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Movement Economies in Fractured Urban Systems:
The Case of Boston, Massachusetts

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0.0 Abstract

This thesis explores the influence of configuration on movement in fragmented, low intelligibility spatial systems. Traditional space syntax theory holds that correlation between space and movement breaks down in such situations, resulting in lower predictability and / or apparently chaotic behaviour.

This thesis uses the case study of Boston, Massachusetts to test three hypotheses; 1) that space is indeed influential on fragmented systems, 2) that other variables are less important than space in predicting movement, and 3) that space – movement correlations are distributed non-uniformly between areas and user groups. These are tested through the use of multiple regression analysis and a new technique named "correlation contour mapping," which outlines the boundaries of predictability within complex spatial systems.

It will be shown that space plays a significant role in pedestrian movement in Boston, but that it correlates non-uniformly with different areas and users. An understanding of sub-area definitions and the effect of overlapping patterns of correlation is therefore necessary in order to fully comprehend the effects of fragmentary configuration. It is suggested that the use of correlation contouring may achieve this and might be a useful tool for exploring the interaction of different user groups in urban space.

This understanding is then used to construct a pedestrian movement model to forecast the effects of a large-scale urban regeneration project in Boston, known as the "Big Dig". The implications of these findings for other fragmented cities are also discussed in a context of successful urbanisation, based on the work of Lewis Mumford, Jane Jacobs, Kevin Lynch, and Bill Hillier.

Keywords: Intelligibility, fractured spatial systems, American cities, urban regeneration, pedestrian movement modelling

Contents

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"Currently the most popular and effective means of destroying a city is the introduction of multiple-lane expressways, especially elevated ones, into the central core. This came about immediately after elevated railways for passenger service were being demolished as public nuisances. Although Los Angeles presents the hugest example of large-scale urban demolition by incontinent expressway building, Boston is perhaps an even more pitiable victim, because it has more to lose, since it boasts a valuable historic core, where every facility is in walking distances, and a metropolitan transit system that, as far back as the eighteen-nineties, was a model of effective unification… Boston's planners are attempting to cover their initial mistakes by repeating them on a larger scale."

Lewis Mumford, *The City in History*, 1961

1.0 Introduction

This thesis fits into a tradition which asks, "What makes for successful urbanism and what, if any, role does spatial layout play in this process?" It uses one of the largest civil engineering projects in American history as a case study to explore the role of complex space in this question, building on the work of Lewis Mumford (1961), Jane Jacobs (1963), Kevin Lynch (1969), and Bill Hillier (1996).

This thesis specifically addresses the influence of configuration on movement in fragmentary spatial systems. The relationship between integration and movement has been well documented in space syntax literature, but the correlation between these variables tends to break down under conditions of low intelligibility (Peponis, 1990; Penn, 2001; Chang and Penn, 1998; Conroy-Dalton, 2001; Hillier 2003). It has been suggested (Hillier and Hanson, 1984; Hillier, 1989; Peponis, 1989; Major et al., 1999; Hillier, et al, 1993; Hillier, 1996) that cognitive processes may account for this lack of correlation, but additional investigation is necessary if researchers are to understand the dynamics of movement in compartmentalised and/or incoherent spatial systems.

This thesis uses multiple regression analysis and a new technique known as 'correlation co-efficient contouring" to test the following null hypotheses related to these issues:

1) Space does not play a significant role in low intelligibility systems
2) Other variables such as land use or attractors are more important in fragmentary systems
3) When it predicts, space predicts uniformly for all users and uses

The city of Boston, Massachusetts is used as a case study to test these hypotheses. Boston has become an iconic symbol of fragmented American cities, having undergone a series large urban renewal interventions in the 1950's that significantly altered its spatial structure. The destruction caused by these projects has played an important role in the thinking of urban theorists like Mumford and Jacobs, making Boston an important case study to include in any discussion of fragmentation or urban renewal. Currently the city is undergoing massive transformation to its spatial structure, known as "the Big Dig", which offers a useful natural experiment to test the role of space in successful urbanisation. Although similar conditions exist in many other American cities, few are as influential in scale or significance.

This thesis uses the techniques of space syntax axial line mapping to describe and analyse the spatial conditions before, during, and after the Big Dig, relating the city's morphological characteristics to patterns of pedestrian movement. It also discusses the role of urban design in sub-area formation and neighbourhood identity, offering a methodology which may be of use for better defining and understanding such sub-areas. Finally, it discusses the conditions necessary for creating the sense of vitality and life sometimes known as the ‘urban buzz’.

2.0 Literature Review

2.1 Theories of Successful Urbanisation

The challenge of understanding what makes for successful urbanisation is an enduring and relevant question. The interaction between city form and the life of urban spaces has particularly important implications for the way that we design and build our cities, given the numerous examples of failed public spaces and urban regeneration projects in the 20th century. Current debates over social and environmental sustainability add a particular urgency to the need for understanding these components of successful city building.

Clearly, any discussion on the relationship between urban design and successful urbanisation must concede that this process is the result of both physical and social efforts. But what mixture of physical and social factors can account for the mysterious quality of vitality experienced in some spaces and some cities, while simultaneously describing the reasons for the equally dead and inactive spaces in other cities? What influence can design have on stimulating the socialisation and vibrant activity that is normally associated with a thriving urban community? And what, if any, specific lessons or tools can the contemporary architects and urban planners utilise to help maximise the chances of success in their projects?

In an early essay on the modern city, historian Lewis Mumford writes that “one cannot base an adequate architectural conception [of the city] on such a crude sociology as that which led a group of modern architects and planners to examine the modern city with reference to only four functions; work, transportation, dwelling, and recreation. The city, if it is anything, is an expression of man’s wholeness – a representation in buildings of his nature and purposes.” (Mumford, 1963, p.162)

For Mumford, successful urbanisation results from an interrelated “cellular” approach to urban form, “each cell balanced and partly self-contained but also part of a wider social whole.” (Mumford, 1972, p.170). He asserts that cities are not conceivable as a pattern of highways, streets, and public spaces alone, “capable of indefinite extension”. They must be understood as an interrelated series of overlapping sub-areas, each area functional in their own right with a balance of uses, users, and interfaces. They should be fractal reflections of the structure of the city as a whole, themselves an overlapping ecology of users and groups – in his words, “the city writ small”. (Mumford, 1972, p. 171). But sub-areas cannot be islands unto themselves. Mumford is clear that the connection of such areas to the larger network of the city is vital for the health of both sub-area and macro-structure.

Mumford's vision of systems level urbanism provides a crucial context for the discussion of successful urban structures, but requires additional criticism to be of specific use for architects and urban planners. Jacobs expands upon Mumford's general ideals in her seminal work, *The Life and Death of Great American Cities* (1963), in which she offers more detailed examples of how such networked processes can manifest successful urban cultures.

Jacobs also emphasised the primacy of the neighbourhood sub-area as the nexus of urban community life. Using the neighbourhoods of Boston as an example, Jacobs outlined four specific components of successful, self-organised urbanisation. These were:

1) Foster lively and interesting streets
2) Make the fabric of these streets as continuous a network as possible throughout sub-area districts
3) Use parks, squares, and public buildings to intensify and knit together different uses, sub-areas, and levels of complexity
4) Emphasize the functional identity of areas large enough to work as districts

Although the bulk of her work focused on the elements of successful neighbourhood life, she did not harbour illusions of sub-area self-sufficiency. She levelled powerful criticisms at the "ideal of supposedly cosy, inward-turned city neighbourhoods" of approximately 7,000 people, each with their own independent school system, shopping street, and community centre. (Jacobs, 1963, p. 124) The point of cities, she writes, is the interconnectivity of human activities and the opportunities that these connections provide. "The conception of neighbourhoods in cities is meaningless – so long as we think of neighbourhoods as being self-contained units to any significant degree, modelled upon town neighbourhoods." (Jacobs, 1963, p. 127) She concludes by emphasizing that "the city's very wholeness in bringing together people with communities of interest is one of its greatest assets, possibly the greatest." (Jacobs, 1963, p.129) For Jacobs, this process occurs on the neighbourhood level, but only insofar as these neighbourhood structures allow for appropriate levels of intermixing with other sub-areas and activity groups.

The writing of Jacobs has proven invaluable in articulating the necessary processes and forms required for successful urbanisation. Her work, however, lacks more detailed guidelines that could assist architects and planners in understanding the conditions of real sites within specific cities, each of which are no doubt unique and idiosyncratic in nature. Jacobs placed valuable emphasis on the political aspects of neighbourhood and city administration, but aside from emphasis on small block sizes and well-connected pavement networks, she focused relatively little attention on the precise design typologies that could contribute to vital urban life.

A more detailed understanding of the morphological conditions that contribute to sub-area definition is therefore necessary. The work of Kevin Lynch (1960) is considered one of the classic references on the relationship between urban design, sub-area definition, and spatial cognition. Lynch interviewed a small sample of professional class Boston residents and had them draw maps of their image of the city. He then used these maps to construct a generalised map of Boston's sub-areas, which allowed him to extrapolate on the built form variables that influenced sub-area definition and spatial cognition.

Lynch identified five elements that influenced a city's "imageability". These elements were:

1) Paths, or common routes of movement
2) Edges, that are linear elements that defined boundaries between other elements
3) Districts, into which observers mentally "enter" and that are identifiable from inside and out
4) Nodes, which are the "strategic spots" in a city that allow transfer between Districts or Paths
5) Landmarks, that are "point-reference" objects which act as recognisable place markers to enhance observers' understanding of their location

Lynch built a theory of "good city form" from these five elements (Lynch, 1981). Aside from a general discussion of how these elements should be balanced, however, Lynch's work also lacks adequate specificity to be of practical use for planners and architects. The limits of his sample size (less than 30 individuals) and the vagueness of his terminology limit the falsifiability of his hypotheses. Lynch himself admits that "better methods must be evolved" to be of use to urban designers. (Lynch, 1960, p. 156).

The research of Hillier and his colleagues at the Space Syntax Laboratory provide a more rigorous and testable framework to evaluate the theories of Mumford, Jacobs, and Lynch. Hillier et al's earlier work (1987) outlines the foundations of the space syntax approach. This work seeks to answer the questions, "does spatial layout influence the pattern of space use and movement", and if so, "does this have social consequences?" (Hillier et al, 1987, p. 234)

Hillier et al's work over the last twenty years has provided convincing evidence that urban form and spatial layout exerts a strong influence on movement patterns, creating "probabilistic fields of encounter" between social groups and activities in urban space. The intensity and likelihood of these fields is directly influenced by degrees of spatial accessibility, which can be measured by line-of-sight, least line "axial maps".

The findings of this research suggest that pedestrian traffic tends to utilise more "integrated" routes for movement and that different types of activities and land uses require different levels of integration to function. Hillier suggests that movement-intensive land use patterns such as retail are attracted to locations with high natural movement, and non-movement seeking land uses such as residences are located in low integration locations. This creates a "multiplier effect", where attracted uses then attract more movement to high movement locations, which in turn attracts further uses, creating a feedback cycle of activity resulting in "an urban pattern of dense mixed use areas set against a background of more homogeneous, mainly residential development." (Hillier, 2001).

Hillier (2001) calls such patterns "configurational inequalities", or different concentrations and distributions of integration that mediate the relationship between less integrated, private sub-areas and well integrated public spaces and routes. This fits well with the thinking of Mumford and Jacobs. In his essay, "A Theory of the City as Object" (2001), he writes,

> "Movement emerges as the 'strong force' that holds the whole urban system together… In light of these results, we can reconceptualise the urban grid as a system of *configurational inequalities* - that is, the differences in integration values in the lines that make up the axial map - which generates a system of *attractional inequalities* - that is the different loadings of the lines with built form densities and land use mixes - and note that in the last analysis, *configuration generates attraction."*

Penn et al (1993) provide an example of how configurational inequalities influenced activity between different groups in their study of the South Bank Centre in London, England. The Centre occupies a privileged location in the heart of London, with stunning riverfront views, close proximity to major tourist attractions and transit facilities, and is surrounded by mixed-use offices and residential neighbourhoods. Yet despite possessing all the factors apparently necessary for urban vitality, the area was frequently underutilised and criticised for failing to realise its potential. Using axial analysis, it was found that the site was segregated from the major integrating lines of movement surrounding it, resulting in different and unrelated patterns of use by different groups.

This relativistic capacity of space, affording different possibilities for different scales of movement and users, has powerful implications for understanding how successful urbanisation comes about. As Mumford and Jacobs repeatedly emphasized, successful urbanisation requires a balanced and structured mixing of different uses and groups that allows for both global combination and local separation. Hillier's measures of integration and his study of the structures of "configurational inequalities" may provide the missing element that could allow architects and planners to realise Jacobs' vision of successful urban environments. It also offers a quantitative tool to test Lynch's elements of urban form and "imageability" in more precise terms. A study of a city's patterns of integration can therefore yield powerful objective insights into the activity and vibrancy of the process of urban social life. Integration, in other words, could be seen as an objective, quantitative index of urbanisation.

But how does this process function under conditions not conducive to natural movement? The following section reviews the existing literatures on this issue and frames the topic of this thesis in more detail.

2.2 The Role of Intelligibility and Fragmentation in Urban Movement

A wide variety of space syntax studies have examined the relationship between integration and pedestrian movement under normal circumstances (Hillier and Hanson, 1984; Hillier, 1989; Peponis, 1989; Major et al., 1999; Hillier, et al, 1993; Hillier, 1996). It is not uncommon to achieve correlation co-efficients of 0.8 or higher between integration and observed movement when conditions approximate all-point to all-point movement. Hillier et al. (1993) refers such movement as "natural movement", or the percentage of movement resulting from the configuration of the urban grid itself.

Natural movement relies on an adequate level of intelligibility, or the ratio of connectivity to global integration measures (Hillier et al., 1987). Intelligibility measures the degree to which local spatial conditions convey information about global structure and position, thus encouraging wayfinding ability and ease of navigation. It has been found that complex environments with difficult or confusing layouts often result in conditions of "unintelligibility", or low correlation between these two variables. This makes navigation and wayfinding more difficult, often weakening the relationship between space and movement (Peponis, 1990; Penn, 2001; Chang and Penn, 1998; Conroy-Dalton, 2001; Hillier 2003).

Penn (2003) suggests that the consistent correlation between configurational spatial properties and pedestrian movement can be explained by looking at the underlying mechanisms by which people perceive, understand, and then navigate their surroundings. He asserts that cognitive space is made sensible through the locomotive exploration of the environment, and the more intelligible the environment, the better the spatial cognition.

Several studies from both the space syntax and cognitive science literatures provide evidence to support this notion. Peponis et al. (1990) used space syntax to map the interiors of hospitals, then gave study participants a tour of each hospital. Participants were then asked to conduct wayfinding activities within each hospital and their performance was measured in a variety of ways. It was found that participants were able to more quickly find interior landmarks in higher intelligibility environments than lower intelligibility environments, suggesting that spatial layout strongly affects navigation in complex interior environments.

In his study of adjacent neighbourhoods in a north London suburb, Kim (2001) asked residents to draw sketch maps of their local environment and then conducted axial analysis of these maps. These were then compared to axial maps of the actual neighbourhoods under study. Kim found that the degree of intelligibility of each neighbourhood corresponded to the accuracy of the sketch maps drawn by its residents, suggesting that a higher degree of intelligibility resulted in better spatial understanding.

Conroy–Dalton's (2001) work provides an interesting bridge between these two scales of study (the architectural and the urban). Using virtual reality technology, Conroy–Dalton (2001) analyzed the behaviour of real people navigating virtual environments with different degrees of intelligibility. In addition to finding that people tended to follow angle-minimizing pathways, she found that people tended to take longer to navigate less intelligible spatial systems and got lost more frequently in low-intelligibility virtual worlds than in high intelligibility ones. Based on this evidence she concludes that local visual cues that are well related to global structure helped subjects navigate more effectively, while local cues that are not well representative or even misleading of global structure can produce the opposite effect. All of these studies indicate that environmental intelligibility is an important variable in learning, understanding, and navigating complex spatial systems.

There are many studies from cognitive science that support these findings, but their measurement of space is often less precise than space syntax research. Haq and Girotto (2003) cite a study by Wiesman (1981) in which seventy-three self-reports regarding wayfinding in ten university buildings were analyzed relative to the "simplicity" of the floor plan of each building. It was found that simplicity related strongly to self-reported wayfinding performance. O'Neill (1991) also found that higher levels of configurational understanding in test subjects was frequently associated with better wayfinding performance. Golledge (1999) also reviews a variety of studies that suggest that errors in cognitive maps inhibit spatial problem solving, suggesting that global spatial cognition is a vital component of wayfinding and navigation behaviour.

These findings suggest that there is an important relationship between the configurational properties of space and people's ability to form topological understandings of their environment, which may be of use in the discussion of sub-area interaction discussed in the previous section. Findings from space syntax suggest that this interaction is mediated by the relationship of local to global spatial properties.

But what happens in low intelligibility environments? Can natural movement occur in such conditions, and if so, how is it different? The remaining sections of this thesis use the case study of Boston, Massachusetts, as evidence to explore these questions in more detail.

3.0 Study Area

The City of Boston is home to nearly 600,000 residents, several institutions of higher education (including Harvard and MIT directly across the Charles River in Cambridge), and several major cultural institutions. The city was first incorporated in a town in 1630 and as a city in 1822, making it one of the oldest continually occupied settlements in the United States.

Like many historic American cities, it is a combination of organic growth and piecemeal modern development, resulting in a complex and idiosyncratic spatial structure. The city exhibits a combination of historic neighbourhoods such as the North End, which retains a distinctly 'Old World' flavour of European-style street networks, small blocks, and mixed uses, and areas such as the former West End and Government Center, both which have become case studies in Modernist urban renewal gone wrong. Large block size, undifferentiated, empty public squares, and forbidding concrete towers now stand in what were once functioning immigrant communities with vibrant spatial cultures.

Boston's development holds a special place in American planning literature. Nearly every stage in America's social and cultural evolution can be found in Boston – from the early foundations of Protestant capitalist democracy, to the challenges of immigration, integration, and racial equalisation, and the city's struggle with suburbanisation, redevelopment, and urban regeneration. Boston's physical and social history thus provides a powerful lens through which to view the process of urbanisation in American life.

The social and physical history of Boston's Central Artery Project bears particular interest for students of urban development and those interested in creating, or destroying, vibrant urban communities. A series of large-scale urban renewal projects from the 1950's onwards has fundamentally transformed the spatial structure of Boston, offering valuable case studies into the effects of such transformations on urban life. They also act as a series of natural experiments that provide quantitative data to test hypotheses of urban growth that often guide the policy decisions behind such transformations.

A detailed understanding of the causes and effects of the Big Dig may offer important lessons for planners engaged in less grandiose but equally important regeneration efforts throughout the United States and abroad. This thesis attempts to uncover and elaborate upon those lessons. It will attempt to use them to help forecast the specific changes to the city of Boston, but also to reflect upon their implications as part of the larger debate over successful urbanisation led by theorists such as Mumford, Jacobs, and Hillier.

Figure 1 displays a map of central Boston, outlining the nine sub-areas commonly known as Beacon Hill, the West End, the Bulfinch Triangle, the North End, Government Center, the Financial District, Chinatown, the Wharf District, and the Leather / Theater District. The location of the "Big Dig" Central Artery construction project is demarcated in yellow.

Figure 1 – Central Boston Study Areas ("Big Dig" parcels illustrated in yellow)

4.0 Methodology

An analysis of the Boston, Massachusetts' spatial structure, land use distribution, and current pedestrian circulation patterns was conducted during the summer of 2004 in order to test hypotheses outlined in Chapter 1.0 - *Introduction*.

Data was procured from the Boston Redevelopment Agency, in the form of MapInfo GIS tables and aerial photography, which formed the base maps for analysis. Land use information was purchased from the City of Boston Assessors Office, which listed land use categories, parcel area, building height, and gross taxable values for all parcels within the metropolitan Boston area.

A detailed field survey was also conducted under the sponsorship and guidance of Space Syntax Limited which gathered high resolution pedestrian observations of the Central Boston area. Observations were made at 158 pavement locations through-out the city, conducted in 5 minute segments every hour between 8 AM to 8 PM on Wednesday, August 4th and Saturday, August 7th, 2004. Three different demographic groups were recorded, logging the movements of workers, residents, and tourists at each location.

Pedestrian movement at all gates was found to be non-normally distributed, and were transformed using the square root of observed values to create a more normal distribution. High resolution gate data for each side of the pavement was then aggregated into a single count for 82 separate locations. Hourly counts were then added together an averaged into two hour time periods to assist in the analysis of flow variation through-out the day. Both steps were completed after it was decided to aggregate axial line data from a high resolution map to a traditional resolution map, resulting in the need to combine gates into a single spatial entity.

Axial line configuration maps were then drawn using standard mapping technique to quantify the spatial structure of the study area. A preliminary series of high resolution axial maps were created, tracing both sides of the street as separate axial lines following pavement geometry. Initial analysis revealed that this approach added a significant amount of depth to the spatial system and it was decided that they did not accurately capture the spatial structure of Boston, which exhibits a large number of curving streets with multiple axial segments.

In response, traditional resolution axial maps representing only the "space between buildings" were drawn. To track the changes involved with the Big Dig construction project, three separate time periods were modelled. The first modelling time period reflected conditions before the raised portions of the Central Artery were destroyed and motor vehicle traffic was diverted into the tunnel beneath the site. Aerial photographs from 2001 were used as base maps to model this time period. The second period reflects existing conditions as of August, 2004, were the majority of important highway infrastructure has been completed but the pedestrian pathways and park parcels of the Rose Kennedy Greenway are still under construction. The final spatial model is based upon plans for the most recent designs of the Rose Kennedy Greenway and reflects what the spatial conditions of the area will be like after completion.

One challenge during the axial mapping process resulted from Boston's isolated position on a peninsula, with very few pedestrian pathways in or out of the central area. To correct for this natural 'edge effect', the axial map was extended to the south and east and all analysis was conducted at the Radius – Radius level, which both correlated best with observed movement and corrected potentially deleterious edge effects around the study area.

After the completion of the axial maps, multiple regression analysis (MRA) was conducted to explore the statistical relationships between different variables to the square root of observed movement. MRA techniques allow the comparison of multiple variables simultaneously and can result in significantly stronger explanatory correlations. To test the null hypotheses of this thesis, all variables were correlated individually and then step-wise in groups to determine the optimal correlation combinations, given adequate p-values and statistical validity. An important measure of statistical validity in MRA is the *t-ratio*, which must be greater than 2 or less than -2 to be significant. After a significant p-value and t-ratio have been established, the *scaled estimates* from each input variable (such as integration or land use) can be used in an equation for forecast future changes in the outcome variable (pedestrian volume). **Table 2** lists all the variables utilised for multiple regression analysis and the type of variable they are.

Table 2 – Input variables for Multiple Regression Analysis (MRA)

Variable	Abbreviation	Variable Type
Sum of built floorspace / axial line	Sum_Area	Continuous
Step depth to transit	SD_Transit	Ordinal (1 through 4)
Step depth to rail (North Station)	SD_NStation	Ordinal (1 through 4)
Step depth to rail (South Station)	SD_SStation	Ordinal (1 through 4)
Step depth to Wharf	SD_Wharf	Ordinal (1 through 4)
Step depth to Quincy Market	SD_Quincy	Ordinal (1 through 4)
Pedestrianised Zone	Pedestrian	Dummy (0 or 1)
Tourists Trail	Tourists_Trail	Dummy (0 or 1)

An additive process of gate inclusion and exclusion was performed after all MRA's were conducted for all gates and all variables. This process began with clusters of gates that appeared to correlate well, starting with a small group of four to six gates per cluster. Individual gates were then added and step-wise regression performed with all input variables to determine the extent of correlation. Gates were added in this fashion to form two dimensional "correlation contours" which traced the descriptive accuracy of group of gates. A "correlation landscape" was thus created, tracing the extent of correlation between movement and explanatory variables such as integration and the number of topological steps to the nearest transit station. The resulting correlation contour maps allow discrete sub-areas of movement to be described and quantified, creating an overlapping map of descriptive utility which allows for detailed exploration of the data and finer movement correlations.

The resulting equations derived from the process of MRA and correlation contouring were then input into the MapInfo GIS and predicted pedestrian volumes for changes after the Big Dig were calculated. Four equations were used, corresponding to the four major correlation clusters described in the following chapter. These equations are listed in **Table 3** below, and produced all day average hourly movement rates for all user groups combined. These were then mapped and included below for analysis.

Table 3 – MRA Equations Utilised to Forecast Post-Big Dig Movement Rates

Area	**Equation**
South Area	y = ((-45.7301158602021) + (25.1341487110182 * INT_RRAD4) + (3.867729687424 * SD_Sstation) + (-6.69701745067978 * SD_Transit) ^{2}
Wharf / Gov't Center	y = ((1.38880836020284) + (12.3157704703684 * INT_RRAD4) + (-1.53118225282771 * SD_Quincy) + (-4.56253423189515 * SD_Wharf)) ^{2}
North End	y = ((-90.766044607271) + (39.3065742124728 * INT_RRAD4) + (0.533031528366971 * SD_Wharf)) ^{2}
Bulfinch Triangle	y = ((47.4619255436936) + (-4.89491484215572 * INT_RRAD4) + (-3.21441858392652 * SD_Nstation) + (-13.9312306932075 * SD_Transit)) ^{2}

Because several of these equations have a negative intercept, a condition was discovered which produced unrealistically high pedestrian per hour predictions when any variable approached zero. Very low integration, dead-end lines, therefore displayed average hourly forecasts of 3,000 or more. This was a serious limitation of the modelling approach and was dealt with by excluding those lines that were forecast to carry less than 50 pedestrians per hour or more than 2,200. These were displayed in grey on the map of forecasted movements in Chapter 5 – Findings.

5.0 Findings

5.1 Spatial Configuration

The axial map of Boston before commencement of the Central Artery project (**Figure 2**) reveals a relatively fragmented spatial system with several clusters of integration, but no powerfully integrating lines uniting the system into a coherent whole. The Radius-Radius integration for the system is Radius 4 and the mean Rad-4 integration value is 2.35. The most integrated line within the downtown area is Beacon Street, that displayed a Rad-4 integration value of 3.916. The southern segment of Tremont Street was found to display an Rad-4 integration value of 3.7974, making it the second most integrated street, while the south eastern segment of Summer Street crossing the bridge displayed the third highest integration value (3.768). The lowest integration lines were found in the heart of the West End (0.33) and near Government Center, behind the District A-1 Police Station just north of City Hall Plaza (1.1257).

Figure 2 –Spatial Accessibility *before* Construction (circa 2001, Rad-4)

The intelligibility and synergy of the pre-construction downtown area is 0.36 and 0.54, respectively. **Table 4** displays the intelligibility and synergy scattergrams for the area at this time.

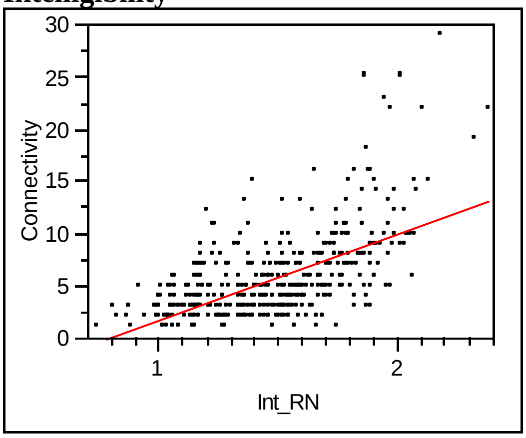
Figure 3 displays the spatial conditions of the mid-construction situation, when the majority road infrastructure for the Big Dig has been completed, but the final pedestrian network had not yet been opened.

Changes in Rad-4 integration can already be seen around the Government Center area, with the emergence of more powerfully integrated connections between Hanover Street in the North End and City Hall Plaza. The Rad-4 integration of Hanover Street increases from 2.91 to 3.06, a change of approximately 5%. The average integration of the junction at New Congress Street and State Street, just east of City Hall exhibits no significant change, remaining at a mean Rad-4 value of 2.96. The mean integration of the entire area also exhibits little change, moving from 2.35 to 2.36. The top three most integrated lines are still Beacon Street, Tremont Street, and Summer Street.

There is a slight increase in overall system intelligibility, from 0.36 to 0.37, while synergy increases slightly to nearly 0.58. Table **5** displays these changes.

Table 4 – System Intelligibility and Synergy, pre -Big Dig

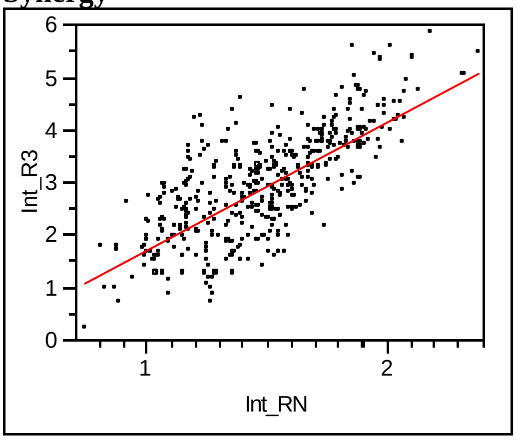
Intelligibility



Summary of Fit

RSquare	0.366927
RSquare Adj	0.365527
Root Mean Square Error	3.25477
Mean of Response	5.614537
Observations (or Sum Wgts)	454

Synergy



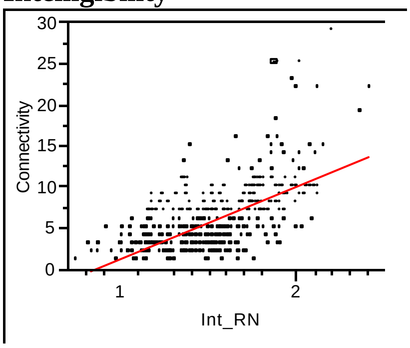
Summary of Fit

RSquare	0.539758
RSquare Adj	0.53874
Root Mean Square Error	0.676479
Mean of Response	2.884159
Observations (or Sum Wgts)	454

Figure 3 – Spatial Accessibility *during* Construction (August, 2004, Rad-4)

Table 5 – System Intelligibility and Synergy, during the Big Dig

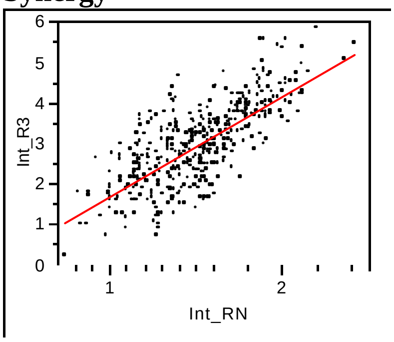
Intelligibility



Summary of Fit

RSquare	0.376246
RSquare Adj	0.374878
Observations (or Sum Wgts)	458

Synergy



Summary of Fit

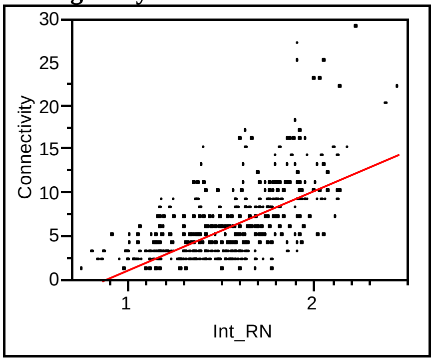
RSquare	0.557137
RSquare Adj	0.556166
Observations (or Sum Wgts)	458

Figure 9 illustrates the Rad-4 integration of Boston after completion of the Central Artery Project. Several of the routes discussed above are significantly heightened as individual connections. A major change can be seen in the east-west axial line connecting the north side of the Long Wharf Marriot to City Hall Plaza, running through the centre of Quincy Market. This connection results in a change of Rad-4 Integration of over 20%, from 2.71 to 3.41. Congress and New Congress Streets are highlighted as powerful north – south connectors, exhibiting a change in integration of nearly 5%. The junction of State and New Congress Streets becomes an important cross-roads, elevating the integration of that area by nearly 10%. Additionally, the north segment of Tremont Street becomes much more important, offering access to the heart of City Hall Plaza from the southern portion of the city. In particular, the east-west connections within the Financial District bring that area's mean integration to 3.04 (a change of ~12%) and the new north-south access in front of the Wharf District brings that area to a new integration level of 2.94 (or a 7% change).

Figure 4 – Spatial Accessibility *after* Construction (circa 2006, Rad-R)

Table 6 – System Intelligibility and Synergy, post-Big Dig

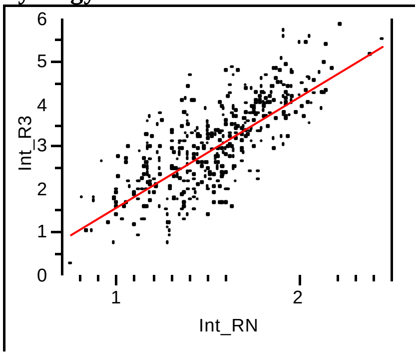
Intelligibility



Summary of Fit

RSquare	0.386577
RSquare Adj	0.385261
Observations (or Sum Wgts)	468

Synergy



Summary of Fit

RSquare	0.565954
RSquare Adj	0.565022
Observations (or Sum Wgts)	468

5.3 Pedestrian Movement Patterns

Movement in central Boston area is highly segmented between neighbourhoods, time periods, and demographic groups. **Figures 5** through **8** illustrate the hourly average movement rates for all groups, workers, locals, and tourists on weekdays and weekends. These maps are colour coded according to the same scale, such that different colours represent the same values across each map for accurate comparison. Dark blue gates represent 0 to 44 pedestrians per hour, while dark red gates represent 555 to over 1,000 pedestrians per hour.

Figure 5 illustrates the general movement patterns in the study area during the weekday. Two clusters of high movement can be seen, the first just south of City Hall and the second just north of the South Station transit centre (both circled in white). Movement appears to originate at South Station and diffuse north and west, while movement around City Hall appears to originate at the Government Center "T" stop in City Hall Plaza and disperse south and east, through Quincy Market and towards the Aquarium and Long Wharf Marriot. There is relatively little movement in and around the south edge of the North End, compared to overall movement elsewhere.

Graphing the relationship of users on a space by space basis demonstrates that there is a strong separation of use for different categories. A strongly bi-furcated, or "L-shaped" pattern can be seen, indicating little system-wide overlap between demographic groups. **Table 7** displays the scattergrams of suits versus locals, suits versus tourists, and tourists versus locals.

Figure 5 – Hourly Pedestrian Movement, All Categories, Weekday Average

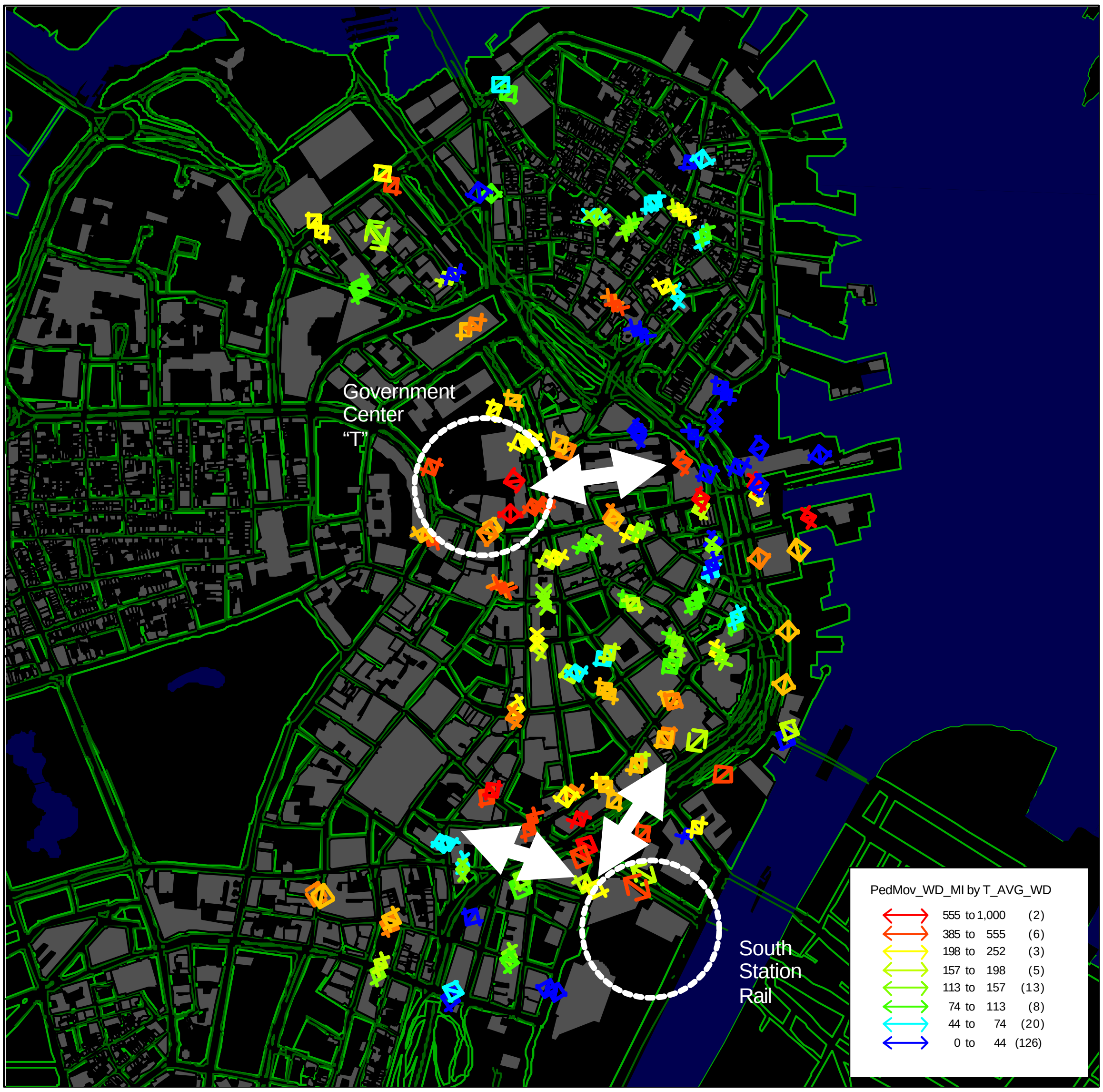


Table 7 – Pedestrian Demographic Space Use Correlations

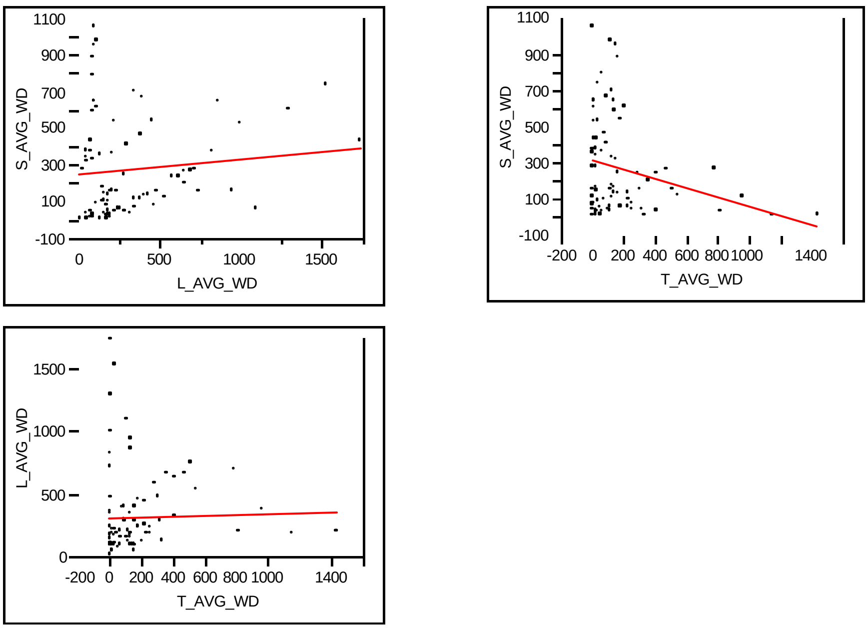


Figure 6 – Hourly Pedestrian Movement, Workers, Weekday Average

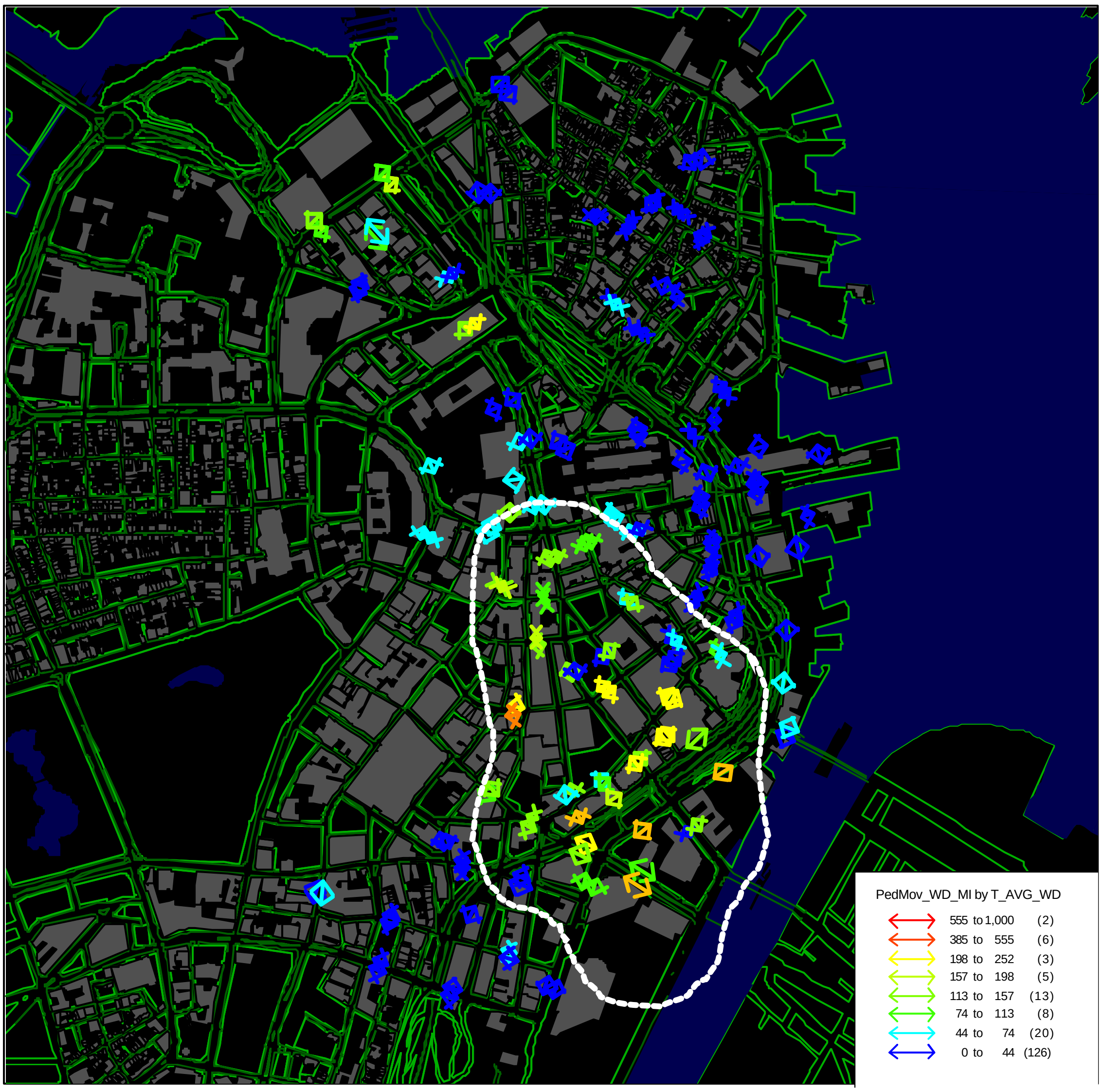
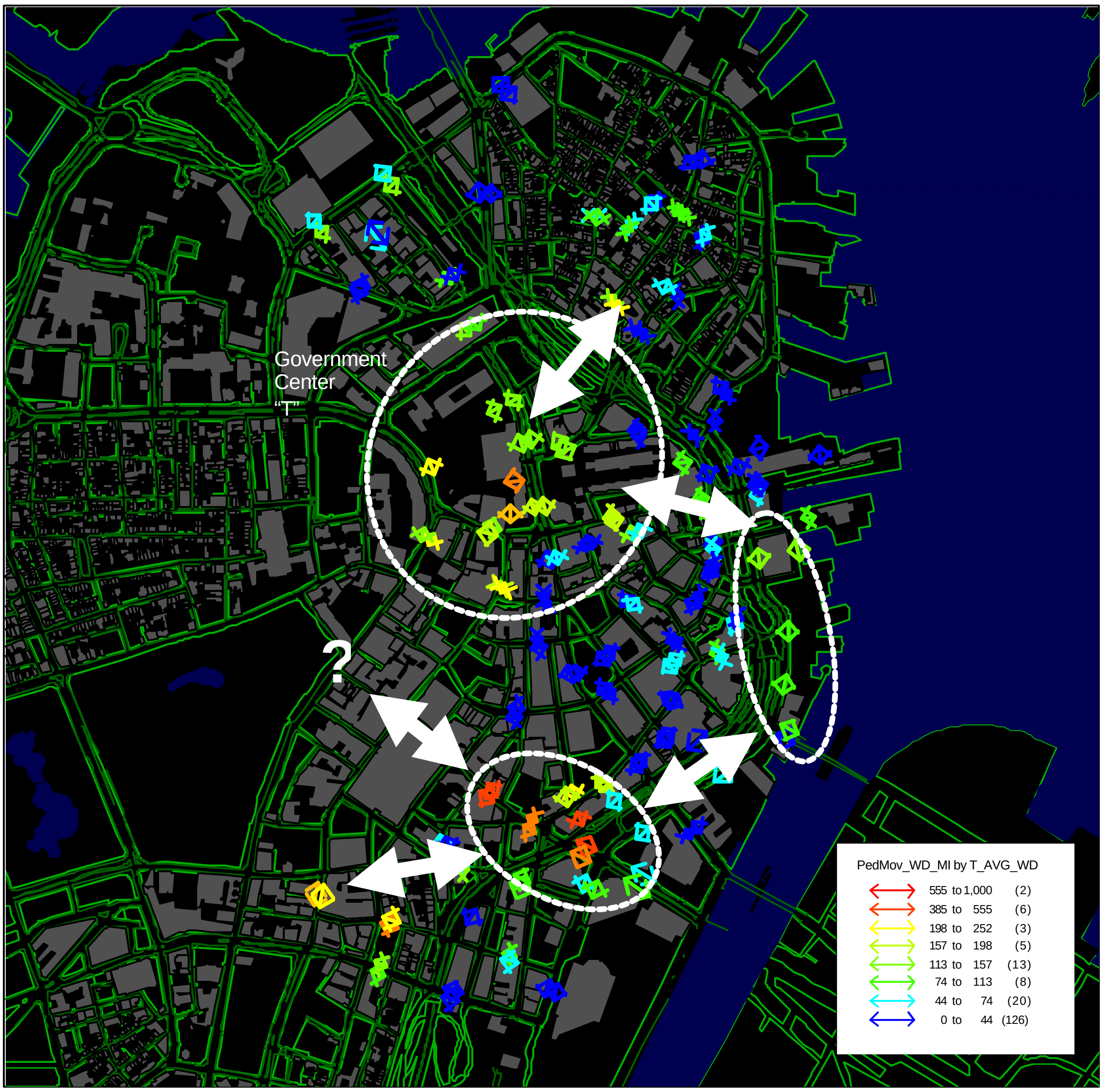


Figure 6 segments the weekday data by suits and workers, revealing that movement is heavily concentrated in the Financial District area, particular in the southern half towards South Station. There is also a moderate amount of worker movement in the North, likely originating from the North Station regional rail station next to the Fleet Center and travelling to and from the Federal buildings to the west. There is strikingly little movement of suits outside of this area (none is some cases), especially in the Chinatown, Wharf District, and North End areas.

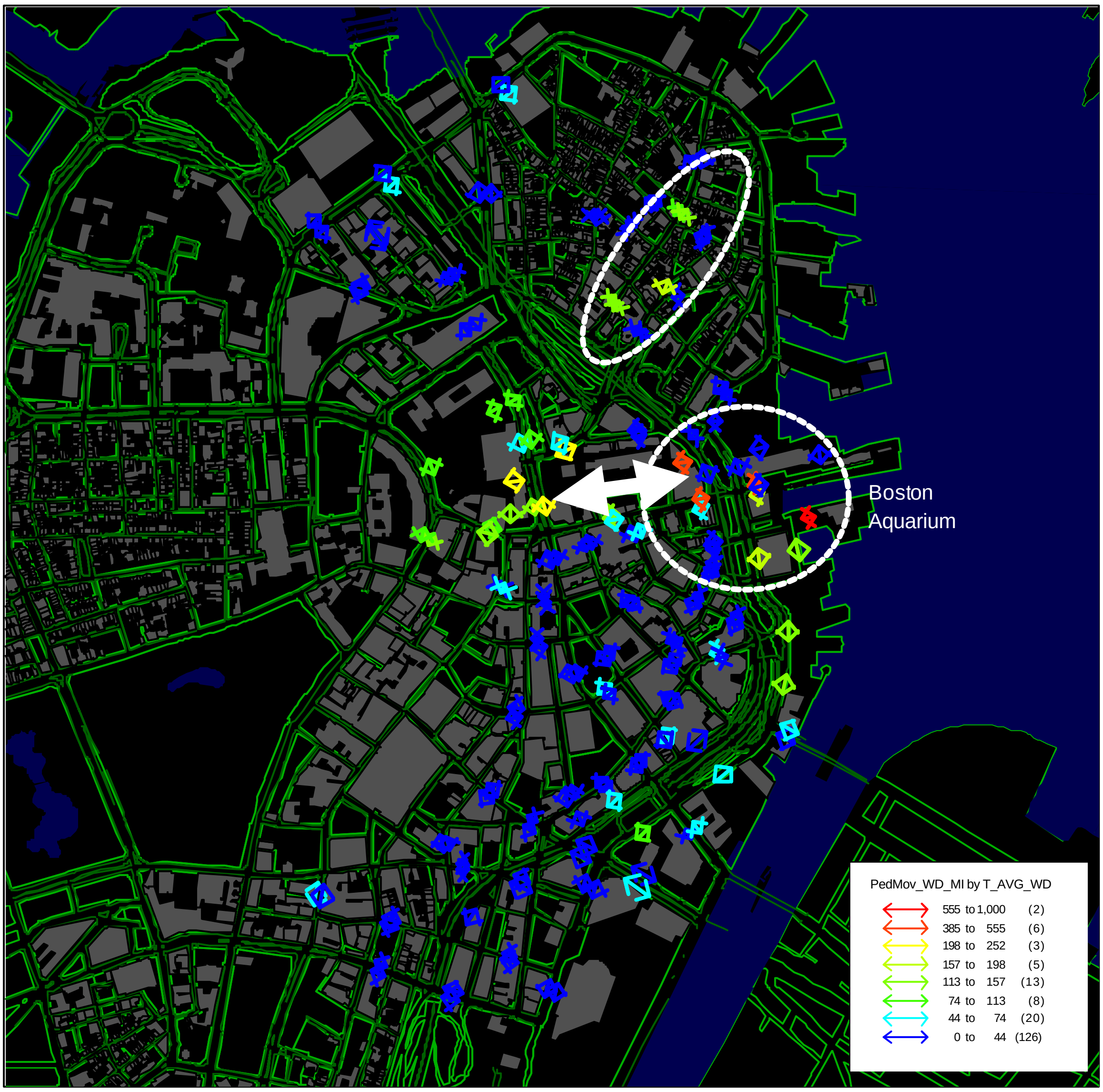
Figure 7 illustrates movement for locals within the Central Boston area. This picture is nearly the inverse of the workers movement patterns, with very little penetration into the Financial District and heavy traffic in the Chinatown and Government Center areas, as well as in the Leather District, Wharf District, and North End areas. It appears that the majority of local traffic originates in the South Station area and disperses west into Chinatown and the Leather District, while a secondary volume originates in the City Hall area and disperses to the North End, the Wharf District, and south and west into the western edge of the Financial District or towards Boston Commons.

Figure 7 – Hourly Pedestrian Movement, Locals, Weekday Average



The picture of weekday tourist movement is even more distinct, with specific individual routes emerging and key attractors becoming apparent. **Figure 8** displays the distribution of tourists during weekdays. The heaviest tourist traffic was found directly in front of the Aquarium, that is also the central loading and unloading point for all tour busses in the Boston area. From this point, it is clear that the majority of tourists travel westward to Quincy Market, with a diminishing but significant number going onwards to City Hall Plaza or north to Hanover Street (the main retail street in the North End). An equally significant number travels north-south along the waterfront in front of Rowes Wharf. The Financial District, Chinatown, and Leather Districts experienced practically no weekday tourist traffic, nor did the Bulfinch Triangle or the rest of the North End outside of Hanover Street. This combination of targeted activity and general inactivity suggests a distinct pattern of tourist movement that corresponds closely to major sites and attractions.

Figure 8 – Hourly Pedestrian Movement, Tourists, Weekday Average



Weekend pedestrian activity followed a generally similar pattern to weekday, but with less distinct boundaries and surprisingly higher rates of movement in the North End and Government Center areas. There was also more dispersion of general traffic into the heart of the Financial District, although the area around South Station experienced a drop in activity likely related to commuting workers.

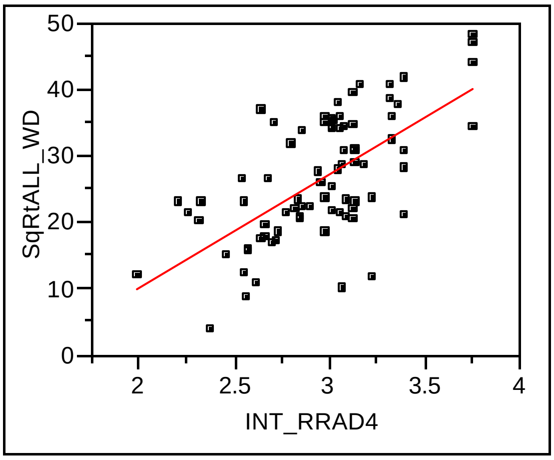
The strong Aquarium – Quincy Market – City Hall Plaza connection experienced even more use, while the North End / Hanover Street corridor experienced over 1,500 people per hour at its peak. There was generally less north – south movement, however, suggesting a more dispersed, all purpose movement instead of a specific origin – destination movement centring around transit hubs and commercial office attractors.

It can be seen that despite axis' of high movement through-out parts of Boston, suits, locals, and tourists exhibit strongly split patterns, with suits dispersing outward from regional rail stations and diffusing generally within the Financial District and Government Center. Tourists are strongly point source based and tend to follow specific routes emanating from the Aquarium / Long Wharf area and travelling directly through Quincy Market, south along the Wharf, or from Quincy into the North End via Hanover Street. Locals are more evenly distributed, penetrating into all areas some greater or lesser degrees. With the exception of the crossroads in front of South Station and between City Hall and Quincy Market, there is little overlap between movement groups.

5.3 Statistical Correlations

A multivariable regression model was constructed to explore the relationships between spatial configuration, land use activity, and pedestrian movement in the study area. **Table 8** displays the correlation between Radius 4 integration and the square root of the average hourly weekday pedestrian movement for all groups. It can be seen that movement co varies with integration to with an r-squared of roughly 0.42. The addition of other explanatory variables, including topological step depth from the Wharf and from Quincy Hall, raises the city-wide correlation to approximately 0.52.

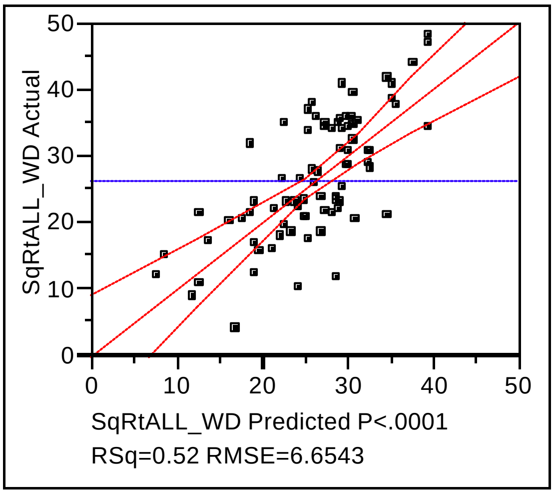
Table 8 – Integration and Square Root of All Day Movement



Summary of Fit

RSquare	0.412793
RSquare Adj	0.40536
Root Mean Square Error	7.201423
Mean of Response	26.41851
Observations (or Sum Wgts)	81

Table 9 – MRA of Integration, Step Depth, and Square Root of All Day Movement



Summary of Fit

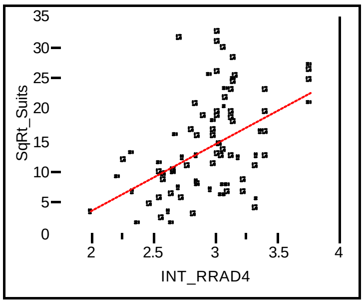
RSquare	0.517666
RSquare Adj	0.49228
Root Mean Square Error	6.654316
Mean of Response	26.41851
Observations (or Sum Wgts)	81

Scaled Estimates

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	26.418509	0.739368	35.73	<.0001
INT_RRAD4	12.264053	2.22795	5.50	<.0001
SD_Wharf	-3.838596	1.604417	-2.39	0.0192
SD_Quincy	2.8778769	1.183947	2.43	0.0174

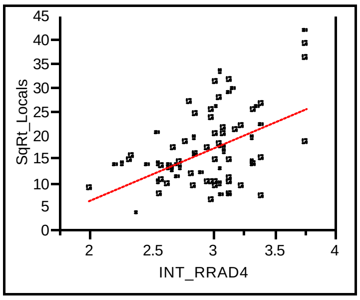
Table 10– Spatial Correlations with Suits, Tourists, and Locals

Suits



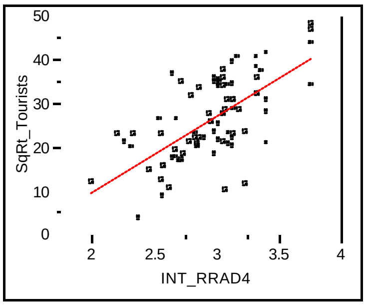
R-squared = 0.2241

Locals



R-squared = 0.2268

Tourists



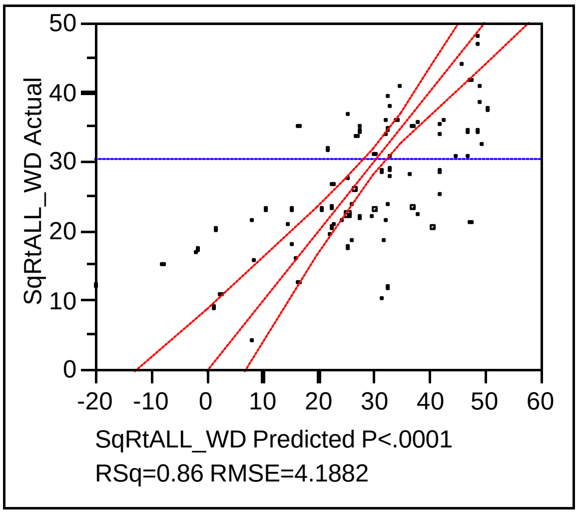
R-squared = 0.412793

Space also correlated differently with different user groups. Both suits and locals movement correlated to space with an r-squared of 0.22, while tourists correlated nearly twice as well with an r-squared of 0.41. **Table 10** compares these user groups and summarizes their correlations. The addition of topological step depth from transit and the Wharf raised the correlation for suits to 0.42, locals to 0.32, and tourists to 0.48 after stepwise multiple regression analysis.

The overall low intelligibility of central Boston was thought to contribute to the low correlations displayed in **Table 10**. To explore the effects of sub-areas on movement, the analysis was subdivided into four areas based on estimates of their spatial coherence. These estimates were tested through combinatorial experimentation, adding or removing observation gates in roughly contiguous convex areas and evaluating the effect on the correlation of that sub-area. Stepwise regression analysis was then repeatedly re-run for all variables until stable islands of correlation were observed. These islands were then mapped, resulting in correlation contour maps for all user groups. **Table 11** summarizes the strongest correlations for each group and for all groups combined, illustrating the scattergrams for each area and the scaled estimates of each variable where multiple variables were utilised. **Figures 9, 10, 11,** and **12** display the graphic representations of these correlation contours.

Table 11 – Summary of Area Correlations and Scaled Estimates

Southern Area

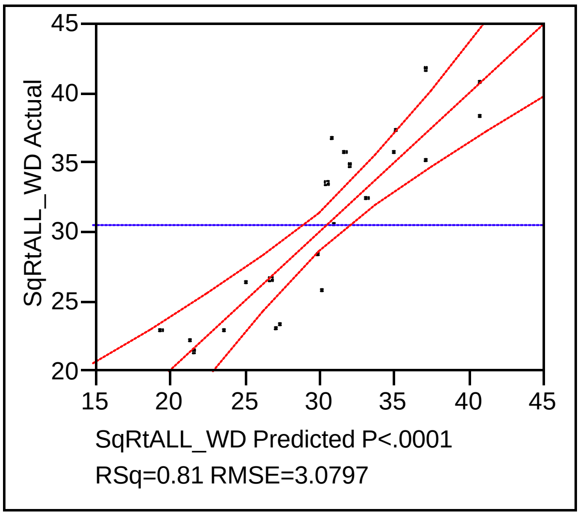


Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	30.368126	0.892923	34.01	<.0001
INT_RRAD4	17.313265	2.08278	8.31	<.0001
SD_Sstation	5.8015945	2.500096	2.32	0.0323
SD_Transit	-6.697017	2.438154	-2.75	0.0133

Wharf / City Area

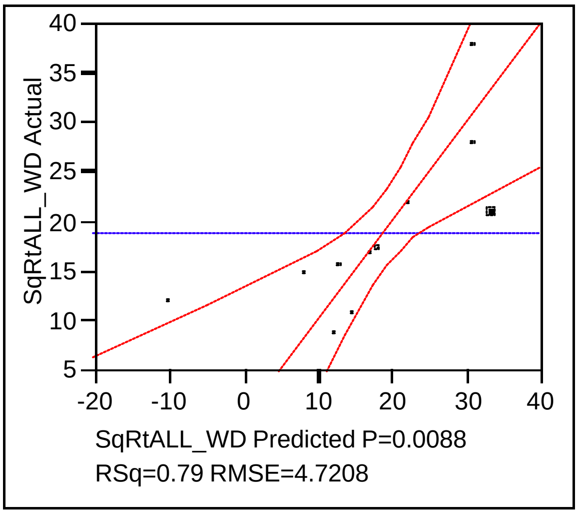


Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	30.501294	0.656603	46.45	<.0001
INT_RRAD4	7.3106479	1.063979	6.87	<.0001
SD_Wharf	-6.843801	1.217462	-5.62	<.0001
SD_Quincy	-3.062365	1.577548	-1.94	0.0681

North End

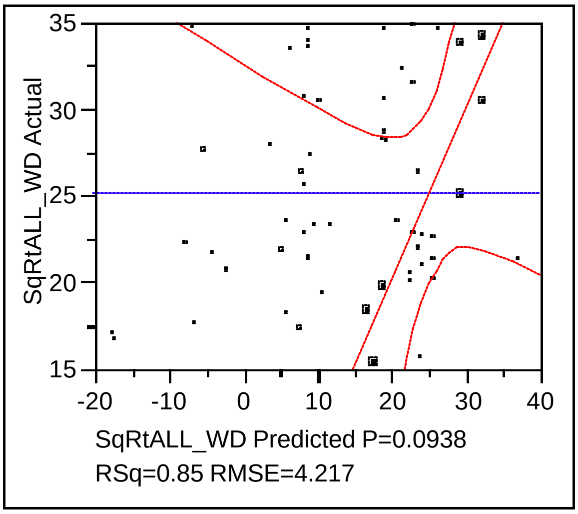


Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	18.846429	1.573602	11.98	<.0001
INT_RRAD4	11.606795	3.842703	3.02	0.0234
SD_Wharf	0.2665158	2.585756	0.10	0.9213

Bulfinch Triangle Area



Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	25.258017	1.593871	15.85	0.0005
INT_RRAD4	-1.870684	5.419837	-0.35	0.7528
SD_Nstation	-1.607209	2.158239	-0.74	0.5105
SD_Transit	-6.965615	3.872895	-1.80	0.1699

Figure 9- Correlation Contour Map for All Groups, Weekday

It can be seen that there are four major islands of correlation between all group pedestrian movement and the movement model. Integration Radius 4 is the most powerful predictor in all cases, although the power and prevalence of other predictor variables changes with each area. The area to the south displayed an overall correlation of 0.86, with topological step depth to transit stations and to the South Station regional rail station as other important variables. Correlation remains around 0.80 until the contours reach Post Office Square, that exhibited a pocket of lower movement rates than expected, resulting in a correlation co-efficient of 0.57.

North and east of Post Office Square, a deformed kidney bean shaped zone of high correlation, covers the eastern edge of the Financial District, the Wharf District, Quincy Market, and the Government Center complex. Correlation can be seen to be the greatest on the east – west axis of Quincy Market, between Government Center and the Long Wharf Marriot. In this area correlation peaks at 0.81, with step depth to transit and step depth to the wharf as supplementary variables to Radius 4 integration. Correlation drops to 0.65 as the contours move south and west and begin to overlap with the southern area.

To the north, the Bulfinch Triangle / North End areas can be considered as two related sub-systems (correlating to 0.76 or as separate sub-systems (correlating to 0.85 and 0.79, respectively). In both cases, space correlates most powerfully, with step depth to the Wharf step depth to the North Station regional rail station as supplementary in variables.

Figure 10 displays the correlation contours for weekday suits, which has a more distinctly structured shape, but one with a strongly bounded range of influence. Space and step depth to the two regional rail stations combine to create a correlation co-efficient of 0.82, with pockets of lower correlation in the heart of the Financial District, especially along the east – west routes of Franklin and High Street.

These streets exhibited extreme peaks of movement at midday and much lower levels throughout the remaining times, resulting in lower correlations for these areas (between 0.59 and 0.76). A buffer zone was also observed along the observation gates in the Wharf of r-squared 0.76. Correlation dropped towards the Bulfinch area as well, falling specifically around the parking garage north of Government Center. Finally, the outlying gates in the edge of the north end correlated to approximately 0.63, exhibiting a tight boundary of sub-area correlation in that region.

Figure 10 - Correlation Contour Map, Weekday Suits

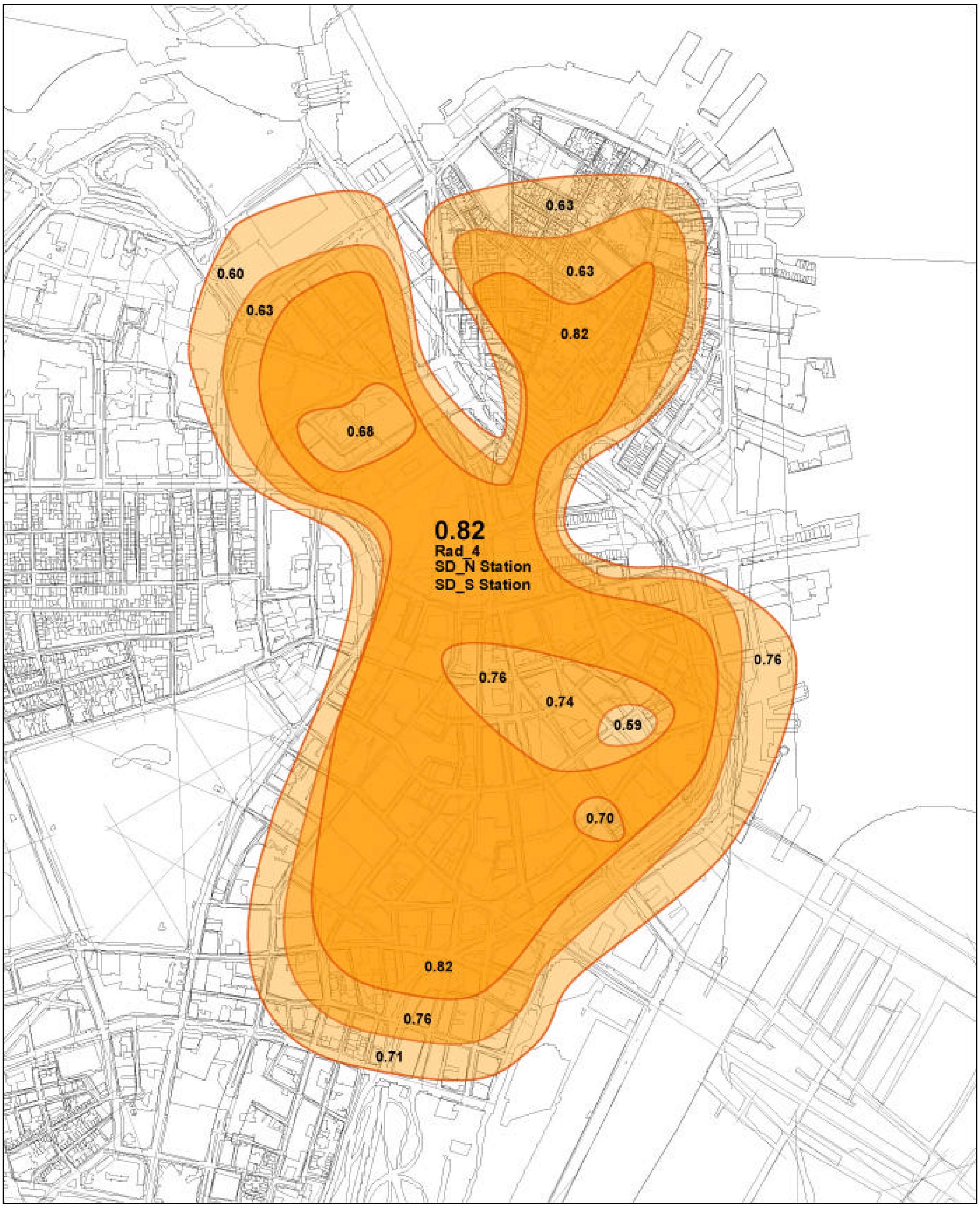


Figure 11- Correlation Contour Map, Weekday Tourists

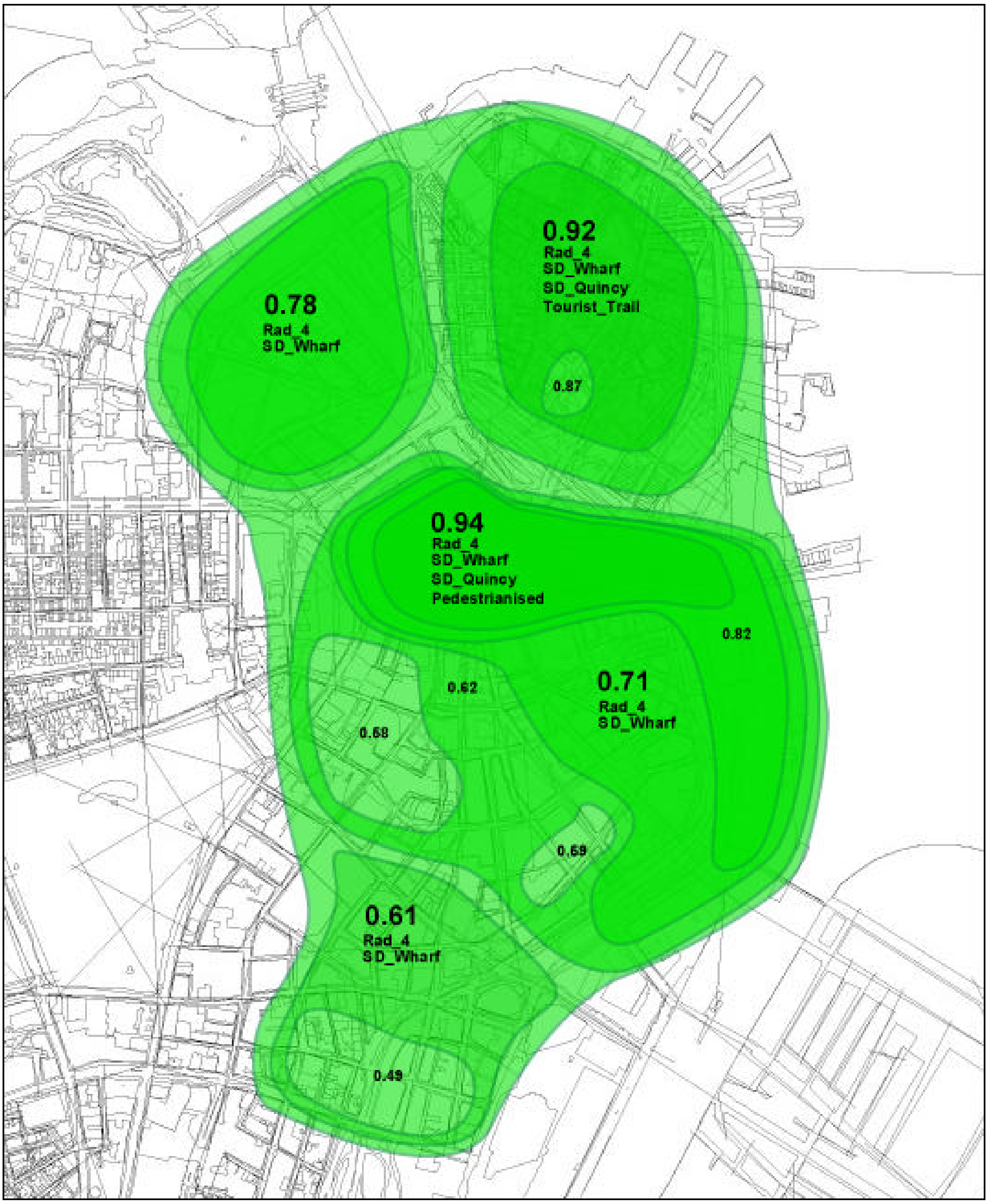


Figure 11 displays the contour map for weekday tourists, which has several strong 'peaks and valleys' of correlation. The Wharf / Quincy / Government Center axis correlates to a remarkable 0.94 with Radius 4 integration, pedestrianisation, and step depth to the Wharf and to Quincy Market. The North End was equally well correlated, exhibiting an r-squared of 0.92 between the square root of tourist movement and Radius 4 integration, step depths to the Wharf and to Quincy Market, and the presence of tourist trails. Correlation is stronger along the north – south axis of the Wharf, but drops off to 0.71 and then 0.62 further west into the Financial District, suggesting sub-area delineation between these zones. Finally, correlation in the southern area is the lowest, with a minima of 0.49 in the southern edge of the Leather District / South Station area.

Figure 12 - Correlation Contour Map, Weekday Locals

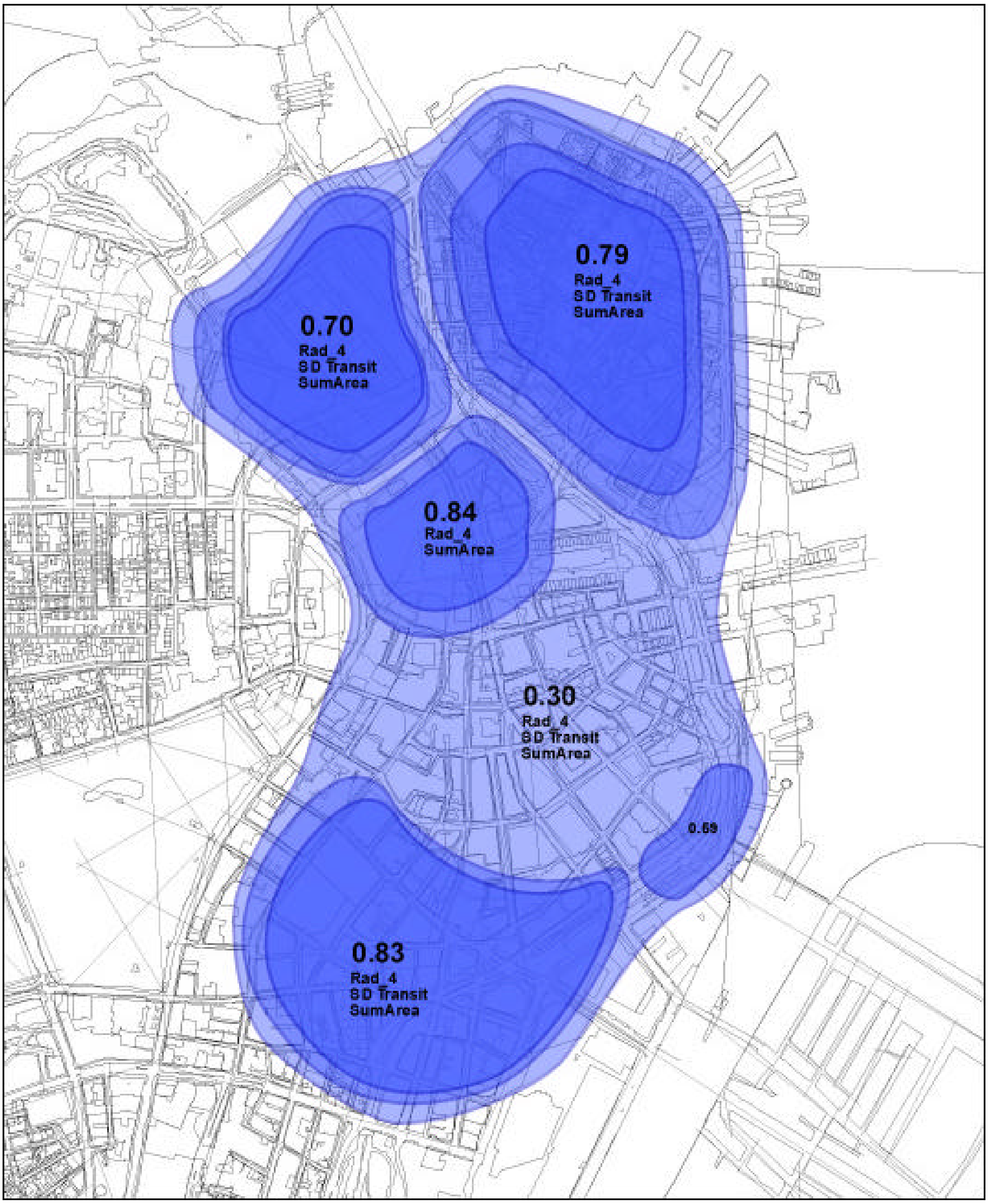
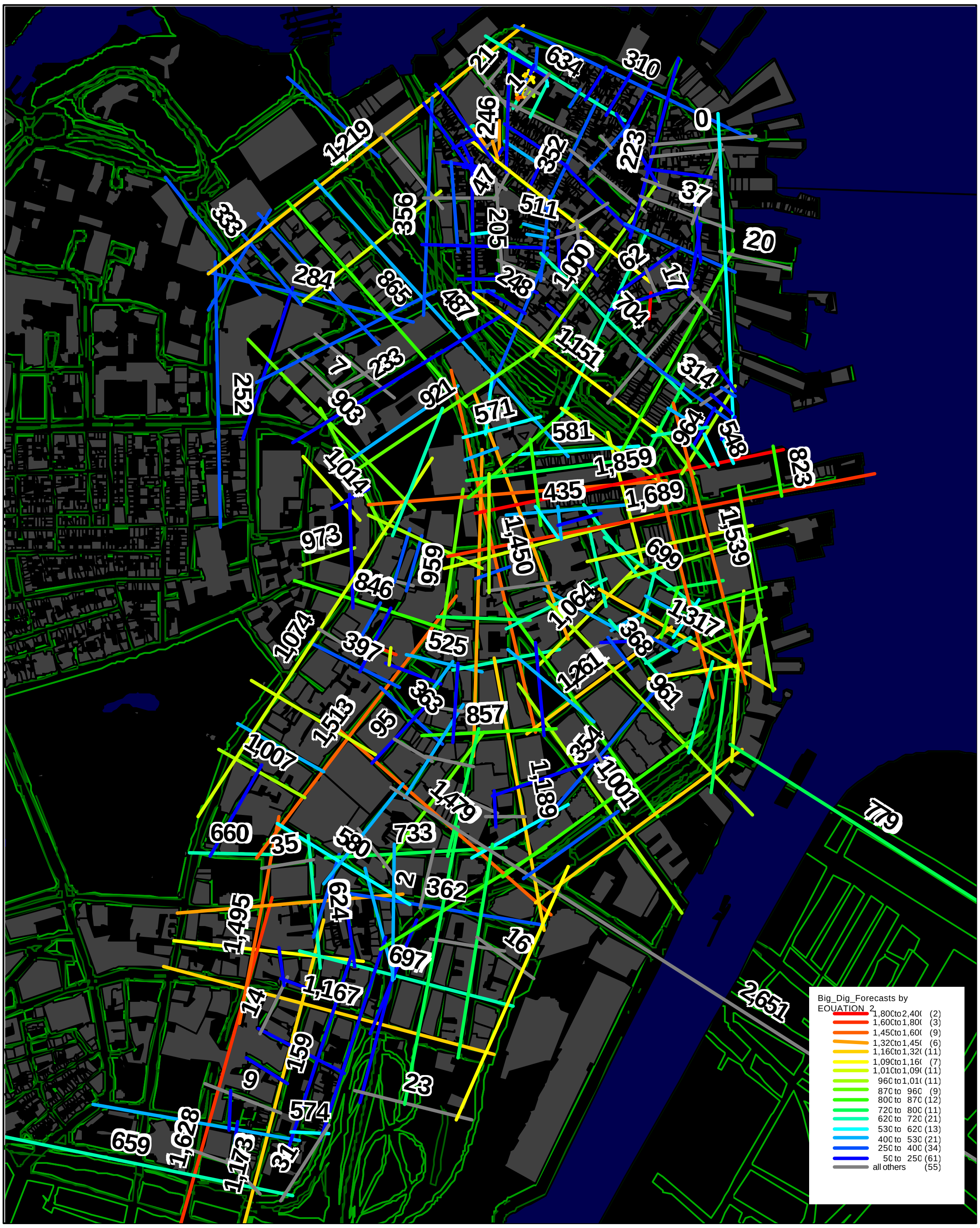


Figure 12 illustrates the correlation contours for weekday locals, which exhibits clear boundaries of sub-area correlation. It shows a tightly bounded contour around Government Center (r-squared 0.84 between space and the sum of built area), dropping rapidly to a low of 0.30 in the heart of the Financial District, even with step depth to transit and the sum of built area included in the multiple regression model. The southern area is also strongly bounded, with very good correlation in the Leather District / Chinatown area when factoring Radius 4 integration, step depth to transit, and the sum of built area (r-squared = 0.83). The northern sub-areas displayed equally sharp boundaries and correlated to 0.70 and 0.79 for Bulfinch and the North End, respectively.

5.4 Movement Forecasts

After having used the correlation contours and MRA equations derived in Sections 5.2 and 5.3 to identify strong associates between the square root all day average hourly movement, these equations were input into MapInfo as expressions and new all day average hourly movement rates were calculated for Boston after the Big Dig was completed. **Figure 13** displays the map of future movement in the downtown area.

Figure 13 – Forecast Hourly Movement Rates in Downtown Boston



It can be seen that the major lines of forecasted movement run east-west along State Street and through Quincy Market, reaching up to ~1,900 pedestrians per hour. Summer Street running northwest from South Station is forecast to experience approximately 1,450 pedestrian per hour, while Washington Street is expected to carry a similar amount. Federal Street is still the major north –south entryway into the Financial District, with movement either funnelling east along Atlantic Avenue towards the Wharf or east along Franklin Street.

Major movement (~1,500 pedestrians per hour) are expected to move north – south on the edges of the new Greenway, which should serve to bring a new level of movement into the eastern edge of downtown via Broad Street, although movement can be seen to dissipate rapidly off either side of Broad. Very little movement is expected to occur on the segment of High Street west of Oliver / International Place, suggesting that pedestrian will prefer to travel along Purchase Street next to the new parks if possible, or along Franklin Street in the heart of the Financial District if necessary.

The North End can be seen to remain relatively stable, with an approximate 25% increase along Hanover Street to ~1,000 pedestrians per hour. One surprising change suggested by the model can be seen on Cross Street, the east west line on the south side of the North End. This axis wil benefit significantly from the connection to the new parks and to the Long Wharf Marriot, suggesting that this may become the new tourist line of travel from the Wharf to the North End.

Friend Street, running south from North Station / Causeway Street in the Bulfinch Triangle, is expected to become a more prominent route towards the Government Center, with approximately 900 pedestrians per hour expected on this line. This points the way to an important crossroads, right in the middle of the city between Quincy Market and City Hall. The intersection of New Congress, State Street, and the line of movement coming from Quincy Market suggests an average movement rate of approximately 1,500 people per hour and is the only location in the city which becomes a major intersection of important high volume lines.

It is likely that the Summer Street Bridge segment also carries a high volume of pedestrians into and out the city, making the intersection in front of South Station another highly active area. But it can be seen that this segment is greyed out because it exceeds 2,000 pedestrians per hour, nearly twice the observed volume of this line, suggesting that this is a case which is outside the bounds of the predictive model.

6.0 Discussion

Boston was chosen as a case study to explore the effects of spatial fragmentation on movement and correlation. Do these findings warrant sufficient evidence to prove or disprove the null hypotheses introduced at the beginning of this thesis?

6.1 Is Boston a Valid Case Study?

It can be seen from the axial analysis that the spatial structure of Boston exhibits low intelligibility and a clustering of integration islands, with few integrators connecting them. Overall correlation between integration (Radius 4) and the square root of hourly pedestrian movement is low, most likely as a result of the fragmented configuration and low intelligibility of the system. These conditions indicate that the case of Boston is therefore a useful case that can offer useful insights into the primary null hypothesis this thesis, which was "space does not correlate well with movement in fragmented spatial systems with low intelligibility".

Boston also displays a range of land use values which were analysed in the MRA along with other urban design characteristics such as topological step depth to regional rail, transit, and key attractor facilities. This second set of conditions implies that the second null hypothesis of this dissertation may be answerable, as well. That was "in low intelligibility conditions, other variables (such as distance to transit, land use, etc.) will be able to explain movement better than space.

Finally, movement patterns within Boston appear to exhibit a variety of heterogeneous movement patterns; especially between different user groups. Scattergrams in Chapter 5 indicate an L-shaped distribution between different user groups, suggesting functionally separated spatial systems. Correlation contour maps strengthen this interpretation, indicating that different groups correlate better with different sub-areas, suggesting a different pattern of potential use between groups. It appears that these findings are able provide the necessary information for answering the last and final null hypothesis, that "space predicts uniformly for all users and users, when it predicts."

The cumulative impression of these findings is that they indicate that Boston is indeed well suited to prove or disprove the null hypotheses at the centre of this research inquiry. So are thses hypotheses valid or not? The following subsections will address each null hypothesis in detail.

6.1 Null hypothesis #1: "Space does not correlate with movement under low intelligibility conditions"

The overall intelligibility in central Boston was 0.36 before construction began on the Big Dig, 0.37 during, and is estimated to be 0.38 after. This increase is minor and even after the Big Dig is complete indicates that Boston will remain a city with poor local to global correlation, despite the efforts of the planners responsible for the big dig. Drawing from Penn (2003) and Hillier's (2003) work, it is suggested that Boston will continue to be difficult to navigate even after completion of the Big Dig project as result of this spatial condition.

A more detailed configurational analysis suggests why this may be the case. Several historic routes in Boston retain integration values higher than average, thus drawing integration towards the historic centre (including as Tremont, Beacon, Cambridge, and Summer Streets). But the intervention of the Government Center redevelopment project in 1969 appears to exert a decentralizing disruption, blocking direct connection of these important routes or dissipating them into lower integration neighbourhoods. As a result, higher integration lines lead to clusters of segregation and pockets of segregation can be seen in the heart of the city, which should appear as the most integrated area.

Given these conditions of low intelligibility and poor configurational inequalities, it would be expected that natural movement would not be observed in very significant amounts. It would also be expected that correlation between integration and movement would be low. Indeed, this appears to be the case in Boston. The overall correlation between integration Radius 4 and the square root of hourly pedestrian flow was only 0.41, while MRA correlation between integration Radius 4, step depth to the Wharf, and step depth to Quincy Market raised this correlation to approximately 0.52. The MRA reveals that space is the most powerful predictor of the three, accounting for nearly twice the correlation co-efficient of either step depth variables.

Space performed even worse when correlated individually against suits, locals, and tourists, averaging around 0.22 and peaking with tourists at 0.41, the system-wide average. These correlations were statistically significant ($p < 0.0001$), but are not powerful enough on their own to disprove the null hypothesis that space does not matter in low intelligibility systems.

Much more powerful correlations were achieved by partitioning the spatial system into intuitively determined sub-areas and testing these using the correlation contour method. In the case of the southern area, statistical correlations of approach 0.9 were found, with correlation averaging around 0.76. The addition of step depth variables increased this correlation to an r-squared of 0.86, with space performing more than four times more powerfully than step depth. Similar results were found in all three other areas.

Taken together, it is clear that space *can* and *does* correlate powerfully with movement, even in a spatially fragmented, low intelligibility such as central Boston. But this is only true once a more detailed understanding of sub-area definition is achieved. They key to understanding spatial influence in fractured, low intelligibility environments, lies in the utilisation of correlation contours to define movement sub-areas of the larger system, then analysing the interaction between such movement areas.

6.2 Null hypothesis #2: "Other variables are more important than space for low intelligibility systems"

The findings previously discussed illustrate the lesser role that topological step depth variables play in movement correlation for central Boston. Other variables performed poorly or not at all. Nevertheless, it is worth testing the null hypothesis in more detail to rule it out completely. Land use variables, such as total floor space, are of particular interest to this question given the focus of such variables in traditional land use transportation models.

It was shown that the sum of floor space did not correlate with space or with movement in any cases, except for average local movement patterns. This is an interesting exception wherein which built area accounted for approximately 25% of the correlation, step depth to transit 25%, and integration Radius 4 the remaining 50%. Why would this be the case with locals but no other group?

The correlation contour maps may shed light on this question. The correlation contours for locals exhibit the sharpest transition between high and low correlation zones of any other demographic group. Correlation is clustered in sharply defined "peaks" around the Chinatown / Leather District area, Government Center, and the North End / Bulfinch. There was also a striking correlation "valley" between these zones in the Financial District. The land use analyses of these areas indicated that the Chinatown and North End area were mixed used neighbourhoods with large proportion of their total floor space devoted to residential or apartment uses (36% for Chinatown, nearly 50% for the Leather District, and over 65% in the North End). This may indicate a connection between local residences and movement among local categories, an explanation that would make sense given the explicit contours of these zones and the fact that land uses are traditionally considered the primary "trip generators" in traditional transport models.

The fact that the sum of built area accounts for between 20% and 30% of observed correlation in these cases is significant. It does not, however, prove the null hypothesis to be true. Over 60% to 70% of correlation was derived from integration Radius 4 in these cases, clearly indicated the prominence of this variable in the correlation matrix. These findings suggest an interesting dynamic between residential land uses and spatial variables, but the evidence appears to disprove the null hypothesis and support the notion that even in low intelligibility spaces within Boston, integration is the most important and powerful explanatory variable.

6.3 Null hypothesis #3: "Space predicts uniformly for all users and users, when it predicts"

The use of correlation contours in the city of Boston illustrates the varying degrees to which space effects movement in complex, low intelligibility systems. It is of interest that the contours mapped differently for each user group, highlighting relative areas of coherent movement for different types of pedestrians.

If the null hypothesis were true, correlation would exert a uniform effect for all groups across a given area. This is clearly not the case, with larger differences in the location and significance of spatial influence for different groups. This suggests that different groups utilise the inherent properties of space different depending on their locations, goals, and desires.

Hillier (2003) suggested such a phenomenon may result from the differentiation of *ego-centric* and *allo-centric* world views. Allo-centric spatial cognition involves an understanding of the world as *others see it*, suggesting a powerful cognitive link between space and urban navigation. The variation in correlation contours between groups appears to indicate that the allocentric process is an important part of urban sub-area definition. Like spaces within a J-graph, what appears like "part of the neighbourhood" changes from location to location based on the who is making the observation and from where.

The strong correlation between sub-area definition and movement, clearly indicates that space is heterogeneous and non-uniform in nature. While it is clear that the causes, nature, and implications sub-areas definition requires more research, the findings presented above demonstrate that space does *not* affect all groups uniformly in Boston, thus disproving the third and final null hypothesis of this thesis.

6.4 Chaotic boundaries, ecologies of correlation, and issues for complex systems modelling

What can be learned from the disproval of the three null hypotheses in the case of Boston? This thesis raises two interesting issues for understanding movement in complex fractured systems. The first is methodological and the second, theoretical.

First, the findings of this thesis remind us that there may be a necessary trade-off between accuracy and precision in the modelling process. Measurement always imposes a numerical structure on data, which may be able to be parsed into an infinite variety of alternative structures. When attempting to estimate complex sociological phenomenon such as “the urban buzz” or the mixing of socio-spatial boundaries, it is important to utilise the appropriate measurement tools and scale.

Tucker (2004) emphasizes that scores may be very precise but highly inaccurate. This may have been the case with the first round of spatial modelling in this thesis, which precisely measured change of direction using a high-resolution pavement geometry, yet failed to pick up the fundamental spatial relationships with movement. “The more precise a measure”, Tucker reminds us, “the more difficult it is to achieve high levels of validity.” (Tucker, 2004)

Care must therefore be taken at every stage of the modelling process to ensure that what is being measured in the appropriate variable (such as space versus land use) and that the relationships described are valid not only statistically, but theoretically as well. Over precision can undermine the accuracy and validity of the measurement, resulting in misleading correlations or forced statistical relationships. This point is especially important in fragmented spatial systems and low-intelligibility sub-areas, where small changes can result in large modelling differences.

This raises a second point, which is more theoretical in nature. The correlation contour maps of Boston’s sub-areas raise questions about the nature of correlation contour maps and why they display the types of “peaks and valleys” which were observed.

It has been suggested that urban systems behave similar complex dynamic systems such as ecologies, which exhibit a variety of properties including “bounded equilibrium” (Kellert, 1994). The phenomenon of bounded equilibrium is where stable patterns persist over time in the midst of chaotic conditions. Such patterns exhibited strongly bounded areas in which order drops off towards chaos at the edges, as was seen in the correlation contours of Boston. Although first discovered in turbulent water experiments, this property has been observed in things as diverse as weather patterns, population dynamics, and astrophysics (Bak, 1996).

If cities are indeed complex dynamic systems that are subject in some way to phenomenon like bounded equilibrium, it is possible that the changes in correlation contours observed in Boston relate to the degree of stability and coherency found within bounded sub-areas. Like a smoothly flowing river, it could be that space and movement work together within such contours, but that overlapping influences result in chaotic or less predictable movement toward their edges or in-between sub-areas.

A complex systems understanding may be a compelling line of reasoning for investigating the nature and function of the correlation contour islands found in the city of Boston. But there may be alternative explanations which need attention, resulting from unmeasured variables or a hither-to undiscovered relationship between those variables measured. In any case, it is clear that further theoretical investigation is required to fully understand the implications of the "correlation island effect" seen in Boston.

6.5 Towards a New Urbanism in Boston: Forecasting Movement Conditions after the Big Dig

Another focus of this thesis was the role of space in creating vibrant urban cultures. What insights can these findings provide for students of successful urbanisation and what can they tell us about the likely effects of the completed Big Dig on Boston's future? What lessons can be learned for similar regeneration projects elsewhere? And what, in particular, can they contribute to our understanding of the social effects of architectural form, as discussed generally by writers such Mumford (1961) and Jacobs (1963) and by Hillier (1996)?

The arguments outlined in the literature review suggest that a balanced mixture of sub-areas and user groups is necessary to create the feeling of 'social capital', 'urban buzz', or 'virtual community' described by Mumford, Jacobs, and Hillier. Evidence from the city of Boston suggests that such a mixture does not take place in the majority of the city's spaces, resulting in less activity and a lack of vibrant street cultures. How will the changes of the Big Dig influence these spaces and what can the movement forecasts presented offer a discussion of Boston's urban future?

The most "urban" social space within Boston is the space to the east of City Hall, around the junction of State and New Congress Streets. This intersection was the only one that displayed a strong mixture of users in space and in time, with South Station coming close but working in a much more periodic fashion. An ironic note to the State / New Congress intersection is that the use of such a space appears to be an unplanned consequence of the urban regenergation of City Hall (which eliminated the previous meeting point of high integration lines in Scollay Square) and Quincy Market.

The movement model forecasts increased activity in this area, resulting in the highest combined movement rate of anywhere in the city. Clear lines of access from the tourist destinations at the Wharf, Government Center to the west, and the financial district to the south will place additional emphasis on this space, making it a prime location for development that can take advantage of the natural opportunities possessed at this site.

A final change worth mentioning is the surprising change in use that is predicted to result from the strengthening of east-west connections along the State Street axis. By building the accessibility of these connections, it was forecast that the north – south axis of Washington Street will experience a rise in utilisation, lying in between Tremont Street and the heart of the Financial District. Even though this area is remote from the Big Dig, the strengthening of connections which connect to this area will increase movement rates along this segment higher than those on on Tremont Street, which has been the historic north – south access into the heart of the city. Because Washington is already embedded in a strong mixed use neighbourhood with a thriving pedestrian mall at the junction of Winter Street, it is suggested that the entire west Chinatown / Theatre district will experience an increase in use and the potential urban buzz that comes with mixed pedestrian traffic.

Taken as a whole, these findings suggest that the use of integration may be a useful index for measuring the degree of pedestrian usage, and that by combing integration analysis with multi-group correlation contour mapping, an 'urbanisation index' may be able to be developed. If such a strategy were to prove successful, it could provide extremely important data planners working on regeneration or development sites in other American cities.

7. <u>Conclusion</u>

This thesis examined city of Boston, Massachusetts as a case study to evaluate the following null hypotheses:

1. Space does not play a significant role in low intelligibility systems
2. Other variables such as land use or attractors are more important in fragmentary systems
3. When it predicts, space predicts uniformly for all users and uses

It was shown that space did play a significant role in movement in low resolution systems, but that it was necessary to analyse and define movement sub-areas for such correlations to become apparent.

Other variables were tested during this process, included the sum of built area per axial line, topological step depths to transit and major attractors, and urban design characteristics such as pedestrianisation or tourist trails. It was shown that space was the major explanatory variable in every case and often the only explanatory variable at smaller scales of analysis.

Finally, space use and movement areas were explored through the use of correlation contouring to discern the boundaries of sub-areas within the system. Space was shown to correlate differently with space and observed pedestrian movement in different areas, thus disproving the third and final null hypothesis.

Building on these findings it was suggested that the use of correlation contours offered insight into the nature of complex, fractured urban systems such as Boston, and that the specific structure of intermixing between these contours may relate to successful patterns of urbanisation in cities across America.

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