Performance metrics for sustainable urban transport – accessibility and greenhouse gas emissions

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1   Introduction

The principal meaning of sustainability was identified in the three pillars of sustainable development in ground breaking work by the United Nations in the last decades of the 20th century. The pillars of environmental sustainability (or stewardship), social equity and economic efficiency are identified as embracing all aspects of sustainability (World Commission, 1987).

A key to sustainability in cities has been identified as all three pillars of environmental sustainability (stewardship), social equity and economic efficiency working together. Therefore an effective sustainability performance requires all three pillars to achieve complementary outcomes rather than simply individual outcomes. This paper discusses a sustainability challenge for cities and introduces some visualisation methods for sustainability performance assessment.

2   A sustainability challenge for cities

For cities, the challenge of sustainability is centred on the urban form, the transport characteristics and the interactions between these and the communities they support. The question of which urban form provides the best sustainability was seen to be dependent on the dynamics of these interactions (for example ECMT, 2004; Doi, *et al.*, 2007; Black, *et al.*, 2007). It was observed that this appears to be influenced significantly by the particular characteristics of each city's own communities. Outcomes of these urban dynamics shape the sustainability performance of a city, which can feedback to reshape the urban dynamics. The outcomes of these urban dynamics can feedback to affect the characteristics of the urban form and transport elements themselves.

A principal gap in methodology to support the holistic assessment of sustainability performance in cities has generated a number of challenges. These include a holistic assessment framework, methodologies to better understand urban dynamics, the drivers that produce sustainability performance and to objectively measure the performance of all three pillars of sustainability. A particular challenge to researchers is to not only fill the sustainability assessment methodology gap, but to provide methodologies and tools that are able to be simply and meaningfully understood and used by community and government.

3   Visual metrics in a sustainability framework

In a new approach to sustainability analysis (Doust, 2008), a sustainability framework is formulated to bring the three pillars of sustainability together, and a holistic consideration of the urban system, the urban dynamics and the resulting sustainability performance. Figure 1 summarises the framework, which lays out the frame points for ensuring that the systems elements and interactions that drive the sustainability performance of the city are visible and measured.
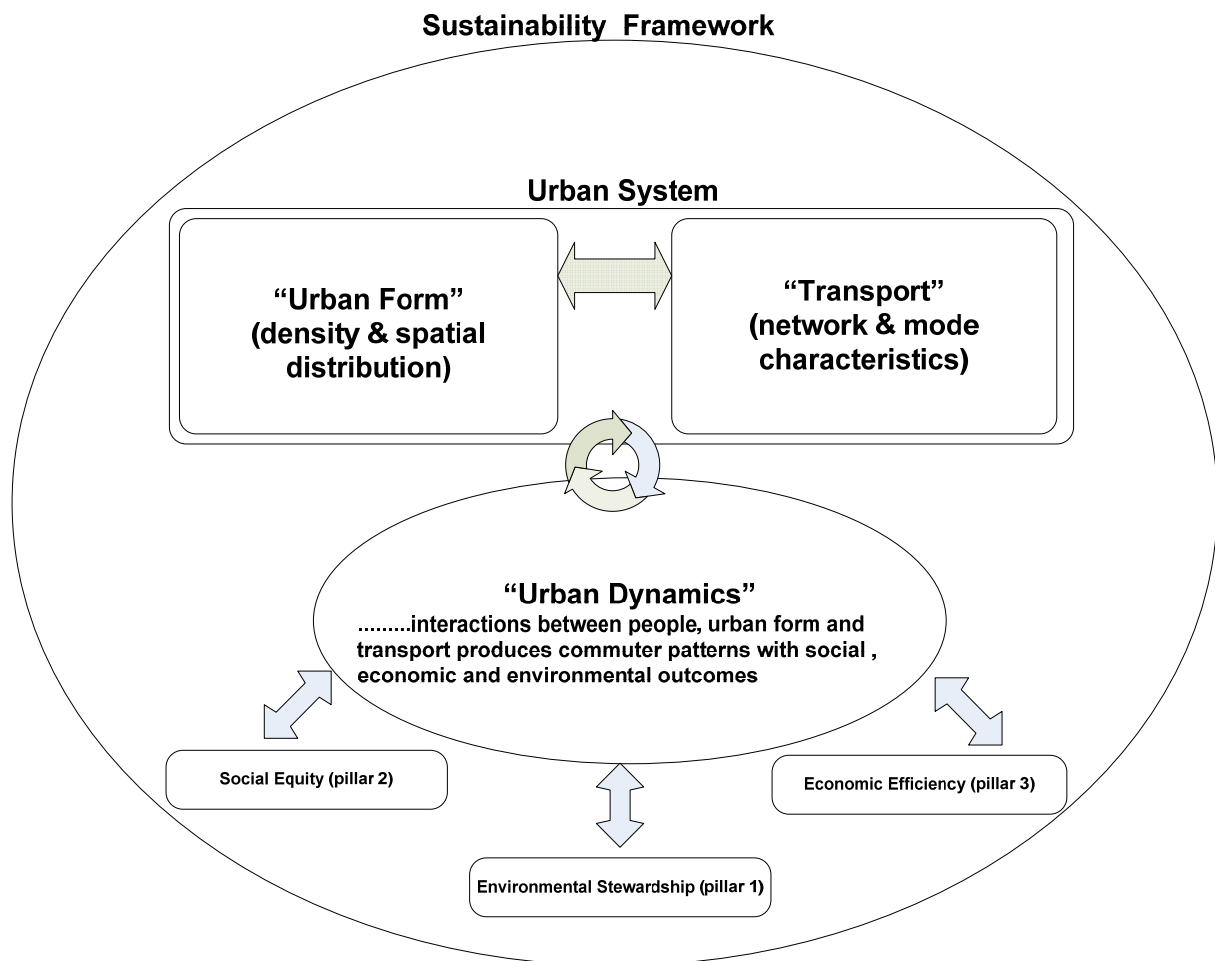
Sustainability Framework

Urban System

"Urban Form"
(density & spatial
distribution)

"Transport"
(network & mode
characteristics)

"Urban Dynamics"
.........interactions between people, urban form and
transport produces commuter patterns with social ,
economic and environmental outcomes

Social Equity (pillar 2)

Economic Efficiency (pillar 3)

Environmental Stewardship (pillar 1)

Figure 1 –   The urban "sustainability framework"

The "Urban System" is the physical aspect of the framework, consisting of the "Urban Form"
and "Transport" elements which define the structural configuration of the city. Interaction
between these two elements shows their interdependencies. "Urban Form" is characterised
by density and spatial distribution of land-use. "Transport" on the other hand is characterised
by the transport network spatial layout and the specific mode characteristics.

The system function is to provide for the needs of the community (including industry).
Response of the community to the "Urban System" produces interactions that result in
selection of location of residence and workplace, industry and trips and so on. These
interactions are collectively known as "Urban Dynamics". It is an iterative process as
indicated by the circular arrow having feedback effect between each element. The resulting
"Urban Dynamics" outcomes generate the sustainability performance in terms of the three
pillars included as elements in Figure 1. Each pillar has a feedback to the "Urban Dynamics"
and consequently the "Urban System". This is indicated by the double headed arrows in the
figure.

Existing visualisation methods using GIS and graphical displays illustrate the value of visual
metrics in communicating urban dynamic outcomes and sustainability performance.
Visualisation using GIS techniques is proving to be effective in displaying complex
information in a simple but meaningful way as illustrated in Figure 2 and Figure 3.
Visualisation of the spatial change in employment density has enabled a clear picture of the
changes in ranked employment density over time to be mapped, giving a visual means of
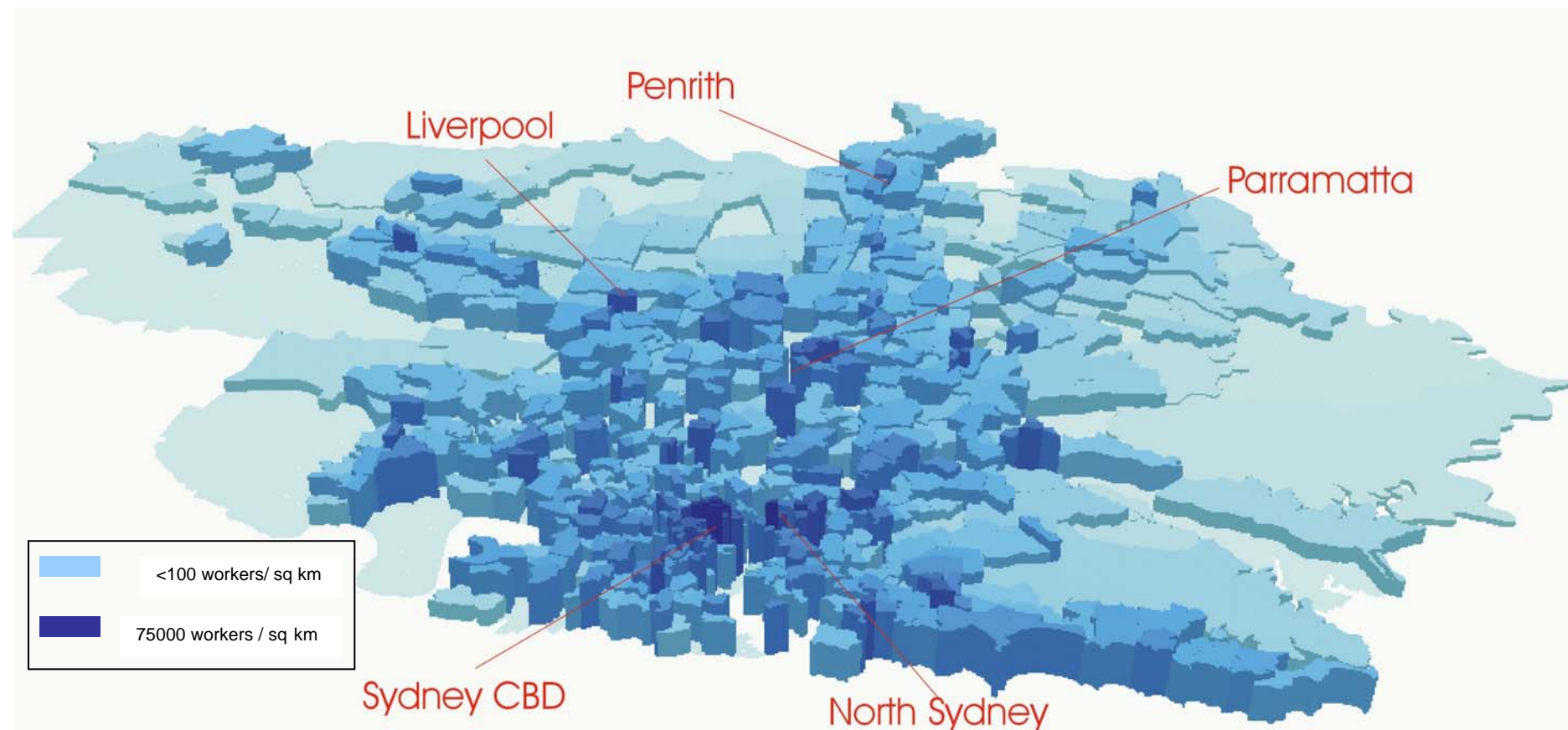assessing the outcomes of urban dynamics.

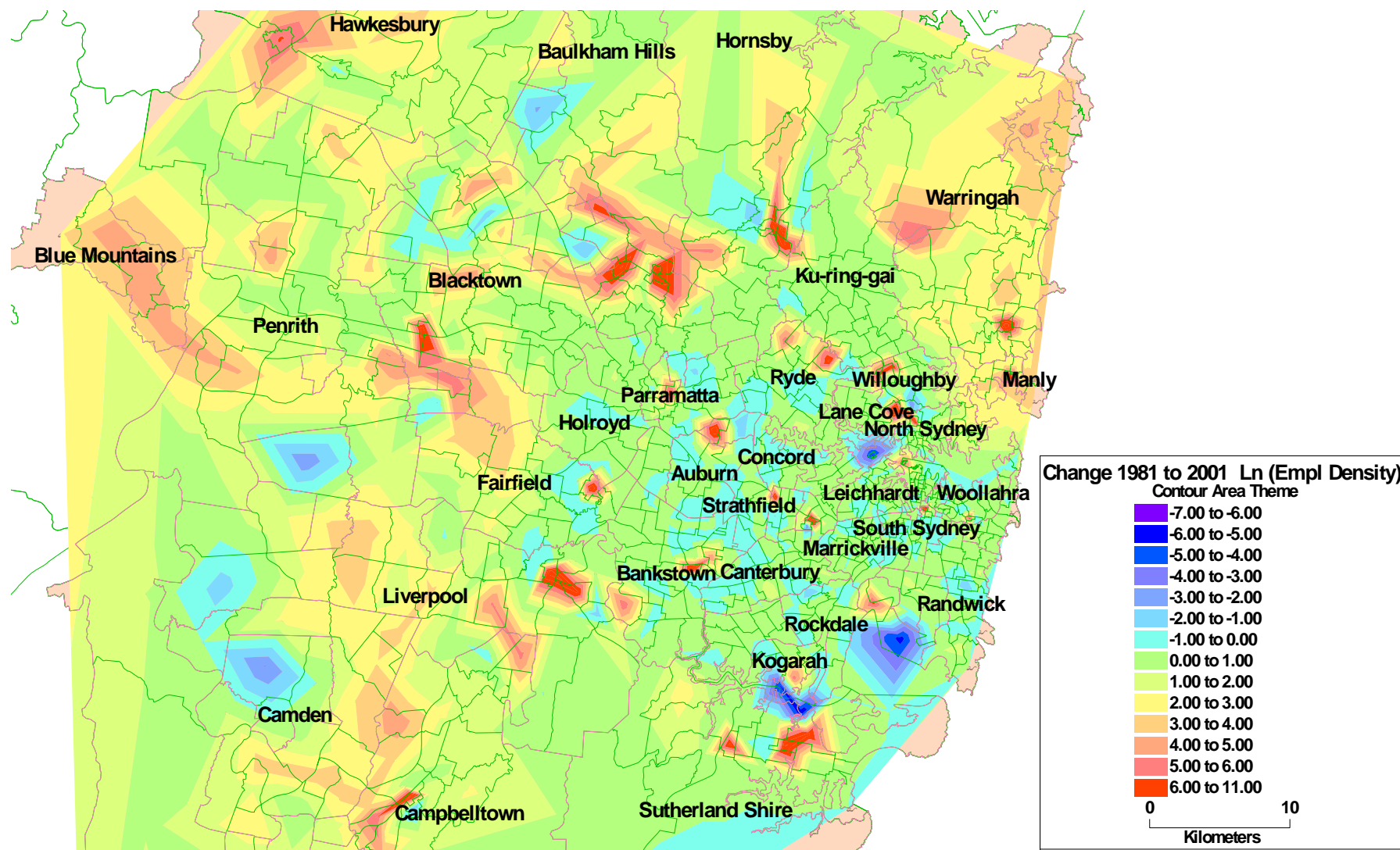**Figure 2 – 1981 to 2001 change in employment density**

Figure 3 – **Change in Ln(Employment Density) spatial distribution for 1981 to 2001**

Sydney, a global city with a history of planning policies since 1948 and a long running series of journey to work data sets, was selected to case study test these techniques. Trips to and from work account for a significant proportion of the transport pressures on sustainability in cities and as such is a good subject for illustrating techniques in sustainability assessment.

With the sustainability framework shown in Figure 1 providing the conceptual reference points, several measures have been calculated for the Sydney case study area. These include employment location rank size distributions over time for employment density across zones of Sydney, two- and three-dimensional plots using Transcad GIS software, accessibility ranking, desire lines for the journey to work, and employment-specific preference functions, to identify the spatial characteristics of the workforce.
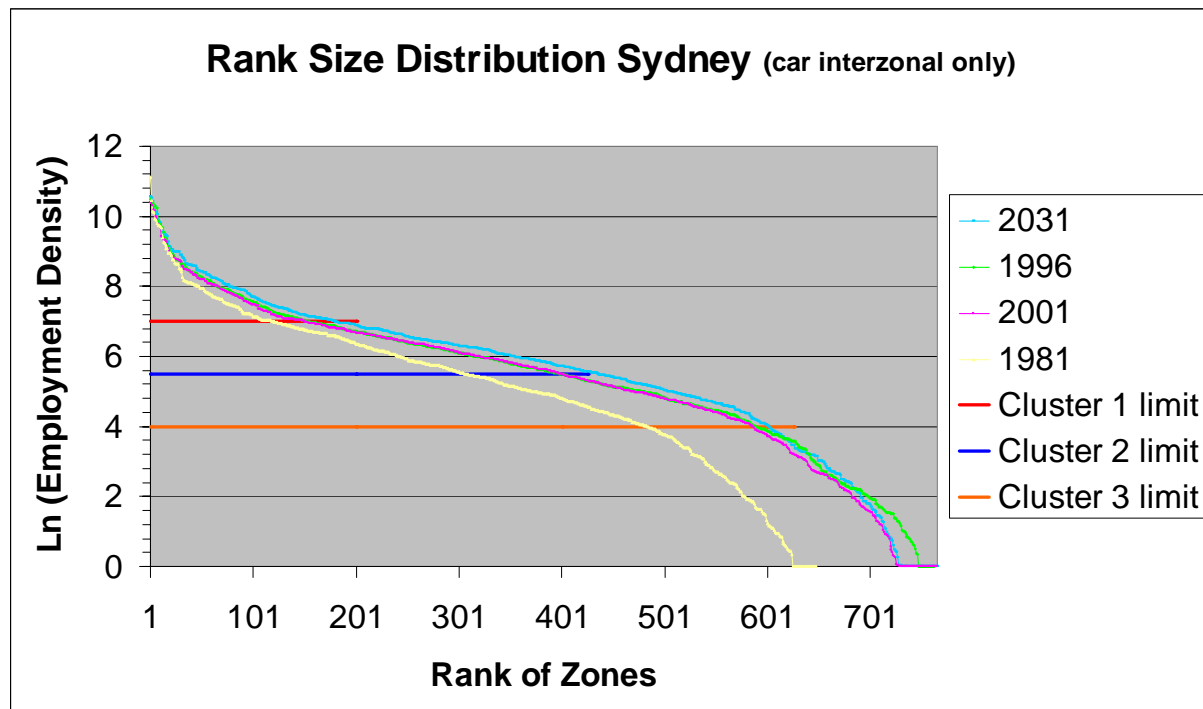

Figure 4 –   Employment density distribution for jobs accessed by car only

These visualisations collectively build up a holistic picture of the urban dynamics outcomes. Trends in business and industry location, residential location and journey to and from work trip choice were able to be made visible for the Sydney case study through the use of these metrics.

Having developed a picture of the urban dynamics in the Sydney case study, sustainability metrics, using visualisations in "environmental sustainability – accessibility space" of a metric indicating the accessibility to jobs for workers from their place of residence were generated. Visualisations for measures of environmental sustainability and economic efficiency focused accessibility (the first and third pillars of sustainability) were also produced.

4   Visual metrics of sustainability performance

Visualisation of metrics using GIS and graphical displays has been identified as a key approach in communication of urban dynamic outcomes and sustainability performance in a simple, meaningful way to community and decision makers alike.

An approach to visual sustainability metrics has been developed based on the concept of a sustainability goal in "environmental sustainability – accessibility space". Figure 5 illustrates this spatial concept and the idealised performance goal. A city's sustainability performance in relation to the goal can be analytically quantified and simply visualised in plots for assessing the three pillars of sustainability in cities.

The environmental sustainability measure (Pillar1) can be formulated from many different parameters (e.g. traffic noise generated, ecological stress, particulate emissions, resource usage). For illustrative purposes a measure based on known fuel consumption of vehicles (see Cosgrove, 2003, p342) with speed was used to calculate CO_2-e footprints for motor vehicles. Detailed operational methods were developed (Doust, 2008, Chap 4) and applied to generate a quantifiable measure. Accessibility has been identified as a useful measure of social and economic aspects of sustainability (see Expert Group on the Urban Environment, 1996; Warren Centre for Advanced Engineering, 2003; Kachi, *et al.*, 2005;2007). Accessibility measures were derived (Doust, 2008, Chap 4) for each travel zone pair. Separate operational methods were developed to generate worker and employer focussed accessibility measures. These are measures of social equity (Pillar 2) and economic efficiency (Pillar 3) respectively.
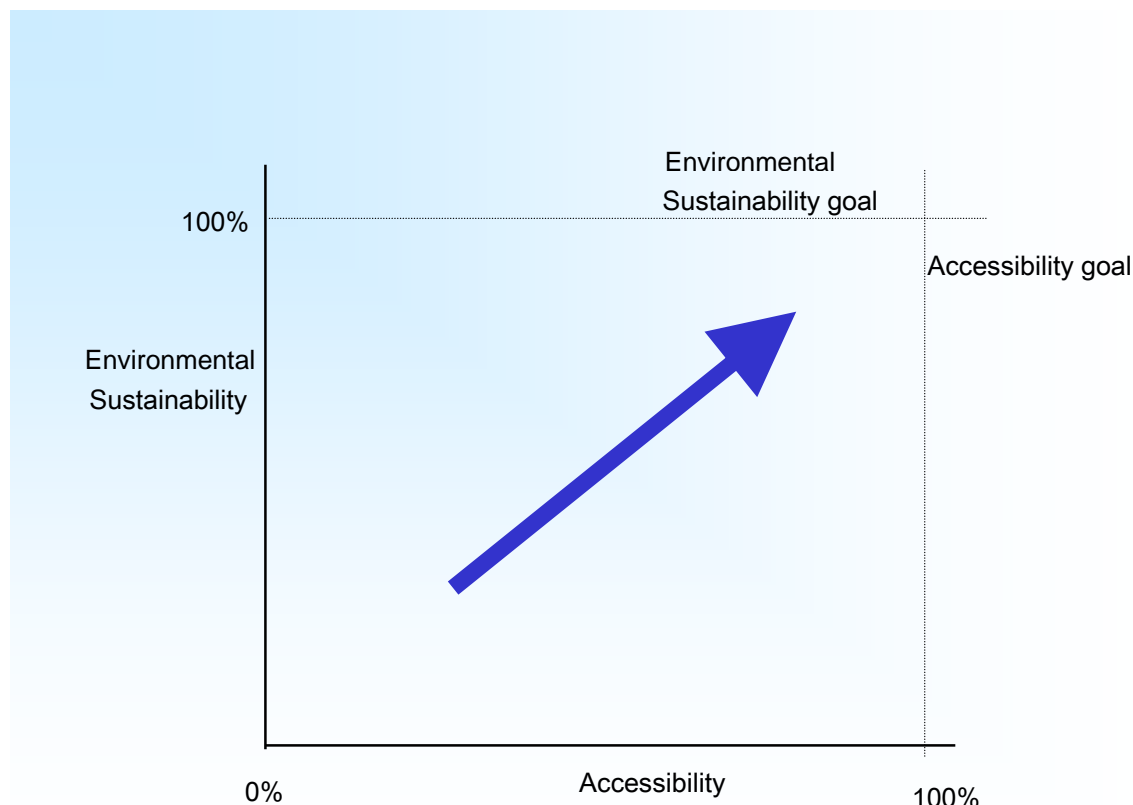

Figure 5 –   Environmental sustainability – accessibility space

The sustainability metrics developed were measures of environmental sustainability and accessibility in the form of scatter plot and prism map visualisations. These typologies were shown to indicate the sustainability performance characteristics for the three pillars of sustainability in terms of data set shape, frequency and spread in the "environmental sustainability – accessibility space".

The following simple five zone example provides the fundamentals of the zone pairs. The scatter plot shown in Figure 6 shows the sustainability performance against the desirable trend in sustainability. A shift to the top right hand corner and a limited spread in accessibility is identified as the theorised optimum.
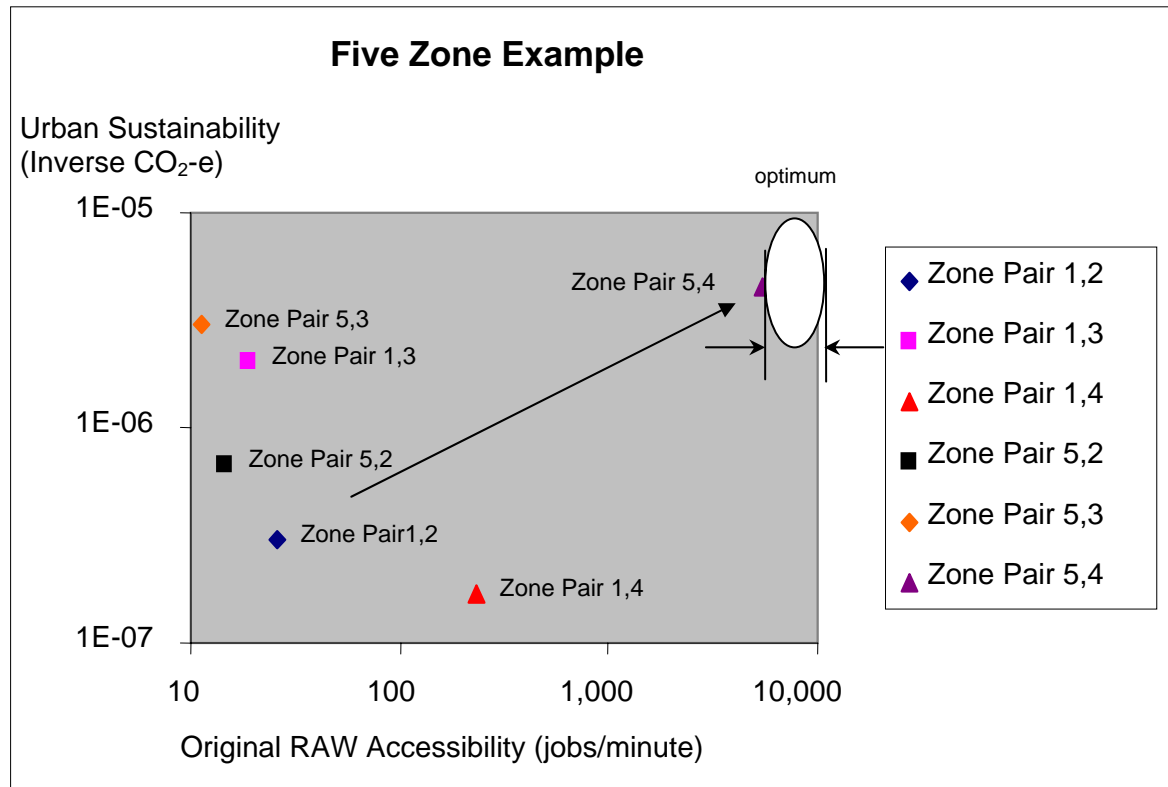
Notes:
1. Origin RAW Accessibility is defined as the accessibility to jobs at a destination zone (TZj) from an origin zone (TZi) calculated by dividing the total attractions from all origin zones to TZj by the transport impedance from TZi to TZj. Units are workers/ minutes, where workers are a proxy for jobs.
2. Environmental sustainability measure is defined as the inverse of CO_2 emissions from the total JTW trips between zone pairs, including an allocation of emissions from manufacture of vehicle and road infrastructure. This is calculated as a sum of the carbon dioxide equivalent (CO2-e) per unit trip km at the average speed with the shortest path trip length and number of trips. The carbon dioxide equivalent (CO2-e) is calculated as the sum of the quantity of greenhouse gas and the Global Warming Potential Index (AGO,2005,Appendix 3)

Figure 6 –   Environmental sustainability – "Raw" accessibility (Pillar3) goal

The metrics were able to be determined for large data sets for the Sydney case study (792 travel zones) by systematic analytical techniques using trip tables, network skims and car emission rates as inputs. These techniques have given the metrics a clear objective basis traceable to the source data. The visualisations although built from many thousands of pieces of data provided a simple representation giving a holistic view of the sustainability characteristics and trends. Figure 7 and Figure 8 illustrate the scatter plot form of the visualisation.
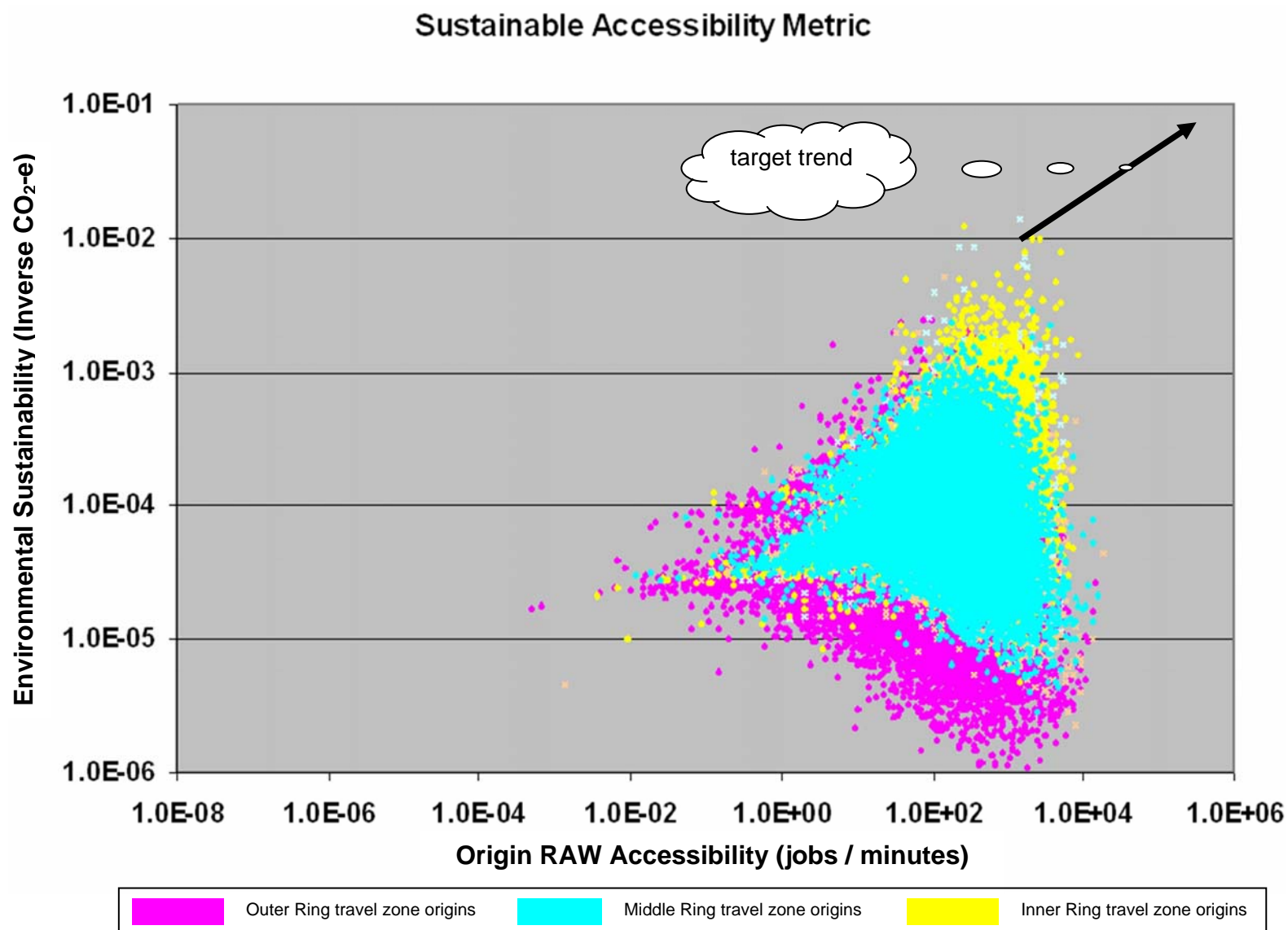
Figure 7 –   Scatter plot form of sustainability performance of Inner, Middle and Outer Ring areas of Sydney in 2001
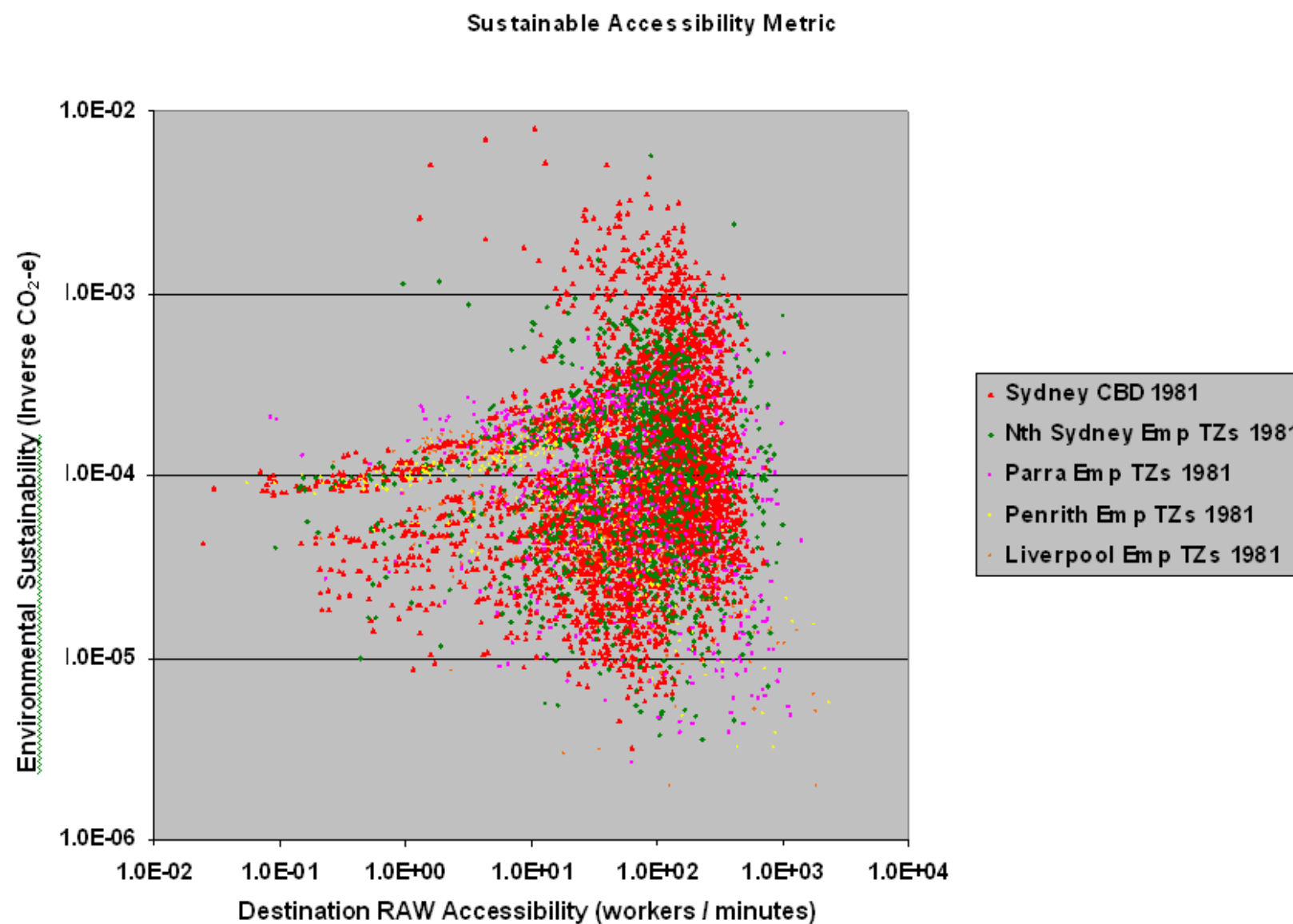
Sustainable Accessibility Metric

Figure 8 – Scatter plot form of sustainability performance of Sydney centres in 1981
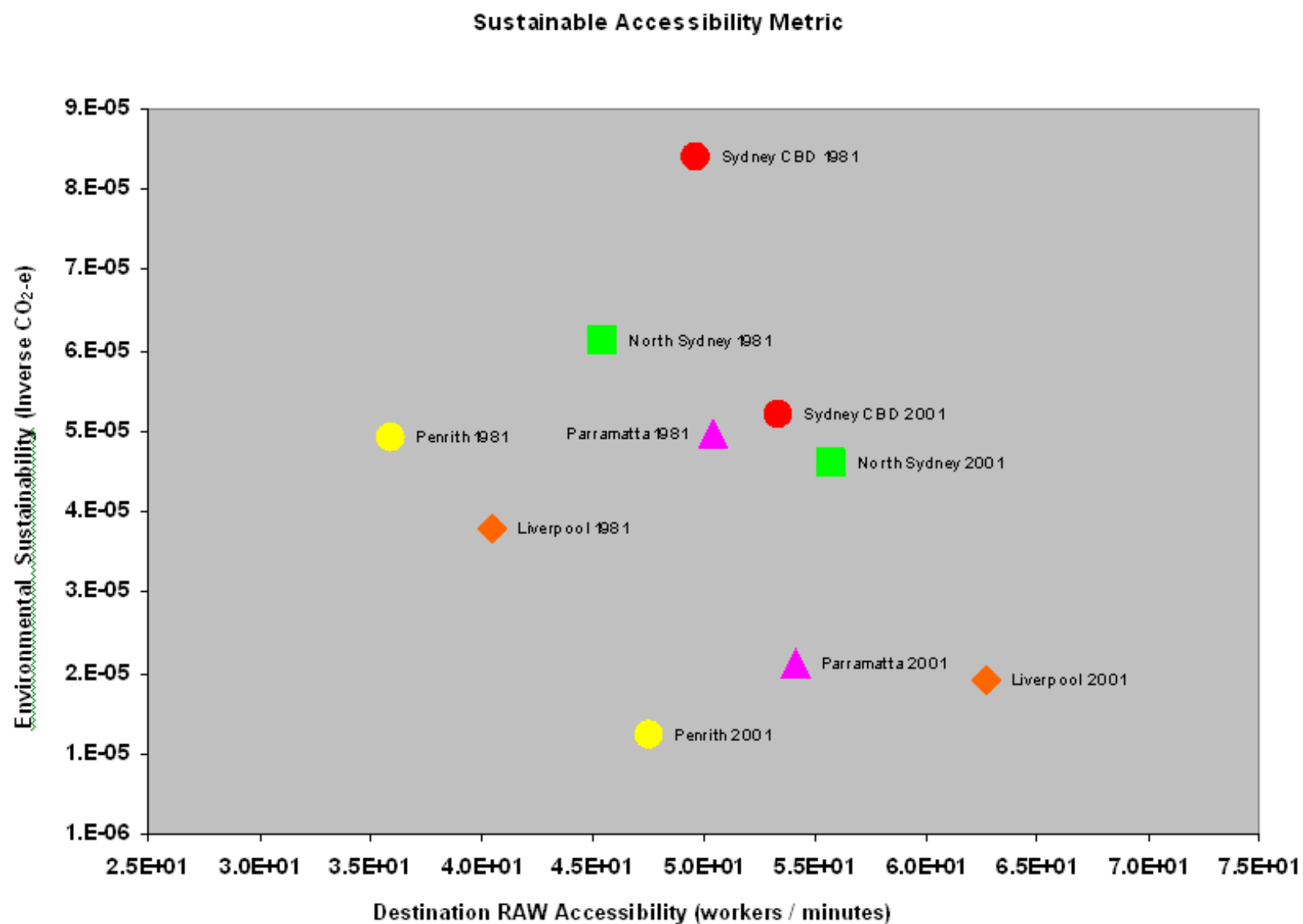
Sustainable Accessibility Metric

Figure 9 –   Average scatter plot form of sustainability performance for Sydney centres for 1981 and 2001

The richness of travel zone pairs in these sets makes it difficult to interpret the data within the sets from scatter plots, unlike the smaller sets where the internal patterns of the set is visible.

To give a greater degree of visualisation of the data sets, the "environmental sustainability – accessibility space" was divided into a grid. The grid overlays the log scales of the scatter plot, with each grid cell being one order of magnitude different to the environmental sustainability or accessibility cell next to it. For example, the bottom right corner cell (bin) ranges from $1e^{-8}$ to $1e^{-7}$ units of environmental sustainability, while the cell (bin) immediately above is an order of magnitude greater in environmental sustainability.

By counting the number of travel zone pairs that are positioned within grid cells, a visualisation is produced that summarises the concentration of points in the scatter plots. These are shown in Figure 10 as prism maps of the frequency in "environmental sustainability – accessibility space" for each of the sets. Through these three dimensional visualisations of the data sets, a number of differences between each set become visible.

An increase from 1981 to 2001 in the number of travel zone pairs in the bins with lower environmental sustainability indicates a shift away from the target direction. In particular an increase in the number of travel zone pairs with lower environmental sustainability values increases the frequency counts of the $1e^{-7}$ to $1e^{-6}$ and $1e^{-6}$ to $1e^{-5}$ bins from 1981 to 2001.

A significant contribution of this research has been the development of the concept of environmental sustainability – accessibility space and methods that enable the disaggregation of a city's sustainability performance into this space. An important next step is the methodology to disaggregate these sustainability metrics back into geographic space using GIS. It is hoped that practitioners are able to use this work to further the sustainability expectations and hopes that the community have for their cities.

In summary it was found that the scatter plots provide the raw point to point spatial location and spatial distribution of the data sets, however they have the disadvantage that trends in internal travel zone pairs are swamped by detail when more than 20,000 travel zone pairs are in the set. The overlay of environmental sustainability – accessibility grid bins and the frequency count of travel zone pairs for each bin enable these internal trends to be clearly seen through the prism map.

Each of these visualisations provide insight into the position, spread and internal distribution trends for a city's urban sustainability pillars of environmental stewardship, social equity and economic efficiency.
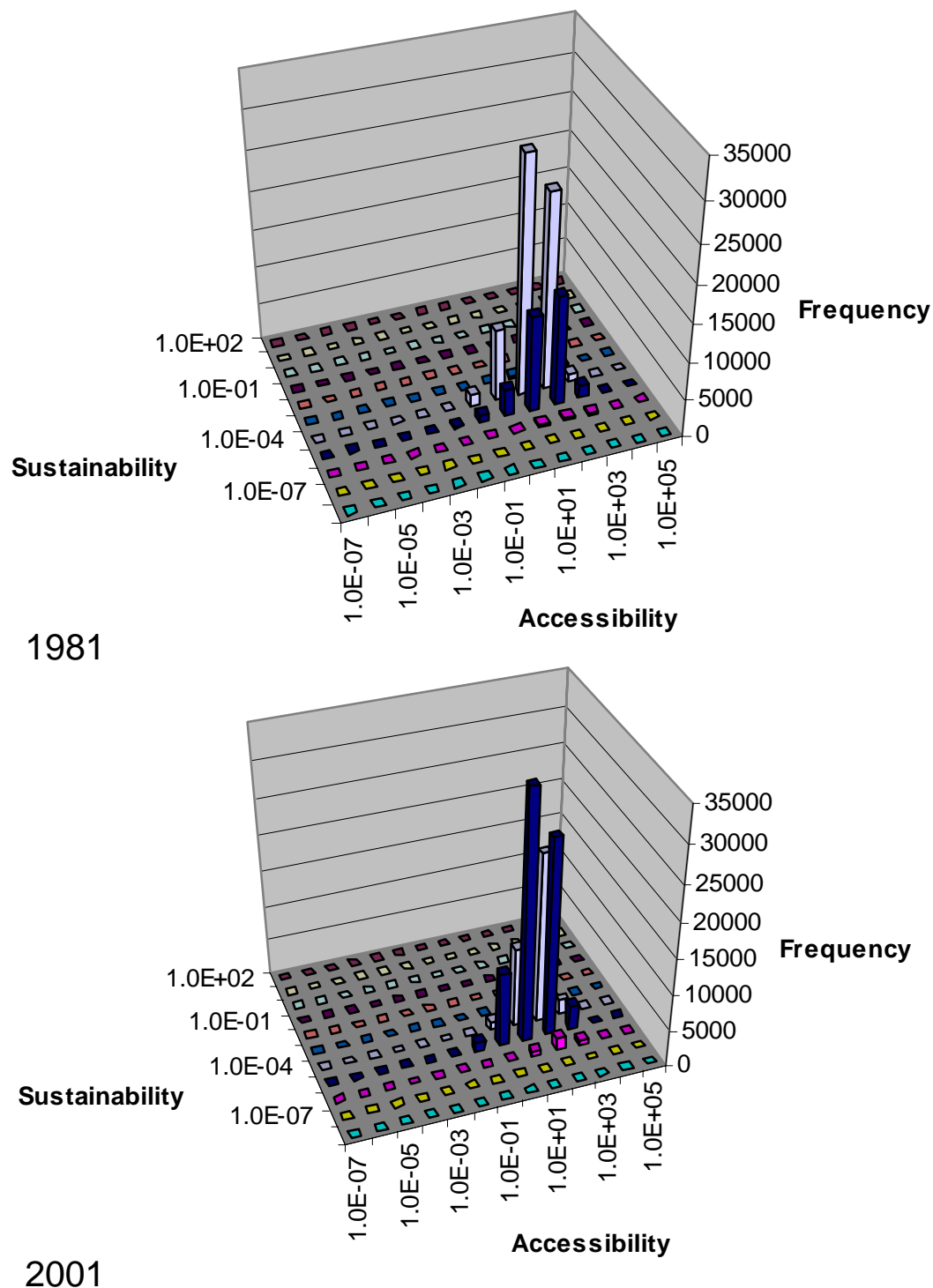
1981

2001

Figure 10 – Comparison of prism map metrics 1981 and 2001

5   Conclusion

The case study results demonstrate that a discernable difference in environmental sustainability and accessibility is able to be displayed using these metrics and as a result the sustainability in terms of the three sustainability pillars. Thus practical, traceable methodology with visualisation techniques that spatially disaggregate into environmental sustainability – accessibility space are shown to contribute to meeting the challenge of a meaningful yet simple visualisation of sustainability performance.

A particular strength of using the sustainability framework and the metrics demonstrated is that they are derived from data sets that have been commonly used by planners for many years. These are commonplace amongst transport and city planning departments. With these inputs and the assistance of readily available GIS/T software, all of the urban dynamics and sustainability metrics are able to be derived. The sustainability framework enables the holistic picture of sustainability to be maintained during the assessment process.

An important aspect of the metric methodologies is their analytical basis. All visualisations are traceable back through the algorithms to the source inputs. This is a particular strength when checking results, making scenarios changes and applying different planning instruments.

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