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Toward a typology of sustainability for cities

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Abstract: Sustainability responses must accelerate to avoid major risks to cities. Climate change impact on cities, likely to be significant if global sustainability initiatives are not quickened, is a paramount example of the risk. World wide meetings of city planning practitioners and researchers agree that an urgent agenda is to work together to empower cities and their governments with funds, tools and mentoring to make the responses needed. In the spirit of this urgent agenda, this paper introduces some practical methods for assessing sustainability associated with transport and urban form in our cities. A concept of strategic scans of future scenarios, which underpins the backcasting approach, has been introduced at the 12th World Conference on Transport Research(WCTR) in 2010 and has broken urban and transport planning trend. These strategic scans are based on a sustainability framework, the elements of which provide evidence based drivers of sustainability. The framework culminates in metric visualisations for each of the three pillars of sustainability. The paper details some of the operational aspects of these metrics in the form of environmental sustainability-accessibility space, putting into practice measures of environmental stewardship, social equity, economic efficiency, and the relationship among them. The paper concludes with a call of developing a typology of sustainability performance using the strategic scan methodology to extend the principles of the methodology into a useful tool for city governments and contribute to assembling a database of city forms, transport structures, and their sustainability performances.

Key words: transport; sustainability; cities; backcasting; climate change; metrics

1 Introduction

Sustainability has become a fundamental expectation in our societies today. With the experience of growing cities under stress through loss in environmental quality, liveability and numerous inequities, community and governments alike have an imperative to do things better and strive for values and a future vision that has collectively become known as sustainability. The reality of climate change is im-

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posing an overarching new timeframe for sustainability action.

A new imperative for sustainability responses and the clock is ticking. The need to respond is setting an urgent timeframe for cities to act. In 2009 Marseille Symposium by World Bank set an urgent agenda for cities to respond to climate change. Sustainability responses for mitigation and adaptation must accelerate to avoid major risks. The symposium set the challenge for practitioners and researchers to work together to empower cities and their governments with funds, tools and mentoring to make the responses needed.

The objective of this paper is to introduce some practical methods for enabling sustainability assessment in our cities to move from visions to operate infrastructure that delivers the sustainability outcomes needed. Specifically this paper connects to a research discussion at the 12th WCTR in 2010 which introduced the concept of strategic scans of future scenarios to underpin the backcasting approach for trend breaking urban and transport planning.

The paper concludes with a call of developing a typology of sustainability performance using the strategic scan methodology to extend the principles of the methodology into a useful tool for city governments and contribute to assembling a database of city forms, transport structures, and their sustainability performance.

2 Concept of strategic scan

It has been common in many cities for planning continuation of past trends. Transport planning, for example, often involves a process of estimating future demand based on recent past trends. The results in continuation of the status quo to transport supply, urban form, and other policy instruments. Issues such as climate change, rapidly increasing population and urbanization, and resource limitations are requiring future scenarios to be envisaged that are trend breaking. Over the past years one approach to developing trend breaking futures is to use vision and backcasting as a form of scenario building (Hickman and Bannister 2009). However a weakness in this method by itself, and indeed all methods for selecting a different future, is how to underpin the choice of scenarios and policy steps to get there with evidence based methods to reduce the risk of making the wrong choices.

As presented at the 12th World Conference on Transport Research in Lisbon (Black et al. 2010), the concept of providing sustainability strategic scan was introduced, with the aim of providing quick evidence based assessment to underpin the optioneering of different urban structures and transport networks coming from back casting techniques. The concept of the strategic scan process, also known as the land use and transport scenario assessment model, is shown in Fig. 1.

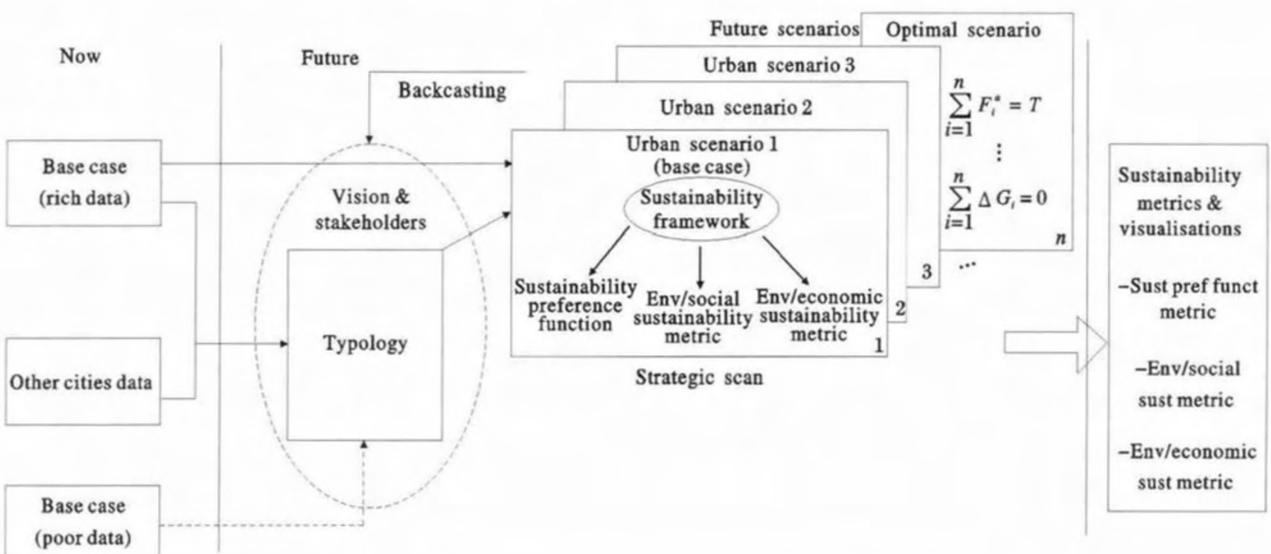

Fig. 1 Land use and transport scenario assessment model (Black et al. 2010)

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The process generates simple visualizations to give the evidence basis to the scenarios being assessed in vision and backcasting. The logic is that strategic scans of the performance of each scenario are necessary to help choose the most desirable future, including an optimization as one of the potential scenarios.

If we have a present situation of any city of the world (the "now") there are really two possibilities of data on land use, transport, and travel: rich data and poor data (for example, the case of many cities in the developing world). The "base case" in Fig. 1 assumes a case study area where rich data sets. In the latter city, it should follow through the steps for vision and backcasting. A group of stakeholders are involved in a vision study of city and will almost certainly derive information (typologies) about desirable futures from experience in other "rich data" cities of the world. Vision will help lead to various future scenarios. Backcasting will help formulate a sequence of policy packages or actions to achieve the most desirable future.

The sustainability framework provides the metrics for such an assessment of the best scenario, as shown on the right side of the flow diagram in Fig. 1. It should be noted that in the case of a poor data case study city, to assist in the formulation of appropriate scenarios for that particular city, planners must rely on the typologies of other relevant cities where such information is available. The metrics proposed can then be applied in this situation. The significance of this approach is that it becomes a valuable tool for stakeholders and their consultants in developing countries where international agencies such as World Bank and Asian Development Bank are attempting to forge strategies to make developing cities more sustainable.

The sustainability framework embedded in Fig. 1 enables the proposed land use and transport scenario assessment model to generate logical sustainability assessment metrics and optimization algorithms that include accessibility and green house gas trade-offs, (Black et al. 2010). The main features are:

- Preference functions to capture zonal travel behaviour;
- Triple bottom line assessment of the optimum pattern of urban development and travel (mean trip length of journey to work as a key sustainability indicator);
- The assessment includes accessibility to employment from residential zones (social equity), accessibility to labour from employment zones (economic efficiency) and carbon dioxide emissions from the road network;
- A land use optimization process using these travel preference functions to constrain commuting travel patterns to match the observed behaviour.

The model is built on the use of sustainability assessment metrics for gauging how the urban system, policy packages and resulting urban dynamics perform. A challenge for researchers is to provide methodology that is not only objective but also able to be simply and meaningfully understood, and used, by the community and governments.

Two independent research areas contribute to these sustainability metrics that are able to characterize the sustainability performance of existing and future scenarios. The metrics selected (Black et al. 2010) are the sustainability preference functions, together with environmental-social equity and environmental-economic efficiency sustainability metrics. Both of these are set in the sustainability framework discussed in the next section and reflect the behavioural responses of the community to the urban system and the other drivers.

3 Urban sustainability framework

A framework for developing methodology with the above features is shown in Fig. 2. The "urban system" is the physical aspect of the framework shown in Fig. 2, consisting of the "urban form" and "transportation" elements which define the spatial configuration of the city. Intentional changes to the "urban system" can be viewed as strategic instruments that enable governments to have some levers to shape how the city functions. Response of the community to the "urban system" produces interactions that result in selection of location of residence and workplace, industry, trips and so on. These interactions that have a time dimension are collectively known as "urban dynamics". The resulting "urban dynamics" outcomes generate the sustainability performance in terms of the

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three pillars included as elements in Fig. 2. Each pillar has a feedback to the "urban dynamics" and consequently to the "urban system" (indicated by the double headed arrows in Fig. 2).

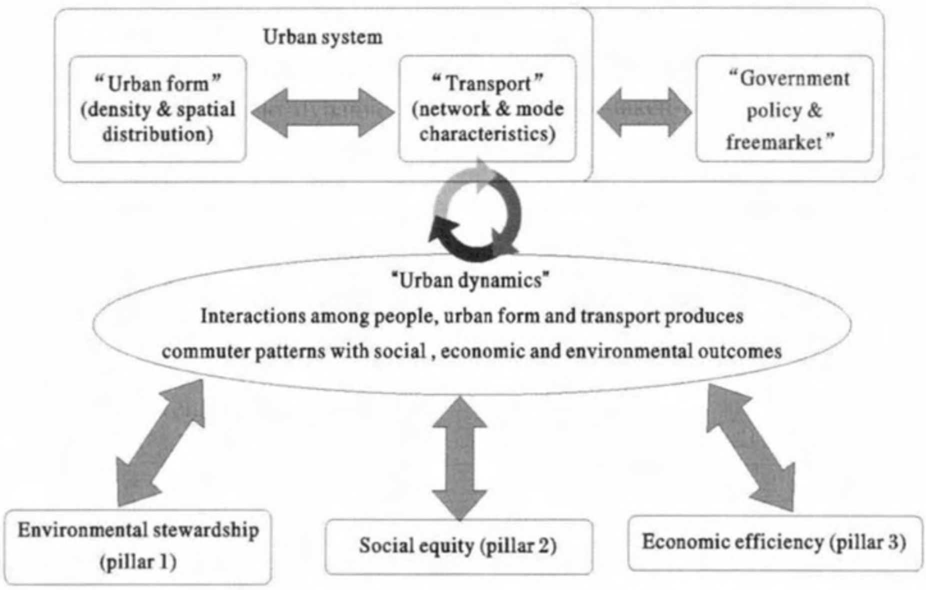

Fig. 2 Urban sustainability framework

An accepted central requirement for sustainability metrics is a methodology that results in a holistic assessment of the complementary performance of all three pillars of sustainability. The three pillars of environmental stewardship, social equity, and economic efficiency have been recognised as mutual objectives. This dates back to the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg (United Nations 2002). A holistic assessment methodology can be viewed as having three functions and corresponding practical outcomes.

- To identify the system elements and interactions that drive the sustainability performance of the city (What to measure).
- To formulate measures that are objective and traceable (How to measure).
- To formulate methods of assessing mutual performance of the three pillars of sustainability in a manner that engages community and decision makers (How to assess).

Of the two metric types selected for the strategic scan process (Black et al. 2010) the environmental-social equity and environmental-economic efficiency sustainability metrics are the subjects of the remainder of this paper.

In particular the paper focuses on how these metrics are able to become operational techniques from current transport and land use planning practice. Traditional building block methods form the foundations of the required metrics methodology, enabling common land use, and transport data to build up a database and typologies of sustainability performance.

4 Concept of sustainable accessibility

Social equity and economic efficiency, two of the three pillars of sustainability, have a relationship to accessibility. Social equity is able to be measured using accessibility, where worker accessibility to jobs or other opportunities is the focus of the measure. This is a measure of the physical spatial equity which is a measure of social equity when adjusted by the socio-economic characteristics. Economic efficiency is also able to be measured using accessibility, where industry or business accessibility to workers is the focus of the measure. Other factors are also drivers to industry and business efficiency, such as accessibility to markets and suppliers. Financial capability of firms to choose the most efficient locations and compatability with other land use are other factors. However, even with these qualifications, accessibility is regarded as a crucial measure in social equity and economic efficiency performance.

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A key connection between environmental sustainability and accessibility is that appropriate levels of both are needed, with the idealised target being 100% of both. A novel concept of a sustainability goal in terms of environmental sustainability and accessibility is introduced here and provides a simple collective approach for assessing the three pillars of sustainability in cities. In the concept original to the author, a city's sustainability performance in relation to the goal can be analytically quantified and simply visualised in plots on what shall be called "environmental sustainability-accessibility space" (Fig. 3). This figure refers to "environmental sustainability" as meaning stewardship and "accessibility" as meaning accessibility of workers to places of employment, shopping schools and so on or alternatively meaning accessibility of employment to workers.

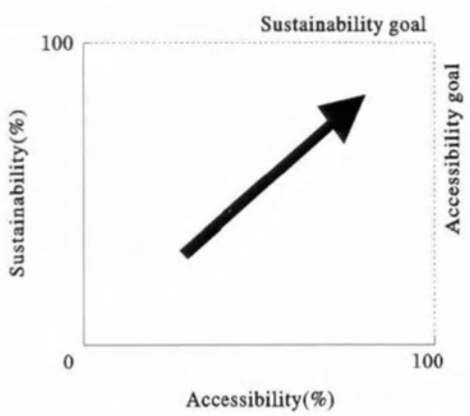

Fig. 3 Environmental sustainability-accessibility space

For either accessibility subject (worker or employment for example), the figure shows that the environmental sustainability performance on the ordinate can be plotted with the corresponding accessibility performance on the abscissa for any pair of land use zones. The concept enables both a quantifiable measure and a visual representation of the mutual performance. A goal or target for environmental sustainability and accessibility is also able to be applied and visually represented in the same space. The 100% goal position may vary depending on the relative weighting or priority of the two pillars.

The two dimensional environmental sustainability-accessibility space has a parallel to the GIS for geographic space. In geographic space, spatial disaggregation enables a visual appreciation for example of land use distribution. In environmental sustainability-accessibility space, it is contended that spatial disaggregation enables a visual appreciation of the sustainability performance distribution. For example, the dual pillars of sustainability distribution for land use zonal pairs in a city. The concept could also apply to the mutual performance of the dual pillars of social equity accessibility and economic efficiency accessibility. In this case the visualisation space would be "social equity accessibility-economic efficiency accessibility space".

In relation to the functions of a holistic assessment methodology, the above concepts were shown to be objective and to visually enable assessment of mutual performance of the three pillars of sustainability (Doust 2009a). The metrics shown in Figs. 4, 5 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 (Doust 2009b). These techniques have given the metrics a clear objective basis traceable to the source data.

By choosing metric parameters founded on the building block methods, the methodology provides traceability to source data and definable analysis methods. Although the visualisations was built from thousands of simply representative data, it provided a holistic view of the sustainability characteristics and trends. For community and decision makers these visualisations give a simple snapshot of overall sustainability performance, for each scenario considered. Change the scenario to produce a new metric plot and see the sustainability effect. Stakeholders can see measurable change for their communities in relation to sustainability goals.

The sustainability risk boundaries are specific to each city, and influenced by the population's estimated resilience. This sustainability risk rating can then be replotted back onto geographic space using GIS thematic mapping. Fig. 5 illustrates the visual effectiveness of this technique for the outer ring of Sydney, replotting the red coloured points falling in the high risk squares in Fig. 4 using a hypothetical levels risk boundaries to demonstrate the method.

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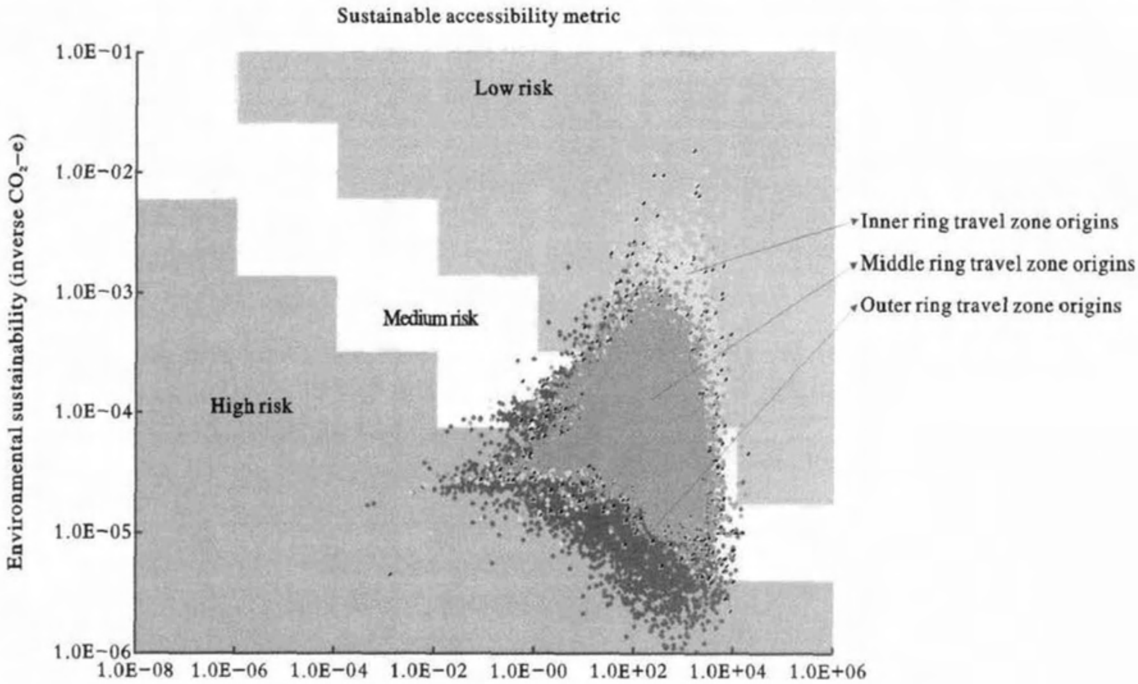

Fig. 4 Sustainability risk visualisation

Fig. 5 High sustainability risk in outer ring

5 Operational metrics

To illustrate how the sustainability metrics derived in the previous section are able to be determined, a case study of Sydney, Australia (a major beta level global city), is used to illustrate the operational methods.

Sydney has also been the recipient of ongoing efforts to plan the city's urban form and transport networks from the 1920's Bradfield initiatives for infrastructure, rail and tram lines (Spearritt 2007), the 1948 County of Cumberland Planning Scheme through to the present day Metro Strategy (Black et al. 2007). While this has had varying outcomes, it has left Sydney with a legacy of transport and population data over many years. Of particular value is the Census of Population and Housing with Journey to Work Trip tabulations of trips to work for the whole Sydney population over a long period from 1961 to 2011. The Sydney Area Transportation Study collected the first data base for all trips in 1971.

5.1 Data sources and derived data

To prepare the metrics a range of source information is required about the urban system of Sydney and the travel pattern outcome of the urban dynamics. Zonal data and network data are two of the information sources needed for each of the selected census years. This enables trip times and trip distances to be derived between origin and destination zones. This data is used to form the transport impedance variable, used in the transport impedance function to calculate the deterrence to take a trip. In addition, parameter values A, α and β are also required to establish shape and position of the transport impedance functions. Observed trip distribution data provides the community response to the urban system for each of the four census years. Metrics of environmental sustainability and accessibility performance are derived from the building block methods in combination with data on environmental performance of vehicles.

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5.2 Data

Journey to work (JTW) data sets are derived from the Census of Population and Housing each five years. This data provides a survey of every household on the day of the census. As such this data is not a sample survey but a survey of the full population of workers in Sydney on census day. Tables of origin-destination trip frequencies are available from this data at either statistical local area (SLA) or travel zone (TZ) levels.

The more detailed zonal system based on TZ, yields better representation of the trip distribution than a coarser zonal system based on local government areas. The JTW data sets in Sydney are available at a travel zone level for the census years 1981, 1991, 1996, 2001, 2006 and 2011.

5.3 Zonal data

When drawing data from a series of census years, a common zonal system increases the quality of the data comparisons. For Sydney, the zonal system boundaries have changd over successive census. The 1991 zonal system was selected as the baseline zonal system. This enabled zonal systems from 1996 and 2001 to be rolled up to the 1991 system for like comparison across the years. The 1981 data was able to be correlated, but required a number of the larger zones to be split to match the 1991 travel zones. The zonal system defines both the spatial boundaries of each zone and the zone centroid coordinates.

The Sydney and surrounds zonal system are shown in Fig. 6. The city of Sydney originated around the coastal settlement on the harbour of Port Jackson in the late 1700's. The harbour has remained the focal point for the city as it has grown to the west, north and south to today where it remains the CBD and focal point for rail transport. The 1991 travel zones are shown in Fig. 6. The travel zones extend from Newcastle/Williamtown in the north to Wollongong/Nowra in the south and the Blue Mountains in the west. In total they cover the Greater Sydney Metropolitan area and the adjacent cities and regions of Newcastle and Wollongong. Fig. 6 also displays some of the attributes of each travel zone. Each travel zone has an individual ID number, but it needs to be correlated with the ID numbers for the other layers of data such as networks. The area for each travel zone in square kilometres can be seen in the second field and unique Transport Data Centre Travel Zone Numbers are displayed in the third field.

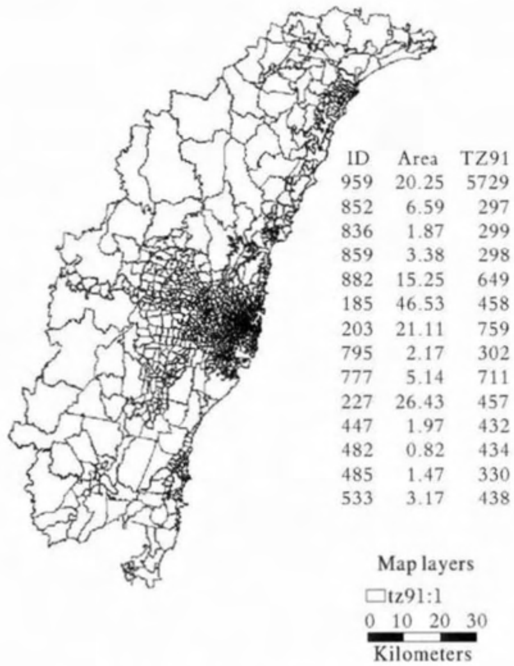

Fig. 6 1991 travel zones (TZs)

It is observable in these figures that the travel zones are smaller in area around inner Sydney, Newcastle and Wollongong and conversely, larger in area towards the fringes. A characteristic of the larger area travel zones is that they are not generally in close proximity to the source file networks. This presents a difficulty when estimating the travel time along lengthy connectors linking the travel zone centroid and the nearest available access to the networks. The trip makers assume to start and finish their trips at the centroid of each zone. Each travel zone centroid requires connecting to the network by connectors. In travel zones with centroids closer to networks, an average speed of 25 kph is assumed to give typical representation of speeds and thus access times to the networks. This is not the case with the lengthy connectors.

To solve the issue with lengthy connectors, the decision was taken to set the boundaries of the case study area to exclude the travel zones generating these connectors. The zones included in the case study area

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and their boundaries are shown shaded in Fig. 7. Generally the boundaries are the natural boundaries of the Hawkesbury River to the north of Sydney, the Blue Mountains to the west and the water catchment and national parks to the south of Sydney.

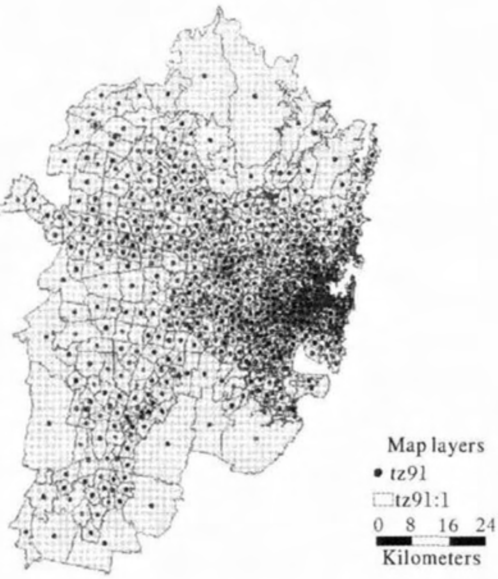

Fig. 7 1991 travel zones in case study

5.4 Network data

The network data was sourced from 2001 EMME 2 models loaded with the 2001 NSW Roads and Traffic Authority (RTA) ' s Sydney road network and the Sydney rail network. The network includes link length, free flow speed on the link and link vehicle capacity. Other data include the type of link, namely local, sub-arterial, arterial, highway, expressway etc. It can be seen that the network includes a number of local roads, indicated by the code 1 in field titled link. However, only sufficient local roads have been included to give a reasonable representation of the road network in the local area. Fig. 8 shows the road network with some flows indicated. Over the case study area approximately 17000 links are included. The network is characterised by major arterial roads with a web of lower hierarchy roads. The road network should be matched to the census year to ensure only appropriate links are identified for that year.

The links are assumed with free flow conditions. Congestion is not included in the scenario base case, but should be factored for sensitivity testing of scenarios. Modifying the link times and fuel consumptions to reflect congestion is important for future interpretations of urban trends. Congestion has a high cost in all three pillars of sustainability (Centre for International Economics 2005; Bureau of Transport and Regional Economics 2006).

Fig. 8 Road network in case study

5.5 Observed trip distribution data

Preparation of data requires a process of cleaning and then transferring these large tabulated data sets into a form suitable for derivation of sustainability performance metrics. To validate the procedure, the mean trip length and the trip length distributions of the processed data are compared with the distributions calculated by others, using the same source JTW data. This is standard industry practice for this type of data set.

5.6 Transport planning/GIS software

To apply building block methods, Transcad or other similar transport planning software tool can be utilised. Transport networks and land use zones are able to be spatially represented in GIS. Transcad has the capability to derive data from the GIS using the four step transport modelling procedures and the census tabulations. For this research, the trip distribution procedure was employed. Matrix tabulations are able to be manipulated using Transcad. Custom methodologies are applied to achieve traceability as a result. A key capability of Transcad is able to spatially disaggregate the derived data into geographic space using GIS and to provide visualisations such as thematic maps and prism maps.

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5.7 Location

Metric points that sustainability and accessibility are calculated from census based data and for varying locations across Sydney. Locations selected for the case study include inner travel zones, middle travel zones further from the CBD which were suburbs established pre 1950, and outer travel zones more characterised by urban fringe development that has occurred since the 1950's. Other locations are employment centres at locations targeted under the NSW government strategic plans from 1948 to the current 2005 Sydney Metropolitan Strategy.

5.8 Origin destination transport impedance manipulation

The trip distributions from the origin-destination trip tables (e.g. 1981, 1996 and 2001) are adopted for strategic scans. The process requires the establishment of a multiple shortest path matrix (MSPM), which is a matrix of the shortest path between each travel zone pair in terms of either distance or travel time.

A building block method is utilised to derive this matrix. To determine a MSPM, it is necessary to create a network of road links, attributes of travel time per link or distance and average speed on each link. Together with a shortest connector from the travel zone to the network and travel time on the connector, the baseline network is created, from which Transcad creates the MSPM. This process is shown in Fig. 9. The network is adjusted for each subsequent census year to add or delete links that were in place at the time of the census.

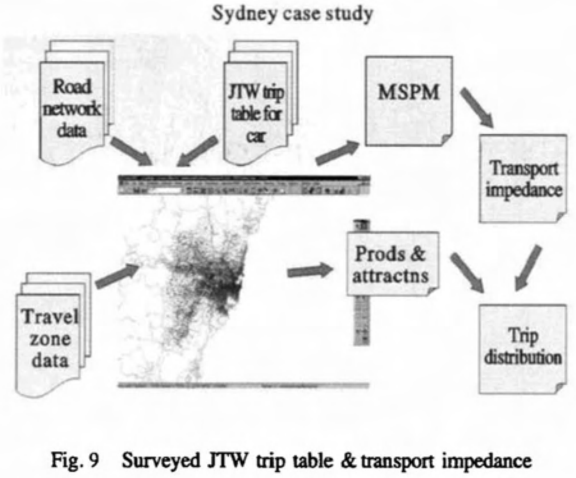

Fig. 9 Surveyed JTW trip table & transport impedance

The transport impedance is quantified in terms of a transport impedance function $fn(C_{ij})$. Variants on $fn(C_{ij})$ are usually one of three forms:

Power function $fn(C_{ij}) = C_{ij}\alpha$

Exponential function $fn(C_{ij}) = \exp(\beta C_{ij})$

Gamma function $fn(C_{ij}) = AC_{ij}\alpha\exp(\beta C_{ij})$

A particular form of the Gamma function is the Tanner function where the parameter "A" is 1. Cheng and Black (1989) analysed census data between 1961 and 1981 and found that the Tanner function provided the best fit gravity distribution model to the census distributions of 1961 to 1981 for Sydney.

The Transcad modelling platform procedure can be adopted to determine the impedance variable C_{ij}, as the shortest path travel time. The network and travel zones spatial relationship, together with known attributes of travel time on each link are used to determine the shortest path between each origin and destination zone via the road network. Each of these, for each origin and destination pair is stored into the multiple shortest path matrix.

The gamma form of the impedance function is then calculated, using the C_{ij} values and A, α and β parameters (or a, b, c in Transcad), to create the friction factor matrix for all origin-destination pairs in the case study area. A, α and β parameter values assumed for the case study were 1, 0.001, −0.0999 respectively.

To simplify the complexity of the building block modelling, the use of origin and destination data sets from census data or surveys already stratified by mode can negate the need for mode split and assignment steps, where a first pass comparison of scenarios is sufficient. The risk is that extrapolation may not be as reliable as using the complete distribution, mode split and assignment steps.

5.9 Environmental sustainability and accessibility metrics

Environmental sustainability is definable with many different measures. For the purpose of quantifying for strategic scans, a measure of CO_2 equivalent (CO_2-e) is useful. A methodology based from the building block methods enables the metrics of sustainability to develope from source data with traceable

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quantifiable steps. The steps in developing the metrics through derived data are shown in Fig. 10. The MSPM for each census year provides input to calculation of the transport impedance function which in turn is input to the accessibility measure.

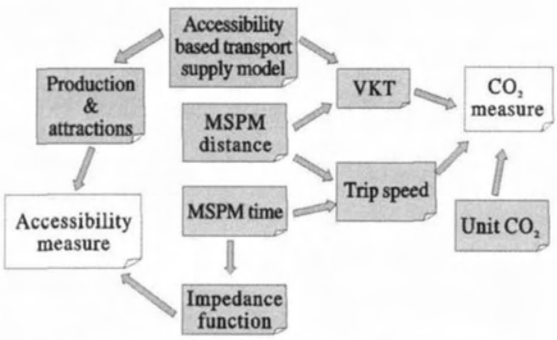

Fig. 10 Accessibility measure and environmental sustainability measure

Accessibility measures use transport impedance together with employment or workforce opportunity. For the purpose of the case study testing, the socio-economic differences across Sydney are not applied, but could provide a further enhancement of the strategic scan. Similarly for economic efficiency assessment the accessibility to markets and suppliers, influences of firm financial capability and compatability constraints with other land use are all excluded for simplification of the analysis but recognised as important factors for future research. Therefore for the operational methods accessibility to jobs, a measure of social equity and accessibility to workforce, and a measure of economic efficiency are considered.

5.10 Operational measure of environmental sustainability: a greenhouse gas emission measure

A greenhouse gas emission measure used as an operational measure is derived by estimating the total greenhouse gas emissions rate from a trip in the Sydney network. The method of deriving is by estimating the greenhouse gas emissions over the life of the transport supply system. This is expressed as grams per trip kilometre for each person that travels on the system. For road based trips the Australian Greenhouse Office provides data on greenhouse gases produced (CO_2-e) from use of petrol as a fuel and typical fuel consumption in litres/100km.

In combination with Bureau of Transport Economics data on petrol consumption variation with vehicle speed, the emission rate was able to be established for a range of vehicle speeds (Cosgrove 2003). Petrol consumption variation with vehicle speed is shown in Fig. 11, with petrol consumption at 40 kph as the reference.

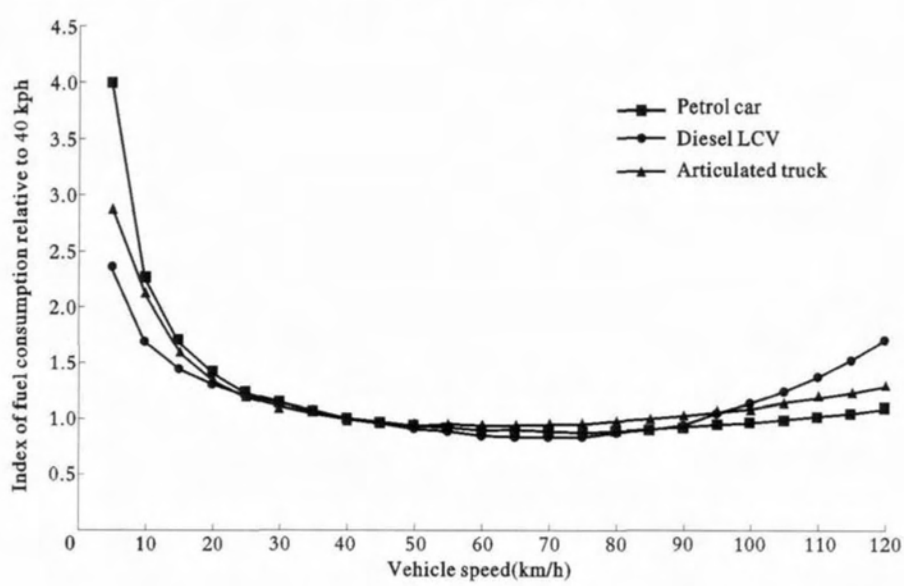

Fig. 11 Speed variation in petrol consumption (Cosgrove 2003)

Emissions for car trips are shown in Tab. 1, which includes both CO_2-e from fuel usage and resources used for both car and roads. The CO_2-e emissions have been annualised to a person kilometre rate by

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proportioning by average asset life and average vehicle occupancy.

For rail based trips the primary energy source in Sydney is coal fired electricity. The Australian Greenhouse Office provides emission rate for the production of coal fired electricity, which in combination with state rail average energy usage per train, has been used to derive greenhouse gas emissions per trip kilometre for each person travelling on the rail system. Emissions for rail based trips are shown in Tab. 2. It includes both CO_2-e from coal fired electrical energy used, its transmission and from resources used in both train vehicles and fixed infrastructure. The CO_2-e emissions have been annualised to a person km rate by proportioning out and by asset life and average annual patronage.

Table 3 summarises the total greenhouse emissions for road and for rail based trips. These unit rates represent global environment impact and are used as the basis for the operational environmental sustainability measure.

Tab. 1 CO_2-e emissions for road trips at 40 kph

Greenhouse gases	CO_2-e emissions	Unit	Notes
Fuel usage	185.960	grams/person km	
Steel for cars	0.065	grams/person km	5 year life
Roads contruction & maint	13.878	grams/person km	35 year life
Sum	199.903	grams/person km	

Tab. 2 CO_2-e emissions for rail trips

Greenhouse gases	CO_2-e emissions	Unit	Notes
Energy usage	118.54000	grams/person km	
Steel for trains	0.00500	grams/person km	35 year life
Railway rails & OH masts	0.00300	grams/person km	50 year life
Railway concrete sleepers	0.18400	grams/person km	50 year life
Railway stations	0.06100	grams/person km	50 year life
Railway bridges	0.01600	grams/person km	100 year life
Railway signal posts	0.00002	grams/person km	50 year life
Sum	118.80902	grams/person km	

Tab. 3 CO_2-e emissions

Sustainability measures			Global environment impact CO_2-e (grams)
Rail links/person km			118.809
	speed	10 kph	489.170
	speed	20 kph	313.543
	speed	30 kph	241.225
	speed	40 kph	220.563
Urban local roads/person km	speed	50 kph	210.232
	speed	60 kph	199.901
	speed	70 kph	199.901
	speed	80 kph	199.901

The environmental sustainability measure for car based trips is calculated from this CO_2-e unit rate data in the following manner.

The trip lengths from the MSPM for distance and the number of trips between each origin-destination TZ pair are multiplied providing person kilometres

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travelled. When coupled with car occupancy rates this produces vehicle kilometres travelled (VKT):

$$\mathrm{VKT}_{ij} = Q_{ij}\, d_{ij}/O_{cc}$$

where Q_{ij} is trip frequency between TZ_i and TZ_j; d_{ij} is shortest path distance between TZ_i and TZ_j; O_{cc} is ratio persons per car.

Similarly, the MSPM for time when divided into MSPM for distance provides on estimate of average speed between each origin-destination TZ pair. This is able to couple with an average CO_2 emissions index per speed of car trip (see detail later in this section) and the number of trips between travel zones to give a measure of CO_2 emissions per trip kilometre per travel zone pair.

$$CO_{2\ ij/\mathrm{trip/km}} = S_{ij}E$$

where S_{ij} is shortest path average speed between TZ_i and TZ_j; E is ratio of CO_2 per average trip speed/trip/km.

A proxy for the shortest path average speed between TZ_i and TZ_j is determined by dividing the shortest path distance by the shortest path trip times. This measure represents the characteristic transport system CO_2 emissions for the travel zone pair, including CO_2 emissions coming from infrastructure, vehicle construction and operations (amortised over the infrastructure, vehicle life and network path to a single trip figure).

However, taking this step further, the following measure is the overall journey to work transport CO_2 emissions for each travel zone pair resulting from the actual demand. The measure represents the effects of the transport system acting with the level of land use activity that characterises the particular land use scenario:

$$\text{Total } CO_{2\ ij} = \mathrm{VKT}_{ij}\, S_{ij}E$$

In contrast to the previous measure, as the spatial distribution and density of worker's place of residence and employment vary, so does the VKT_{ij} and the CO_2 emissions.

An improvement in environmental sustainability occurs with a decrease in CO_2 emissions. The measure selected to plot in environmental sustainability space is:

$$\text{Environmental sustainability measure} = (\text{Total } CO_{2\ ij})^{-1} = (\mathrm{VKT}_{ij}\, S_{ij}E)^{-1}$$

5.11 Operational measure of accessibility

Accessibility of each travel zone to opportunities can be calculated, whether it is the accessibility to employment from a zone TZ_i or accessibility to workers for an employment zone TZ_j.

Using an accessibility measure of the activity based form the accessibility to destination travel zones from the origin zone TZ_i can be determined:

$$H_i = \sum D_J fn(C_{iJ})\,\mathrm{step1}$$

where H_i is accessibility measure of TZ_i; D_J is potential opportunity at TZ_j measured as the total attractions from all origin zones to TZ_j; $fn(C_{iJ})$ step1 is travel impedance function.

However, this measure is for the total opportunity available from the origin zone. It does not provide any comparative information as to the accessibility performance between any two pairs. That is unless the H_i measure is disaggregated into its constituent parts. The accessibility measures adopted for case study testing enable degrees of comparison between travel zone pairs.

Relative accessibility and raw accessibility are the two forms of accessibility measures that make up the operational methodology for the case study. These are defined mathematically in Fig. 12.

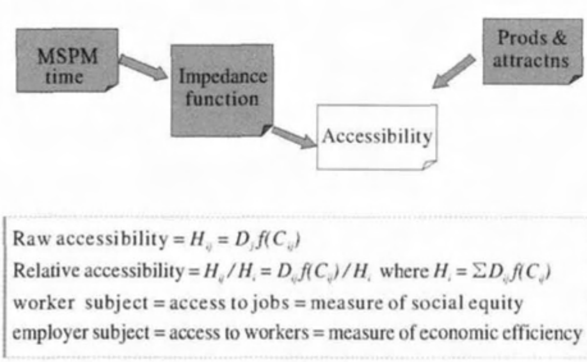

Fig. 12 Relative and raw accessibility measures

The raw accessibility measure is a useful measure for comparing trends across travel zone pairs with different origins. The term is an absolute value. Relative accessibility on the other hand is a relative ratio of accessibility opportunity that represents the proportion of accessibility offered by the destination TZ for the origin TZ compared to the total accessibility available to

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the origin TZ.

Figure 12 also shows the inputs used in the calculation of accessibility. These inputs are derived from the building block methods that underpin the methodology for this case.

These operational measures are detailed through simple examples considering the accessibility of workers to jobs. With workers as the subject of the operational accessibility measure, assessment is able to be made for social equity amongst workers.

Figure 13 illustrates the principles with a simple four-zone system, three employment zones, and one worker residential zone. Each employment zone has an assumed number of jobs "E" matching the competencies offered by the workers "W" at the residential zone. For the workforce to reach jobs "E" at each employment zone, a trip is required by the workforce which has an assumed transport impedance as "C_{1j}" which relates specifically to the transport characteristics between the residential zone and the respective employment zone.

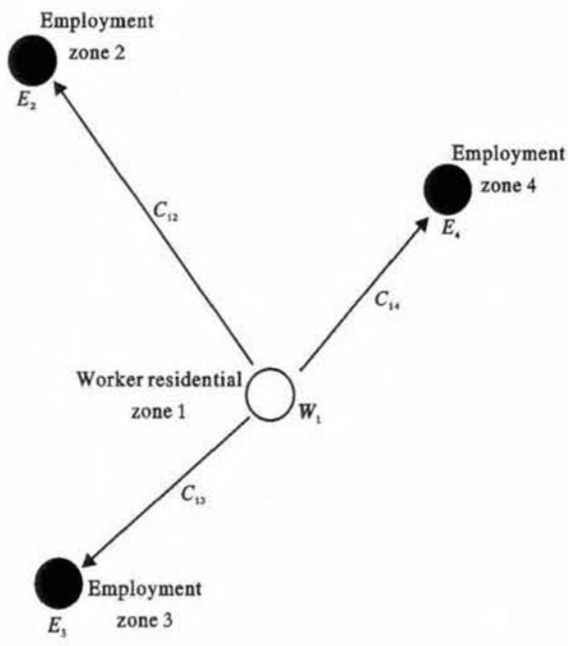

Fig. 13 Inputs to worker accessibility to jobs

The total accessibility of worker residential zone 1 to jobs in this simple system is simply the sum of the "raw" accessibility components. Each of these "raw" values are the ratio "E/C_{ij}" in Fig. 14, or "$D_j \times fn(C_{ij})$".

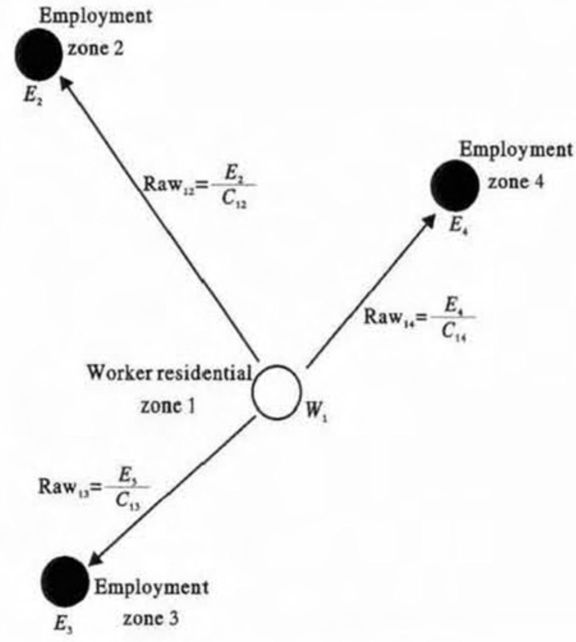

Fig. 14 "Raw" accessibility components

Figure 15 shows the formulation of the relative accessibility measure used. This measure is a simple ratio of the "raw" accessibility component to the total accessibility of worker residential zone 1 to jobs in the system, calculated as shown in this figure.

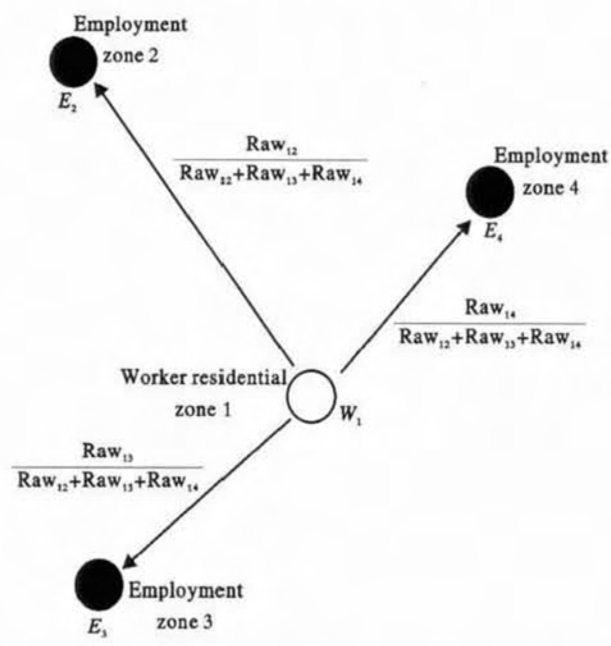

Fig. 15 Formulation of relative accessibility measure

It is constructive to illustrate these principles further with a simple example. Taking the four-zone system of Fig. 13 and assigning a hypothetical number of jobs and travel impedance values to the system, the me-

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chanics of these principles can be illustrated. Tabs. 4, 5 and Fig. 16 show a four-zone system example with the corresponding "raw" accessibility values derived from the number of jobs available from each employment zone and the travel time between the worker residential zone and each employment zone shown in Fig. 17.

Tab. 4 Shortest path time matrix

O/D SPMA (minutes)	Zone 2	Zone 3	Zone 4
Zone 1	40	20	30

Tab. 5 Employment matrix

Jobs in destination zone	Zone 2	Zone 3	Zone 4
	600	200	1500

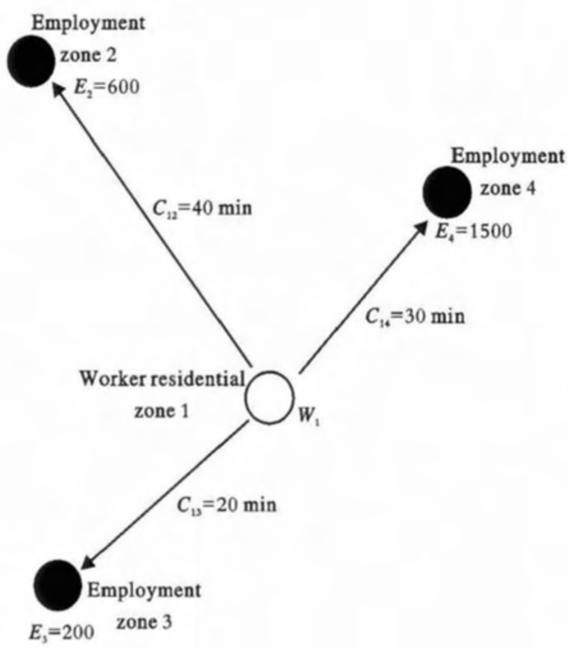

Fig. 16 A simple four-zone example

The overall accessibility to workers for the worker residential zone 1 is shown in Tab. 6, calculated as the sum of the "raw" accessibility from zone 1 to each other zone:

Tab. 6 "Raw" accessibility sum

O/D raw accessibility	Zone 2	Zone 3	Zone 4	Sum
Zone 1	15	10	50	75

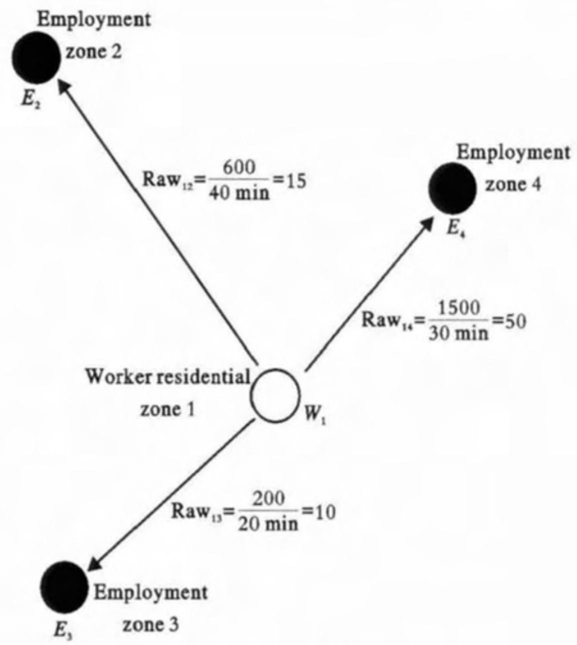

Fig. 17 "Raw" accessibility

$$\text{Accessibility to jobs from zone 1} = Raw_{12} + Raw_{13} + Raw_{14}$$

Figure 18 and Tab. 7 show the relative accessibility for each worker residential zone-employment zone pair. The zone 1, zone 4 pair provides the employment at zone 1 with the largest proportion of accessibility to jobs, 67% of the overall accessibility.

Because there are no other worker residential zones in this example all of these jobs are potentially available to workers from zone 1.

Tab. 7 "Relative" accessibility sum

O/D relative accessibility	Zone 2	Zone 3	Zone 4	Sum
Zone 1	20%	13%	67%	100%

The relative accessibility measure in this context is a measure of the opportunity to work, available to workers at this location. Where the spread of relative accessibility is small and a high frequency of like relative accessibilities to jobs exists, it stands that the worker is in a position to have more choices in job opportunities.

It is useful to use the simple four-zone example above to demonstrate how the measure of environmental sustainability is derived and with the corresponding relative accessibility measure, how it gives

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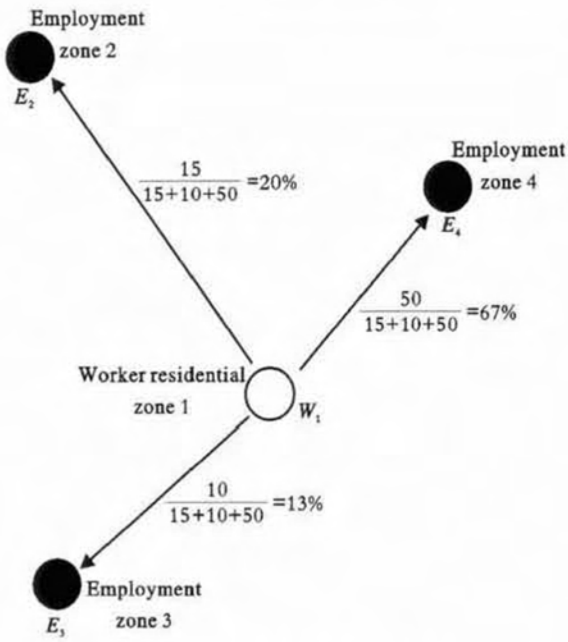

Fig. 18 "Relative" accessibility

a metric point in the "environmental sustainability-accessibility space". The environmental sustainability measure adopted is the inverse urban CO_2-e measure. The unit is (grams of CO_2)$^{-1}$. Fig. 19 shows the CO_2-e calculation principle for the four-zone example.

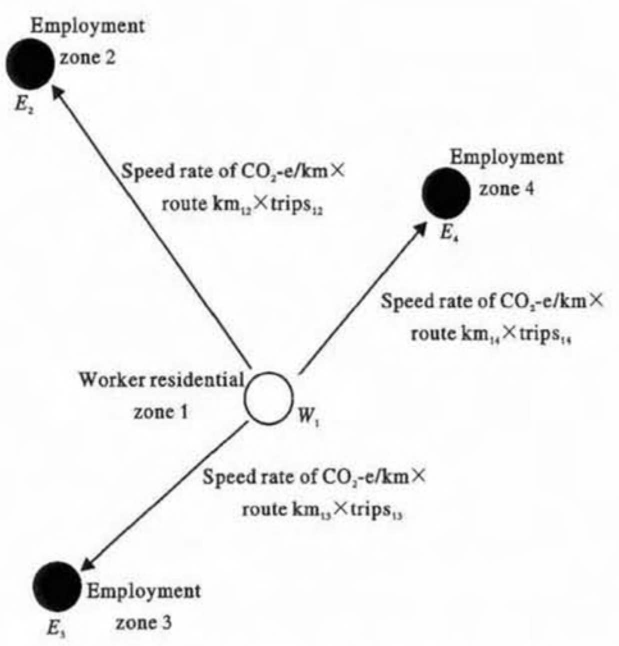

Fig. 19 Principle of CO_2-e calculation which is inversed to form the environmental sustainability measure

Trips between the worker residential zone 1 and each of the other zones were calculated assuming 2000 workers needing jobs and shares that might be expected to give the relative accessibilities. Tab. 8 shows the assumed origin-destination (OD) matrix.

Tab. 8 Trip matrix assumed in simple four-zone example

O/D (trips)	Zone 2	Zone 3	Zone 4
Zone 1	500	200	1300

The speed rate of CO_2-e is derived from Tab. 3 discussed earlier. The corresponding speed rate of CO_2-e at 40 km/h average speed is 221 grams of CO_2-e and at 45 km/h average speed is 215 grams of CO_2-e. The speed for each zonal pair is calculated by dividing the shortest path distance shown in Tabs. 9, 10 by the shortest path travel time between each zone from Fig. 16.

Tab. 9 Shortest distance matrix

O/D SPMA (km)	Zone 2	Zone 3	Zone 4
Zone 1	30	15	20

Tab. 10 Average speed matrix

O/D Ave speed (km/h)	Zone 2	Zone 3	Zone 4
	30/40 ×60 =45	15/20 ×60 =45	20/30 ×60 =40

Figure 20 shows the CO_2-e calculation results for the four-zone example.

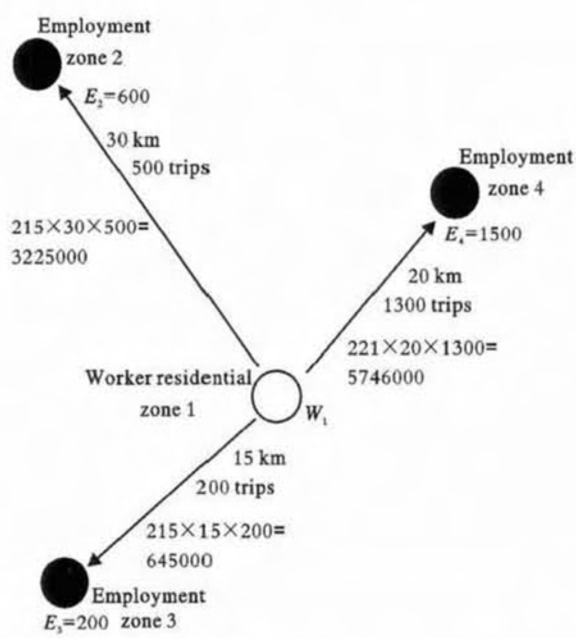

Fig. 20 CO_2-e calculations in four-zone example

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The environmental sustainability measure is calculated by inverting the CO_2-e for each zone pair as shown in the four-zone example in Tab. 11.

Tab. 11 Environmental sustainability measure calculated in the simple four-zone example

O/D ($1/CO_2$-e)	Zone 2	Zone 3	Zone 4
Zone 1	1/3225000 = 3.0E −7	1/645000 = 1.6E −6	1/5746000 = 1.7E −7

These environmental sustainability measures are plotted with the corresponding relative accessibility measures to produce the visualisation for the simple four-zone example in Fig. 21.

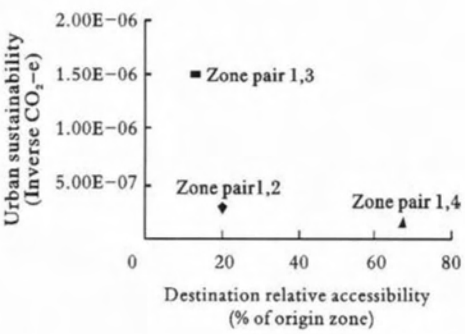

Fig. 21 Environmental sustainability-accessibility space visualisation for simple four-zone example

6 Conclusions

This paper has discussed the concept of strategic scans to provide quick turnaround analysis to underpin the assessment of the sustainability performance of scenario options. The methodology is an important direction in providing tools for city planning with the unfolding impacts of climate change and other sustainability pressures. A novel approach to evidence based sustainability metrics as part of the strategic scanning was discussed. Some examples of metrics developed from a case study in Sydney demonstrate the potential of simple visualisations input to option selection as part of the backcasting process.

This paper has elaborated the operational aspects of creating these metrics to provide incite for other researchers and planning agencies on the minimum level of data needed and some key algorithms for the metrics.

For the strategic scan approach to provide a contribution to supporting the backcasting process, a database of metrics applied to multiple cities is needed. This will enable a typology of sustainability performance over time to guide decision makers on suitable trend breaking urban form and transport network structures tailored to each city.

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