random walk where the probabilities of moving up and moving down are both 0.5. The expected value of any future state (at any time) is equal to the current value. A martingale will converge to a Wiener process as the number of time intervals increase.

The Wiener process is the model that is often used to characterise Brownian motion, ie the instantaneous motion of particles suspended in fluid observed by Robert Brown. The term Wiener process and Brownian motion are often used interchangeably.

A model often employed in finance is one that describes geometric Brownian motion (GBM). There are two extra features that distinguish a GBM from a Wiener (or Brownian motion) process: first, the variable characterised by the GBM is the log of the random variable of interest; and second, this logged variable is determined by the sum of a scaled Brownian motion variable and a drift parameter. That is, the random variable, once logged, will distribute itself around a trend. This leads to the percentage change between the random variable at any two time periods as being approximately the drift parameter multiplied by the time lapsed plus a random amount that can also potentially increase/decrease linearly with time. The relative size of the drift parameter and the combined scale and variance parameters will determine how close future values will be to an extrapolation of the underlying trend (note measuring the drift parameter will involve estimation error). The random walk with many time intervals will resemble a GBM.

In notation form, the GMB for a variable X with mean μ and standard deviation σ is:

$$log_e(X_t/X_0)= at+ bW_t \qquad \text{(Equation A.6)}$$

where ‘a’ can be shown to equal ($\mu - \sigma^2/2$) and ‘b’ equals σ.

A4 Stochastic analysis of Auckland Harbour Bridge traffic flows

This section provides a time series analysis of traffic on the Auckland Harbour Bridge (AHB). Plus an exercise showing how a risk-based analysis might have favoured delay to a hypothetical investment.

Uncertainties with regard to traffic flows do not arise solely from the advent of new modes of transport. They may also arise from fundamental changes to the economic environment, changes in social attitudes (possibly across different generations that may, in turn, reflect changes to other forms of access such as wireless communications), and from technical changes to the existing modes of transport (eg driverless cars). We illustrate how use of historical risk-based probabilities would have led to difficulties in predicting changes to transport patterns that occurred starting in 2007. To do so, we place ourselves in the shoes of a transport planner at the start of 2007 whose job is to predict the time series of traffic flows through to 2015.

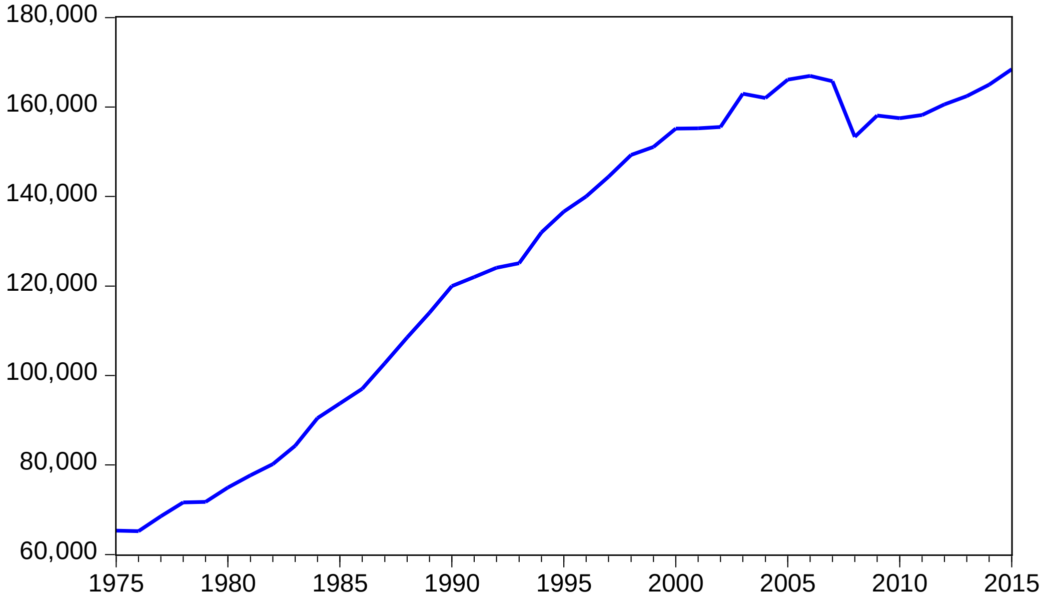
Our example uses annual average daily traffic flow data for the AHB from 1975–2015.[103] This period is not affected by the unpredictability of traffic flows associated with the initial opening of the bridge (which pre-dates the start of our sample by 16 years), or by the changes in flows associated with the ‘clip-on’ extensions in 1969.

Figure A.15 graphs the traffic flows across the AHB (AHB-flows) for 1975–2015. An apparent structural break appears to occur after 2006. We conduct our initial analysis of the series for the period up to and including 2006, ie as if we were modelling the traffic flows at the outset of 2007. We then use the derived time series properties of the data as a guide to predicting future traffic flows. Subsequently, we model

[103] 1975–1988 data was obtained from www.nzta.govt.nz/resources/state-highway-traffic-volumes/; data for 1989 onwards was sourced from the Transport Agency, missing 1985 and 1987 data was interpolated.

traffic flows for the whole period to understand how the additional data (if it were known) would have helped the planner in 2007.

Figure A.15 Auckland Harbour Bridge annual average daily traffic flows



The first thing to note about the series through to 2006 is that it more closely follows a linear trend than an exponential trend. In other words, between 1975 and 2006 traffic flows tended to increase by the same number of trips per annum rather than exhibiting the same percentage growth rate per annum.[104] This suggests, in turn, that any relationship with GDP – which more closely follows an exponential trend – must have been non-linear (if it existed at all).

A closer look at the time series properties of the AHB-flows variable reveals that a change in the traffic flow in any year tends to have a permanent effect on the level of future flows.[105] Thus, for instance, if traffic flows increased by 3% in one year, then this new level forms the relevant base for the following year with no evidence of reversal of the previous jump.

Given this information (and without, initially, drawing on any other information), a reasonable estimate of the expected traffic flow in any year t is the flow in year t-1 plus the expected trend change. Using the data for 1975–2006 (ie as viewed by the planner at the start of 2007), the estimated mean change is 3,279 pa. Thus given the 2006 flow of 166,952, one might estimate that the expected flow in 2007 would be 170,231 and the flow in 2008 would be 173,510. In fact, the actual 2007 traffic flow turned out to be 165,747 while flows for 2008 were even lower at 153,324.

[104] The correlation coefficient between a linear trend and the AHB flow series (0.961) exceeds that between a linear trend and the logarithm of AHB traffic flows (0.944).

[105] ie statistically AHB-flows is a non-stationary variable. An Augmented Dickey-Fuller (ADF) test on AHB-flows with constant and linear trend included has a p-value of 0.747. An ADF test on the change (Δ) in AHB-flows with a constant included has a p-value of 0.000. Thus AHB-flows is integrated of order one, I(1), while ΔAHB-flows is stationary or integrated of order zero, I(0). In each case, the sample period is 1975–2006.

If one were to use the annual mean change to extrapolate over future years in a deterministic fashion, the expected flow in 2015 would have been 196,463. This figure compares with the actual flow in 2015 of 168,449, ie actual flows in 2015 were 14% below their extrapolated level from 2006.

If the planner (in 2007) was operating using the concept of risk; however, they would not have relied purely on an extrapolation based on mean changes; they would also account for the variation in annual traffic changes. The mean change in annual traffic flow over the 1975–2006 period was accompanied by a standard deviation (of annual changes) of 2,213.[106] The planner at the outset of 2007 might then have forecast a mean traffic flow for 2007 of 170,231 with a two-standard deviation band around this figure[107] of 165,806 to 174,657.

The actual 2007 traffic flow (165,747) was just below the lower bound of this interval while the flow for 2008 was 20,186, nine standard deviations below the expected value for 2008! In these circumstances, the risk-based extrapolative planner would seriously have had to reconsider their forecasting approach.

One possibility is that a risk-based approach remained appropriate but that extrapolation was too simple a forecasting method. Another possibility is that the example is one in which uncertainty (as opposed to risk) is present. We examine these possibilities further below.

A potential explanation for such an apparently unlikely series of traffic flows occurring over 2007–2015 is that the extrapolative risk-based model used above is too simple. Instead, it may be hypothesised that the statistical model for traffic flows should incorporate both real GDP (ie the volume of economic activity) and real petrol prices (ie petrol prices deflated by the Consumers Price Index).[108]

In so doing, we introduce two new sources of uncertainty: model uncertainty and parameter uncertainty. Model uncertainty arises when we do not know what is the true model that explains a certain variable, either because we do not know the correct variables to include or do not know the correct functional form for the included variables. Parameter uncertainty arises when we think we know the true model but do not know the correct size of parameters in the model. We demonstrate these sources of uncertainty below.

The three series for AHB-flows, real GDP and real petrol price are graphed in figure A.16[109]

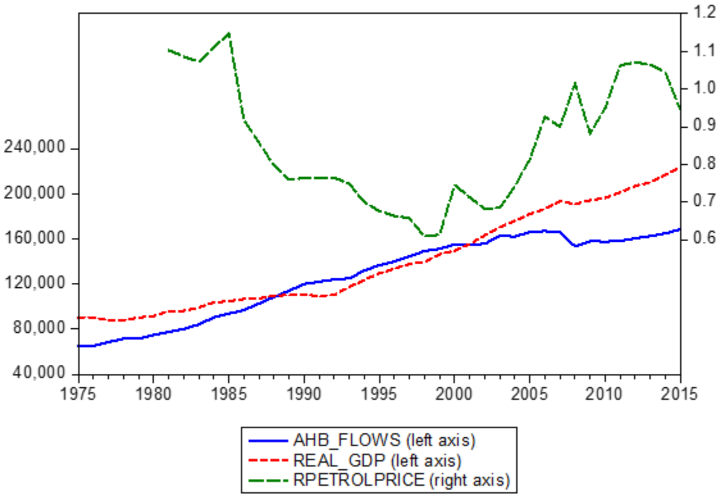
[106] The absolute average deviation of 2,149 is very similar to the standard deviation so it matters little which of these two measures we use in the analysis below.

[107] ie approximately a 95% confidence interval.

[108] Our real GDP series is Statistics New Zealand's annual real GDP (expenditure) series backdated prior to 1987 using Statistics New Zealand's long-term (INFOS) data series. The GDP year in each case is a March year so, for instance, we use GDP for the year to March 2016 as the GDP figure for calendar 2015. Petrol prices and the CPI are also sourced from Statistics New Zealand. Disaggregated prices (and hence the petrol price) are only published by Statistics New Zealand from 1981 onwards.

[109] All three series are non-stationary, I(1), according to an ADF test (with and without linear trend included).

Figure A.16 Auckland Harbour Bridge flows, real GDP and real petrol prices



In order to obtain a 'better' model for AHB-flows, we estimate a set of equations that relate AHB-flows to real GDP and real petrol prices. A complication of the modelling is caused by the finding that all three series (and their logarithms) are 'non-stationary' (ie a change in a variable in any period constitutes a permanent, rather than a temporary, change). In these circumstances, a standard equation linking the variables may provide spurious regression results.[110] In order to overcome this problem, we test whether each relationship that we estimate is *cointegrated* – which is a requirement for the relationship to be regarded as anything other than spurious.[111] This requirement is often overlooked in studies that draw relationships between traffic flows and variables such as GDP.

Given that the traffic flow data and the GDP series are each available for the period beginning 1975 while the petrol price data only begins in 1981, we begin by examining the bivariate relationship between AHB-flows and real GDP. As before, we do so from the vantage point of an observer at the start of 2007, so we use data covering 1975–2006.

Reflecting model uncertainty, we estimate the relationship between the two variables in 12 different ways. We use each of the level and the logarithm of each variable (yielding four different functional form relationships) and for each of these relationships we variously include a constant, constant plus linear trend, and constant plus quadratic trend. Importantly, none of these relationships is cointegrated[112]; thus there is no meaningful bivariate relationship between traffic flows and real GDP over the 1975–2006 period.

One of the reasons for the lack of a relationship may be the exclusion of fuel prices. We therefore investigate the relationship between AHB-flows, real GDP and real petrol prices for the 1981–2006 period, again using all the level and log combinations coupled with the various trend specifications. This yields 24 separate equations. At the 5% significance level, none of the 24 equations is cointegrated,[113] but four of

[110] On this matter, see any standard time series econometrics text, such as Davidson and MacKinnon (2004).

[111] In a cointegrated relationship, the equation's residual is stationary, ie its mean (and other moments) is constant over time, so that there are no long departures of the residual from zero and no trending patterns in the residual. We use the Engle-Granger tau-statistic test with AHB-flows as the dependent variable to test for cointegration.

[112] Details of statistical tests are available on request.

[113] ie we cannot reject the null hypothesis of a unit root in the residual.

the combinations are significant at the 10% significance level. Each of the latter includes a linear trend variable. However, with the inclusion of this trend variable, the estimated coefficient on the (level or log) GDP variable is negative, implying that an increase in GDP is related to a decline in traffic flows. This is not plausible, so we conclude there is no statistically valid relationship determining AHB-flows that includes GDP as a separate influence.

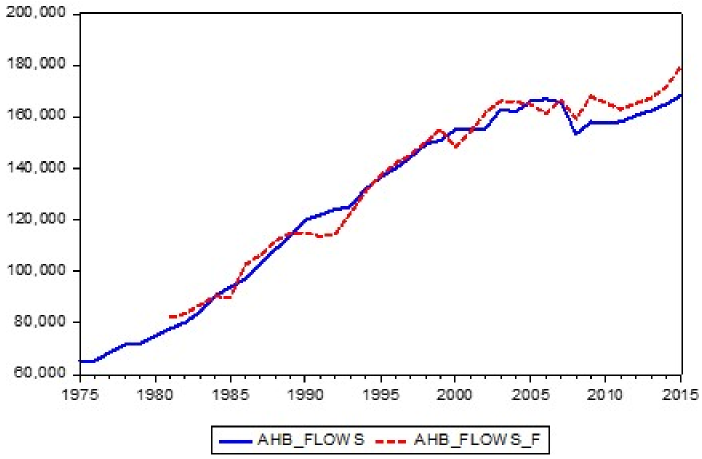
The most plausible relationship (ie a relationship that has coefficients of the expected signs) occurs for a regression in which traffic flows are modelled against the logarithms of real GDP and the real petrol price with no trend components added. The resulting equation is shown below.[114]

*AHB_FLOWS = 106366*log(REAL_GDP) – 47686*log(RPETROLPRICE) – 1133232* (Equation A.7)

If a planner had taken this equation at face value (despite it not being statistically valid owing to its lack of cointegration) they would have interpreted the estimated coefficients to imply that each 1% increase in real GDP leads to approximately a 1,064 increase in traffic flows while each 1% increase in real petrol prices leads to a decline of approximately 477 in the traffic flow.

The planner would still have had to predict the future outcomes for real GDP and real petrol prices in order to predict traffic flows. To abstract from this source of uncertainty, consider what would have happened if the planner (in 2007) was able to perfectly predict the outcomes for both variables. They would then have forecast traffic flows as shown in figure A.17 (in which AHB_FLOWS_F is the forecast flow). The forecast flow for 2015 (179,615) is 6.6% above the actual 2015 figure (168,449).

Figure A.17 Forecast vs actual flows based on model estimated to 2006



Even if there was no uncertainty about the outcomes for real GDP or petrol prices and no model uncertainty, there would still have been parameter uncertainty. We show this by re-estimating the same equation for the full period (1981–2015). Using this extended dataset, the estimated equation becomes:

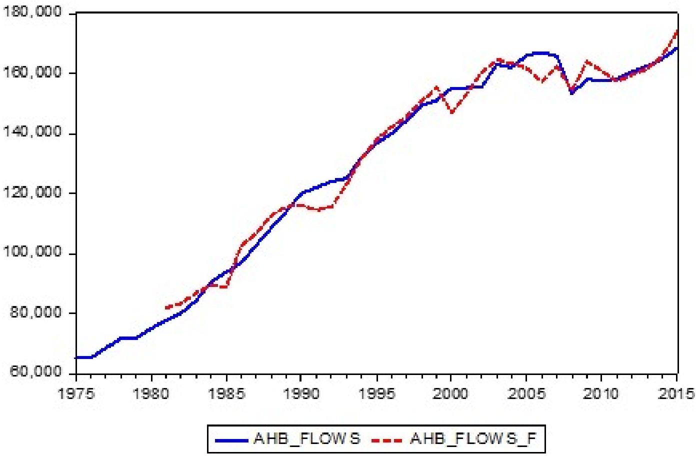
*AHB_FLOWS = 98851*log(REAL_GDP) – 53624*log(RPETROLPRICE) - 1046657* (Equation A.8)

[114] Conventional t-statistics have p<0.0001 but these are not valid for testing significance with non-stationary variables; the R^2 (=0.977) is also not informative in this case. The Engle-Granger tau-statistic (p=0.2980) indicates the residuals are not stationary so the equation is not cointegrated.

The equation using the extended data is cointegrated[115] so this is a statistically valid equation. We now see that there is a valid long run relationship between traffic flows, real GDP and real petrol prices. The effect of a 1% increase in real GDP is now estimated to be an increase in traffic flows of approximately 989 while a 1% increase in petrol prices is estimated to lead to a reduction of approximately 536 in traffic flows. Using these parameters, the traffic flow for 2015 is estimated at 173,978 which is closer to (albeit still above) the actual flow of 168,449. Figure A.18 graphs the forecast versus actual traffic flows based on the equation estimated through to 2015.

It is important to stress that a planner in 2007 could not have concluded on the basis of the *statistical* evidence this long run relationship existed. Furthermore, even if she had (erroneously) done so, her estimated parameters would not have been correct (albeit not too dissimilar in this instance).

Figure A.18 Forecast vs actual flows based on model estimated to 2015



We might use the extrapolative information in the ABH traffic flow analysis above to give some illustrative guidance as to how to plan for future traffic flows using a binomial option approach. We repeat, though, that this analysis would have been inappropriate given the lack of known long-run relationship.

In this example, we take as our starting position an investment decision required in 2006 and we ascribe an equal possibility of an upper change AADT estimate of a 5,492 increase (= the mean of 3,279 plus one standard deviation) and a lower change estimate of a 1,066 increase (= the mean minus one standard deviation) each year.[116] On this basis, from a 2006 perspective, we would place equal probabilities for 2007 flows of 172,444 and 168,016.

Noting that increments to traffic flows are permanent (because of the non-stationary nature of the series), we can then use each of these figures as a base for predicting potential flows in 2008 and so on in each succeeding year.[117] This approach is detailed in table A.3. The top half of the table provides the upper

[115] The Engle-Granger tau-statistic has p=0.0291.

[116] The example is illustrative, and statistical properties will depend on the nature of the distribution of annual traffic flow changes. For a normal (triangular) distribution, we expect 68% (65%) of outcomes to lie within one standard deviation of the mean.

[117] Since we are looking at the future from the perspective of a real option based planner at the start of 2007, we retain the same estimated mean and standard deviation calculated from 1975–2006 for each future year since there is no additional information available about how future parameters may change.

and lower AHB-flow estimates for each year given a particular base for the preceding year; the bottom half of the table provides the probability of each cell occurring.[118]

Concentrating on the estimates for 2015, we can sum each of the traffic flows multiplied by its corresponding probability to calculate the expected value for 2015 AHB-flow. The resulting expected value is 196,463. Given the symmetric and linear approach adopted, this expected value is equal to the base 2006 value plus nine[119] times the annual mean increment of 3,279.

Just taking the analysis to this stage provides insights into an ROA.[120]

Table can be used to demonstrate two features pertaining to real options (within a risk-based framework). First, the precision of our estimates about the future reduces as the time horizon lengthens. Based on our assumptions, the width of our estimate for 2007 is 4,426 whereas this widens to 39,834 by 2015. The decreasing precision of the estimate as time lengthens is a consequence of the non-stationarity of the data.

Second, the usefulness of the ROA is evident from the example – provided the world were characterised as having no Knightian uncertainty. For instance, assume a trigger point exists where an expanded (or new) bridge is required if AHB-flows reach 196,000, and assume it takes five years to build the new bridge. At the end of 2006, the expected value of flows in 2015 is 196,463. A foresighted traffic planner, using a deterministic approach, might argue to expand the bridge based on this expected value estimate. However, in practice, no estimate for 2011 (ie five years later) exceeds the trigger level of 196,000 so the bridge decision can be delayed by at least a year.

Table A.3 Binomial tree – traffic flows and probabilities

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Binomial tree traffic flows									216380
								210888	
							205396		211954
						199904		206462	
					194412		200970		207528
				188920		195478		202036	
			183428		189986		196544		203102
		177936		184494		191052		197610	
	172444		179002		185560		192118		198676
166952		173510		180068		186626		193184	
	168018		174576		181134		187692		194250
		169084		175642		182200		188758	
			170150		176708		183266		189824

[118] The probabilities for each year sum to unity; probabilities are shown to four decimal places so minor rounding errors may occur.

[119] We multiply the mean historical yearly increment by nine since that is the number of years over which the projection is being made.

[120] An ROA would require mapping of the AADT to an asset value and a conversion of any asset value to its certainty-equivalent form.

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
				171216		177774		184332	
					172282		178840		185398
						173348		179906	
							174414		180972
								175480	
									176546
Probabilities									0.0020
								0.0039	
							0.0078		0.0176
						0.0156		0.0313	
					0.0313		0.0547		0.0703
				0.0625		0.0938		0.1094	
			0.125		0.1563		0.1641		0.1641
		0.25		0.25		0.2344		0.2188	
	0.5		0.375		0.3125		0.2734		0.2461
1		0.5		0.375		0.3125		0.2734	
	0.5		0.375		0.3125		0.2734		0.2461
		0.25		0.25		0.2344		0.2188	
			0.125		0.1563		0.1641		0.1641
				0.0625		0.0938		0.1094	
					0.0313		0.0547		0.0703
						0.0156		0.0313	
							0.0078		0.0176
								0.0039	
									0.0020

At the end of 2007, if the lower estimate for AHB-flows (168,018) occurs, we can see from the table there is no combination of future outcomes that reaches the trigger level by 2012, so the decision could be delayed again by at least a further year. If the high outcome for 2007 occurs, then there is some (low) probability that the 196,000 level could be triggered by 2012, and the decision on whether to start building or not will be determined by the net costs of having a bridge that is too small (multiplied by the low probability of that occurring) relative to the net costs of building the bridge when it was not required (multiplied by the high probability of that occurring). In this case, one practical approach may be to undertake preliminary works (eg planning and foundations work) without committing fully to the five-year building programme, pending further information in the following year about traffic flow developments.

By the end of 2010, the real-option risk-based planner will have a clearer idea of whether the bridge is required or not. If a series of low outcomes had occurred in each previous year (so that AHB-flows were 171,216) there would have to be five positive outcomes in succession for the trigger point to be reached (with probability of 3.1%); no other combination of high and low outcomes would reach the trigger point. Thus unless the costs associated with having an inadequate bridge were massive, one would not decide to build the bridge at the end of 2010 (and instead may undertake some preliminary works). Higher values for 2010 traffic flows would successively increase the need to commit to building the bridge.

The above analysis of the Auckland harbour bridge AADT using risk-based techniques is academic. As stated above, the AADT series does not display a stable relationship over time and hence this risk-based analysis is inappropriate. As it turned out, a choice in 2006 to delay would have been advantageous. However, the unanticipated shock of 2007–2008 could have been different – there may have been a shock that raised AADT. The point is that such models cannot produce accurate forecasts when future outcomes are fundamentally uncertain.

Appendix B: Glossary

AADT	average annual daily traffic
AGV	automated guided vehicle
ANZSIC	Australian and New Zealand Standard Industrial Classification
AHB	Auckland Harbour Bridge
AWHC	Additional Waitemata Harbour Crossing
ART	Auckland Regional Transport
ATAP	Auckland Transport alignment project
BAU	business as usual (scenario)
BCR	benefit-cost ratio
BOP	Bay of Plenty
BOPM	Binomial Options Pricing Model
BRT	bus rapid transit (system)
BSOPM	Black-Scholes Option Pricing Model
CAPM	Capital Asset Pricing Model
CAU	census area unit
CBA	cost–benefit analysis
CBD	central business district
CRL	city rail link (of Auckland)
DCF	discounted cash flow
DfT	Department for Transport (UK)
DM	do minimum (scenario within an appraisal)
DS	do something (scenario within an appraisal)
DTA	decision tree analysis
EEM	*Economic evaluation manual* (NZ Transport Agency)
FDA	Federal Drug Agency
GBM	geometric Brownian motion
GDP	gross domestic product
GEH	Empirical formula named after London transport planner Geoffrey E Havers
GTC	generalised travel cost
HOV	high occupancy vehicle
HPMV	high performance motor vehicles

ITF	International Transport Forum (at the OECD)
Knightian risk	Unknown future events have known distribution, which can involve outcomes perceived to be both positive and negative (see section 2.2.1)
LEED	linked employer-employee dataset
LRT	light rail transit (network)
LUTI	Land Use Transport Interaction (model)
MCS	Monte Carlo simulation
MRIO	multi-regional input-output (models)
NPV	net present value
NZIER	New Zealand Institute of Economic Research
NZMUGS	New Zealand model users group
PBC	programme business case
POAL	Ports of Auckland Limited
POT	Port of Tauranga
PPP	public private partnership
PT	public transport
PV	present value
PWC	Pricewaterhouse Cooper
R&D	research and development
RLTP	regional land transport plan (of New Zealand regional councils)
ROA	real option analysis
RoNS	roads of national significance
SDV	self-drive vehicle
SKM	Sinclair Knight Merz
TAG	transport analysis guidance
TPICS	Transportation Project Impact Case Studies (US)
Transport Agency	New Zealand Transport Agency
UNISA	Upper North Island Strategic Alliance
vkt	vehicle kilometres travelled
WRTM	Waikato Regional Transportation Model