

Article

Study on the Regeneration of City Centre Spatial Structure Pedestrianisation Based on Space Syntax: Case Study on 21 City Centres in the UK

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Abstract: Pedestrian priority is an important requirement for city centre regeneration. The quantitative analysis of the separation degree of pedestrians and vehicles is a key technique to measure the walkability of city centre regeneration. This paper proposes a method for measuring the walkability of the spatial structure in city centres, based on spatial topological relationships. Using space syntax as a platform, the walkability of the spatial structure of city centres is quantitatively analysed from the perspective of separation of pedestrians and vehicles, and the regeneration of pedestrianisation. Based on 21 cases of major city centres in the United Kingdom (UK), the trend of pedestrianisation regeneration from the early 20th century to the present is analysed. The analysis of the separation degree of pedestrians and vehicles and the analysis of regeneration models and the comparative analysis found that: (1) from the early 20th century to the present, the spatial structure of major city centres in the UK clearly trended toward pedestrianisation. (2) The regeneration process can be categorised into three models: the Gradual Growth Model, One Step Model and Long-Term Planning Model. (3) The three models contribute differently to the separation of pedestrians and vehicles in city centres, and their advantages and disadvantages differ. This study has implications for the theory and practice of pedestrianisation regeneration in city centres.

Keywords: city centre; spatial structure; pedestrianisation regeneration; separation degree of pedestrians and vehicles; regeneration model; space syntax; UK



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1. Introduction

Pedestrianisation is a key aspect of spatial quality enhancement in the city centre. The city centre is the main commercial and business area of a city. The city centre serves a wide range of people and is characterised by dense pedestrian flows, important status, complex structure and prominent contradictions, making it the main battleground for spatial quality improvement. The pedestrian system is an important carrier of human activities and spatial organisation in the city centre and plays an irreplaceable role in improving the quality of the city centre. The regeneration and optimisation of the pedestrian priority can promote human activities, improve spatial quality, enhance urban vitality and optimise spatial structure. Internationally, many city centres have constructed a spatial structure with a high-quality pedestrian system as the framework, which has effectively improved spatial quality [1].

The United Kingdom (UK) has a wealth of practical experience in the regeneration of city centre pedestrianisation and has achieved some success. In terms of regeneration trends, the central role of the pedestrian system in the city centre has been clearly defined, and the total amount of pedestrian space has steadily increased over the years. In terms of

spatial structure, a “ground-level pedestrian-core, public-transport-first, pedestrian-vehicle-separated circle structure” has been constructed [2,3]. In terms of the design approach, the design focuses on the in-depth integration of urban and architectural spaces led by the pedestrian system. In terms of management techniques, a variety of traffic restriction methods are used to achieve fine spatial management. In terms of regeneration practice, many excellent city centre regeneration projects with pedestrian systems at their core have been born, such as Oxford Circus (London, 2012), Paradise Circus (Birmingham, 2018), New Street Station (Birmingham, 2015), Media City UK (Manchester, 2013), Liverpool One (Liverpool, 2009), Trinity Leeds (Leeds, 2013), St David’s Centre (Cardiff, 2009) and many others. Birmingham has been ranked as the city with the highest quality of life in the UK for its successful network of pedestrian, plaza and public spaces in the city centre [4]. The separation of pedestrians and vehicles is an important means of enhancing walkability. It can provide a safer and more comfortable environment for pedestrians, a faster and undisturbed environment for vehicles, and more easily provides a suitable environment for buses, scooters, and bicycles in transition areas for both pedestrians and vehicles.

The separation of pedestrians and vehicles can be achieved through many means, including physical isolation, such as pedestrian bridges and vehicular tunnels, access management, such as restricted roads, bicycle and bus lanes, and pedestrian streets, and spatial structure optimization, such as ring road construction and road network regeneration.

The regeneration of city centre spatial structure pedestrianisation in the UK has been ongoing for at least a hundred years and has become a significant reference for improving city centre walkability. However, a key question that must be answered to conclude from the UK experience is how to quantitatively analyse the effects of different spatial structure regeneration models in improving the walkability of city centres from the perspective of the separation of pedestrians and vehicles in the UK. This question can be divided into three parts: first, how to quantify the separation of pedestrians and vehicles in the city centre spatial structure and its regeneration trends. Second, what regeneration models have been used to regenerate the spatial structure of major city centres in the UK? Third, what are the actual results of the various regeneration models and what are the advantages and disadvantages of each?

This paper focuses on the separation of vehicles and pedestrians achieved through spatial structure regeneration, and proposes a method for quantitatively measuring the walkability of spatial structures in city centres and their regeneration, based on spatial topological relationships, using space syntax as a platform.

We collected information on the regeneration of the spatial structure of 21 major cities in the UK from the early 20th century to the present day and developed the study based on three aspects. First, a technical method is proposed to quantitatively measure the separation degree of pedestrians and vehicles of a city centre spatial structure, based on space syntax. Second, the regeneration models of the 21 major city centres are categorised according to their regeneration processes. Third, the actual results achieved by the various regeneration models are compared, and each regeneration model is then comparatively analysed.

2. Literature Review

The regeneration of city centres is an important research topic in the international academic community [5]. In recent years, research has focused on “people-oriented and sustainable development” [6]. Peter Hall discussed the development trend of contemporary cities and pointed out that a good city is one that provides people a high quality of life [7,8]. Jan Gehl also emphasises the humanised city and studies urban space from a human perspective [9,10]. The regeneration and development of the city centre should not only aim at “efficiency first and growthism” [11], but should also focus more on “people”, their living, working and living environment [12], increasing the resilience of the city [13] and making it suitable for people’s activities [14]. In addition to green space [15], commerce [16] and culture [17], walkable streets have been widely valued for their important role in carrying ‘human activity’ [18–22], and Tallon outlines aspects of

what a sustainable central area should be [23]. The contribution of central area traffic patterns [24,25] and open space organisation patterns [26,27] to reducing carbon emissions and achieving humane and sustainable development has been widely recognised [28]. Superblocks (also known as Superillas and Supermanzanas) in Barcelona show a typical regeneration case of pedestrianisation [29]. Similarly, the quality of the urban environment influences people's behaviour and drives change in the urban structure [30].

Over the years, the concept and policy of pedestrian priority in the UK have matured. The concept of pedestrian priority in the UK emerged in the context of the proliferation of cars and the degradation of the environment [31]. Home Zones were introduced in the UK in the 1930s, closing roads to motor vehicles to create a liveable street environment [32]; traffic calming began in the Netherlands in the 1980s, was replicated in Germany and introduced in the UK, where it has been widely developed due to its own successful track record [33,34]. The "Basic Road Statistics 1987" aims to protect residents, pedestrians and cyclists by reducing speeds through various measures [35]. The "Traffic Calming Act 1992" provides a convenient and efficient approval process for its implementation, controlling traffic, enhancing safety, and protecting and improving the environment [36,37]. Since the 2000s, the UK's own policies have progressively improved, and walking priorities have been refined in various ordinances and plans. In 1998, the "White Paper: A New Deal for Transport" [38] was published, restricting car travel and encouraging walking, cycling and public transport. In 2000, the "Transport Act 2000" [39], the "Transport Ten Year Plan 2000" [40] and the "Framework for a Local Walking Strategy" [41] were introduced, which were seen as a follow-up to the 1998 "White Paper: A New Deal for Transport" and were widely received and acclaimed. In 2004, the "White Paper: A New Deal for Transport" was republished as "The Future of Transport" [42], explicitly promoting walking and cycling over the next 20–30 years. Plans, such as the 2017 "Birmingham Development Plan" [4], clarify the centrality of pedestrians to transport in the city centre in the form of statutory provisions.

A growing body of research focuses on quantitatively evaluating pedestrian networks. Such evaluation tools have been developed in several countries, including the Walk Score and Walkability Score in the USA and the Walkability App in Europe, etc. International perspectives on walkability include social factors [43], facilities [44], physical activity [45], social justice [46], aging-friendliness [47–49] and neighbourhood [50]. The tools for evaluating walkability include space syntax [51,52], GIS [53], deep learning [54], environmental sensors [54], virtual reality [55], hierarchical clustering technique [56], mobile methodologies [57] and BIM [58]. In the UK, the "4Es" evaluation criteria have been established for linear slow-moving spaces, in terms of "Experience, Enhancement, Engagement and Economy" and so has The Pedestrian Environment Review System (PERS). In the US, the Neighbourhood Environment Walkability Scale (NEWS) and the Pedestrian Environmental Quality Index (PEQI) have been established. New Zealand has established the Community Street Review (CSR).

Space syntax is an effective method to study pedestrian behaviour in city centres. It is a network analysis method invented in the 1970s [59,60] by Bill Hillier [61] and Julienne Hanson at University College London. The main research institutions are the Space Syntax Laboratory at University College London [62] and the Space Syntax Company [61]. The method can quantitatively measure and analyse the impact of architectural spaces and urban spaces on people and their movement through space [63,64]. Although space syntax has its limitations [65–67], it can be applied to study spatial network structure [68], spatial morphological evolution [69], bicycle traffic [47,70], public transport [71], ecological network [72], tourism [73] and many other aspects. In the research of city centre spatial structure pedestrianisation regeneration, space syntax can be used for pedestrian movement [74–78], street network [79–81], comparison between pedestrians and vehicles [82] and spatial structure evolution [83].

3. Materials and Methods

3.1. Study Area

The UK has 28 cities with a built-up area population of 200,000 or more [84]. Of these cities, 21 (accounting for 75% of the total) were selected to obtain a full picture of the spatial structure and regeneration of city centres in the UK over the past century (Figures 1 and 2, and Table 1). This study excludes London since, with a population of 8.78 million (7.3 times that of the second-ranked city of Birmingham), it is very different from the other cases in terms of spatial structure and is thus considered a special case, not general in nature.



Figure 1. Location of studied city centres.

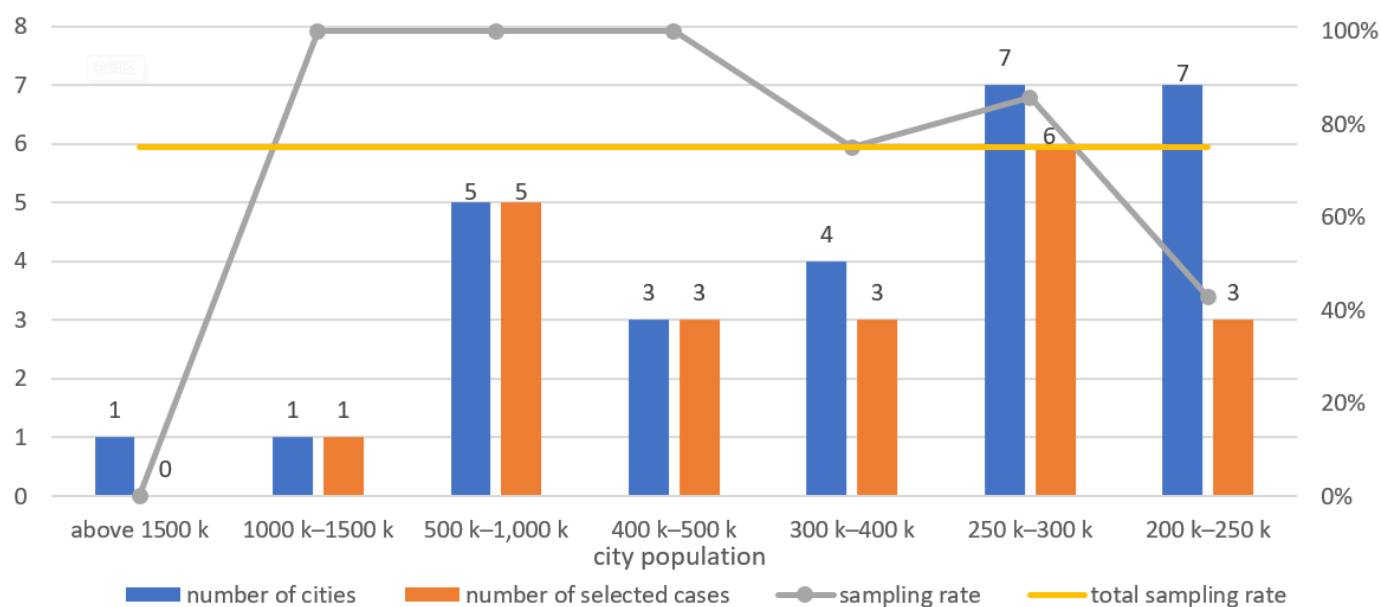


Figure 2. Number of studied cases and sampling rate. The numbers of cities in each population range in the UK are 1, 1, 5, 3, 4, 7, 7. The numbers of cities studied in this research in each population range are 0, 1, 5, 3, 3, 6, 3. The sampling rates in each population range are 0%, 100.0%, 100.0%, 100.0%, 75.0%, 85.7%, 42.9%. The total sampling rate is 75.0%.

Table 1. Studied cities and their population.

Population	Number of Cities	Number of Studied Cities	Sampling Rate	City Names	City Population
above 1,500,000	1	0	0.0%		
1,000,000–1,500,000	1	1	100.0%	Birmingham	1,121,408
500,000–1,000,000	5	5	100.0%	Glasgow	631,690
				Leeds	536,321
				Liverpool	506,552
				Edinburgh	505,310
				Sheffield	500,552
400,000–500,000	3	3	100.0%	Manchester	470,411
				Bristol	425,232
				Leicester	406,588
300,000–400,000	4	3	75.0%	Cardiff	348,546
				Coventry	344,322
				Bradford	333,931
250,000–300,000	7	6	85.7%	Nottingham	299,797
				Newcastle	286,468
				Brighton	277,106
				Derby	275,599
				Plymouth	266,983
				Stoke	260,602

Table 1. Cont.

Population	Number of Cities	Number of Studied Cities	Sampling Rate	City Names	City Population
200,000–250,000	7	3	42.9%	Southampton	249,604
				Wolverhampton	234,015
				Portsmouth	223,312
Total	28	21	75.0%		

3.2. Method Design

The research methodology contains three main components, including separation degree of pedestrian and vehicle analysis, regeneration model categorisation analysis and their comparison analysis.

3.2.1. Separation Degree of Pedestrians and Vehicle Analysis

The analysis has six steps to quantitatively measure the separation degree of pedestrians and vehicles and the regeneration trend (Figure 3).

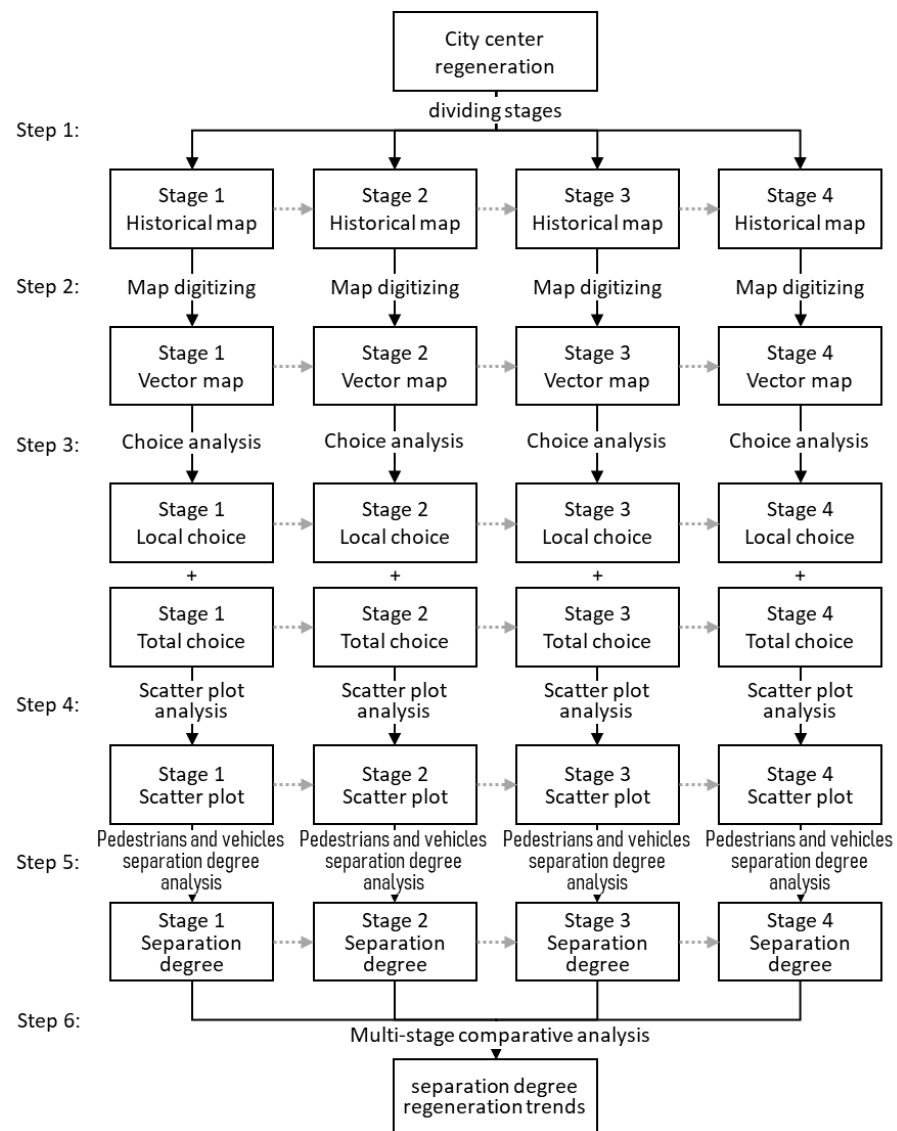


Figure 3. The flowchart.

(1) Dividing stages

From the early days until the early 20th century, the spatial structure of the city centres was characterised by a mix of pedestrian and vehicle traffic. From the early 20th century to the present, the concept of pedestrian priority was enriched and the practice of pedestrian-oriented urban regeneration developed. This study takes the early 20th century as the starting point and divides historical maps of 21 case cities into four stages: the early, mid, and late 20th century and the early 21st century, to summarise and analyse the general trend of pedestrianisation in the spatial structure regeneration of city centres in the UK over the past two centuries. The historical maps of each phase were selected as the basis for the study (Figure 4).

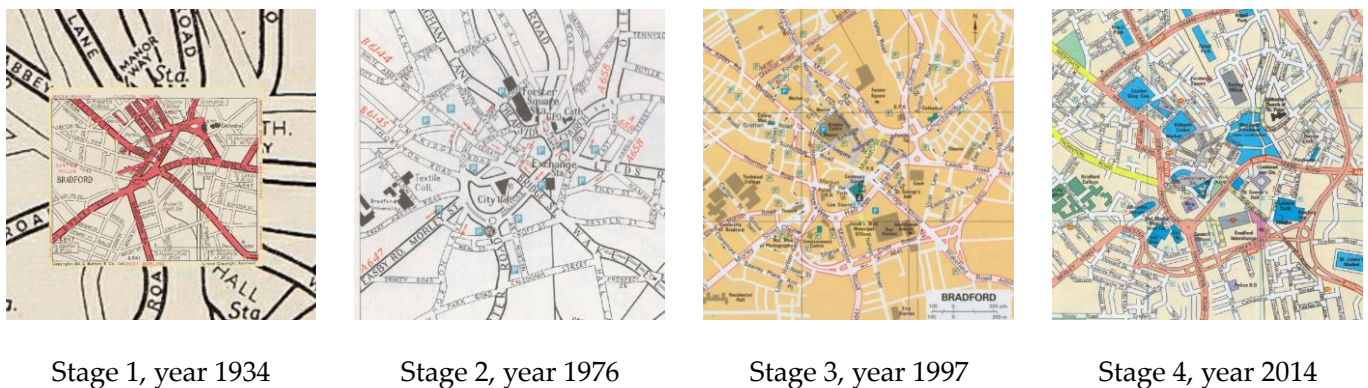


Figure 4. Maps of each stage taking Bradford city centre as an example.

(2) Map digitalization

The historical maps of the various stages were collected and the road axes mapped in AutoCAD (Autodesk), then imported into the depthmapX (an open source computer software originally developed by Alasdair Turner [85]) and converted into the Segment Map for analysis. In a segment map, road axes are broken at their intersections into road segments that are connected together as a network [86]. The segment is the base for segment analysis including Choice analysis in the next step.

Taking the Bradford city centre as an example, the maps of the four stages of the city centre were digitised. The same criteria were used to translate the various stages of the historical maps into a uniform style, to meet the analysis requirements (Figure 5).

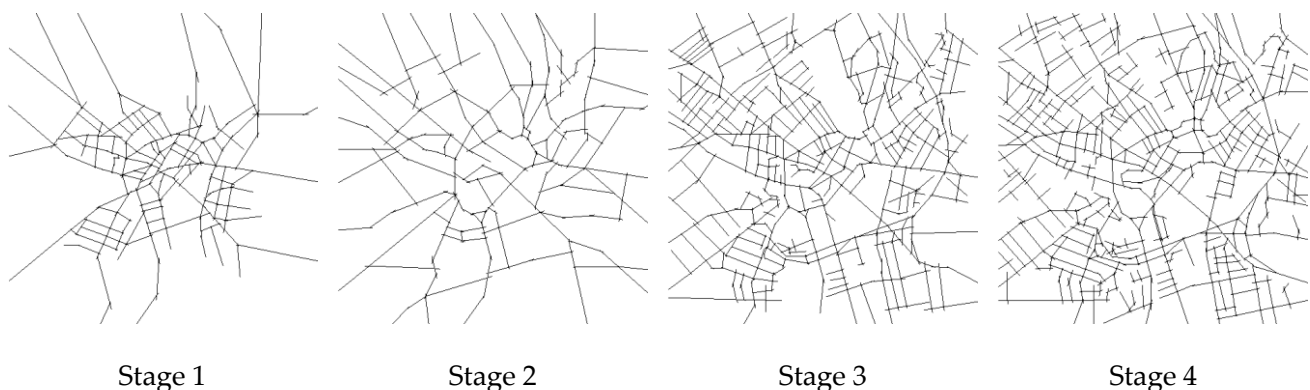


Figure 5. Vector maps of each stage taking Bradford city centre as an example.

(3) Choice analysis

The study uses the space syntax “Choice” as the basis indicator. In the line segment model, any two line segments can be connected through other line segments. Choice

measures the frequency with which a line segment is used as the shortest topological distance between two line segments in the entire system or within a predetermined distance (radius) from each segment [87]. Choice reflects the importance of the line segment in network interconnections. Total Choice reflects the importance of a line segment in global interconnections. The Local Choice reflects the importance of a line segment in local interconnections within a specified radius.

In this study, the Total Choice of a road segment represents its importance in long-distance traffic, including transit traffic and external traffic, which is normally vehicle traffic. The Local Choice of a road segment represents its importance in short-distance traffic, including internal traffic, which is normally pedestrian traffic (Figure 6).

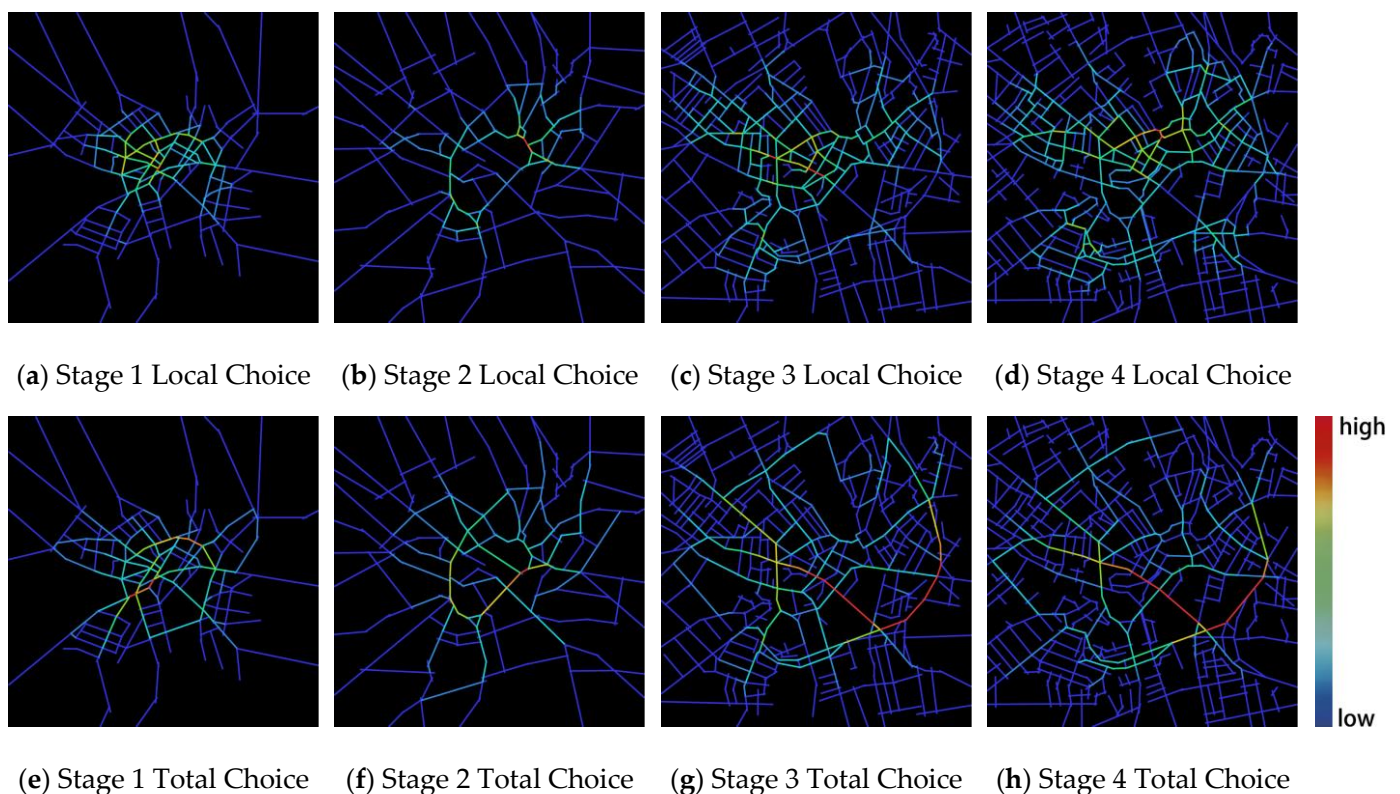


Figure 6. Local Choice and Total Choice analysis of each stage taking Bradford city centre as an example.

If road segments with high Total Choice and high Local Choice are the same road segments, it means that these roads are important for both vehicles and pedestrians (Figure 6a,e). If road segments with high Total Choice and high Local Choice are different, it means that roads important for both vehicles and pedestrians are different roads, so there is a separation between vehicles and pedestrians (Figure 6d,h).

(4) Scatter plot analysis

A coordinate system is constructed using the Total Choice as the horizontal coordinate and the Local Choice as the vertical coordinate. Each line segment is labelled at its corresponding position in the coordinate system. Each point in the scatter plot corresponds to a segment in the line segment model, and the vertical and horizontal coordinates of the point in the scatter plot are the values of the Local Choice and Total Choice of the corresponding segment, respectively (Figure 7).

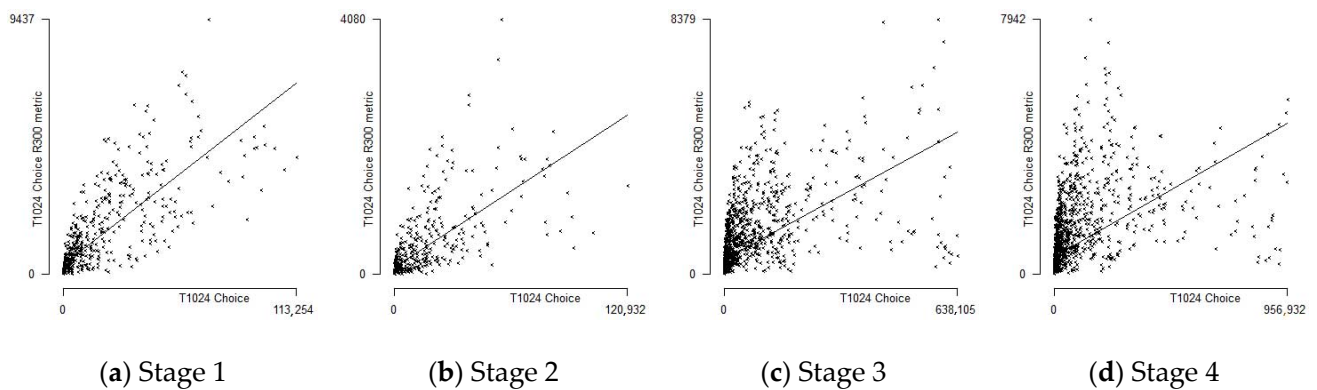


Figure 7. Scatter plot and regression analysis of each stage taking Bradford city centre as an example.

The scatter plot can be interpreted as in Figure 8. The scatter plot can be divided into two main areas, those with low Total Choice and Local Choice called the 'low-value area', and those with high Total Choice or Local Choice, or both, called the 'high-value area'. The high-value area can be divided into three areas, the 'middle area' and the two 'wing areas'. The middle area has high Total Choice and Local Choice, while the two wing areas have only one high value. The analysis finds that most of the road segments are located in the low value area, which weakly affects the traffic in the city centre. The road segments in the high value area have a greater effect on the traffic in the city centre, and these roads in the high-value area are the main object of the study.

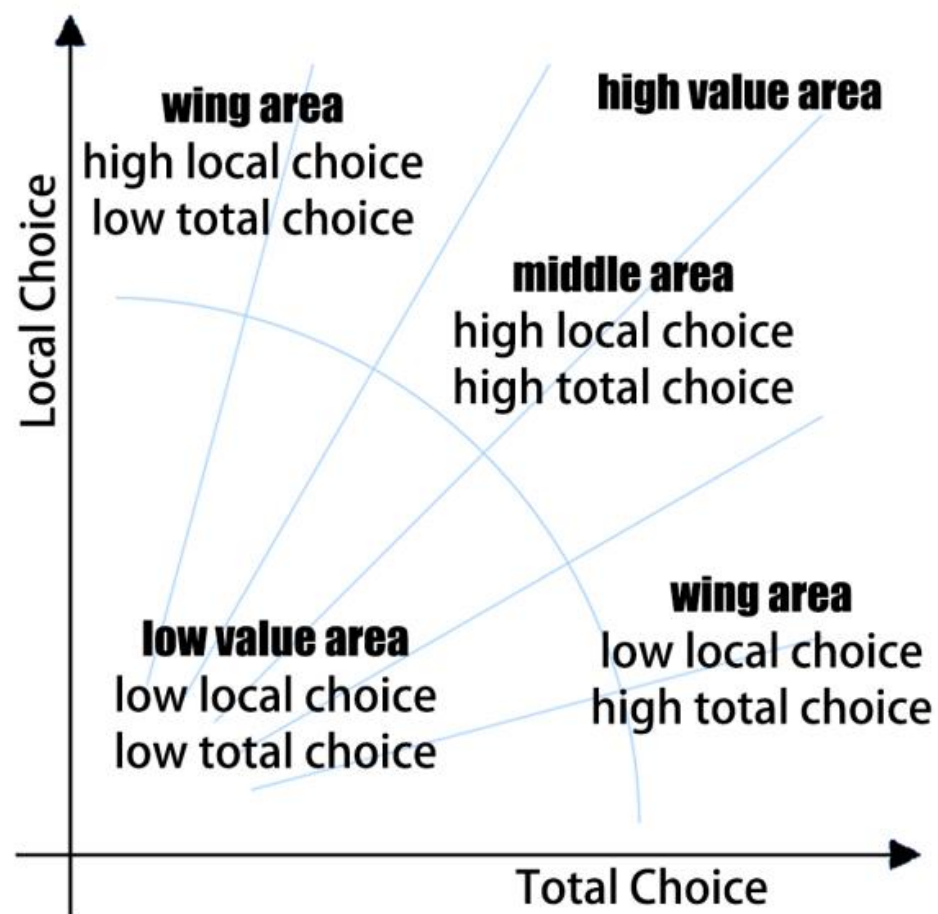


Figure 8. Scatter plot interpretations.

The distribution of road segments in the high value area can reflect the separation of vehicles and pedestrians. If more road segments in high value area are distributed in the middle area, it means that these roads have both high Local Choice and high Total Choice, and these roads are important for both the vehicles and the pedestrians (Figure 7a). If more road segments in high value area are distributed in the two wing areas, it means that roads important for vehicles and for pedestrians are different roads, so there is a separation between vehicles and pedestrians (Figure 7d).

(5) Separation degree of pedestrians and vehicles analysis

The separation degree of pedestrians and vehicles means “the degree of separation between the space for pedestrians and the space for vehicles of city centres”. It also reflects “the degree of separation between the space for the internal traffic and the space for the external (transit) traffic of city centres”. The space syntax platform expresses it as “the degree of spatial separation between the Local Choice representing pedestrian and internal (transit) traffic and the Total Choice representing the vehicle and external traffic of the city centre”.

Linear regression was performed on the scatter plot to find a straight line, expressed as $y = ax + b$. The linear regression of a total of 84 samples from 21 cities revealed that all the regression lines had one important feature in common: the coefficients a in the regression line $y = ax + b$ were all positive, and the lines all led from near the origin of the low-value area to the middle of the high-value area in the scatter plot.

The Goodness of Fit refers to the degree to which the regression line fits the observed values. The coefficient of determination, R^2 , which ranges from 0 to 1, measures the Goodness of Fit. The closer the value of R^2 is to 1, the better the fit of the regression line to the observed values; conversely, the closer the value of R^2 is to 0, the worse the fit of the regression line to the observed values.

Let the “separation degree of pedestrians and vehicles” be “ A ”, then

$$A = 1 - R^2$$

where A is the separation degree of pedestrians and vehicles, and R^2 is the Goodness of Fit of the scatter plot.

The “ A ” value can reflect the separation degree of pedestrians and vehicles. The lower “ A ” is, the higher the Goodness of Fit is, the closer road segments are distributed to the regression line, the more road segments are distributed in the middle area in the scatter plot, and the lower is the separation degree of pedestrians and vehicles. The higher “ A ” is, the lower the Goodness of Fit is, the farther road segments are distributed from the regression line, the more road segments are distributed in the two wing areas in the scatter plot, and the higher is the separation degree of pedestrians and vehicles.

(6) Multi-stage comparative analysis

When comparing the “ A ” values of individual city centres at various stages, the trend clearly reflects the change in the spatial separation between the local and global traffic in the city centre. An increase in “ A ” indicates that the local traffic in the city centre tends to spatially separate from the global, which means that pedestrian traffic separates from vehicle traffic and internal traffic separates from external (transit) traffic. A decrease in “ A ” indicates that the local traffic in the city centre tends to spatially coincide with the global, which means that the pedestrian traffic coincides with the vehicle traffic, and the internal traffic coincides with the external (transit) traffic (Figure 9).

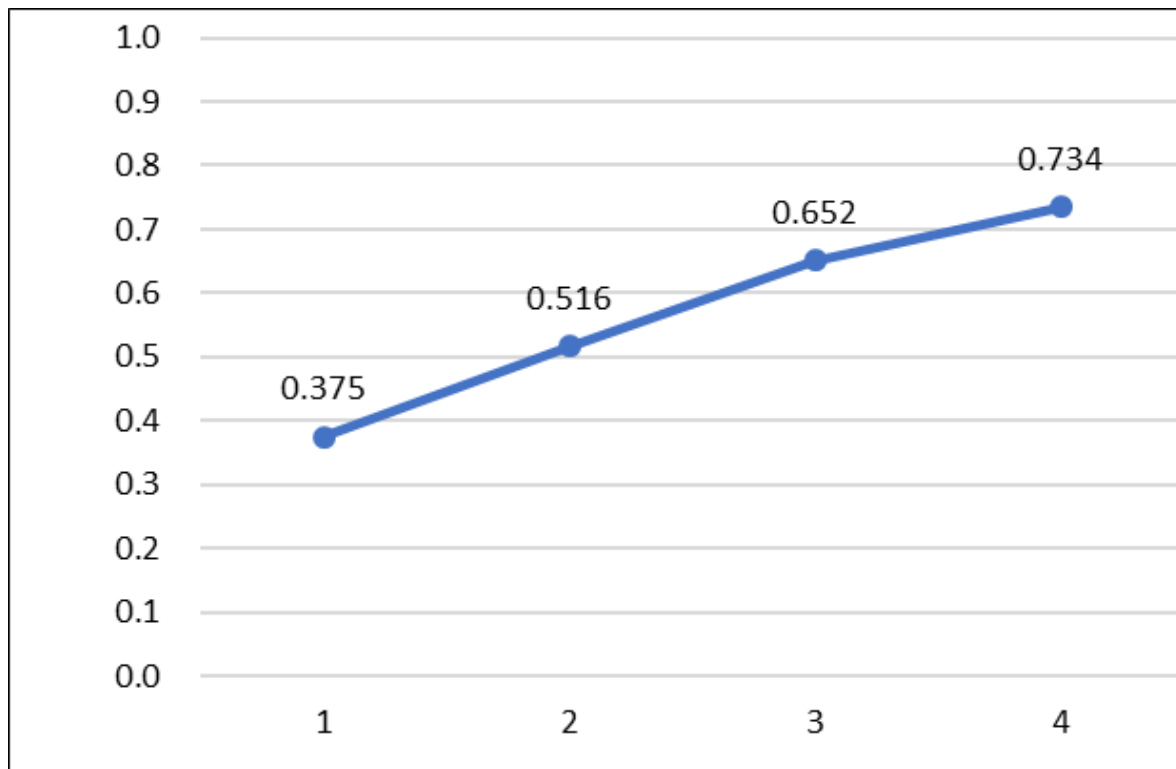


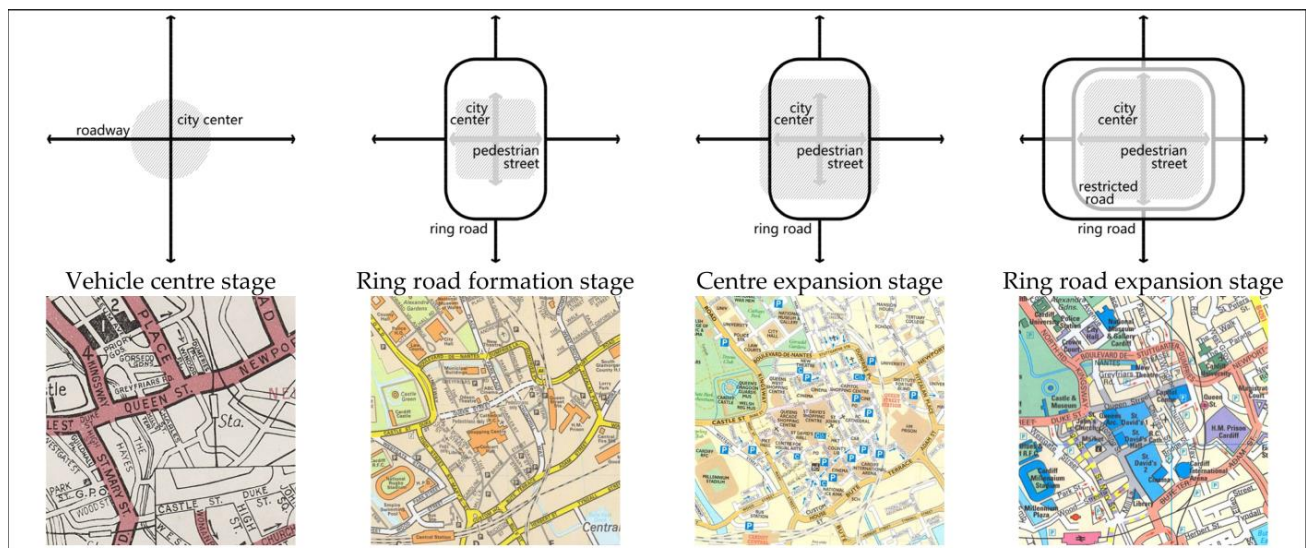
Figure 9. Changing trends of the separation degree of pedestrians and vehicles taking Bradford city centre as an example.

3.2.2. Regeneration Model Categorisation Analysis

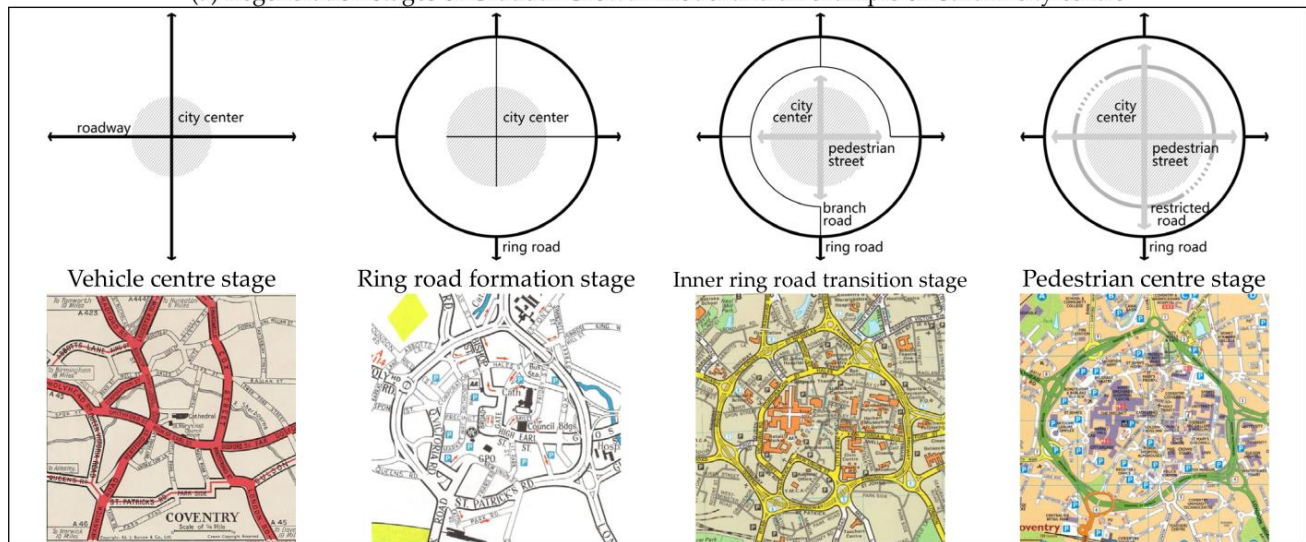
The 21 cases selected were categorised and analysed to determine the model the regeneration of each city centre area falls into.

(1) Model summary

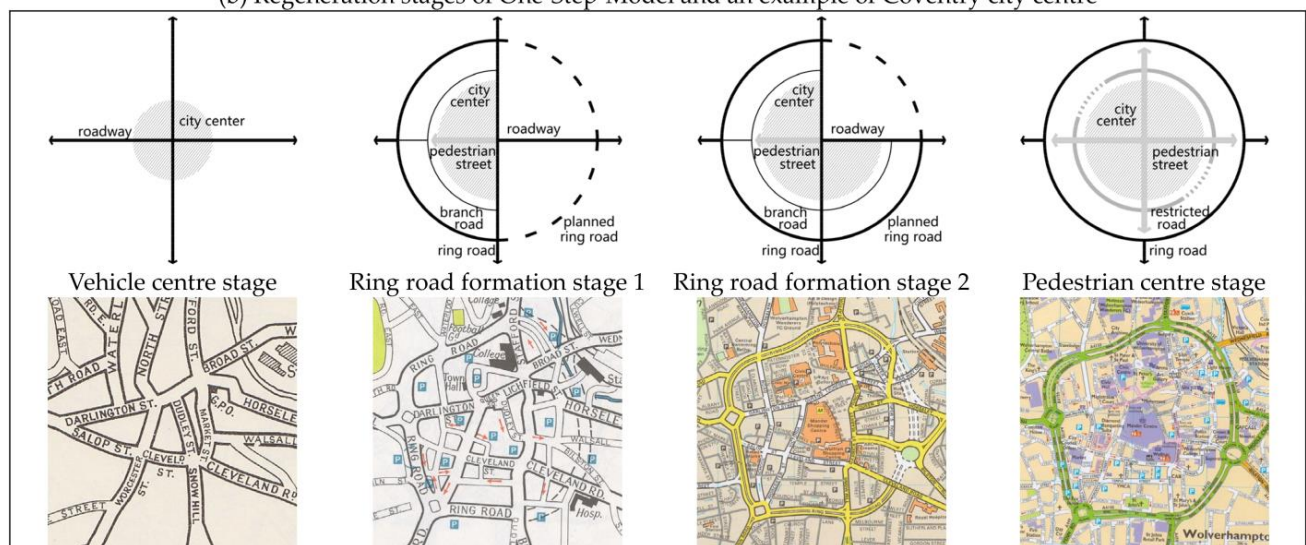
The regeneration histories of the 21 city centres were analysed by historical map sorting and summarizing. Over the past 100 years, city centres in the UK have been transformed from a vehicle core spatial structure to a pedestrian core spatial structure, thanks to the consistent long-term pedestrian-oriented urban policies and spatial plans. However, the regeneration models vary from city to city. Three regeneration paths can be summarised as the “Gradual Growth Model, One Step Model and Long-Term Planning Model”. Of the three regeneration models, the pedestrian core is formed similarly, with the core carriageway being downgraded and gradually transformed into pedestrian paths forming a pedestrian core. The main difference lies in the way the vehicle ring road is formed. In the Gradual Growth Model, the vehicle ring road is mainly created by the grade adjustment and partial reconstruction of existing roads. The regeneration process includes the vehicle centre stage, ring road formation stage, centre expansion stage and ring road expansion stage (Figure 10a). In the One Step Model, a new ring road is planned and built in a short period of time. The regeneration stages include the vehicle centre stage, ring road formation stage, inner ring road transition stage and pedestrian centre stage (Figure 10b). In the Long-term Planning Model, a new ring road is planned, but built in stages over several years. The regeneration stages include the vehicle stage, ring road formation stage 1, ring road formation stage 2 and pedestrian centre stage (Figure 10c).



(a) Regeneration stages of Gradual-Growth-Model and an example of Cardiff city centre



(b) Regeneration stages of One-Step-Model and an example of Coventry city centre



(c) Regeneration stages of Long-Term-Planning-Model and an example of Wolverhampton city centre

Figure 10. Regeneration stages of three models and examples.

(2) Categorisation of cases

The main development stages of the 21 cities were compared with the three regeneration models, and the regeneration processes of the 21 city centres were grouped into three groups, which were used to support the analysis of the regeneration effects of each regeneration model.

3.2.3. Comparison Analysis

The changes in the separation degree of pedestrians and vehicles in the spatial structure of each city centre were compared with their regeneration models to study the effects of various regeneration models on the separation degree of pedestrians and vehicles.

(1) Effectiveness analysis

By comparing the data, the amount of change in the separation degree of pedestrians and vehicles brought about by each regeneration model is quantified and analysed.

(2) Mechanism analysis

The advantages, disadvantages and application scenarios of each regeneration model are analysed.

3.3. Research Data

The study spans the period from the beginning of the 20th century to the present day, and the representative year maps were selected on the basis of two principles. First, the interval years are approximately equal. Second, the maps of representative years can reflect the main characteristics of the spatial structure of the city centre area at that stage. The representative years for the 21 city centre districts selected for this study are listed in Table 2.

Table 2. Study cities and their data years (source: references [88–97]. Maps of 10 different years were used in all, and were derived from 10 atlases. Maps of the same year were all from the same atlas).

City Name	Stage 1	Stage 2	Stage 3	Stage 4
Birmingham	1934	1972	1997	2014
Glasgow	1934	1972	1997	2014
Liverpool	1934	1972	1997	2014
Bristol	1934	1972	1997	2014
Sheffield	1934	1972	1997	2014
Manchester	1934	1972	1997	2013
Leeds	1934	1972	1997	2013
Edinburgh	1951	1972	1997	2013
Leicester	1934	1972	1997	2013
Bradford	1934	1972	1997	2014
Cardiff	1934	1972	2001	2014
Coventry	1934	1972	1989	2014
Nottingham	1934	1972	1997	2014
Stoke	1961	1976	1997	2013
Newcastle	1934	1972	1997	2014

Table 2. Cont.

City Name	Stage 1	Stage 2	Stage 3	Stage 4
Derby	1951	1972	1997	2014
Southampton	1961	1972	1997	2014
Portsmouth	1934	1972	1997	2014
Plymouth	1951	1972	1997	2014
Brighton	1934	1972	1997	2014
Wolverhampton	1961	1972	1985	2013

4. Results

4.1. Overall Changing Trends of Choice

Analysis of Local Choice of the 21 city centres in the UK shows that the areas with high Local Choice have remained in the same location over the century and have gradually developed in their original locations. This indicates that the spatial location of local traffic, such as pedestrian and internal traffic, is relatively stable in UK city centres.

Analysis of Total Choice in the 21 city centres in the UK shows that over the past 100 years, areas with high Total Choice have shown an outward migration. This indicates that global traffic, such as car and transit traffic, has been gradually evacuated to the periphery of the central area in the UK city centres (Figures 11 and 12 are two examples of Coventry and Stoke city centre).

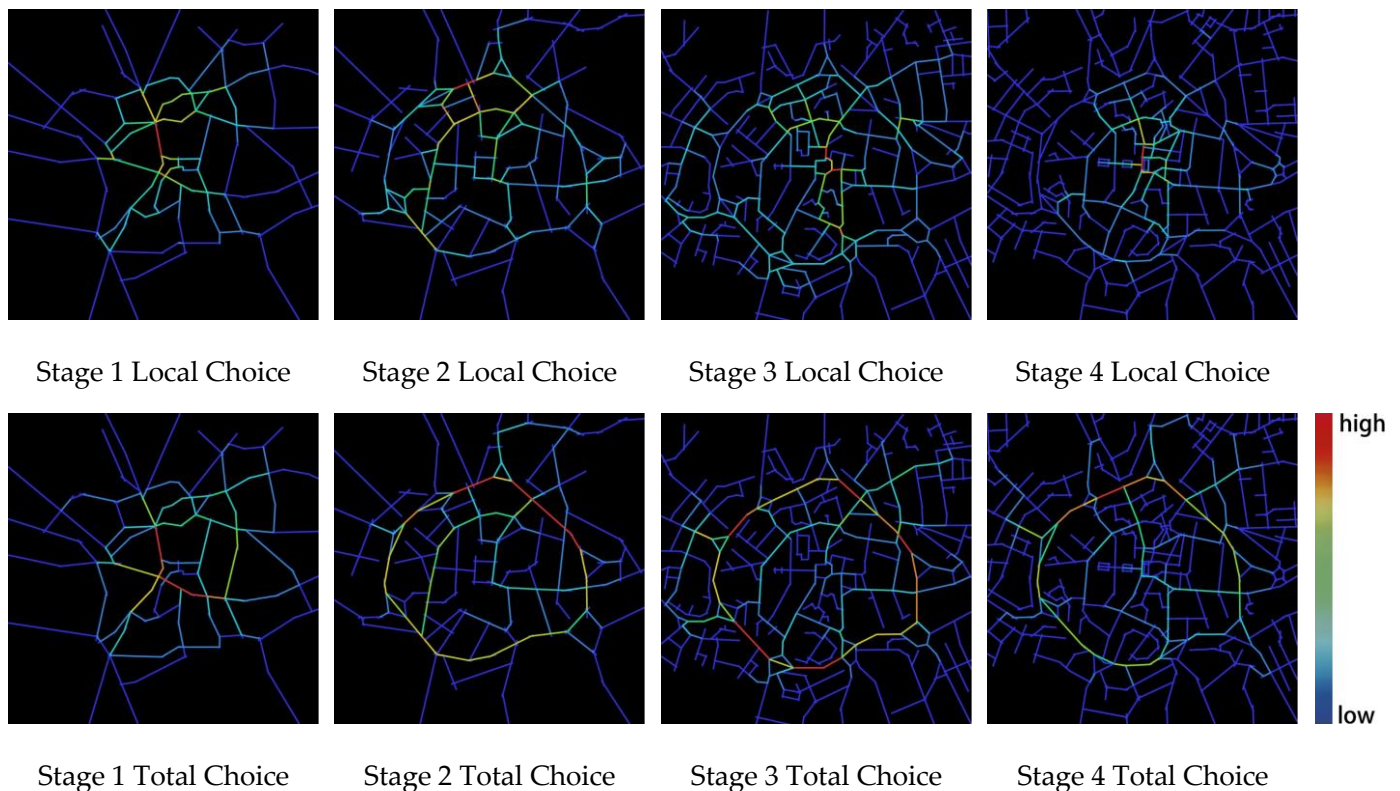


Figure 11. Coventry city centre Local Choice and Total Choice analysis of each stage. At stage 1, high Local Choice roads and high Total Choice roads were basically the same roads. By stage 4, high Local Choice roads and high Total Choice roads were separated. High Local Choice roads remained at the central area, while high Total Choice roads changed to the periphery of the central area.

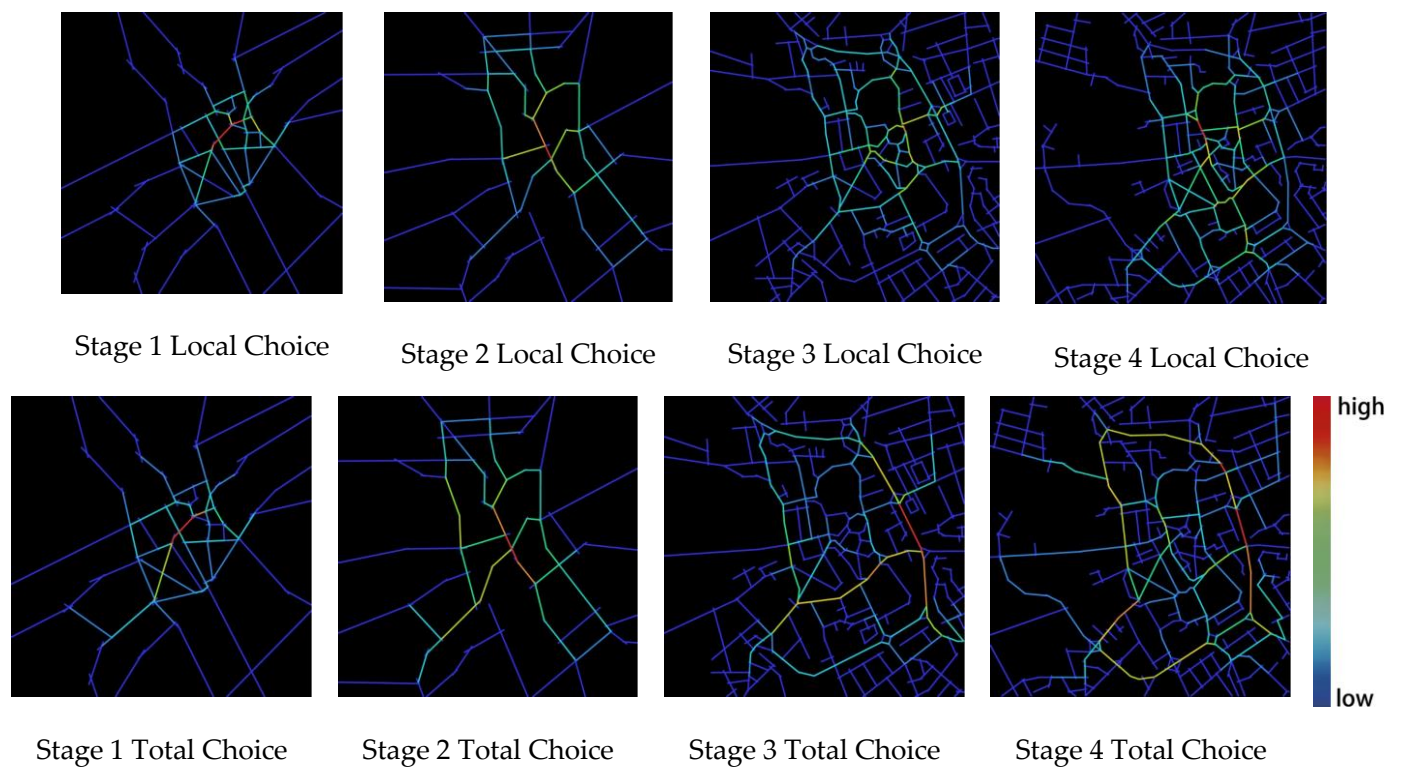


Figure 12. Stoke city centre Local Choice and Total Choice analysis of each stage. Stoke showed the same trend with Coventry that high Local Choice roads and high Total Choice roads separated from stage 1 to stage 4. High Local Choice roads remained at the central area, while high Total Choice roads changed to the periphery of the central area.

4.2. Changing Trends of the “Separation Degree of Pedestrians and Vehicles”

The study was carried out in 21 cities, with four stages in each city, to obtain values for the separation degree of pedestrians and vehicles (Figure 13, Table 3).

Table 3. Separation degree of four stages of UK city centres.

City Name	Stage 1	Stage 2	Stage 3	Stage 4	Total Change Amount
Birmingham	0.379	0.643	0.678	0.572	0.193
Bradford	0.375	0.516	0.652	0.734	0.360
Brighton	0.544	0.485	0.640	0.596	0.052
Bristol	0.547	0.708	0.825	0.672	0.124
Cardiff	0.469	0.466	0.673	0.557	0.088
Coventry	0.414	0.531	0.765	0.834	0.421
Derby	0.129	0.265	0.492	0.574	0.445
Edinburgh	0.519	0.443	0.721	0.574	0.055
Glasgow	0.678	0.741	0.702	0.747	0.069
Leeds	0.252	0.480	0.282	0.388	0.136
Leicester	0.352	0.454	0.680	0.638	0.286
Liverpool	0.330	0.379	0.404	0.504	0.175
Manchester	0.499	0.573	0.549	0.496	-0.003

Table 3. *Cont.*

City Name	Stage 1	Stage 2	Stage 3	Stage 4	Total Change Amount
Newcastle	0.514	0.476	0.525	0.613	0.098
Nottingham	0.377	0.585	0.728	0.461	0.084
Plymouth	0.433	0.755	0.630	0.651	0.218
Portsmouth	0.730	0.528	0.811	0.800	0.071
Sheffield	0.484	0.535	0.700	0.751	0.268
Southampton	0.462	0.501	0.545	0.534	0.072
Stoke	0.138	0.223	0.609	0.592	0.454
Wolverhampton	0.159	0.279	0.318	0.402	0.243
Average	0.418	0.503	0.616	0.604	0.186

The results show an increasing trend in the separation degree values. This indicates that the regeneration of city centres in the UK over the last 100 years follows a clear trend towards the separation of local from global traffic, the separation of pedestrians and vehicles, and the separation of internal and external (transit) traffic (Figure 14).

The separation degree of pedestrians and vehicles shows a clear upward trend in 21 cases overall, although some cities have experienced up or down fluctuations over the four stages of regeneration. In 20 cases, the separation degree of pedestrians and vehicles increased, with the largest increases in Stoke (0.454), Derby (0.445), Coventry (0.421), and Bradford (0.360), and only one city, Manchester, with a small decrease of 0.003 (Table 3, Figure 15).

The average separation degree of pedestrians and vehicles for the 21 cities increased from 0.418 to 0.604, an increase of 0.186 (Table 3).

In stage 4, the four cities with the highest levels of separation were Derby (0.871), Stoke (0.862), Wolverhampton (0.841) and Leeds (0.748).

4.3. Cities Categorised into Three Regeneration Models

The historical maps of the 21 case cities show that the regeneration history of each city centre can be summarised into three categories: “Gradual Growth Model, One Step Model and Long-term Planning Model”. Thirteen city centres, or 62% of the total, regenerated using the Gradual Growth Model, including Bradford, Liverpool, Cardiff, etc. Four city centres, or 19% of the total, regenerated using the One Step Model, including Coventry, Plymouth, Birmingham and Bristol. Four city centres, or 19% of the total, regenerated using the Long-term Planning Model, including Stoke, Derby, Leicester and Wolverhampton (Table 4).

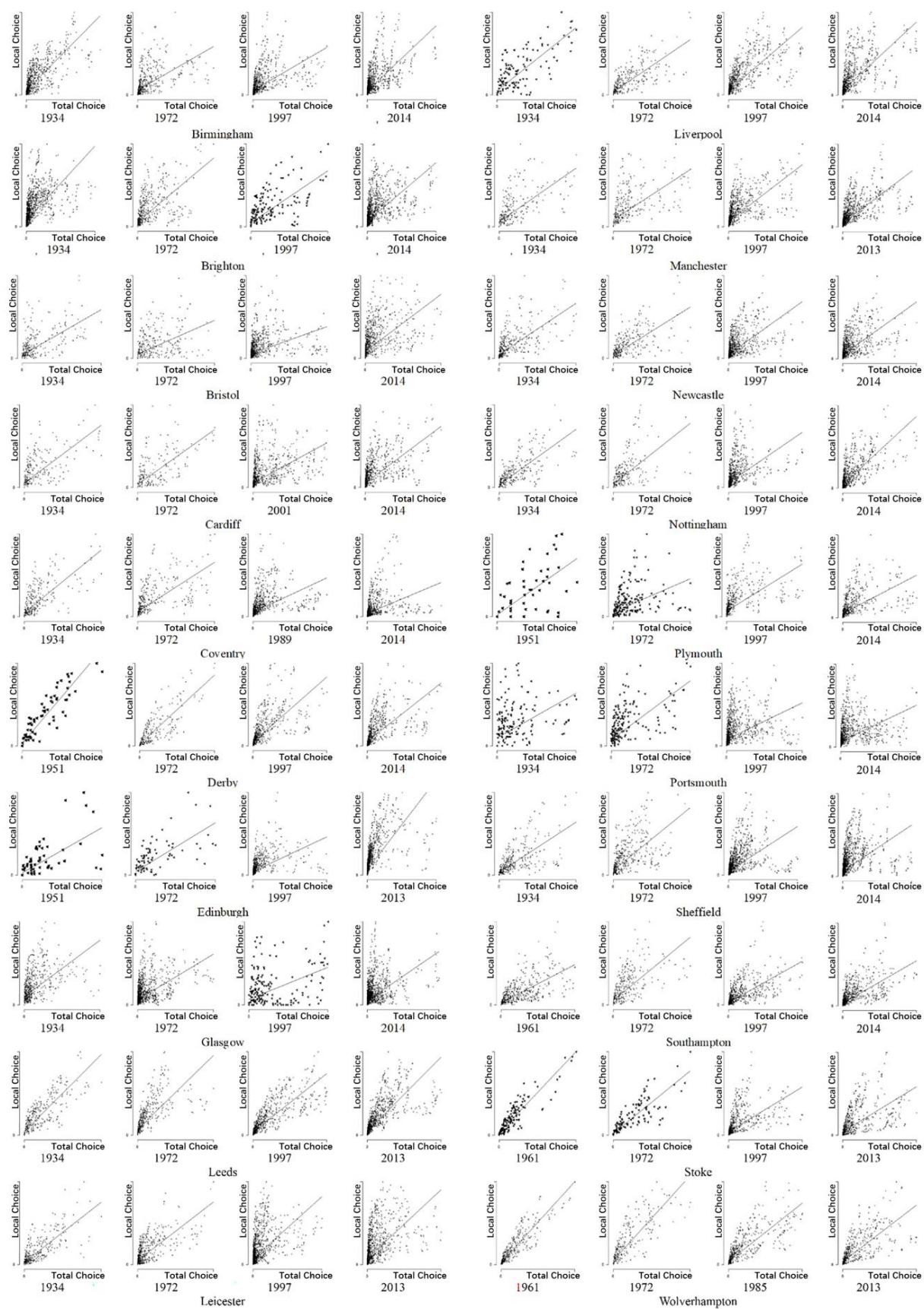


Figure 13. Scatter plot of four stages of UK city centres.

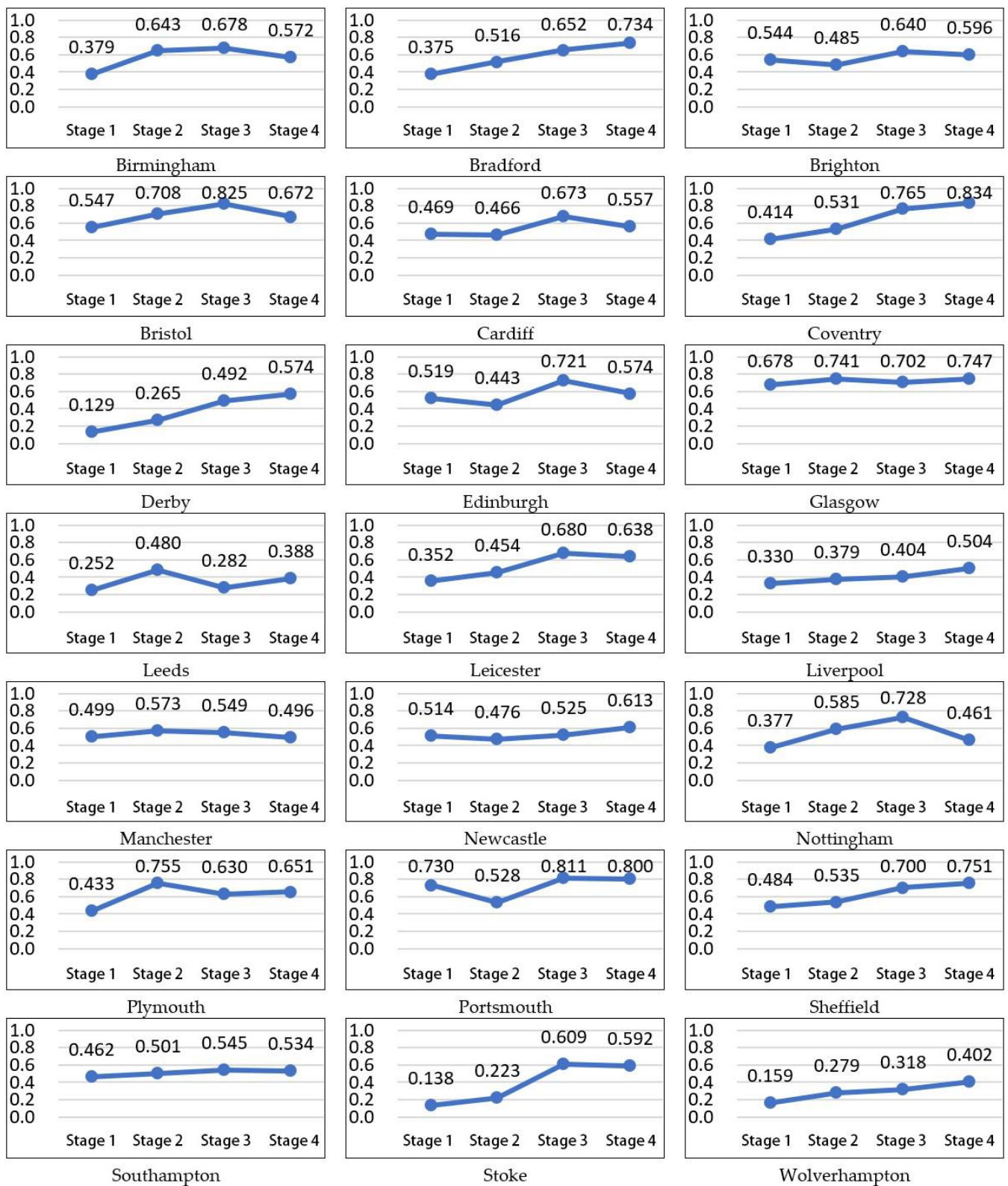


Figure 14. Separation degree change trends of UK city centres.

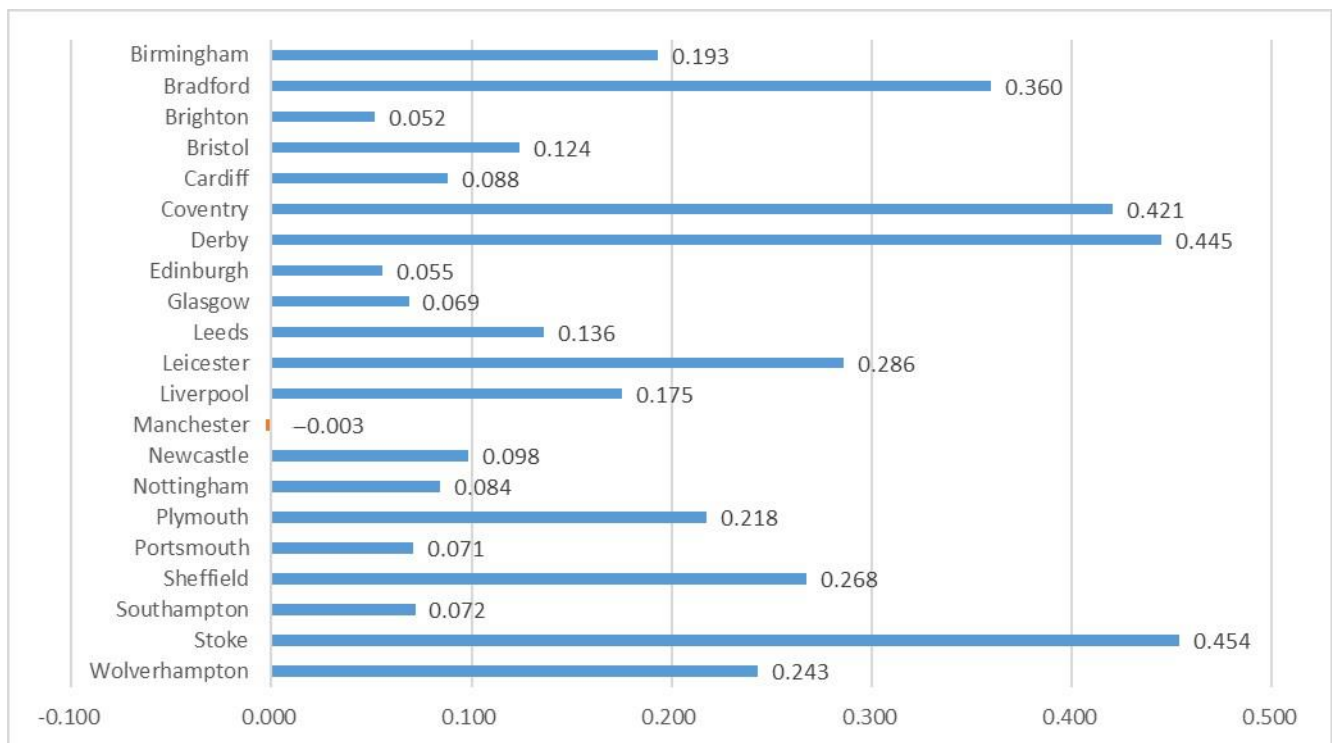


Figure 15. Amount of separation degree total change in UK city centres since the 1930s.

Table 4. Cities categorised into three regeneration models.

Model Type	Number of Cities	Model Type Percentage	Name of Cities
Gradual Growth Model	13	62%	Manchester, Brighton, Edinburgh, Glasgow, Portsmouth, Southampton, Nottingham, Cardiff, Newcastle, Leeds, Liverpool, Sheffield, Bradford
One Step Model	4	19%	Bristol, Birmingham, Plymouth, Coventry
Long-Term Planning Model	4	19%	Wolverhampton, Leicester, Derby, Stoke

4.4. Comparison of the Increase between the Three Models

The following conclusions can be drawn from comparing the change in the separation degree of the three models (Figure 16).

All three regeneration models result in a general increase in the separation degree of pedestrians and vehicles. All three regeneration models produced a significant increase. Among the four city centres with the highest increases, two are in the Long-Term Planning Model (Stoke, Derby), one is in the One Step Model (Coventry) and one in the Gradual Growth Model (Bradford), suggesting that all three regeneration models effectively increase the pedestrian/vehicle separation.

Among the three regeneration models, the one that most increases the separation of pedestrians and vehicles is the Long-term Planning Model, with an average increase of 0.357, followed by the One Step Model with an average increase of 0.239, and the least is the Gradual Growth Model with an average increase of 0.117 (Figure 17).

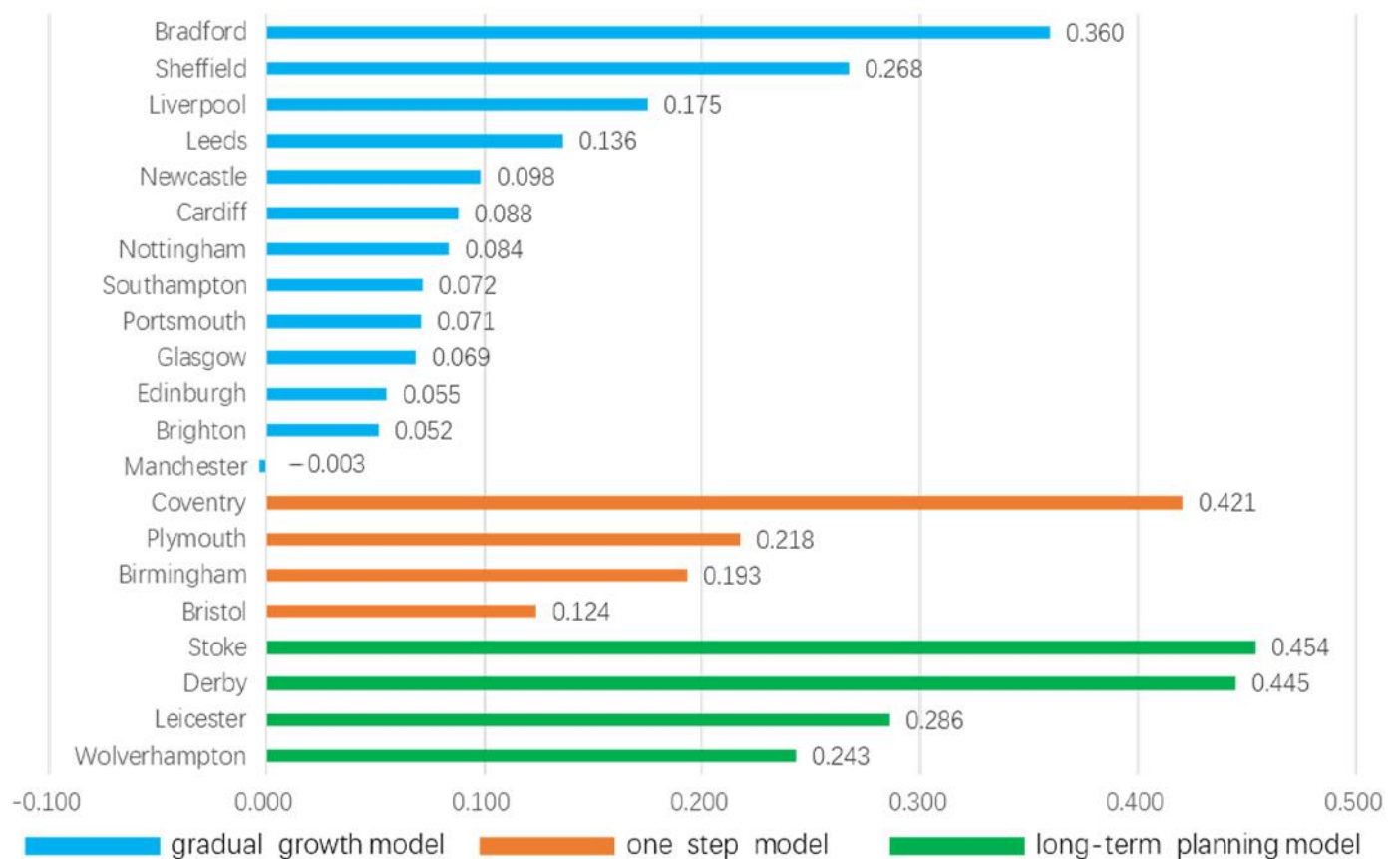


Figure 16. Separation degree increase of cities of three regeneration models.

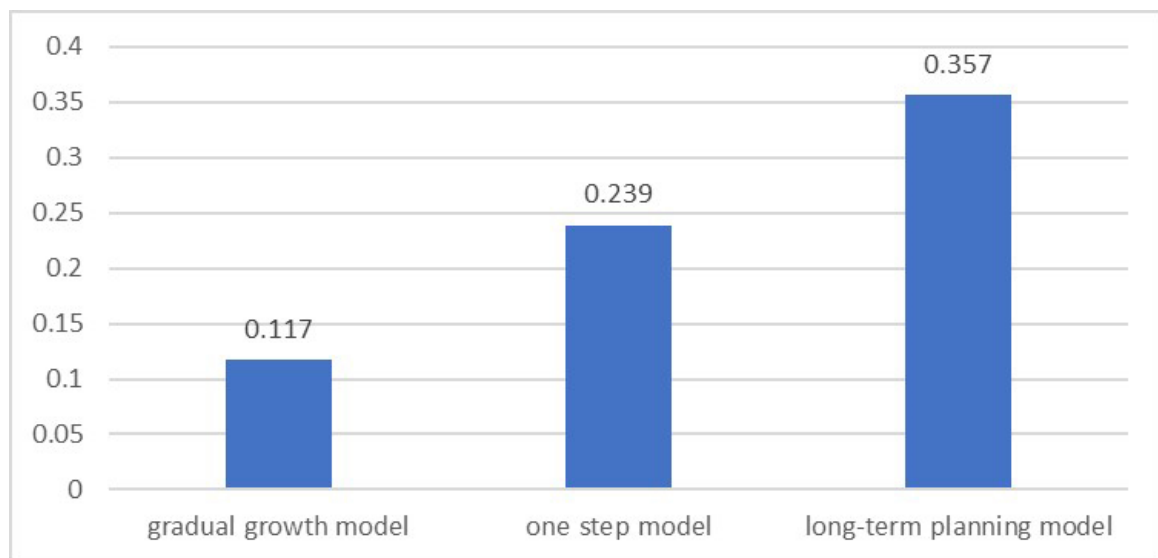


Figure 17. Average separation degree increases of three regeneration models.

5. Discussion

5.1. General Characteristics of the Regeneration of Spatial Structure Pedestrianisation

The spatial structure of the major city centres of the UK has become pedestrianised over many years of regeneration, guided by the concept of pedestrian priority. This change is reflected in two ways: the gradual pedestrianisation of the core roads in the city centre and the development of ring roads in its periphery to disperse vehicle traffic to the periphery.

5.1.1. Decentralisation of the Vehicle Traffic to the Periphery around City Centres

The UK city centre is characterised by a circular structure separating pedestrian and vehicular traffic. Vehicle ring roads divert transit traffic from the central area and organise external traffic to the central area, so that traffic is diverted to the periphery of the central area, and pedestrians and vehicle traffic can be separated. A safer and more comfortable environment for pedestrians was provided. In addition, a suitable environment for buses, scooters, and bicycles was also provided in transition areas of pedestrians and vehicles.

5.1.2. Gradual Pedestrianisation of Roads in City Centres

The UK city centres were initially developed with a network of crossroads, with the city centre located at the intersection of major roads [98]. The pedestrian priority concept has significantly transformed this structure. Under the pedestrian priority philosophy, most of the major vehicle roads in the UK city centres have evolved into pedestrianised streets and pedestrian-oriented restricted roads. Notably, in city centres the road space previously occupied by vehicle traffic does not disappear or become displaced by buildings, but remains where it was and is only artificially defined and pedestrianised as a pedestrian road.

The conversion of vehicle roads to pedestrianised streets in city centres is a widespread practice in the UK, with almost all city centres experiencing the conversion of major vehicle roads to pedestrianised streets or restricted roads to a greater or lesser extent. This objectively reflects the UK's philosophy on the creation of pedestrianised city centres. By converting vehicle roads into pedestrianised streets, an approach that improves the pedestrian system and limits vehicle traffic, people can be effectively encouraged to choose pedestrian transport as a means of travel, achieving an environmentally friendly, healthy, liveable and sustainable development.

5.2. Differences between Regeneration Models

Although all of them achieve increased separation of pedestrians and vehicles, the characteristics of the three regeneration models differ (Table 5). The Long-term Planning and the One Step Model result in a greater increase in the separation degree of pedestrians and vehicles. While the Gradual Growth Model results in a smaller increase, this model was employed in the largest number of city centres among the three models. This indicates that each of the three approaches has its own advantages and disadvantages.

Table 5. Comparison of the three regeneration models.

Model Type	Gradual Growth Model	One Step Model	Long-Term Planning Model
Formation of a pedestrian core	Core vehicle roads conversion into pedestrian streets		
Formation of vehicle ring roads	Grade adjustment of existing roads	Plan and build a new ring road in a short time	Plan a new ring road, and build the ring road over a long period
Advantages	Faster realisation, good suitability	Regular shape	Regular shape, good suitability
Disadvantages	Irregular shape	Higher cost Less flexible	Long period

5.2.1. Gradual Growth Model

In city centres where the Gradual Growth Model is adopted, the spatial structure is mainly developed through grade adjustment and partial reconstruction of existing roads. As the city centre develops, the spatial scale of the vehicle ring road is adjusted to maintain a match with the city centre.

The advantages are as follows. Faster realisation—no need to specifically build roads at a large scale, so the ring road takes less time to build. High adaptability—no matter what the original road network form is, the spatial structure can be transformed through the

grade adjustment and partial reconstruction of existing roads. High suitability—flexibility of the ring road for traffic, the ability to keep pace with the development of the city centre and always fit the scale of the city centre.

The disadvantage is that the increase of separation degree of the Gradual Growth Model is lower than the other two models, because the spatial structure is not regular in form, as it is mostly based on existing roads, resulting in a less regular spatial form.

5.2.2. One Step Model

In city centres where the One Step Model is adopted, completely new vehicle ring roads are planned and built in a short period of time. As the ring road might be too large for the city centre due to its plan for development over a long time, an inner ring road may initially exist for transitions, such as in Coventry city centre.

Its advantage is that its form is regular. The vehicle ring road and the spatial structure are carefully planned and built within a short period, which is conducive to the formation of a perfect spatial structure with complete form and function.

Its disadvantages are as follows. More costly—building a vehicle ring road in the old city centre in a short period requires massive changes to the original urban road network and construction, which is difficult and costly to achieve. Inflexible—the ring road is fixed in scale and less flexible to match the scale development of the city centre. For example, in Birmingham city centre, when the scale of the pedestrian zone grows beyond the ring road, the ring road becomes an element that even hinders the development of the city centre and is eventually broken up [99,100].

5.2.3. Long-Term Planning Model

In city centres where the Long-Term Planning Model is adopted, a new ring road is planned, which is not built at once, but in stages over a long period. In the process of construction, the new roads are combined with existing urban roads to form a semi-ring structure, which serves as a transition.

The advantage is both regular shape and good suitability. While the form of the ring road is relatively regular, its scale gradually increases during the transition period to match the development of the city centre.

The disadvantage is the long construction period, which can last for decades, during which the planned spatial structure does not fully play its role.

6. Conclusions

This paper proposes a new method for effectively and quantitatively measuring the walkability of spatial structures in city centres and their regeneration, based on spatial topological relationships, using space syntax as a platform, from the perspective of the separation of pedestrians and vehicles.

Twenty-one major city centres are used as examples to analyse the trend of the regeneration of city centre spatial structure pedestrianisation from the early 20th century to the present in the UK. The following conclusions were found.

- (1) City centre spatial structure optimization can effectively enhance the walkability of city centres from the perspective of the separation of pedestrians and vehicles. From the early 20th century to the present, the spatial regeneration of major city centres in the UK has clearly trended towards pedestrianisation. The separation degree of pedestrians and vehicles analysis based on space syntax shows that the spatial structure of the major city centres of the UK has been significantly enhanced in terms of the separation of pedestrians and vehicles.
- (2) The regeneration process can be categorised into the Gradual Growth Model, the One Step Model and the Long-Term Planning Model, all of which are effective in transforming the spatial structure of city centres from vehicle to pedestrian core.
- (3) The three models contribute differently to the separation degree of pedestrians and vehicles in the city centre, and their advantages and disadvantages differ. Among the

three models, the Long-Term Planning Model and the One Step Model have achieved better results in practice, while the Gradual Growth Model is easier to realise and can also achieve significant results.

This study also has some limitations. The pedestrianisation of the city centres is a complex mega-system, involving a wide range of aspects. This study examines only the degree of separation of pedestrians and vehicles in the spatial structure, but the public transport, parking layout, functional layout of city centres, and so on also play an important role in the regeneration of city centre pedestrianisation, and further research is needed.

According to this study, different regeneration models can be chosen to optimise the pedestrianisation of the city centre spatial structure according to its own circumstances and different requirements.

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