ROUTE STRUCTURE ANALYSIS

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0. ABSTRACT

This paper presents a new method of characterising kinds of network and route type, based on the analysis of route structure. This Route Structure Analysis (RSA) offers an alternative to existing methods for representing and analysing street networks. The method is essentially a form of 'structural analysis' rather than 'flow analysis'. Therefore, while the method offers a means of 'modelling' the structure of a street network, in terms of its description, this paper does not address the modelling nor prediction of network movements. However, this kind of 'structural analysis' could have applications to other kinds of network or structure.

1. INTRODUCTION

1.1 Background

Current debates about sustainable mobility and urban design often focus concern on the structure of street layouts, based on desired kinds of street type – such as 'connector streets' (Calthorpe 1993) and desired kinds of network type – such as grid networks (see for example Murrain, 1993; Katz, 1994; Ryan and McNally, 1995; Berman, 1996; Morris and Kaufman, 1998; Boarnet and Crane, 2001; Hebbert, 2003).

Urban designers and planners often call for more 'connective' networks, such as grid patterns, rather than networks based on 'loops and culs-de-sac' or tributary configurations. Whichever kinds of pattern are advocated, there is not necessarily clear or consistent means of describing network structure that can capture key properties such as connectivity, that might be tested in terms of their performance or travel behaviour. For example, some kinds of layout may be associated with more or less 'sustainable' travel patterns. To establish this, it is first necessary to be able to describe those patterns consistently and succinctly.

Pattern and structure can be complex entities that are not as easily describable as other properties typically used in transport/planning analysis – which are often simple metric quantities (e.g. length of road) or ratios (e.g. vehicles per hour, cost per square metre). Typically, network structure or pattern is described in terms of either simple polarities (e.g. grid-like versus tree-like); perhaps assessed somewhat subjectively by visual inspection or judgement (for example, Ewing, 1996; Crane and Crepeau, 1998), or based on proxy measures such as proportion of 4-way intersections (see for example Handy, 1992; Cervero, 1996;

Southworth 1997), which can give some indication of connectivity but do not capture fully the structure of those networks (Stead and Marshall, 2001).

Accordingly, a new method has been devised which may be used to represent and analyse networks in terms of their route structure, which allows the identification of a series of structural properties, and the identification of both network type and route type according to those structural properties. This paper introduces this method of 'route structure analysis' (RSA) which offers an alternative to existing methods for representing and analysing street network structure.

1.2 Overview

This paper firstly briefly discusses two existing types of representation and analysis applied to street networks – conventional transport network analysis and space syntax (Section 2). Section 3 then demonstrates how a street network may be represented as a 'route structure', and how it is then possible to recognise certain properties of routes – such as connectivity and continuity – which may form the basis of quantitative analysis.

Having established the basic working of route structure analysis (RSA), the paper goes on to demonstrate how route structures and route structural properties may be used to characterise and classify different types of route and network, using a combination of quantification and graphical presentation.

Section 4 demonstrates the application of RSA to identify different types of route, based on their role in the network configuration. This allows, for example, the identification of different kinds of 'collector' or 'connector' routes. Section 5 demonstrates the application of RSA to identify different type of network, based on their structure of routes. This allows identification of a spectrum from 'more griddy' to 'more tributary' layouts.

The paper concludes by summarising the main features of the method and its application. This paper cannot cover all the details of this method or its application, but gives sufficient amount to demonstrate the basic workings, which could allow immediate application in practice.

2. NETWORK REPRESENTATION AND ANALYSIS

2.1 Introduction

This section gives a brief overview of two existing methods of network representation and analysis. Space does not permit a full critique or comparative analysis, but the discussion serves to indicate briefly why and to what extent route structural analysis provides an alternative to those methods.

Both methods may be related to graph theory. Lowe and Moryadas describe graph theory as a branch of combinatorial topology which offers "a powerful, versatile language which allows us to disentangle the basic structure of transportation networks" (1975:79). Transport networks have traditionally been examined in terms of a 'skeletal' structure, or a 'graph' comprising nodes and links (Lowe and Moryadas, 1975:81). Basically, this means that the structure under analysis is the topological configuration of nodes and links. As well as application to transport, graph theory has had a wide application in many fields, including medicine, linguistics, anthropology, sociology, building design and management, and spatial information systems (Haggett and Chorley, 1969:7; Laurini and Thompson, 1992).

2.2 Conventional transport network analysis

Conventional transport network analysis applies a direct correspondence between the links – the linear elements that movement takes places along – with the edges of a graph, and the junctions or nodes with the vertices of the graph (Kansky, 1963). This relationship is simple and intuitively obvious. In discussions of network modelling or analysis, it is typically taken as given, without requiring any comment.

However, while this convention is useful for analysing networks where the differential status of nodes is significant, as the principal subject of analysis, it is not necessarily the best way of trying to establish differential status of lines of movement, especially for representing road and street networks. This is because in road and street networks, routes have a significant degree of continuity through junctions (nodes). Due to the differential degree of continuity through junctions – with a variety of through and side roads, longer and shorter roads – it is possible to identify a 'hierarchy' or 'typology' of different route types in any network. This sense of the differential status of routes does not feature in conventional analysis, where there are no routes as such, only links. Links only run from one node to the next, so the route nature is lost (i.e. not represented directly in the graph). If route status is to be represented, it has to be separately 'attached' or 'encoded' into the links (Marshall, 2004, forthcoming).

This suggests the value of considering alternative methods of representation and analysis that put continuous lines of movement as the principal focus of concern.

2.3 Space syntax

Space syntax is a method of spatial analysis developed by Bill Hillier and colleagues at the Bartlett School of Graduate Studies, University College London (Hillier and Hanson, 1994; Hillier, 1996). Space syntax considers street layout in terms of segments of space represented by 'axial lines', which may then be analysed in terms of properties such as 'integration'. Using the property of 'integration', space syntax has been employed to predict the intensity of pedestrian activity and vehicular flows (Hillier *et al.*, 1993; Penn *et al.*, 1998; for further comment see also Jiang *et al.*, 1999).

Methodologically speaking, space syntax is useful in focusing attention on axial lines, which correspond more or less to lines of movement. Since these axial lines continue through junctions, their connectivity may be related to their length or continuity through space. This allows differentiation of lines of different status.

In effect, space syntax is useful for analysing 'convex spaces' and street networks where paths of movement are significantly defined by buildings – such as in traditional street-grids – in other words, where axial lines of site fit closely with actual lines of movement.

However, this would appear not to be the only way of analysing road or street network structures – especially in modern open plan layouts – where movement is more related to actual road alignments, and the continuity of routes through junctions, irrespective of those routes' sightlines, 'bendiness' or relationships with buildings. This suggests the possibility of exploring alternative methods.

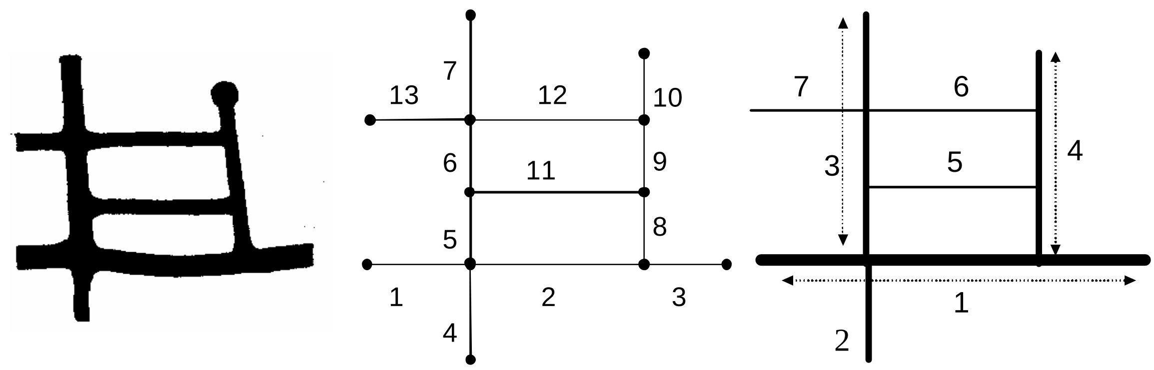
3. ROUTE STRUCTURE ANALYSIS

3.1 Introduction

This section sets out some definitions and conventions for route structures (3.1), and how these may be used to interpret and represent street networks (3.2), and then defines three basic route structural properties (3.3) and demonstrates their application to example networks (3.4).

3.1 The formation of routes from links

We can start by defining the basic element of route structure – the route – in terms of the basic linear element of conventional transport network analysis, the link. In this context, a ***route*** may be considered as a linear aggregation of links. For example, Figure 1 shows a street layout (a) represented conventionally as a graph comprising 13 links (b), which is subsequently converted into a ***route structure*** comprising 7 routes, (c).



(a) Road layout plan (b) Conventional network graph (13 links, 12 nodes) (c) Route structure (7 routes, 6 joints)

Figure 1. Layout plan, network graph and route structure.

The points at which links are joined together to form routes are referred to as **joints**. A basic convention defining the relationship between routes and joints is given in Box 1.

Box 1. Conventions for routes and joints
1. A route comprises a link or a linear aggregation of conjoined links. (Linear aggregation means a series of links joined serially, end-on.) 2. A joint is a node with one and only one conjoined route passing through it. (A joint has a minimum of two links and one route.)

By the convention of Box 1, links are aggregated into routes in such a way that each joint has a **through route** through it. Since at each joint two links will be joined to from a through route, the number of routes will be less than the number of links. Indeed, by this convention, the number of links will exceed the number of routes according the number of joints present, since at each joint two links are joined to form a single through route. Put another way, each joint present *reduces by one* the number of routes relative to the number of links. This gives us a first and fundamental equation for relating routes, links and joints:

$$R = L - J \qquad \text{[Equation 1]}$$

where R = no. of routes; L = no. of links; J = no. of joints.

For example, in Figure 1 earlier, there are 13 links and 6 nodes where links meet, which may be equated with joints. Hence from Equation 1 we obtain 7 routes.

A notation convention is given in Box 2.

Box 2. Notation convention

For Route Structure Analysis, the following notation convention is used:

- Upper case letters are used to indicate properties of whole networks.
- Lower case letters are used to denote properties of elemental parts of networks, such as routes, nodes or joints.
- Roman letters are used to denote basic elemental properties which can be more or less directly read from the route structure diagram, or simple sums or differences of these. These are therefore integer values.
- Greek letters are used to denote derived properties such as ratios, which imply computation of fractions. Such properties might be conveniently expressed as vulgar fractions as well as decimals.

For example:
The number of links in a route is l;
The number in a whole network is $L = \Sigma l$;
The relative continuity of a route is λ;
The relative continuity of a network is $\Lambda = \Sigma\lambda$.

3.2 Interpretation of patterns of aggregation

The way in which links are aggregated into routes will affect the 'structural performance' of the network. For a given network topology, and the convention set of Box 1, we will have a given number of routes. For example, given the graph in Figure 1 (b), we know (from Equation 1) that there will be seven routes formed. The layout suggested in Figure 1 (c) is just one possible route structural interpretation of the original layout. There will be a multitude of possible route structural configurations, each representing a different permutation of aggregation of links into routes. In the layout in Figure 1, there will be almost 3000 permutations. This is calculated as the product of all possible permutations at each joint (6x6x3x3x3x3 = 2916; equation in Marshall, 2003, 2004 forthcoming).

The question arises as to which of all these possible patterns of aggregation is chosen to represent the given network. The answer is that there can be no single 'correct' pattern of aggregation. The most appropriate route structure – or pattern of aggregation of links to form routes – will not be completely determined from the intrinsic network topology. In other words, there is not an automatic correspondence between a given base plan – or network graph – and the set of routes formed from it.

This is no different from the degree of indeterminacy in selecting which links are included in the network in the first place: which parts of a street plan are recognised as the object of analysis, and where the boundaries of the network are drawn (Marshall, 2004 forthcoming). This situation applies whether one is choosing which links to represent in a conventional transport network diagram, or converting a base plan to an axial diagram for analysis using space syntax. As with these other methods, the specification of elements for analysis properly relies on some degree of contextual interpretation. In each case, a judgement is necessary to allow significant characteristics of the actual site context to be taken into account, for the particular purposes of the analysis. The actual quantitative analysis is of course comparing the properties of abstract structures, not actual ground plans. How well the modelled structures match the ground plans will depend both on the site context and the context of application (i.e., intended use).

With route structure analysis, then, the way routes are specified will reflect judgement based on what the abstract route structure is trying to represent in terms of the physical characteristics and movement patterns on the ground. In Route Structure Analysis, the aggregation of links into routes is supposed to represent the most continuous paths of movement through a junction, which reflects a structure of more major and more minor routes.

Some suggestions and conventions for determining appropriate patterns of aggregation that would give rise to typical, recognisable representations of road layout structure are given in Box 3.

Contextual interpretation is used to choose whether, for example, to use links 8+9+10 (Figure 1 b) to form route 4 (Figure 1 c) or alternatively to form a route from links 8+9+12; leaving link 10 as a separate route – or leaving it out altogether.

Box 3. Contextual guidance for route formation

1. Where there is a designated route classification known, this classification can be used to form routes. Hence, at any junction, a single though route may be selected from two links with the same route designation (eg, ‘A’ road number).

2. Where the route structure is not resolved by (1), then actual junction priority may be used, where known. That is, at any junction where a single through route has priority, that route is allocated as ‘the’ through route.

3. Where the route structure is not resolved by (1) or (2), then continuity of physical alignment may be used to select the through route. (This mirrors space syntax practice.) This tactic may be useful where working (only) from a plan rather than site experience.

4. Other possible means of determining the through route would be continuity of street name, or designation according to which route was constructed first, historically. These imply more detailed site knowledge. (The through route could also be determined from traffic flow patterns; however, this implies more detailed data, that would fluctuate over time.)

Further discussion on the representation of networks, and the significance of routes relative to classification of routes within the national network is given in Marshall (2004, forthcoming).

Having arrived at a system for deriving a route-based interpretation of a network, it is now possible to consider the structural properties of different routes. Some conventions for specifying these properties set out next.

3.3 Route structure properties

Route Structure Analysis makes use of three key route properties which are described in this section: continuity, connectivity and depth. These basic route properties are subsequently used as a basis for constructing other properties of both routes and networks (Sections 4 and 5 respectively).

Continuity is taken as the number of links that a route is made up of, or the length of a route measured in links (l). The label ‘continuity’ reflects how many junctions a route is continuous through.

Connectivity is taken as the number of routes with which a given route connects (c). Connectivity reflects both the number and ‘nodality’ of joints along a route.

Each route has two terminating ends: the convention here is that any and all routes interfacing at those points are included in the connectivity count – therefore a route terminating at a crossroads is deemed to be connective with both of the other routes joining at that point. Where two routes meet at more than one point along their lengths – or where a route terminates on itself – connectivity is counted on each occasion. These conventions are compatible with and support Equation 1.

Figure 2 demonstrates the distinction between continuity and connectivity. Route 1.3 is said to be more *continuous* than route 1.2.1 – even though the former ends in a cul-de-sac – since it consists of three links, continuing through two junctions (i.e., l=3). Route 1.3 is also more *connective* than route 1.2.1 because the former connects with three routes in total (c=3), while the latter connects only to two (c=2). Meanwhile, Route 1.2 is the most connective route (c=5).

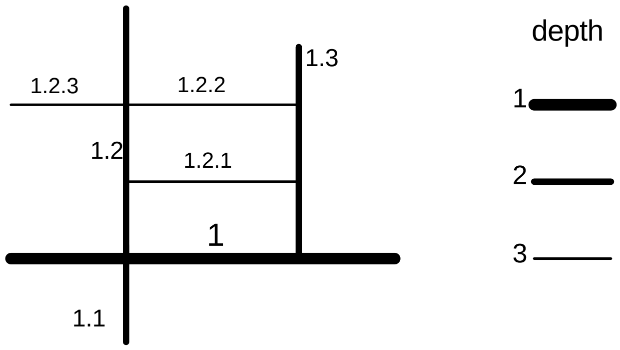


Figure 2. Example illustrating continuity, connectivity and depth of routes.

Depth is a property which measures how distant a route is from a particular ‘datum’, measured in number of steps of adjacency (d). The more steps distant a route is from the datum, the ‘deeper’ it is; the fewer steps distant, the ‘shallower’. Routes may be numerically labelled according to their branching. Hence, the route labelled ‘3’ in Figure 1(c) becomes route ‘1.2’ in Figure 2; and route ‘5’ becomes ‘1.2.1’. In this way, length of the label reflects the depth of the route.

The convention used here will be that the datum route will have a depth of 1, and routes connecting directly to the datum will have a depth of 2, and so on. The convention adopted here is to measure depth from a single datum route, selected by allocation, intended to represent a strategic connection to outside the network, such as a national route passing through the network.

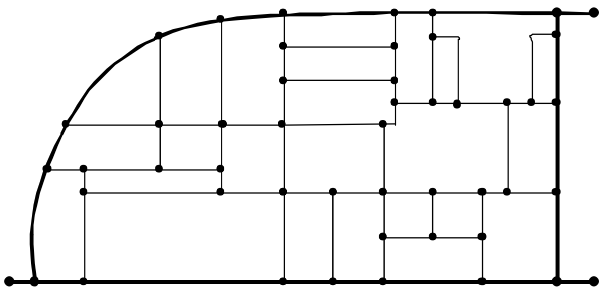
The position of the datum will affect the pattern of depth of routes in a network. As before, contextual discretion must be relied upon to enable an appropriate datum to be selected. The determination of depth is no more or less arbitrary than the selection of network to be analysed in the first place – given that most urban networks are selective sub-networks of national or continental networks. The selection of the datum is no more or less arbitrary than the roads authority’s selection of which links form a ‘national route’ in the first place.

If continuity represents the internal connecting-up of links to form a single route, and connectivity represents the immediate direct external connections to a route, then depth reflects a route’s connective position relative to the widest possible network context. The properties of continuity, connectivity and depth will now be used to quantify properties of networks represented as route structures.

3.4 Illustration of the basic route-structural properties

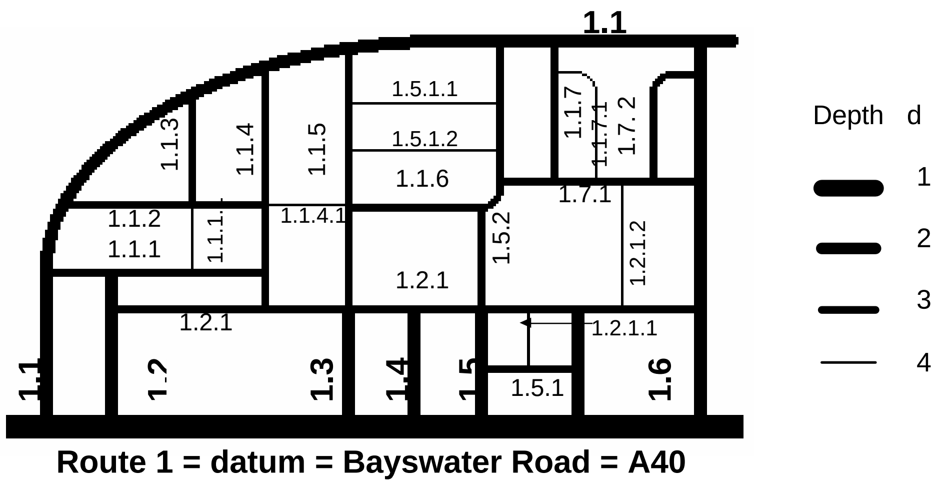
A demonstration of the calculation of route-structural properties is now made, by application to an actual street network. The example chosen is Bayswater, a nineteenth century suburb of inner London, equating with a 'traditional' urban layout, a kind of irregular grid.

The Bayswater network is shown first as a conventional network 'graph' of nodes and links (Figure 3 a). In total there are 73 links and 49 nodes. Of the 49 nodes, 46 are junctions proper – represented as joints – while the remaining 3 nodes represent external connections. From Equation 1, the number of routes formed by any permutation of aggregation will be R = 73 – 46 = 27.



73 Links, 49 Nodes, 46 Junctions

(a) Graph representation (links and nodes)



27 Routes, 46 Joints; maximum depth 4

(b) Route structure representation

Figure 3. Representations of the Bayswater network.

Figure 3(b) then shows a corresponding route structure. The chosen pattern of aggregation was based on actual junction priority. The bottom route (which is the A40, Bayswater Road) is taken as the 'datum' (labelled route 1; depth 1). The depth of all other routes is measured from this datum route. The values of continuity, connectivity and depth are given in Table 1.

Table 1. Bayswater network: continuity, connectivity and depth

Route	Continuity[(a)] (l)	Connectivity (c)	Depth (d)	Route Type[(b)]
1	8	7	1	a
1.1	9	9	2	b
1.2	2	3	2	c
1.3	1	3	2	d
1.4	1	2	2	e
1.5	2	4	2	f
1.6	2	3	2	c
1.7	4	5	2	g
1.1.1	3	4	3	h
1.1.2	2	5	3	i
1.1.3	1	3	3	j
1.1.4	3	5	3	k
1.1.5	4	7	3	l
1.1.6	5	7	3	m
1.1.7	2	3	3	n
1.2.1	8	11	3	o
1.5.1	2	3	3	n
1.5.2	1	3	3	j
1.7.1	5	6	3	p
1.7.2	1	2	3	q
1.1.1.1	1	3	4	r
1.1.4.1	1	4	4	s
1.1.5.1	1	2	4	t
1.1.5.2	1	2	4	t
1.1.7.1	1	2	4	t
1.2.1.1	1	2	4	t
1.2.1.2	1	2	4	t
Network total	**73**	**112**	**79**	**20** types

Notes
(a) The sum of continuities equals the number of links (73).
(b) This identifies routes by their specific combination of continuity, connectivity and depth (Section 4). This network has 20 such route types (a-t).

This analysis tells us something about the character of the different routes in the network. We can see a general distribution of a small number of long, connective routes and a larger number of shorter routes. Note that the deepest routes are short: all routes at depth 4 are one link long. Yet even short, deep routes can be *relatively* connective (e.g., Route 1.1.4.1); while routes adjoining the datum – having low absolute depth – can be *relatively* deep (e.g., Route 1.4).

The identification of route type is addressed next, in Section 4. The route structure analysis also tell us something about the character of the network as a whole. The identification of network type will be addressed in Section 5.

4. APPLICATION TO ROUTE TYPE

4.1 Introduction

A route type may be defined by the structural role that it plays in the network (route structure). The final column in Table 1 shows that there are 20 unique combinations of continuity, connectivity and depth in the Bayswater network, that may be equated with 20 distinct types of route. At present these are simply expressed as numerical combinations. But we can gain a better impression of the meaning of these types by means of a graphical presentation, that can depict the continuum of possible route types, in such a way that route types that are structurally alike will appear close together, while those less alike will appear further apart. In this way we should be able to distinguish systematically the degree to which one route type is more or less like a 'spine route' or a 'connector route'.

This section defines some new *derivative* route-structural parameters, that is, derived from the initial basic properties of continuity, connectivity and depth; and demonstrates their plotting on a 'routegram' that allows different types of route to be identified.

4.2 Relative continuity, connectivity and depth

This analysis is based on the *relative* values of continuity, connectivity and depth, for each route in a network. We can generate values of relative continuity (λ), relative connectivity (χ) and relative depth (δ) for a route, by dividing each of the absolute values (l, c, d) by their sum value (s):

Relative continuity	$\lambda = l/s$	[Eq. 2.1]
Relative connectivity	$\chi = c/s$	[Eq. 2.2]
Relative depth	$\delta = d/s$	[Eq. 2.3]
Where 's' is the sum value	$s = l + c + d$	[Eq. 2.4]
Hence the relative values sum to one:	$\lambda + \chi + \delta = 1$	[Eq. 2.5]

As an example, in the Bayswater network discussed previously, we see that for Bayswater Road (route 1), the continuity (l) is 8, the connectivity (c) is 7 and the depth (d) is 1. The sum of the values of continuity, connectivity and depth (s) is 16. The values of relative continuity (λ), relative connectivity (χ) and relative depth (δ) are respectively 0.5, 0.44 and 0.06. These last three values sum to one.

This set of relative values indicates that, relatively speaking, Bayswater Road is relatively continuous (continuous through several junctions) and also relatively connective, though slightly less so. Relatively speaking it is not 'deep'. This set of characteristics is in accord with a road that is a major through road with several side roads.

4.3 The Routegram

Having obtained this set of relative values, these can be plotted on a triangular diagram, to demonstrate the relative character of a network. This diagram can be called the *routegram*: each plotted point on the routegram represents a route (Figure 4).

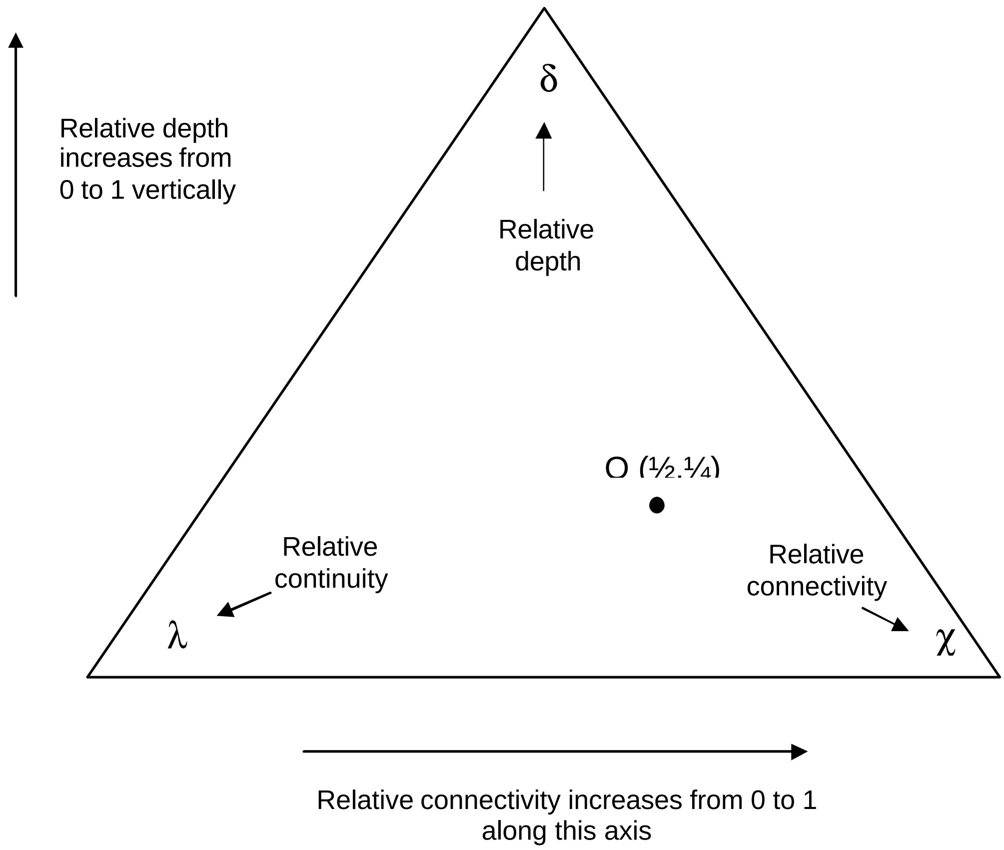


Figure 4. The Routegram. Each plotted point on the routegram represents a route, whose position is specified by its combination of relative continuity (λ), relative connectivity (χ) and relative depth (δ). For any position on the routegram, $\lambda + \chi + \delta = 1$. Positions can be specified by two co-ordinates (χ, δ). For example, the point Q is (χ=½, δ=¼).

The notational convention suggested here is that when three co-ordinate values appear together they are represented thus: (λ, χ, δ). However, for brevity – and since only two values are needed to uniquely specify a point – a two-figure convention or co-ordinate system is used, thus: (χ, δ). Since the properties λ, χ and δ are rational numbers, they may conveniently be represented using vulgar fractions; for example, the point Q is (χ=½, δ=¼).

A conventional Cartesian plot effectively represents a smooth 'level playing field' of possibility, with a fine continuum of positions represented by real numbers. For the routegram, however, some positions are more likely than others to correspond to actual route types. These positions may be conveniently located in relation to certain key reference lines, that equate with simple ratios (Figure 5). It is possible and convenient to depict the routegram showing only these reference lines, rather than labelling the boundary axes or filling the plot area with parallel 'grid lines' based on decimals (e.g. steps of 0.1).

Each reference line on the routegram is a line of some constant value (e.g., j=1) or relationship (e.g. $\lambda=\chi$). A reference line passes through a series of positions each representing routes in a network. In routegram analysis, the use of the term 'reference line' (rather than 'line' or 'grid line') allows a clear distinction to be made between routes and reference lines, both of which have 'ends' and intermediate 'intersections', or may be associated with 'grid patterns'.

The position of Bayswater Road on the routegram is shown in Figure 5, lying on the reference line $\lambda = {}^{1}/_{2}$. Its position is (0.5, 0.44, 0.06) or more simply (${}^{7}/_{16}$, ${}^{1}/_{16}$).

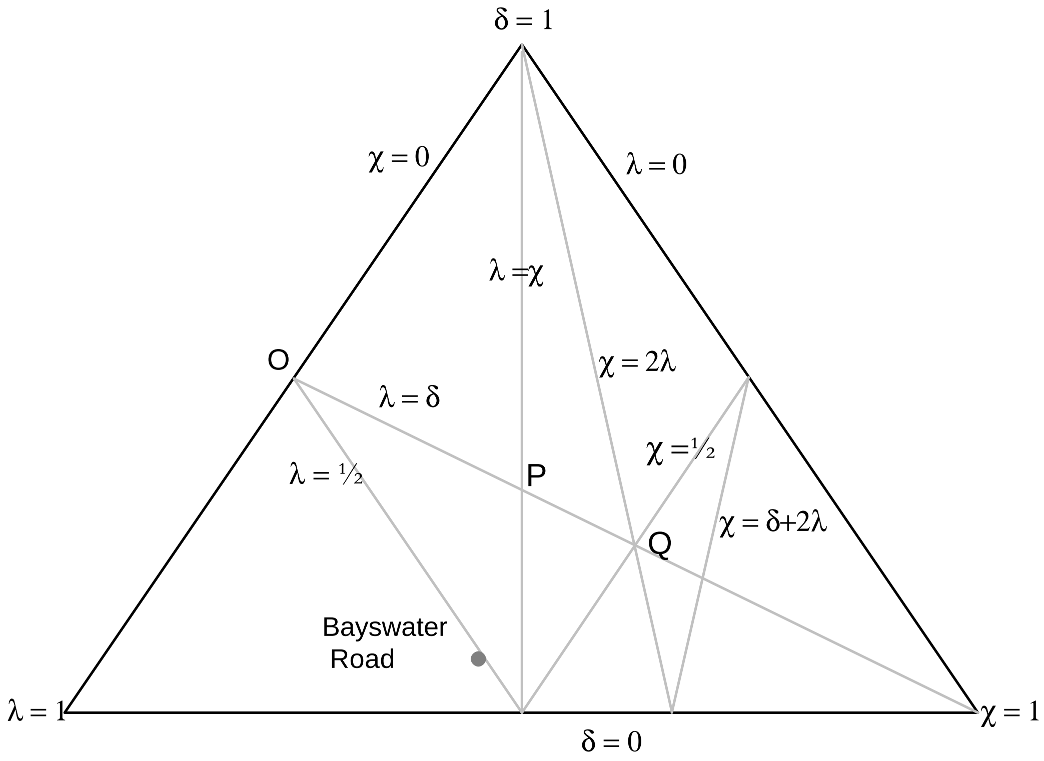


Figure 5. The Routegram, showing position of Bayswater Road. Plotted positions may usefully be oriented with respect to key reference lines, shown here by fine grey lines. Those shown here are selected to be of use in orienting theoretical combinations of λ, χ and δ typical for road networks. For example the position of Bayswater Road is (${}^{7}/_{16}$,${}^{1}/_{16}$), located on the key reference line $\lambda={}^{1}/_{2}$. This position demonstrates that Bayswater Road has relatively high continuity and connectivity, and low depth.

The routegram may be used to compare the structural character or role of different routes in a network, or different routes across networks, or compare the complete set of routes in a network with those in another network.

4.4 The routegram for a whole network

The procedure carried out for Bayswater Road (Figure 5) can be carried out for all 27 routes in the Bayswater network. We can then plot the positions for all of the different types of route in the network on a routegram, to show the overall distribution of routes in the whole network. The distribution of routes for the Bayswater network is shown in Figure 6.

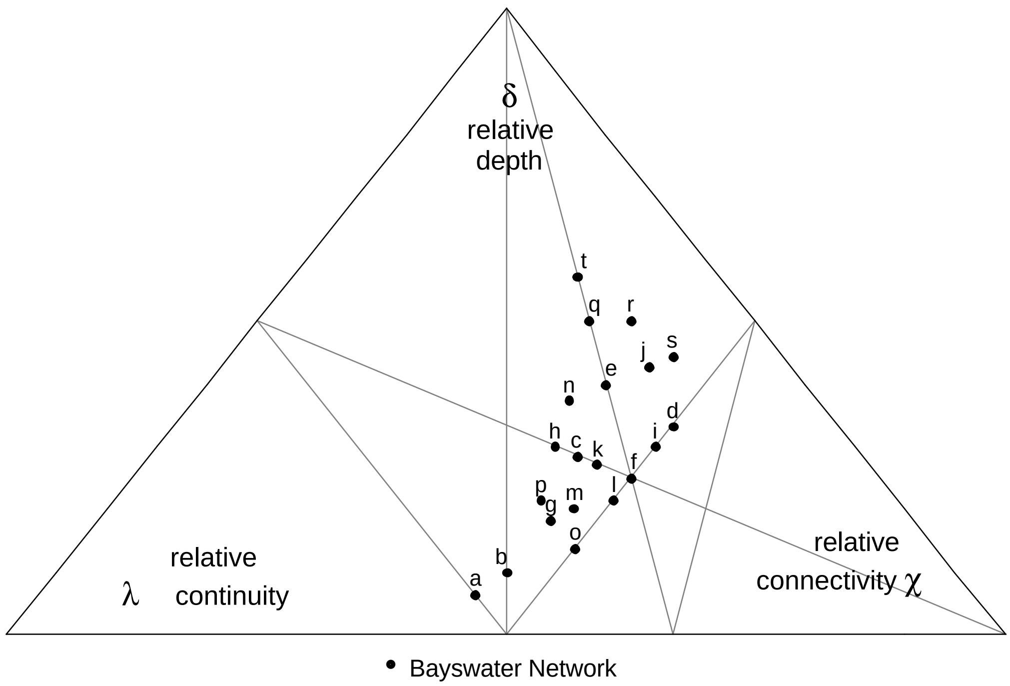


Figure 6. The Routegram for the Bayswater Network. This plots all the route types featuring in Table 1, representing the route structure shown in Figure 3 (b). There are 20 individual route types (labelled 'a' to 't' in Table 1) – representing 20 distinct permutations of l, c and d – hence 20 plotted points on the routegram.

From Figure 6 we can see that type 'a' (corresponding to Bayswater Road, Route 1), is relatively both the most 'continuous' route (ie, highest value of relative continuity), as well as being the least deep route. A series of routes types vie for being the most 'relatively connective', among them is type 'o' (corresponding to Route 1.2.1). In such a way the routegram can be used to map out the different combinations of route type in a given network.

4.5 The routegram as a map of route types

The routegram has been used to demonstrate the complete scatter of routes in a network. Each position on the routegram may be associated to some extent with a kind of route type. We can therefore use the routegram to identify route types based on their structural role in the network, that is, based on the combinations of λ, χ and δ. We can plot out a theoretical solution space of all types of route. From this, we can mark out areas and lines on the routegram that corresponds to different route types. Figure 7 was obtained by generating series of routes of different types – of different continuities, connectivities and depths) and plotting a scatter of resulting positions.

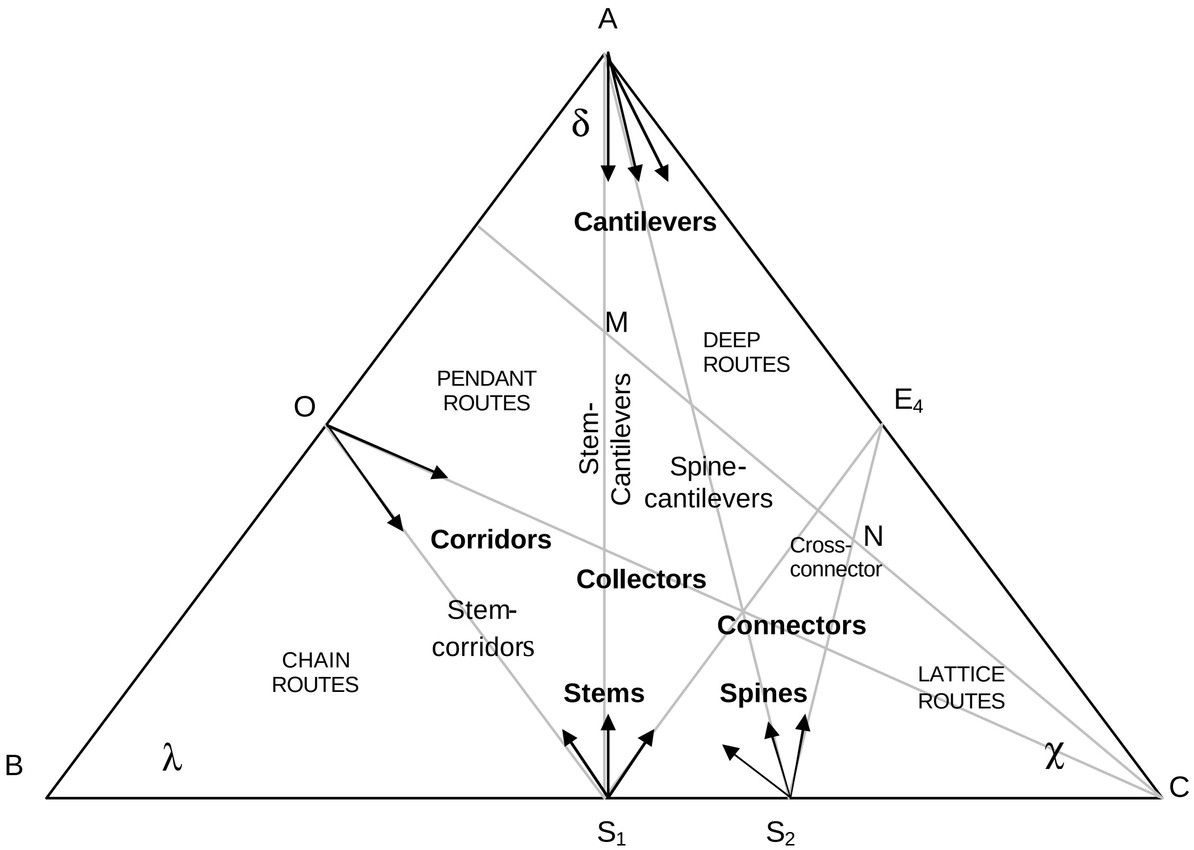
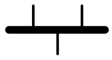
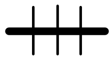
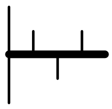
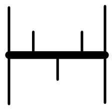
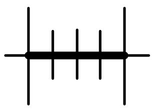
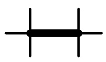


Figure 7. Route types defined on the Routegram. Structural types found commonly as routes in street networks are shown in shown in lower-case. These mostly fall within the bounds of points S_1, M, N, and S_2. The set of stems radiates from point S_1, the set of spines from point S_2. Corridors radiate from point O, cantilevers from point A. These types are tabulated and explained in Table 2. Types shown in upper-case represent regions of the routegram containing types of structural element less commonly found as routes or streets. This diagram gives a necessarily selective impression of the location of types, and care should be taken with further interpretation.

Table 2 explains some possible definitions for different kinds of route defined according to structural role. These refer to several commonly recognisable types, which seem to offer the most useful applications in accounting for route types that are the subject of practical interest. By this system, Bayswater Road – as represented by the route structure in Figure 3(b) – is a stem-corridor.

A fuller analysis and interpretation of types, based on a systematic exploration of the theoretical 'solution space' of the routegram, is given elsewhere (Marshall, 2003, forthcoming; 2004, forthcoming).

Table 2 Suggested route types based on structural role (see Figure 7)

Route Type	Structural description
STEM 	All intermediate junctions are 3-way.
SPINE 	All intermediate junctions are 3-way.
CORRIDOR	Both ends are pendant (usually both are externally connecting).
CANTILEVER 	One end is a 3-way junction; the other end is free. A stem-cantilever is a cantilever with all intermediate junctions 3-way. A spine-cantilever has all intermediate junctions 4-way.
COLLECTOR 	Both terminating junctions are 3-way junctions. A stem-collector is a collector with all intermediate junctions 3-way. A spine-collector has all intermediate junctions 4-way.
CONNECTOR 	Both terminating junctions are 4-way intersections or crossroads. A stem-connector is a connector with all intermediate junctions 4-way. A spine-connector has all intermediate junctions 4-way.
CROSS-CONNECTOR 	A short deep connecting street, which due to its depth and relative discontinuity would have a high value of relative connectivity.

5. APPLICATION TO NETWORK TYPE

5.1 Introduction

This section formalises and demonstrates a series of route-structural parameters derived from the initial route-structural properties of continuity, connectivity and depth, but formulated at the network level. Graphical presentations are used to represent the positions of networks relative to each other, allowing *network types* to be identified.

To do this, we first work out the set of route-structural properties applicable at the network level, and how these may be presented graphically on a triangular diagram, the *netgram*.

5.2 Relative continuity, connectivity and depth

The process that we applied to routes to generate the routegram can be replicated for whole networks to create a 'netgram'. That is, we can generate values of relative continuity, relative connectivity and relative depth for a whole network, based on the total summation of each of those properties over all routes.

First we generate network sum parameters:

Network Sum Continuity	$L = \Sigma l$ (the total no. of links)	[Eq.3.1]
Network Sum Connectivity	$C = \Sigma c$	[Eq.3.2]
Network Sum Depth	$D = \Sigma d$	[Eq.3.3]
Network Sum Value	$S = L + C + D$	[Eq.3.4]

Then we generate network-level values of Relative Continuity (Λ), Relative Connectivity (X) and Relative Depth (Δ), by dividing each of the absolute values (L, C, D) by their sum value (S):

Relative Continuity	$\Lambda = L/S$	[Eq. 4.1]
Relative Connectivity	$X = C/S$	[Eq. 4.2]
Relative Depth	$\Delta = D/S$	[Eq. 4.3]
Hence the relative values sum to one:	$\Lambda + X + \Delta = 1$	[Eq. 4.5]

As an example, in the Bayswater network presented previously, we see that the sum of individual route continuities is 73; the sum of route connectivities (C) is 112 and the sum of route depths (D) is 79 (Table 1). Hence, the sum of these (S) is 264. The values of relative continuity (Λ), relative connectivity (X) and relative depth (Δ) are 0.28, 0.42 and 0.3 respectively. These sum to one.

These values indicate that, relatively speaking, the Bayswater network is 'relatively more connective' than it is 'relatively deep' or 'relatively continuous'. This would confirm our intuition that this grid-like network is relatively 'connective' or 'inter-connected', as networks go.

5.3 The Netgram

Having obtained this set of relative values, these can be plotted on a triangular diagram, to demonstrate the relative character of a network (Figure 8). The triaxial logic of this diagram, which we can call the *netgram*, echoes that of the routegram (Figures 4-7). Just as each plotted point on the routegram represents a route, each point on the netgram represents a network – or more strictly speaking, a network's route structure.

As with the routegram, the notational convention suggested here is that when three co-ordinate values appear together they are represented as (Λ, Χ, Δ); or where a two-figure convention is used, as (Χ, Δ). For actual street networks, Χ and Δ typically provide greater differentiation than Λ. Also, the (horizontal, vertical) orientation of (Χ, Δ) on the netgram echoes the conventional (X, Y) reading of axial values on Cartesian plots. Similarly, the diagonal (Δ=Χ) echoes the Cartesian (Y=X).

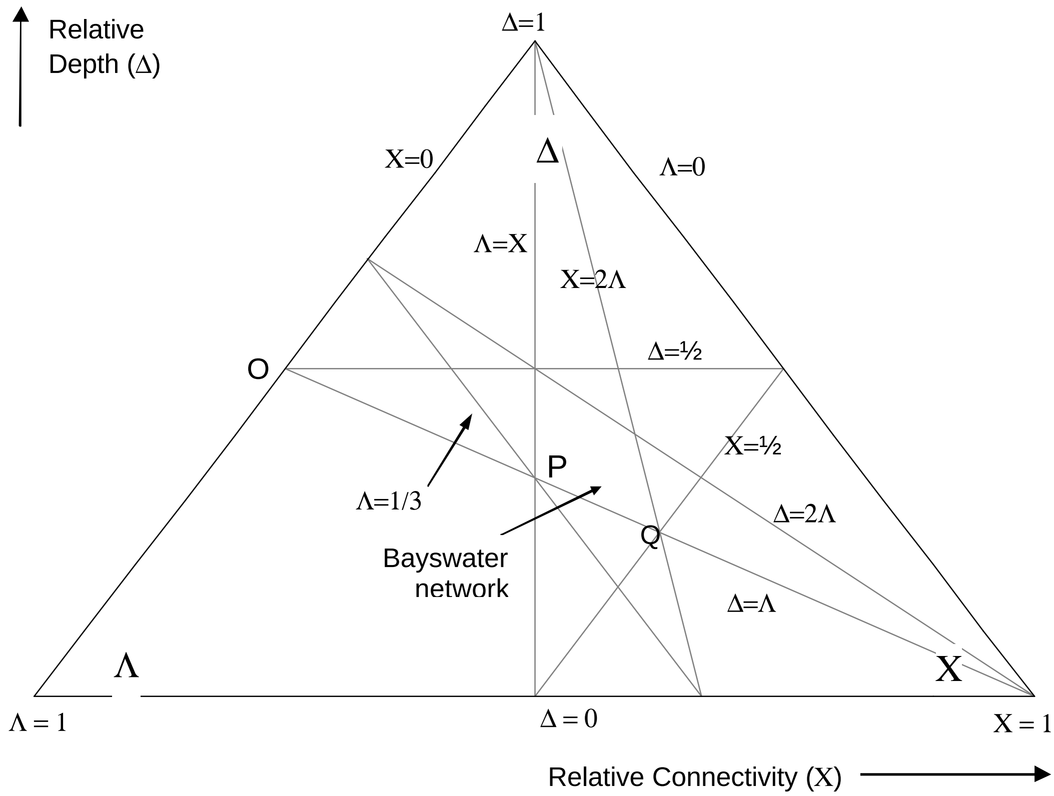
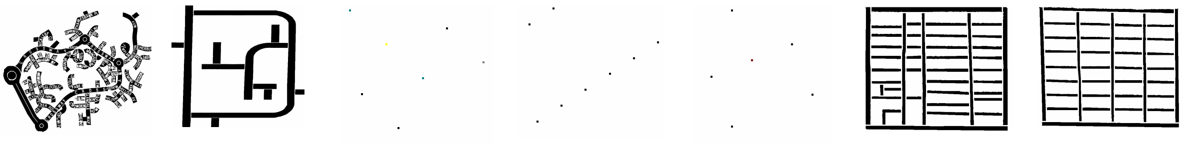


Figure 8. The Netgram. Each position on the netgram represents a combination of Relative Continuity (Λ), Relative Connectivity (Χ) and Relative Depth (Δ). For each position, Λ + Χ + Δ = 1. On the bottom axis, where Δ = 0, Λ = (1–Χ). Positions may be uniquely represented by just two co-ordinates (Χ, Δ). A set of key reference lines may be used to conveniently locate positions on the netgram, using simple relationships between Λ, Χ and Δ and vulgar fractions. Compare with the routegram equivalent, Figure 5.

The position of the Bayswater network is shown on the netgram in Figure 8. Its position is (0.28, 0.42, 0.30) or simply (0.42, 0.30). The position on the netgram is effectively a weighted average of all the points on the equivalent routegram. Therefore, there is a clear relationship between the routegram and the netgram. As routes are added to (or subtracted from) a network, points will appear on (or disappear from) the routegram, and the position of the resultant network on the netgram will tend to shift slightly.

5.4 Comparing Network Type

The netgram may now be used to compare different networks and recognise network types based on their relative connectivity. A sample of networks with representative values of relative connectivity is now plotted on the netgram to demonstrate the ability of the netgram plot to distinguish distinct recognisable types of pattern (Figure 9).



(a) (b) (c) (d) (e) (f) (g)

Figure 9. Seven networks used to demonstrate the netgram. These form a spectrum from tributary (a) to griddy (g). Layout (a) is a highly tributary modern road layout (Thamesmead); Layout b is a less deeply branching 'tributary' example; the set of layouts (c) to (g) is based on that used by Ewing to qualitatively characterise network type (Ewing, 1996).

Table 3 shows the relative values of a sample of networks which represent a graduated range of relative connectivity values, approximating to a series of steps between 0.25 and 0.5. This sample of networks is then plotted on the 'netgram' (Figure 10).

Table 3. Relative values of networks depicted in Figure 9 and plotted in Figure 10.

Point	Network	Relative Continuity (Λ)	Relative Connectivity (X)	Relative Depth (Δ)
	Bayswater	0.277	0.424	0.299
(a)	Thamesmead	0.243	0.260	0.497
(b)	Tributary	0.275	0.275	0.450
(c)	Ewing-5	0.256	0.346	0.398
(d)	Ewing-4	0.263	0.410	0.327
(e)	Ewing-3	0.257	0.444	0.300
(f)	Ewing-2	0.240	0.474	0.286
(g)	Ewing-1	0.218	0.500	0.282

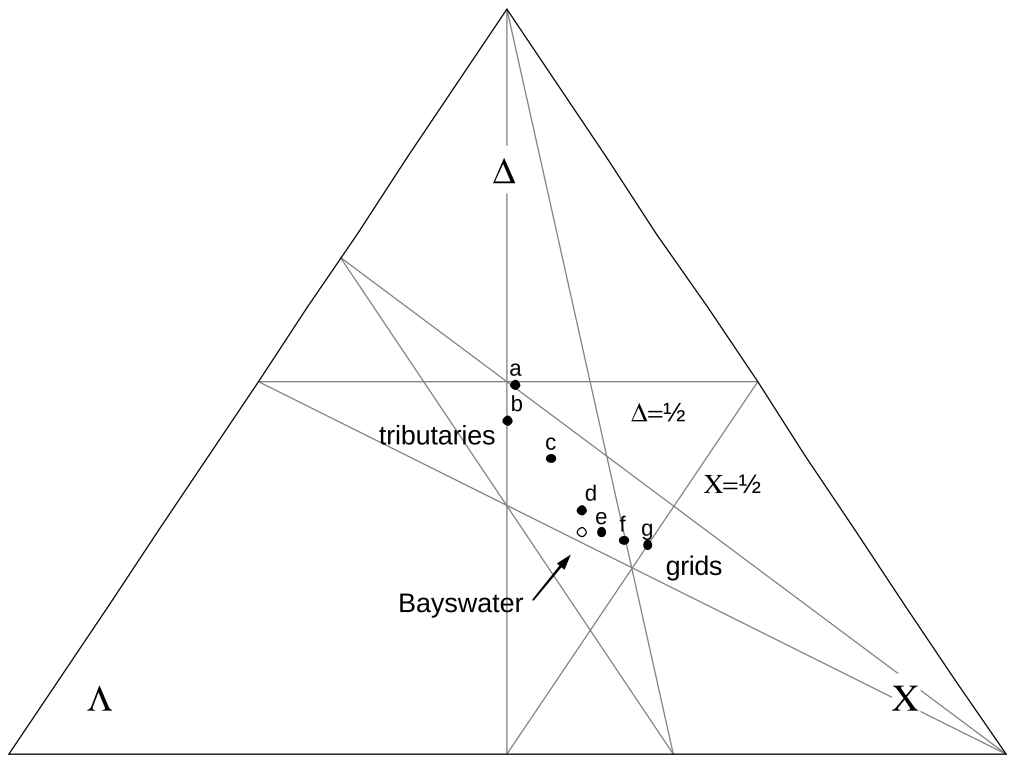


Figure 10. The tributary-griddy spectrum. Netgram demonstrating a spectrum of relative connectivity, for networks shown in Figure 9 (plotted values in Table 3).

Figure 10 simply demonstrates that it is possible to discern a spectrum from ‘tributary’ (low relative connectivity, high relative depth) to ‘griddy’ (high relative connectivity, low relative depth). This means that the netgram is able to demonstrate the ordered gradation of a spectrum of representative types, from tributary to grid. The Bayswater network (plotted earlier in Figure 8) is seen to lie between type ‘d’ and ‘e’ (Ewing’s types 3 and 4), indicating a reasonably grid-like form.

The netgram can therefore be used to systematically distinguish different network types. Further application of netgram plotting is given in Marshall (2004, forthcoming).

6. CONCLUSIONS

The paper has set out the basics of a methodology, Route Structure Analysis (RSA), which may be applied to the representation and analysis of street networks. This provides an alternative both to conventional transport network analysis and space syntax methods, while it combines some of the advantages of each. The method uses the route – appropriately defined – as the fundamental unit of structure, rather than the ‘link’ or the ‘axial line’ of those existing methods. Which method is most appropriate will depend on the context and purpose of application:

- Conventional transport network analysis is appropriate for networks where discrete paths of movement are identifiable, and where the emphasis is on relationships between nodes, and differentiation of nodes; this typically applies to a variety of road, rail, air and water transport networks.
- Space syntax was devised to analyse urban spatial structure, and is appropriate for the analysis of bounded areas of space which may or may not easily resolve into discrete sections of ‘road’; it is particularly appropriate for traditional street networks (and circulation within buildings) where lines of movement are important in themselves as the focus of analysis, and where axial lines of sight correspond significantly with actual lines of movement;
- Route Structure Analysis was devised to represent street network structure, and is appropriate for analysis of streets formed by discrete routes of movement; where lines of movement corresponding to roads or routes are the focus of analysis. It is appropriate for application to contexts where the identifiable elements of concern (in this case, routes) are continuous through connections (junctions or joints), allowing interpretation of the differential status of those elements (i.e. identification of a route typology).

Route Structure Analysis allows both explicit quantification of the properties of structure, and graphical representation of different routes and network types in terms of those properties. This allows different types of route and network to be plotted and compared, and if desired, to be categorised or classified at a variety of scales of resolution. This method is by no means the only way to classify route or network type, but may have applications in particular circumstances, where the connectivity of routes within a network is significant, or the connectivity of a whole network.

This kind of characterisation allows onward application in either performance testing or design guidance. This therefore addresses contemporary concerns relating to advocating and testing desired network structures. For example, it might be of particular interest to those assessing the sustainability implications of ‘neo-traditional’ street grids. The benefit is that it provides explicit ‘indicators of urban structure’ against which to test any ‘indicators of performance’ (e.g. travel behaviour or sustainability).

The method is essentially a form of ‘structural analysis’ rather than ‘flow analysis’. Therefore, while the method offers a means of ‘modelling’ the structure of a street network, in terms of its description, this paper does not address the modelling nor prediction of network movements. However, this kind of ‘structural analysis’ could have applications to other kinds of network or structure.

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