ENVIRONMENT DESIGN GUIDE

THE COSTS OF URBAN SPRAWL – PREDICTING TRANSPORT GREENHOUSE GASES FROM URBAN FORM PARAMETERS

Roman Trubka, Peter Newman and Darren Bilsborough

This is one of three companion papers taken from a study that assesses the comparative costs of urban redevelopment with the costs of greenfield development. The first paper, GEN 83: The Costs of Urban Sprawl – Infrastructure and Transportation*, showed that substantial costs would be saved in infrastructure and transport if urban redevelopment were the focus. This paper assesses how these different urban typologies perform with respect to greenhouse gases. The final paper* GEN 85: The Costs of Urban Sprawl – Physical Activity Links to Healthcare Costs and Productivity *discusses the health costs and productivity losses that can be linked to human inactivity in suburban living.*

The redevelopment option in Australian cities is around 4.4 tonnes less greenhouse gas intensive per household per annum than greenfield development. The study shows how greenhouse gases can be calculated for any development based on simple physical planning parameters such as the distance to the CBD (a reflection of distance travelled and a proxy for density) and transit accessibility. Although the actual costs of greenhouse gas are small the significance of this work is that governments will need to demonstrate how they are reducing climate change impacts and thus greenfields developments will find it hard to pass this fundamental criteria of assessment.

Keywords:
urban sprawl, transportation, greenhouse gases, urban form, urban planning

Figure 1: Greenhouse gas emissions can be linked to not only urban density, but the distance suburbs are from city centres

(Photo: © iStockphoto /Tim McCaig)

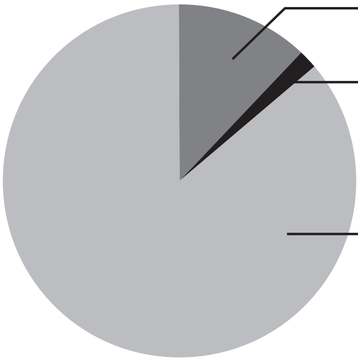


Figure 2: Transport's portion of Australia's GHG emissions

(AGDCC, 2007).

1.0 GREENHOUSE GAS ISSUES

1.1 Background

The combustion of fossil fuels is leading to anthropogenic increases of carbon dioxide equivalent gases (CO_2-e) in the earth's atmosphere and as a result, global warming has become a primary international concern. The United Nations Framework Convention on Climate Change initiated the Kyoto Protocol, an international treaty designed to limit global greenhouse gas emissions, in 1997. When Australia ratified this agreement in December 2007, it made a commitment to limit its greenhouse gas emissions to 108 per cent of its 1990 levels in the 2008/12 period. Reducing the rate of growth in greenhouse gases is difficult as the 'Business As Usual' (BAU) scenario suggests that Australia's greenhouse gas emissions would reach 124 per cent of its 1990 levels over the Kyoto period (AGDCC, 2007). However the world is now moving to reductions in greenhouse gases and hence Australia is committed to five per cent reductions by 2020 from 1990 levels (or 15-30 per cent if land based carbon offsets is included). Many people want much stronger targets but even these are not going to be easy. Urban development priorities can make a big difference as to whether this will be possible to reach. In 2009, the Council of Australian Governments (COAG) chose to support the new Federal planning agenda that requires all infrastructure investment to demonstrate reductions in climate change impacts. All future development will need to demonstrate reductions in greenhouse gases by estimating their carbon content and implied usage patterns.

This paper will examine the greenhouse gas implications of two urban development typologies: urban redevelopment and greenfield development – being land that is ex-agricultural or other previously non urban land or on the edge of communities to which new roads and services are usually required (Your Development, undated). Although there will be differences due to the greenhouse gas associated with buildings, this study will focus more on transport greenhouse gases. There is evidence that higher density buildings do save on GHGs over lower density buildings due to the shared insulating effect (Newton and Tucker, 2007), though there is still some uncertainty about this as argued by Troy (1996). Rickwood (2009) in his empirical work estimates that semi-detached units and flats have 15 per cent less energy use than detached housing units. Apart from this recent empirical work, there are plenty of thermal simulation studies suggesting apartments and terraces have significantly lower heating/cooling through a combination of less air volume and better insulation. Examples of the simulation work include the works of Miller and Ambrose (2005) and Newton et al. (2000).

There is considerable work going into the carbon implications of different built forms but often they neglect the transport aspects (e.g. the inner-urban Bed Zed residential development in the UK only examines building operational and embedded energy in its methodology for calculating carbon neutrality (see Lazarus, 2003).

Thus this paper will examine the transport greenhouse implications of different urban forms in Australian cities and will seek to set up a model for estimating these in any urban development.

1.2 Emissions from Transport

Currently, transportation in Australia accounts for 14 per cent of total GHG production and road transport is responsible for 88 per cent of this figure or 12.3 per cent of total GHG production as shown in Figure 2 (AGDCC, 2007). Projections for this sector are based on demographic indicators such as GDP and population forecasts, vehicle technology and the future travel behaviours of Australian residents. According to these variables, GHG emissions in this sector are expected to increase by 42 per cent of the 1990 level during the Kyoto period, reaching 88 million tonnes per annum (AGDCC, 2007).

1.3 Reducing Emissions from Transport

Approaches identified to reduce the effects of GHG emissions from transportation have been identified as either technological in nature or demand based. The limitations of technological solutions are that they can be expensive (e.g. hybrid vehicles), currently unviable or unavailable on a regional scale (e.g. electric vehicles and high-intensity recharge stations), or simply shift the GHG production to elsewhere in the supply chain (e.g. biofuels and hydrogen power), and are susceptible to the 'rebound effect', where increased efficiency leads to increased use and hence there is no/marginal net benefit.

Demand based solutions reduce the need for private travel and in some cases, remove the need for motorised travel altogether. This can be achieved through urban planning by bringing people closer to their desired destinations and making non-motorised modes of travel more attractive. Both solutions have their benefits and deficiencies depending on the time frame of reference; however, they are not mutually exclusive. An opportunity exists for urban planning and technological development to combine and produce sustainable outcomes on a city scale.

1.4 Setting a Price for GHG Production

Nominating a price to place on the generation of greenhouse gases for the authors' purposes is not a clear and distinct matter, especially because carbon offsetting is not yet a mandatory responsibility for polluters in Australia. The emerging emissions trading scheme (ETS) in Australia only covers large industry polluters, although the ETS proposed by the Garnaut Review was designed to include all emitters. Even with an ETS in place, however, the price of carbon is not set but only the quantity is capped.

Alternatively, it is possible to use a value of carbon equal to the price of a carbon offset, which in Australia can be anywhere within the range of $8 to $40. The variation in price can depend on a number of criteria, including the type of project being invested in (i.e. biosequestration projects versus technological investments), the level or type of assurance or accreditation, and the offset provider's business model (Ribon and Scott, 2007). It is important to identify, however, that the price of a carbon offset has little to do with the actual cost to society of producing the carbon in the first place.

Social Costs of Carbon

In 2002, the UK Government Economic Service presented a review of available literature on the estimated social costs of carbon. Within a range of 35–140£ per tonne of carbon dioxide equivalent GHG (tCO_2-e), the paper suggests an average social cost of 70£/tCO_2-e or roughly $175 in 2000 prices (Clarkson and Deyes, 2002). In 2007 prices this value would be more in the area of $215. A social cost of carbon (SCC) can be defined as the cost of market and non-market impacts associated with the additional production of a unit of greenhouse gas emissions. It represents what society should be willing to pay today to avoid the carbon damages from emissions produced today and their contribution to world emissions in the future.

As a result of the GHG pricing uncertainty and variability, the economic valuation of an urban form's transport induced greenhouse gas impact becomes equally susceptible to cost variation. Where carbon credits only reflect the value of traded emissions rights and not the social cost of carbon, they fail to reflect the incremental damage being done. On the other hand, if confronted with the choice to suffer a loss of $215 or pay $25, the rational choice would be to abate and this would continue to be the case until the marginal cost of abating would equal the social cost of the carbon. Pursuing this logic, the ensuing calculation in this paper will assume carbon to be valued at $25 per tonne but will also show the implications of choosing the social cost of carbon at $215 per tonne.

2.0 EMISSIONS RELATED TO CITY PLANNING

2.1 The Effect of Urban Form and Transport Provision Factors

There are some simple observations that can be made about transport:

- The further that people live from their frequented travel destinations, the less likely they are to accomplish that travel through active means, whether it is by walking or cycling.
- Areas with poor or no transit services are reliant on private vehicle travel.
- The more people living or working in a particular area, the more viable public transport becomes to that place.
- The easier it is to walk or cycle in an area the more likely it is that they will do that.
- The closer that a development is to the CBD then all these factors come into play providing increased amenity and economy for less car dependent travel.

The importance of quantifying these relationships in a model is that they can then become part of any planning system.

To determine greenhouse gas emissions for the two alternative forms of development a predictive model had to be made. A subjective method does not reliably show the trend that develops between transport greenhouse gas emissions and various urban form parameters, nor is it able to report on the explanatory significance of any of the parameters of interest. A predictive model in this sense had to be developed where urban form characteristics could be proven on some account to be associated with transport emissions.

To establish a quantitative model for how urban form in Australian cities affects per capita GHG emissions, data and information was drawn from a study previously done at Murdoch University's Institute for Sustainability and Technology (ISTP) department in Western Australia (Chandra, 2006). The study estimated fuel use (and therefore GHG production) at the local authority area level from household travel survey data and average fuel consumption figures sourced from the Australian Greenhouse Office for the cities of Sydney, Perth, and Melbourne. The Perth data were very dated so they were not used in the key conclusions. The amount of daily per capita private vehicle travel was statistically related on several transport-influencing factors such as:

- density (persons per hectare)
- jobs (jobs per hectare)
- activity intensity (persons plus jobs per hectare)
- permeability (number of intersections per hectare)
- linear distance to CBD (kilometres)
- and transit accessibility (per cent of area with public transport services beyond a specified threshold).

Equation

$$y = x/10 + 3$$

Where:

y represents daily per capita GHG emissions in kilograms of CO_2-e

x represents the distance to the CBD in kilometres

Box 1: Equation for GHG emissions relevant to distance to CBD

Equation

AI = population + jobs per hectare for a given area

Box 2: Equation for GHG emissions relevant to activity intensity

2.2 Factors Affecting Emissions

A summary of the simple regression results of the best three explanatory parameters from the list above follows:

Distance to the CBD: The distance to the CBD was the dominant factor in explaining daily per capita GHG emissions (explains 71 per cent of the variance in Sydney and Melbourne). This single variable alone is a very powerful determinant of vehicle energy use and emissions production. From the data a formula was generated to model GHG emissions as a function of distance to a city centre's CBD and it proved to hold in all three cities: Perth, Sydney and Melbourne. The formula is y = x/10 + 3, where 'y' represents daily per capita GHG emissions in kg CO_2-e and 'x' represents the distance to the CBD in kilometres. The limitation of the formula is most evident in comparing its estimates against outliers such as Blue Mountain and Mornington (ex-urban areas) where their actual emissions tend to be much higher than are predicted – a potential result of poor proximal amenity in outlying regions.

Activity Intensity: Activity Intensity (AI) is calculated by adding together the population (in number of residents) and the number of jobs per hectare for a given area. This explains 56 per cent of the variance in Melbourne and 71 per cent in Sydney. The difference in explanatory power is perhaps because Sydney has a larger variation in AI across its Local Government Area's (LGAs). Sydney's CBD has an activity intensity of roughly 330 persons/ha where as Melbourne's is closer to 100 persons/ha.

Public Transit Access: Public transit access has similar statistical significance to activity intensity as it explains 61 per cent of the variance in GHG emissions for Melbourne and 58 per cent of the variance for Sydney. Public transit ties in closely with activity intensity because an efficient transit system needs a higher population level to support it. This parameter is defined as the proportion of an LGA that has a transit service frequency of greater than 15 minutes as well as service on weeknights and weekends.

Regression Analysis – Regression analysis is a statistical technique focused on using one or more independent variables to predict the value of a single dependent variable. It is particularly useful in predicting how a change in one independent variable (holding all other variables constant) can affect the value of a dependent variable.

Simple Regression – A regression comprised of only two variables, a dependent (y) variable and an independent (x) variable.

Multiple Regression – A regression comprised of one dependent variable and two or more independent variables.

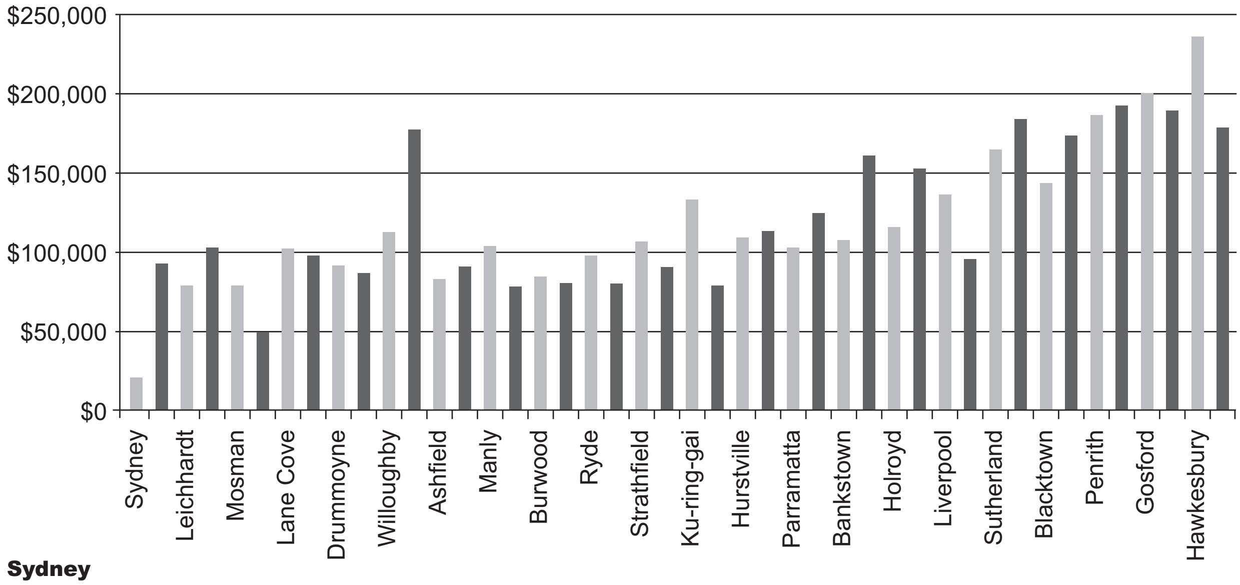
P-value – In statistical terms the p-value is the probability of committing a 'type I error', i.e. presuming there is a relationship where there is none. Thus the lower the p-value, the more confident one can be that a relationship truly exists. Generally speaking, p-values of 0.10, 0.05, and 0.01 are considered adequate thresholds at which to reject a null hypothesis, thus leaving one 90 per cent, 95 per cent and 99 per cent confident, respectively, that a relationship exists between the variables.

Coefficient/Parameter Estimate – A coefficient in a simple regression is a value that represents the amount by which the predicted value, or 'y' variable, will change given a 1-unit increase in the 'x' variable. In multiple regression it bears a similar interpretation with the added condition that all other variables are held constant.

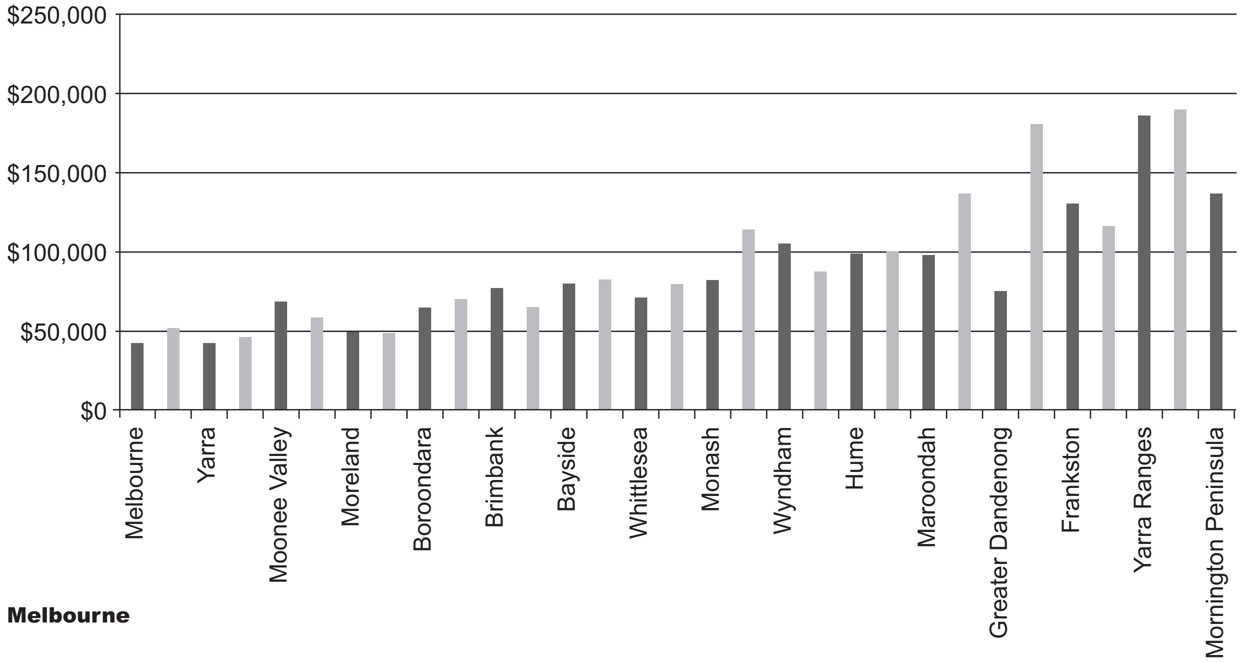
R-Squared – The r-squared value represents the amount of variance in a dependent variable that a model is able to explain. This is expressed as a value between '0' meaning there is no correlation and '1' meaning that 100 per cent of the variance is accounted for by the model. In a simple regression, the r-squared value is also the correlation coefficient between the two variables or in other words, it represents the strength in the relationship between them. If R-squared is 0.6 then 60 per cent of the variance is explained.

Adjusted R-Squared – As it seldom occurs in reality that two seemingly unrelated variables can be completely uncorrelated, adding more independent variables to a regression will generally improve the r-squared value by some amount, even if they come out insignificant. The adjusted r-squared essentially includes a penalty for including redundant variables in a model. In simple regression, the r-squared and adjusted r-squared are equal.

Box 3: Statistical terminology



Sydney



Melbourne

Figure 1: Annual Transport GHG Costs for 1000 Dwellings in Sydney and Melbourne

Shown for Local Government Areas ordered nearest to furtherst from the CBD

(Source: Chandra, 2006)

2.3 Results

The data from Chandra's (2006) study was made available for this work. Before another model was attempted, a spreadsheet was made for each of the three cities on which their local government areas were ordered from nearest to furthest from their respective central business districts (see Appendices). For each local government area, data was entered for their respective actual daily per capita transport GHG production. Another column was added calculating the daily transport GHG emissions costs for 1000 dwellings and finally another column calculating an annual figure for these values. The price attributed to the generation of one tonne of GHG was hypothetically set at $25, a reasonable estimate given current carbon offset prices. The resulting information when graphed appears as follows:

Basing an economic assessment on distance to CBD alone creates a fairly good prediction of per capita GHG emissions and therefore associated costs, but it was thought that working other variables into the model could improve its effectiveness. The data from

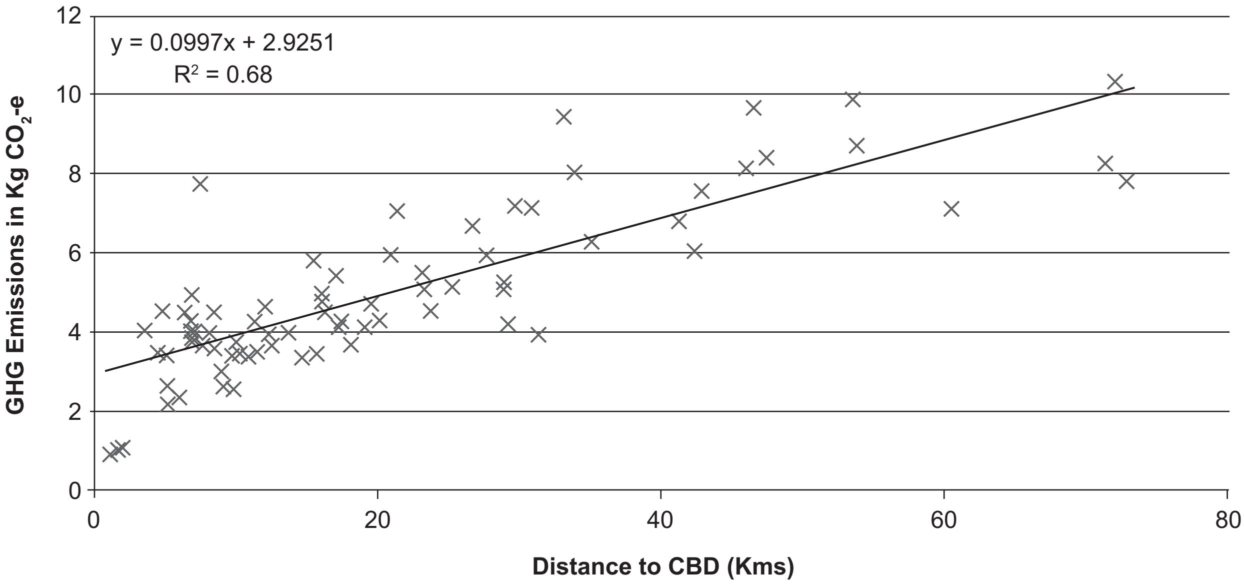


Figure 4: GHG Emissions relative to distance to CBD for Sydney and Melbourne

Daily per capita GHG emissions shown.

Chandra's report was run again several times with different parameters. Seeing as distance to CBD, activity intensity, and transit access are the three variables of distinct interest, a simple linear regression was done for each of them with combined data for Sydney and Melbourne.

Distance to CBD

The relationship of 'distance to CBD' to daily per capita GHG emissions is quite clear in this linear regression. The R-squared value of 0.68 is quite high, implying that distance to CBD explains about 68 per cent of the variance in GHG. There is, however, a fair bit of dispersion around the line. In particular it tends to highly overestimate per capita GHG emissions for CBD residents where the factors relating to the ease of walking become very obvious.

Activity Intensity

The exponential relationship of activity intensity to daily per capita GHG emissions (Figure 4) is also strong in this example, but with an R-squared value of 0.6016 it is a less effective predictor than distance to CBD is alone. By observing the trend-line it is

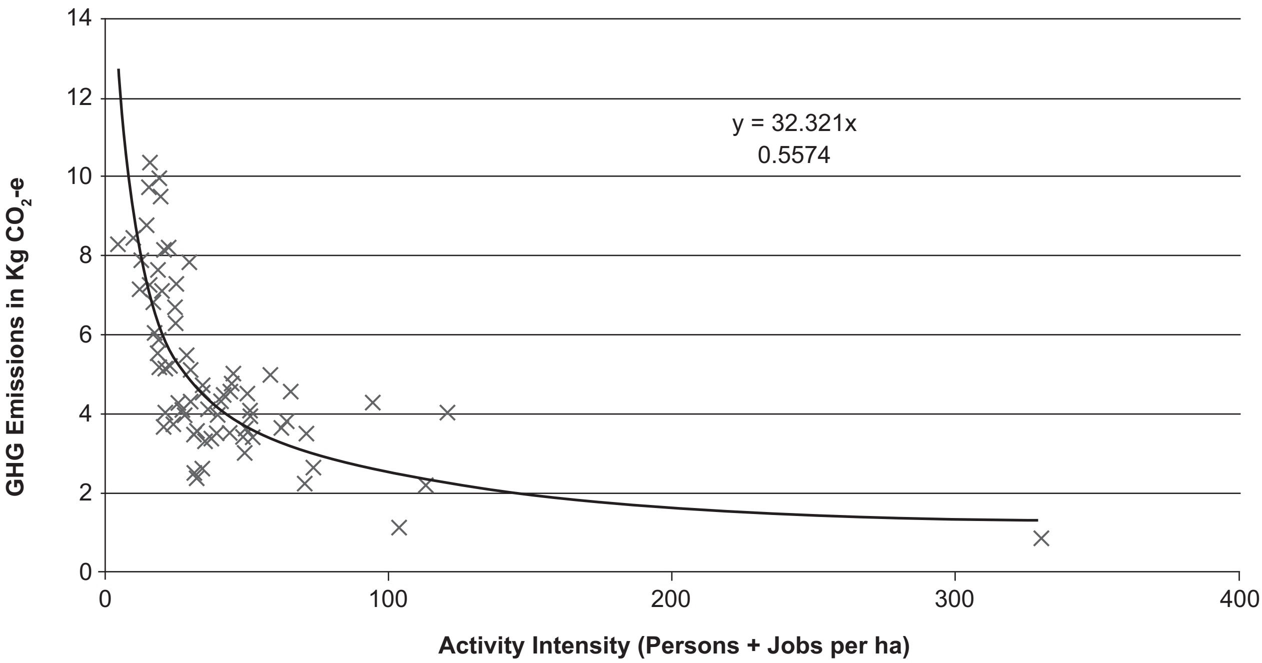


Figure 5: GHG Emissions regressed on Activity Intensity – Sydney and Melbourne

Daily per capita GHG emissions shown

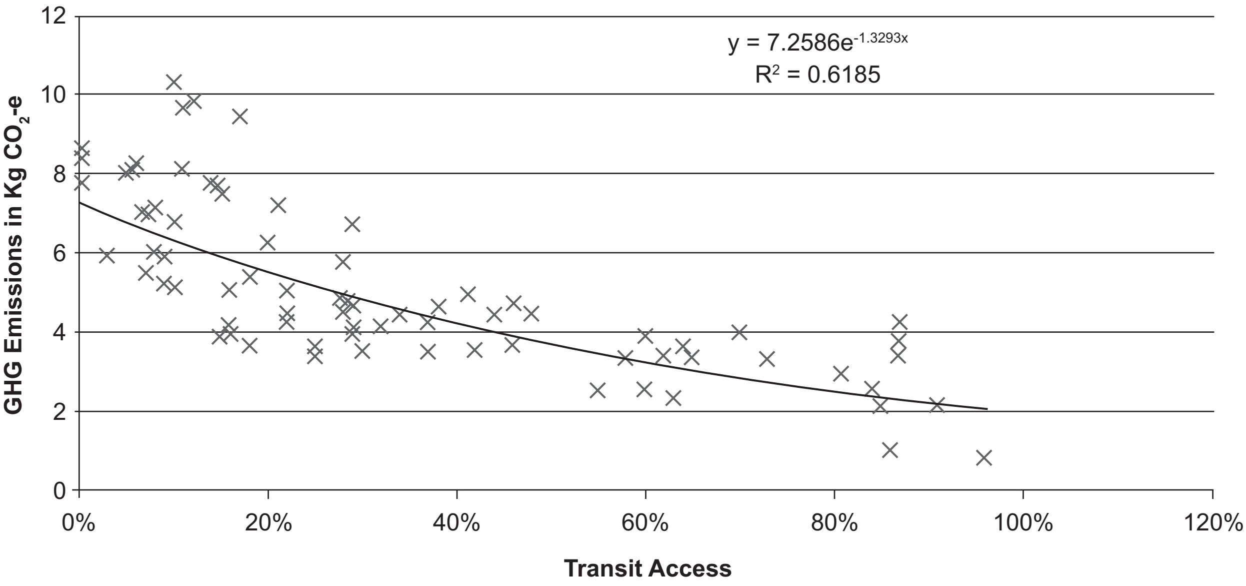


Figure 6: GHG Emissions regressed on transit accessibility for Sydney and Melbourne

Daily per capita GHG emissions shown.

evident that there is an activity intensity level of roughly 35 persons and jobs per hectare above which GHG emissions are most dramatically reduced. This is consistent with findings from Newman and Kenworthy (1999, 2006).

Transit Access

The parameter of public Transit Access (TA) also seems to be a fairly good predictor of GHG emissions with a similar measure of good correlation (R-squared) to activity intensity (Figure 7). The majority of the variance seems to be in areas of poor transit access. Again, alone it does not seem to be as strong a predictor of emissions as distance to CBD.

Modelling Emissions as a Function of Various Parameters

Running a multiple regression analysis of the three parameters of distance to CBD, Activity Intensity and Transit Access, together resulted in the highest level of correlation of all the combinations (see Figure 7). In this case, however, Activity Intensity as a parameter comes out highly insignificant (with a p-value of -0.5503 and a very low coefficient of -0.002) so there is no use leaving it in the model.

The outcome of activity intensity becoming insignificant in the multiple regression is not surprising as it tends to be a surrogate of distance to CBD. In

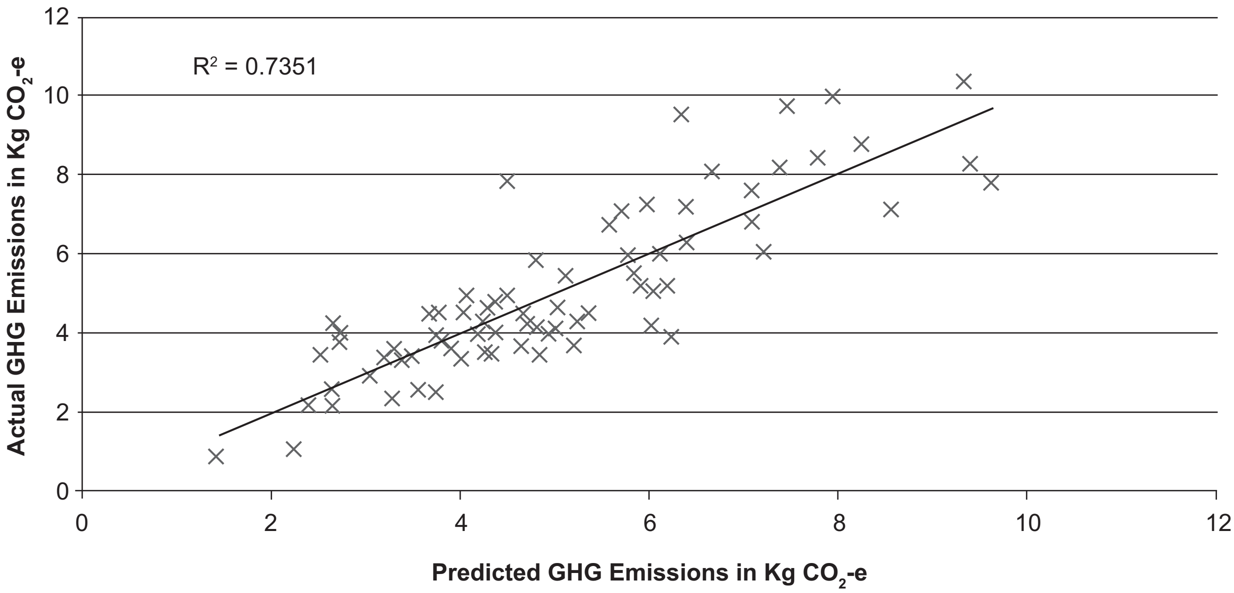


Figure 7: Predicted against actual GHG emissions for Sydney and Melbourne

Predicted values include Distance to CBD, Activity Intensity and Transit Accessibility parameters in their estimation

	Coefficients	P-value
Intercept	4.38	1.44E-15
To CBD	0.07	7.30E-10
Activity Intensity	-0.00	0.59
Transit Access	-2.28	0.00

Regression Statistics	
Multiple R	0.86
R Square	0.74
Adjusted R Square	0.72
Observations	75

Table 1: Predicted GHG, and actual GHG compared to distance to CBD, activity intensity, and transit accessibility

other words, it is characteristic of most cities that the inner cores would be high in number of residents and jobs and that this intensity would diminish as distance from the city centre increases. Activity intensity was withdrawn from the model and another attempt was made at modelling GHG emissions with just distance to CBD and transit accessibility (see Figure 8).

The resulting analysis produced the equation y = .073x – 2.5z + 4.35, where 'y' is the daily per capita GHG emissions, 'x' is the distance to the CBD, and 'z' is the level of transit service expressed as a percentage of the area covered. The results were significant at the five per cent level and the equation generated accounts for 73.4 per cent of the variance in GHG.

It is worth considering any other possible factors such as social or economic factors that could be impacting on this equation. It could be expected that higher income means more driving (Luk and Hepburn, 1993) however the authors' data shows the reverse, as in Australian cities income levels decrease with distance from the CBD and their petroleum consumption and car use increase. Social factors such as different ethnic and racial groups also are not likely to explain the data as in Australian cities there are no strong groupings for these various demographics that appear to have any significantly different travel patterns.

2.4 Calculating Emissions Costs for the Alternative Development Typologies

The equation in Box 4 is useful in estimating the daily per capita GHG emissions for any given area where the distance to the city centre and the transit accessibility is known. For the purpose of this economic assessment, however, it was used to estimate the GHG costs for the two dichotomous development types: inner-city type redevelopments and fringe developments. For this the equation had to be amended to accommodate the economic reporting requirements.

The desired end estimate of the equation was to predict the annual economic GHG emissions impact for a development of 1000 dwellings. By adjusting the equation to achieve this we get the following:

The next critical step was to choose values for the variables in the equation to represent the two opposing urban forms of interest. The furthest local government area from the city centre of Melbourne in the data was measured at just over 60km and of Sydney it was nearly 73km, while the transit accessibility for the most distant local government areas was seven per

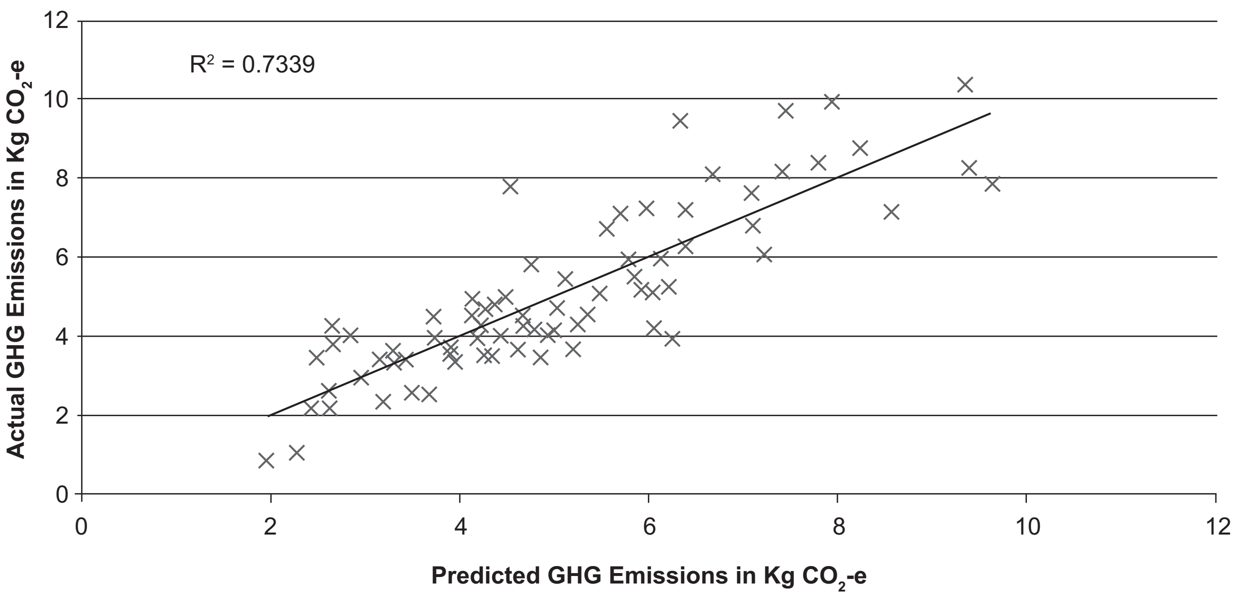


Figure 8: Predicted against actual GHG emissions for Sydney and Melbourne

Predicted values include the distance to CBD and transit accessibility parameters in their estimation

	Coefficients	P-value
Intercept	4.35	9.8E-16
To CBD	0.07	4.97E-10
Transit Access	-2.50	0.00

Regression Statistics	
Multiple R	0.86
R Square	0.73
Adjusted R Square	0.73
Observations	75

Table 2: Output results from regressing GHG on distance to CBD and transit accessibility

cent and zero per cent for the two cities respectively. Averages were taken of these respective figures to represent the inputs for estimating the annual cost of GHG production in a fringe development. The figures for an inner-city type development we determined a little differently. Choosing the immediate centre would perhaps be an ambitious suggested location for a new development of 1000 dwellings, although still very possible as demonstrated by Vancouver and envisioned in projects like North Port Quay and the Gateway project in Perth. Therefore a development within a 30minute walking distance (3km) from the city centre was chosen. For both Sydney and Perth this represents roughly a transit accessibility of 85 per cent. It is feasible to imagine developments in various parts of the city that demonstrate the kind of central/inner-core urban form where 85 per cent of the development has a transit service of better than 15 minutes. Taking these inputs into account, the estimated daily per capita GHG emissions and the annual emissions costs for 1000 dwellings (at $25/tonne) for the two opposing city forms were estimated as follows:

For the most part, the estimates are quite accurate against the actual data for the two cities; however, the formula tends to overestimate the per capita GHG emissions, and therefore costs, of inner-city type areas

Equation:

$$y = 0.073x - 2.5z + 4.35$$

Where:

x = distance to the CBD in kilometres
y = daily per capita GHG emissions in kilograms of CO_2-e
z = the level of transit service expressed as a percentage of the area covered

Box 4: Equation for daily GHG emissions per capita related to distance from CBD and transit accessibility

while providing a more accurate estimate as distance to CBD increases. Data points from Sydney's and Melbourne's inner areas report daily per capita emission of roughly 2.5 kg GHG, which is roughly half of what the equation generates as a predicted value. This is likely due to the greater proportion of walking trips and higher level of amenity in their inner cores. This disparity for inner area estimates in the end adds a conservative character to the economic comparison between the two urban forms.

When applying the formula, the annual greenhouse gas emissions associated with the two iconic development types for a development of 1000 units is 8,400 tonnes for the fringe and 4,000 tonnes for the inner-urban redevelopment.

Next, the present value of the recurring greenhouse gas costs was calculated over a 50-year period at a three per cent discount rate . Net Present Value is a term that accounts for the understanding that people value money in the present more than they would the same sum of money at a given time into the future, and a discount rate is the factor of reduction. For fringe developments of 1000 households this equates to a

Equation

$$Y = (365\ \text{days/yr})(\text{price/kg } CO_2\text{-e})(\text{No. of dwellings})(\text{Inhabitants/dwelling})(0.073x - 0.25z + 4.35)$$

$$= (365)(0.025)(1000)(2.5)(0.073x - 0.25z + 4.35)$$

$$= 22{,}812.5(0.073x - 0.25z + 4.35)$$

where:

X = distance to CBD
Y = annual cost
Z = transit accessibility

Box 5: Equation for GHG gas cost for 1000 dwelling development as a function of distance to CBD and transit accessibility

greenhouse gas cost of $5.40 million and for inner-city type development within 3km of the CBD this equates to $2.56 million. This means there is a saving of $2.84 million for a 1000 unit development over 50 years or if the social cost of carbon ($A215) were used then this would be $24.42 million.

Daily Emissions:

Y(Outer) = [0.073 (66.5) - 0.25 (0.035) + 4.35]
= 9.2 kg CO_2-e per capita

Y(Inner) = [0.073 (3.0) - 0.25 (0.85) + 4.35]
= 4.4 kg CO_2-e per capita

Annual Costs:

Y(Outer) = 22,812.5 [0.073 (66.5) - 0.25 (0.035) + 4.35]
= 22,812.5 (9.19575)
= $209,778

Y(Inner) = 22,812.5 [0.073 (3.0) - 0.25 (0.85) + 4.35]
= 22,812.5 (4.3565)
= $99,383

where:
Y = annual cost
X = distance to CBD
Z = transit accessibility

Box 6: Equation for calculating per capita daily GHG emissions for inner-city and outer fringe development

3.0 CONCLUSION

If inner area-type development is preferred to fringe area-type development there will be savings of around 4.4 tonnes per household per annum in transport greenhouse gases which is around 20 per cent of an average Australian household's contribution to climate change. This will mean a saving of around $2,840 per household over 50 years (Net Present Value) if carbon is priced at around $25 per tonne, or $24,420 per household if it is to cover the social cost at $215 per tonne. Compared to the magnitude of the costs associated with transport and infrastructure, GHG costs alone are unlikely to catalyse urban planning reform based on a carbon cost. Given the growing attention that all governments must give to reducing national emissions, the cost of climate change impacts are not indicative of a large urban benefit. The next phase of urban development is likely to require a simple assessment that asks what is a proposed development doing to reduce GHG. The model presented in Box 6 of this paper can be used to show savings if there is evidence of redevelopment at higher densities with reasonable transit accessibility. A model or tool of this sort is in itself useful to planners who can then build accordingly to reduce greenhouse gas emissions by estimated amounts. The next paper in this series will examine the health and productivity aspects of more activity-oriented urban design (GEN 85: The Costs of Urban Sprawl – Physical Activity Links to Healthcare Costs and Productivity).

ACKNOWLEDGEMENT

This paper and the companion papers come from a research that was commissioned by Parsons Brinckerhoff Australia, although they have been adapted, and in some places expanded, then peer reviewed before being included in EDG. The original report is available online from: http://sustainability.curtin.edu.au/local/docs/Curtin_Sustainability_Paper_0209.pdf

REFERENCES

Australian Government Department of Climate Change (AGDCC), 2007, *Tracking to the Kyoto Target: Australia's Greenhouse Emissions Trends 1990 to 2008-2012 and 2020*, Department of Climate Change, Canberra.

Chandra, L, 2006, *Modeling the impact of urban form and transport provision on transport-related greenhouse gas emissions*, masters thesis, Murdoch University, Perth.

Clarkson, R and Deyes, K, 2002, *Estimating the Social Cost of Carbon Emissions*, report by the Environment Protection Economics Division, DEFRA, London, UK.

Garnaut, R 2008, *The Garnaut Climate Change Review*, Cambridge University Press, Port Melbourne.

Lazarus, N 2003, *Beddington Zero (Fossil) Energy Development: Toolkit for Carbon Neutral Developments*, Bioregional Development Group, London, UK.

Luk, J and Hepburn, S, 1993, *New Review of Australian Travel Demand Elasticities*, Australian Road Research Board, Melbourne.

Miller, A and Ambrose, M, 2005, *Energy efficient multi-storey residential developments*, Conference on Sustainable Building South East Asia, Kuala Lumpur, Malaysia.

Newman, P and Kenworthy, J 1999, *Sustainability and Cities: Overcoming Automobile Dependence*, Island Press, Washington DC.

Newman, P, and Kenworthy, J, 2006, 'Urban Design to Reduce Automobile Dependence', *Opolis*, 2(1), pp 35-52.

Newton, PW, Tucker SN and Ambrose MD, 2000, 'Housing form, energy use and greenhouse gas emissions', In: Williams K, Burton E, Jenks M. (eds). *Achieving Sustainable Urban Form*. E & FN Spon: London, UK. pp 74-83.

Newton, P and Tucker, S 2009, 'Hybrid Buildings: Towards zero carbon housing', *Architectural Science Review*, 52(2), in press.

Price, R, Thornton, S and Nelson, S, 2007, *The Social Cost of Carbon and the Shadow Price of Carbon: What the are, and how to use them in economic appraisal in the UK*, Office of Public Sector Information, DEFRA, London, UK.

Ribon, L and Scott, H 2007, *Carbon Offset Providers in Australia 2007*, (unpublished), Global Sustainability at RMIT University, Melbourne.

Stern, NH, 2007, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, UK.

Troy, P, 1996, *The Perils of Urban Consolidation*, The Federation Press, Leichhardt, NSW.

United Nations Framework Convention on Climate Change (UNFCCC), no date, *An introduction to the Kyoto Protocol Compliance Mechanism*, viewed 16 May 2008: unfccc.int/kyoto_protocol/compliance/introduction/items/3024.php

Your Development, undated, web based sustainability resource, viewed May 2010: www.yourdevelopment.org/glossary

BIOGRAPHY

Roman Trubka is a PhD candidate at the Curtin University Sustainability Policy (CUSP) Institute in Western Australia.

Dr. Peter Newman is a Professor of Sustainability and Director at the Curtin University Sustainability Policy (CUSP) Institute in Western Australia.

Darren Bilsborough is the Director of Sustainability at Parson's Brinkerhoff (PB) and an adjunct professor of sustainability at Curtin University Sustainability Policy (CUSP) Institute in Western Australia.

APPENDIX 1: GHG EMISSIONS COSTS FOR LOCAL GOVERNMENT AREAS – SYDNEY

These figures assume a cost of \$25 per tonne for CO_2-e gas.

LGA	Distance from CBD km	GHG emissions car CO_2-e kg/day	Car emissions per capita kg/capita/day	GHG cost per day \$/1000 dwellings/day	GHG Cost per year \$/1000 dwellings/yr	Share of Total Cost %	GHG savings per year \$1000 dwellings/yr
Sydney (CC)	0.10	17,695	0.889	\$55.56	\$20,280.31	0.38%	\$216,330.94
North Sydney	3.40	228,084	4.034	\$252.13	\$92,025.63	1.75%	\$144,585.63
Leichhardt	4.30	216,510	3.467	\$216.69	\$79,090.94	1.50%	\$157,520.31
Woollhara	4.60	229,842	4.516	\$282.25	\$103,021.25	1.95%	\$133,590.00
Mosman	4.90	88,898	3.434	\$214.63	\$78,338.13	1.49%	\$158,273.13
South Sydney	5.00	200,239	2.171	\$135.69	\$49,525.94	0.94%	\$187,085.31
Lane Cove	6.20	138,528	4.504	\$281.50	\$102,747.50	1.95%	\$133,863.75
Waverly	6.60	259,363	4.275	\$267.19	\$97,523.44	1.85%	\$139,087.81
Drummoyne	6.70	132,690	4.024	\$251.50	\$91,797.50	1.74%	\$144,813.75
Marrickville	6.70	279,022	3.800	\$237.50	\$86,687.50	1.64%	\$149,923.75
Willoughby	6.70	293,790	4.950	\$309.38	\$112,921.88	2.14%	\$123,689.38
Hunters Hill	7.30	99,129	7.810	\$488.13	\$178,165.63	3.38%	\$58,445.63
Ashfield	7.50	143,874	3.643	\$227.69	\$83,105.94	1.58%	\$153,505.31
Botany	7.90	143,281	3.991	\$249.44	\$91,044.69	1.73%	\$145,566.56
Manly	8.20	170,071	4.525	\$282.81	\$103,226.56	1.96%	\$133,384.69
Randwick	9.60	413,492	3.403	\$212.69	\$77,630.94	1.47%	\$158,980.31
Burwood	9.80	111,118	3.709	\$231.81	\$84,611.56	1.60%	\$151,999.69
Concord	10.00	94,393	3.513	\$219.56	\$80,140.31	1.52%	\$156,470.94
Ryde	11.10	409,550	4.278	\$267.38	\$97,591.88	1.85%	\$139,019.38
Rockdale	11.50	312,232	3.527	\$220.44	\$80,459.69	1.53%	\$156,151.56
Strathfield	11.90	131,386	4.658	\$291.13	\$106,260.63	2.02%	\$130,350.63
Canterbury	12.20	517,443	3.952	\$247.00	\$90,155.00	1.71%	\$146,456.25
Ku-ring-gai	15.30	590,484	5.826	\$364.13	\$132,905.63	2.52%	\$103,705.63
Auburn	15.50	195,499	3.468	\$216.75	\$79,113.75	1.50%	\$157,497.50
Hurstville	15.90	338,012	4.785	\$299.06	\$109,157.81	2.07%	\$127,453.44
Kogarah	15.90	250,806	4.982	\$311.38	\$113,651.88	2.16%	\$122,959.38
Parramatta	16.10	652,438	4.515	\$282.19	\$102,998.44	1.95%	\$133,612.81
Warringha	16.90	702,831	5.455	\$340.94	\$124,442.19	2.36%	\$112,169.06
Bankstown	19.30	779,676	4.708	\$294.25	\$107,401.25	2.04%	\$129,210.00
Pittwater	21.20	374,942	7.101	\$443.81	\$161,991.56	3.07%	\$74,619.69
Holroyd	23.20	436,193	5.086	\$317.88	\$116,024.38	2.20%	\$120,586.88
Hornsby	26.50	982,347	6.730	\$420.63	\$153,528.13	2.91%	\$83,083.13
Liverpool	27.50	924,301	5.991	\$374.44	\$136,669.69	2.59%	\$99,941.56
Fairfield	29.00	764,935	4.204	\$262.75	\$95,903.75	1.82%	\$140,707.50
Sutherland	29.50	1,471,140	7.244	\$452.75	\$165,253.75	3.13%	\$71,357.50
Baulkham Hills	33.70	1,129,224	8.100	\$506.25	\$184,781.25	3.50%	\$51,830.00
Blacktown	34.90	1,618,947	6.315	\$394.69	\$144,060.94	2.73%	\$92,550.31
Cambelltown	42.70	1,111,737	7.622	\$476.38	\$173,876.88	3.30%	\$62,734.38
Penrith	45.80	1,411,810	8.189	\$511.81	\$186,811.56	3.54%	\$49,799.69
Camden	47.30	371,556	8.455	\$528.44	\$192,879.69	3.66%	\$43,731.56
Gosford	53.70	1,358,030	8.781	\$548.81	\$200,316.56	3.80%	\$36,294.69
Blue Mountains	71.20	616,266	8.292	\$518.25	\$189,161.25	3.59%	\$47,450.00
Hawkesbury	72.00	633,436	10.372	\$648.25	\$236,611.25	4.49%	-
Wyong	72.70	1,026,623	7.846	\$490.38	\$178,986.88	3.39%	\$57,624.38
Total		**22,371,863**			**\$5,272,881.25**	**100.00%**	

(Source: Chandra, 2006)

APPENDIX 2: GHG EMISSIONS COSTS FOR LOCAL GOVERNMENT AREAS – MELBOURNE

These figures assume a cost of $25 per tonne for CO_2-e gas.

LGA	Distance from CBD km	GHG emissions car CO_2-e kg/day	Car emissions per capita kg/capita/day	GHG cost per day $/1000 dwellings/day	GHG Cost per year $/1000 dwellings/yr	Share of Total Cost %	GHG savings per year $1000 dwellings/yr
Melbourne	1.00	72,560	1.070	$66.88	$24,409.38	0.73%	$202,506.57
Port Phillip	4.97	209,989	2.620	$163.75	$59,768.75	1.78%	$167,147.19
Yarra	5.41	148,770	2.187	$136.69	$49,890.94	1.49%	$177,025.00
Maribyrnong	5.81	142,019	2.376	$148.50	$54,202.50	1.62%	$172,713.44
Moonee Valley	8.31	378,122	3.563	$222.69	$81,280.94	2.43%	$145,635.00
Stonnington	8.75	261,513	2.992	$187.00	$68,255.00	2.04%	$158,660.94
Moreland	8.87	339,095	2.581	$161.31	$58,879.06	1.76%	$168,036.88
Darebin	9.63	314,038	2.536	$158.50	$57,852.50	1.73%	$169,063.44
Boroondara	10.72	503,250	3.350	$209.38	$76,421.88	2.28%	$150,494.07
Hobsons Bay	12.31	293,734	3.652	$228.25	$83,311.25	2.49%	$143,604.69
Brimbank	13.50	654,809	4.011	$250.69	$91,500.94	2.73%	$135,415.00
Glen Eira	14.49	397,819	3.367	$210.44	$76,809.69	2.29%	$150,106.25
Bayside	17.10	350,496	4.168	$260.50	$95,082.50	2.84%	$131,833.44
Banyule	17.28	488,445	4.276	$267.25	$97,546.25	2.91%	$129,369.69
Whittlesea	17.90	392,445	3.687	$230.44	$84,109.69	2.51%	$142,806.25
Whitehorse	18.90	582,401	4.138	$258.63	$94,398.13	2.82%	$132,517.82
Monash	19.93	675,837	4.307	$269.19	$98,253.44	2.93%	$128,662.50
Manningham	20.76	636,298	5.973	$373.31	$136,259.06	4.07%	$90,656.88
Wyndham	23.00	447,716	5.515	$344.69	$125,810.94	3.76%	$101,105.00
Kingston	23.56	584,181	4.558	$284.88	$103,979.38	3.10%	$122,936.57
Hume	25.11	654,918	5.175	$323.44	$118,054.69	3.52%	$108,861.25
Knox	28.69	745,187	5.257	$328.56	$119,925.31	3.58%	$106,990.63
Maroondah	28.73	493,494	5.116	$319.75	$116,708.75	3.48%	$110,207.19
Melton	30.70	350,424	7.201	$450.06	$164,272.81	4.90%	$62,643.13
Greater Dandenong	31.19	485,786	3.929	$245.56	$89,630.31	2.68%	$137,285.63
Nillumbik	33.00	453,164	9.501	$593.81	$216,741.56	6.47%	$10,174.38
Frankston	41.09	736,346	6.822	$426.38	$155,626.88	4.65%	$71,289.07
Casey	42.20	993,651	6.066	$379.13	$138,380.63	4.13%	$88,535.32
Yarra Ranges	46.40	1,032,522	9.731	$608.19	$221,988.44	6.63%	$4,927.50
Cardinia	53.40	128,669	9.947	$621.69	$226,915.94	6.77%	$0.00
Mornington Peninsula	60.30	813,414	7.164	$447.75	$163,428.75	4.88%	$63,487.19
Total		**14,761,112**			**$3,349,696.25**	**100.00%**	

(Source: Chandra, 2006)

APPENDIX 3: GHG EMISSIONS COSTS FOR LOCAL GOVERNMENT AREAS – PERTH

These figures assume a cost of $25 per tonne for CO_2-e gas.

LGA	Distance from CBD km	GHG emissions car CO_2-e kg/day	Car emissions per capita kg/capita/day	GHG cost per day $/1000 dwellings/day	GHG Cost per year $/1000 dwellings/yr	Share of Total Cost %	GHG savings per year $1000 dwellings/yr
Perth	1.40	36,047	2.749	$171.81	$62,711.56	1.59%	$292,159.69
Vincent	3.00	110,906	5.606	$350.38	$127,886.88	3.24%	$226,984.38
Subiaco	4.10	36,350	4.949	$309.31	$112,899.06	2.86%	$241,972.19
South Perth	4.80	196,886	6.035	$377.19	$137,673.44	3.49%	$217,197.81
Victoria Park	5.20	73,750	3.735	$233.44	$85,204.69	2.16%	$269,666.56
Claremont	7.80	30,064	4.924	$307.75	$112,328.75	2.85%	$242,542.50
Bayswater	8.10	362,442	5.914	$369.63	$134,913.13	3.42%	$219,958.13
Medlands	8.10	82,524	4.351	$271.94	$99,257.19	2.52%	$255,614.06
Cambridge	8.30	189,199	5.661	$353.81	$129,141.56	3.27%	$225,729.69
Belmont	8.60	120,167	4.13	$258.13	$94,215.63	2.39%	$260,655.63
Stirling	9.50	981,428	5.64	$352.50	$128,662.50	3.26%	$226,208.75
Canning	9.80	213,977	5.55	$346.88	$126,609.38	3.21%	$228,261.88
Melville	9.80	462,567	6.418	$401.13	$146,410.63	3.71%	$208,460.63
Peppermint Grove	9.90	6,930	5.575	$348.44	$127,179.69	3.22%	$227,691.56
Bassendean	10.00	32,148	4.065	$254.06	$92,732.81	2.35%	$262,138.44
Cottelsoe	10.30	37,436	6.958	$434.88	$158,729.38	4.02%	$196,141.88
Mosman Park	10.90	69,687	9.043	$565.19	$206,293.44	5.23%	$148,577.81
East Fremantle	12.50	29,641	5.209	$325.56	$118,830.31	3.01%	$236,040.94
Fremantle	14.50	95,283	4.481	$280.06	$102,222.81	2.59%	$252,648.44
Gosnells	16.70	356,948	6.687	$417.94	$152,547.19	3.87%	$202,324.06
Kalamunda	17.00	234,881	6.349	$396.81	$144,836.56	3.67%	$210,034.69
Swan	17.30	78,706	4.799	$299.94	$109,477.19	2.77%	$245,394.06
Cockburn	19.40	171,920	5.463	$341.44	$124,624.69	3.16%	$230,246.56
Joondalup	19.60	443,553	6.661	$416.31	$151,954.06	3.85%	$202,917.19
Armadale	25.50	279,105	7.267	$454.19	$165,778.44	4.20%	$189,092.81
Wanneroo	27.70	142,278	5.203	$325.19	$118,693.44	3.01%	$236,177.81
Kwinana	30.50	38,170	6.909	$431.81	$157,611.56	3.99%	$197,259.69
Mundaring	37.30	290,837	15.556	$972.25	$354,871.25	8.99%	-
Rockingham	45.00	110,844	7.072	$442.00	$161,330.00	4.09%	$193,541.25
Total		**5,314,674**			**$3,945,627.19**	**100.00%**	

(Source: Chandra, 2006)

APPENDIX 4: SYDNEY AND MELBOURNE DATA: DAILY PER CAPITA GHG AND MODELED PARAMETERS

Suburb	GHG/Capita	To CBD	Activity Intensity	Transit Access	Suburb	GHG/Capita	To CBD	Activity Intensity	Transit Access
Melbourne	1.070	1.00	104.491	86%	Sydney (CC)	0.889	0.10	330.6339	96%
Port Phillip	2.620	4.97	74.37067	84%	North Sydney	4.034	3.40	121.8281	70%
Yarra	2.187	5.41	71.32699	85%	Leichhardt	3.467	4.30	71.86342	87%
Maribyrnong	2.376	5.81	31.18083	63%	Woollhara	4.516	4.60	66.41607	22%
Moonee Valley	3.563	8.31	33.04913	42%	Mosman	3.434	4.90	48.7702	62%
Stonnington	2.992	8.75	49.66764	81%	South Sydney	2.171	5.00	113.8737	91%
Moreland	2.581	8.87	34.94962	60%	Lane Cove	4.504	6.20	51.24671	44%
Darebin	2.536	9.63	33.6832	55%	Waverly	4.275	6.60	95.10611	87%
Boroondara	3.350	10.72	36.07256	73%	Drummoyne	4.024	6.70	51.78653	16%
Hobsons Bay	3.652	12.31	22.11571	25%	Marrickville	3.800	6.70	64.37259	87%
Brimbank	4.011	13.50	22.11571	16%	Willoughby	4.950	6.70	58.96366	28%
Glen Eira	3.367	14.49	37.8036	58%	Hunters Hill	7.810	7.30	30.77002	14%
Bayside	4.168	17.10	30.5488	32%	Ashfield	3.643	7.50	62.40785	64%
Banyule	4.276	17.28	26.69309	37%	Botany	3.991	7.90	40.32756	29%
Whittlesea	3.687	17.90	24.69786	18%	Manly	4.525	8.20	46.70056	48%
Whitehorse	4.138	18.90	30.32901	29%	Randwick	3.403	9.60	52.13946	65%
Monash	4.307	19.93	30.74724	22%	Burwood	3.709	9.80	63.90592	46%
Manningham	5.973	20.76	18.33446	3%	Concord	3.513	10.00	40.06209	30%
Wyndham	5.515	23.00	19.19991	7%	Ryde	4.278	11.10	40.98237	37%
Kingston	4.558	23.56	34.87298	28%	Rockdale	3.527	11.50	44.24853	37%
Hume	5.175	25.11	20.36164	10%	Strathfield	4.658	11.90	34.91641	38%
Knox	5.257	28.69	24.13857	9%	Canterbury	3.952	12.20	51.74705	60%
Maroondah	5.116	28.73	22.07024	16%	Ku-ring-gai	5.826	15.30	20.88535	28%
Melton	7.201	30.70	15.19053	8%	Auburn	3.468	15.50	31.85958	25%
Greater Dandenong	3.929	31.19	27.47892	15%	Hurstville	4.785	15.90	44.94621	46%
Nillumbik	9.501	33.00	20.12773	17%	Kogarah	4.982	15.90	46.03009	41%
Frankston	6.822	41.09	17.71661	10%	Parramatta	4.515	16.10	43.71826	34%
Casey	6.066	42.20	18.92039	8%	Warringha	5.455	16.90	29.96319	18%
Yarra Ranges	9.731	46.40	16.0437	11%	Bankstown	4.708	19.30	34.55737	29%
Cardinia	9.947	53.40	19.82883	12%	Pittwater	7.101	21.20	20.54202	7%
Mornington Peninsula	7.164	60.30	13.20078	7%	Holroyd	5.086	23.20	31.12426	22%
					Hornsby	6.730	26.50	25.35693	29%
					Liverpool	5.991	27.50	20.89103	9%
					Fairfield	4.204	29.00	35.95417	16%
					Sutherland	7.244	29.50	25.4291	21%
					Baulkham Hills	8.100	33.70	21.09561	5%
					Blacktown	6.315	34.90	24.84111	20%
					Cambelltown	7.622	42.70	19.0944	15%
					Penrith	8.189	45.80	23.51239	11%
					Camden	8.455	47.30	10.79457	0%
					Gosford	8.781	53.70	15.06618	0%
					Blue Mountains	8.292	71.20	5.30491	6%
					Hawkesbury	10.372	72.00	16.30905	10%
					Wyong	7.846	72.70	13.44757	0%

(Source: Chandra, 2006)