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AN INVESTIGATION OF COMBINED EFFECTS OF ROAD CAPACITY AND ACCESSIBILITY ON URBAN DENSITY, LAND USE MIX, AND VITALITY

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ABSTRACT

This study examines the combined impact of road accessibility and road capacity on urban form characteristics such as land use mix, building density, and vitality. The investigation was conducted in three cities in Sri Lanka: Colombo, Kurunegala, and Mawanalla. The study recognises the fundamental role of accessibility in shaping land use mix and urban densities and acknowledges the reciprocal relationship between transport infrastructure and land use decisions. It also recognises that the capacity of road infrastructure can influence land use choices and development patterns. Accessibility, in this context, can be thought of as the degree to which different parts of the city are well-connected and easily reachable. It includes not only the presence of roads but also their connectivity. By investigating how variations in accessibility and road capacity affect land use mix, densities, and vitality within the study areas, the study aims to discern the intricate relationships between transportation networks, land use, and density decisions. This study finds that accessibility has a stronger influence on density, land use mix, and vitality than road capacity. Further, the study finds that the influence of vehicle movement on land use mix, density, and vitality indicated a strong relationship, while the influence of pedestrian movement indicated a weak relationship. Accordingly, the findings of this study have practical implications for both transport and urban planning professionals and academics. Transport engineers can help promote desirable urban form characteristics by improving the accessibility of the road network. Urban planners can consider key findings when making zoning plans and urban development plans.

Keywords: *Accessibility, Road Capacity, Urban Form, Land Use Mix, Vitality*

1. INTRODUCTION

Urbanisation and urban form are closely intertwined with transport infrastructures, particularly road networks, transit systems, and walkways. The development and evolution of these transport infrastructures contribute to the determination of urban areas and the spatial structures they exhibit [1]. The road network, in particular, is a crucial component of urban form. It serves as a fundamental element in measuring, characterising, and evaluating the demand for various land use types and densities within a city. Studies have highlighted the interrelationship between road networks and urban form, emphasising the reciprocal influence between the design and layout of roads and the intended uses and densities of the surrounding urban areas [2, 3, 4]. The configuration of a road network, including factors such as street patterns, connectivity, and spatial layout, significantly impacts the performance, mobility, and accessibility of transportation within a city [2]. The arrangement of roads influences traffic flow, pedestrian movement, and access to different parts of the urban area [3, 4]. Well-designed road networks can enhance efficiency, connectivity, and safety. Conversely, poorly planned configurations may result in congestion, limited accessibility, and transportation challenges [5]. Accordingly, many studies have highlighted that understanding the relationship between urban form and road networks is essential for urban planners, transportation engineers, and policymakers [2, 3, 4]. By considering the interaction between transportation infrastructure and urban form, they can make informed decisions regarding land use planning, transportation system design, and urban development strategies. However, many existing studies on the relationship between urban form and road networks have primarily focused on isolated associations rather than examining the combined impact of land use mix, density, accessibility, and mobility factors [6, 7, 8]. While some studies have explored how topological accessibility influences land use mix, density, and vitality, and others have investigated the effects of geometric characteristics and road capacities on land use mix, density, and vitality, there is a lack of research that integrates both topological accessibility and road capacity to understand their combined impact [6, 7]. Furthermore, there are contemporary studies that discover the connection between accessibility and both pedestrian and vehicle traffic volume. However, there is a gap in the research studies conducted to explain the combined effects of accessibility and road capacity on both pedestrian and vehicle traffic volumes. In that scenario, further investigation is required to gain a comprehensive understanding of how accessibility and road capacity influence urban form characteristics such as land use, density, and vitality, and vice versa. A comprehensive understanding of the combined impact of these factors would provide valuable insights for both transport and urban planning professionals and academics in planning and designing more accessible and vibrant cities. Rota et al. [5] have described vehicle ownership as having both a micro and macro context. In this context, the main objective of the study is to examine the combined impact of road accessibility and capacity on urban form characteristics such as land use mix, building density, and vitality. It would be a substantial contribution to the fields of urban planning and transport planning. The remainder of this paper is organised as follows. The second section introduces the theoretical framework and definition of key variables used in the study. The third section outlines the case study areas and methods adopted in the study in detail. The fourth section presents the analysis and key findings of the study. This section presents the findings derived from scatter plots and partial correlation in regression analysis. The fifth section concludes the study and offers recommendations based on the findings and their implications for urban planning and transport planning.

2. LITERATURE REVIEW - THEORETICAL FRAMEWORK

Definitions and computation methods of key variables and the conceptual framework within which the research was developed are given in this section.

2.1. Definitions and Computation Method

2.1.1. Accessibility

'Accessibility', as used in this context, refers to how convenient it is to move between different places. In this research, the proximity centrality measure is used to quantify ease of access. The study uses the closeness centrality (CC) parameter to measure accessibility. Accordingly, local closeness centrality (LC) and global closeness centrality (GC) are used to measure the accessibility of a specific location, such as a transportation node or a road segment, based on its proximity to nearby locations [9] (in the case of LC) and at a larger scale, typically at the city level [9] (in the case of GC). The formula introduced by Freeman [9] is used to measure the CC of the road segments in each road network.

2.1.2. Road Capacity

Road capacity refers to the maximum number of vehicles or amount of traffic (vehicles or pedestrians) that a road or a specific lane can effectively handle within a given period [10]. It represents the ability of a road to accommodate traffic flow while maintaining an acceptable level of service. Lane widths and sidewalk widths have a significant impact on how well an urban space function and early studies have used these factors to evaluate the capacity of the road network in city-scale studies [11]. Accordingly, the study uses road widths and walking path widths (i.e., sidewalk widths) as indicators of road capacity.

2.1.3. Vitality

According to Yue and Zhu, urban vitality specifically refers to the level of pedestrian activity on city streets and the volume of vehicles moving along roads [12]. Urban vitality captures the extent to which people are physically active and engaged in their urban environment. Several studies have indicated that urban vitality is influenced by factors such as the concentration of people, including residents, workers, and visitors, traffic flow, and the movement of vehicles on roadways or transportation networks [12, 13]. In line with this understanding, the study uses vehicular traffic flow volume along road segments and pedestrian volume along sidewalks as indicators of urban vitality in specific locations. These indicators reflect the level of activity and movement by both vehicles and pedestrians, which contribute to the overall vitality and vibrancy of the urban area.

2.1.4. Land Use Mix

To study the land use mix in urban areas, researchers have developed different approaches [14]. Two notable approaches are the Mixed-Use Index and the Land Use Classification System. The study uses the land use classification system introduced by Ye and Van Ness, which categorises land uses into distinct types based on their functions [15, 16]. This system typically includes residential, amenities (service functions), and working (primary employments) as key land use types. By classifying land uses into these categories, researchers can analyse and evaluate the distribution and composition of different functional areas within an urban setting. These approaches provide tools for assessing the spatial arrangement and diversity of land uses in urban forms. These enable researchers to examine the extent to which different land use types are mixed or segregated within a given area.

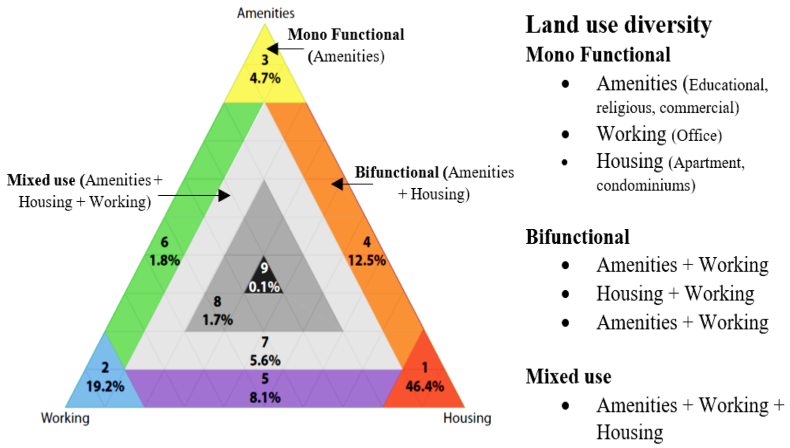


Figure 1: Graphical view of the Land Use Mix Indexed Proposed by Ye and Van Nes [16]

2.1.5. Urban Density

Urban density, traditionally measured as the number of population or buildings per unit area, has evolved in recent studies to be viewed as a multivariate phenomenon. Recognizing that density encompasses various aspects of urban form and development, researchers have employed the "space matrix" approach to measure density using multiple indicators [15]. The space matrix approach considers different dimensions of density to provide a comprehensive understanding of urban spatial characteristics [15, 16]. Several indicators are commonly used within this approach: Floor Space Index (FSI): FSI, also known as the Floor Area Ratio (FAR). The study adopted the approach adopted by Ye and Van Ness [16].

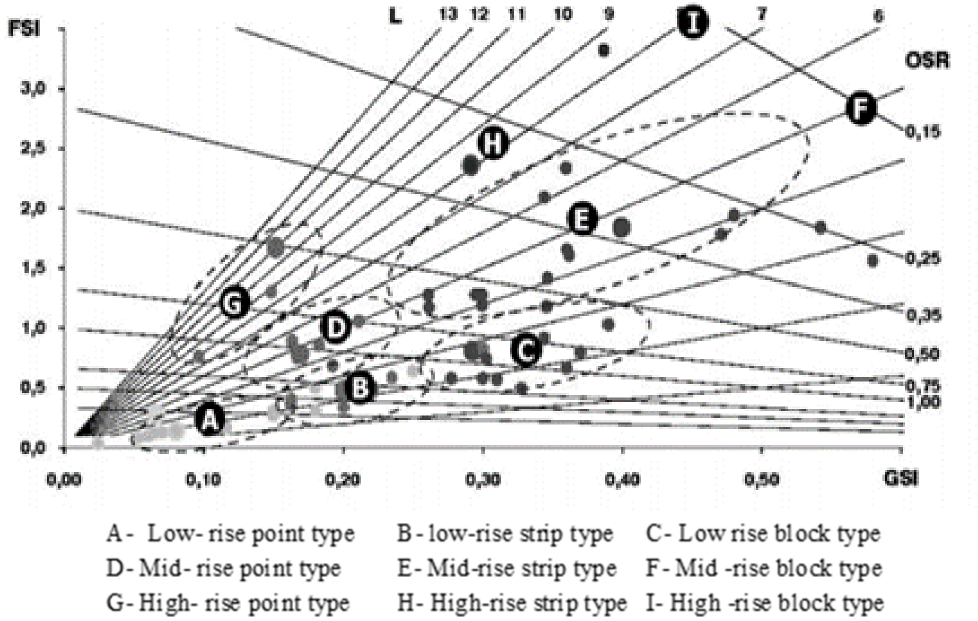


Figure 2: Categorization of Space Matrix Index

Source: [16]

2.2. Conceptual Framework

Two important theories form the basis of the study's conceptual framework: these are the theory of natural movement economies and the theory of the transport-land-use feedback cycle. According to the theory of natural movement economies, land use (LU) and densities (D) are influenced by the level of accessibility (A) or configuration of the road network [17]. The theory suggests that areas with higher levels of accessibility or integration are more likely to attract activities, traffic, and characteristics associated with higher land use mix, density, and vibrancy. It emphasizes the relationship between transportation and land use, where the level of accessibility shapes the spatial distribution of land uses and densities. The transport land use feedback cycle highlights the strong association between the accessibility and capacities of transport infrastructure and land use activities and density [18]. Accordingly, accessibility and capacity significantly influence land use activities and density [19]. For example, areas with well-accessible and high-capacity transportation networks are more likely to attract a higher land use mix and density.

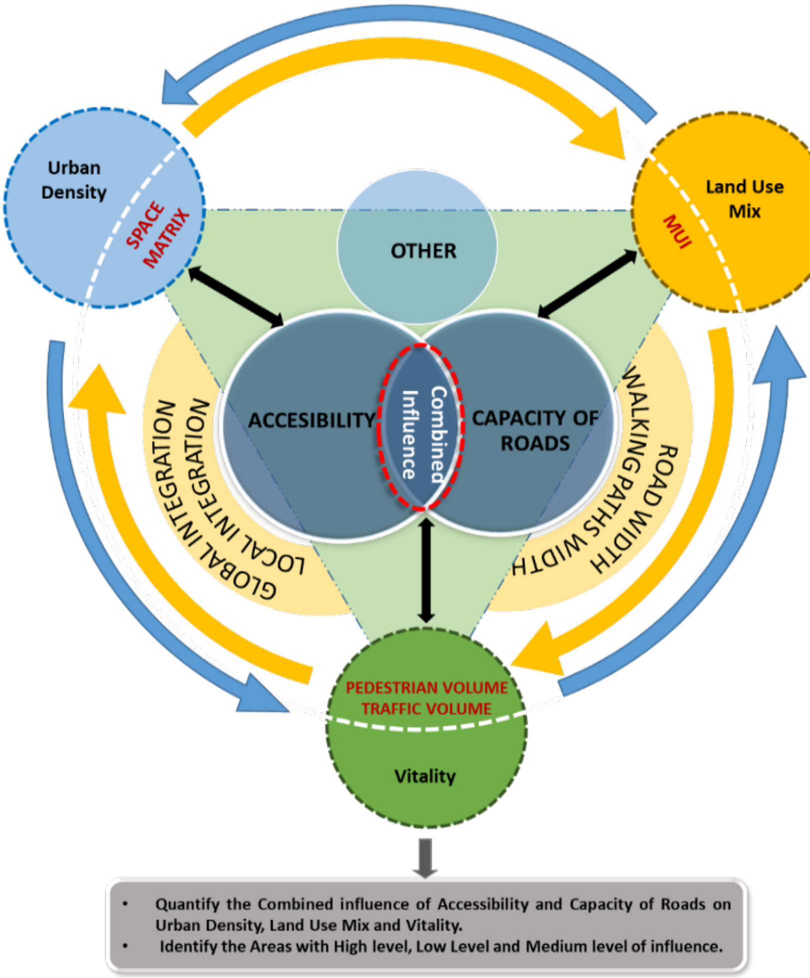


Figure 3: Conceptual Framework

Source: Author

This study proposes the conceptual framework illustrated in Figure 3. The framework recognizes the fundamental role of accessibility in shaping land use mix, urban densities, and vitality. Areas with better accessibility and connectivity are likely to attract a diverse mix of land uses, leading to a more vibrant and dynamic urban environment. The study examines how variations in road infrastructure accessibility, are measured through indicators such as street local closeness centrality and global closeness centrality. Furthermore, the framework acknowledges the reciprocal relationship between transport infrastructure and land use decisions. It recognizes that the capacity and quality of road infrastructure can influence land use choices and development patterns. Factors such as road capacities, traffic flow, and connectivity have a feedback effect on land use decisions, shaping the intensity and density of building development. The study investigates how variations in road capacity and infrastructure affect land use mix, urban densities, and vitality within the study area.

2.3. Proposed Concept

According to the natural movement economy theory and, the transport land use feedback theory, urban form and its relationship can be explained by using accessibility and road capacities on land use, density, and vitality parameters. The following logic explains those relationships.

Argument 01 (**Natural Movement Theory**): Land use (LU), density (D), and vibrancy (V) can explain as a function of the configuration (C) and accessibility [17].

$$\boxed{\begin{array}{c} LU = f(C) \\ D = f(C) \\ V = f(C) \end{array}} \longrightarrow \boxed{A = f(C)} \longrightarrow \boxed{\begin{array}{c} LU = f(A) \\ D = f(A) \\ V = f(A) \end{array}}$$

Argument 02 (**Land use transport feedback cycle theory**): Land use density and vibrancy are functions of the capacity of roads.

$$\boxed{\begin{array}{c} LU = f(RC) \\ D = f(RC) \\ V = f(RC) \end{array}}$$

Argument 03: Land use density and vibrancy are functions of the accessibility and capacity of road Infrastructure.

$$\boxed{\begin{array}{c} LU = f(A.RC) \\ D = f(A.RC) \\ V = f(A.RC) \end{array}}$$

Based on argument 3 the combined influence level can be assessed and validated. The study can be conceptualized under the following concept.

Conclusion : LU. D. V = f (A.RC) -----------------► 1

3. MATERIALS AND METHODS

3.1. Case Study Areas

The three main cities, namely Colombo, Kurunegala, and Mawanella were selected as case study areas for this study. The criteria for selecting cities consider factors such as the degree to which they have been urbanized, the size of their populations, and the type of current urban form. The selected cities are examples of a variety of urban shapes, including monocentric, polycentric, and linear city layouts. A thorough examination of how transport infrastructure affects land use patterns and densities across various urban configurations is made possible by including cities with a variety of urban forms.

Figure 4: Case Study Areas

Table 1: Characteristics of Case Study Areas

Attributes	Case Study Areas			Source
	Colombo	Kurunegala	Mawanella	
The level of urbanization (City Hierarchy)	1st order city	2nd order city	4th order city	National Physical Planning Department, 2010
Urban Form	Polycentric city	Mono centric city	Linear city	By Author
Population	889,000	38,596	18,171	Council, 2018
Population Density	115 persons / ha	53 persons / ha	30 persons / ha	Council, 2018
Building Density	0.73	0.53	0.35	Council, 2018
Area Extent	4,362 ha	1,100 ha	230 ha	Council, 2018

3.2. Data Preparation

Based on the parameters outlined in Table 2, the study quantified the variables using spatial analysis tools available in the geographical information system - GIS. In addition, the study conducted a primary survey to collect data related to the capacity of road infrastructure and traffic volumes. The authors selected sample road segments within the study areas and collected data specifically for those segments. By combining GIS analysis and primary field survey data, the study obtained a comprehensive spatial dataset. This spatial database set allows for a detailed analysis of the relationships between accessibility, road capacity, land use mix, building density, and urban vitality within the selected case study areas.

Table 2: Variables and Data Sources

Variables	Parameters	Data Source
Accessibility	Closeness Centrality (Global and Local Centrality)	Computed based on Open Street Map Road network
Road Capacity	Road Width and Walking Path Width	Collected from primary field survey
Land use	Land Use Mix Index	Computed based on land use maps prepared by the Urban Development Authority (UDA)
Urban Density	Space Matrix	Computed based on Google Earth Maps
Vitality	Traffic Volume and Pedestrian Volume	Collected from primary field survey

The main tasks in the data preparation process are

1. Road Segment map preparation for all study areas.
2. Prepare data for land use, accessibility, density, and vitality parameters.

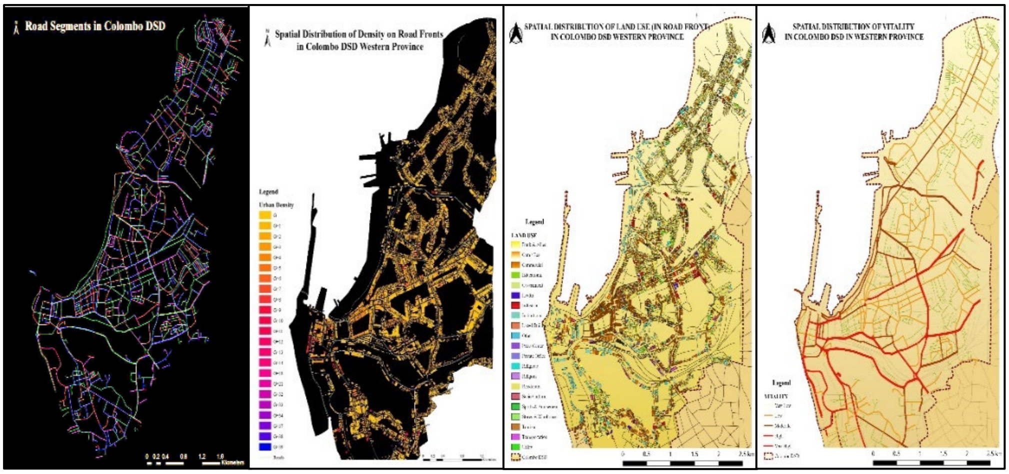


Figure 5: Road Network, Land use, Density and Vitality in Colombo

4. ANALYSIS AND RESULTS

4.1. Validation Results

4.1.1. Correlation Analysis

Correlation analysis is the best method to identify the relationship between every parameter (two variables). Pearson correlation has been calculated for three cities. To measure accessibility, there are two measures: local scale as local integration and city scale as global integration. The capacity of the road parameter is calculated by using road widths for the city scale and walking paths for the local scale. land use mix and density are calculated by the mixed-use index and the space matrix. Lastly, the vitality parameter is calculated based on traffic volume for the city scale and pedestrian volume for the local scale.

- If the correlation value is (+) positive, the relationship has a positive direction, and if the correlation value is (-) negative, the relationship has a Negative direction.
- If the correlation value is less than 0.3, it has a weak relationship; if the correlation value is between 0.3 to 0.7, it has a moderate relationship; if the correlation value is between 0.7 to 1 it has a strong relationship.
- The significance of the result can be identified as 0.01 level and 0.05.

To interpret the outputs, it has to identify the direction and the significance of the relationship.

Table 3: Pearson Correlation - Colombo

Pearson Correlations	Accessibility		Road Capacity		Land Use Mix	Urban Density	Vitality		No. of Segments
	Global Integration	Local integration	Road Width	Walking Path Widths			Traffic Volume	Pedestrian Volume	
Global Integration	1	.607**	.567**	.480**	.545**	.691**	.631**	.	389
Local Integration		1	.467**	.520**	.400**	.420**	.	.433**	389
Road Width			1	.385**	.448**	.534**	.495**		389
Walking Path Widths				1	.331**	.376**		.383**	389

**. Correlation is significant at the 0.01 level (2-tailed)

Table 4: Pearson Correlation - Kurunegala

Pearson Correlations	Accessibility		Capacity of Roads		Land Use Mix	Urban Density	Vitality		No. of Segments
	Global integration	Local Integration	Road width	Walking Path widths			Traffic Volume	Pedestrian Volume	
Global Integration	1	.570**	.532**	.408**	.628**	.786**	.590**		235
Local Integration		1	.197**	0.017	.425**	.485**		.515**	235
Road Width			1	.352**	.429**	.545**	.504**		235
Walking Path Widths				1	.350**	.375**		.374**	235

**. Correlation is significant at the 0.01 level (2-tailed)

Table 5: Pearson Correlation - Mawanalla

Pearson Correlations	Accessibility		Capacity of Roads		Land Use Mix	Urban Density	Vitality		No. of Segments
	Global Integration	Local Integration	Road width	Walking path			Traffic volume	Pedestrian volume	
Global Integration	1	.583**	.577**	.624**	.567**	.752**	.696**		102
Local Integration		1	.643**	.328**	.339**	.503**		.474**	102
Road Width			1	.454**	.446**	.670**	.663**		102
Walking Path Widths				1	.316**	.272**		.304**	102

**. Correlation is significant at the 0.01 level (2-tailed)

Colombo MC is the first-order city, Kurunegala is a second-order city, and Mawanalla is a fourth-order city according to the National Physical Plan. In this study, Colombo DSD, Kurunegala, and Mawanalla were selected as sample areas for further analyses. According to the correlation analysis every parameter has a positive correlation with each other in all cities.

4.1.2. 3D Scatter Plot Diagrams

The study used various geospatial statistical techniques to analyse the relationship between variables. At first, the study employed MATLAB software to create 3D scatter plot diagrams and analysed the relationships. This allows for visualization and analysis of the relationships between multiple variables simultaneously. By plotting the variables in a three-dimensional space, the study examines how accessibility, road capacity, land use mix, building density, and urban vitality are interconnected and understands the patterns and trends within the data. The following sections of the study provide a detailed analysis and interpretation of the results obtained from the 3D scatter plot diagrams in Colombo.

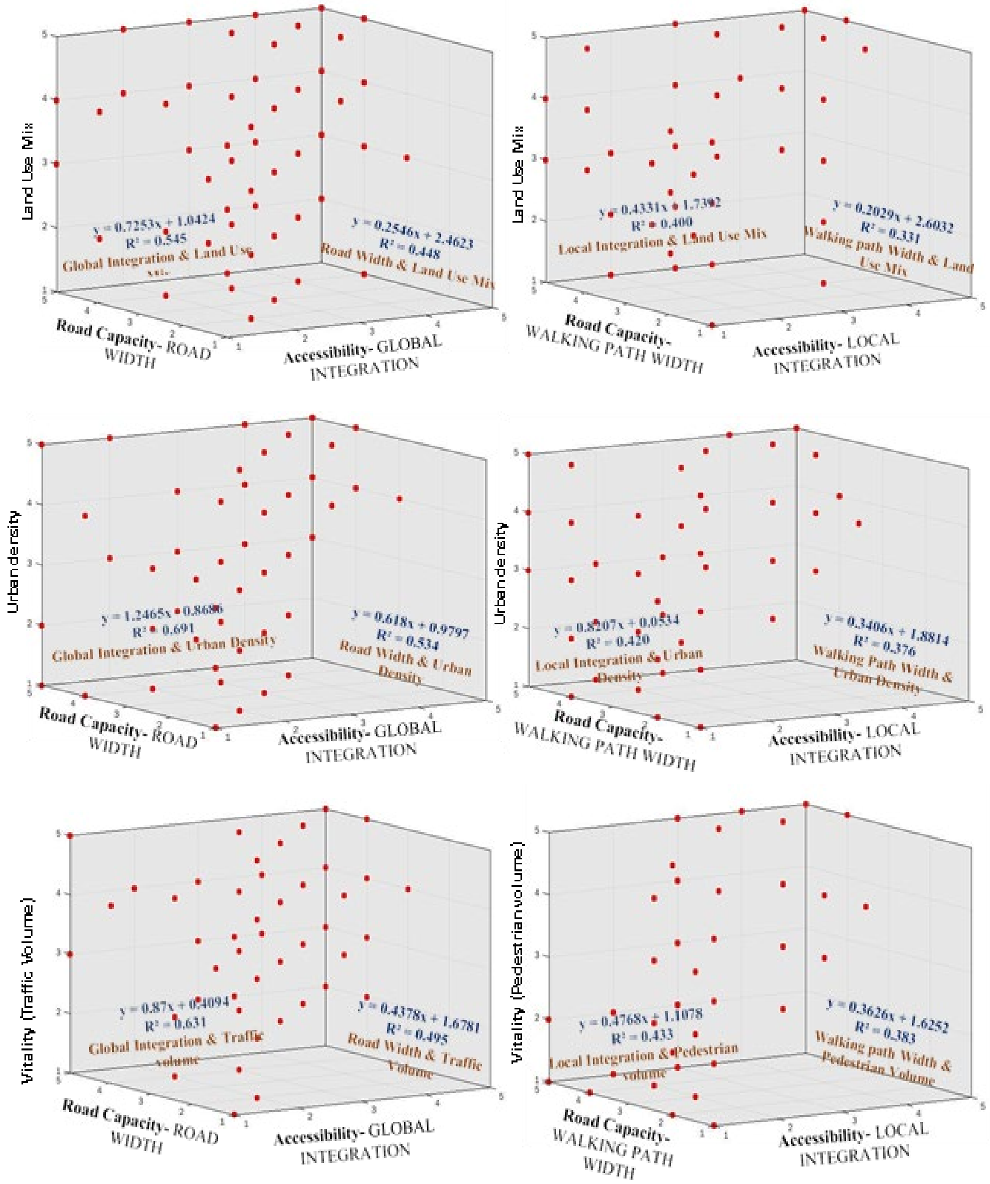


Figure 6: 3D scatter plot diagrams in Colombo

According to the above 3D scatter plots, Colombo land use mix, density, and vitality clearly show a positive corresponding relationship with the global integration and road width rather than the local integration and walking path width.

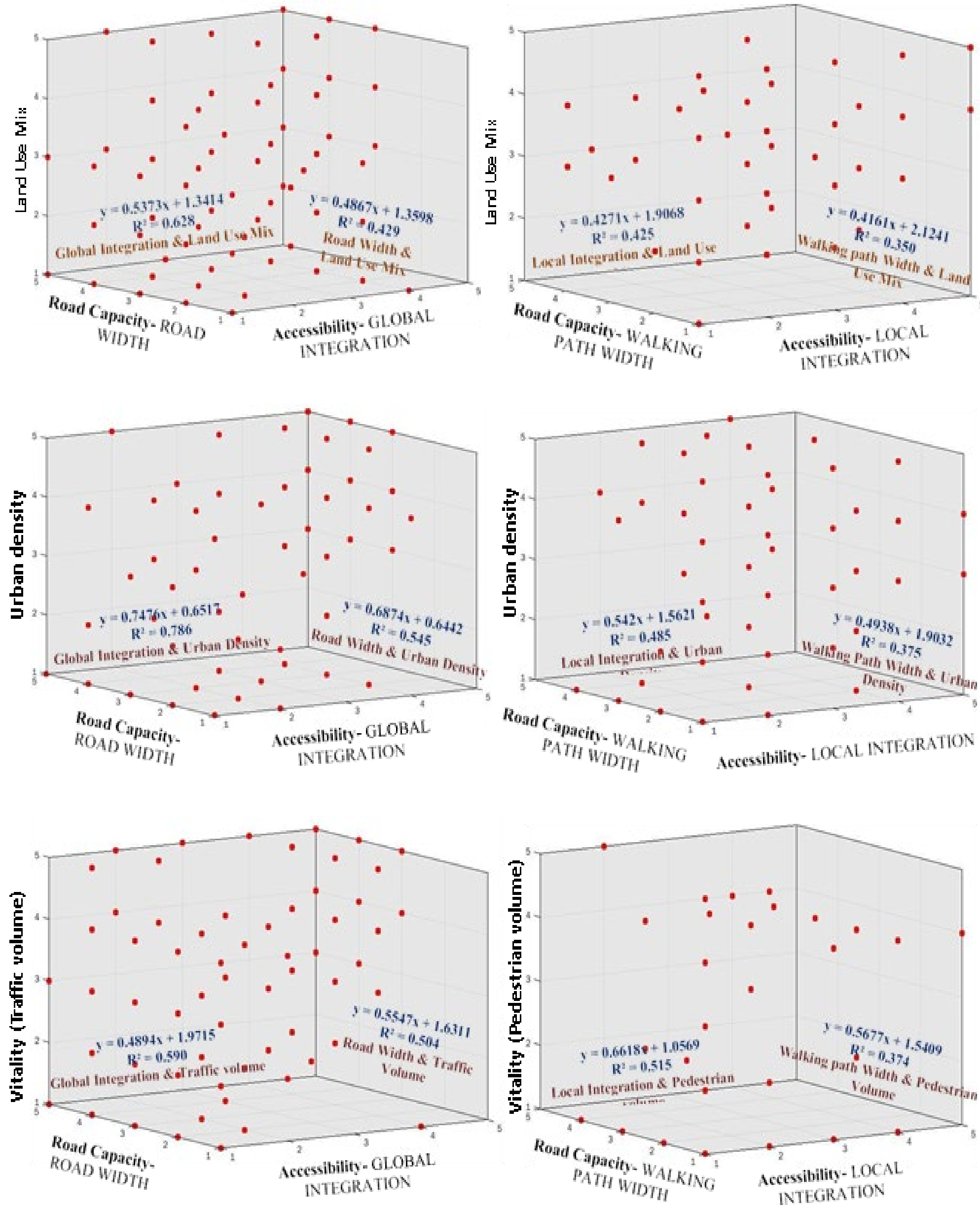


Figure 7: 3D scatter plot diagrams in Kurunagala

According to the above 3D scatter plots Kurunegala land use mix, density, and vitality clearly show the corresponding positive relationship with the global integration and road width rather than the local integration and walking path width.

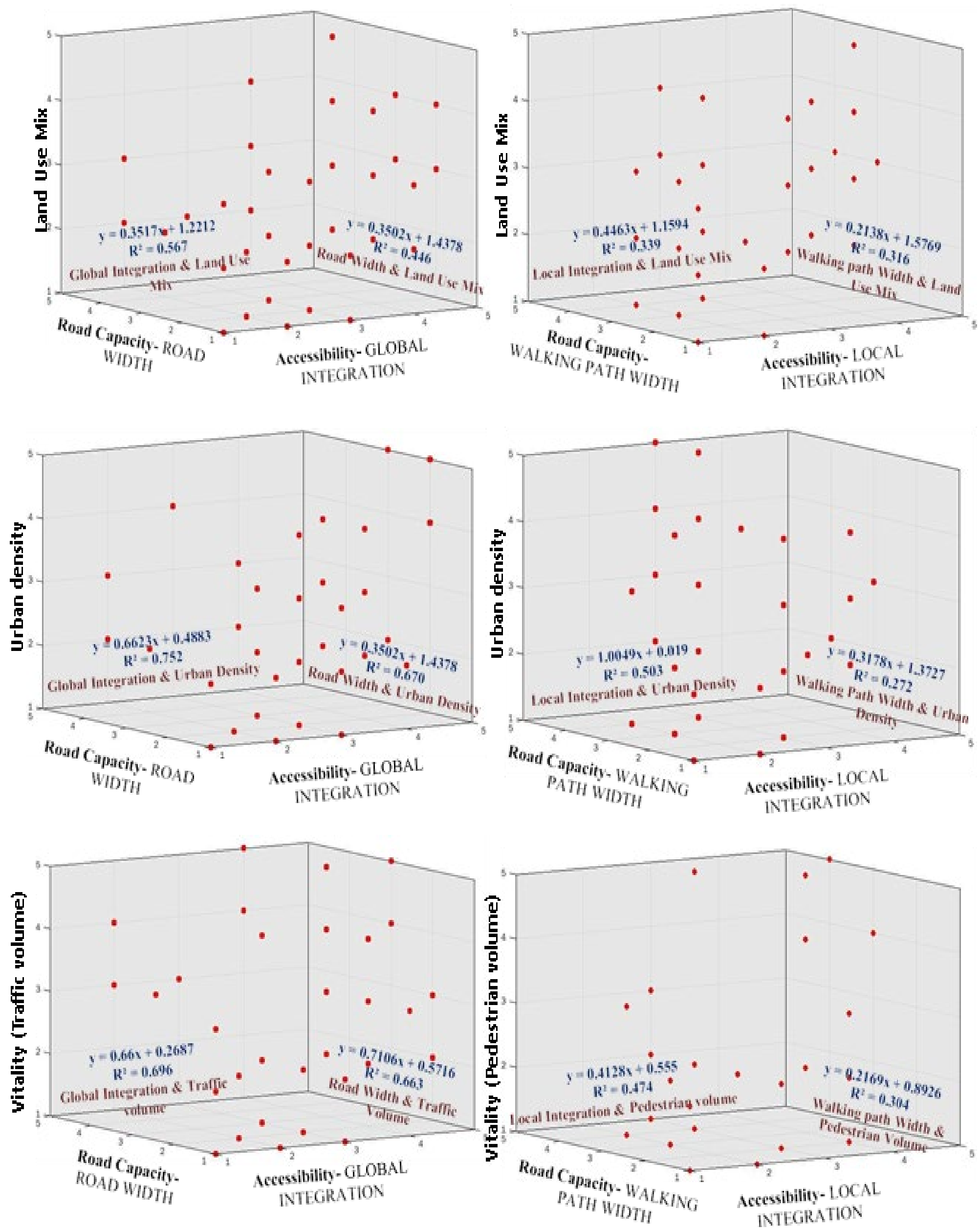


Figure 8: 3D scatter plot diagrams in Mawanalla

According to the above 3D scatter plots, Mawanalla land use mix, density and vitality show a moderately corresponding relationship with global integration and road width similar to the other case studies.

On one hand, the study has found a strong positive relationship between land use mix, building density, and urban vitality with GC and road width (rather than LC and walking path width) in all three case study areas (Colombo, Kurunegala, and

Mawanalla). The positive corresponding relationship suggests that as GC, which represents accessibility at the city scale, and road width increase, there is a tendency for land use mix, building density, and urban vitality to also increase. This indicates that areas with better accessibility and wider road infrastructure tend to have a higher diversity of land uses, a higher density of buildings, and a more vibrant urban environment. On the other hand, the study did not find a strong relationship between LC, which represents accessibility at the local scale, and walking path width with land use mix, building density, and urban vitality in the case study areas. This suggests that the immediate accessibility of a location within its immediate vicinity and the width of walking paths may not have as significant an impact on land use patterns, building density, and urban vitality compared to city-wide accessibility and road width. These findings provide important insights into the combined impact of road accessibility and capacity on various urban form characteristics. The study suggests that improving global closeness and road width can contribute to the promotion of diverse land uses, increased building density, and a more vibrant urban environment.

4.1.3. Regression Analysis

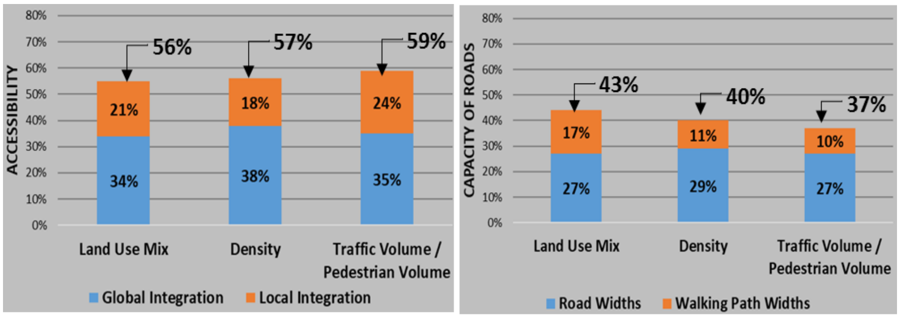
To determine the relative importance of each variable, the researchers used regression analysis and part and partial correlation analysis functions in SPSS's software environment. The associations between the independent variables (road accessibility and capacity) and the dependent variables (land use mix, urban density, and vitality) were calculated using part and partial correlations, with other factors held constant. The subsequent table displays the overall findings of the part and partial correlations. Table 4 and figures 6 and 7 provide information on the influence levels of each dependent variable measured through part and partial correlations. The influence levels are presented as percentages to better understand the relative impact of the independent variables. The results indicate the individual influences of accessibility and capacity of roads.

The influence of accessibility on land use mix, density, and vitality ranges from 50% to 60% in all case study areas. This suggests that accessibility has a relatively high influence on these variables compared to the capacity of roads. On the other hand, the influence of the capacity of roads on land use mix, density, and vitality ranges from 30% to 45%. This indicates that the capacity of roads has a somewhat lower influence compared to accessibility. The results of the analysis also considered the influence of road infrastructure on both the city scale (vehicles) and the local scale (pedestrians). Road widths and global closeness were used to evaluate the influence on the city scale, while local closeness and walking path widths were used for the local scale. The results show that vehicle movements have a significant influence on land use mix, density, and vitality, with percentages ranging from 55% to 80%. On the other hand, pedestrians' movements have a low impact in the case study area, ranging from 25% to 40%. These findings suggest that the perspective of vehicular traffic has a more significant impact on urban form compared to the perspective of pedestrian movement. These results provide valuable insights into the relationships between road infrastructure accessibility and capacity, and various urban form indicators. The analysis highlights the significant influence of accessibility, particularly from a vehicular perspective, on land use patterns, building density, and urban vitality.

Table 6: Partial Correlation and Influence / Effect on Cities

Factor			Partial Correlation			Influence / Effect		
			Colombo	Kurunegala	Mawanalla	Colombo	Kurunegala	Mawanalla
Accessibility	Global Closeness	Land use mix	0.409	0.333	0.341	41%	33%	34%
	Local Closeness	Land use mix	0.158	0.166	0.214	16%	17%	21%
Accessibility influence on land use mix in cities						57%	50%	55%
Road Capacity	Road Width	Land use mix	0.320	0.243	0.266	32%	24%	27%
	Walking Paths	Land use mix	0.117	0.152	0.165	12%	15%	17%
Road Capacity influence on land use mix in cities						44%	39%	44%
Accessibility	Global Closeness	Urban Density	0.393	0.414	0.382	39%	41%	38%
	Local Closeness	Urban Density	0.160	0.135	0.184	16%	14%	18%
Accessibility influence on urban density in cities						55%	55%	56%
Road Capacity	Road Width	Urban Density	0.337	0.345	0.288	34%	35%	29%
	Walking Paths	Urban Density	0.111	0.090	0.111	11%	9%	11%
Road Capacity influence on urban density in cities						45%	44%	40%
Accessibility	Global Closeness	Vitality (Vehicle)	0.380	0.313	0.351	38%	31%	35%
	Local Closeness	Vitality (Pedestrian)	0.202	0.210	0.236	20%	21%	24%
Accessibility influence on vitality in cities						58%	52%	59%
Road Capacity	Road Width	Vitality (Vehicle)	0.304	0.273	0.271	30%	27%	27%
	Walking Paths	Vitality (Pedestrian)	0.104	0.104	0.101	10%	10%	10%
Road Capacity influence on vitality in cities						40%	37%	37%

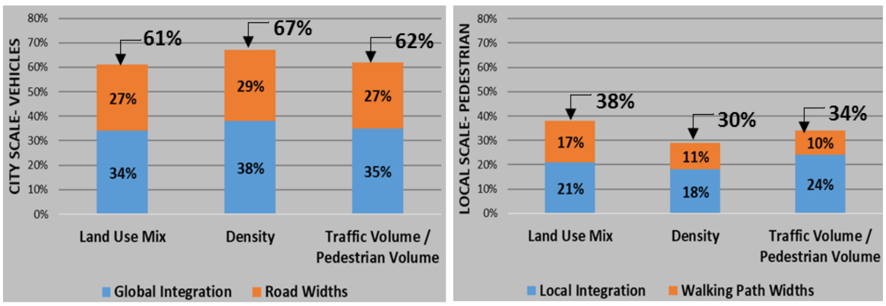
Accessibility and Capacity of Road parameters work as guide of the land use mix, urban density, and vitality of the urban form. Change in unit of the of the road network will increase accessibility and capacity of roads, it will influence changes in land use, and density vitality at different degrees. The degree of influence is different from context to context, but the influence of accessibility on land use mix, density, and vitality is in the range of 50% to 60% in all cities. In addition to that, the influence of the capacity of roads is in the range of 30% to 45%. According to that both parameters combined influence land use mix, density, and vitality, but accessibility has a higher influence than the capacity of roads.



Influence of Accessibility **Influence of Capacity of Roads**

Figure 9: Influence of Accessibility and Road Capacity

Accessibility and capacity of road parameters influence city scale (vehicles) and local scale (pedestrian scale). To assess city scale influence, it used global integration and road widths and to assess local scale it used Local integration and walking path widths. The analysis has identified a high influence of vehicles within the range of 55% to 80% on LU, density, and vitality. But the pedestrian's influence varies from 25% to 40% in Mawanalla. According to the above results, the urban form of the cities is highly influenced by the vehicular perspective and less influenced by the pedestrian perspective.



Influence of Global integration and road width **Influence of Locall integration and walking path width**

Figure 10: Influence of City Scale / Vehicles and Local Scale / Pedestrian

5. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study was to examine the combined impact of road accessibility and capacity on land use mix, building density, and vitality. It used scatter plots, and partial correlation in regression analysis to analyse these relationships using Colombo, Kurunegala, and Mawanalla in Sri Lanka as case study areas. The key findings suggest that accessibility has a stronger relationship with urban form characteristics such as urban density, land use mix, and vitality than road capacity. The influence levels vary across the three cities, with accessibility ranging from 50% to 60% and road capacity ranging from 30% to 45%. The study also examines the combined influence of vehicle and pedestrian movement. Vehicle movement is analysed using global closeness and road width, while pedestrian movement is analysed using local closeness and walking path width. The influence of vehicle movement on land use mix, urban density, and vitality indicated a strong relationship, while the influence of pedestrian movement indicated a weak relationship.

Accordingly, the findings of the study provide practical implications for both transport and urban planning professionals and academics. Transport engineers and planners can help promote desirable urban form characteristics by improving the accessibility and connectivity of the road network. Urban planners can consider key findings when making zoning plans and urban development plans. Accordingly, urban planners can use the findings of the study to model urban form characteristics under different transport network scenarios.

However, further research studies are required to validate the study's findings by conducting a comparative analysis among different cities in Sri Lanka and worldwide. Further, it is worthwhile to consider additional variables such as the availability of public transport options, and socio-economic and environmental factors. The study would like to suggest conducting more research addressing those research areas and enhancing the understanding of the interactions between transport infrastructure and urban form characteristics, which will mutually benefit both transport and urban planning professionals and academics.

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