The contribution of public transport to economic productivity
January 2013

Tim Hazledine, Stuart Donovan and John Bolland

NZ Transport Agency research report 514

ISBN 978-0-478-70421-1 (electronic)

ISSN 173-3764 (electronic)

NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

Hazledine, T, S Donovan and J Bolland (2013) The contribution of public transport to economic productivity. *NZ Transport Agency research report 514.* 63pp.

Contact: Stuart Donovan, sdonovan@mrcagney.com, MRCagney, PO Box 3696, Auckland 1010, New Zealand.

Keywords: agglomeration economies (AE), economic productivity, public transport (PT)

An important note for the reader

Acknowledgements

The authors would like to gratefully acknowledge the contribution to this research from the following:

- NZTA project managers, Jeremy Traylen and Peter Kippenberger
- peer reviewers, David Maré and David Simmonds
- members of the Steering Group:
  - Susan Fairgray, Auckland City
  - Pete Clark, Auckland Transport
  - Ian Duncan and Hamish Bunn, Ministry of Transport
  - Dieter Katz, Treasury
  - Graeme Belliss, NZTA

Abbreviations and acronyms

AE	agglomeration economies
AGC	average generalised cost(s)
APTA	American Public Transportation Association
BCR	benefit–cost ratio
CBA	cost-benefit analysis
CBD	central business district
CGE	computable general equilibrium
DTEW	double tracking and electrification to Waikanae
ED	effective density
EEM	*Economic evaluation manual* (NZTA 2010)
NPV	net present value
PT	public transport or public transit
SDG	Steer Davies Gleave
WEB	wider economic benefits

Contents

Executive summary

Background

The objective of this research project was to 'quantify the contribution of public transport to economic productivity'. The need for this project arose in response to the government's desire for investment in public transport (PT) to support economic productivity and growth in New Zealand.

The NZ Transport Agency (NZTA) *Economic evaluation manual* (EEM) contains a methodology for assessing the economic costs and benefits of transport investments. The brief for this project suggested that this methodology had been relatively underutilised in the area of PT, particularly for assessing the contribution to productivity made by an overall network of services. The brief also noted that the EEM focused on what are known as 'traditional economic benefits', such as congestion reduction benefits to road users, although we note that 'wider economic benefits' such as 'agglomeration' have recently been incorporated.

The EEM's processes do not address the potential for PT improvements to make a distinctive contribution to economic productivity, above and beyond what might be associated with general transport improvements. The NZTA considered that the dense urban environments in which PT tends to operate may experience productivity impacts that extend beyond what is currently covered in the EEM.

Our preferred model

Our review of the literature on the economic implications of transport systems led us to adopt and extend the model developed in Venables (2007). Here all the productivity 'action' comes from agglomeration economies generated in city centres, or other nodes of concentrated employment. Such benefits are dependent on the density of employment, which in turn depends on the number of people willing to commute to work centrally, which in turn depends on the costs of commuting from the residential suburbs. Thus, the focus of our model is on commuting costs, rather than other input costs such as freight costs. Since commuting is an activity usually carried out during the morning and evening peak periods, it may result in transport networks becoming congested (slower journeys to/from work) at these times. It may be through the relief of such congestion that transport improvements, especially PT, have their primary effect on economic productivity.

The key strength of Venables' approach is that it *explains* the level of employment as the resolution of two opposing forces: Agglomeration benefits and commuting costs, and thence to *predict* changes in employment resulting from a shift in commuting costs. Existing transport models, including those used in New Zealand following the EEM procedures, rely on exogenous forecasts of employment levels, or at the most apply off-the-shelf elasticities to link changes in generalised transport costs to changes in employment or commuting trips. The Venables' model thus offers the prospect of a major step forward in the scope of our transport modelling – and all this within a surprisingly tractable analytical framework.

To place our research in context, the major areas where we have sought to 'add value' to Venables' model are threefold. First, we modelled directly (and in detail) the implications for congestion and travel speeds of mode shifts induced by the PT innovation, with capability built in to handle a variety of types of innovation, including changes in fares, service and capacity of either bus or rail PT systems. Second (and because PT innovations in general affect the use of private vehicles for central city commutes) we allowed for change in land use within the CBD, specifically the consequent change in demand for and supply of car parking. Third, we implemented the model in a readily accessible and replicable spreadsheet format. We applied the model to evaluate the productivity benefits associated with two recent PT improvements, namely:

- the Central Connector bus corridor, Auckland
- double-tracking and electrification of the rail corridor, Waikanae (DTEW).

For the Central Connector case study, applying the model found that the reduction in generalised commuting costs due to the development of the Central Connector supported an approximate increase in total CBD employment of 0.8%. This increase in CBD jobs would be matched by an equal loss of lower productivity suburban jobs, which is welfare enhancing because the people switching to CBD jobs are better off, even after allowing for the longer commute. The agglomeration economy gains, along with the productivity bonus of CBD land freed up from car parking and put directly to more productive use (presumably as additional office space) would generate a 0.1% increase in the productivity of all CBD workers. Our model predicted agglomeration effects totalling $1.991 million/year in 2021. This should be compared with the 'conventional' transport benefits in 2021 of $8.78 million, of which the 'productivity' benefits are just below 23%.

For the DTEW case study, the NPV of additional benefits was found to be $3.45m. This is 3% of the 'conventional' benefits of $117.42m. This relatively low percentage (at least in comparison to the Central Connector case study) is probably a reflection of the comparatively small nature of the DTEW scheme – its impact on PT mode share is less than 2%. In this case the productivity benefits are much lower.

Conclusions and recommendations

We drew the following conclusions from our research:

1. The aim of this study was to develop a framework to model the contribution of PT to economic productivity. We concluded that aggregate macroeconomic models are insufficiently nuanced to capture this. Microeconomic studies are more useful as they identify explicit channels through which PT may be expected to support economic productivity.
2. The most obvious microeconomic channels through which transport impacts on productivity is through agglomeration economies (AE), which describe the benefits that arise from spatial concentrations of economic activity. PT can both encourage and enable increased employment in central city locations, by reducing commuting costs in congested transport networks and freeing up space that would otherwise be required for car parking. Through these two channels PT is able to make a somewhat unique contribution to economic productivity in denser urban environments.
3. Venables (2007) provides an appropriate microeconomic framework for capturing the contribution of PT to economic productivity. Venables' model considers how transport improvements can reduce commuting costs, which in turn facilitates an expansion in city centre employment. This in turn leads to increased productivity (through AE), with the benefits captured by workers (in the form of wages), landowners (in the form of higher rents), and the government (in the form of tax wedges). Venables' model is both plausible and tractable. We extended Venables' framework to incorporate non-linear commuting costs, which are symptomatic of the conditions in which PT operates, as well as additional AE arising from the (partial) reallocation of space used for car parking, namely accommodating additional employment. Applying our model to two case studies identified productivity benefits of 3% to 23% of conventional transport benefits. Sensitivity testing suggested these results were relatively robust to changes in key input parameters.

4 Current EEM processes for estimating AE consider how changes in average generalised travel costs contribute to AE. The processes by which AE are calculated are 'separable' in the sense that they consider contributions for each mode, zone and trip type. Because the economic benefits predicted by our model arise solely from the use of PT for journeys to work in central city zones, the benefits predicted from our model can supplement existing processes, providing the latter is calculated in a way that excludes agglomeration impacts with the same trips. Loss of AE from lower employment in peripheral areas can be estimated using existing processes. Alternatively, our model could be generalised to account for impacts on zones beyond the city centre.

Based on the results of this research, we formulated the following recommendations:

1 When the EEM is next reviewed, which we understand to be sometime in 2012/13, we recommend the concepts discussed in this research be considered as an input, possibly subject to further analysis and verification. Specifically, there is a need for the EEM to consider the potential for PT to make an additional contribution to economic productivity in central city areas, where strong localised AE are present, such as Auckland and Wellington.

2 Government agencies investigate opportunities to increase the funding envelope for PT to improve access in central city areas that are subject to strong localised AE. This should also consider opportunities for complementary walking/cycling improvements that enable commuters to access PT services and in turn the city centre.

3 The NZTA considers further research into the contribution of PT to economic productivity, particularly with regard to:

   a empirical research into the exogenous parameters used in our model

   b the potential for AE in consumption (as well as in production).

4 The NZTA considers updating the EEM to address:

   a *Impacts of PT on population health*. Where new PT users are diverted from private vehicles, then this would be expected to generate net health benefits. On the other hand, where new PT users are diverted from walking and cycling, then this may result in a net health disbenefit. Including health impacts of PT is not only reasonable, but may be expected to favour PT improvements that compete most vigorously with private vehicles, thereby aligning with wider strategic objectives.

   b *Impacts of road transport improvements on the demand for car* parking. A natural corollary of our research is that road transport investments that increase the demand for parking in central city areas can effectively undermine AE. Further research is required to assess whether these effects exist and if so, whether they have significant effects on density and consequently ramifications for AE.

Abstract

The objective of this research was to quantify the contribution of public transport to economic productivity. Based on our review of the literature we decided to extend and apply Venables' microeconomic model of the productivity benefits of transport improvements, which considers the interplay between commuting costs and agglomeration economies. We extended Venables' model in two ways: first, we incorporated non-linear congestion costs that are typical of major urban centres in which public transport tends to operate. Second, we allowed for space previously used for car parking to be reallocated, primarily for employment, which in turn would generate additional agglomeration economies. The model was subsequently applied to two transport case studies and we found additional productivity benefits in the order of 3% to 19% of conventional transport benefits. These findings have implications for the economic evaluation of public transport improvements and transport funding priorities.

1 Introduction

The objective of this research project was to ‘quantify the contribution of public transport (PT) to economic productivity, particularly in relation to congestion relief in Auckland and Wellington. This project recognised that the government’s priority for its investment in land transport is to increase economic productivity and growth in New Zealand. The following sections outline the scope and structure of this report.

1.1 The scope of this research

The NZTA (2010) *Economic evaluation manual* (EEM) specifies approved procedures for assessing the economic costs and benefits of transport investments.

The brief for this project noted that the EEM’s procedures have been relatively underutilised in the area of PT, particularly for assessing the contribution to productivity made by an overall network of services. There is very little reporting on and monitoring of the contribution of PT to the New Zealand economy, as well as limited experience in the application of economic appraisal in a PT context.

The brief for this project also noted that the EEM focuses on what are known as ‘traditional economic benefits’, such as congestion reduction, although we note that wider economic benefits (WEBs) such as ‘agglomeration’ have recently been incorporated. Current processes do not consider the potential for PT investment to make a distinctive contribution to economic productivity, above and beyond what might be associated with normal transport investment. It was felt that the urban environments in which PT tends to operate may experience productivity impacts that extend beyond what is normally considered in the EEM.

In completing this research, we strived to meet the following objectives, all of which were specified in the original brief:

- Produce research that is practical and able to be applied.
- Consider relevant literature and advise on best practice (where appropriate).
- Ensure that the research takes into account and complements existing procedures and related research funded through the NZTA's research budget.

In meeting these objectives the project team were tasked with delivering:

1. An assessment of the value and feasibility of applying various economic appraisal procedures to PT networks at the strategic level
2. A recommended procedure for estimating the benefit of PT to economic productivity
3. A current assessment of the benefit of PT to the New Zealand economy, for example through case studies in major urban centres
4. Discussion on the implications of the findings for future investment.

The following section defines some key concepts used in this report.

1.2 Defining key concepts

Before we proceed it is worth defining some key concepts that are relevant to this study. First, productivity is defined as the ratio of value of output to the value of input. This means that increases in productivity can be achieved by:

- an increase in output, holding input constant, and/or
- a reduction in input, holding output constant.

Changes in productivity are therefore changes in the ratio of output to inputs, exclusive of changes in prices. Productivity does not involve changes in total economic activity, or changes in consumer welfare.

Second, when we talk about PT we are referring to the patronage of publicly funded PT services, most commonly buses, trains and ferries. Increased patronage of PT can be achieved through a number of interventions, such as:

- lowering the direct price, eg through operating subsidies
- lowering the perceived cost of travel, eg through speed, reliability and frequency improvements
- reducing transactions costs, eg ticketing improvements
- increasing service quality, eg more comfortable services.

A variety of complementary interventions may increase PT patronage, such as improvements in pedestrian and/or bicycle access to stops/stations. As a result, we focused our research not on the interventions through which increased PT patronage is achieved (of which there are many), but instead on how an increase in PT patronage (by whatever means) might contribute to economic productivity.

Our research needed to inform analyses for both individual projects and for wider systems. As such, it had to be flexible to handle relatively localised applications (such as the impact of a particular infrastructure improvement) through to larger, system-wide initiatives, such as a change in fares.

1.3 Economic reasoning

At this point it is worth placing our research within the wider context of economic reasoning. In our experience, economic reasoning tends to proceed by way of the following three steps:

1. Observation of stylised socio-economic facts
2. Formulation of economic models and hypotheses
3. Empirical calibration and validation of the models and hypotheses.

Of course the economic reasoning process is not usually straightforward and nor does it have a well-defined end point. Most importantly, a ‘feedback’ loop is typically observed between steps 2 and 3, whereby the results of empirical analyses in step 3 are used to refine the formulation of economic models and development of hypotheses in step 2. Table 1.1 seeks to illustrate this process, where models of new economic geography are used as an example.

Table 1.1 Economic reasoning process

Economic reasoning process	Example: New economic geography
Step 1 Observation of stylised socio-economic facts	**Step 1** Rise and persistence of US manufacturing belt
Step 2 Formulation of economic models and hypotheses	**Step 2** Interplay between industry economies of scale, transport costs and market size → 'home market effects'
Step 3 Empirical calibration and validation of models and hypotheses	**Step 3** Regression analyses confirm presence of home market effects, eg forced population relocation in Finland.

In many cases step 3 will throw up information that requires revisiting step 2. In this way, economic reasoning proceeds through both theoretical development and empirical application – one informs the other and vice versa; they are, if you like, synergistic. For example, the new economic geography models (originally developed by Krugman) were subsequently refined and improved on by empirical analyses, whereas theoretical developments have identified new areas of potentially fruitful empirical research.

But what does all this mean for our project? We started from the stylised observation that cities with well-developed PT systems tended to be more productive; that is step 1 essentially taken care of.

We also noted that the project brief explicitly called for a 'framework' to determine the contribution of PT to economic productivity. Such a framework would sit most squarely within step 2 in the process outlined above, and accordingly we attempted to formulate an economic model and develop hypotheses.

That is not to say we eschewed empirical analyses altogether and in section 1 we have applied the model to two case studies. Nevertheless, the development of the model identified several areas where further empirical analyses were required.

1.4 The structure of this report

The following chapters of this report are structured as follows:

- Chapter 2 summarises the results of our literature review.
- Chapter 3 presents our preferred model for estimating the contribution of PT to economic productivity, in both mathematical and graphical forms.
- Chapter 4 applies our preferred model to evaluate the productivity impacts of two case studies, as well as testing the sensitivity of results to changes in key parameters.
- Chapter 5 discusses the wider implications of the model, in terms of the relationship to WEBs, implications for the EEM, implications for government priorities, and opportunities for further research.
- Chapter 6 outlines our conclusions and recommendations.

2 Literature review

2.1 Background to our review

This literature review considers how the use of and investment in PT contributes to economic productivity and aims to keep open all the options that might result in expansion of PT modes.

Hence, it includes a review of the efficiency and productivity implications of investments and other policies, recognising that the ways in which higher PT usage is achieved can have efficiency implications (eg increased subsidies versus improved service frequencies). In this review we have used a broad concept of productivity, which includes the efficient use of resources generally, and possible un-priced welfare benefits to households and third parties (externalities). This broader focus was maintained throughout the research.

2.1.1 Scope of the literature review

The focus of the review is on evidence-based findings and considers two types of studies. The first analyses actual events and empirical data through which impacts might be measured, such as econometric studies. These studies search for evidence of linkages between the variables of interest that do (or do not) exist and determining how quantitatively significant these are where they exist. Such investigations are known as *ex post* studies.

In contrast, predictive, or *ex ante* studies use a model that pre-specifies the nature of the linkages. These studies are used to ask 'what if?' questions, for example, about the patronage increases from proposed changes in the supply of PT in a city. These models can also be used to answer 'what happened?' questions, examining the impact of an actual historical event. However, they will always do so by comparing it to a 'counterfactual' scenario in which the event did not actually happen. In this sense, they will not be tied to the data, as in the case of ex post studies.

Of course, to be useful, predictive modelling should be grounded as solidly as possible in the empirical evidence. In practice, such evidence will rarely be sufficient (either from a scope or reliability perspective) to fully specify a predictive model, and additional assumptions and broader evidence sources will need to be called upon. The reliability of these models therefore varies. At the end of this review we note and comment on the available procedures for predictive modelling.

This research has drawn on both ex post and ex ante outputs. Our two case studies (which are presented in subsequent sections) evaluate the actual productivity impacts of PT investment in New Zealand. We have developed modelling templates from these that can be flexibly applied to predict the impacts of possible or proposed PT investments or policy changes.

2.1.2 Summary of research methods

The literature review has been directed at uncovering the results and findings of relevant scientific research as recorded in articles in scholarly journals, books and institutional working paper series. As well, relevant reports (such as government commissioned studies), including those dealing specifically with transport issues in New Zealand, have been canvassed. We do not, at this stage, consider NZTA's current *Economic evaluation manual*, although it is discussed in more specific detail in section 5.1.

A standard database to search for scientific research outlets in economics is the reference tool *EconLit*, maintained by the American Economic Association. *EconLit* covers more than 2000 journals in economics and related disciplines (including most, but not all, field journals with a transportation focus), as well as books and economics working paper series. It does not normally include government reports and the like.

We instructed *EconLit* to search the abstracts of its holdings for the words 'productivity' *or* 'efficiency' and the phrases 'public transport' *or* 'public transit', and limited the search to publications and papers from 1985 onwards. Each of these combinations of keywords yielded fewer than 30 results, with much overlap, and with many of the studies turning out to be not of significant interest or relevance to our study. However, as is usually the case, a number of the most recent articles cited led to other relevant papers to provide a more robust academic base.

Two recent papers were of particular relevance. The first is the review of the implications of transport infrastructure investment for growth and productivity carried out by the noted British economic historian Nicholas Crafts (2009). The second is the very impressive empirical study by two University of Toronto economists, Duranton and Turner (2009).

2.2 Aggregated macroeconomic studies

The standard economics template for analysing productivity is the growth accounting/production function model.[1] This method systematically relates measured levels of productive inputs (land, capital, labour) to the output of goods and services (GDP) at the country level. In this way, the contribution, or productivity, of individual inputs can be isolated and measured, either over time and/or across countries or industrial sectors. At this very high level of aggregation the actual physical levels of inputs and outputs cannot be identified. For example, the usage of PT would be assumed to match the value of the capital stock of transport infrastructure and equipment, and would normally be subsumed into a wider variable measuring all public infrastructure – including roads – and also non-transport investments.

2.2.1 Contribution of public infrastructure to GDP

In Crafts' and several other papers, attempts to isolate a contribution to total output of public infrastructure capital are traced back to Aschauer (1989). Aschauer's famous paper estimated the returns or productivity of such to be rather enormous, implying an annual rate of return on investment in the order of 100%. This finding provoked a good deal of sceptical follow-up research, resulting in substantially reduced estimates of the elasticity of GDP with respect to changes in the stock of public infrastructure capital to around the 0.1–0.2 range. These seem more plausible, but nonetheless are still quite substantial (cf Crafts 2009, pp335–337, for discussion and references). It must be noted that Aschauer's major methodological problem was a neglect of causality. A strong link between capital and output at the aggregate economy level can go two ways – more capital produces more output, but more output also means more income to generate the funds for investing in public capital. Once the endogeneity of the capital output link is allowed for in the econometric procedures, estimates of capital's independent effect decrease (cf Turner 2009, p9).

Canning and Bennathan (1999) in a study for the World Bank using a panel of cross-country data for the 1960–90 period, found it likely that the contribution to total GDP of road infrastructure investment was about the same as for capital more generally. Fernald (1999) uncovered evidence of a high return in terms of national productivity of investment in the US interstate highway network. This return lasted only until 1973, by which time the network of motorways created by the massive post-war US highway development programme had been essentially completed. Turner (2009, pp9–10) noted that Fernald's results conflicted with other studies, which found road productivity effects after 1973. Turner suggested that failure to control for endogeneity might in this case have biased Fernald's estimated returns downwards, and also

[1] When motivated by profit maximisation or cost minimisation, this model can usually be equivalently represented in 'dual' form, as a profit or cost function.

noted that the studies finding a positive post-1973 effect were micro in their focus – looking for effects at the city or county level. Thus it is possible that investments at this level simply move resources from one region to another (the 'transfer' effect), and thus wash out at the national or aggregate level – a possibility which Turner considered 'merits further investigation' (2009, p10).

Overall, the literature seems to conclude that investment in public infrastructure has indeed contributed to increases in GDP, but the aggregate-level studies do not tell us how this contribution has been made (direct or indirect). Nor are the aggregate-level studies able to specify how it was divided between particular types of infrastructure (eg transport vs communications, or road vs rail). Even more importantly, the literature is unable to determine whether the contributions matched the true costs of the investments, given economists' expectations of a 'distortion' from raising investment capital through taxation. This distortion arises because raising a dollar of tax revenue costs more than a dollar of GDP as income taxation distorts other choices (eg the work/leisure choice). A reliable finding that investments in PT or infrastructure have earned a real rate of return over time of over 10% (which is good) would need to be qualified if the opportunity cost to the economy associated with the up-front investment exceeded its face value.

2.2.2 Productivity of public transport systems

Whether or not they cost more than their face value to collect, funds distributed to firms or industries as subsidies, and public policies (such as minimum parking space requirements imposed on urban development), may change the prices perceived by transport system operators. Input choices may be distorted, resulting in lower allocative and/or productive efficiency within the sector itself, potentially extending to the productivity of the wider urban economy. On the other hand, policies may correct distortions, by implicitly internalising externalities, and/or by compensating for a subsidy to other transport nodes, such as under-priced parking for private vehicles.

So, although our primary interest here is in what we could call the downstream effects of PT on urban growth and productivity, we should not ignore the fact that the sector itself is a substantial user of resources. The efficiency of its own input use may be relevant, in particular if it is affected by policies aimed at promoting downstream benefits.

There is quite a large field of literature on the productivity or efficiency of urban PT systems. Brons et al (2005) undertook a meta-analysis of 35 such studies. However, their findings focused on the traits of the studies themselves (eg what measure of output was used, what type of database was utilised) rather than *reasons* why PT systems might be more or less efficient. This is reflective of a focus in the surveyed literature on measurement rather than explanation. A general problem with this literature, fully recognised by Brons et al, is that, in the absence of any absolute benchmarks for efficiency, it is generally only possible to compare PT systems with each other (ie to measure the *variance* in productivity or efficiency) within each study's sample, without being able to judge whether the whole sample is, on average, closer or further away from some absolute efficiency benchmark.

A particularly impressive study is Karlaftis and McCarthy (2002) which is based on a large panel database covering 256 US PT systems observed over nine years (1986–94). Their major finding was that the scale of the system mattered. The largest US urban PT systems tend to have lower average costs due to both increasing returns to scale of the network and to their generally higher rates of capacity utilisation (eg passengers per bus). These scale effects count as a direct industry-level contribution to national productivity. If they apply under New Zealand conditions, then they should be identified and quantified in project appraisal within the EEM template. Note that, in general, direct productivity improvements of PT systems will be valued equally whether they apply to final demand (households, commuters) or intermediate demand (work trips and freight movements).

Our *EconLit* search uncovered just two journal articles dealing directly with the issue of policy induced efficiency effects in PT. Obeng and Sakano (2002; 2008) found evidence of subsidy induced input price inefficiencies in a cross-section database of US bus PT systems.

2.2.3 Wider indirect effects

Now we return to the matter of distinguishing the wider or downstream productivity impacts of PT. Some economists have attempted to apply the growth accounting/production function methodology at a more disaggregated level.

Two independent studies of regions in Spain (Moreno and López-Bazo 2007; Ezcurra et al 2005) both found evidence of rather low or even negative direct returns to highway investments in that country. Egert et al (2009) in an OECD study, found that rail and road infrastructure investment had significantly positive indirect effects on productivity in other sectors. Affuso et al (2009) concluded that the UK had over-emphasised rail over road investment, in terms of the productivity returns. Be this as it may, we note that in New Zealand, the bias has plausibly been in the opposite direction, particularly in recent decades when the privatisation of the rail network led to a situation where the rail was required to deliver commercial returns on the total value of the underlying assets. The road network (which has never been privatised) has, in contrast, only ever been required to fund the ongoing costs of maintenance and expansion (indeed, the underlying capital value of the road network – especially the value of land on which it is sited – has, as far as we could determine, never been quantified).

There are not many empirical results directly and narrowly relevant to transport investment – much less to PT – using the economist's mainstream growth accounting/production function approach. It seems that the latter is simply too blunt an instrument to reliably distinguish the contribution to total GDP of a particular sector of the economy, especially when this is at a fairly detailed level, such as transport networks. More disaggregated analysis is required, though we note that descending to this level must inevitably eliminate opportunities to pick up any of the economy-wide impacts that contribute to the overall rates of return upward of the 10% noted above.

2.3 Microeconomic studies

Microeconomic or case studies take particular transportation projects or policies (either actual or proposed) and analyse their economic impacts to the extent that these can be traced. Forward looking or *ex ante* case studies include the cost–benefit analysis (CBA) required to accompany all major PT investment proposals in New Zealand. *Ex post* studies look at the effects of particular projects, either as a one-off case study, or in econometric or other empirical analysis, requiring a database of PT systems.

Harford (2006) is a notable example of the latter approach. Using estimates of PT-attributable reductions in congestion costs for 85 urban areas, he came up with figures for total system benefits compared with the operating costs of the system. Harford found that congestion savings and the direct benefits to passengers being able to use the system are the main positive effects of PT systems. Environmental impacts (greenhouse gases and pollution) are assessed to be minor. Benefit–cost ratios (BCRs) are quite small, averaging 1.34 on a 'medium' scenario, and being less than one for most urban areas. The largest cities and PT systems tend to have the highest BCRs; largely because these cities tend to have the highest congestion costs (lowest urban traffic speeds). It is noted that these results depend on the values placed on time savings, which differ between countries.

Bento et al (2005) using transport and urban form data, found some evidence of the latter affecting driving behaviour in 114 US urban areas, and that increased road density was not only associated with higher vehicle miles travelled and car ownership rates, but also with higher probabilities of bus ridership.

Harford (2006) took estimates of congestion cost savings due to PT and incorporated these into a CBA. Congestion savings arise from two possible causal routes: direct and indirect. An investment or other intervention that encourages commuters (and/or other travellers) to switch to PT can reduce road congestion directly by taking people out of cars, and indirectly by inducing a more compact urban form. This reduction in 'urban sprawl' comes primarily in terms of where people live in relation to where their jobs are.

On the latter issue, Su and DeSalvo (2008) used data on 518 US urban transit agencies to investigate the effects of transportation subsidies on urban sprawl. They found that PT subsidies reduced sprawl and automobile travel subsidies increased it. The average number of households in the urban areas in their sample appears to be around 80,000, which means that they were dealing with urban areas of comparable size to larger New Zealand cities. They noted that, in the US, utilisation of the bus systems was on the whole quite low, with just 11 passengers on average for every 40 seats capacity. This suggests the possibility of increased cost effectiveness from achieving higher utilisation rates, a finding which could be relevant to Harford's (2006) results and to policy more generally (for example when setting fares).

Since anything that reduces the market price of urban transport reduces commuting costs, at least in the first instance, it is not obvious *a priori* that subsidising PT should encourage more compact urban form. Su and DeSalvo used the standard monocentric city model to explore the theory behind this. The structure of their argument was premised on the assertion that a reduction in PT resulted in higher real incomes for PT users. It followed that they would bid up property values where property provided access to PT, making private vehicle commuters comparatively worse off and inducing them to live closer to the centre of the city. We do not find this chain of reasoning to be totally compelling; there may be other linkages to be explored.

Baum-Snow (2007), looking only at highway investments, found (in the US) that these caused people to concentrate near highways and further from central cities (a result relevant to the discussion below of agglomeration economies (AE)). Turner's take on this is:

> *[Baum-Snow] does not give us a lot of insight into the welfare implications of these changes. We suspect "too much" migration out of central cities because congestion and pollution are un-priced. On the other hand, we know that people prefer these locations because they choose them. These two effects work in opposite directions, and we cannot assess whether, at the margin, there are too many highways or not enough.* (Turner 2009, p11)

Turner draws attention here to two factors that should never be ignored by policy planners. First, people do have their reasons for doing things which should usually be given full weight; and second, many targeted policies or programmes are subject to 'second best' considerations. In this case, the value of improvement in PT services may be affected by the presence or absence of related policies (eg the lack of congestion pricing or the presence of minimum car parking requirements).

We could make good use of more empirical evidence on the impact on urban road congestion of supply-side investments in PT and/or roads. In New Zealand, the project-specific CBAs of new or expanded roads and motorways are almost totally dominated by (supposed) travel time savings, which generally assume that an increase in supply of roads will not induce an increase in the demand. A major unresolved issue in transport economics is the propensity of demand to follow capacity, which (in its extreme form) has been encapsulated in the 'Fundamental law of traffic congestion' (Downs 1962). This 'law' states or claims that any given percentage increase in road capacity is soon matched by an equal percentage increase in vehicle kilometres travelled, with, in particular, no effect on congestion (travel speeds).

Duranton and Turner (2009) justified Down's law as being the aggregate of three effects of increasing road capacity: i) households drive more (ie make more and/or longer private vehicle trips); ii) people and businesses migrate to live in the cities where road capacity has increased (ie a locational effect); and iii) transport intensive industries expand in or relocate to these urban areas (ie an industry response).[2] Duranton and Turner also suggested a corollary of Down's law would be that increases in PT usage generated by improvements (eg by subsidised prices or better service) would in the long run have **no** impact on road congestion. This is because the removal of cars of new PT users from the roads would be equivalent to an increase in the supply of roads. This would induce the same response (additional vehicle traffic), until the equilibrium level of congestion was again restored. This proposition requires further investigation, in the light of the use reported below of 'diversion ratios' for the (non-one-for-one) effects of increasing PT supply on private vehicle use. We note that Duranton and Turner's results were generated in the US system, in which buses (to which their study was limited – ie no light rail or subways) were not on average very important, and that they did not distinguish between commuting and other types of travel.[3]

These are dramatic predictions for the first of which (ie the relationship between road supply and road usage) the authors found strong empirical support in econometric modelling of vehicle kilometres travelled (VKT) on the urban segments of the US interstate (motorway) system. We do not know to what extent the predictions apply to other urban roads, including non-motorway major arterial roads, except for Duranton and Turner's (2009, p2646) finding that: 'Surprisingly, diversion of traffic from other road networks does not appear to play a large role' (in the increase in interstate traffic when capacity is increased).

The issues raised by supply responsive demand for road travel were also discussed in a lively symposium in the journal *Transport Reviews* spurred by David Metz's (2008) article 'The myth of travel times savings'. This proposition requires further investigation. It is worth repeating in full Duranton and Turner's conclusions from an earlier version of their paper:

> *High levels of induced demand do not necessarily imply that improvements to the highway system are not in the public interest. However, our calculations suggest that an average extension of the inter-state network does not result in sufficient travel time improvements to justify its costs. Two caveats apply here. First, our welfare calculation excludes some possible external benefits unrelated to travel time savings. Second, certain specific improvements of the system, for example inexpensive improvements to bottlenecks, may well be justified even if an across the board expansion [is] not.*
>
> *A similar comment applies to public transit. The fact [sic] that increases in public transit do not reduce traffic does not imply that such improvements are not in the public interest. While we are not able to perform a welfare calculation to evaluate extensions to bus based public transit, we suspect on the basis of earlier research...that improvements to bus based public transit are often welfare improving.* (2009, pp42–43)

2.3.1 Agglomeration economies

In recent times, the external benefits of transport infrastructure improvements have increasingly been associated with the concept of 'agglomeration economies' (AE). The origins of AE are still somewhat

[2] It is still not obvious why the net result of these three effects should be – exactly – Down's law.

[3] Duranton and Turner's summary statistics reveal that on average there are around 100 lane-kilometres of road per 10,000 urban population, but only 1.34 peak service large buses (2011, table 1, p.2623).

mysterious, but they reflect the apparently substantial increases in welfare (however it is measured) generated by (or at least associated with) the concentration of people and firms in compact urban areas.

Maré and Graham's (2009, p7)[4] succinct definition is that 'agglomeration economies describe the productive advantages that arise from the spatial concentration of economic activity'. We like this definition, although caution that the focus on 'productive advantages' seems unnecessarily premature; we see no *a priori* reason why AE may not also fall to consumers – a point that is discussed in more detail below.

By definition, AE are the benefits received by third parties (externalities) when businesses and people crowd together (agglomerate) in a dense urban setting. They can occur at four levels:

- *Internal to individuals/households*: when individuals gain from wider job opportunities, better retail services, and more social, cultural and recreational opportunities
- *Internal to firms*: when firms gain from thicker labour markets, and from economies of scale generated by access to effectively larger accessible output markets
- *Internal to industries*: technological (knowledge) spillovers; better choice of intermediate inputs; larger skilled labour pool
- *Internal to the city*: scale of local markets and the more efficient provision of infrastructure and public administration.

'Internal to firms' economies are those captured by a firm even if they are the only firm in their industry in the region; 'internal to industries' economies are spillovers across a group of firms in the region and in the same or similar line of business. In practice there may not always be a major distinction between these categories. For example, a thicker labour market could be for a generic skill, such as IT or secretarial which any firm can gain from, whereas technological spillovers will be restricted to the particular activity undertaken in an industry. We note that little is as yet known about the relative importance of these conceptually distinct generators of AE.

Note that what is missing from the above list is whether at a national level, the benefits gained at city level are amplified (by further spillovers from the leading urban areas to the hinterland) or diminished (as the population growth of one city means the decline of others, and/or because the faster growing metropolis sucks away the 'best and brightest' from less favoured regions)[5]. In helping to understand this connection just one of the articles in our literature review is relevant. Chandra and Thompson (2000) found (with US data) that a new major road increased economic activity or incomes in the directly affected counties by around 10%, but reduced incomes in bordering counties by around 3%. This suggests that some degree of economic transfer is occurring at finer spatial levels, as one would expect.

We have not sought to survey the empirical literature on agglomeration[6], but note the finding of Rice et al (2006), from a detailed analysis of sub-regions (averaging a population of around 500,000) of Great Britain, that doubling the mass of a region is associated with average productivity across the region being 3.5% higher. Other studies found slightly higher elasticities, but rarely in excess of 10% and most around 3% to 6%, which is somewhat consistent with those found in New Zealand studies and used in the EEM.

The link from AE to transport policy comes through the word 'mass'. For agglomeration to be effective, it is not sufficient to have a lot of people located within a given geographical space, but it also requires that

[4] Maré and Graham (2009) estimate AE for New Zealand urban areas.

[5] The regions losing people could be in other countries, if migration is affected by productivity changes.

[6] Ascari Partners (2007) have a good bibliography of AE studies, in the context of their discussion of agglomeration and related issues in Auckland.

those people can get to each other within a reasonable time frame. Hence, Rice et al (2006) have defined economic mass in terms of the population within certain driving time bands around the urban area. They found that adding population located more than 80 minutes away had no productivity effect. Transport clearly matters; as it is the speed of travel along with the distance travelled that together determine trip travel time. The link between AE and generalised travel costs has been a focus of research by Graham (2007a; 2007b).

The theoretical framework for considering the impact of changes in travel time (more generally, travel costs) on productivity is provided by Venables' diagram (2007, figure 1c; reproduced in a number of papers, including Crafts (2009, figure 1, p332). Venables infers a commuting decision made by workers living evenly spread out in suburbs outside the inner city. There are jobs available in both areas, with an unvarying (perfectly competitive) wage available close to home and a higher wage paid by inner-city jobs. The inner-city wage premium reflects the AE of the inner city, and therefore increases with the number of workers prepared to commute to the city, though with decreasing returns. The worker's decision of whether or not to commute depends on both the wage premium and the commuting costs (which are assumed to be linear in distance from the CBD). The equilibrium occurs at the level of inner-city employment where the concave wage premium curve crosses the linear commuting cost line. Here, the marginal commuter is the worker living just far enough away that their costs of commuting are equal to the wage premium gained by working in the inner city.

So, any transport innovation (eg improved PT, better roads, cheaper petrol or more economical cars) that flattens the slope of the commuting cost line will encourage some workers and employers previously located outside the economic commuting zone to move their work into the city. This will necessarily be at a higher wage premium, which all previously commuting workers will also benefit from. Note that the Venables' framework does not envisage higher employment in the CBD (or other job node) reducing *overall* unemployment in the national or regional economy – rather, it is the result of lower commuting costs making it economic for workers and employers to *shift* jobs into the central area, to take advantage of the AE found there.

Graham (2007a; 2007b) formalised the idea of distance and commuting speed or other costs mattering in the concept of 'effective density'. He applied this in the context of his own econometric estimates of AE for UK firms, comparing spatial distance and effective density (based on actual data on average vehicle speeds) as explanatory variables for the extent of realised AE. Although simple distance does explain AE quite well, effective density is better, resulting in higher estimates of AE externalities, more consistent with Venables' theoretical model. Interestingly, excluding Greater London from Graham's sample does not reduce the AE estimates, which demonstrates that it is not only large urban centres that benefit from agglomeration.

Duranton and Turner (2009) found that the estimated elasticity of VKT with respect to the population of urban areas was well below one, possibly even less than one half. An elasticity of 0.5 means that a doubling of city size increases vehicle miles by only 50%: 'people in large cities drive less, per capita, than they do in smaller cities' (2011, p2625). Part of this lower elasticity may be a response to the generally higher traffic congestion (slower journey speeds) in larger cities, and part to better PT facilities, but is also likely to be in part an effect of agglomeration. With increased population density, the chances of finding who and what you want within reach (ie without having to drive elsewhere) are that much higher.

We note one final point: current literature emphasises the presence of AE in production. This suggests that people and firms become more productive when they are spatially concentrated. But there is no *a priori* reason to presume that AE do not also exist in consumption, to the degree that the spatial concentration of economic activity may provide consumers with economic benefits, such as a more diverse range of goods and services. Research by Tabuchi and Yoshida (2000) on relative living standards in Tokyo's urban areas suggests that AE in consumption exist and that they may be substantial. AE in consumption, if they do indeed exist, are unlikely to be reflected in economic indicators such as output or wages. Instead, they are expected to be capitalised into the value of land. This is an important area for further research, even if it lies outside the scope of this study.

2.4 Detailed empirical studies

While very interesting, the research we have surveyed includes no empirical studies (ie analysing actual data) digging down to the disaggregated level where different modes of transport and transport innovations, in particular in PT, are analysed. The following sections focus on two particularly important sources of information in the literature; the first discusses relevant New Zealand studies whereas the second considers an American Public Transportation Association (APTA) study on the economic benefits of PT.

2.4.1 New Zealand studies

In addition to the work of Maré and Graham (2009) referred to above, we note the detailed analysis of productivity and employment density in and beyond Auckland by Maré (2008). This paper provides striking evidence on the size of spatial differences in labour productivity and their link with employment density, finding in particular that the largest productivity premium is earned in the Auckland CBD. Maré was able to control for industry composition effects, but not for differences in labour quality. He found, overall, evidence that localisation agglomeration effects (from spatial concentration of firms in the same industry) were more important quantitatively than urbanisation effects generated by employment density across the city. A cautionary note is that Maré did not find evidence of the productivity/density link operating over time – that is, in this data, changes in density in a particular region or industry could not be reliably associated with changes in productivity.

Kernohan and Rognlien (2011) is a recent NZTA research report which provides a comprehensive analytical survey of AE and other wider economic impacts of transport innovations, though it does not focus on PT. We will relate our work to Kernohan and Rognlien's in more detail in chapter 5 of this report.

Grimes and Liang (2008) used changes in land values to measure the gross benefits of a major transport infrastructure investment, in this case the successive extensions to the length of Auckland's northern motorway. They found large effects on land values near the new exits of the motorway, as well as employment and population increases. From these, they calculated a BCR greater than six.

Jakob et al (2006) carried out a case study of the internal (private) and external (social) costs of private transport and PT in Auckland. They estimated that external costs sum to more than 2% of Auckland region's GDP, with the vast majority of these being generated by private transport. They concluded that 'not only are the external costs of vehicle transport high, but that contrary to popular belief the total costs of private transport are subsidised by public transport users' (p55).

Greer and van Campen (2011) used 2006 Census data for 344 area units of urban Auckland to estimate a cross-sectional model explaining the propensity of residents to use bus transport in their journey to work. They found that population density, distance to rail or ferry station (being the PT alternative), and the frequency of bus services during rush hour were positively related to bus use. Household car ownership, distance to the city centre, and household income were seen to have negative effects.

Wang (2009) used quarterly time series data available from the late 1990s through 2008 to estimate models of the demand for urban PT (buses and trains) in Auckland, Wellington and Christchurch. Various long and short-run effects are reported for income and spatial variables, but no details on the statistical significance of the models are given.

Covec's (2008) overview report *Drivers of economic growth in Auckland* has a useful summary of the AE results, but does not extend to transport investment and policy issues.

Ascari Partners (2007) is one of the studies summarised in Covec (2008). It also has a discussion of the London *CrossRail* project and the large effect that predicted AE had on the successful case made for this. It also shows some bivariate correlations for Auckland between pairs of variables, including what appears to be a link between transport accessibility and employment density (figure 8.5, p42).

2.4.2 American Public Transportation Association

The 2009 APTA-sponsored overview and review of the economic impacts of PT compiled by Glen Weisbrod and Arlee Reno relies heavily on studies (apparently widespread in the US) that use economic impact analysis (EIA) to evaluate the effects of events such as new investment in PT (Weisbrod and Reno 2009). The EIA methodology starts with this spending event and then traces its purported passage through the economy via 'indirect' and 'induced' effects mediated by an input-output model. The result is a predicted 'multiplier' of the original spending shock, which seems to invariably turn out to be about two, regardless of the industrial, geographic, or temporal setting of the study.

To the independent outsider, it can often appear that a main purpose of commissioned EIA models is to produce impressive looking numbers which the hopeful sponsors of some scheme can use to bolster public and perhaps political support. The EIA methodology actually has very little standing amongst academic and other professional research economists.[7] Its basic flaw is neglect of the supply side of the market economy – that is, opportunity costs, or the alternative use of resources. Only a small fraction of the resources called on by spending on any particular new project would in a modern economy be drawn from reserves of unemployed labour and idle industrial capacity. The bulk of the goods and services claimed directly and indirectly by the project will have to be diverted from other valuable uses. Overall, the changes in total spending predicted by the EIA method must usually be an exaggeration of what actually would occur.

This flaw is most clearly revealed in the Weisbrod and Reno (2009) report in its treatment (cf exhibit 4–12, p58) of cost savings generated by travellers switching from private vehicles to PT (through lower vehicle operating and ownership expenses). The report assumes that all these savings will be spent elsewhere, and so they likely will. However, it fails to state that they would previously all have been spent too, on vehicle operating and ownership expenses! There is therefore no net change in spending to be multiplied and put to the credit of the PT investment.[8]

[7] For a particularly robust critique of EIA, see Crompton (2006), which is one paper in a symposium on evaluating the economic impact of tourism, including the Dwyer et al (2010) paper. A typically crass example of an EIA of public transport is Sharma and Pitafi (2009).

[8] Note (another common error) that cost savings from persuading people to switch from private vehicles to PT are not efficiency or welfare benefits that can be put to the credit of the PT investment or policy in a CBA. This is because the vehicle owners were *willingly* incurring these costs before switching, implying that the utility they got from using their cars was worth at least that much to them. Because travellers switching could always choose not to, there will be an improvement in their wellbeing from the switch, but it will be measured under EEM procedures as a small 'rule-of-half' triangle gain, probably much smaller than savings in petrol, depreciation etc. By the same token, people switching to an improved PT service from low-resource cost travel modes such as walking or cycling, do not thereby lose welfare by the amount of their new added disbursements on PT fares.

Weisbrod and Reno (2009, p11) provide a long list of regional US studies that have 'documented' the 'direct, indirect and induced impacts of PT and operating spending on region-wide jobs and wages'. However, we believe that all of these studies, and just about all EIA reports in general, are predictive, not empirical – that is, they use their multiplier methodology to predict what will happen, never returning to find out if these predictions were accurate (with the exception of property value studies, which are covered in a wide-ranging list, cf. p24). The lack of econometric support for EIA may be 'the dog that didn't bark in the night' in this case; there are no extant empirical validations of EIA predictions because these predictions are false.

To its credit, Weisbrod and Reno's (2009) report has some useful tables on PT costs (p46), which although not relevant to spending flows in the economy are important for the CBA of welfare and efficiency effects. There is also a useful section on the treatment of 'diversion rates'; the percentage of new PT users who have switched from driving themselves, which depends on the extent to which a more attractive PT system encourages new trips, and longer trips by existing users (pp 50–1). However, no empirical studies or evidence are cited to help select likely values of diversion rates, and the resulting impact on road traffic speeds (congestion).

Finally, the report takes the PT argument to AE, claiming that 'many studies' (p53) have shown that adding PT results in higher urban density, even going as so far to provide a rule of thumb (p53): each 1% increase in PT's 'mode capture' increases metropolitan density by 650 people per square mile. While an interesting claim, no citations are given for this or other studies.

2.5 Predictive models

There are various analytical tools which can be used to *predict* the impact of transport policies or investments, aside from the flawed EIA methodology discussed above. As noted, these combine data, estimates of possible parameter values taken from empirical research, and assumptions about how the economy operates into a model which can be asked to generate answers to 'what if?' questions. These models differ in the reliability of their empirical grounding and in the plausibility of their theoretical assumptions about the operation of markets and the economy.

Graham (2007b) reported modelling for the UK Department for Transport, incorporating his estimates of agglomeration effects. His work estimated that AE would increase the *predicted* benefits of CrossRail (a major proposed London rail scheme) by about 25% from already substantial levels that depended wholly on predicted travel time savings.

Feldman et al (2008) reported work, in part using a gravity-type model (extensively used in the international trade literature to explain flows of goods, services, capital and travel between countries), to predict UK location choices in the context of measures of 'accessibility'. This sets the issue within the very big problem of explaining where people live and work, where firms locate, and how transport affects all this. This paper shows ratios of WEBs to conventional benefits for a wide range of possible transport innovations.

Computable general equilibrium (CGE) models do in general include the supply side of the economy and impose some sort of summing constraint (eg that total employment in the economy is constant with respect to what is being modelled). They tend to be very much limited to a 'static' equilibrium solution, and hence are not as good at predicting long-run growth effects of investments and policies. Notwithstanding these concerns, there is no sophisticated off-the-shelf CGE model available in

New Zealand at a level of industrial and regional disaggregation that could usefully be set to deal with urban transport issues[9].

2.6 Proposed approach

We found in the literature ample evidence of public infrastructure and service investments, including transportation infrastructure and services, playing their role as a productive input in the economic process.

There is, however, no stable rule of thumb that can be applied to specific projects, each of which must be treated on its merits. These merits include direct benefits to users that are not well placed to access alternative travel modes (ie non-car owners), and also environmental effects. The major impacts generally operate through the substitution of private vehicles for PT, and on urban traffic congestion and induced travel (in the medium to long run, induced location effects will also be seen).

Relief of congestion yields direct benefits to remaining private vehicle users, lowering commuting and freight costs, as well as encouraging more traffic overall. Both these effects are likely to result in a denser and better connected urban area. This in turn will generate the AE, identified as both the major factor in urban economic growth, and the major payoff associated with better transport systems (as opposed to travel-time savings, which seem to be a transient phenomenon, at least in the absence of road pricing).

Our preferred model for assessing the contribution of PT to economic productivity is discussed in more detail in the next chapter. Nonetheless, from the literature discussed thus far we can already conclude that it should be:

- firmly grounded in microeconomic theory
- firmly grounded in sound transport engineering models
- firmly grounded in parameters that can be derived from real world data
- capable of handling a variety of PT investment and policy scenarios
- set up to encourage and facilitate sensitivity analysis, wherein the impact of alternative assumptions and parameter values on the results can be tested
- capable of examining welfare effects, including important externalities.

The following chapter expands on the formulation of our preferred model for quantifying the contribution of PT to economic productivity.

[9] Applied CGE policy modelling is much further advanced in Australia. See Dwyer et al (2006) for an application of the impact of tourism spending.

3 Model formulation

An objective of the research was to advise the NZTA on the nature of any effects on productivity of specific PT innovations (new pricing, policies, programs, infrastructure, equipment), with the ultimate goal of presenting an accessible and easily implemented model to complement the procedures set out in the EEM or the results of transportation modelling carried out under the aegis of the EEM.

Our review of the literature on the economic implications of transport systems led us to adopt and extend the model developed in Venables (2007), where the productivity 'action' comes from AE generated in the city centre, or other nodes of concentrated employment. Such economies depend on the density of employment in the city centre, which in turn depends on the number of people willing to commute to work there, which in turn depends on the costs of commuting from the residential suburbs compared with the pay-off in terms of higher wages. Thus, the focus is on commuting costs, rather than other input costs such as freight costs. Since commuting is an activity usually carried out twice a day during the morning and evening peak periods, it may result in transport infrastructure becoming congested (slower journeys to/from work) at these peak times. It may be through the relief of such congestion that transport innovations, including PT, will have their primary economic effect.

The key strength of the Venables' model is that it enables us to *explain* the level of employment in the node as the resolution of two opposing forces: agglomeration and commuting costs, and thence to *predict* changes in employment resulting from a shift in transport costs. Existing approaches, including those used in New Zealand following the EEM methodology, simply accept exogenous forecasts of employment levels, or at the most apply off-the-shelf elasticities to link changes in generalised transport costs to changes in employment or commuting trips. The Venables' model thus offers the prospect of a major step forward in the scope of our transport modelling within a surprisingly tractable analytical framework.

In this chapter we give an account of the Venables' model and its 'story', and then detail and document the steps we have taken to apply Venables' analytical approach to the specific issue of PT innovations. To place our work in context, the major components of our work where we have sought to 'add value' to Venables are threefold:

- First, we model directly (and in detail) the implications for congestion and travel speeds of mode shifts induced by the PT innovation, with capability built in to our model to handle a variety of types of innovation, including changes in fares, changes in service, and changes in capacity of either bus or rail PT systems.[10]
- Second, and because PT innovations in general will affect the use of private vehicles for central city commutes, we allow specifically for change in land use within the CBD as a result of changes in the number of private vehicles entering each day.
- Third, we have implemented the model in an accessible and replicable spreadsheet (see www.nzta.govt.nz/resources/research/reports/514/).

[10] Venables gets his model moving with a simple rotation of a linear per distance travel cost function. This would only apply accurately in the specific case of a fare change (eg through a change in subsidy) to a PT system with excess capacity in a setting where all commuters use that system.

3.1 Overview of the model

We are interested in the productivity effects of PT innovations in urban areas. We note that urban PT is used predominantly for the carriage of people, not goods, and that the three main types of trips undertaken by urban residents within their city are:

1. Journeys to/from work, eg commuting
2. Journeys at work, eg for work purposes
3. Non-work journeys, eg shopping, school and recreational activities.

Most at-work journeys in New Zealand are undertaken in private cars or trucks, mostly during the work day outside the main commuting peak periods. This limits the relevance of PT innovations to such trips. The most important likely exception to this is an innovation that improves access to a major employment node, such as the potential extension of the rail network to link the Auckland CBD (and other business nodes) to Auckland International Airport. An innovation of this scale would justify a bespoke modelling approach, for which the model developed here could serve as an initial template. PT innovations may indeed be important to non-work travel, and such travel is important to consumer and household welfare, but it does not have a direct linkage to productivity (production of commercial goods and services). However, to the extent that commuters and non-work travellers do compete to use transport systems, we will need to allow for such in our modelling.

So, our focus is on the productivity implications of PT innovations through their effect on journeys to/from work in major employment nodes – that is, commuting. We do not focus on smaller urban settlements, where people tend to live quite close to their work, and/or travel to it on an uncongested road infrastructure. In these situations, we suggest that the analytics of PT project appraisal are quite straightforward, and can be dealt with using the standard EEM procedures, or some variant thereof.

Our contribution is to provide a model which can be used to evaluate the productivity impacts of a PT investment or innovation in the setting of an urban economy, a city, which is large enough to have the following characteristics:

- The residents of the city live spread out over a substantial contiguous geographical area.
- The city has (one or more) economically significant centres, or central business districts (CBD), in which a relatively large amount of economic activity takes place within a compact area, and highly local AE are clearly present.
- Most CBD workers do not live there, so there are substantial daily commuter flows, and because of the size of the city commuting distances are not, on average, insignificantly small.
- Moreover, because of the size and density of the city the road network is significantly congested during morning and evening commuting peak periods.

We calculate the likely productivity impacts of a PT investment or policy innovation in this context. The following section discusses the paths for productivity effects of PT innovations in this setting in more detail.

3.1.1 The paths for productivity effects of PT innovations

In this setting we identify the following events:

- A PT innovation is implemented that reduces commuting costs (objective and subjective – known in total as 'generalised costs') for existing users of PT; as a result some private vehicle commuters switch to PT.
- If PT competes with private vehicles for the same road space, and because PT carries more people per vehicle-metre than do private cars, the shift in mode share reduces congestion and private vehicle journey times are reduced. This congestion reduction effect is even more pronounced for rail improvements, which do not compete at all for road space with private vehicles.
- Some marginal PT users, who would have otherwise switched to PT due to the improvement, change their minds and revert back to private vehicles due to the reduction in journey times. The last effect is a 'rebound effect'; it will partly counter the number of people who switch to PT.
- If the PT improvement is (at least partly) implemented by reducing private vehicle capacity (eg bus lanes), then private vehicle congestion levels could remain unchanged or even increase. If the PT innovation is especially badly designed then the net effect could even be an increase in generalised commuting costs. However, a reasonable PT innovation will probably generate an overall improvement in commuting times.

In any case, commuting will remain a costly activity, so we need to ask why people are willing to do it at all, given that in most large urban conurbations there are numerous non-CBD jobs, and that, indeed, probably most residents of the city do work locally, with generally shorter and perhaps uncongested commutes. The primary economic reason is that wages are higher in the CBD (for similar jobs and/or similar workers).

The source of the higher CBD wages is higher productivity, which in turn is generated through the externalities of density: *Agglomeration economies.* The more people there are working together within the confined geographical area of the CBD, the more communication and diffusion of ideas and information (knowledge spillovers); the finer the feasible division of labour (increased specialisation); and the thicker the labour market (more choices and better matches between workers and jobs). That is, average labour productivity (and thus wages paid, given other assumptions about elastic supply of capital and competitive urban labour markets) increases as a function of total CBD employment. Jobs outside of the CBD are assumed to be too dispersed for the densities to reach the levels beyond which significant AE kick in. That is, the non-CBD wage is exogenous to density.

But this begs the question as to why it is that not everyone commutes for the higher-paid CBD jobs, perhaps initiating an endless upward spiral of more workers, higher productivity, still more workers, still higher productivity and so on ad infinitum?

The primary reason is commuting costs, which increase non-linearly at the margin with growth in the total number of commuters. The marginal worker will be the one who is located the furthest away from the CBD in terms of travel costs. Workers willing in principle to work in the CBD decide whether or not to do so by subtracting their personal cost of commuting from the CBD wage premium. Workers living in close proximity to the CBD will commute, and workers living far out will choose to work locally instead, given that commuting costs increase with distance. The marginal worker will be indifferent between working locally and commuting. It is the location of that marginal worker which determines the size of the labour force that is available to the CBD, given the current CBD wage premium. Thus PT innovations that reduce commuting costs (both directly for users and indirectly for private vehicle users) increase the geographical reach of the CBD over the surrounding workforce.

Note that 'infra-marginal workers', who receive some economic rent, or benefit, from living closer to the CBD, will find their benefit capitalised into land values. As a result, actual property rents will be higher, the closer the house or apartment is to the CBD. In our model we have not attempted to make any assumptions about where people choose to live. As the CBD wage premium increases over time with growth in CBD employment, there is also likely to be a tendency for people to crowd closer to the CBD, living in smaller apartments or in houses on smaller sections. There has been such a tendency observed, at least in Auckland and Wellington; however, we have not incorporated this into our current version of the model. This is perhaps the next logical step in model development for this research question.

3.1.2 The equilibrating processes that enable the model to be solved

The outcome (equilibrium) of this model is reached at the level of CBD employment where AE (determined by the CBD wage as an increasing function of employment), match the commuting cost of the marginal worker (being an increasing function of distance from the CBD, also strictly determined by the level of employment, ensuring that the marginal commuter lives furthest away).

When attempting to find the equilibrium between two increasing functions, there is no mathematical guarantee that these will meet. However, economically there is such a guarantee. We have specified the CBD wage function to increase with employment but at a decreasing rate (ie gets flatter), as diminishing returns set in to moderate the productivity gains from an increasing number of workers in one limited central space. We also have specified that the commuting cost function increases at an increasing rate (ie get steeper) as an increasing number of commuters travelling on a fixed road network increases congestion leading to slower journey speeds.

Thus, given that both functions start at the origin (no employment means no productivity premium and no commuting cost), it should be guaranteed that they will eventually come together at an equilibrium point that defines the number of people employed in the CBD, balancing productivity and commuting costs, as shown in figure 3.1. Note that the CBD wage here is the premium paid over the wage available to a worker of given skills working in the suburbs, where AE do not come into play.

3.1.3 The new equilibrium

In our modelling we take the current situation to represent such an equilibrium, which we then 'shock' by the exogenous event of a PT innovation. The effect of this is to shift both the commuting cost and the wage premium curves or functions. Having determined how each curve is affected, we can compute a new equilibrium and compare this (in terms of the productivity changes) to the current situation.

The PT innovation shifts the (private vehicle) marginal commuting cost curve by way of its effect on the mode share of PT and private vehicle, and the resulting reduction in congestion and increase in travel speeds for any number of commuters. The speed of PT itself is included in our model implicitly through the marginal assumption that the split between PT and private vehicle use is determined by the commuter indifferent between the two modes, and whose subjective costs from the two alternatives must therefore be the same. That is, the full (generalised) commuting cost of the marginal private vehicle commuter is the same as of the marginal PT commuter located the same distance from the CBD.

The PT innovation will also directly shift the CBD wage premium curve, which is determined by the production function, by freeing up some CBD land for productive use. The idea here is simply that privately owned land in the city can have three commercial uses: for car parking; for 'productive' development (which in a modern city is predominantly office buildings plus some shopping and personal services) and for residential use.[11] We assume that total available land in the CBD is restricted by a combination of geography,

[11] Of course a given plot of land could be simultaneously developed in two or more commercial uses, with a basement car park, perhaps street level retail and then offices and condominiums above.

infrastructure (such as Auckland's central motorway junction), and zoning rules (such as limits on maximum building height). Thus these three commercial uses will compete in the market, and in a well-functioning real estate market, land rents will be roughly equal for all uses of similar land.

Now consider the situation where we disturb the current equilibrium with a PT innovation that results in fewer commuters using private vehicles, which necessarily means fewer cars coming into the CBD each day. This reduces the demand for, and thus the market return from, space used for car parking (either surface parking or purpose-built garages). To restore balance in the market, the private sector will at the margin (and possibly in the future) switch some parking space land to other, more profitable, uses.

In effect, fewer private vehicles needing daily storage (and roading) free up land *within* the spatial confines of the CBD for other productive uses. Since 'land' (more generally, floor space) is an input to production, including commercial office space that accommodates employees, then the outcome is a (small) upward shift in the wage premium/average productivity curve due to AE.

Our proposition is standard microeconomics: space previously used for car parking is, upon a reduction in demand for storing private vehicles, subsequently redeployed to other uses. This is represented in the EEM and elsewhere by the use of elasticities of demand with respect to price or cost. In empirical applications the issue will be to supply realistic parameters determining the actual size of the shift in land use following a reduction in demand for space to store private vehicles.[12]

3.1.4 Productivity impacts

Our new equilibrium will have higher CBD employment, higher wages and also higher travel costs for the marginal commuter (who is travelling further). The expected effects on net productivity include:

- Existing commuters have both lower travel costs and higher wages from their higher productivity – both to be counted as productivity benefits.[13]
- New (additional) commuters receive higher wages than they earned before working outside the CBD, but most of this is offset by their costs of commuting. There will be a small 'rule-of-half' triangle efficiency gain to be counted for the average new commuter.
- A major contribution of the Venables' paper upon which we have based our model was the observation that income taxes drive a wedge between wages paid and wages received. (Pre-tax) wages paid by employers match the productivity of workers, but (given that travel to work costs are not tax deductible) workers pay for their commute with after tax dollars. There is, therefore, a gap between the marginal commuter cost and the average productivity of all commuters, which is a pure productivity gain, captured by the government.

3.2 Graphical representation of the model

We first show the model as depicted graphically by Venables, then represent graphically the alterations we have made to cope with PT's unique contribution.

[12] Given the paucity of research on the nature of the relationship between the supply for car parking with respect to demand for private vehicle travel, we have assumed that 50% of the space 'freed up' is reallocated to productive uses that increase the density of the CBD, which is a value consistent with the induced demand effects currently assumed in the EEM. Further research could seek to establish an appropriate value for this parameter.

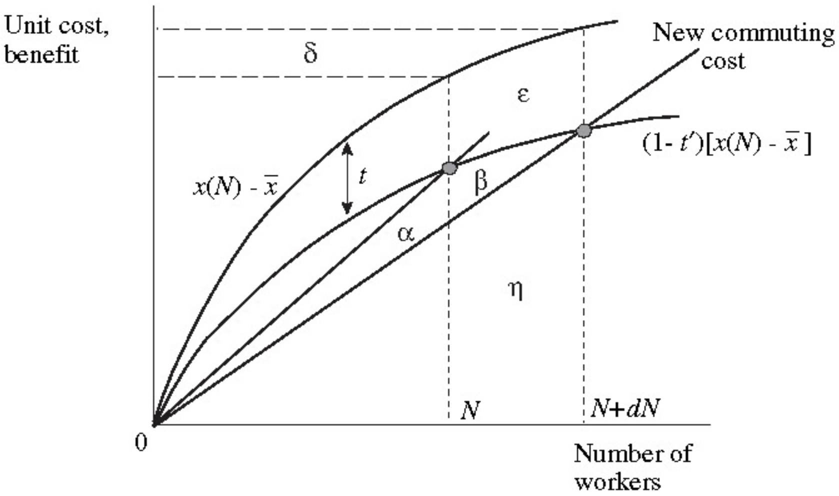
[13] As mentioned previously, the 'rents' from lower travel costs are likely to be mostly capitalised into land values.

3.2.1 Venables model

Figure 3.1 is taken from Venables (2007). Basically, as we have noted above, a reduction in unit travel costs makes it economic for workers to commute from further afield, and the resulting increase in the CBD workforce generates higher wages for all workers, thanks to AE.

The zero-point in figure 3.1 represents the situation of a suburban resident working locally (ie not requiring a significant commute in most cases) and earning the competitive wage or salary for whatever job they do, with this determined by their productivity in that job, and this productivity in turn being unembellished by the benefits of AE, because suburban firms are too dispersed to experience agglomeration effects. The upper curved line then tells us the productivity premium (ie the excess of the CBD over the suburban wage, for a given worker or type of worker) generated in the CBD through AE, where the horizontal access gives us the number of CBD employees commuting into work each day.[14] Of course, this line is upward sloping – more people result in more agglomeration externalities. Venables also draws it with a decreasingly positive slope, realistically reflecting the likelihood of diminishing returns as more and more workers locate in the CBD.

Figure 3.1 Graphical representation of Venables' (2007) model – net gains from transport improvement with linear transport costs, endogenous productivity and tax wedge



A competitive labour market (operating behind the scenes here) ensures that the wage everyone gets (controlling for differences in skills etc) is set by the marginal productivity of the 'last' worker hired. But this productivity is not 'money in the hand', because the government extracts some income tax. So, the lower curved line in figure 3.1 shows the after-tax wage premium, which is the relevant number for the suburban resident weighing up whether it is worth their while to make the commute.

The costs of commuting are drawn by Venables as being constant per unit distance – that is, a linear total cost of commute, depending simply on distance travelled. A linear commuting cost curve could be realistic for the case where all workers travel by rail (or perhaps by buses using bus lanes) at a constant speed not affected by the total number of commuters (ie no congestion), and pay a simple distance-based fare.

So, we start from an initial equilibrium where the Nth furthest out commuter is indifferent about whether they work in the CBD or locally – that is, for this commuter the after-tax CBD wage premium is just

[14] Venables could have allowed for people living and working in the CBD by starting the curved line from a positive value on the vertical axis. This would not change the basic story.

gobbled up by the (full) costs of the daily commute. Then, a PT innovation, such as a system-wide reduction in fares, improves the commuting cost line by rotating it down. Existing commuters will of course continue to commute, and be happy at the reduction in their travel costs and with their higher wages due to agglomeration externalities, at least until these become absorbed into their housing rates or rents. As for the dN new commuters who join them each day on the system: all of these apart from the dNth realise some net improvement in their economic situation, again until property values adjust. We get to a new equilibrium with higher wages, and a nice income tax windfall for the government (which, it is here implicitly assumed, is 100% not wasted, perhaps because it could be used to offset the need for income taxes across the board).

3.2.2 Our model

Figure 3.2 represents our development of the Venables' model. The two changes that we can show at this level of abstraction are: a) a shift in the wage premium curve due to the productivity bonus from freed-up CBD productive land (ie reduction in parking); b) a non-linear transport cost curve allowing a wider range of PT innovation scenarios, of which the most likely in a New Zealand setting are policies or programmes or investments which increase the propensity of commuters to use PT (bus and/or train), in the setting of pervasive congestion of private vehicle commuting. With otherwise the same story as before, we move from one equilibrium point to the other as CBD employment increases from N_0 to N_1.

Turning to the welfare economics (normative evaluation) of the situation: the total surplus or social profit generated by the CBD is the difference between the value of CBD output and the full opportunity costs of the resources needed to produce the output. In this case the opportunity costs are the wage the commuters could earn working outside the CBD (assumed fixed and exogenous), and the costs of commuting to the CBD.[15]

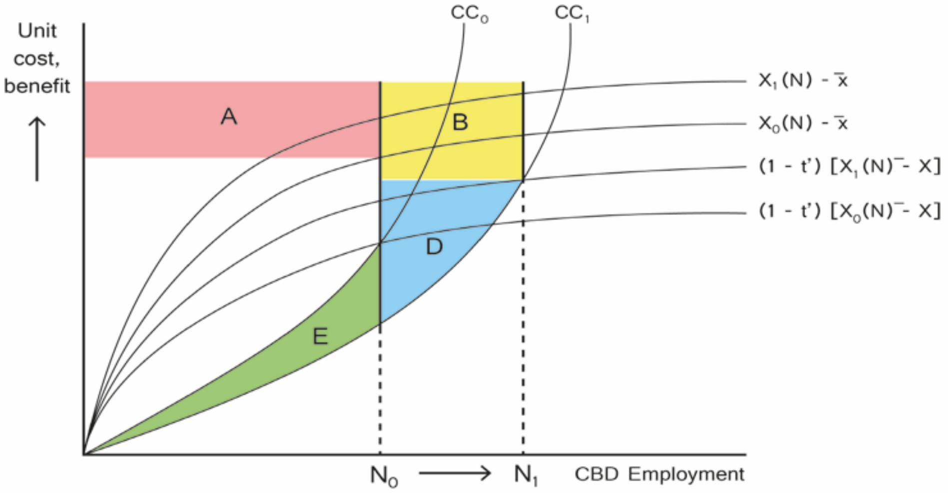
The net productivity effect of the PT innovation is simply the difference in total surplus before and after the implementation. The figure breaks down the effect into its four components:

- The rectangle A is the total increase in output produced by the original CBD commuters.
- The rectangle B is the tax wedge of surplus captured from the new CBD commuters.
- The triangle D measures the transport cost rents earned by infra-marginal new commuters.
- The triangle E measures the benefit to the original commuters of a less congested road system (Note: these benefits are also estimated by conventional transport models).

It should be noted that figure 3.2 is not drawn to scale. Because the change in the total number of commuters is quite small, area E is larger and area D smaller in our quantitative simulations.

[15] Taken literally, the implicit assumption here is that commuting costs to suburban jobs are zero. In fact, of course, there is a huge variety of residence/employment linkages, many involving lengthier commutes than the distance to the CBD. This is not a problem – what the economic or elasticity-based approach followed here (and in the EEM) depends on for its usefulness is the existence of a significant *margin* of suburb dwellers, for whom the most relevant choice is the trade-off between commuting to the CBD and whatever their best alternative is.

Figure 3.2 Graphical representation of our model – net gains from transport improvement with congested transport costs, endogenous productivity and tax wedge



3.3 Mathematical representation of the model

Although figure 3.1 gives a reasonable depiction of the basic 'story' underpinning our development of the Venables' model, our actual spreadsheet implementation required a more complex and specific mathematical treatment, in particular to model mode share shifts and non-commuting road users.

In this section we follow the notation of Venables (2007) as far as is appropriate. We begin by representing the city as a smooth, bounded area at the centre of which is located the CBD. The CBD will itself have sufficient spatial mass for this to matter in production, but not enough for its mass to be significant in analysing commuting flows and costs.

3.3.1 Distribution of workers across the city

The density function of uniformly distributed workers located (ie living) at distance z from the CBD (where k and θ are constant parameters) is:

$$n = n(z) = kz^{\theta} \qquad \text{(Equation 3.1)}$$

So, if the city is a straight line with the CBD at its centre, then $\theta = 0$ (assuming that the number of workers at each point on the line is constant). This will also be the case if the city is set out with arterial 'spokes' leading into the CBD, along the length of which commuters are concentrated (as in Venables' worked example in his appendix). If the city is a circular disk with the CBD at its centre (and maintaining the assumption that the distribution of workers across space is uniformly even) the number of workers at distance z is the length of the circumference of the circle with radius z, so $\theta = 1$, given that the length of the circumference is given by $2\pi z$. Equation 3.1 can be integrated to get the total number of workers, N living at or within the distance z of the CBD (where K is a constant compound of the parameters k and θ):

$$N = \left[z^{(1+\theta)}\right]\left[\frac{k}{(1+\theta)}\right] \quad \text{or} \qquad \text{(Equation 3.2)}$$

$$z(N) = \left[N^{\left(\frac{1}{1+\theta}\right)}\right]K = N^{\sigma}K \qquad \text{(Equation 3.3)}$$

The distribution of distance travelled:

$$n(z).z = kz^{1+\theta}, \qquad \text{(Equation 3.4)}$$

can be integrated to get the total distance travelled by *N* commuters where *N* is the total number of commuters living at or within distance *z* of the CBD:

$$D = z^{2+\theta}[\frac{k}{2+\theta}] \qquad \text{(Equation 3.5)}$$

The average distance travelled by each commuter is therefore:

$$d = \frac{D}{N} \qquad \text{(Equation 3.6)}$$

So, for example, if the scale factor $k = 1$ (ie one commuter per unit space), and $\theta = 0$ (linear city case), then the total distance would be $z^2/2$ – ie the number of commuters times the average distance travelled, which in the linear case is one half of the maximum distance.

Substituting equations 3.5 and 3.2 for *D* and *N*, and simplifying, we find that:

$$d = z[\frac{(1+\theta)}{(2+\theta)}] \qquad \text{(Equation 3.7)}$$

We can invert to get the expression for the distance travelled by the marginal commuter:

$$z = \left[\frac{2+\theta}{1+\theta}\right] d \qquad \text{(Equation 3.8)}$$

If we can assign values for θ and *d* (the latter perhaps from existing transport models), then we can solve for *z*. Then, we can rearrange equation 3.2 and solve for *k*, with the equation becoming:

$$k = \frac{(1+\theta)N}{z^{1+\theta}} \qquad \text{(Equation 3.9)}$$

3.3.2 Determining the travel time cost equation

In a city with a given road network, traffic flows freely at low densities of road usage, but with higher densities congestion will develop. Venables summarises the congestion effect with a simple exponential function, although in his diagrammatic exposition he simplifies the situation to exclude congestion effects. Such effects are an essential component of the commuting speeds in a large city with a large CBD, and we allow explicitly for them here.

We rely on a formula developed and applied extensively by traffic engineers in their computer modelling of traffic speeds and flows. Equation 3.10 gives the average time per vehicle per kilometre travelled (*t*) as a non-linear function of the number of vehicles (*V*) using the road system over a time period, such as the morning or evening commuting peak period:[16]

$$t = t_f[1 + \alpha(\frac{V}{V_{cap}})^{\beta}] \qquad \text{(Equation 3.10)}$$

In this expression, V_{cap} is the limit or capacity of the road system, and α and β are parameters, often (we believe) assigned the values 0.15 and 4, respectively. So, for small values of vehicle flow, the ratio of *V* to V_{cap} is very small, and time per kilometre (the inverse of average vehicle speed) is close to t_f, representing the free flowing speed of the road system (possibly, close to the speed limit). Then as the traffic flow

[16] In practice disaggregated traffic models apply equation 3.10 only to lengths of road between interruptions, such as junctions. This does not matter for us, as can be seen.

approaches capacity, the exponential term grows non-linearly, and speeds drop accordingly, as is observed in congested road networks.

We use an exponential approximation to equation 3.10, which is a good approximation over the likely range of outcomes, and has the advantage of analytical tractability – in particular, it can be integrated to get total travel times. So, we write:

$$t = a.V^b \qquad \text{(Equation 3.11)}$$

Where *b*, being the elasticity of *t* with respect to *V*, can be exactly derived from equation 3.8 to be:

$$b = \beta(1 - \frac{t_f}{t}) \qquad \text{(Equation 3.12)}$$

Where b is calculated as the current or do-minimum value for the actual average trip time, *t*. This gives the average time per kilometre (inverse of speed) for **all** road users when the total number of vehicle equivalents is *V*. Equation 3.11 is simple and flexible enough to be calibrated realistically to most transport systems, at least over a reasonable range.

We need to relate the number and composition of vehicles to the number and types of road users. Our concern is with the impact of commuting, which can limit us to considering the morning and evening peak periods. However, even at those times commuters will share the road with other users (eg students, shoppers, work travellers), some of whose trips may be responsive to trip time. These will therefore be endogenous to an extent; to the number of commuters given that the latter impacts on congestion and travel times. Given the non-linearity in the system from equation 3.10, this system feedback is not analytically tractable. As we expect to be dealing with fairly small changes in behaviour, we will use linear approximations to deal with induced non-commuter travel changes, as described below. Our goal is to specify a reasonably accurate relationship giving changes in trip times as a function of changes in the number of commuters, with the endogenous feedback effects included within this.

In the first illustrative application of our model, the PT intervention relates to a series of bus improvements, where buses are required to share arterial commuting roads with private cars and other vehicles. Factors involved here include i) average number of passengers per private vehicle; ii) average number of passengers per bus; iii) congestion impact of a bus relative to a private car; iv) average trip distances; and v) differences in all these parameters between commuters and other road users, on average.

The number of vehicle equivalents generated by *N* commuters is:

$$p_n v_n N + (1 - p_n) w_n N = \rho_n N \qquad \text{(Equation 3.13)}$$

p_n is the proportion of commuters using PT and v_n and w_n are coefficients converting numbers using each mode into vehicle equivalents. Similarly, the number of vehicle equivalents generated by *M* non-commuters is:

$$p_m v_m M + (1 - p_m) w_m M = \rho_m M \qquad \text{(Equation 3.14)}$$

We use the private car as the numéraire, and set the parameter w_m = 1/1.3, with 1.3 passengers per private car on average number in peak periods. Then we set v_m= 1/8, which would be appropriate if, say, the average peak period bus carries 24 passengers and has the same impact on road speeds as three private cars. If the PT innovation is linked instead to a rail improvement, or to dedicated stand-alone bus corridors, where there is no interaction with private vehicles, then we can handle this in the model simply by setting v_m = 0.

So, the total number of vehicle equivalents is:

$$V = \rho_n N + \rho_m M = \rho_n (N + \gamma M) \qquad \text{(Equation 3.15)}$$

Substituting equation 3.15 into equation 3.11:

$$t = A{\rho_n}^b (N + \gamma M)^b \qquad \text{(Equation 3.16)}$$

Since *N* is going to be our 'action' variable, any changes to it bring the system into a new equilibrium following a PT innovation, and we need to substitute to get *M* in terms of *N* in equation 3.16. Given the mixture of linear and non-linear forms in this equation, such substitution is only possible using linear approximations. The calculations are shown in appendix A2. They involve linear approximations resulting in an elasticity of vehicle equivalents, *V* with respect to the number of commuters, *N* which can be combined with the elasticity *b* in equation 3.16, which becomes:

$$t(N) = A(\rho_n N)^e \qquad \text{(Equation 3.17)}$$

So, using equations 3.3 and 3.17, the total trip time of the marginal (*N*th) commuter is:

$$T_N = z(N).\,t(N) = A({\rho_n}^e) K N^{\sigma + e} \qquad \text{(Equation 3.18)}$$

Then, the daily travel commute cost of the marginal commuter is:

$$TC_N = 2GA({\rho_n}^e) K N^{\sigma + e} = r N^{\sigma + e} \qquad \text{(Equation 3.19)}$$

In this equation, *G* is the full (subjective and objective) or 'generalised' cost of commuting per unit time. All the constants are now bundled together in one parameter, *r*, which we can solve for as described below. Since we have computed values of *a, ρ* and *K*, we will also be able to infer the value of *G*, and compare these with the EEM and other estimates of the cost of travel time.

3.3.3 Determining the production function

Now we turn to determining the output produced by whatever number of workers, *N*, commute to the CBD. We ignore in this version the contribution of people living and working in the CBD, which has been a quite small (though increasing) proportion of the total workforce – around 11% to 12% in Auckland. Venables specifies total output per worker (average productivity), as:

$$x = x(N) \qquad \text{(Equation 3.20)}$$

Additionally, we assume that x' > 0, and x'' < 0, where the apostrophes denote the first and second derivative respectively. That is, output per worker is a positive function of total numbers of workers, but with a decreasing slope – the function is concave to the origin. So, there are AE (all workers' productivity is enhanced by a greater density of workers in the CBD), although these benefits exhibit diminishing returns. This is a result of the congestion as increasing number of workers exist in a fixed total space – in this case, the CBD. However, neither land nor capital is explicitly included in the expression.

We are here interested in the 'productivity premium' generated by AE in the CBD, which in the Venables' set up is written as $x - \bar{x}$, where $\bar{x}$ is the outside option productivity of a representative worker in the suburbs. We call this premium *y*, and use an exponential representation of the function that determines its value (known in this context as a Cobb-Douglas function). We continue to abstract from the contribution of capital – which can be justified by assuming that 'capital' (eg building supplies, office equipment) is elastically supplied at constant prices and used in constant proportion to the amount of labour. However, we explicitly include the contribution of space or land (*L*) in the production process:

$$y = cN^{\delta} L^{\eta} \qquad \text{(Equation 3.21)}$$

Both of these exponents are set as small, positive parameters. When a shift away from private vehicle use frees up usable space in the CBD, the effective value of *L* increases, and the functional form of the relationship between *N* and *y* shifts up. Deflating by the marginal income tax rate gives the net CBD premium which is equated to the marginal commuter's travel cost from equation 3.8, using *N* to adjust to bring about equilibrium.

3.3.4 Travel time savings

Equation 3.19 can be used to give the commuting costs of the *n*th commuter (where commuters are sorted by distance from the CBD):

$$TC(n) = rn^{\sigma+e} \qquad \text{(Equation 3.22)}$$

This can be integrated over the range [0,*N*] to get total travel costs of all commuters:

$$TTC(N) = \frac{rN^{(\sigma+e+1)}}{\sigma+e+1} \qquad \text{(Equation 3.23)}$$

We wish to know the change in the travel costs of the original group of commuters following the PT innovation. Since the distance travelled by the original group is unchanged, we just need to compare the new and original travel speeds and multiply the ratio of these by the original total travel costs from equation 3.21 to find the travel time savings for the original group.

3.4 Response to questions

Our decision to extend Venables' model educed several questions from members of our steering group. For this reason we saw value in creating a separate stand-alone section that explicitly addresses questions relating to the model and its application.

3.4.1 Do polycentric cities suggest the Venables' model is flawed?

Economic models attempt to capture key features of the world, not replicate it in all its complexity. To suggest that the existence of polycentric cities proves the Venables' model is 'theoretical' (and hence false) is analogous to rejecting gravity models (which are commonly used in transport modelling) because they do not adequately deal with zero flows (which of course occur in reality).

What the Venables' model does is hypothesise the existence of a relationship between commuting costs and the supply of labour to a city centre, or another concentrated employment node susceptible to agglomeration effects. As commuting costs decrease (for example by way of a transport improvement) then the supply of labour to the CBD, or another employment node increases. And because of AE, an increase in the supply of labour to the city centre tends to increase wages and generate additional benefits; above and beyond the transport improvement's direct impacts on mobility (ie travel times).

It is essential to note that the key relationships within Venables' model are commuting costs, labour supply and productivity (reflected in wages). The fact that some people work outside the city centre (whether in centres or otherwise) is not problematic for the model, and indeed is what the model depends on, ie the switching of employment from lower wage dispersed local jobs to higher wage jobs concentrated in the CBD, or another node. It is true that, if 'local' jobs are themselves subject to milder AE, then losing these jobs could have a negative effect on local productivity and wages for the remaining workers. The present model does not capture such welfare effects, but it should be easy to do so – for example one could draw on existing EEM methodology for AE.

3.4.2 Is the link between transport and agglomeration dubious?

It was suggested that the theoretical link between transport and agglomeration identified in Venables (2007) was 'dubious'. We first note that our regard for Venables' model is shared by a number of other economists, such as David Maré and Daniel Graham who (in previously published research for NZTA) commented: 'an excellent theoretical account of the link between transport and agglomeration is set out by Venables (2007)'. Venables' model is further supported by David Maré in his review of this research, where he stated: 'My overall view was (and still is) that the Venables' model is an appropriate and useful model for the analysis of transport investments, albeit a stylised one'.

Critics of the Venables' model have not, as far as we are aware, been able to offer an alternative explanation for the puzzle of why, given the higher wages that are available in the city centre, not everyone works there? Venables' intuitive and tractable answer is that commuting costs limit the supply of labour to the central city; this is the story that we have built on. As mentioned previously, the interplay between commuting costs and agglomeration benefits means that a disproportionately high density of employment (but not all) occurs in the central city.

In our research we have suggested that PT improvements also reduce commuting costs and increase the labour supply to centres constrained by congestion and available land, and thereby are likely to generate additional agglomeration benefits. At the same time they reduce the demand for car parking and increase the space available within the city centre, which in turn can accommodate additional employment and hence lead to further AE. We feel this is a plausible economic framework for analysing the interactions between PT improvements and AE.

3.4.3 Empirical analyses versus economic theory

Some members of the steering group felt that our model placed too great an emphasis on economic theory, rather than empirical analyses; we think not.

As mentioned in section 1.3, the process of economic reasoning tends to proceed from observations of stylised facts, through to the formulation of economic models and hypotheses, and finally empirical analyses. In this research, we have drawn on the stylised fact that higher rates of PT use tend to be positively correlated with economic productivity. We have in turn formulated a microeconomic model and developed hypotheses about key relationships that may explain this stylised fact. While we have not taken the final step of undertaking empirical analyses, this invalidates neither the model nor the hypotheses; empirical research is not a substitute for economic models and vice versa.

The brief for this project called explicitly for a 'framework' to determine the contribution of PT to economic productivity. While further research, ie empirical analyses, is certainly important, it lies somewhat outside the scope of this project. We believe that our focus on developing an economic model to achieve this end is therefore appropriate. Moreover, in chapter 4 we estimate reasonable parameter values in the process of applying the model to two case studies. While further empirical research would be useful for refining these values, we suggest that the model is ready and able to be applied in its current form.

3.4.4 Will greater use of public transport free up car parking?

The steering group requested we support our claims that greater use of PT would lead to a reduction in the demand for and supply of car parking, which would subsequently 'free up' space for other activities, some of which would be used to accommodate increased numbers of employees, thereby enabling the city centre to realise greater AE.

We note there are two assumptions to be supported: First, that an increase in the use of PT leads to a reduction in the demand for and supply of car parking and, second, that a reduction in the supply of car parking leads to increased density (and by extension AE). The following two documents seem to support our assumption that greater use of PT leads to reduced demand for car parking:

- *National guidelines for transport system management in Australia: volume 4 – urban transport* (NGTSM) (ATC 2006). Part 1 of the NGTSM comments that economic appraisals of PT initiatives should consider the 'extent and timing of reduced need for car parks' (p18) and that 'the principle concern is the number of car parking spaces that will be avoided as a result of the initiative' (p29). The NGTSM also suggests that 'the approach used here, based on "diversion rates" (ie the proportions of new PT users "diverted" from the various alternative modes), is considered preferable …' (ATC 2006).
- *The economic evaluation manual,* (EEM) *volume 2,* section 3.7 (NZTA 2010) notes that 'reduced vehicle travel may result in a reduction in the demand for parking facilities ...'. The EEM also notes the 'timing of any parking cost saving must be carefully assessed. Reductions in vehicle trips may provide few savings in parking costs in the short-run if there is abundant parking supply. However, over the long term, the excess parking spaces or their land can be used for other purposes' (pp3–11). SP9-1 of the EEM also includes 'parking' as one of the primary benefits of new passenger transport services.

These two documents seem to provide ample support for our claim that increased use of PT leads to a reduction in the demand for and supply of car parking.

We turn now to considering empirical evidence for our second assumption, that a reduction in the supply of car parking leads to increased density (and hence agglomeration benefits). McCahill (2012) used detailed GIS analysis to investigate relationships between levels of private vehicle commuting, parking supply and total density across a sample of 14 US cities in 2009. He found:

- a strong positive correlation (R^2=0.59) between levels of private vehicle commuting and the area used for parking
- a strong positive correlation (R^2=0.73) between levels of private vehicle commuting and total density (which he defined as the sum of residents and employees).

To finish, we quote from his conclusions (p40): 'By planning for and investing in diverse transportation systems that require less land, cities can free up productive land over time, build strong urban environments, and improve their capacity for development'.

This empirical evidence tends to support our suggestion that increased use of PT will free up space used for car parking and, in turn, facilitate higher urban densities.

3.4.5 Transport improvements operate in both directions

Members of the steering group observed that transport improvements could have divergent impacts on agglomeration, ie they might cause employment to disperse away from the central city, rather than agglomerate. This is true, insofar as transport improvements tend to lower the generalised costs of travel in both directions.

Transport improvements, however, are likely to cause a relatively larger reduction in generalised transport costs in the peak direction of travel. For example, a transport improvement may cause a 20% reduction in travel times in the peak direction, while only causing a 10% reduction in the off-peak direction (which is less affected by congestion).

The net effect of the transport improvement will be to tilt people's locational choices in favour of more central city employment, rather than more dispersed employment. So while transport improvements do have impacts in both directions of travel, their impacts on peak direction travel costs are likely to be disproportionately greater. Hence transport improvements in congested conditions are more likely to result in further agglomeration.

4 Applying the model

In this section we describe how we applied and interpreted the model to estimate the productivity benefits of PT innovations in the New Zealand context.

4.1 Case studies

We applied the model developed in the previous section to two recent PT case studies, namely:

- the Central Connector bus corridor, Auckland
- double-tracking and electrification of the rail corridor, Waikanae.

The model was implemented in Excel and closed (ie the new equilibrium was found) using Excel Solver. In both cases the model was calibrated to approximate the economic and transportation situation in Auckland and Wellington before and after the projects were implemented.

We note that we are undertaking an *ex post* re-creation of the analysis that would normally be undertaken *ex ante*. Because the PT innovations have already been implemented and we did not have access to the transportation models on which they were based, our case studies are presented as illustrative, rather than conclusive. More specifically, our chosen parameter values may not exactly match the actual situation in every case. The impacts of changes in key parameter values are considered in more detail in section 4.2.

The following sub-sections examine each of the case studies in more detail. For further details on the analysis interested readers are referred to the spreadsheet that accompanies this report (see www.nzta.govt.nz/resources/research/reports/514/).

4.1.1 The Central Connector, Auckland

The Central Connector is a system of interlinked on-street side bus lanes in the corridor connecting Newmarket to Auckland's CBD. The value of this case study, we believe, is that it shows how the effects of a particular PT innovation operating within a larger commuting network can work through the system, inducing changes in commuting behaviour and additional productivity spillovers that are not currently considered in the EEM.

4.1.1.1 Previous evaluations

A number of evaluations were carried out during the period 2004–08 and we have used the most recent that was available to us. The evaluation was undertaken on the assumption of an opening date of 2008 and we have used that again in our evaluation for consistency; in practice the scheme opened slightly later.

The previous evaluation was fully consistent with the evaluation procedures current at the time, using the forerunner of the EEM. We have therefore set our assumptions around discounting to be consistent with the EEM guidelines at the time of evaluation, which differ in some places from those used now (eg a discount rate of 10% was used instead of the 8% that applies now).

The result of the Central Connector (as predicted in detailed transportation models which we were not able to access), was shorter and faster bus trips. Private vehicle trips, on other hand, were slightly slower due to a loss of lane space to bus lanes, plus the need to detour around Grafton Bridge, which was closed to general traffic under the scheme.

The quantified benefits included in the tangible BCR calculation comprised:

- passenger transport user benefits

- travel time savings
- improved journey time and schedule reliability
- benefits occur to existing users and new users diverted from private transport
- private vehicle users
- changes in travel time due to rerouting
- changes in travel time, journey time variability and vehicle operating costs due to congestion
- bus operating cost and time savings
- CO_2 emission costs
- accident reduction benefits

These were derived, we believe, by the application of suitable transport models.

The net present value of the costs of completing the Central Connector was calculated to be $26.1M according to EEM procedures. The net present value (NPV) of benefits was $62.4M, giving a BCR of 2.4 based on 'conventional' transport benefits. At the time of the evaluation the discount rate was 10% and the evaluation period 25 years.

4.1.1.2 Our economic modelling of the Central Connector

In our model application the CBD is defined as the three census area units (CAUs): Auckland Harbourside, Auckland Central East, and Auckland Central West. In the 2006 Census the resident population of these three CAUs totalled 17,900, of which about 8000 worked in the CBD. Total employment in the CBD was 81,200 in 2009.

The model was run for two future years, 2013 and 2021. In calculating the benefit stream it was assumed there would be no benefits on project opening in 2008 but that benefits would ramp up to their full value in 10 years, ie 2018, after which they would remain capped.

For the year 2008 simulations, we used a figure of 80,000 as the pre-innovation number of daily commuters to the CBD, 12,500 of which use roads that are involved in the Central Connector. This was then split with 6000 travelling by bus and 6500 by private vehicles. The mode split was based on counts by the former Auckland Regional Council undertaken on a cordon around the CBD. A further 12,500 non-work commuters (mainly assumed to be students) also come into the CBD on this route during the morning peak period; this is a higher than average value but reflects the proximity of two major universities to the corridor.

The impact of the Central Connector on its introduction in 2008 was assumed to be that the mode split would change from 48% by bus to 52% by bus, based on the available transport model results and standard elasticities. Values for future years were derived using annual growth based on recent trends, including the indication that the number of cars able to enter the CBD was approaching capacity. We used an average one-way trip time of 15 minutes and an average (congested) trip speed of 37.5km/h, assuming uncongested traffic would travel at the built-up speed limit of 50km/h.

For the productivity block of the model, we needed four parameters: 1) average wages outside the CBD; 2) the CBD wage premium over wages paid in the wider Auckland job market; 3) the AE elasticity of output with respect to CBD employment; and 4) the elasticity of output with respect to available productive land within the CBD. Our choices for these parameters were made as follows:

1 For the wages paid outside the CBD for the types of jobs found within the CBD we used the figure of \$60,000/year. We believe this is perhaps a little high and in a real application of the model, greater attention would need to be paid to this number.

2 We proposed a premium of \$15,000, or 25%, paid to match higher productivity within the CBD. Although occupational composition effects may be a factor here, this premium is consistent with the findings of Maré and Graham (2009) relating wages/productivity to employment density. Within the CBD, where the effect is particularly marked, average wage rates are almost 20% higher than the average for the city as a whole, and are up to 35% to 50% higher than those in suburban locations (p36). Hence, we have used 25% as our value for the premium.

3 The elasticity of productivity to employment density derived in Maré and Graham is about 3% for the area that previously defined Auckland city. This suggests that a 1% increase in employment results in a 0.03% increase in productivity. However, in our model it was not total productivity, but the premium that we were working with, so the implied elasticity of this premium with respect to employment would therefore be around 0.12 (= 0.03/0.25). The number we used in the application of the model was 0.10, which on this basis is slightly conservative. We note that the official agglomeration economy estimates in the EEM, from Maré and Graham's research, are around 0.08 for finance and business services industries, which might seem to suggest a much larger elasticity for the wage premium. However, as Mare and Graham have noted, there are likely to be diminishing returns to the benefits of agglomeration. We have simply selected a conservative value and flag the matter as requiring further analysis and research. For the elasticity of the productivity premium with respect to available CBD land, we used the value 0.2, without any empirical support at this stage. Such support or evidence would come from data on the rateable value of bare land, relative to the value added of the business sector.

4 Mindful of the weak empirical support for the output/land elasticity, we were quite cautious in determining the parameters surrounding the amount of land freed up for other productive use by any reduction in the use of private vehicle parking. To calculate a proxy figure, we took the total of the three CAUs (4 km^2) and assumed that half of this land was currently in direct 'productive' business use. Assuming that each private vehicle requires 25m^2 of parking space (so that the current total of such land is 0.615 km^2), and that when a private vehicle ceases to enter the city one-half of this space could be switched to directly productive commercial use over time, we reached a figure of 0.004 km^2 (4000 m^2) 'new' land in the CBD to shift the productivity premium factor.

4.1.1.3 Outcome

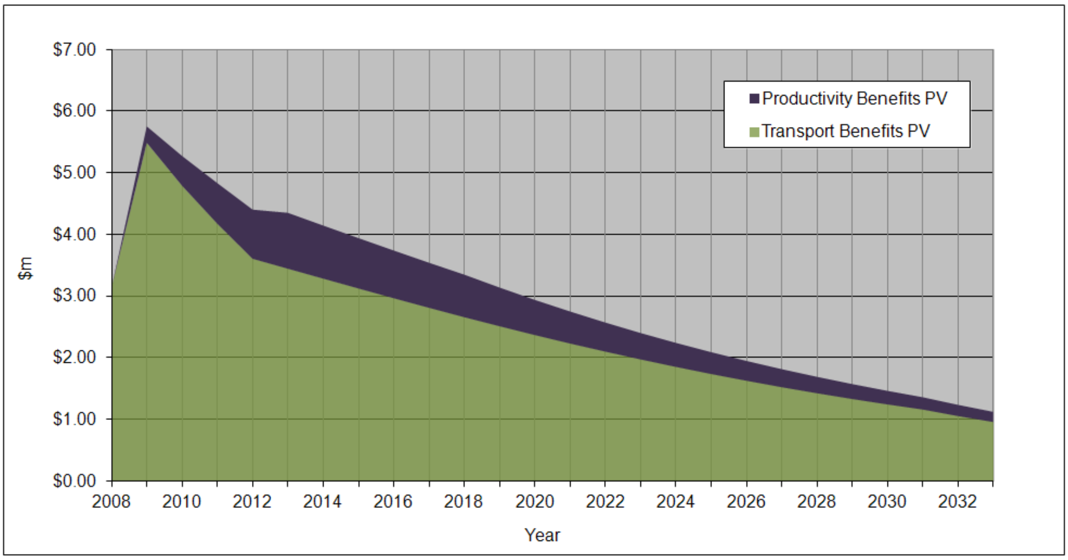
In applying the model we found that the reduction in generalised commuting costs due to the development of the Central Connector supported an approximate increase in total CBD employment of 0.8%. This increase in CBD jobs was matched by an equal loss of lower productivity suburban jobs, which is welfare enhancing because the people switching to CBD jobs are better off, even after allowing for the longer commute. The agglomeration economy gains, along with the productivity bonus of CBD land freed up from car parks and put to directly productive use (presumably as additional office space) would generate a 0.1% increase in the productivity of all CBD workers.

Our model predicted agglomeration effects would total \$1.991M/year in 2021. This should be compared with the 'conventional' transport benefits in 2021 of \$8.78M, of which the 'extra' benefits are just below 23%. Looking at present values (using 10% and 25 years), the NPV of conventional benefits is \$63.4M whereas the additional productivity benefits are in the order of \$12.2M, or 19%. The comparison of PVs is more appropriate as this is the basis on which transport projects are usually assessed.

Figure 4.1 shows how the stream of conventional benefits, as calculated in the original evaluation, compares with the productivity benefits using our model, taking the NPV at a discount rate of 10%. Note that the former have been back-calculated from the available information so may have a small margin of error.

Both sets of benefits tail off in later years due to the impact of discounting, notwithstanding the underlying growth of around 3% pa. The key difference is that the productivity benefits take time to ramp up in the early years whereas the conventional benefits have a high value on opening. This is due to the fact that productivity benefits take time to have an impact whereas benefits such as travel time savings begin (pretty much) the day the scheme opens.

Figure 4.1 Conventional and productivity benefits associated with the Central Connector, Auckland



4.1.2 Waikanae double-tracking and electrification, Wellington

The second case study draws on an evaluation of the proposal for an upgrade of the western rail line in Wellington, namely double tracking and electrification to Waikanae (DTEW). The key part of the scheme was to extend the electrified part of the Wellington rail passenger network from Paraparaumu to Waikanae.

In simple terms DTEW would provide three types of improvements to passenger service on the Paraparaumu line:

- extension of urban commuter services to Waikanae
- improved reliability due to removal of some sections of single track
- shorter peak headways – 15 minutes rather than 20 minutes – on services to Paraparaumu and Waikanae, with the option of further reductions in future.

Each of these was expected to attract new users to rail, some of whom would have otherwise driven – thereby bringing about a reduction in road traffic on competing corridors.

While its main focus is at the northern extremity of the rail network, DTEW was expected to bring benefits on the whole corridor from Waikanae to Wellington. More frequent and reliable long distance trains would bring improvements for all users since reliability problems have considerable knock-on effects over time and across the network. Double tracking would also provide improved resilience in the event of delays due to other factors, for example late running caused by slow passenger boarding, where the present single track left no room for error.

4.1.2.1 Previous evaluation

The evaluation was done in 2007–08 and the scheme opened early in 2011. A full economic evaluation was carried out which was consistent with the EEM at the time. With year zero taken as 2007/08, benefit and cost streams were computed for 25 years and discounted at 10% pa. The 'do minimum' was taken as retaining the status quo. Patronage impacts of the scheme were drawn from a combination of the Wellington Regional Transport Model and the use of standard elasticities.

The results of the economic evaluation ($ million PV) are given in table 4.1; it can be seen that the BCR is 2.1. Approximately 60% of benefits accrue directly to PT users, with the rest going to the remaining road users in the corridor.

Table 4.1 Summary of conventional benefit-cost analysis for DTEW

Benefits and costs	Value
Passenger benefits	$73.08
RU benefits	$44.34
Total benefits	**$117.42**
Costs	$72.81
Extra revenue	-$16.85
Net costs	**$55.96**
Benefit–cost ratio	**2.1**

4.1.2.2 Economic modelling of DTEW

The total number employed in Wellington in 2008 was estimated at 62,000 (drawn from a number of sources). Using rail passenger data and traffic counts from the parallel SH1 the total number of affected commuters on the study corridor was a little over 6000 in each AM peak, which was split between rail and car (the use of bus on the corridor is small). Of this the rail share was 42.7% and this was forecast in the evaluation to increase to 44.6% following DTEW (all for 2008).

The model was run for two future years, 2016 and 2026. In calculating the benefit stream it was assumed that benefits would ramp up from opening to reach their full value within 10 years, ie 2021, after which they would be capped for the remainder of the evaluation period. These ramp-up assumptions were consistent with those used in the Central Connector case study.

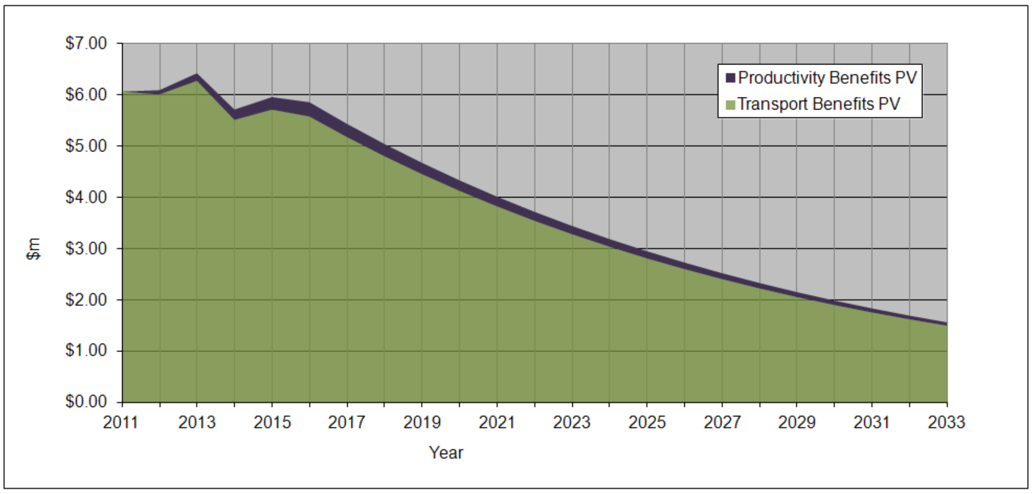
The key assumptions for wages outside the CBD; the CBD wage premium; and the elasticity of productivity with respect to density that were made for case study 1 were retained for case study 2, with the amount of available land in the CBD being the notable exception. This parameter was calibrated to Wellington values. We set the trip time used in the model to 40 minutes, which represented an average along the corridor for both road and rail.

4.1.2.3 Outcome

With discounting carried out on the same basis as in the original evaluation (10% and 25 years), the PV of additional benefits was found to be $3.45m. This was 3% of the 'conventional' benefits of $117.42M. This relatively low percentage (at least in comparison to the Central Connector case study) was probably a reflection of the comparatively small nature of the DTEW scheme – its impact on PT mode share was less than 2%.

Figure 4.2 shows the PV benefit stream in a similar way to the one for the Central Connector. The graphs are of a similar shape as before but in this case the productivity benefits are much lower.

Figure 4.2 Conventional and productivity benefits associated with the DTEW, Waikanae



4.2 Sensitivity testing

We undertook several sensitivity tests to assess how the results were impacted by changes in key input parameters. Table 4.2 summarises the parameters that were tested, their base value, the range of new values that were tested, and the subsequent 'elasticity' of productivity benefits with respect to changes in the parameter values.[17]

Sensitivity tests were applied only to the Central Connector case study. These sensitivity tests highlighted the impact of changes in parameters on the economic benefits predicted by the model. We see that results are most sensitive to changes in the CBD wage premium, as we would expect given that the wage premium is the key measure of the benefits associated with increase central city employment. Benefits also seem sensitive to changes in the effective marginal tax rate, because this determines the size of the wedge and its subsequent impacts on the location of employment. The model seems to be less sensitive to changes in other parameters.

Table 4.2 Summary of sensitivity tests

Parameter tested	Base value	New values	Elasticity
CBD wage premium	25%	20-30%	+1.000
Space needed per private vehicle entering CBD	25m^2	10–40m^2	+0.202
Elasticity of wage premium wrt employment	10%	0.05–0.15	+0.274 to +0.297
Elasticity of wage premium wrt CBD land	20%	0.10–0.30	+0.203
Effective marginal tax rate	33%	0.25–0.30	+1.772
Exponent in speed-flow function	4	3.5–4.5	+1.114 to +100.7

We note that the elasticity of benefits with respect to changes in the exponent in the speed-flow relationship is not only high, but also rather asymmetric. Stated differently, the reduction in the exponent from 4 to 3.5 causes a relatively larger drop in benefits than an increase from 4 to 4.5. This hints at the

[17] By 'elasticity' we refer to the ratio of the percentage change in benefits to the percentage change in input parameter. For example, increasing the CBD wage premium from the base value of 25% to 30% (which is a 20% increase) is associated with a +20% increase in benefits. Hence the 'elasticity' is calculated as 20%/20% = +1.000.

significant role congestion plays in our model and in turn suggests it may be important to calibrate the speed-flow function to the PT innovation being analysed, rather than using a generic value as we have done here.

To round out this sensitivity testing, we used the range of parameter values presented in the table above to generate low and high scenarios for the productivity benefits of the Central Connector case study. In our 'base' case we were predicting productivity benefits (excluding travel-time savings) of around $1.991M per year by 2021, which we refer to as our central estimate. When we applied the low and high parameter values we found the predicted benefits varied from $0.968M to $3.08M per year. Thus our low and high scenarios are fairly evenly distributed around our central estimate.

From this we conclude that the productivity benefits predicted by our model are somewhat sensitive to changes in key parameter values, but that the impacts are fairly symmetrically distributed on the high and low side.

5 Wider implications

In this section we consider implications of our model in the context of other research and of the EEM.

5.1 Relationship to wider economic benefits

Our model estimates AE generated by increased CBD (or any other major business node) employment. The increase in employment is made economically feasible by decreased generalised commuting costs following a PT innovation, which encourages a relocation of jobs (at the margin) within the urban area.

We relied on two of the five sources of WEBs recognised in the research literature as possible in principle, as recently surveyed comprehensively in Kernohan and Rognlien (2011), hereafter referred to as Steer Davies Gleave (SDG) 2011).

- agglomeration economies
- job relocation benefits
- labour supply benefits
- imperfect competition
- increased competition.

We incorporated the first two of these, but not the other three. SDG (2011) recognised agglomeration effects but did not focus on them, because they were already dealt with in the EEM. They recognised relocation benefits, as do we, and presented an adept analytical representation of these in their section 11.2 (SDG 2011, pp66–7).

Aggregate labour supply effects may in principle generate WEBs because of the income tax wedge between the value of a new worker's output and the after-tax wage received by the worker. In practice, they are hard to find in the data, on which SDG (2011, p55) noted:

> *Other research … finds labour supply among working individuals unresponsive to commuting time, mainly because travel time savings are exchanged into longer commuting distances…*

Longer commuting distances are the driver of the job relocation effects in both our model and that of Venables. In their own application to the case of the proposed second Auckland Harbour Crossing, SDG (2011) made use of an aggregate labour supply elasticity response to overall reductions in generalised transport costs.

We presented our model in terms of already employed workers switching from suburban to CBD jobs. Then the 'free' tax wedge is generated only on the CBD wage premium. If, however, it was deemed reasonable to expect that some proportion of the new commuters would be encouraged by the lower commuting costs and higher CBD wage premium to re-join the workforce from having been out of employment (or that some of the job-switchers had their previous suburban jobs filled by new workers), then it would be appropriate and quite simple to add to the productivity benefits computed in our model a further sum to represent the tax wedge on non-premium wages, as was done by SDG.

Imperfect competition and increased competition effects are problematic. The theoretical basis for imperfect competition effects is based on the partial equilibrium analysis of restriction of output in a particular industry (as shown in SDG's figure 8.1, p41). But if **all** (or nearly all) industries are imperfectly competitive – as SDG indeed assumed in their empirical calculations – the partial equilibrium calculations do not apply. Ever since the discovery of the 'law of second best' more than half a century ago, economists have appreciated that the general equilibrium efficiency implications of imperfect competition cannot even be signed *a priori*, much less assigned values, if positive price/cost margins are ubiquitous[18].

As for any benefits from increased competition – we are not aware of theoretical or empirical justification for expecting an increase in agglomeration to have any significant net effect on the extent of market competition in an economy. Therefore we are comfortably in agreement with SDG (2011, p53) that such effects are not worth attempting to quantify in this context.

5.2 Relationship to the EEM

5.2.1 The EEM methodology for calculating agglomeration benefits

The EEM includes a methodology for calculating AE generated by transport improvements (NZTA 2010, appendix 10.4). There are some interesting and relevant matters to be raised here. In general, the EEM focuses conceptually on two main types of agglomeration effects:

- *Localisation economies*, generated by increases in the scale (employment) of an industry, or closely related industries, which operate in close spatial proximity to each other
- *Urbanisation economies*, generated across the board by increases in the total size (total working population) of a large city *or* by decreases in the costs of travelling within the city.

The current EEM methodology for calculating AE first splits the urban area into zones, which are then assigned an allocation of full-time equivalent employees.[19] The methodology for calculating AE then proceeds as follows:

1 A transport improvement is implemented that reduces the average generalised costs (AGC) of travel for trips between zones (step C).

2 The reduction in AGC increases the effective density (ED) of individual zones, by bringing them closer (in an economic sense) to the employment in other zones (step D).

3 The increase in ED results in a commensurate increase in productivity, proportional to the agglomeration elasticity assigned to each zone (step E).

The agglomeration benefits can then be calculated as the sum of the 'productivity uplift' that occurs across all individual zones. The extent of the zones, their employment levels and AGC of travel are normally defined by, or calculated, using a four-stage transport model. The EEM methodology therefore revolves around three key equations: 1) the change in AGC associated with a transport investment (step C); 2) the change in ED that flows from the change in AGC (step D); and 3) the change in productivity that flows from the change in AGC (step E).

[18] Using the SDG parameters of a 20% imperfectly competitive profit margin and an aggregate demand elasticity of -0.6 (p46) literally imply that total GDP *and employment* in New Zealand are 12% lower than they would be in a hypothetical perfectly competitive counterfactual. We believe that no plausible general equilibrium model would generate numbers like this. We note too that the use of price/cost margins are indicators of imperfect competition is of doubtful validity, given that such margins do not allow for capital and entrepreneurial returns.

[19] These can be further broken down by ANZSIC industry grouping to allow for more refined estimates of agglomeration elasticities.

It is important to understand the structure of these individual equations in more detail. First, the equation for AGC is illustrated below:

$$AGC_{ij}^{s} = \frac{\sum_{m,p} D_{i,j}^{*,m,p} . GC_{i,j}^{S,m,p}}{\sum_{m,p} D_{i,j}^{*,m,p}} \qquad \text{(Equation 5.1)}$$

Where: AGC = average generalised costs; D = demand; GC = generalised cost; S = do minimum or option; m = mode; p = trip purpose; i = origin zone; and j = destination zone.

The key point to note about equation 5.1 is that it is made up of the sum of separate contributions by destination zone, mode and trip purpose. This structure means it is relatively simple to selectively include/exclude zones, modes and trip purposes, or combinations thereof, from the calculation of AGC. For example, if we wanted to consider the contribution to AGC made solely by journeys at work, then we could restrict p = journeys at work. Alternatively, if we did not want to include agglomeration benefits associated with travel to particular zones, then we could exclude those zones from our set or destination zones j. The only caveat on the 'separability' of this equation is that the AGC for the base scenario would have to be calculated in the same way. The relevance of this separability to our model becomes apparent in sub-section 5.2.2.

The second key equation in the EEM's process for estimating agglomeration benefits captures changes in ED, which is specified as:

$$ED_{i}^{s} = \sum_{j} \frac{E_{j}^{s}}{AGC_{ij}^{s}} \qquad \text{(Equation 5.2)}$$

Where:

- ED_i^S is the effective density in zone j following the transport improvement
- E_j^S is the employment in zone j following the transport improvement (usually fixed)
- AGC_{ij}^S is the AGC of travel between zone i and all other zones j, in the do minimum and option scenarios respectively.

Interpreting the equation is fairly straightforward: The ED of a zone i is defined as the sum of the employment in other zones j, divided by the AGC of travel from i to j in both the do minimum and option scenarios. Naturally, in the latter we would expect the denominator AGC to decrease, thereby increasing ED.

The third and final equation in the EEM's methodology for AE describes how changes in ED manifest as changes in productivity, as shown below:

$$\delta PR_i = \left(\frac{ED_i^{OPT}}{ED_i^{DM}}\right)^{\varepsilon_i} - 1 \qquad \text{(Equation 5.3)}$$

Where δPR_i denotes the relative change in productivity in zone i attributed to the option, while ED_i^{OPT} and ED_i^{DM} denote the ED in zone i in the option and do minimum scenarios respectively. The interpretation of this equation is again straightforward: It transforms the percentage change in ED to a percentage change in productivity via the agglomeration elasticity. The δPR_i term is then multiplied with the original GDP of each zone and summed across all zones to estimate the change in productivity associated with the option.

It appears to us that the EEM methodology in practice focuses on urbanisation economies, because the ED measure weights the (generalised) travel costs between different parts of the city by the *employment* levels of each zone. For this reason it could be argued that it is not completely correct to interpret ED as a proxy for 'accessibility to employment', ie workers to jobs (SDG 2011, p15). It is not the accessibility of workers to jobs that ED measures, but the accessibility of already employed people to each other. We do accept, however, that these different measures of accessibility are likely to be strongly positively correlated and also that research in both the UK and New Zealand has found that ED seems to provide a reasonable proxy for how accessibility impacts on agglomeration.

5.2.2 Relating our model to the EEM

In general, the EEM's standard process for estimating agglomeration benefits focuses primarily on how transport improvements (referred to as the 'option') impacts on the AGC of travel between zones, ie urbanisation economies. Of particular importance is the assumption in the current EEM methodology that the levels of employment in each zone are exogenous, ie they are defined prior to, and not subsequently influenced by, any changes in AGC of travel associated with the transport investment.

This is precisely where our model differs significantly from the EEM methodology. Our review of the literature led us to focus on commuting to the city centre (or similar intensive employment mode) as the prime conduit for PT-generated productivity improvements. Our model subsequently focuses clearly on localisation economies within the city centre itself, which follow from an expansion of the labour force within commuting reach. Thus employment levels within the CBD are determined endogenously within our model, primarily in terms of how commuting costs and AE are affected by employment levels.

Whereas the ED measure is concerned with *journeys at work*, our model focuses on *journeys to work*. We implicitly assume the at-work journeys that matter to AE are the opportunities for face-to-face contacts within the CBD itself, for which the travel costs are taken to be trivially small. Indeed, that is in effect how the CBD or other node is defined; it is an area compact enough for people working in it to be able to meet easily during the working day. We repeat that a notable strength of Venables' model is that it determines total employment – and thus journeys to work – endogenously.

At this stage, we suggest the following procedure to ensure that appropriate agglomeration benefits are neither missed nor double counted. As our model focuses on journey-to-work-trips by PT to the CBD, integrating our model with the existing processes simply requires that these trips are excluded from the summations that are involved in the calculation of AGC in the current EEM methodology. More specifically, this means excluding from the EEM calculations the case of m = public transport, p = journey to work, and j = CBD, where our notation refers to the subscripts used in the EEM. Instead, agglomeration benefits generated by these trips would be estimated using our model. Agglomeration benefits associated with other combinations of these parameters can be calculated as per the existing method, if desired.

To highlight how this would work, consider the following example of the process that would be followed to calculate conventional and agglomeration benefits for both a road and PT-based intervention:

5.2.2.1 Road projects

1 Conventional economic benefits, plus

2 Standard agglomeration benefits, for all modes m, trip types p, and destinations j.

5.2.2.2 PT projects:

1 Conventional economic benefits, plus

2 Standard agglomeration benefits, excluding those associated with journey-to-work trips made by PT trip to any central city zone, plus

3 Additional agglomeration benefits of PT to these zones are then calculated using our model.

Our estimates of AE thereby supplement (rather than replace) those generated by the current methodology.

We emphasise that we are not suppressing or ruling out urban agglomeration effects that operate at larger scales beyond the city centre. We are *supplementing* these effects (which can be modelled using the existing EEM procedures) with the local AE that are obtained by inducing more people to work in intensive employment nodes such as the city centre – jobs which are more productive **because of** local AE.

This distinction is probably reasonable for Auckland city centre and for other New Zealand urban employment nodes. It probably does not apply to very large urban centres such as London, where the AE ascribed to, for example CrossRail, would be generated by both journeys to and journeys at work, ie both local and regional AE.

5.2.3 Other implications for the EEM

Appendix A11.7 of EEM1 'Applying elasticity methods' authorises policy modellers to use 'off the shelf' elasticities of the demand for travel with respect to generalised travel cost changes. Four such elasticities are given, for situations of low/high modal competition and peak/off-peak travel periods. The elasticities are to be applied similarly to each of the three general types of travel: i) commuting to/from work; ii) journeys at work; iii) non-work related travel. These elasticities are offered as 'default' estimates, needed because 'In general, elasticities specific to a study area will not be available'.

In our modelling we use these default elasticities for non-work-related travel during the peak commuting period. But in the peak period itself we model the travel demand response explicitly, because we model CBD employment endogenously, and (of course) a change in full-time employment in the CBD has a very close relationship to the number of both-way commuting trips (after allowing for changes in CBD resident employment).

Further, the intensity of modal competition between private and public transit is also modelled explicitly in our procedure, using cross-price elasticities of demand. In our model the economic benefits of the increase in CBD employment (which is a primary cause of induced demand) is considered net of the additional congestion that this might cause. Hence, rather than viewing induced demand purely as a negative (insofar as it impacts on congestion) we are able to consider its net economic benefits, once agglomeration benefits have been captured.

It is to be expected that a switch from car to PT will bring other benefits that are not captured by the above methodology, such as a resource cost saving from reduced parking costs due to reduced parking requirements.

We note that the EEM's current treatment of car parking seems somewhat inconsistent. For example, parking resource costs are included in the benefits of travel behaviour change (TBCh) schemes, such as school travel plans and passenger transport projects.[20] On the other hand, they are not included as disbenefits of road projects, a treatment that seems – on the surface at least – to be quite inconsistent. One of the corollaries of our model is that it suggests where road projects increase vehicle access into an area that supports high density of employment, then this access will tend to undermine AE.

Finally, we also suggest that where PT competes with private vehicles then a switch to the former will bring additional health benefits from increased use of active modes, such as walking and (perhaps to a

[20] We note that the resource cost savings associated with reductions in parking supply would not be double counting benefits when applied in conjunction with our model. The process we have developed considers the agglomeration benefits that come from the (partial) redeployment of parking space to accommodate increased employment. This is a true externality. In contrast, resource cost savings from parking occur because parking is often highly subsidised or at the very least bundled into costs elsewhere. As such, the resource cost saving relates to the benefits of reducing the resources needed to provide parking in situations where the costs are not being borne directly by users.

lesser extent) cycling, for access and egress to PT stops. As the EEM is now able to quantify the health benefits from increased use of active modes it would be a logical extension to include health benefits associated with increased use of active modes that follows a switch from private vehicles to PT. Clearly however these benefits would need to be offset by the loss of health benefits associated with PT users who switch from active modes to a combination of active and PT. Including net health benefits from PT in this way would tend to improve the relative performance of interventions that compete with private vehicles, as opposed to active modes, which is we think a desirable outcome.

5.3 Implications for government policies and priorities

Our research has provided a framework for quantifying the contribution of PT to economic productivity, above and beyond what is already included in the EEM. By extension, this has several possible implications for government policies and priorities, namely:

- Increased overall funding assigned to PT improvements compared with other transport modes, all other factors being equal. We note that both central and local government benefit from the productivity gains of PT, which are likely to be captured through a combination of higher property values and higher income taxes.
- Within the funding pool that is assigned to PT improvements, there should be a shift in funding towards measures that improve access in central city areas with strong AE, all other factors being equal.
- Within the funding pool assigned to walking improvements, a greater proportion of funding should be assigned to improving access to PT corridors leading to central city areas that experience AE.

5.4 Areas for further research

We suggest that the NZTA consider further research into the following areas:

- **Exogenous parameters used in our model**, as detailed in appendix B. Our model extends Venables' powerful framework in ways that better capture the contribution of PT to economic productivity. The model rests on a number of exogenous input parameters that in some cases have not been empirically quantified. As such, further research into appropriate values for these parameters is warranted. We note, however, that in our case studies we have estimated reasonable parameter values, which have in turn yielded reasonably plausible results. As such the application of the model is not contingent on further research into these parameter values, even if it would benefit from it.
- **Agglomeration economies in consumption**, which describe agglomeration benefits that accrue to consumers, as opposed to producers. These AE could arise where increased urban density enables greater specialisation in consumer goods and services, such as speciality retail stores and restaurants. AE in consumption are unlikely to show up in productivity indicators, such as GDP or wages, but instead are more likely to manifest in the form of higher land rents, as consumers compete with firms for space and thereby bid up the price of land in areas that facilitate access to the specialised goods and services that they seek.

6 Conclusions and recommendations

The following sections summarise the conclusions and recommendations from this research. We also address some questions that have been raised in discussions with the project's steering group and wider stakeholders.

6.1 Conclusions

Based on our research we have drawn the following conclusions:

1. Aggregate macroeconomic models are insufficiently nuanced to capture the contribution of PT to economic productivity. Microeconomic studies are more useful as they can help to identify the explicit channels through which PT may be expected to support economic productivity.
2. The most obvious microeconomic channels through which transport impacts on productivity is through AE, which describe the benefits that arise from spatial concentrations of economic activity. PT can both encourage and enable increased employment in central city locations, by reducing commuting costs in otherwise congested transport networks and freeing up space that would otherwise be required for car parking. Through these two channels PT is able to make a somewhat unique contribution to economic productivity in denser urban environments.
3. Venables (2007) provides an appropriate microeconomic framework for capturing the contribution of PT to economic productivity. Venables' model considers how transport improvements can reduce commuting costs, which facilitates an expansion in city centre employment. This in turn leads to increased productivity (through AE), for which the benefits are captured by workers (in the form of wages), landowners (in the form of higher rents), and the government (in the form of tax wedges). We suggest Venables' model is both plausible and tractable.
4. Nonetheless, we have sought to extend Venables' framework so that it incorporates non-linear commuting costs, which are symptomatic of the conditions in which PT operates, as well as additional AE arising from the (partial) reallocation of space used for car parking, namely accommodating additional employment. Applying our model to two case studies identified productivity benefits of 3% to 19% of conventional transport benefits. Sensitivity testing suggested that these results were relatively robust to changes in key input parameters.
5. Current EEM processes for estimating AE consider how changes in average generalised travel costs contribute to AE. The processes by which AE are calculated are 'separable' in the sense that they consider contributions for each mode, zone, and trip type. Because the economic benefits predicted by our model arise solely from the use of PT for journeys to work in central city zones, the benefits predicted from our model can supplement existing processes, providing the latter is calculated in a way that excludes agglomeration impacts with the same trips. Loss of AE from lower employment in peripheral areas can be estimated using existing processes.

6.2 Recommendations

1. When the EEM is next reviewed, which we understand to be sometime in 2012/13, we recommend the concepts discussed in this research be considered as an input, possibly subject to further analysis and verification. Specifically, there is a need for the EEM to consider the potential for PT to make an

additional contribution to economic productivity in central city areas, where strong localised AE are present, such as in Auckland and Wellington.

2 Government agencies investigate opportunities to increase the funding envelope for PT improvements that give better access to central city areas that are subject to strong localised AE. This should also consider opportunities for complementary walking/cycling improvements that enable commuters to use PT services that in turn facilitate access to the city centre.

3 The NZTA considers further research into the contribution of PT to economic productivity, particularly with regard to:

   a empirical research into the exogenous parameters used in our model

   b the potential for agglomeration benefits in consumption (rather than production).

4 The NZTA considers updating the EEM to include:

   a *Impacts of PT on population health*. Where new PT users are diverted from private vehicles, then this would be expected to generate net health benefits. On the other hand, where new PT users are diverted from walking and cycling, this may result in a net health disbenefit. Including health impacts of PT is not only reasonable, but may be expected to favour PT improvements that compete most vigorously with private vehicles, thereby aligning with wider strategic objectives.

   b *Impacts of road transport improvements on the demand for car parking*. A natural corollary of our research is that road transport investments with the potential to increase the demand for parking in central city areas can effectively undermine AE. Further research is required to assess whether this situation does exist and whether it has a significant effect on density and hence ramifications for AE.

7 References

Affuso, L, A Angeriz and M Pollitt (2009) *The impact of privatisation on the efficiency of train operation in Britain*. London: University of London, School of Business and Management, Centre for Globalisation Research.

Arzaghi, M, and V Henderson (2008) Networking off Madison Avenue. *Review of Economic Studies 75*, no.4: 1011–1038.

Ascari Partners Ltd (2007) *Assessing agglomeration impacts in Auckland: linkages with regional strategies*. Report prepared for Auckland Regional Council. Accessed 29 November 2012. www.arc.govt.nz/albany/fms/main/Documents/Auckland/Aucklands%20growth/Assessing%20agglomeration%20impacts%20in%20Auckland%20linkages%20with%20regional%20strategies%20Feb%202007.pdf

Aschauer, D (1989) Is public expenditure productive? *Journal of Monetary Economics 23*, no.2: 177–200.

Australian Transport Council (ATC) (2006) *National guidelines for transport system management in Australia: volume 4 – urban transport* (NGTSM). Accessed 3 December 2012. www.atcouncil.gov.au/documents/files/National_Guidelines_Volume_4.pdf

Baum-Snow, N (2007) Did Highways Cause Suburbanization? *The Quarterly Journal of Economics 122,* no.2: 775–805.

Bento, AM, ML Cropper, AM Mobarak and K Vinha (2005) The effects of urban spatial structure on travel demand in the United States. *The Review of Economics and Statistics 87*, no.3: 466–478.

Brons, M, P Nijkamp, E Pels and P Rietveld (2005) Efficiency of urban public transit: a meta analysis. *Transportation 32*, no.1: 1–21.

COVEC (2008) Drivers of economic growth in Auckland. Auckland, New Zealand.Canning, D and E Bennathan (1999) The social rate of return on infrastructure investments. *Research working papers 1*, no.1: 1–48.

Chandra, A and E Thompson (2000) Does public infrastructure affect economic activity? Evidence from the rural interstate highway system. *Regional Science and Urban Economics 30*, no.4: 457–490.

Crafts, N (2009) Transport infrastructure investment: implications for growth and productivity. *Oxford Review of Economic Policy 25,* no.3: 327–343.

Crompton, JL (2006) Economic impact studies: instruments for political shenanigans? *Journal of Travel Research 45*: 67–82.

Downs, A (1962) The law of peak-hour expressway congestion. *Traffic Quarterly 16*, no.3.

Duranton, G and MA Turner (2009) The fundamental law of road congestion: evidence from US cities. *National Bureau of Economic Research working paper series no. 15376*.

Egert, B, T Kozluk and D Sutherland (2009) *Infrastructure and growth: empirical evidence*. OECD Publishing.

Ezcurra, R, C Gil, P Pascual and M Rapún (2005) Public capital, regional productivity and spatial spillovers. *The Annals of Regional Science 39*, no.3: 471–494.

Feldman, O, J Nicoll, D Simmonds, C Sinclair and A Skinner (2008) Use of integrated transportation land use models in the wider economic benefits calculations of transport schemes. *Transportation Research Record: Journal of the Transportation Research Board 2076:* 161–170.

Fernald, JG (1999) Roads to prosperity? Assessing the link between public capital and productivity. *The American Economic Review 89,* no.3: 619–638.

Graham, DJ (2007a) Agglomeration, productivity and transport investment. *Journal of Transport Economics and Policy 41*, no.3: 317–343.

Graham, DJ (2007b) Variable returns to agglomeration and the effect of road traffic congestion. *Journal of Urban Economics 62*, no.1: 103–120.

Greer, M and B van Campen (2011) *Influences on public transport utilization: the case of Auckland*. Accessed 29 November 2012. www.nctr.usf.edu/wp-content/uploads/2011/07/JPT14.2Greer.pdf

Grimes, A and Y Liang (2008) *Bridge to somewhere: the value of Auckland's northern motorway extensions*. Motu working paper 08–07.

Harford, JD (2006) Congestion, pollution, and benefit-to-cost ratios of US public transit systems. *Transportation Research Part D: Transport and Environment 11*: no.1: 45–58.

Jakob, A, JL Craig and G Fisher (2006) Transport cost analysis: a case study of the total costs of private and public transport in Auckland. *Environmental Science & Policy 9*: 55–66.

Karlaftis, MG and P McCarthy (2002) Cost structures of public transit systems: a panel data analysis. *Transportation Research Part E: Logistics and Transportation Review 38*, no.1: 1–18.

Kernohan, D and L Rognlien (2011) Wider economic impacts of transport investments in New Zealand. *NZ Transport Agency research report 448*. 128pp.

Litman, T (2010) *Evaluating rail transit criticisms.* Victoria, British Columbia.

Maré, DC (2008) *Labour productivity in Auckland firms*. Motu working paper 08–12.

Maré, DC and DJ Graham (2009) *Agglomeration elasticities in New Zealand*. Moto working paper 09–06.

McCahill, C (2012) The influence of urban transport and land use policies on the built environment and travel behaviour. PhD thesis. University of Connecticut.

Metz, D (2008) The myth of travel time saving. *Transport Reviews 28*, no.3: 321–336.

Moreno, R and E López-Bazo (2007) Returns to local and transport infrastructure under regional spillovers. *International Regional Science Review 30*, no.1: 47–71.

New Zealand Transport Agency (NZTA) (2010) *Economic evaluation manual, volumes 1 and 2*. Wellington: NZTA.

Obeng, K and R Sakano (2002) Total factor productivity decomposition, input price inefficiencies, and public transit systems. *Transportation Research Part E: Logistics and Transportation Review 38*, no.1: 19–36.

Obeng, K and R Sakano (2008) Public transit subsidies, output effect and total factor productivity. *Research in Transportation Economics 23*, no.1: 85–98.

Rice, P, AJ Venables and E Patacchini (2006) Spatial determinants of productivity: analysis for the regions of Great Britain. *Regional Science and Urban Economics 36*, no.6: 727–752.

Sharma, SC and B Pitafi (2009) On public capital investment and economic growth in Illinois. *Paul Simon Public Policy Institute occasional paper 14*.

Steer Davies Gleave (SDG) (2011) See Kernohan and Rognlien (2011).

Su, Q and JS DeSalvo (2008) The effect of transportation subsidies on urban sprawl. *Journal of Regional Science 48*, no.3: 567–594.

Tabuchi, T and A Yoshida (2000) Separating urban agglomeration economies in consumption and production. *Journal of Urban Economics 48*, no.1: 70–84.

Turner, M (2009) *The effects of transportation infrastructure on cities: a review of the evidence*. Lectures for EAERE Summer School, Venice.

Venables, AJ (2007) Evaluating urban transport improvements: cost benefit analysis in the presence of agglomeration and income taxation. *Journal of Transport Economics and Policy 41*, no.2: 173–188.

Wang, J (2009) Appraisal of factors influencing public transport patronage in New Zealand. *NZ Transport Agency research report 434*. 177pp.

Weisbrod, G and A Reno (2009) *Economic impact of public transportation investment*. American Public Transportation Association. TCRP project J-11(7).

Appendix A: Notes to the mathematical derivation

A1 Allowing for indirectly affected commuters

Although a PT innovation may directly reduce (or increase) the travel times of a spatial subset of commuters, the resulting increase (or decrease) in CBD productivity through AE, and with it the increase in CBD wages, will attract a wider range of workers from other parts of the urban area, with further productivity impacts, even though the road and PT infrastructure have not changed for these commuters. Simply, with a higher wage as attractor, the marginal CBD commuter will travel further than before.

Since all CBD workers receive the same wage, we can use this to link the two commuting groups, knowing that, given also similar tastes for commuting, real wages (wage less commuting cost) must also be equal for the marginal commuter in each group.

Using the travel cost expression (equation 3.16) we have, for group i of N commuters:

$$TC_N = r_i N^{(e+\sigma)} = r_i N^s \qquad \text{(Equation A.1)}$$

We use 0 and 1 to denote before and after PT innovation, and U and N for unaffected and affected commuters and the numbers of these. So, we can write the expression for the equality of travel costs of marginal commuters:

$$r_{N0} N_o^s = TC_{N0} = TC_{U0} = r_u U_0^s \qquad \text{(Equation A.2)}$$

So, given initial T and U, solve for r_u, which will remain unchanged. Then we write the expression giving equality of travel costs after the innovation:

$$r_{N1} N_1^s = T_{N1} = T_{U1} = r_u U_1^s \qquad \text{(Equation A.3)}$$

This is rearranged to get U in terms of our 'action' variable, N:

$$U_1 = (\frac{r_{N1}}{r_u})^{\frac{1}{s}} N_1 \qquad \text{(Equation A.4)}$$

So, when N is changed, so too will U, with the sum of these changes affecting CBD productivity through the agglomeration effect

A2 Endogenising affected non-commuting travellers

For tractability, we wish to eliminate M from equation 3.16 (the average vehicle trip time per kilometre) by expressing it in terms of our action variable N. The complication here is that non-commuting travel responds directly to a shift in the trip time function, unlike commuter numbers which come through the AE generated by higher CBD employment levels. Our strategy is to derive an elasticity which can be used to go from equation 3.16 to equation 3.17 expressing trip time as a function solely of N. First, we approximate equation 16 as:

$$t = t_0 + c(N + yM) \qquad \text{(Equation A.5)}$$

With t_0 and c found by solving equation 3.16 at two points – the current (pre-innovation or do minimum) point, and a larger value, depending on the magnitude of the shift in the trip time function caused by the PT innovation. So, if the shift were, say, 10%, then a reasonable second value for N + γM might be 5% larger than the current (do min) value.

Next, we write down a linear representation of the function determining the number of non-commuting trips:

$$M = M_0 - mt \qquad \text{(Equation A.6)}$$

The parameters M_0 and m are calibrated using the current or do min values of M and t and an outside estimate of the induced travel elasticity, such as is recommended in the EEM. So, we have two equations which can be used to eliminate M from the relationship between t and N. Substituting yields:

$$t = \frac{t_0 + cy}{1 + cym} M_0 + \frac{c}{1 + cym} N = g + hN \quad \text{(Equation A.7)}$$

Now we want to get back to an exponential expression, which we need for analytical tractability (ie to be combined smoothly with the exponential trip distance equation 3.3). We do this simply by using equation A7 to calculate the elasticity, e, of t with respect to N at their current values, using this elasticity as the exponent of (ρN), and then calculating the intercept, A, of equation 3.17 given t and N.

Note that the elasticity of trip time per kilometre (ie the inverse of speed), with respect to changes in total vehicle numbers will always be larger than the elasticity with respect to the number of just commuting vehicles. This is because non-commuting travel changes in the other direction. For example, if the number of commuters using a particular transport system increases, this will increase travel time and discourage some non-commuting travel, so that the net effect on travel speed is muted to an extent.

A3 Calculating the travel time elasticity

Equation 3.10 (travel time) used in urban traffic modelling in congested situations

$$t = t_f[1 + \alpha(\frac{V}{V_{cap}})^{\beta}]$$

can be used to generate an elasticity for travel time with respect to changes in the number of vehicles using a given roading system, to calibrate the exponent, b, in the exponential travel time function (equation 3.12) that we use in this model. This can be done by generating a range of 'actual' elasticities for different parameter values in equation 3.10, as demonstrated on the worksheet 'speed elasticity' in the Excel workbook.

However, we can find the elasticity analytically, as follows. Rewrite equation 3.10 as:

$$t = t_f(1 + AV^{\beta}) \quad \text{(Equation A.8)}$$

Noting that the components of A are all constants, then:

$$\frac{dt}{dV} = \beta t_f AV^{\beta} \quad \text{(Equation A.9)}$$

and the elasticity:

$$\left(\frac{dt}{dV}\right)\left(\frac{V}{t}\right) = \beta(\frac{AV^{\beta}}{1 + AV^{\beta}}) \quad \text{(Equation A.10)}$$

After cancelling tf from top and bottom lines, it is easy to show that the term in equation A.10 equals:

$$\frac{t - t_f}{t} \quad \text{(Equation A.11)}$$

That is, the travel time elasticity is the product of the congestion exponent, β, and the percentage increase in actual travel time compared with 'free flow' travel time. So, if one of these is 4 and the other is 0.25 or similar, then the elasticity of trip time with respect to an increase in the number of vehicles using the roads is about 1.

Appendix B: Guide to exogenous parameters

The following table, which summarises the exogenous parameters in our model, suggests a range for sensitivity testing, references to equations in our report (where appropriate) and provides some explanatory notes. Note that exogenous parameters are highlighted in green on the spreadsheet (see www.nzta.govt.nz/resources/research/reports/514/).

Table B.1 Explanation of model parameters

Excel row	Parameter	Period		Sensitivity testing		Eqn. no.	Explanatory notes
		0 (base)	After[21]	Min.	Max.		
12	Income tax rate (at the margin)	0.33	0.33	0.25	0.40		Most CBD workers will be paying the highest tax rate at the margin (=0.33)
15	Non-wage CBD worker utility factor	1	1				If people have a preference for/against working in CBD, apart from wages. This could possible reflect consumption opportunities in the CBD. If factor =1, implies no preference
17	Number of trips per work day	2	2				Journey to work/journey home
18	Number of workdays per year	230	230				Assumes 46 5-day working week equivalents (assumes 4 weeks annual leave and 10 statutory public holidays).
19	Annual outside-option wage, $	60,000	60,000	50,000	75,000		CBD workers tend to be more skilled than the average worker, hence higher than average earnings even in the suburbs
20	CBD wage premium ratio	0.25	0.25	0.20	0.30		Here assume a CBD wage/productivity premium of 25% on top of average outside option wage of $60K
21	Directly affected CBD commuting workers, 000s, N	10	End.				Approx. number of daily commuters to CBD using PT before PT intervention is implemented.
22	Unaffected CBD commuting workers, 000s, U	70	End.				Approx. number of daily commuters to CBD using other routes before PT intervention is implemented.
23	Commuting mode share PT	0.6	End. or Exo.				Commuting mode share for PT. This parameter value after the change can be determined by external transport models or endogenously within the model.
28	Full price of private vehicle commute, Ppv	1	1				Scaled =1; does not change

[21] ‘End.’ = determined endogenously within the model; ‘Exo’ = determined exogenously using another model.

Excel row	Parameter	Period		Sensitivity testing		Eqn. no.	Explanatory notes
		0 (base)	After[21]	Min.	Max.		
29	Full price of PT commute, Ppt	1	0.75				Scaled = 1 initially; reduced to 0.75 to generate endogenously a new mode share of 0.7 as predicted by transport models
30	Elasticity of PV mode share wrt relative price	-0.5	-0.5				If the relative price (generalised cost) of PV compared to PT changes by 10%, then the PT mode share will change by 5 percentage points (estimated).
31	Elasticity of PV mode share wrt distance	0.1	0.1				Allows possibility of mode share differing according to distance of commute – here set to reflect private vehicles being relatively more attractive the longer the commute.
32	Average trip time, minutes	23.0	End.				Input values sourced from external transport models.
34	Free-flow traffic speed, km/hour	50.0	50.0				Urban speed limit
37	Commuter/distance parameter, theta	0.000	0.000	0.000	0.250	3.1	Implies that the PT innovation takes place on a 'line' or linear spoke of the city, heading in to the CBD
39	Exponent in travel-time model, beta	4	4			3.10	From 'standard' traffic speed-flow curve (modified to exponential functional form).
40	Ratio free-flow trip time to actual average trip time	0.750	1			3.10	Relative change in trip-time due to congestion.
46	Commuters per private vehicle	1.30		1.1	1.5		Vehicle occupancy.
50	PT/PV congestion equivalent factor	8.00		6.00	10.00		Number of PT commuters that generate as much congestion as one private vehicle (based on occupants and size of vehicle). Changes for bus/rail.
52	Number of non-commuter travellers per peak period, 000s	10.00	End.				Approx average number of non-commuters travelling in a 2-hour peak period
53	Commuter/non-commuter equiv. factor, gamma	1.00					Number of non-commuters that have same travel time impact as one commuter
56	x% change traveller numbers for linearisation	0.05					For computational purposes – take a 5% change to calculate the linearised version of the exponential model.
60	Elasticity non-commuters wrt trip	-0.50	-0.50	-0.25	-0.75		% change in number of non-commuters for a 1% change in trip

Excel row	Parameter	Period		Sensitivity testing		Eqn. no.	Explanatory notes
		0 (base)	After[21]	Min.	Max.		
	time						time/km.
73	Space needed per private vehicle entering CBD, m2	25	25	10	40		Average space needed by each additional private commuting car for parking in the CBD.
74	Space-saving factor	0.5					Assume that not all of the vacated parking space is returned for productive economic uses.
76	Total area CBD, km2	4.00					The three CAUs making up the Auckland CBD cover approximately $4km^2$.
77	Ratio productive /total land	0.50					Proportion of CBD land used for productive economic purposes.
81	AE employment exponent, delta	0.1		0.05	0.15	3.21	Production function parameter as described in text at equation 3.20
82	AE available land elasticity, neta	0.2		0.1	0.3	3.21	Production function parameter as described in text at equation 3.20