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## Configurational modelling of urban movement networks

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**Abstract.** Transportation research has usually seen road networks as inert systems to be navigated and eventually filled up by traffic. A new type of 'configurational' road network modelling, coupled to detailed studies of vehicular and pedestrian flows, has shown that road networks have a much more constructive role. They strongly influence the pattern of flows through quantifiable properties of the network 'configuration'. Recent research results are presented showing that rates of vehicular movement in road segments are to a greater extent than previously realised the direct outcome of the location of those segments in the network configuration as a whole and that this is the case especially in the fine structure of the urban grid. A supply and demand model of urban movement is proposed in which the degree to which a street alignment is on simplest routes between all other pairs of alignments in the system determines the demand side of the equation, and the effective road width available to traffic determines the supply side. Regression analysis shows that these two factors alone account for the majority of the variance in flows from street to street ( $r^2 \sim 0.8$ ). A model is then proposed of the evolution of the city in allocation of land uses to land parcels, and the allocation of capacity in the road network, where each reinforces the underlying configurational logic through a feedback 'multiplier' effect. These findings suggest the possibility of using urban design parameters, such as the plan configuration of the street grid, building height, and street width, to arrive at a better controlled relationship between vehicles and pedestrians in urban areas. As these design parameters are under the direct control of the urban master-planner, the new techniques lend themselves to application in design decision support. A case example of the application of these techniques in the master-planning of the redevelopment of London's South Bank cultural centre is presented.

### 1 Introduction

Conventional traffic models use relatively simple representations of the road network coupled to quite complex cost functions which are calibrated with data on origins and destinations of trips and observed flows on the network. Traffic assignment models assume perfect knowledge of the system and, as 'cost' is generally taken as travel time, knowledge of congestion of the route options ahead of the driver is assumed so that drivers make a 'rational' choice of route. As the drivers' choices create the patterns of congestion, their decisions feed back into the cost functions, and the models iterate until they converge to a solution.

These modelling techniques are now well established and are proven in application. However, there are a number of areas in which they appear to have limitations. The construction and calibration of traffic models is a costly procedure in which the cost is related to the resolution with which the origin–destination (O–D) data are gathered and the size of the model measured in terms of the number of nodes and links represented in the network. Models are therefore seldom constructed to represent the finest scale structure of the street network and their performance at this scale is not well understood. Models are generally developed based on the travel to work trip, for which the best O–D information is available; however, there is often little information available on other trip types and for other modes. In particular, O–D information is lacking for the pedestrian mode (Pushkarev and Zupan, 1975) and this is where it seems likely that the fine-scale network will be of most relevance. At the same time,



there is an emerging demand for the ability to give rapid qualitatively correct appraisals of design proposals and for the ability to address the more 'human' aspects of urban traffic many of which involve both vehicular and pedestrian modes. Advice on traffic calming schemes which require predictions in the finest scale structure of the street grid for vehicular and pedestrian modes provide a case in point. For these applications conventional modelling techniques have begun to show their limitations, and engineers rely more often than not on intuition, experience, and experiment.

Methods for the analysis of spatial configuration developed at the Bartlett School of Architecture and Planning, University College London, are beginning to suggest the possibility of a new approach. These methods are based on the use of a detailed representation of the pattern of space through which pedestrians or cars move. By measuring the properties of these patterns considered not merely as localised spatial elements—this street or that intersection—but as an entire configuration of elements each related to the others, it is possible to search for effects of the design of the street grid on the way that flows are distributed through the network and the way that different modes are brought into contact with each other. Previous research has shown that these models provide strong predictions of pedestrian movement patterns (Hillier et al, 1993). More recently the methods have been applied to studies of simultaneous vehicular and pedestrian movement patterns (Penn and Dalton, 1994). The methods are now being tested under a far wider range of different urban conditions and are beginning to shed light on the way that city structure and patterns of movement are related.

### 1.1 The basis of configurational analysis

Configurational models quantify the pattern properties of the street network by first breaking up the pattern of continuous open space through which one moves [see figure 1(a)] into the fewest and longest lines of sight and access that pass through all circulation routes [see figure 1(b)]. We call this the 'axial' map. Next, each line in the map is represented as a node in a graph with each intersection between lines represented as a link in the graph. In this way configurational models reverse the description of the network by the conventional traffic model, in which road intersections are the nodes and street segments the links. Once a graph has been constructed it is a simple matter to devise measures of the properties of the graph and then to use statistical methods to see whether there are any detectable correlations between the pattern properties of the network and observed traffic behaviour. One of the simplest measures of the graph is the 'connectivity' (valency or degree) of the node; however, this is a purely local measure of the pattern. More interesting—and as it turns out more useful—measures are 'global' in that they quantify aspects of how a node figures in the larger scale pattern.

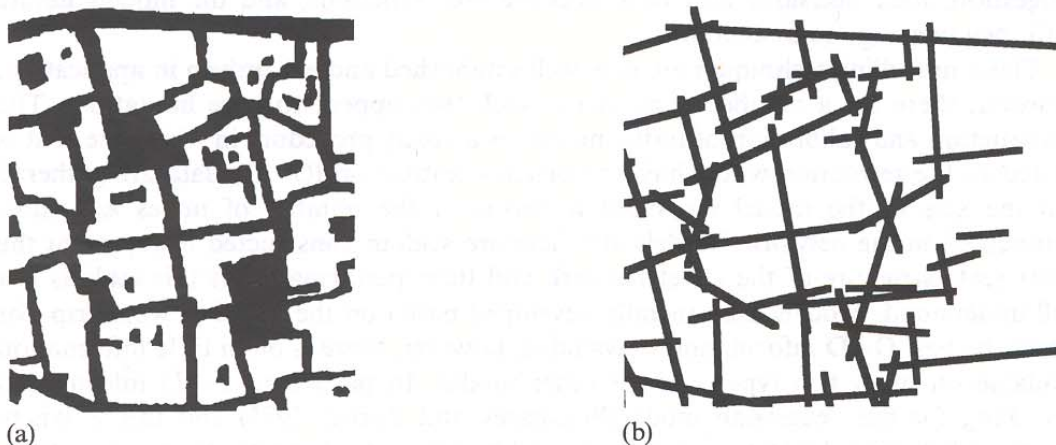


Figure 1. The open space of an irregular street grid (a) and its axial representation (b).

One of the most useful of these is a measure of the mean depth of a node within the graph—taking every move along a link to add a step of depth and normalising the figure twice, once according to how deep it could possibly be with that number of nodes in the graph, producing a measure of the relative asymmetry ( $A^{\text{rel}}$ ) of a node in the graph according the formula:

$$A^{\text{rel}} = \frac{2(d^{\text{mean}} - 1)}{k - 2}, \quad (1)$$

where  $d^{\text{mean}}$  is the mean depth of all nodes in the graph from the node in question, and  $k$  is the total number of nodes in the graph.

A second empirical relativisation eliminates the effect by which real cities overcome the effects of sheer size through the use of a longer and better connected primary line structure by dividing  $A^{\text{rel}}$  by the  $D$  value for that number of spaces, where the  $D$  value is the  $A^{\text{rel}}$  value of the node at the root of a diamond-shaped graph with that number of spaces (for a full derivation of  $D$  values see Hillier and Hanson, 1984). We call the relativised measure ‘real relative asymmetry’ (RRA) and, more colloquially, we call the reciprocal of RRA ‘global integration’ (by taking the reciprocal of relativised mean depth, a shallower or more integrated line acquires a greater value than a deeper and more segregated one).

Figure 2 shows the global integration map for London within the North and South Circular roads and west of the Lea Valley. The map represents all street segments open to vehicular traffic within the area by using some 16 000 lines and 50 000 links coloured up from red for the ‘shallowest’ or most integrated lines through the spectrum to blue for the ‘deepest’ or most segregated lines in the area. It is striking that the most integrated line in the whole of this area is Oxford Street and that the remainder of what we would recognise as the primary route structure of the area is picked out by a purely configurational analysis, without any reference to land uses, capacities, development densities or even one-way systems and traffic management. (A second vehicular model incorporating major traffic management measures, such as the restrictions on the use of Oxford Street which effectively break it into two disconnected line segments for private vehicles, is discussed later in this paper.)

There is, however, a marked ‘edge effect’ evident in figure 2. Certain lines near the edges of the mapped area are segregated purely as a result of our selection of the boundary for analysis. If we had selected a larger boundary, they would have appeared to be more integrated. This is a natural result of any completely global depth measure which measures the ‘depth of this line with respect to this system of lines’. One way of overcoming these edge effects involves calculating the mean depth of all nodes within some fixed radius (number of steps of depth or changes of direction in the axial map) of each node in turn. Thus mean depth at a given radius  $n$ ,  $d_n^{\text{mean}}$ , is calculated according to the formula:

$$d_n^{\text{mean}} = \frac{\sum_{r=0}^n kd}{\sum_{r=0}^n k}, \quad (2)$$

where  $k$  is the number of nodes at depth  $d$  in the graph. In the calculation of relative asymmetry  $d_n^{\text{mean}}$  is substituted for  $d^{\text{mean}}$  in equation (1), whereas in relativisation to derive radius RRA the  $D$  value is used for  $\sum_{r=0}^n k$  for each node (for definitions of the  $D$  value, see Hillier and Hanson, 1984).



The radius measures effectively create a moving boundary around each line in turn. The restricted radius measures of integration turn out to be important for urban movement patterns and particularly for disentangling the relationship between different modes and different roles of routes in the road hierarchy. The most local of these measures is 'radius 3 integration' (see figure 3) although we find that a range of other radii are of interest. Figure 3, which actually plots the logarithm of radius 3 integration because the measure is highly skewed, shows the almost complete elimination of the edge effect and highlights the most locally integrated lines distributed throughout the London area, many of which turn out to be local shopping streets. These simple measures of the topology of the road network reveal a subtle range of properties of urban systems without the need to invoke the metric concepts of distance or cost.

## 2 The movement structure of London

Several factors seem intuitively apparent from a study of these figures. First, it is clear to anyone with a knowledge of London that there is some relationship between the importance of routes, their degree of integration, the densities and kinds of land uses they serve, and the predominant scale of spaces, in terms both of the length of lines and of the width of streets. Second, it seems clear that different spaces figure differently with regard to different radii of catchment. Some spaces are locally integrated but not globally so, others such as Oxford Street are both locally and globally integrated. Third, it seems clear that in global terms there is an integrated 'core' of streets corresponding to the central commercial and retail areas of London, that this core clings to the main radial routes leading from edge to centre, and that the more suburban residential districts fall in between the radials. To this extent, the configurational logic appears to mirror both the development density and the land-use characteristics of the city. Fourth, it seems fair to reason that there should be a relationship between volumes of traffic and the degree of integration of streets within the different parts of the area.

So far as pedestrian movement is concerned we now have considerable evidence for this fourth factor. It is clear that the configuration of the street grid gives rise to a pattern of 'natural movement' for the pedestrian population as a whole and this is reflected in a correlation between spatial integration and pedestrian flow rates. The more integrated a street, the greater the pedestrian flow rate. However, as it also seems that patterns of land use and development density are related to spatial configuration, there is clearly a question of what causes what. We have argued elsewhere that the question of 'which comes first, the people or the shops' is easily resolved by looking at mixed-use areas including retail and monofunctional residential areas (Hillier et al, 1993). In the former there is an exponential rise in pedestrian flows with increased integration, and in the latter the correlation is more or less linear. The likely explanation is that the pattern of the grid gives rise to a pattern of pedestrian movement and this in turn attracts retail land uses to take advantage of the passing trade. In mixed areas the shops site themselves preferentially in spaces that are used for through movement and then become the destinations for to movement, acting as a multiplier on the original flows. The exponential relationship we observe between configurational measures and flows results from this 'multiplier effect'. The model has considerable appeal. It explains both the common experience that where there are shops there are people and it allows an explanation of how the traditional city seems to have evolved to get the right land uses in the right numbers in the right locations—more or less—without tight master-planning controls. It begins to explain why it is that, for pedestrians at least, trying to engineer high levels of space occupancy by siting shopping 'attractors' in the middle of residential estates is so often prone to failure. The key to retail success is not



just the attractiveness of the shop but the 'passing trade' which, almost by definition, is on its way from and to other spaces and so is sensitive to the configuration of the street grid.

Further weight has been given to these findings by a simultaneous study of vehicular and pedestrian movement (reported in Penn and Dalton, 1994). This study found that the degree to which vehicular traffic dominated pedestrian movement in the primary route structure of an urban area varied radically according to the dominant land use. On routes lined with residential land uses, vehicular traffic outnumbers pedestrians at a rate of 8 to 1 but where the dominant land use is shopping the rate is nearer 1 to 1. The key question in seeking to maintain a more viable ratio of vehicles to pedestrians is how to achieve a sufficient quantum of retail land uses on the primary route system. The data suggest that only under certain circumstances do shopping streets become viable: streets that secure high levels of retail need to be well integrated both into the global network and into a local pedestrian catchment. A local catchment alone would attract small-scale convenience shopping but would not reach the threshold required to start the multiplier effect needed to create a shopping 'centre' for comparison goods. Global integration alone led to vehicular 'rat runs' that failed to gain significant retail land uses and also failed to reach the 'multiplier' threshold.

The study reported in Penn and Dalton (1994) found a surprisingly strong correlation between configurational measures of the street grid and vehicular flows. However, that study was limited to a single area in Islington, North London, and it was not clear that vehicular flows were generally related to network configuration. In order to begin to investigate this in more detail it was necessary to determine whether configurational modelling methods would be able to predict vehicular flow rates under a wider range of street grid types and local area characteristics. Six study areas (including the original Islington area) were therefore chosen to reflect a range of different predominant land-use types and mixes, densities of development, and street grid morphologies. The areas are outlined in figure 3 as follows.

- (1) The Islington area was bounded by Caledonian Road on the west and Liverpool Road on the east, Offord Road to the north and Copenhagen Street to the south, although additional counts were made of street segments in the surrounding Essex Road and Upper Street areas. It is a relatively homogeneous 19th century residential district with streets and squares, subject to a fair degree of traffic management though still attracting rat-running traffic.
- (2) The South Bank area was bounded by Blackfriars Road, The Cut/Lower Marsh, and Westminster Bridge Road. It has a rich diversity of land uses including major cultural and transport facilities (such as the South Bank Arts Centre and Waterloo Station), high profile employers and amenities, as well as a strong residential component. The arts complex also has specific problems associated with its upper level pedestrian circulation system and is the subject of considerable debate and a number of proposals for modifications to its road and pedestrian route network.
- (3) The Calthorpe Street area in the south east of Kings Cross and St Pancras is a typical inner-city area with a mixture of residential, industrial, and commercial properties. It was bounded by Grays Inn Road, Frederick Street, Kings Cross Road, and Roseberry Avenue. Apart from Frederick Street, which was a relatively quiet street, all the other boundary streets were very busy through traffic routes.
- (4) The South Kensington Museum area has a large concentration of high-profile cultural and educational facilities including the Natural History Museum, the Victoria and Albert Museum, the Science Museum, the Royal Albert Hall, and the Imperial College of Science and Technology. The area includes some high-grade residential streets and an underground station. The area was bounded by Hyde Park to the north and was crossed by Cromwell Road.





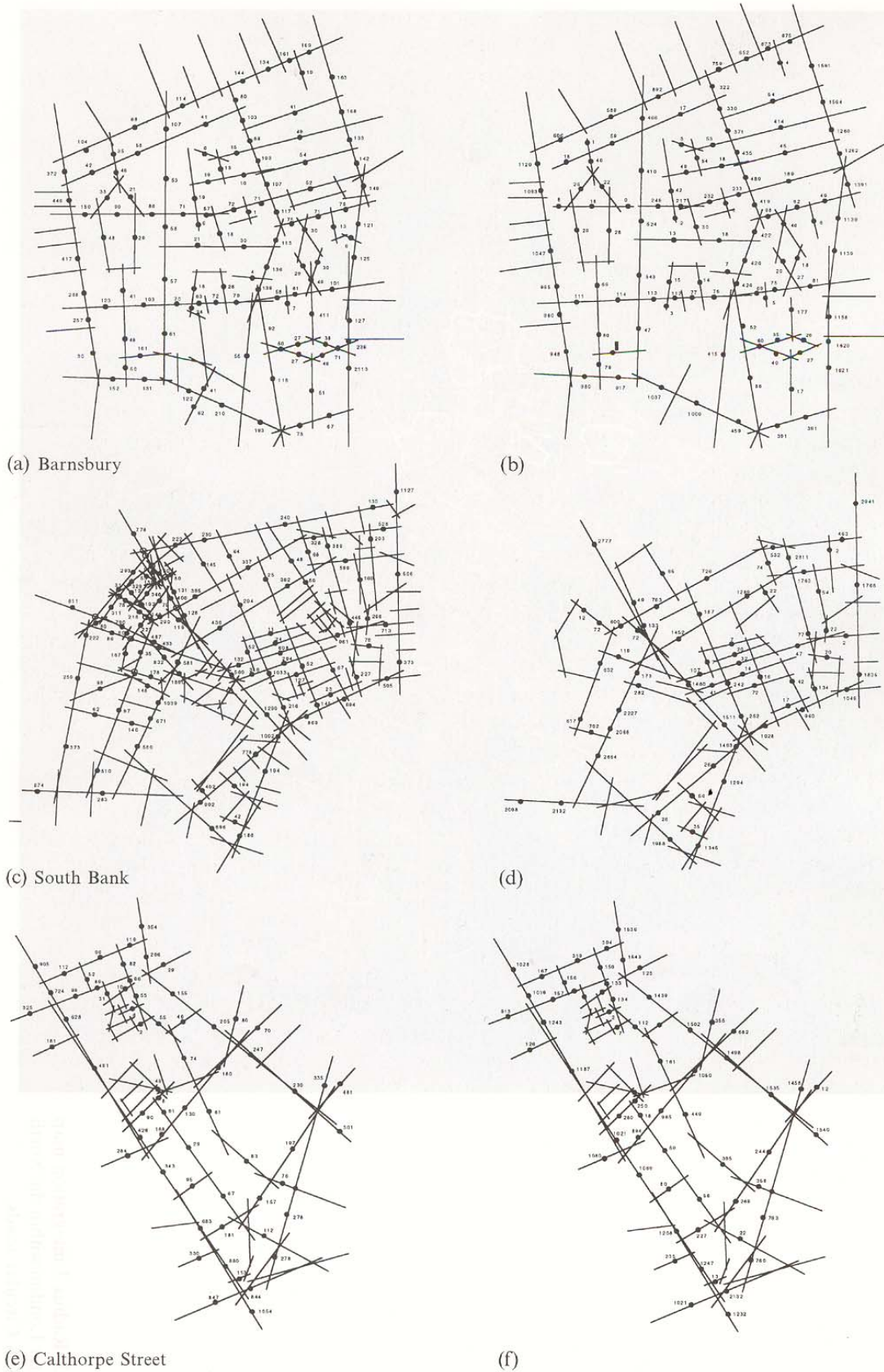
Figure 2. Global integration map of Greater London within the North and South Circular roads.





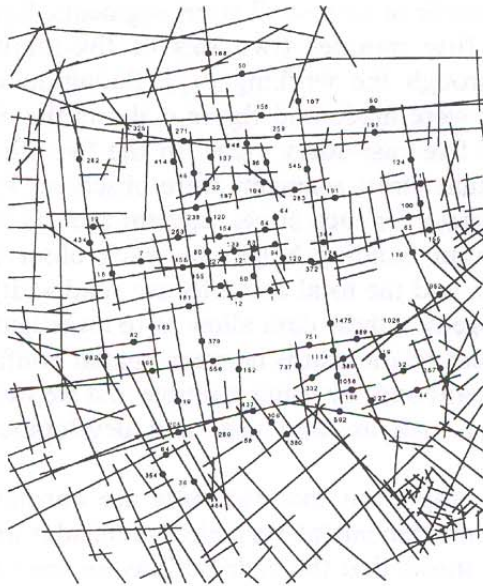
**Figure 3.** Radius 3 integration map of Greater London within the North and South Circular roads.





**Figure 4.** Daily mean flow rates per hour for adult pedestrians [(a), (c), (e), (g), (i)] and motor vehicles [(b), (d), (f), (h), (j)] in the first five case-study areas.

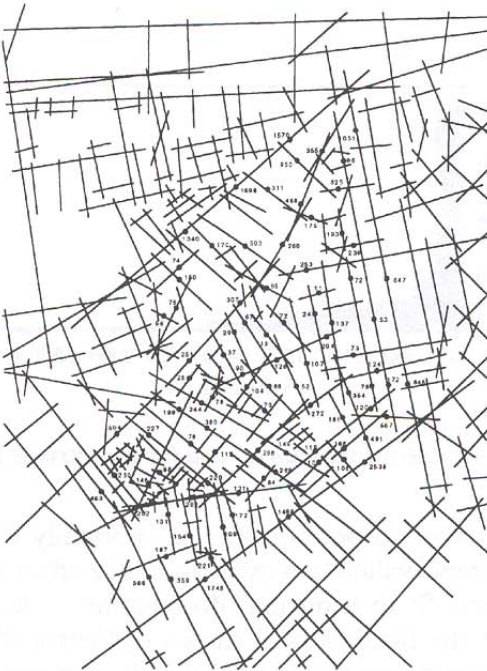




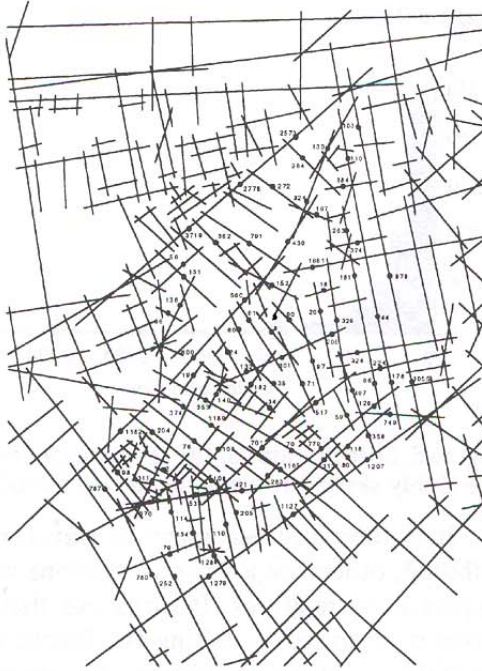
(g) South Kensington



(h)



(i) Brompton Road



(j)

**Figure 4** (continued).

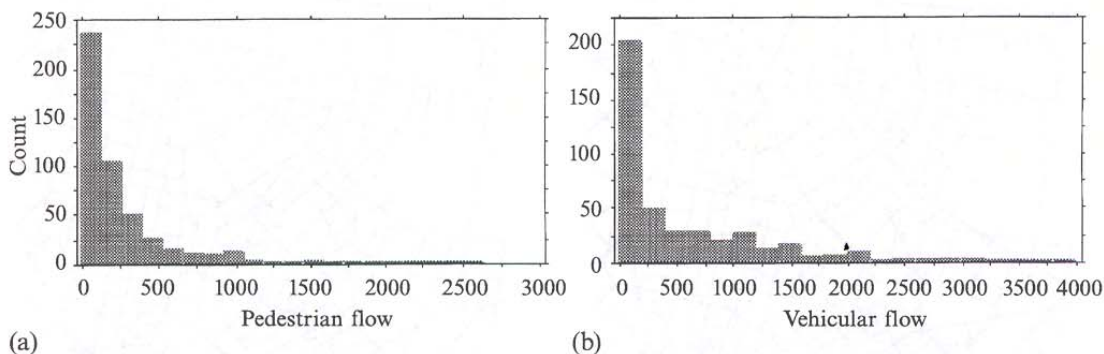
(5) The Brompton Road and Kings Road area is a high-grade residential and shopping area including Brompton Road to the north and Kings Road to the south. It is sometimes characterised as 'village like' in atmosphere.

(6) Finally, two sets of observations were made in the City of London in order to observe the effects of changes to the effective street grid on patterns of movement before and after the introduction of a massive traffic management scheme as a part of the antiterrorist security zone following the Bishopsgate bomb in the City. As the area was subject to considerable disruption following both the bomb and the introduction of the security cordon, this study area is analysed separately from the first five areas.



Within each study area, observations were made of almost all street segments. Each street segment was observed for a total of fifty minutes (two sets of five-minute observations in each of five time periods through the working day). Simultaneous counts of both pedestrian and vehicular flows were made and figure 4 shows the all-day average counts for each mode in the first five case-study areas. In the five study areas a total of 466 pedestrian and 397 vehicular street segments were observed. The study areas were also surveyed to determine factors for each street segment such as the predominant land use, the mean and maximum building height for each observed segment (as a measure of development density), and the total and effective road widths at the narrowest point on the segment. Taken together, these data allow us to investigate, by using simple regression, whether the apparent relationships between spatial configuration and traffic flows are statistically significant and, by using multiple and stepwise regression, the degree to which other factors such as land uses and development densities are also involved.

In order to use statistical techniques it is important that variables are normally distributed; however, the distributions of both the dependent variables—vehicular and pedestrian flows—are highly skewed. Figure 5 shows that the distributions for the two modes across all five case-study areas are strongly skewed towards lower counts—most street segments carry low traffic flows with only a relatively small number carrying the highest flows.



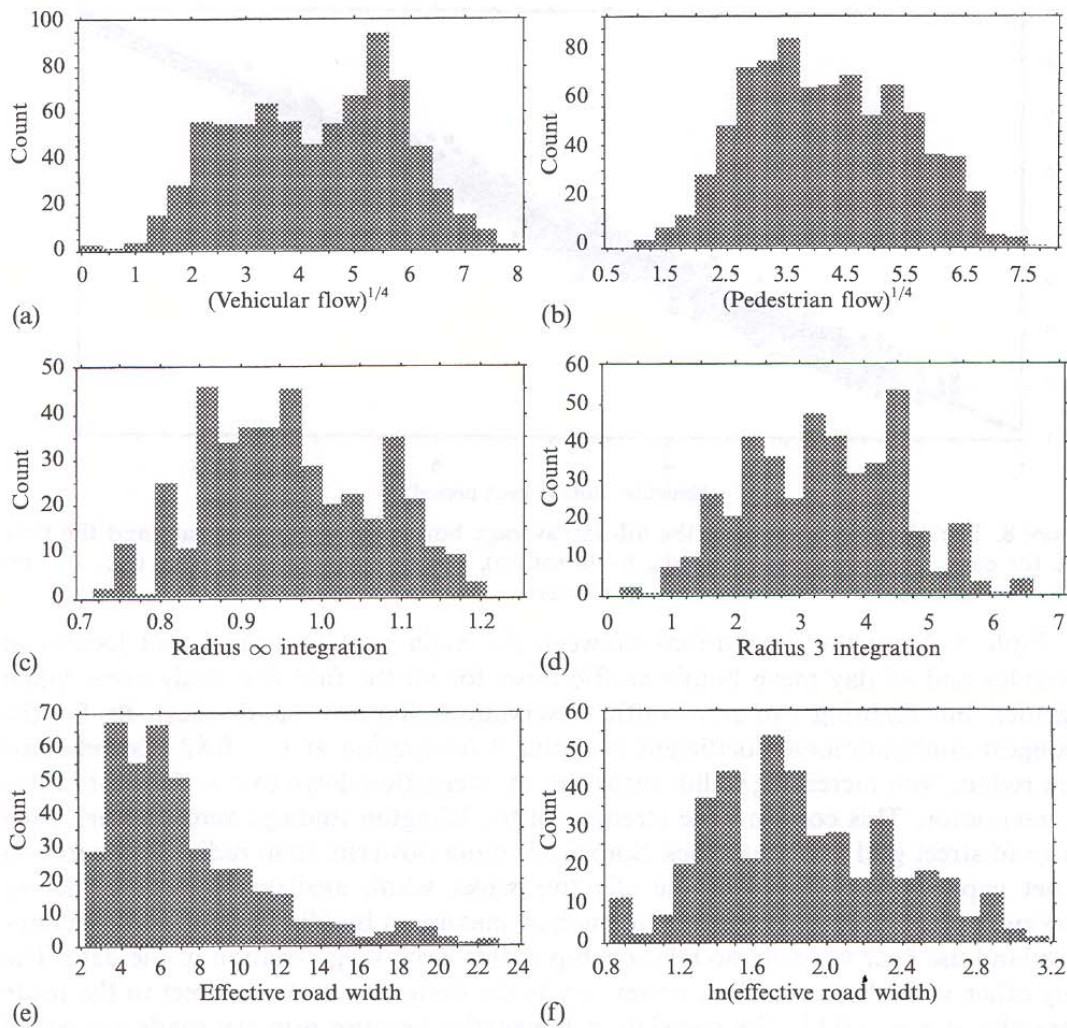
**Figure 5.** Distributions of the all-day mean hourly flow rate for vehicles (a) and for pedestrians (b) are highly skewed towards the lower counts.

It is therefore necessary to transform variables to be more or less normally distributed, otherwise a few observations with extreme values can exert an undue effect on apparent correlations. It turns out that the best fit to a normal distribution in both cases is obtained by taking the fourth root of the flow rates as shown in figures 6(a) and 6(b) and these transformations are used as the dependant variables in the remainder of this investigation.

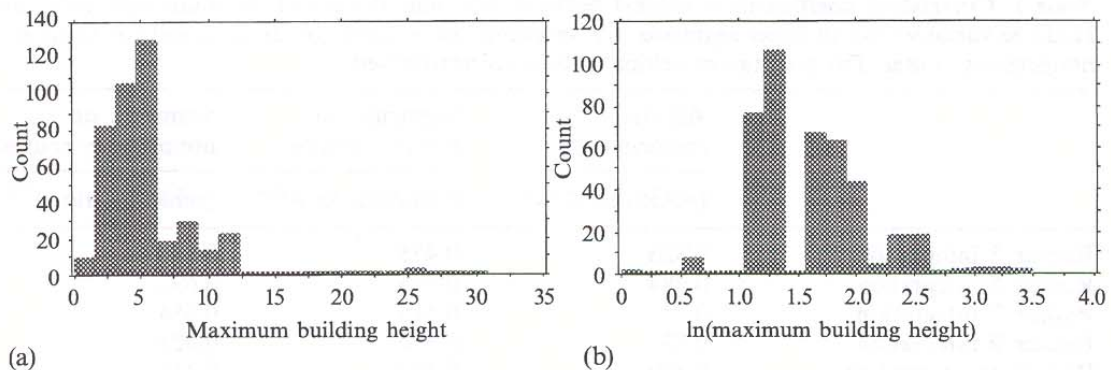
The main configurational measures of integration are more normally distributed [see figures 6(c) and 6(d)] and are used without transformation, although the measure of effective road width (net capacity) is again strongly skewed and best normalised by a logarithmic transformation [see figures 6(e) and 6(f)] as is that for maximum building height, used as a proxy measure for development density (see figure 7).

Traffic flow rates in each time period and the all-day average flow rate are very closely correlated. Figure 8 shows a scatter of each time period against the all-day average figure. In each case  $r^2 = 0.98$ , with the slopes of the regression lines being very nearly coincident. This shows that the degree of spatial variation in traffic flows from one observation location to another far outweighs the degree of temporal variation from one time period to another, suggesting that spatial variations are the main factor to be explained.



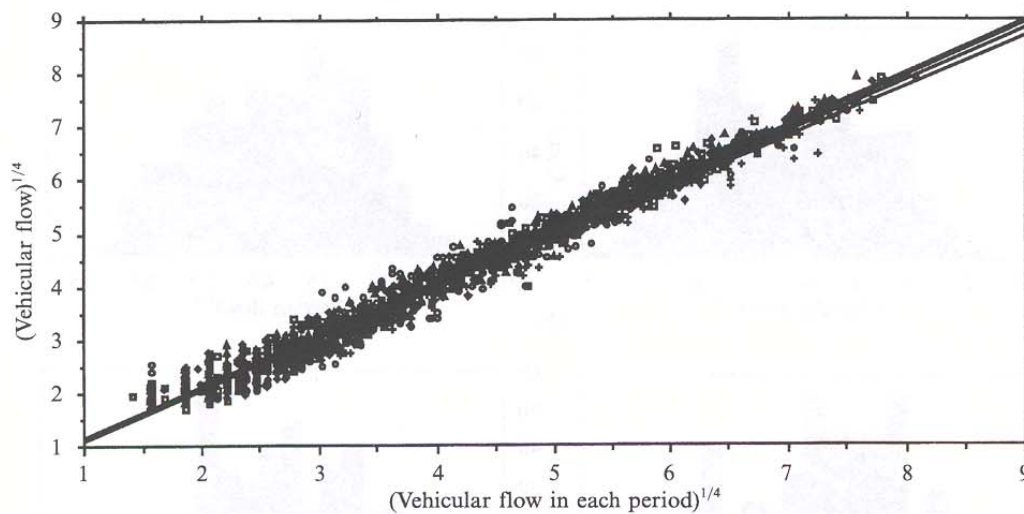


**Figure 6.** Distribution of the fourth root of vehicular (a) and pedestrian (b) all-day mean hourly flow rates. Distributions of configurational measures of integration at most radii are approximately normally distributed, for example, radius  $\infty$  (c), radius 3 (d) integration. The distribution of effective road widths at observed segments (e) and its logarithmic transformation (f).



**Figure 7.** The distribution of maximum building height (a) and its logarithmic transformation (b).





**Figure 8.** The correlation between the all-day average hourly vehicular flow rate and the flow rate for each of the five time periods, 8–10 AM ( $\circ$ ), 10 AM–12 PM ( $\square$ ), 12–2 PM ( $\triangle$ ), 2–4 PM ( $\diamond$ ), 4–6 PM (+);  $r = 0.99$ ,  $p < 0.0001$  in all cases.

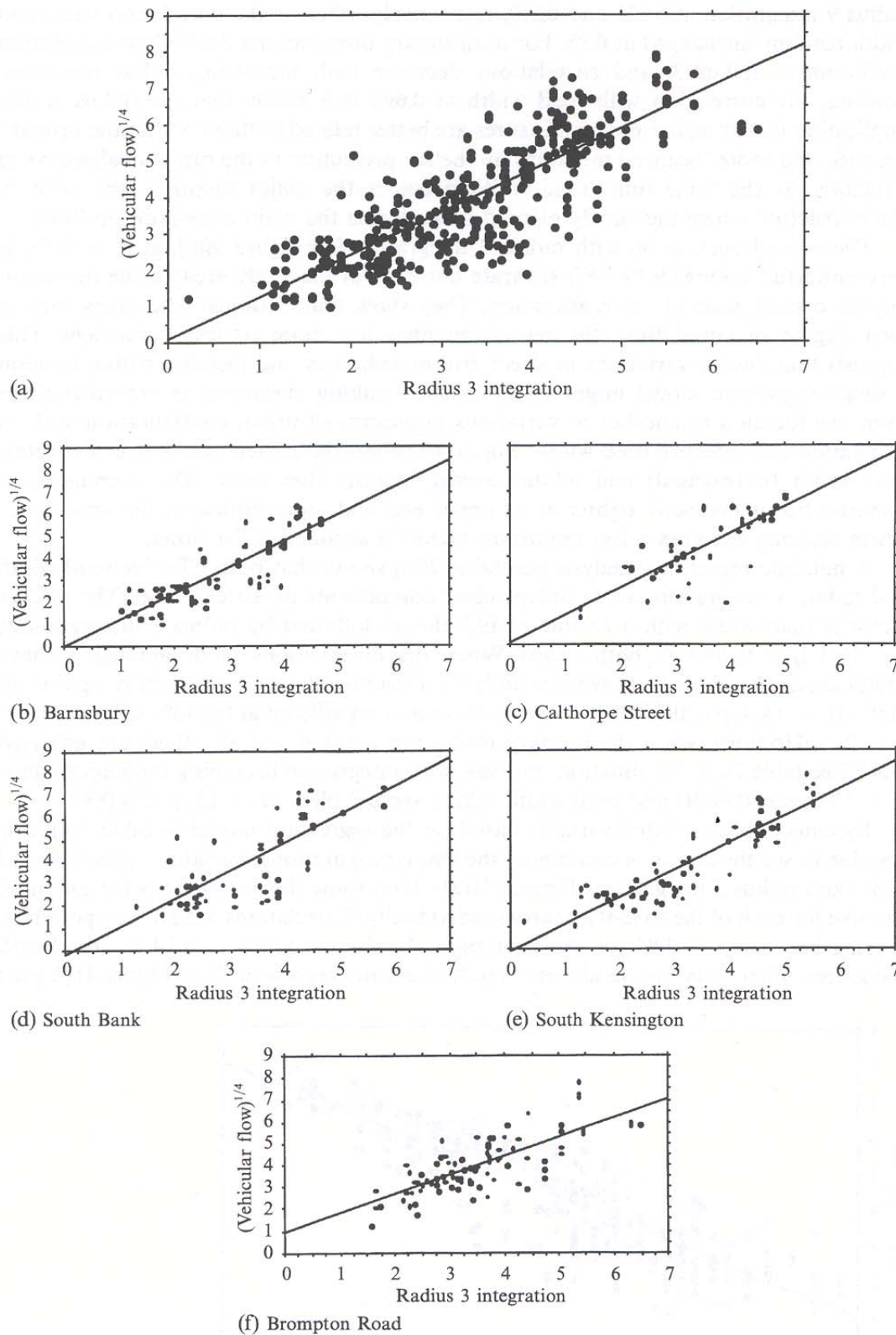
Table 1 shows the correlations between the main configurational and locational variables and all-day mean hourly traffic flows for all the first five study areas taken together, but omitting two zero-traffic observations (both in cul-de-sacs). By far the strongest configurational coefficient is radius 3 integration at  $r = 0.82$ . Correlations then reduce with increasing radius measures of integration down to  $r = 0.58$  for radius  $\infty$  integration. This confirms the strength of the Islington findings across a very wide range of street grid and area types. Somewhat more powerful than radius 3 integration is net capacity, a measure of the effective street width available to traffic, net of parking, at  $r = 0.86$ . Other measures such as maximum building height and predominant land use bear virtually no relationship at this level of aggregation of the data. The only other variable to correlate powerfully is the designation of the street in the route hierarchy at  $r = -0.81$ . The correlation is negative because primary roads are coded as 1, secondary as 2, and so on.

When we subdivide the data set into primary and other routes in the hierarchy (table 1, columns 2 and 3) a more detailed story emerges. For primary route observations alone, the most powerful configurational correlations are with radius 7 and

**Table 1.** Correlation coefficients ( $r$  values) between vehicular flows and the main built form or land-use variables for all street segments, for segments on primary routes only, and for those on nonprimary routes. The measure of vehicular flows is normalised.

	All street segments (vehicular flow) <sup>1/4</sup>	Segments on primary routes (vehicular flow) <sup>1/4</sup>	Segments on nonprimary routes (vehicular flow) <sup>1/4</sup>
Radius 3 integration	0.826	0.475	0.738
Radius 5 integration	0.784	0.495	0.692
Radius 7 integration	0.743	0.515	0.654
Radius 9 integration	0.733	0.510	0.624
Radius $\infty$ integration	0.580	0.340	0.411
ln(Maximum building height)	0.216	0.419	0.154
Land use	0.118	0.236	0.014
Route hierarchy	-0.809		0.165
ln(Net capacity)	0.856	0.850	0.693





**Figure 9.** The correlation between vehicular flows and radius 3 integration (a),  $r = 0.83$ ,  $n = 412$ ,  $p < 0.0001$ . The correlation between vehicular flows and radius 3 integration [(b)–(f)] for each of the five case-study areas.

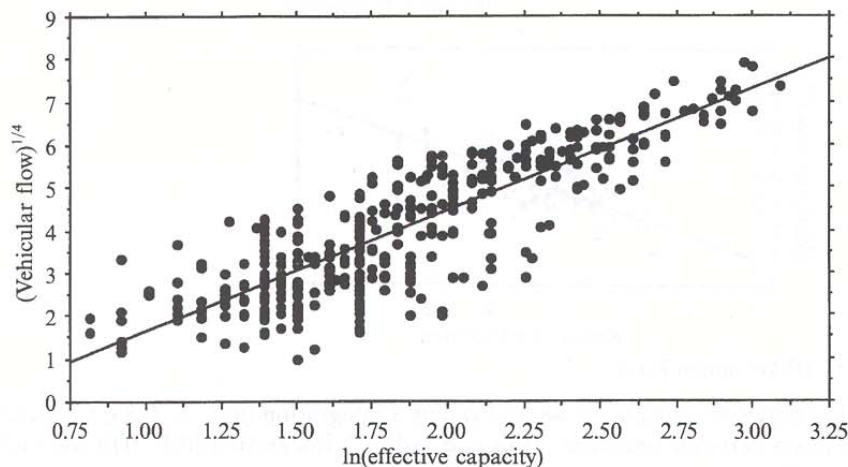


radius 9 integration at 0.515 and 0.510, respectively, whereas the correlation with road width remains unchanged at 0.85. For nonprimary observations the highest correlation coefficient is radius 3, and correlations decrease with increasing radius measures; however, the correlation with road width at 0.693 falls below that for radius 3. The implication is that higher radius measures are better related to flows within the primary network and more localised measures are better predictors in the more localised route structure. At the same time, road width becomes the major factor in the primary route structure where the supply of road space forms the main constraint on flows.

The overall correlation with radius 3 integration [see figure 9(a)], at  $r^2 = 0.69$ , is very powerful. Figures 9(b)–9(f) separate out each of the study areas while maintaining the overall scale of the scattergram. They show that, although the areas vary in their degree of correlation, the regression lines are more or less coincident. This suggests that despite variations in street grid morphology and location within London a single regression model might be established linking variations in vehicular flows from one location to another to variations in aspects of urban configuration such as integration and effective road width. Figure 10 shows the correlation between effective road width (normalised) and all-day average hourly flow rates. The correlation is powerful but is distinctly tighter at its upper end and more diffuse at the lower rates where capacity becomes a less important factor in accounting for flows.

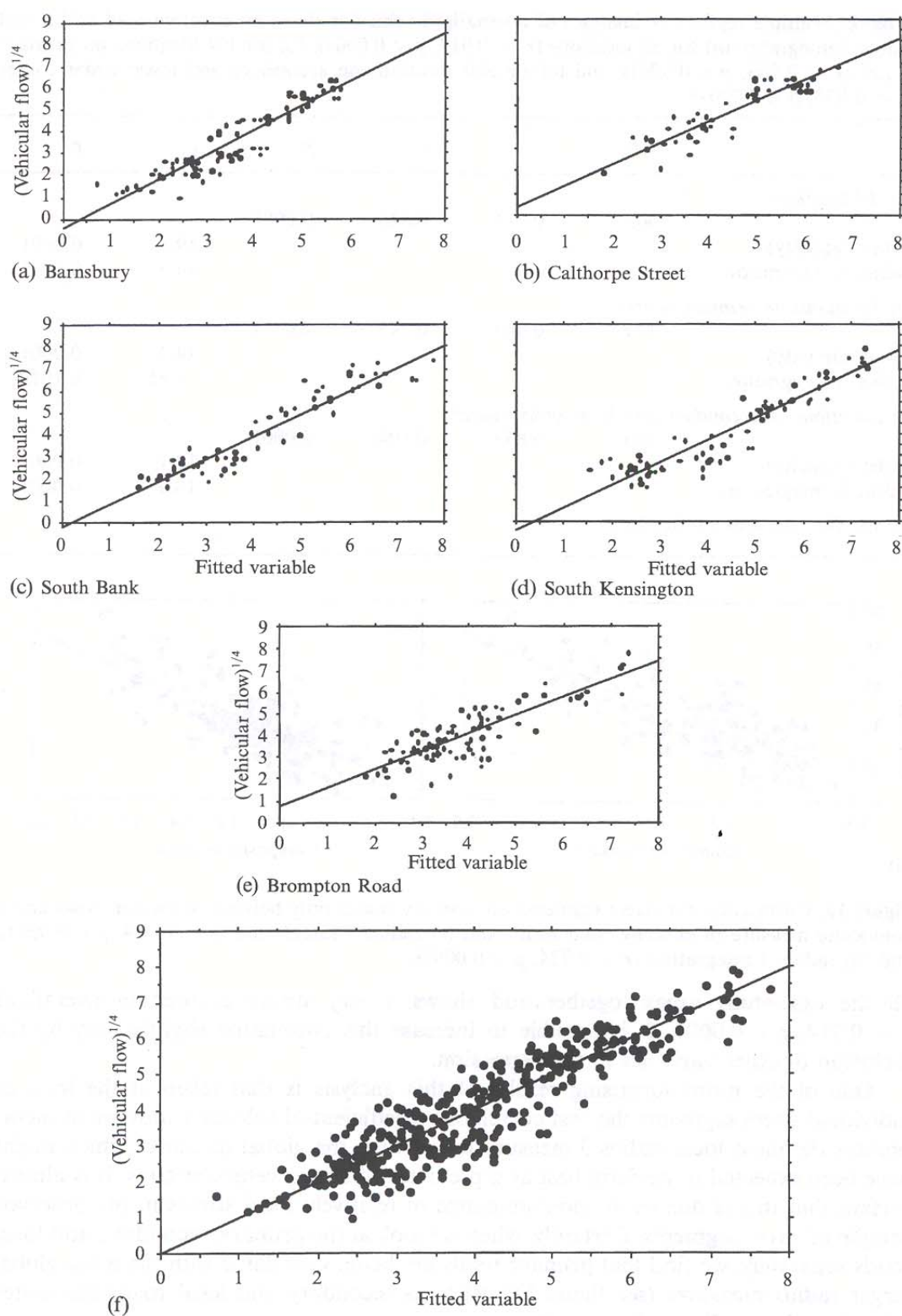
A multiple regression analysis [see table 2(a)] shows that both effective road width and radius 3 integration act as independent components in the equation. The greater factor is road width with a  $t$  value of 19.3 closely followed by radius 3 integration at  $t = 15.3$  ( $p < 0.0001$  in both cases). When the observations of designated primary routes are analysed on their own [see table 2(b)] road width becomes the only significant factor ( $t = 14.4$ ,  $p < 0.0001$ ), with integration only significant at the 10% level ( $t = 1.7$ ,  $p = 0.1$ ). However, when the primary routes are omitted and all others are analysed alone [see table 2(c)], the situation reverses, with integration becoming the major factor ( $t = 13.8$ ,  $p < 0.0001$ ) and road width taking second place ( $t = 12$ ,  $p < 0.0001$ ).

By constructing a fitted variable based on the regression model in table 2(a), it is possible to see the effects of combining the two configurational variables, effective road width and radius 3 integration. Figures 11(a)–11(e) show the correlations for the fitted variable for each of the case-study areas individually. Correlations are all very powerful, varying between  $r = 0.84$  for the Brompton Road area, and  $r = 0.94$  for the South Bank area. Each area lies on almost exactly the same regression line. Figure 11(f) puts



**Figure 10.** The correlation between effective capacity and vehicular flows,  $r = 0.86$ ,  $n = 405$ ,  $p < 0.0001$ .





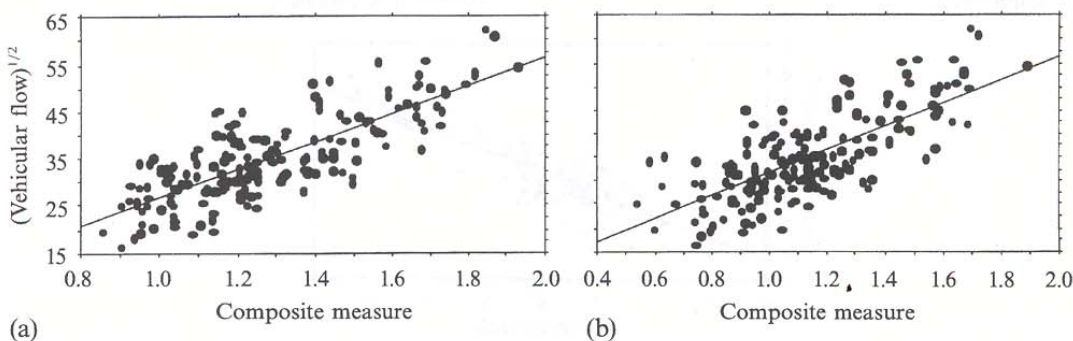
**Figure 11.** The correlation between vehicular flows and the fitted variable incorporating effective road width and radius 3 integration, for each of the five case-study areas [(a)–(e)]. The correlation between a fitted variable incorporating effective road width and radius 3 integration (f) according to the regression model in table 2, and normalised all-day average hourly traffic flows ( $r = 0.914$ ,  $n = 405$ ,  $p < 0.0001$ ).



**Table 2.** Multiple regression analyses of normalised vehicular flows on effective road width and radius 3 integration (a) for all locations ( $r = 0.914$ ,  $p < 0.0001$ ), (b) for 104 locations on primary routes ( $r = 0.863$ ,  $p < 0.0001$ ), and (c) for 300 locations on secondary and lower order routes ( $r = 0.833$ ,  $p < 0.0001$ ).

	DF	$r$	$r^2$	$p$	$t$	$p$
(a) <i>All locations</i>						
	405	0.914	0.835	0.0001		
ln(net capacity)					19.3	0.0001
radius 3 integration					15.3	0.0001
(b) <i>Locations on primary routes</i>						
	104	0.863	0.745	0.0001		
ln(net capacity)					14.4	0.0001
radius 3 integration					1.65	0.1019
(c) <i>Locations on secondary and lower order routes</i>						
	300	0.833	0.694	0.0001		
ln(net capacity)					12.1	0.0001
radius 3 integration					13.9	0.0001

Notes: DF, degrees of freedom



**Figure 12.** Correlation for street segments on primary routes only between vehicular flows and a composite measure of effective road width and (a) radius 7 integration ( $r = 0.784$ ,  $p < 0.0001$ ), and (b) radius 3 integration ( $r = 0.734$ ,  $p < 0.0001$ ).

all the case-study areas together and shows a very strong correlation overall at  $r = 0.914$ ,  $p < 0.0001$ . It is possible to increase this correlation slightly only by the inclusion of other variables in the regression.

One of the more surprising results of this analysis is that taken at the level of individual street segments the best correlation coefficient of vehicular movement incorporates the most local radius 3 measure rather than the global measures which might have been expected to perform best as a predictor of longer vehicular trips. It is almost certain that this is due to the predominance of relatively local streets in the observed sample of street segments. Certainly, when we look at the primary, secondary, and local roads separately, we find that primary roads are better correlated with the more global larger radius measures (see figure 12), whereas secondary and local roads are better related to the smaller radius measures.

### 2.1 A supply and demand model of urban road space

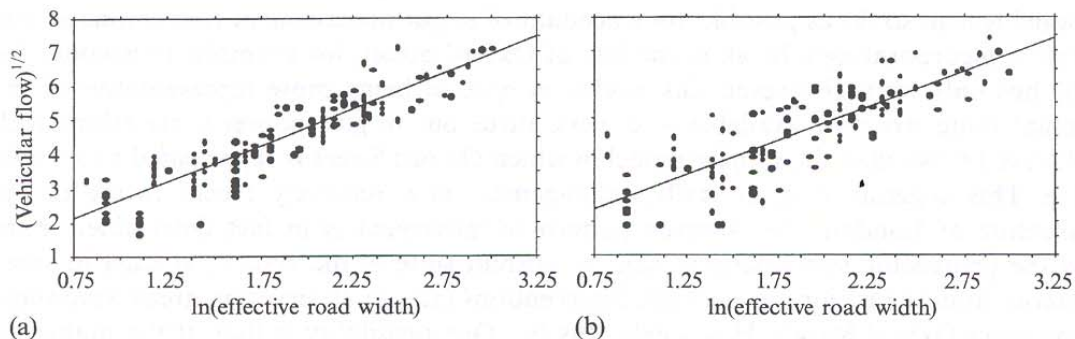
In light of these results it is tempting to suggest that spatial integration contributes the demand side, and capacity the supply side of the equation for vehicular flows in the primary road structure: however integrated you make an area, average flows through it will never rise far above those at capacity. Equally, however wide you make a street



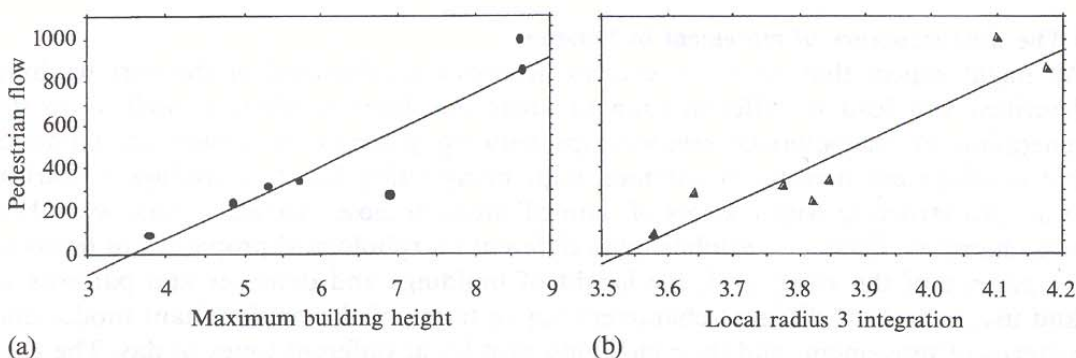
segment the flows through it depend on how it is embedded in the network and whether it is in demand as a through movement space. In this way global integration quantifies the potential for through movement that the lines within an area hold when considered in terms of the topology of the whole network and so effectively quantifies travel demand, not for specific origin–destination pairs but for all origins and destinations in the network.

One of the effects of this appears to be on the way that traffic management, and in particular the supply of effective road width, evolves over time to fit the demand side of the equation. When we look at the effect of the road closures in the City of London immediately following the terrorist bomb in 1992, it is clear that the relationship between vehicular flows and capacity had begun to break down. Figure 13(a) shows that, although the correlation is tight in the narrower, lower flow rate, streets of the city, amongst the primary route structure there was a great divergence between road width and flow. This we believe to be the immediate effect of the closure of two main through routes as a result of the bomb. However, when those routes were reopened, a massive security cordon was established around the whole of the commercial heart of the city.

The cordon restricts entry to the security zone to a limited number of locations and has had a great effect on vehicular flow patterns across the whole area. The effect of the cordon can be seen in a far greater degree of variance in the lower parts of the scattergram in figure 13(b). This suggests that in the evolution of the city a mechanism is in operation which restricts capacity in those street segments that are not in demand



**Figure 13.** Correlation between vehicular flow rates and the effective road width in the City of London ( $r = 0.901$ ,  $p < 0.0001$ ) after the bomb road closures (a), and after implementation of the security zone ( $r = 0.817$ ,  $p < 0.0001$ ).



**Figure 14.** Mean pedestrian movement rates across the London study areas are best related to measures of the average maximum building height (a) and the radius 3 measure of 'local integration' (b).



for through movement, for instance, by allowing on-street parking. However, in the primary globally integrated structure, where there is a demand for through movement, parking will be restricted and capacity maximised through the normal process of traffic management to ease congestion. Following a local change to the network such as that caused by the bomb, the effects are seen only on the routes directly affected by road closures. However, after a massive change in the network topology such as that produced by the security cordon, it seems clear that, although the flow patterns will shift overnight, the pattern of effective capacity will take some time, possibly years, before it adapts to suit the new demand structure through the normal process of traffic management implementations.

The model which is implied is a spatial market in which the demands imposed by the configuration of the grid are met by the supply of road capacity through the continual adaptation and adjustment of individual traffic management and parking provision schemes. The mechanism is self-regulating in much the same way as that which we propose governs the allocation of retail land uses to urban sites through a multiplier effect. At the root is the configuration of the network which it seems may play a far more active role in determining the way the city evolves and behaves than has been thought up to now.

A second piece of evidence supports this view of the city as a dynamic evolving system. When we first set out on this research we believed that configurational measures would prove very limited in their ability to predict vehicular movement patterns because they currently do not support a representation of one-way streets and turning restrictions. In view of this we constructed a vehicular 'management' version of the London model which, so far as possible, took account of major management restrictions on car traffic, incorporating a break in the line of Oxford Street, for example, to account for the bus only route. However, this model, in spite of being more representative of the actual route structure available to drivers, turns out to give poorer correlations with observed flows than the simpler model in which Oxford Street is represented as a single line. This suggests that, as traffic management is a relatively recent factor in the structure of London, the observed pattern of movement is in fact determined more by the preexisting street pattern than the current state of the system, at least in areas remote from the major management interventions (all our observation areas were some way from Oxford Street). How might this be? One possibility is that, if the multiplier effect has indeed allocated land uses and densities according to movement patterns determined by spatial integration, spatial integration itself now serves as a sensitive measure of the allocation of origins and destinations for trips in the network. In effect there may be a long-term inertia inherent in the system.

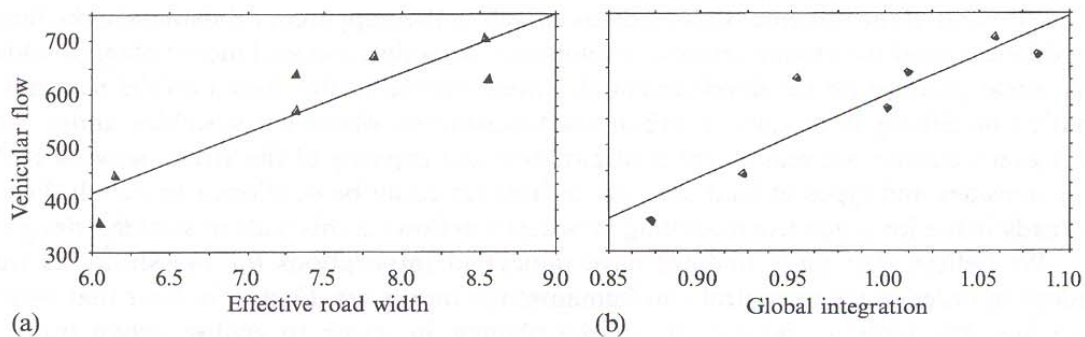
### **3 The area structure of movement in London**

We might expect that, as a city evolves, feedback mechanisms of the sort we have described will lead to differentiation of areas one from another, as well as to the generation of characteristic relationships between patterns of movement, land-use, and development density. In common with many cities, London displays a marked local area structure with a series of 'named' areas in close proximity, each with their own character. Each area exhibits quite different morphological properties in terms of the pattern of the street grid, the height of buildings and densities and patterns of land use, as well as different characteristics in terms of the predominant modes and patterns of movement, and their changing profiles at different times of day. The case studies in the present research selected a series of well-defined areas including the commercial City of London, the shopping area around the Brompton Road, the high-class residential and museum complex in South Kensington, and the 19th



century residential suburb of Barnsbury. Each whole area was described in terms of the main land use, movement, and configurational variables, and a search was made for regular associations between these for all the areas.

At the level of whole areas two factors are correlated with average pedestrian flow rates, a measure of development density—the average of the maximum building heights for each street segment [see figure 14(a)]—and a measure of local (radius 3) integration of the street grid [see figure 14(b)]. Although there are other correlation coefficients of average pedestrian movement rates—notably measures of the predominant land use—these two out rank them by a clear margin. Mean vehicular flow rates are not particularly well related to these two measures; however, they are strongly related to the average effective road width [the total width of the road, less pedestrian pavements and car parking bays; figure 15(a)] and the average global integration of lines in the area [see figure 15(b)].



**Figure 15.** Effective road width (a) and global integration (b) are the two best correlates of mean vehicular flow rates in all road segments of an area.

The findings that, on an area by area basis, average pedestrian flow rates depend on development density and on the degree of local integration of the street grid morphology whereas vehicular flow rates depend on a measure of the average capacity of the roads and their global integration in the city as a whole confirm existing thinking. Development density and capacity are major factors dictating flows. But they move beyond this to suggest that the degree of locality or globality of the street grid configuration measures may indeed be able to quantify aspects of different distributions of trip lengths for different traffic modes and through this suggest a far more active role for the network configuration than has usually been allowed. Importantly, multiple regression analysis suggests that global integration and capacity measured in terms of effective road width account for nearly all the variance in mean vehicular flow rates for the study areas ( $r^2 = 0.966$ , see table 3) with each contributing almost equally. This suggests that it is the location of an area in the whole city that determines its mean level of vehicular movement, with more centralised locations gaining higher movement levels than more peripheral ones but that the mean movement level is almost equally constrained by the capacity of the network. For pedestrians it is the

**Table 3.** Multiple regression of mean vehicular flow rates against measures of mean global integration and mean effective capacity.

	DF	$r$	$r^2$	$p$	$t$	$p$
Mean radius $\infty$ integration	6	0.983	0.966	0.0011	4.3	0.0129
Mean net capacity					4.2	0.0138

**Table 4.** Multiple regression of mean pedestrian flow rates against measures of mean radius 3 integration and mean development density measured as segment maximum building heights.

	DF	<i>r</i>	<i>r</i> <sup>2</sup>	<i>p</i>	<i>t</i>	<i>p</i>
Mean radius $\infty$ integration	6	0.989	0.979	0.0004	4.9	0.0083
Mean maximum building height					2.5	0.0634

degree of local accessibility measured in terms of radius 3 integration coupled to the density of development and the land uses that have most effect (see table 4), with global location being a less important factor.

#### 4 Cities and the local–global interface: humanising the car

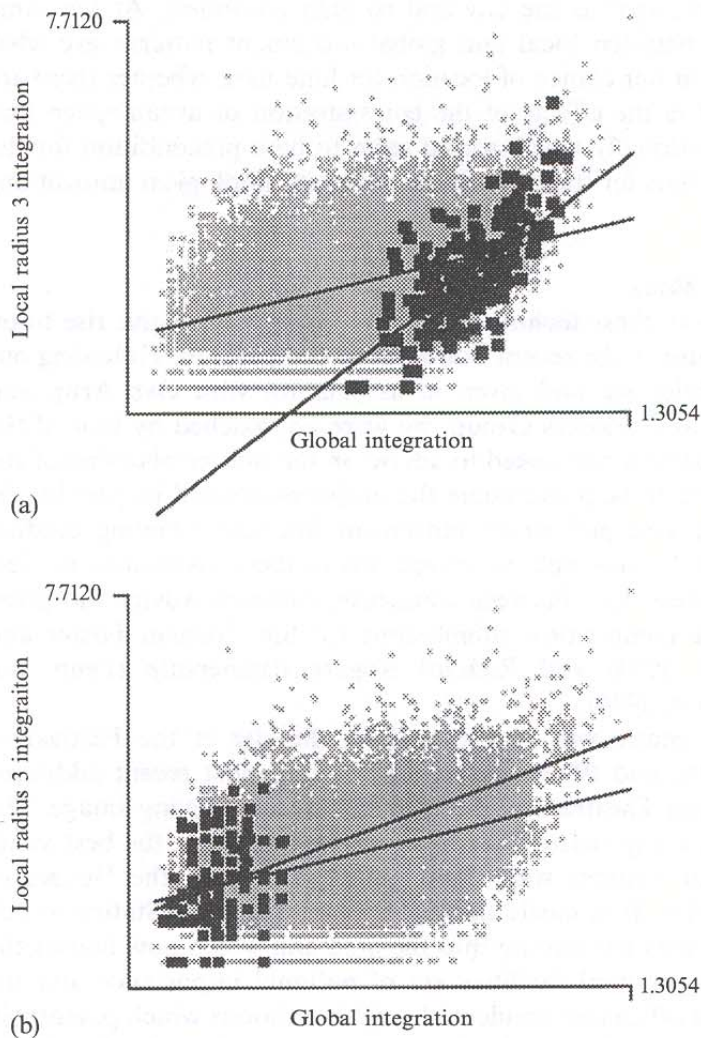
The strength of the vehicular flow findings as well as their apparent robustness in the face of different land-use characteristics, development densities, and grid morphologies holds out great promise for the development of a predictive capability based on the new simplified modelling techniques in urban master-planning where the variables under the designer's control are mainly the configuration and capacity of the street network and the densities and types of land use. The techniques could be developed to match those already in use for predictive modelling of pedestrian flows at this scale of strategic design.

We believe that these findings have important implications for the strategies we adopt in order to try to control and humanise the motor car. First, it is clear that there are four key tools at the disposal of the planner in trying to civilise urban traffic: (1) the configuration of the street grid; (2) the capacity of the street segment; (3) the distribution of land uses; and (4) the distribution of development density. In order to civilise the car it is necessary to bring pedestrian movement onto more equal terms. So long as cars outnumber pedestrians in a space by 8 to 1, they will always appear to dominate urban space. The data show that by attracting a sufficient density of retail and/or commercial land uses pedestrian numbers can be significantly raised and that the recipe for viable long-term retail centres depends on achieving sufficient levels of both local and global integration for the multiplier effect to take off.

Second, it seems possible that, by exploiting self-perpetuating and self-regulating mechanisms such as the multiplier effect, we can achieve stable long-term conditions. Other strategies which seek to work against the natural effects of spatial configuration require continued effort and investment to sustain them. The shop placed in the centre of the housing estate in order to 'liven it up' is a case in point. Experience shows that shops considered as 'attractors' need subsidies or continued investment in order to survive if their location in the street grid is wrong. The more robust formula allows the pattern of through movement generated by the grid configuration to do at least part of the work in ensuring economic viability of land use.

Third, the requirement of local and global integration for the shopping multiplier effect seems to be founded on the need for shops both to maximise the level of passing trade and to even it out through time. In more segregated residential areas the difference in movement levels between the peaks and the low points is significantly higher in percentage terms than it is on primary routes. It thus seems logical to locate newsagents in local integrators—these shops do their business during the peak periods through a large number of very short transactions. However, more specialist types of comparison outlet need a greater size of catchment and a more globally strategic location in order to gain a greater passing trade. For the kind of mix of shopping types that characterise a shopping centre, a full range of local and global catchments is needed.





**Figure 16.** The correlation between local radius 3 and global integration for the whole London model with: (a) the City of London highlighted in black; (b) the Isle of Dogs in London's Docklands highlighted in black.

This last effect seems to underpin one of the key features of urban space. If cities are, as the aphorism has it, 'mechanisms for generating contact', one of their main tools lies in the way that they relate local and large-scale patterns of movement and how both are brought into contact with land uses, thus making possible the interaction and transaction upon which the socioeconomic life of the city depends. In studying the character of urban subareas in large cities like London, we find a consistent pattern in which the measures of local and global integration for all the spaces within a named area regularly correlate strongly together. Figure 16(a) shows the correlation between radius 3 and radius  $\infty$  integration, with the square mile of the City of London highlighted as black dots. In areas which seem to have lost the coherence that people call 'urban', in recent housing estates and run-down industrial areas for instance, these correlations are broken and often replaced by layered hierarchies of spaces. Figure 16(b) shows the complete absence of a local intelligible focus in the Isle of Dogs surrounding the Canary Wharf development. These local to global correlations between spatial properties are exactly what allows the parts of cities to come together to form a global whole and, more importantly, they are what makes the urban network intelligible to us, whether we are pedestrians or drivers. Essentially, intelligible space allows individuals to behave

in a rational way as they move around the city and so gain autonomy. At the same time, the consistent relations between local and global movement patterns are what allows us to behave rationally in our choice of location for land uses, whether these are where to work, sell or live. It is the effects of the configuration of urban space that allows individuals to behave rationally which would seem to be a precondition for the social function of the city and thus for the civilisation of new technological innovations such as the motor car.

### **5 Revitalising London's South Bank**

An example of the application of these techniques and the theories they give rise to on a live design problem is their use in the recent South Bank competition. Following our research in the area, and advice we had given in association with Ove Arup and Partners to the South Bank Land Owners Group, we were approached by four of the ten shortlisted second-stage entrants and asked to advise on the master-planning of the area. Their main concerns were to help overcome the problems created in part by the grade separation of vehicular and pedestrian movement but still avoiding conflict between the two modes. We were only able to accept two of these invitations in view of the need to maintain a 'Chinese wall' between competing entrants. Advice was given to, and incorporated into the competition submissions by, Sir Norman Foster and partners (Hillier and Major, 1994) and Richard Rogers Partnership (Penn and Vaughan, 1994; Penn and Major, 1994).

The South Bank cultural centre was constructed on the site of the Festival of Britain during the 1950s, 1960s, and 1970s (see figure 17). The most recent additions to the complex are the National Theatre and the Museum of the Moving Image. The site has great potential. It has a city centre river frontage with amongst the best views in London. It is less than ten minutes walk from Trafalgar Square, the Houses of Parliament, and Covent Garden. It is easily accessible from Waterloo Station which brings some 40 million passengers per annum into the area and which now houses the Channel Tunnel terminal. The cultural facilities are of national importance and the area is adjacent to commercial office and residential neighbourhoods which potentially provide a strong local constituency for the facilities in the area. However, for all the success of the cultural facilities themselves, the area has come under criticism for failing to make the most of its urban potential. It was the problematic nature of the area, coupled to the use of upper level walkways to separate vehicular and pedestrian traffic that had originally led to its selection as one of the case-study areas for our research. We felt that if configurational modelling techniques were to be of use in understanding the behaviour of vehicular and pedestrian traffic in the fine-scale structure of the street grid they would need to be able to cope with extreme examples of different kinds of spatial design such as the South Bank area.

That research had led to some very specific diagnoses of the problems of the area. In common with many of the more recently developed areas of London facing onto the Thames, the South Bank is effectively on a peninsula. This serves to segregate the site from the rest of the city and, particularly for east–west movement, remove the river frontage from naturally 'integrated' routes. The main alignments to the north are separated in level from the river frontage by the height of the bridges, and the main east–west vehicular route along Stamford Street and York Road acts as an effective discouragement to pedestrian movement from the south.

This has two immediate effects. The first is to separate the different constituencies of pedestrians who use the site: tourists follow the river edge, commuters head for the bridges and station, local residents and workers make for the east–west alignment of streets south of Belvedere Road and Upper Ground. Each group uses one set of spaces





Figure 17. Plan of the South Bank, London.

and is usually there only at certain times of day. In between times the space is taken over by unsanctioned and often antisocial use which takes advantage of the 'lacunae' of mainly deserted walkways and the protection afforded by the lower level service areas.

The second effect is to make retail unviable because shops rely on continuous passing trade. This means that the area has never been successful in starting the multiplier effect that allows traditional urban shopping areas to thrive. It is perhaps the contrast between the great potential of the area and its facilities, and its singular lack of success in taking advantage of these to generate the more informal retail and service land uses that would bring activity and life to the area, that makes its failure so striking. It seemed clear then that the formula for revitalising the area would rely on taking advantage of the potential afforded by through movement—both pedestrian



and vehicular—to make informal land uses viable. Effectively, the retail multiplier effect needed to be kick-started and the central questions asked by the design team turned on the physical and spatial changes that would be needed within the South Bank complex and in its links to the surrounding areas to accomplish that. From the research we were able to isolate four factors which work together to produce the apparently unforced relationships between different kinds of activity and facility in the traditional city and which the South Bank would need to emulate if it were to become sustainable in its role as the cultural centre for the United Kingdom.

(1) The network of streets and spaces in an area produces a pattern of natural pedestrian and vehicular movement. All other things being equal, the routes that people take as they move around an urban area are defined by the pattern of the street grid itself. Main streets tend to be on more routes between different places than back streets and so attract greater levels of use. The number of routes and thus the amount of movement a space will attract can be measured as the degree of spatial integration of the pattern of the grid itself by means of a computer. Where the grids are effectively different for the pedestrian and vehicular modes we construct different models for each. In the case of the South Bank, the pattern of integration in the areas bypasses the central area of the cultural complex, with its heart being segregated and almost all through movement located on the peripheral spaces [see figure 18(a)].

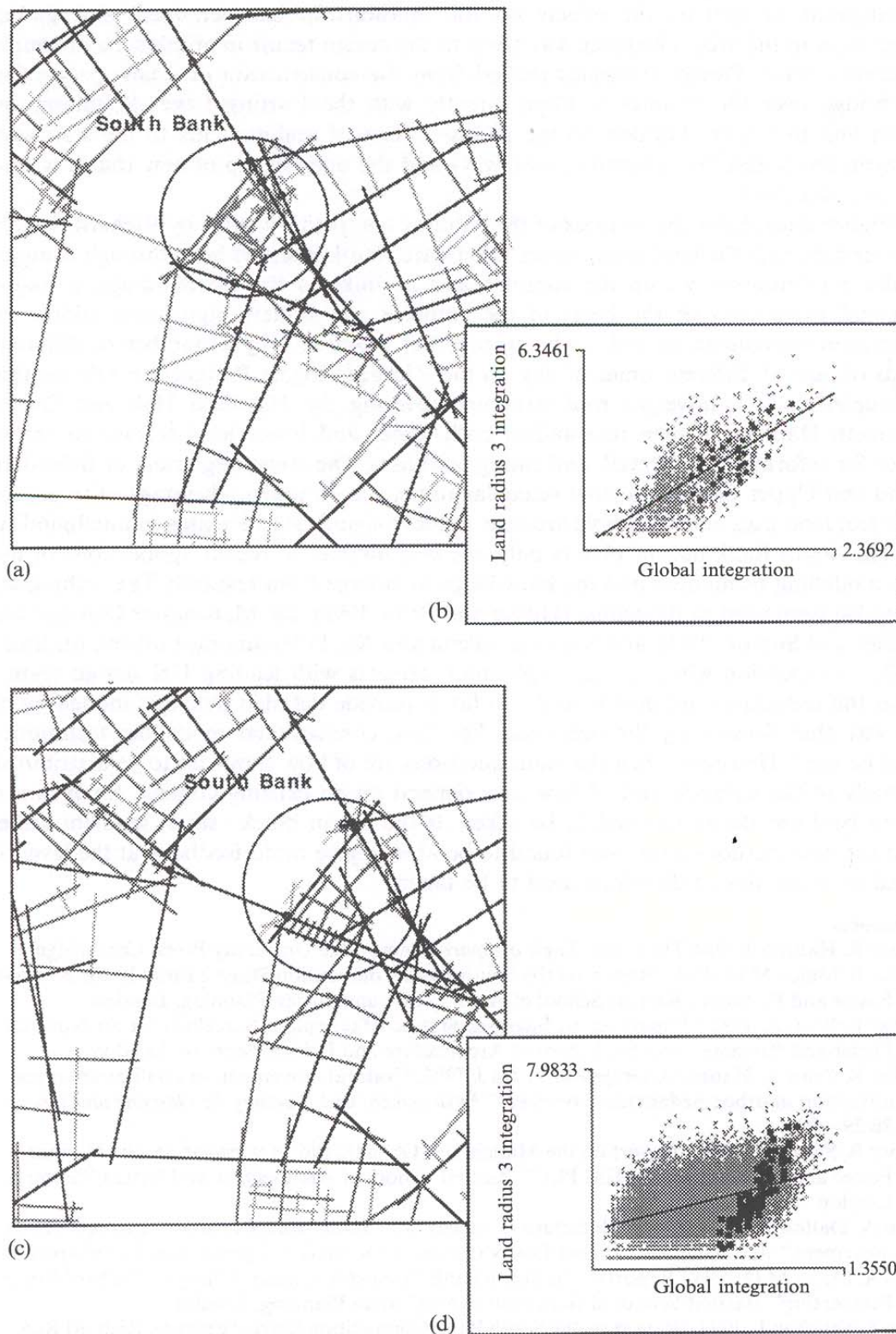
(2) Most movement in urban areas is through movement. The majority of people you see walking down a street tend to be going to and from other streets. However, their presence is one of the main resources of the city. The presence of people makes spaces feel alive and safe, as well as being the main prerequisite for the economic life of the city. For shops to set up and survive, the presence of a passing trade is the single most important factor.

(3) Once shops have set up on a street they become destinations for to movement in their own right. In effect, the presence of shopping in an area acts as a multiplier on the underlying pattern of natural movement induced by the pattern of the grid. The multiplier effect shows itself as a logarithmic relationship between the measure of spatial integration and the flow of pedestrians in an area. It works like this: the more a space is used for through movement, the more attractive it is for shops; the more shops a space gains, the more it becomes a destination in its own right. In this way, the pattern of through movement is the catalyst for a vital and viable urban area. One of the fundamental problems of the South Bank is that it diffuses through movement from different pedestrian and vehicular constituencies onto different spaces so that none of them reach the threshold at which the multiplier effect takes off.

(4) Through movement alone is not enough to produce a successful urban shopping area. It is important that spaces capture both local and larger scale patterns of movement, as it is this that evens out the patterns of movement through the day and provides continuous passing trade. Successful urban areas are characterised by a strong relationship between the degree of local and larger scale integration of the spaces in the area. This 'local focus' is shown as a correlation within the local to global scatter-gram for an area [highlighted dots rising as a tight line across the regression line in figure 16(a), for example]. An analysis of the South Bank area highlighted in this way showed that the area suffered from a lack of coherence between local and global spatial properties [see figure 18(b)].

With these principles in mind, our involvement with the different design teams involved in the competition was through the iterative modelling of design proposals. As various schemes were developed, they would be modelled in terms of their changes to the configuration. As the configuration changes, the whole pattern of integration in the area and in its surroundings also changes and these effects were





**Figure 18.** (a) Local integration map of the existing South Bank which shows that integration is focused around the perimeter of the site and that the site itself is highly segregated; (b) Scatter of the existing South Bank within its larger urban context which reveals a 'lumpy' scatter indicating that the South Bank is unintelligible for movement; (c) Local integration map of the Richard Rogers Partnership proposal for the South Bank showing the increased levels of integration in the site; (d) Scatter of the Rogers proposal for the South Bank within the context of Greater London which indicates that the proposal would generate an intelligible, local area effect.

investigated as well as the effects on the relationship between local and global integration in the area. Feedback was given to the design teams in graphical and simple numerical form. Design strategies ranged from the construction of a new pedestrian footbridge over the Thames to align directly with the Carting Lane–Southampton Street link to Covent Garden, to the precise effects of realignments to the stairways between levels and the removal of walkways and the opening up of new routes within the complex itself.

Figure 18(c) shows the analysis of the winning competition entry by Richard Rogers Partnership, with the local area scatter [see figure 18(d)]. It shows how, through changes to the configuration within the complex and its links to the surroundings, a major diagonal route through the heart of the complex can achieve significant additional pedestrian movement, as well as bring together movement by a number of different kinds of user at different times of day. In the Richard Rogers Partnership scheme this is coupled to a lightweight roof structure covering the Hayward Hall and Queen Elizabeth Hall which then internalises both upper and lower level terrace to create space for informal foyer, retail, and eating land uses. The street alignment of Belvedere Road and Upper Ground, a slow vehicular route, can be taken advantage of to secure on-street land uses and the whole area can achieve significant increases in intelligibility.

The South Bank master plan is only one of a number of recent applications of the new modelling techniques and the knowledge to emerge from research. The techniques have also been used in Barcelona (Hillier and Penn, 1992), the Manchester Olympic bid (Hillier and Stonor, 1993), and Shanghai (Penn and Xu, 1993) amongst others, for high-profile competition winning master-planning projects with leading UK design teams. What the techniques are unable to do so far is provide detailed dynamic modelling of the way that flows vary through time. For this, conventional modelling techniques must be used. However, when the main questions are of how flows are to be distributed spatially in the network and of how they depend on an existing context, for instance where land-use decisions need to be taken at the urban block–street segment scale, then the new methods have been found to be able to give rapid feedback at the level of detail at which design decisions need to be taken.

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