DEVELOPMENT OF A TRANSIT ORIENTED DEVELOPMENT (TOD) INDEX TO IDENTIFY POTENTIAL LOCATIONS THAT REQUIRE TRANSIT CONNECTIVITY

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February，2014

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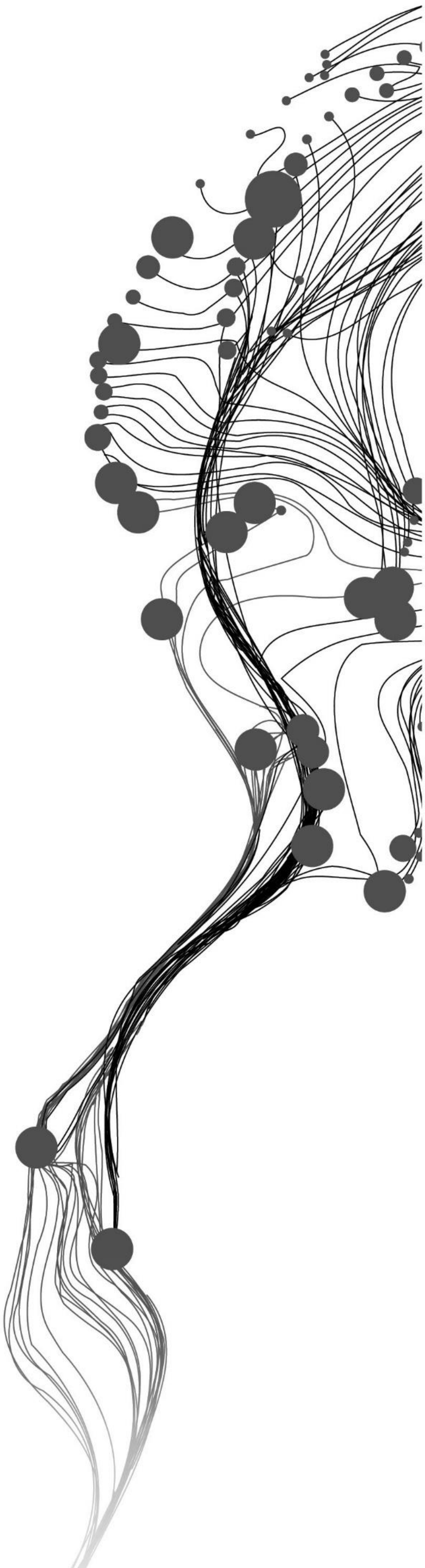

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ABSTRACT

Transit Oriented Development (TOD) is generally defined as a compact, mixed use development near transit facilities with high-quality walking environments which can be an integrated approach to land use and transport planning to achieve sustainable development. Before planning TOD, a correct realization of existing TOD level helps to make right decisions and investments. However, an appropriate measurement tool for measuring the existing TOD level is lacking.

This research developed a TOD index to measure the level of TOD over the context of Arnhem Nijmegen City Region in the Netherlands. The high score of TOD Index means a high level of TOD indicating that the urban development is oriented towards use of transit. Using the index, it is intended to identify areas of high TOD levels but where the access to transit is poor.

The TOD index measures multiple spatial indicators in terms of built environment and economic development based on regular tessellation of space. Various stakeholders from the City region were consulted to weight the indicators and then a Spatial Multi-criteria Evaluation (SMCE) model was performed to obtain the composite TOD index map. In addition, to test the robustness of the index, a sensitivity analysis was carried out by changing the weights of criteria and indicators.

In order to identify the hotspots and cluster of high TOD cells, a series of spatial statistical analyses were performed. This research also used Public Transport Accessibility Level (PTAL) method to measure the accessibility to public transit services for entire City region based on the same spatial unit of analysis with TOD index.

Finally, the locations where high TOD index values exist along with poor access to public transit, are proposed for better transit connectivity.

Key word: TOD, TOD index, Indicators, Criteria, GIS, SMCE, Stakeholder, Sensitivity analysis, PTAL

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Enschede, February, 2014

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LIST OF ACRONYMS

TOD	Transit Oriented Development
SMCE	Spatial Multi-criteria Evaluation
PTAL	Public Transport Accessibility Level
GIS	Geographic Information System
BRT	Bus Rapid Transit

1. INTRODUCTION

1.1 Background

Many counties and regions all over the world are facing the challenge of rapid urbanization. Mainly economic reasons, many people moved and are still moving from rural areas to cities. This process creates heavy pressure on urban public facilities such as transportation and housing, it also has economic, environment, and social impacts.

To alleviate the negative impacts of urbanization, planners are considering integration of land use and transport, which can contribute to a more sustainable future. Renne (2007) points out that sustainable development tries to create an urban environment which maximizes economic development and social equity, at the same time minimizing the impact of negative externalities upon the natural environment. From a land use and transport perspective, the priority in this regard is to reduce automobile dependency through development of mixed land use and compact cities with an array of travel alternatives focused on walking, bicycling, and public transport(Banister et al., 2007).

A comprehensive concept Transit Oriented Development (TOD) was proposed by Calthorpe (1993). It is a mixed-use residential and commercial area designed to maximize access to public transport, and it often incorporates features to encourage transit ridership. It aims to reduce automobile use and promote the use of public transit, cycling and walking through high density, mixed use, environmentally-friendly development within areas of walking distance from transit centres.

If done right, TOD can have a lot of social, environmental and economic benefits for people and communities, from reduced costs of living, better access to jobs, and economic growth, to healthier lifestyles and, through reduced automobile use, important reductions in greenhouse gas emissions (Wood et al., 2009).

This research is going to measure TOD levels all over a region (case study region Arnhem/Nijmegen), looking for those locations where TOD levels are high (measured using the TOD Index to be developed) but transit connectivity is absent or less. This TOD Index will use GIS based spatial models and involve stakeholders at appropriate stages.

1.2 Justification

Transit Oriented Development (TOD) is generally defined as compact, mixed-use development near transit facilities that promotes sustainable communities by providing people of all ages and incomes with improved access to transportation and housing choices, reduced transportation costs that reduce the negative impacts of automobile travel on the environment and the economy(Reconnecting America, 2009).

TOD planning can achieve such benefits through two ways, developing the areas around existing transit stations and locating transit nodes where urban development in oriented to use of transit but need better access to transit. As the transit systems can benefit financially, by way of fare-box revenues and value re-capture(Singh, 2013), if the transit nodes are located in the locations that have high TOD level, people are expected to travel by transit rather than private vehicles. Therefore the objective of this research approach for an urban region is: plan for transit connectivity at those locations or areas where high levels of TOD exist but transit connection is absent or poor.

This study has three main steps, firstly assess the TOD levels in all parts of the region, then measure the accessibility to public transport of high quality service, at last overlay those outputs to help to identify those locations where TOD levels are high but transit connection is poor and make those location more accessible by locating new transit nodes.

However, in a TOD project, there is a lack of systematic measurement framework toward the effect and the level of its development. In order to determine the impact of TOD on urban built environment and economy, there is a need to establish a scientific and feasible spatial index system to provide measurement for TOD.

Fard (2013) has developed a TOD index to measure the existing level of TOD, the index was applied on the entire city region, regardless of transit system. However, his research still has some limitations:

- Several indicators of TOD could not be included in his index because of lack of data at that time.
- Stakeholder-involvement was absent in the research and thereby also the assessment of the importance of various factors in his index.
- Regarding the transit system, his results considered railways only and not BRT (Bus Rapid Transit)
- The measurement of access to transit nodes was based on the Euclidean distance.
- Sensitivity analysis was not carried at that time.

This research is intended to further develop the measurement framework for calculating a TOD index including participation of stakeholders in the region of Arnhem and Nijmegen in Netherlands. Now with a more extensive dataset available, this research will incorporate other factors which can represent more aspects of TOD, hence, number of indicators used in this research will be more than the indicators used by Fard (2013).

Also in order to reflect the different stakeholders' priorities, stakeholder involvement in a participatory multi criteria decision making process is inevitable in this study and the stakeholders can be involved in assigning the weights of TOD criteria and indicators in SMCE platform.

In addition, high-end, infrastructure-intensive BRT systems have been proven to attract and sustain transit-oriented development (Judy, 2007), BRT refers to a bus based service that has improved infrastructure, operating structure, new technologies designed to enhance service quality over ordinary bus service and it is a flexible, cost-effective rapid transit mode (Vincent & Jerram, 2008). So this research will include both train and BRT as transit.

This research will assess the access to transit by using the Public Transport Accessibility Level (PTAL) method, that considers walk distance and transit service, the analysis is based on network distance and provides a scientific way to identify the areas that have poor transit accessibility.

To test the robustness of SMCE model, sensitivity analysis will be employed. Eventually, this research will compare the results with the results of Fard (2013).

Moreover, Geographic Information Systems (GIS) can be a practical and analytical tool to support TOD measurement by performing series of spatial analytical operation using different indicators to measure different TOD aspects. Furthermore, due to the complex nature of a multi-dimensional spatial index, the construction of a composite index map based on the Spatial Multi Criteria Evaluation (SMCE) method is essential and it provides a good platform for cooperating with stakeholders.

1.3 Research problem

The measurement of TOD is subjective and multi-dimensional, no two TOD locations are alike in all respects. One TOD might yield a high transit mode share but lacks social diversity. Another might be deficient in shopping and entertainment choices but provide affordable housing on reclaimed brownfields (Renne, 2007). Lack of a standard and systematically measurement framework of TOD level is still an unsolved problem.

Without measuring TOD, mistakes in investment strategies will continue to be repeated and lack of coordination between land use and transportation planning can lead on disappointing result (Renne & Wells, 2005). Policy makers and stakeholders cannot get a correct understanding of existing TOD levels, which means that they are not aware of the problem of the TOD for areas and what should be improved or maintained. Poor decisions will be made because few planners and decision makers measure the existing TOD level correctly before planning for a new one.

Hence, planning for TOD requires measurement of existing TOD levels in the region and there still lacks an appropriate measurement tool for measuring the existing TOD levels.

1.4 Research objectives and questions

1.4.1 General objective

The objective of this research is "to develop a GIS –based model for measuring the existing TOD levels all over the city region using a TOD index, and to identify potential locations for transit connectivity based on the TOD index and public transport accessibility levels".

1.4.2 Sub-objectives

In order to achieve the research objective, several sub-objectives are planned to be reached:

(1) To identify the indicators for measuring TOD index for e city region.

(2) To develop GIS based spatial model for computing TOD indicators.

(3) To create a participatory-based assessment on calculation of TOD index.

(4) To develop a quantitative model (SMCE) for measuring the index of TOD.

(5) To measure public transport accessibility levels.

(6) To identify those locations where TOD levels are high, but have poor transit connectivity.

1.4.3 Research questions

The research questions related to the sub-objectives are:

Sub-objective (1): To identify the indicators for measuring TOD index for the city region.

(1) Which indicators should be used to measure TOD levels?

Sub-objective (2): To develop GIS based spatial model for computing TOD indicators.

(2) How to quantify the indicators?

(3) What is the spatial unit of analysis?

Sub-objective (3): To create a participatory-based assessment on calculation of TOD index.

(4) What are their preferences and how do they weight different indicators?

Sub-objective (4): To develop a quantitative model (SMCE) for measuring the index of TOD.

(5) How to standardize the indicator values?

(6) How to visualize the quantified TOD index?

Sub-objective (5): To measure public transport accessibility levels.

(7) How to identify the areas with poor accessibility?

Sub-objective (6): To identify those locations where TOD levels are high, but have insufficient transit connectivity.

(8) How to identify the concentrations of significantly high TOD areas?

(9) What or where the transit nodes should be recommended?

1.5 Conceptual framework

Figure 1 presents a framework which illustrates how the main concepts are related in this research.

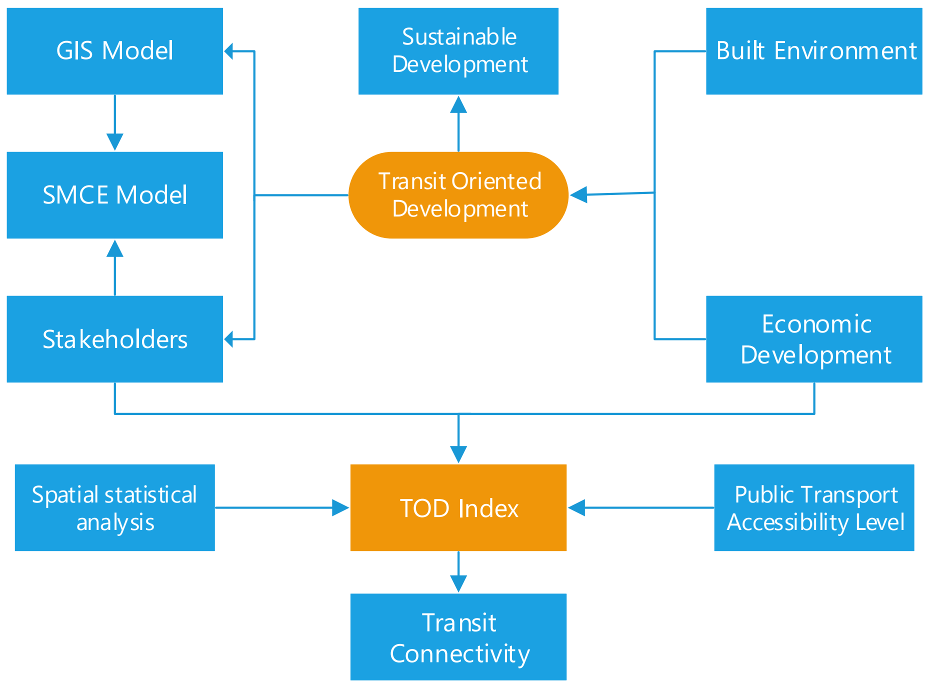


Figure 1 Conceptual framework of this study

As Transit-oriented development (TOD) is gaining wide acceptance as a tool to achieve sustainable development, in order to plan TOD, it is necessary to measure the existing level of TOD in the area, so as to make the right investment strategies.

The measurement of TOD considers the built environment and economic aspects, it includes identifying the criteria and implementing the indicators in GIS model and SMCE tool. With the stakeholders' involvement, TOD index can be calculated. Spatial statistical analysis help to detect spatial concentration of high TOD values, on the other hand, Public Transport Accessibility level is also measured for the region so as to make suggestions for improving transit system by identifying the potential locations have poor accessibility.

1.6 Research design

1.6.1 Operational plan

The Figure 2 shows the overall picture of the research operational plan and presents a brief description for each steps and also provides the relationship between each phases.

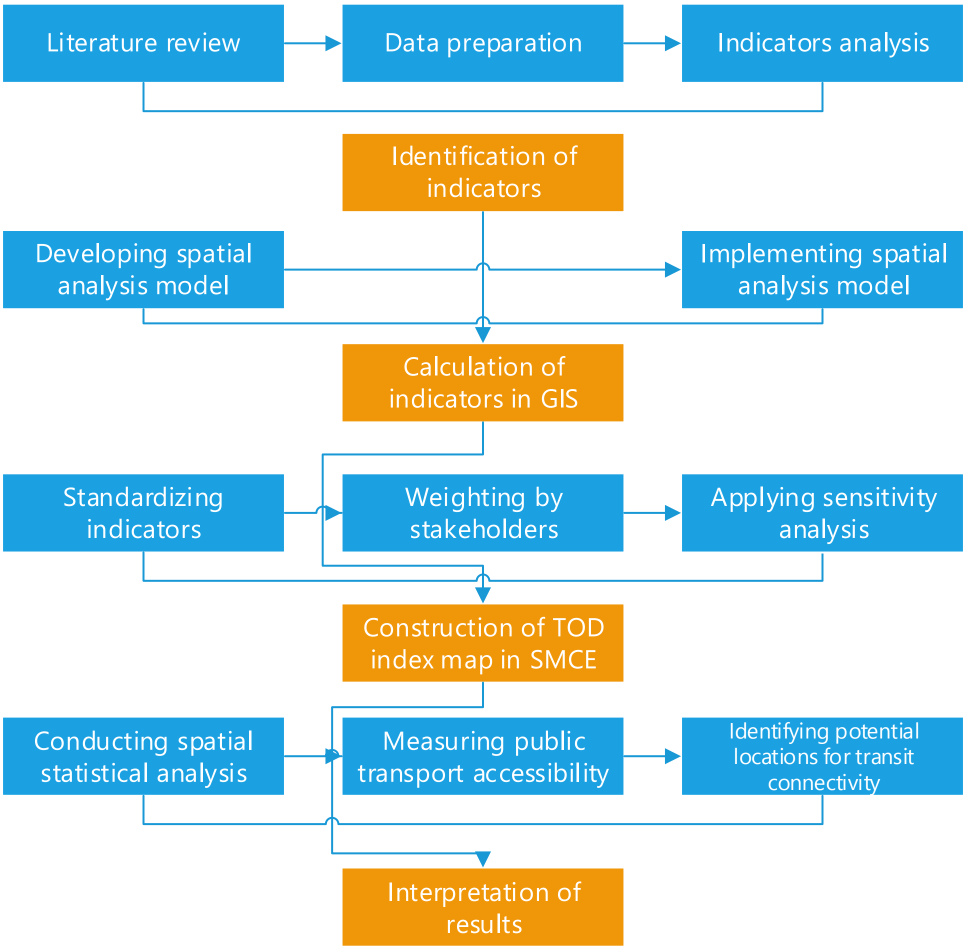


Figure 2 Operational plan of research

1.6.2 Research methods

1. Preparation method

As this research implements a framework to measure the existing TOD level in the region, it is essential to conduct a thorough literature review and to select relevant indicators to measure the different aspects of TOD such as: build environment and economic development. These indicators will be derived from the literature which have significant impact on TOD, they should be consider based on the available and feasible data.

According the regional scale of the study and the adapted list of measuring TOD indicators and related data requirements, no fieldwork is planned for data collection because all required data can be obtained from secondary source such as SAN authority, ESRI Nederland and CBS website and so on.

2. Implementation method

As Geographic Information Systems (GIS) can create, update, analyse and visualize spatial data; it can be a practical and analytical tool to support TOD measurement by performing series of spatial analytical operations such as using different indicators to measure different TOD aspects. Also, due to the complex nature of such multi-dimensional spatial index, this needs to construct a composite index map based on the Spatial Multi Criteria Evaluation (SMCE) method. The SMCE tool can help to standardize the indicators and calculate the values of TOD index.

In addition, setting up a workshop is an important stage before composing TOD index. This process is supposed to gather experts and different kinds of stakeholders such as state and regional government, transit agencies, local government, communities and private developers. It is important to interpret the criteria of TOD to them in an appropriate way and clearly in order to collect their views of weighting the different indicators. As time is limited, this work shop has been conducted by the PhD student Yamini (Singh, 2013) in Nov'13 for the same purpose as mine.

Furthermore, since one of the most critical factors of TOD is the effectiveness of the transit system, only when a transit system effectively connects places does access to transit—the heart of the TOD concept—become a valued commodity. To improve transit system, when calculated the TOD index value. It is also important to measure the public transport accessibility level based on the road network analysis. The two outputs are together used to identify the potential locations where TOD index value are high, but transit connectivity is absent or less.

Besides, a sensitivity analysis is required for testing the robustness of SMCE model after the TOD index has been made. It is performed by changing the weights of each indicators by increasing 10% and decreasing 10%.

3. Interpretation method

This method includes spatial statistical analysis and visualization to improve the understanding of the TOD index values and their spatial distribution. It helps to identify the cluster of high value of TOD area, and the hotspots can be identified. These can then be overlayed with the result of public transport accessibility level analysis to find areas where index value is high but PTAL is low.

2. LITERATURE REVIEW

This chapter presents an overview of literature in terms of the definitions of Transit Oriented Development, TOD planning, TOD measurement and TOD index. It also discusses the importance of stakeholders' involvement in TOD. Finally, this provides the way used to measure the public transport accessibility level.

This chapter provides the background for the concept of TOD and sets out a theoretical framework for measuring existing TOD level based on previous researches on related topics, also it helps to identify the criteria and indicators in chapter 3 which are used to quantitatively measure the TOD.

2.1 Definitions of Transit Oriented Development

The concept of TOD was originated as an alternative to the private automobile centric urban development. Proponents of TOD provide a variety of definitions of the concept and use a variety of terms including "transit stops", "high density" and "high diversity" (Calthorpe, 1993; Cervero et al., 2004; Evans & Pratt, 2007).

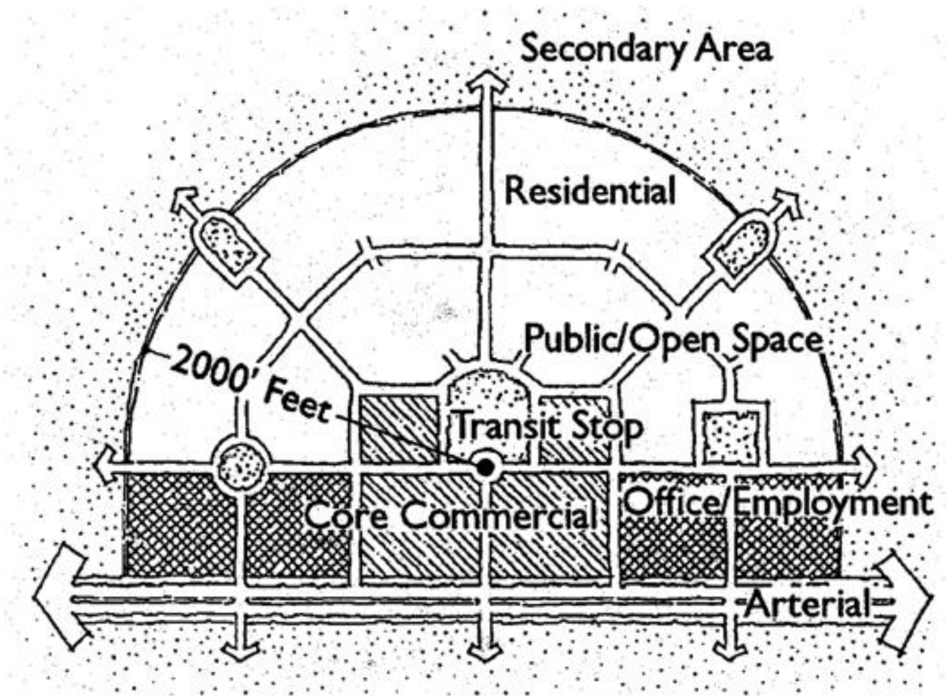


Figure 3 Definition of TOD by Peter Calthorpe

The definition proposed by Peter Calthorpe (Figure 3) described the basic themes of TOD: "A Transit-Oriented Development is a mixed-use community within an average 2,000-feet walking distance of a transit stop and core commercial area. TODs mix residential, retail, office, open space, and public uses in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot, or car"(Calthorpe, 1993).

While Calthorpe's definition focuses more on the physical characteristics of the surrounding area of a transit stop, Schlossberg and Nathaniel (2004) define TOD as an "…integrated approach to transportation and land use planning".

There is no universally accepted definition, core principles refer to high density, mixed-use land use developments located within walkable environment that around a close public transport stop or railway station. In a review of the various definitions for TOD from Cervero et al. (2004)， TODs are regarded as offering the potential to boost public transport ridership, encourage walking activity, mitigate sprawl, accommodate economic growth, and create interesting places. The definition of TOD changes along with the different aims by different agencies and stakeholders.

In addition, TODs can function in both centre city and suburban settings, the main difference being the density in each place (Calthorpe, 1993). TODs are usually based on rail service (either light rail or commuter rail), but bus-based TODs also exist.

Overall, in this research, TOD is defined as a compact, mixed use development near transit facilities with high-quality walking environments.

2.2 TOD planning

TOD planning is an intentional process of mixing of land use and transit through the creation of compact, walkable, mixed-use communities within walking distance of a transit stop or station. It can be done at regional, urban, and local level(CTOD & Reconnecting America, 2011). And the implementation of TOD takes true collaboration between the transit agency, local government, and real estate developers(Meter, 2010).

This concept of Transit Oriented Development (TOD) is strongly related to the largely American neighbourhood concepts of Smart Growth and New Urbanism in USA. However, the concept has been gradually transferred to other parts of the world(Store & Kangas, 2001).

In the US, transit and land-use development are integrated which aim to combat urban sprawl and private car dependence by promoting high density, public transport-accessible, pedestrian-friendly, mixed-use development patterns, through redeveloping urbanized areas that are already served by the infrastructure and greenfield developments. In contrast to sprawled suburban neighbourhoods, these characters should be developed in such a way that "everyday activities, including housing, work, and amenities are within walking distance of each other, in a pedestrian-friendly environment, nearby public transport stops"(Cervero, 2003).

In the Netherlands, the concept of TOD is extended to a regional approach, which will be implemented in the South Wing of the Randstad Holland.

In the South Wing of the Randstad area, where local and regional governments, Dutch Railways (NS) and the national rail network manager work together voluntarily since 2006 to implement an ambitious regional Transit Oriented Development program called StedenbaanPlus (Geurs et al., 2012). The Randstad South Wing is one of the most densely populated areas in Europe， it has 3 million inhabitants and located in the Western part of the Netherlands. The primary aim of StedenbaanPlus is to increase the density of urbanization around more than 30 railway stations and improve accessibility of station areas for bus and slow modes. The aim is also to increase rail ridership to a level which allows NS to increase the local train frequency from 4 to 6 trains per hour(Store & Kangas, 2001).

Over the past decade, TOD has gained in popularity as a planning tool and is expected to promote smart growth and to integrate the land use and transport systems. However, before planning for TOD, it is required to measure the existing TOD level so as to make the right investment and give a planning direction.

2.3 TOD measurement

Benefits of TOD

A report on TOD in the United States (Cervero et al., 2004, p. 119) argues that "The literature is replete with platitudes that have been heaped on the TOD concept; however, relatively few serious studies have been carried out that assign benefits to TOD in any quantitative … sense". The study went on to note that transit ridership impacts and land value gains were the areas with the most amount of quantitative research. Also this study divides benefits of TOD into primary and secondary categories. Primary benefits represent a direct cause and effect between TOD and impacts. Secondary benefits spin off largely from primary ones and thus are collateral. Those benefits are shown in the following table:

Table 1 Primary and secondary benefits of TOD

	Public Sector	Private Sector
Primary	1. Increase ridership and fare box revenues	5. Increase land values, rents, and real-estate performance
	2. Provide joint development opportunities	6. Increase affordable housing opportunities
	3. Revitalize neighborhoods	
	4. Economic development	
Secondary	A. Less traffic congestion and VMT-related costs, like pollution and fuel consumption (1)	G. Increase retail sales (1,2)
	B. Increase property- and sales tax revenues (5)	H. Increase access to labor pools (A, 6)
	C. Reduce sprawl/conserve open space (1, 3, 6)	I. Reduced parking costs (C, 2)
	D. Reduce road expenditures and other infrastructure outlays (1)	J. Increased physical activity (C, E, F)
	E. Reduce crime (3, 4)	
	F. Increase social capital and public involvement (3, 4)	

Note: Values in parentheses represent primary benefits and/or secondary benefits that are the source(s) of the secondary/collateral benefit listed (Cervero et al., 2004).

This research both measure the existing TOD level and public transport accessibility level, by overlaying the results, it can help to identify the areas where necessarily need to be improved the public transit connections. If those area have such transit connections, it definitely increase the transit ridership and fare box revenue. Also the land value where near the transit would be increased as well as the property tax revenue. It encourages people travel by transit, and brings lots of benefits to local government, transit agencies and private developers.

Measurement of TOD

Cervero and Kockelman (1997) categorized indicators to evaluate the influence of built environment on travel behaviour into three groups-density, diversity and design:

· **Density:**

- Population density
- Employment density
- Accessibility to jobs

· **Diversity**

- Dissimilarity index
- Entropy
- Vertical mixture
- Intensity of land use categories
- Activity center mixture
- Proximities to commercial-retail uses

· **Design**

- Street design
- Pedestrian and cycling provisions
- Site design

These indicators were selected to evaluate the influence of built environment on travel behaviour, followed later by destination accessibility and distance to transit (R. Ewing & Cervero, 2010). These D variables all mainly focused on the measures of the built environment. The indicators used in this research are derived from above three criteria based on the aspect of built environment, they can explain the relationship between the land use and transport, and however they might not be sufficient to measure TOD. The objective of this research also require to create economic benefits to local government, transit agencies and private developers, so economic development should be also considered as an essential aspect of TOD as well.

Renne and Wells (2005) revealed and categorized 56 indicators into five groups: travel behaviour, economic, environmental, built environment and social diversity/quality to measure the success levels of TODs, they presented a survey of 30 professionals highlighted fifteen success measures that were considered "very useful" by at least 50% of the respondents.

Based on survey results, respondents were asked to list the three to five most important and least important indicators, brought out transit ridership as the most important indicator. The ridership indicator was followed by density, design quality, and pedestrian friendliness indicators; parking metrics; and economic indicators including tax revenue.

Table 2 presents a summary of the identified key indicators as well as the rankings from the two exercises. However, even the indicators are selected based on these researches based on built environment and economic development, the rankings of indicators in this research would be derived based on the workshop to collaborate with the stakeholders in the study area, which can collect the preferences of stakeholders in realization of TOD.

Table 2 Useful Indicators for TOD Identified by 30 Professionals

Indicator	Category	Percentage Identifying as "Very Useful"	Secondary Ranking
Transit ridership	Travel behavior	70	1
Population/housing density	Built environment	67	2
Employment density	Economic/Built environment	53	2
Qualitative rating of streetscape	Built environment	77	3
Mixed-use structures	Built environment	60	4
Pedestrian activity counts	Travel behavior	77	5
Number of intersections or street crossings improved for pedestrian safety	Built environment	60	5
Estimated increase in property value	Economic	63	6
Public perception	Social diversity/ Quality	63	7
Number of bus, ferry, shuttle, or jitney services connecting to transit station	Travel behaviour	63	8
Number of parking spaces for residents, tenants, visitors, commuters, and shared	Travel behaviour	53	9
Estimated amount of private investment	Economic	57	-
Number of convenience or service retail establishments	Economic	53	-
Estimated amount of private investment by type of land use	Economic	52	-

Stakeholders' involvement

Various researches have discussed that the implementation of TOD requires true collaboration among the stakeholders such as transit agency, local government, and real estate developers(Meter, 2010; Renne et al., 2009).

However, Renne et al. (2009) emphasize perspectives vary between different stakeholders in monitoring the success of TODs. They presented a framework to measure TOD success based on the different perspectives of various stakeholders, including

- State and regional government,
- Transit agencies,
- Local government,
- Communities
- Private developers.

At last they proposed different key questions about TOD goals for each stakeholder group and then recommended different indicators to measure progress towards these goals.

State and regional government look at TOD to address problems like urban growth, urban sprawl, and traffic congestion and environment pollutions. Transit agencies always benefit from TOD by increased transit ridership and revenue. Private developers such as banks and pension funds aim to receive a financial return on their investment(Renne et al., 2009).

Different stakeholders have different goals, so they may emphasize on different indicators. In this research, stakeholders would be involved at multi criteria decision making stage, they are asked to rank the criteria as well as the indicators based on their realization of TOD, this process helps them to clarify the outstanding issues and concerns, identify ideas and suggestions on the importance of various indicators.

Through a collaborative effort that local government can collaborate with other agencies and stakeholders, both informally and informally, can improve land use and transport integration, and as a result of this study, engaged local stakeholders are able to make targeted supportive infrastructure improvements to transit stops.

2.4 TOD Index

A TOD Index was imagined as a general approach to characterize the degree to which a project functions or would function as a TOD, and as a preliminary design-planning guidance tool (Evans & Pratt, 2007). The important elements of TOD would be captured in such an index.

Singh et al. (2012) also pointed out to guide decision making for new transit oriented development it is essential to have a framework and a tool to quantitatively measure current level of TOD at a location and in an area. The tool needs to be flexible and able to support participatory planning process.

Singh et al. (2012) suggested a framework which can be used for assessment of established projects but also more crucially for assessing existing conditions on the ground. This framework comprises of several stages including: defining criteria and indicators set, data preparation, criteria map production and finally carrying out spatial multi criteria analysis (SMCA) assisted by SDSS. The TOD index is calculated in the SMCA tool, the results are used in the SDSS environment where different stakeholders can share their views and suggest intervention to improve TOD-ness of each location.

Recently, Fard (2013) developed an index to measure the TOD level for whole urban region. He categorized the indicators of residential and commercial density, level of residential and commercial mixed use, diversity of land use and business density into four dimensions, which can measure aspects of TOD related to the density, diversity, design and economic development. In addition, few alternative locations were also suggested for establishing new train stations as a part of his thesis.

The objective of this study is measuring the existing level of TOD in Arnhem and Nijmegen city region, the use of index and indicators is a suitable method, also multi-criteria analysis can be a very useful tool to develop index from indicators.

Overall, the TOD index can not only be a backward-looking assessment to evaluate an implemented TOD project, but is able to be a forward-looking planning assignment to measure the existing conditions before the TOD planning takes place. For different purposes, the indicators for the measurement would be different. In this research, TOD index is used as a pre-assessment provides help for TOD planning. Since planning for transit oriented development must consider the existing TOD levels that indicate the level to which a development is oriented towards use of transit, and the TOD index can be used to measure TOD levels, it helps to identify the locations where require transit connections, therefore can guide the planning work to establish new stations as well as improve the quality of transit service at those locations.

2.5 Public Transport Accessibility Level

The objective of this study is identifying the potential locations for transit connections, which can make the public transit more accessible, so measuring the accessibility to public transport is an effective way to find those locations have poor connectivity.

The concept of accessibility were defined by Cervero (1989), "Accessibility is a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time." The measures of accessibility then are capable of assessing feedback effects among urban form, transport infrastructure and spatial distribution of activities (Leck, 2006).

By brief review of accessibility measures such as contour measures, gravity measure and utility based measure etc. These measures have too many limitations regarding data collection, parameters such as distribution of opportunities and number of users are difficult to collect(Braun, 2011). Regarding PTAL (Public Transport Accessibility Level), an accessibility measure that taking into account walk access time and service availability thus can be used on measuring how accessible public transport is in Arnhem and Nijmegen city region.

The current methodology of PTAL was developed by the London Borough of Hammersmith and Fulham in 1992(Transport for London, 2010). Then it has been reviewed, tested and adopted by a London Borough-led PTAL development group. PTAL is now widely used in London transport plan. PTAL calculation also has been used by other researches such as Zhang and Guindon (2006) and Gent and Symonds (2005). The main advantage of PTAL is easy to understand, it provides a direct visualization of data by using a coloured map in which levels of accessibility are clearly shown. PTAL can also be used to identify locations where public transport accessibility is high or low (Zhang & Guindon, 2006).

3. IDENTIFICATION OF INDICATORS

3.1 Selection mothods

This research is measuring the existing TOD level in the whole region, and the approach of this work is to develop a measurement for calculating TOD index, so it is essential to develop a set of indicators which can qualitatively and quantitatively measure the index. The selection of indicators follow these steps:

- Identify the main aspects of TOD regarding the TOD levels for the entire city region.
- Formulate the criteria based on the aspects of TOD.
- Select indicators based on the criteria.

In addition, to be relevant, indicators must be selected also follow the selection principles:

(1) Meet the objective of research.

In this study, when measuring TOD level in the entire region, it mainly focus on the "D" -development, not "T"-transit, as the objective of this research is to measure the TOD level all over the region, and find out the areas with high TOD level , but poor transit connectivity. At these locations, it is work on making transit system more accessible.

So when selecting indicators, they should be able to measure "development" of this area, without consideration of "transit system". Further, all criteria and indicators should be selected from built environment and economic development which are considered as "development" in this research.

(2) Be efficient and ideally measure the targeted criterion.

All the indicators should be essential measures of related criterion, should have significantly impacts on TOD level, these indicators could be derived from literatures we discussed in previous sections.

(3) Be feasible based on the availability of relevant datasets required to quantifying them.

Data availability is an imperative issue when selecting indicators as all the data were obtained from second source. Only the indicators can be quantified with available data will be selected for this research.

3.2 Defining aspects, criteria, hypothesis and indicators

The framework for selection of indicators has four components: aspect, criteria, hypothesis, and indictor. It employs top down approach, firstly, it is required to identify the main aspects of TOD regarding measurement of TOD all over the city region. Then formulate the criteria based on the aspects of TOD, and along with each criterion, the related hypothesis describes how the criteria affects and contribute to TOD level. Finally, based on each criterion and the selection principles discussed in previous section, the indicators used to measure TOD levels are selected from various literatures.

As TOD level in this research indicates the level of urban development, the high level means the areas are ripe for use of transit, so there are two main aspects of TOD identified in this research, build environment and economic development. The follow section describes the TOD aspects in this study as well as the useful indicator based on the criteria and hypothesis.

3.2.1 Main aspects

Built environment

Built environment means physical features of the urban landscape. The density, diversity and design variables came up by Cervero and Kockelman (1997) as measures of the built environment can significantly influence TOD impacts and have a strong positive relationship with transit use. "Higher densities, greater diversity of land uses, and better design are associated with more transit use and walking and fewer automobile trips per resident and per worker." (Pratt, 2007).

The density measure has been recognized as the strongest predictor of travel behaviour(Leck, 2006). TOD must has a minimum density as it is sufficient to enable cost-effective transit service and infrastructure provision, support utility of retail, and keep local attractions and destinations within short walking distances. Higher densities require higher capacity and frequency, and increased frequency can encourage new ridership and high densities are associated with numerous aspects of TOD success(Pratt, 2007).

Diversity which relates to the extent and nature of the mix of uses, that is the intermingling of residential， office, shops, public open spaces, and other consumer amenities amongst one another, yields some transportation benefits is almost undisputable in the literature. The assumption is more diversity of land use can make people less likely to drive and more likely to walk or cycle to their destinations(Leck, 2006). In addition, TOD projects with high diversity offer the possibility of a great proportion of activities, a corresponding reduction in motorized-travel trip generation(Pratt, 2007), and a promotion of non-motorized modal splits.

The third aspect of built environment that contributes to travel behaviour is "design" which plays an important role in TOD plans. "Design complements density and mix by addressing how those characteristics are arrayed and linked to one another"(Kuzmyak et al., 2003). Moreover, TOD refers to design with pedestrian priority, located within an easy walk of major transit stop. Pedestrian-friendly design of TOD such like smaller blocks, continuous sidewalks and highly connected roads will reduce automobile trips, and automobile frequencies and leads to higher transit usage and walking, moreover make people feel safety while walking on the roads.

Economic development

Transit Oriented Development can bring a lot of economic benefits to a variety of stakeholders, to the extend TOD brings increased land value to land owners in proximity to stations, and this increased values will generally lead to increased property tax revenue for government agencies(Pratt, 2007).

TOD can connect job centres to transit, to prevent congestion, major existing job centres should be well served and highly accessible to the regional transit network. In addition, the more connected the transit network is to regional jobs, the more workers will choose to walk, bike or take transit to work, and the increased transit ridership will bring more financial to transit agencies.

Furthermore, area with a high level of economy always have a high demand of economic activities, those activities make people travel, and those activities require more mixed-use living environment which are within easy access.

3.2.2 Useful indicators

Based on the built environment and economic development, the following section shows the useful indicators of TOD measurement which discussed in previous literatures.

Criteria 1: Density

Hypothesis: High density is essential to maximizing the benefits of TOD.

Indicator 1: Population / housing density in the area.

Description: Population /number of houses per acre.

Indicator 2: Employment density in the area.

Description: Number of employees per acre.

Indicator 3: Commercial density in the area.

Description: Commercial units per acre.

Criteria 2: Diversity

Hypothesis: Higher diversity supports higher TOD level through reducing the rates of vehicular travel and shortening the travel distances.

Indicator 4: Diversity of land use. (Entropy index)

Description: The number of different land uses in a given area and the degree to which they are represented in land area(R. Ewing & Cervero, 2010).

Indicator 5: Mix of Housing Types

Description: The number of different type of house in a given area and the degree to which they are represented in land area.

Criteria 3: Urban design

Hypothesis: Good design and pedestrian-friendly environment can support high TOD level by encouraging people to walk and cycle and make it safe.

Indicator 6: level of mixed land use.

Description: Mixed Index, "MI" measures the level of residential vs. commercial/industrial/institutional land use mixing. (Zhang & Guindon, 2006)

Indicator 7: Street connectivity.

Description: Ratio of the number of actual circuits to the maximum number of circuits (Alpha Index).

Indicator 8: Number of intersections/street crossing for pedestrian safety.

Description: Number of intersections in the area.

Indicator9: Quantity Accessible paths for cycling and walking

Description: total length of the accessible paths for cycling and walking.

Criteria 4: Economic development

Hypothesis: Areas with higher economic development should have higher TOD levels.

Indicator 10: Number of service/retail establishments

Description: Total number of service/ retail establishments currently.

Indicator 11: Estimated increase in tax revenue

Description: Amount of estimated increase property and sales tax revenues in the area.

Indicator 12: Unemployment level.

Description: Percentage of unemployment people between ages 15 and 64 years old.

3.3 List of indicators in this study

Those indicators in previous section are considered as the useful indicators, are taken as the basis of TOD measurement for this research. However, due to the repetition of measurement and data availability issue, only those indicators that can be measured in appropriate way with available data will be selected to be analysed in further steps.

Since the population, number of houses are very highly correlated, adding two of them into the indicators set will cause bias which should be avoided. As TOD aims to create a walkable environment around transit stops, and population density is important for planning such facilities and services as transit, retail and recreational areas, however, houses cannot travel and also could be empty, so housing density is a not appropriate indicator. Moreover, it has been found that population and employment density are the most significant factors in determining demand for public transportation. High employment densities is significantly associated with higher probabilities of commuting to work by transit because that the clustering of jobs, especially in close vicinity to bus or rail stations, allows people to either use transit or walk(Leck, 2006). Hence in this study population, commercial density and employment density are selected in further steps.

More diverse land uses create more activities so that generate and attract trips and raise the demand for transit and one other characteristic of land use diversity reflects the proximity of activities to each other, which decrease the travel distance. Also a diversity of housing types reflect different income levels, "Inclusion of below-market-rate housing can support higher levels of transit ridership"(Pratt, 2007), because low income residents may be more prefer use the TOD's transit service rather than buy a car. However, due to data availability housing type is eliminated from consideration. So regarding the characteristics of land use diversity are significant to TOD, land use diversity is included in this research.

In addition, urban form design can reflect urban spatial configuration and the degree to which urban land use components are spatially distributed, the level of mixed use, for example mixture of residential area and commercial area have a significant impact on travel activities, trip distance and travel mode options(Zhang & Guindon, 2006). Also pedestrian-friendly design of street pattern can encourage cycling and walking. Increased street paths for walking and cycling can encourage people travel by foot over by private vehicles, and high density of intersections both reduce travel distance for all modes including walking and bicycling and provide a great number of route options. These two indicators can both be a measure of walkability, in this study number of intersections and quantity of accessible paths for walking and cycling are both selected along with level of mixed use.

Moreover, the high number of service/retail establishments and high employment level can encourage trips and increase transit ridership by creating more daily activities. Moreover, number of service/retail establishments refers to the number of business sectors per area, due to the data constraint, it was replaced by the similar dictator business density which including industrial, commercial and non-commercial sectors in the area. However, due to the data limitation, employment level and tax revenue are excluded in this study.

Based on the analysis, there are 8 indicators to be used further in this research, Table 3 shows the final list of indicators.

Table 3 List of indicators in this study

Aspects	**Criteria**	**Indicators**
Built environment	Level of density	Population density
		Commercial density
		Employment density
	Level of diversity	Diversity of land use
	Level of urban design	Level of mixed land use.
		Quantity accessible footpaths for walking and cycling
		Number of intersections or street crossings
Economic development	Level of economic development	Number of service/retail establishments

4. METHODOLOGY

This chapter provides the methodology of the study and also explains the sequential steps of the procedure. Figure 4 illustrates the main steps in the methodology.

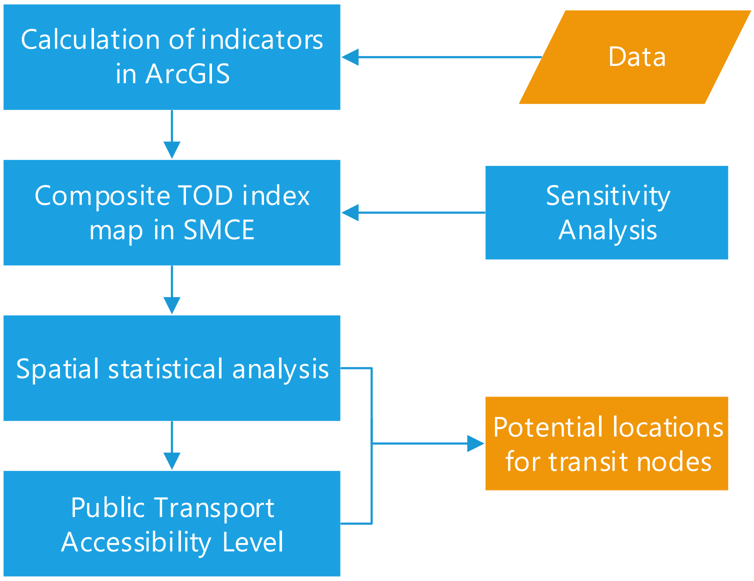


Figure 4 Overview of steps in the methodology

In chapter 3, the indicators to be measured were selected. All the indicators in this research are spatial indicators and will be calculated using GIS platform. Several GIS models are created and various methods are applied to calculate the indicators, such as data apportion, entropy formula and Mixedness Index formula. Especially, MATLAB code is used to conduct spatial calculation for entropy since it requires to repeat the calculation thousands times and therefore cannot be calculated by GIS tools.

Since the outputs of indicators calculation have different units, SMCE helps to standardize the indicators and also weight them and also provides a platform for stakeholders' involvement. The weights are derived from the workshop which has been conducted by Singh (2013) for same research. Then, TOD index map are produced in SMCE model. Moreover, a sensitivity analysis is applied to test the robustness of the model.

In order to clarify the existence and identify the cluster of high value TOD area, several spatial statistical analyses are applied such as spatial autocorrelation analysis, incremental spatial autocorrelation, Getis-Ord and Anslin lical Moran's statistical.

To measure the access to public transit, PTAL (Public transport accessibility level) is carried to measure the accessibility to trains and BRTs for the whole region. This method considers walk access time and of service availability, and it is conducted based on GIS and using network analysis.

Eventually, potential locations are identified by overlaying the results of spatial statistical analysis and PTAL, those locations have higher TOD level but poor accessibility, the result can be recommended to transit authority, therefore, make improvement on public transit connectivity.

4.1 Study area

The Arnhem Nijmegen City Region (Stadsregio Arnhem Nijmegen) is one of the eight Netherlands' city region which located near the Randstad metropolitan area (Figure 5).

Figure 5 Map of Arnhem Nijmegen city region in the Netherlands (Fard, 2013)

The city region consists of 20 municipalities, 19 of them are located within the province of Gelderland and 7 have a shared boundary with Germany.

According to the Stadsregio Arnhem Nijmegen (2013), the Arnhem Nijmegen City Region works hard to encourage regional development. It does so by investing in spatial planning, housing and employment. The City Region is supposed to be the second biggest economic zone in the Netherlands by 2020.

The Arnhem and Nijmegen city region has 736000 inhabitants, however, more than 40 percent of its population settle in the two major cities of Arnhem and Nijmegen which the population are 147,020 and 162,965 respectively (Figure 6).

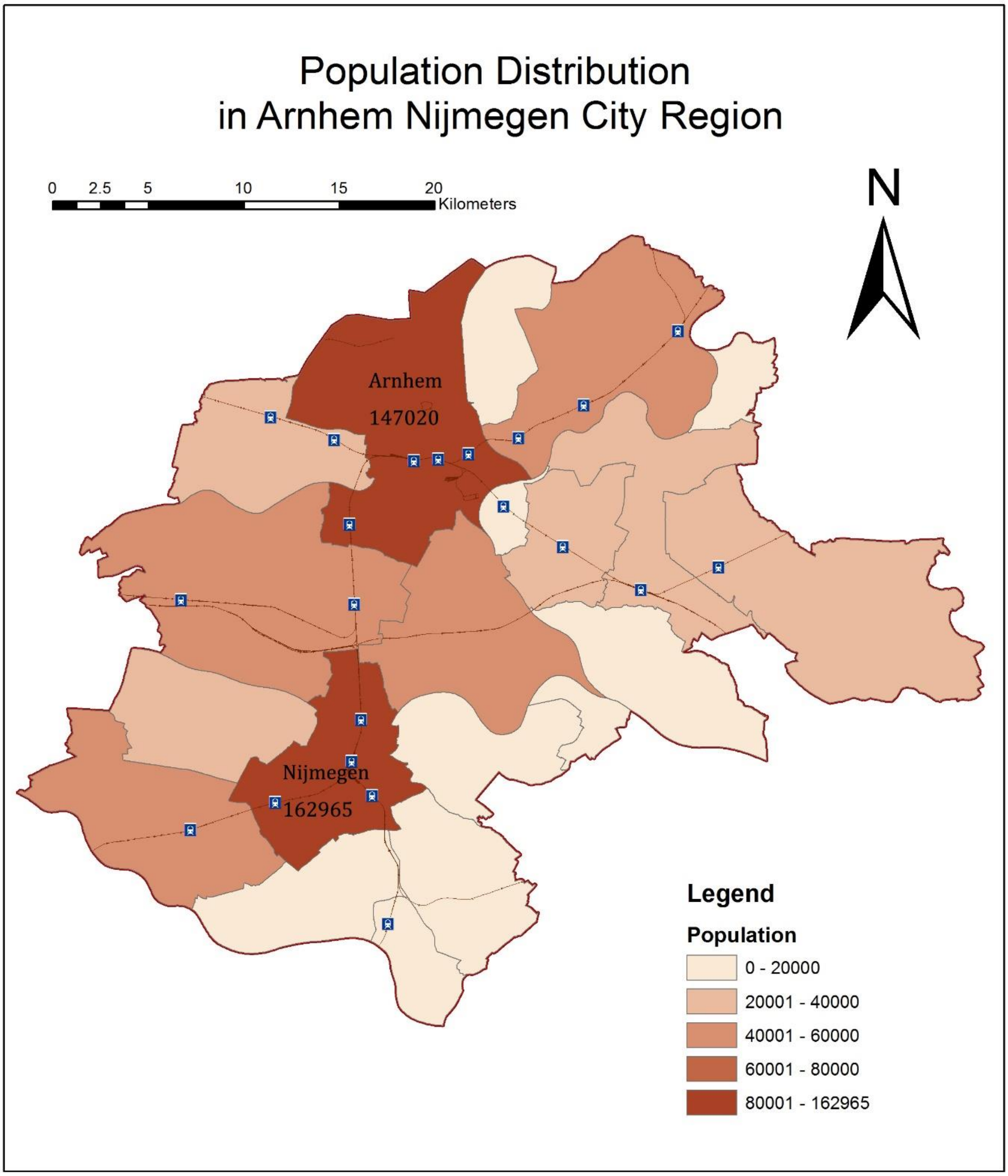


Figure 6 Map of population distribution in Arnhem Nijmegen city region

In order to achieve the aim, they set up an Economic Agenda in collaboration with the municipalities and companies in the region(Stadsregio Arnhem Nijmegen, 2013). The Arnhem Nijmegen City Region primarily want to further improve the region's economic development, including business services, transport and logistics.

The surface are of the region is 1000 square kilometres, and more than 70 percent of the region is covered by natural sites, forest and agricultural lands, and around 20 percent of its area is characterized by built up area (Figure 7).

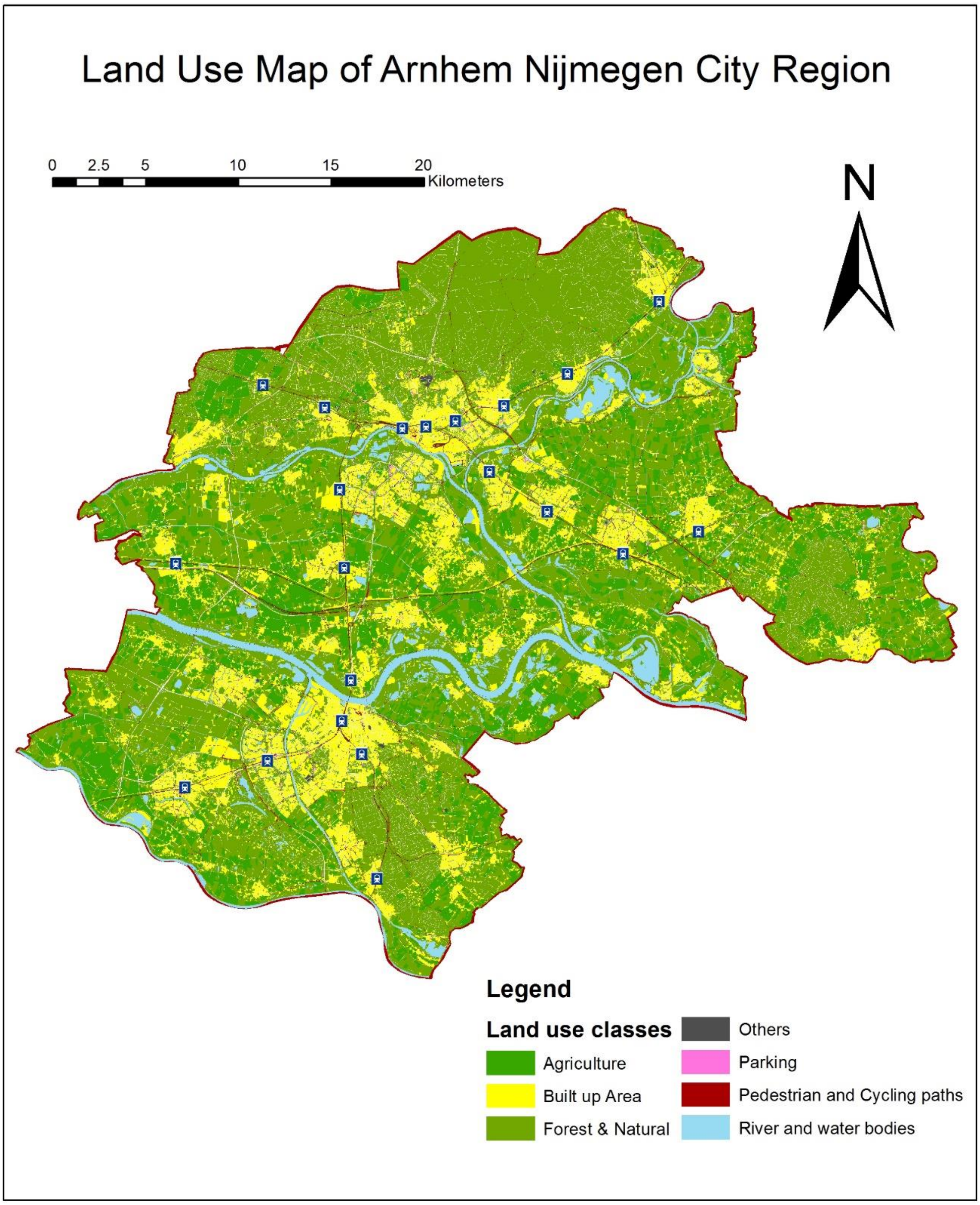


Figure 7 Land use map of Arnhem Nijmegen city region (SAN_Topography)

The region is well linked by road (A12, A50, A73, A15, A325), water (Rijn, Waal, IJssel) and rail (Betuweroute, HSL-Oost) and is in close proximity to various airports (Schiphol, Eindhoven, Düsseldorf) (De Stadsregio Arnhem Nijmegen, 2013).

The Arnhem Nijmegen City Region is legally responsible for preparing and implementing the regional transport policy. It commissions the regional public transport companies and grants permits for train, bus and city region taxi services. The following policies are set improve and maintain mobility at region scale (Stadsregio Arnhem Nijmegen, 2013):

(1) Aligning public transport with private transport;

(2) Promoting spatial development of areas around traffic junctions;

(3) Making public transport into a coherent and distinguishable whole.

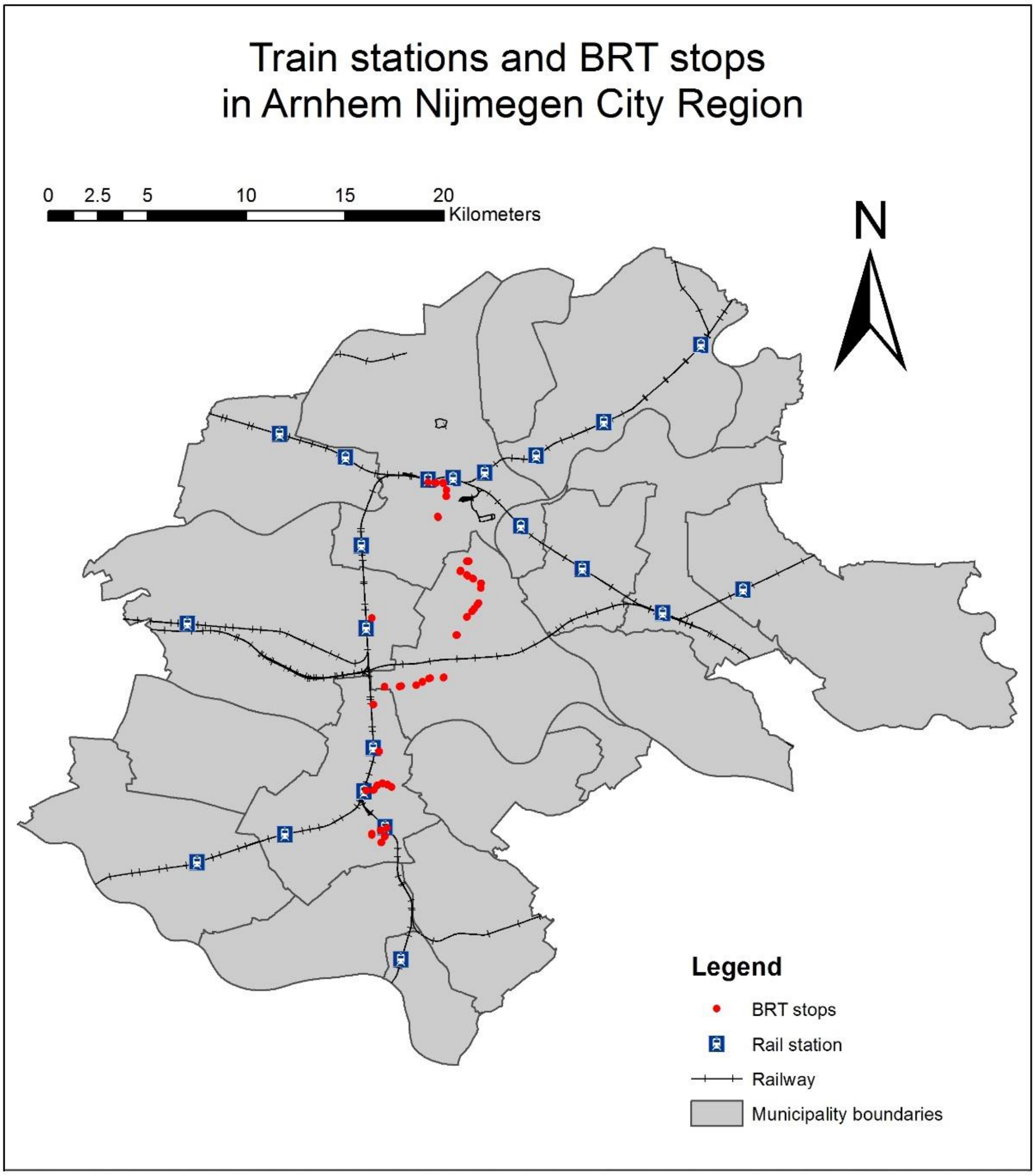


Figure 8 Train stations and BRT stops in Arnhem Nijmegen

4.2 Data preparation

The data has been obtained from SAN authority, ESRI Nederland and CBS website and online sources and there is no field work, therefore data used in this research is limited, all the data has been used for indicators focus on the built environment and economic development aspects of TOD. Table 4 shows the initial collected data layers, type and their corresponding source.

Table 4 Initial collected data layers and their correspondent source

Features	Type	Data source
Building footprints	Polygon	SAN authority
BRT stops	Points	
Administrative boundaries	polygon	CBS
Demographic s data	Table	
Railways	Polyline	ESRI Nederland – TOP10NL
Train stations	Points	
Road network	Polyline	

4.3 Spatial units of analysis

The spatial unit of TOD measurement in this study, should capture and represent the spatial scales of TOD area, more importantly, it should keep the spatial database and computing process, efficient and manageable.

The scale of TOD is defined as the distance that a person willing to walk to take transit, it's about 5 minutes' walk, or 400 to 600 meters, the primary area of TOD is around a station and there is potential for 125 to 250 acres of land for transit oriented development(Pushkarev, 1977). There are still several spatial definitions for TOD area which conceptualize TOD at different level, however, one common character is within a walkable area of radius of 250 meters to 800 meters around a station.

In addition, in Fard (2013)'s research, he had used the gird cells of 300*300 meters as the spatial units of TOD analysis, he tested different gird tessellations of 100*100, 200*200, 300*300 and 500*500 meters, then found out 300*300 meters was performed well by using the GIS spatial analysis functions.

According all above, in this study, grid cells of 300*300 meters also was used as the spatial unit for analysis. There were 12031 grid cells of 9 hectares after overlay with the city region area of Arnhem and Nijmegen.

4.4 Calculation of indicators

The following section describes the methods were implemented to compute these indicators. Since the availability of data is limited, all the land use analysis are based on the map of building footprints in Arnhem and Nijmegen region. Every building has a function.

4.4.1 Density

In a city or urban area with high population and employment density, public transportation is more efficient resulting in lower automobile dependence. Population and employment density, can be simply expressed as:

population/Number of employees per gird cell. While these indicators are conceptually simple, there is a challenge in quantifying the accurate population and number of employees, because CBS data was provided at neighborhood level and it had to be disaggregated to the spatial unit of this study, 300 *300 meters gird cells.

The method is developing a geoprocessing model that, conducts apportioning process based on the total area of building footprints for urban land uses and returns the population and number of employees for each grid cell. Assuming that a building with large footprint houses more people. This method need to select land use classes that are considered 'urban', for example, agriculture, forest/natural sites, and rivers should be excluded.

In this method, by overlaying two layers, one is the total population within the neighborhood boundaries, and another one is our grid cells of spatial units. Then calculate the population for all fragmented features based on the proportion of residential building footprints, so it can easily calculate the population within the grid cells.

In terms of number of employees, the data was at municipality level and the apportion principle is based on all the other kinds of land use footprints excluding residential.

Regarding commercial density, it counts the area under building of commercial sector in each cells. It was be aggregated based on the ratio of the area of commercial building footprints in grid cells and the total area of commercial building footprints in neighbourhood.

4.4.2 Diversity of land use

Land use diversity refers the number of different land uses in a given area and the degree to which they are represented in land area(R. Ewing & Cervero, 2010). Practical method for quantifying diversity of land use is the entropy method proposed by Cervero (Cervero, 1989),as shown in this equation:

$$Entropy = -1 * \sum_{n} \frac{Pi * ln(Pi)}{ln(N)}$$

Where *Pi* is the proportion of developed land in the n^{th} use type.

The entropy method produces an index between zero and one, where a value of one implies a balanced mix of land uses, a value of zero indicates there is no or just one kind of land use.

Since some land uses could not contribute to the diversity which have significant impacts on TOD level, they were not included in the further calculation, such as rivers and water bodies, roads, cycle and pedestrian paths, side buffers. This particular Entropy Index equation in this study considered the following land uses: residential, commercial, industrial, office, service, health care, education and sports.

Entropy represents land use balance, when used in land use applications and is able to quantify land use mix in a manner that the lowest values represent homogeneous land use and higher values indicate a diverse mixture of development within a tract.

In terms of calculation of diversity, firstly it needs to define the analysis window. According to Cervero and Kockelman (1997), the mean entropy for land use categories is calculated within a half-mile radius of developed area surrounding hectare grid cell. As the spatial units of this research is the 300m*300m grid cells, if the analysis window follows the half-mile radius (about 800 meters), it would contain almost 21 cells in each analysis window, this may leads an inaccurate calculation. Also a TOD area is defined within 500 to 800 meters, in this case, the radius of diversity analysis window for each grid cells in this study is adapted to 500 meters, the centre are the centroids of the grid cells, as shown in Figure 9.

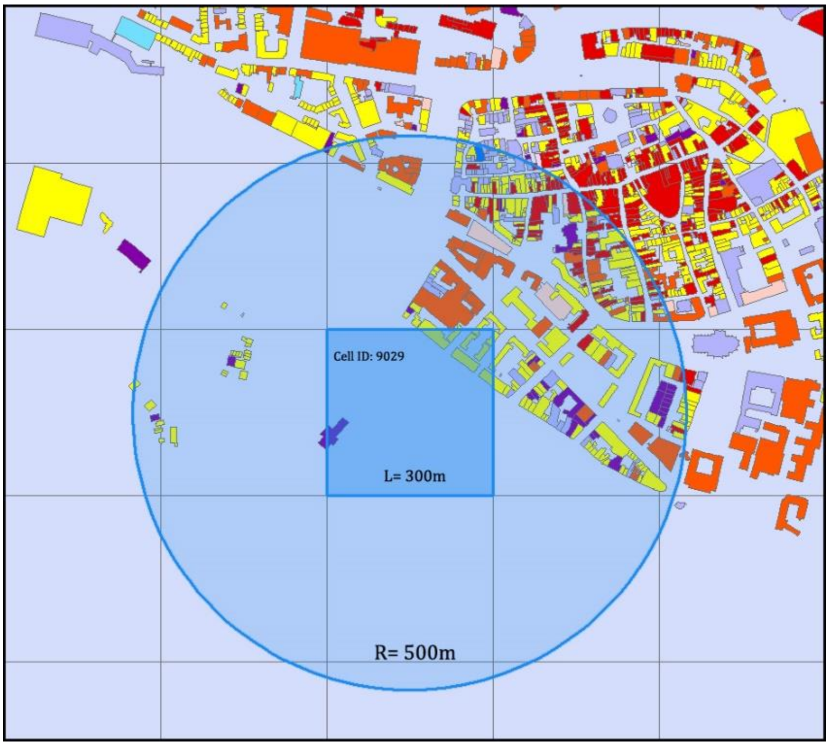


Figure 9 Land use diversity analysis window

Since the entropy formula has a summation expression which is complicated and cannot be calculated by common GIS functions, the formula was expanded and accomplished in several steps.

$$Entropy = -1 * \sum_{n} \frac{Pi * \ln(Pi)}{\ln(N)} \quad (1)$$

$$Pi = \frac{Slui}{Si} \quad (2)$$

S_i= Total area of analysis window i.

S_{lui}= Total area of certain type of building footprints within analysis window i.

N=total number of building footprints types within analysis window i.

First, the total area of each type of building footprints can be summarized within each grid cells. Secondly, the proportion of certain type of footprints Pi could be calculated. The most challenge works are calculating Pi for every types and analysis area, also counting the number of types of building footprints within the analysis area. In this case, the attribute table was exported to MATLAB, and all calculations are done by converting the formula into MATLAB code.

Moreover, the area has no buildings or only contains one type, the value would be given a zero, because having one or nothing indicate no diversity at all.

The Table 5 shows the example of calculation of Entropy index for the analysis window of cell 9029.

Table 5 Example of diversity calculation

Cell ID	Residential (m2)	Commercial (m2)	Industrial (m2)	Education (m2)	Service (m2)
Analysis window of 9029	45563.733243	11244.585064	8713.675007	0	9441.095968
	Health (m2)	**Office (m2)**	**Sport (m2)**	**Number of Land use**	**Entropy value**
	0	24004.266991	398.961012	6	0.784983

4.4.3 Urban design

Level of mixed land use

As spatial distribution of various land uses within a city can reflect where people live, work and shop. From a transportation point of view, this level of mixed land use, especially residential with commercial and industrial, can significantly impact travel activities, trip lengths and travel mode options(Zhang & Guindon, 2006).

In Zhang and Guindon (2006)'s research, they proposed a 'mix index', MI, measures the level of residential vs. commercial/industrial land use mixing, it is defined as:

$$MI = \frac{Nc}{Nc + Nr}$$

Where Nc and Nr are respectively the number of commercial/industrial and residential pixel in the neighbourhood around a residential pixel. The high value means a high level of mixing at the radius under consideration.

However, in this study, mixed land use is selected as a design criterion, it's believed the higher level of mixed residential and other kinds of land uses can significantly reduce the automobile trip, shorten the trip distance so as to encourage walking and cycling. So, Nc means total area of other land uses, and Nr means total area of residential land use within the grid cells.

Another important consideration, it needs to avoid the error or division caused by the grid cells which lacking residential land uses or both residential and commercial. These condition will be given a zero value.

Number of intersections and accessible paths for walking and cycling.

The number of intersections and total length of accessible paths for walking and cycling could be a simple measure of walkability, an area with higher number of intersections can create a pedestrian-friendly environment as people will feel safe in the short length street, can have various route options especially for walking and cycling, the longer cycling paths in each area, makes people prefer travel by walking or cycling rather than by private vehicle.

When calculate these indicators, the number of intersections (including 3 ways intersections) within the grid cells can be directly counted based on the road network, and the total length of paths for walking and cycling was aggregated based on the road network excluding high ways.

4.4.4 Economic development

Number of service/retail establishments

For the number of service/retail establishments, the data of number of business from CBS is used, this data contains the business in industrial, commercial and non-commercial sections.

This indicator can be measured based on the proportion of building footprints except buildings for residential.

4.5 Construction of TOD index map

To deal with a series of different indicators, to express the relative importance and contributions of each indicators for TOD, also to construct a composite TOD index map, it requires using multi-criteria analysis.

Multi−criteria analysis (MCA) method can support comparison of different options on the basis of a set of criteria. They effectively support the assessment of and decision making on complex issues because they can integrate a diversity of criteria in a multidimensional output. The procedures and results obtained from MCA also can be improved with the interaction of stakeholders.

In addition, since TOD requires co-operation between planners and stakeholders, SMCE can be an ideal tool for such an analysis that also uses inputs from multiple stakeholders.

Spatial multi criteria evaluation (SMCE), also called spatial multi criteria analysis (SMCA), is a useful tool for identification and comparison of solutions for locating based on combining multiple factors, which can be shown by information layers in minimum time. SMCE is a method to provide analogical solutions in local problems based on combination of multiple criteria which is shown finally by a composite map(Malczewski, 2006). Due to the complexity of a multi-dimensional spatial index, SMCE can help to standardize indicators and assign weights to criteria, so that can make the composite index map.

For implementing the quantitative model the SMCE module of ILWIS-GIS, it assists in doing a multi-criteria evaluation in a spatial manner. The Input data are various raster maps that are the spatial representation of the criteria. The output is one composite index map which indicates the value of TOD level.

The values in these input maps have a meaning and express different measurement units (e.g. population density, diversity, number of intersections etc.). In order to compare criteria with each other in a way that makes sense, they have to be standardized which means transformed to the same unit. For standardizing value maps, several methods such as Maximum, Interval and Goal can be used to convert the actual map values to a range of o and 1, which 1 means the highest utility. Another consideration in standardization is the contribution of each indicator is benefit or cost in relation to the overall objective. Benefit means the indicators have positive contribution to the TOD level which is considered as favourable such like density, the higher density. The higher level of TOD. Inversely, the low value of cost indicator indicates the high level of TOD. In this research, all the indicators were considered as *benefit* and, they were standardized using *maximum* method.

The next step is weighting standardized indicators, the intention for weighting is expressing importance of each criterion compared to other criteria. For weighting, three main methods can be used: direct method, pairwise comparison and rank order methods.

Since TOD requires cooperation among stakeholders, and different stakeholders have different goals, so they may emphasize on different stakeholders. In this research, stakeholders would be involved at this stage, they would be asked to rank the criteria as well as the indicators based on their realization of TOD, and this process helps them to clarify the outstanding issues and concerns, identify ideas and suggestions on the importance of various indicators.

4.6 Sensitivity analysis

Spatial multiple criteria evaluation (SMCE) has become a well-established tool for solving spatial choice problems, but SMCE model has also been criticized for uncertainty present in outputs(Calthorpe Associates & Development Department, 1992). Therefore, it should be evaluated to ensure the robustness of the model under a wide range of possible inputs, a minimal change of outputs means robust model.

In this research, sensitivity analysis as a systematic approach was carried out by changing the weighs of criteria and indicators to test the robustness of the results of TOD index.

There are 4 criteria and 8 indicators in this research to produce TOD index. To apply the sensitivity analysis, firstly, one criterion was increased by 10% of its own weight and the rest of criteria would be reduced equally based on that 10%, then the criterion was decreased by 10% of its own weight and the rest of criteria would be increased equally based on the 10%. This analysis was carried repetitively for all the 4 criteria and 8 indicators, and the result of sensitivity analysis can be seen at the Table 14 and Table 15.

4.7 Spatial statistical analysis

Since the TOD index has been derived based on the indicators that are by trend higher in populated and built up area, it is logical to expect the high value of TOD index could be clustered in those area. In order to clarify the existence and identify the cluster of high value TOD area so that it can be used for further analysis to improve the accessibility, it is essential to apply a more scientific and robust method to map their spatial distribution and improve the understanding of TOD index values. The spatial statistical analysis was used for analysis:

Spatial autocorrelation analysis

First, to evaluate whether the TOD index values expressed is clustered, dispersed, or random, it was required to use the Spatial Autocorrelation tool based on the calculation of Global Moran's I Statistic. Secondly, the Incremental Spatial Autocorrelation tool in GIS helps identify the conceptualization of spatial relationship for spatial autocorrelation analysis.

The Spatial Autocorrelation (Global Moran's I) tool is an inferential statistic, which means that the results of the analysis are always interpreted within the context of its null hypothesis. According to the Global Moran's I statistic, the null hypothesis states that the attribute being analyzed is randomly distributed among the features in your study area; in another way, the spatial processes promoting the observed pattern of values is random chance. So in this research, the null hypothesis was: the TOD index values are distributed randomly and has no pattern in the study area.

The output of Spatial Autocorrelation (Global Moran's I) tool returns five values: the Moran's Index, Expected Index, Variance, z-score, and p-value. When the p-value returned by this tool is statistically significant, you can reject the null hypothesis. Table 6 summarizes interpretation of results:

Table 6 Interpretation of results of Globe Moran's I Statistic. Source: (ArcGIS10.2 Help)

The p-value is not statistically significant.	You cannot reject the null hypothesis. It is quite possible that the spatial distribution of feature values is the result of random spatial processes.
The p-value is statistically significant, and the z-score is positive.	You may reject the null hypothesis. The spatial distribution of high values and/or low values in the dataset is more spatially clustered than would be expected if underlying spatial processes were random.
The p-value is statistically significant, and the z-score is negative.	You may reject the null hypothesis. The spatial distribution of high values and low values in the dataset is more spatially dispersed than would be expected if underlying spatial processes were random.

Before running the spatial autocorrelation analysis, it is important to setting the parameter of conceptualization of spatial relationship which determines what should be considered as the spatial neighbour of each feature. Also, it was required to define a reasonable threshold distance, and the Incremental Spatial Autocorrelation tool in GIS was used to help identify the conceptualization of spatial relationship.

Incremental spatial autocorrelation

The Incremental Spatial Autocorrelation tool measures spatial autocorrelation for a series of distance and helps to select an appropriate distance threshold for analysis have these parameters, it creates a line graph of those distance and calculate their corresponding z-scores. "Z-scores indicate the intensity of spatial clustering, and significant peak z-scores indicate distance where processes promoting clustering are most pronounced." (ESRI 2012). Those peak distance are the appropriate distance to use as the Distance Band or Distance Radius parameters.

As shown in the Figure 10 and Figure 11, the incremental spatial autocorrelation analysis for TOD index values over all the study area have one significant peak point at the 500 meters. So the threshold distance of 500 meters was set as the Global Moran's I calculation parameters.

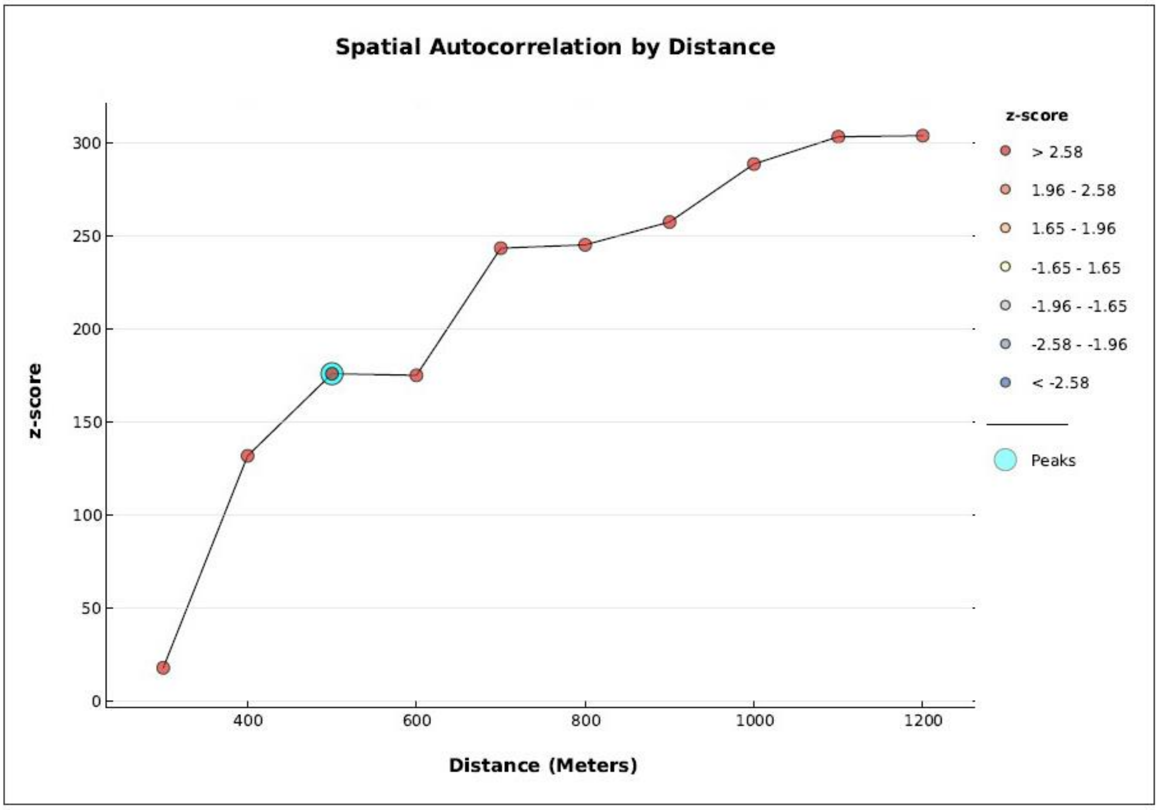


Figure 10 Incremental autocorrelation graph for the TOD index

Global Moran's I Summary by Distance

Distance	Moran's Index	Expected Index	Variance	z-score	p-value
300.00	0.041138	-0.000083	0.000005	18.017847	0.000000
400.00	0.843621	-0.000083	0.000041	131.817921	0.000000
500.00	0.808953	-0.000083	0.000021	175.903850	0.000000
600.00	0.557386	-0.000083	0.000010	175.016652	0.000000
700.00	0.717269	-0.000083	0.000009	243.312817	0.000000
800.00	0.716147	-0.000083	0.000009	245.078264	0.000000
900.00	0.600463	-0.000083	0.000005	257.343869	0.000000
1000.00	0.635612	-0.000083	0.000005	288.478678	0.000000
1100.00	0.606080	-0.000083	0.000004	303.110875	0.000000
1200.00	0.559855	-0.000083	0.000003	303.692895	0.000000

First Peak (Distance, Value): 500.00, 175.903850

Max Peak (Distance, Value): 500.00, 175.903850

Distance measured in Meters

Figure 11 Summary of the incremental spatial autocorrelation table

Spatial clustering analysis

According to the result of spatial autocorrelation analysis, the TOD index values is spatial clustered over the study area, so it was required to detect those location of cluster. The statistical of Getis-Ord Gi* and Anselin Local Moran's I can both identify the hotspots and clusters of TOD index, because of their different specifications and outcomes and to make the result more accuracy, both of them were employed in this study. In ArcGIS, the Hot Spot Analysis and Cluster/Outlier Analysis tools can help to perform those analysis.

The Hot Spot Analysis tool calculates the Getis-Ord GI* statistic for each features in the study area, it works by looking at each features within the context of neighbours, a features with high value may not be the significant hot spot, it was required the surrounded features should have high values as well, besides, the local sum of the values of the features and its neighbours is compared proportionally to the total sum of all features, when the difference is too large , it has a statistically significant results.

The Getis-Ord GI* statistic calculates a z-score for each features, for the statistically significant positive z-scores, if the z-score is larger, the clustering of high values (hot spot) is more intense, for statistically significant negative z-scores, if the z-score is smaller, the clustering of low values (cold spot) is more intense.

The Cluster/Outlier Analysis tool uses Anselin Local Moran's I to identify the spatial cluster of features with high or low values, and spatial outliers. The result gave a code representing the cluster type for each statistically significant feature, such as a statistically significant cluster of high values surrounded by high values (HH), cluster of low values surrounded by low values (LL), outlier in which high value is surrounded by low values (HL), and outlier which has a low value but surrounded primarily by high values (LH). Statistical significance was set at the 95 percent confidence level.

4.8 Measuring Public Transport Accessibility Levels

The PTAL calculation was originally produced by the London Borough of Hammersmith and Fulham, and later was adopted by Transport for London as the standard method for calculating public transport accessibility in London (Transport for London, 2010). It is an accurate measurement of the accessibility of a point to the public transport network, consider walk access time and service availability.

Walk times are calculated from the points of interest (POI) to public transport service access points (SAP), such as bus stops, train stations, underground stations within pre-defined catchment areas.

And then the PTAL also considers the service frequency, it calculates the average waiting time based on the frequency of public transport service at each public transport access points. In addition, it adds the reliability factor to the total access time, then the Equivalent Doorstep Frequency (EDF) is calculated for each point. The PTAL value is summed by all EDFs for all different stops and different transport modes.

The parameters in PTAL are:

· Walking speed.

· Reliability of bus, train.

· Maximum walking time (catchment area).

· Peak hour service frequency of public transport.

The PTAL index is defined as follows:

· **Total access time = Walking time + Average waiting time**

· **Average waiting time = Reliability + Scheduled waiting time**

· **EDF (Equivalent Doorstep Frequency) = 30/Total access time**

Then for a single transport mode, the Accessibility Index value can be calculated by:

· **AImode = EDFmax + (0.5 * All other EDFs)**

Calculating overall accessibility level index is a sum of each AIs over all modes:

· **AIpoi = ∑(AImode1 + AImode2 + AImode3 … AImode n)**

So, the Parameters and Calculation steps of PTAL in this study are in following table:

Table 7 Parameters and Calculation steps of PTAL in this study

Parameters	**Parameter 1**	**Parameter 2**	**Parameter 3**	**Parameter 4**	**Parameter 5**
	POI, SAP	Distance	Frequency of service	weights	Reliability
Calculations	**Step 1**	**Step 2**	**Step 3**	**Step 4**	**Step 5**
	Walking time	Scheduled waiting time	Total access time	EDF	Accessibility index

Points of Interest

To derive accessibility index values one must first define the Points of Interest (POI). As in this study, the TOD values have been calculated based on the grid cells which created before, and PTAL values are actually produced for the same targets, so the centroids of each grid cells are the POI in this research, and values are calculated for related cells.

Service Access Points

SAP is defined as the locations of train stations and BRT stops, BRT stops are classified by pairs. For instance where there is a stop on either side of the road for each direction are classified as one SAP. However, in this case, in terms of high quality of public transport service and data availability, it just considers the train stations and one existing BRT line.

Total access time

Walking time

Walking time are calculated by the walking path distance between POI and SAP into a measure of time using an assumed average walk speed, the walk speed used in Transport for London is 80m/min and it is also used in this study. The total distance between POI and SAP is not a straight line, it takes into account the road network of study area and uses the shortest path following the road network to calculate total walking distance.

In addition, a number of parameters are used to define the extent of the walk catchment area. In Transport for London, for buses the maximum walking distance is defined as 640 meters, and 960 meters is defined for trains. However, in this research, is analysing the accessibility for the TOD area which is defined is defined within 500 to 800 meters, so the extend of the walk catchment area is adapted into 640 meters for BRTs and 800 meters for trains.

Table below summarizes the walk speed, maximum walk distances and reliability factors used in the calculations.

Table 8 Parameters used in calculation of PTAL

Parameter	**Unit**	**Value**
Walk Speed	Meters/Minute	80
Reliability (BRT)	Minutes	2
Maximum Walk Time(BRT)	Minutes	8
Maximum Walk Distance(BRT)	Meter	640
Reliability (Train)	Minutes	2
Maximum Walk Time (Train)	Minutes	10
Maximum Walk Distance (Train)	Meter	800

Average waiting time

Waiting time is the period between when a passenger arrives at a SAP and gets on the service. In PTAL, is assumed people arrive at the SAP at random.

For each SAP the scheduled waiting time (SWT) is calculated based on the frequency of the service. This is estimated as half the headway (i.e. the interval between services), and the formula is SWT=0.5*(60/Frequency).

Reliability

Regarding the reliability of the service, for instance, the regularity of buses and trains can be affected by a variety of factors. So 'reliability' factor are applied to the SWT. This factor should be derived from observed survey data for each service at any time of day, however in the absence of accurate survey data it has been followed by London Transport that reliability of 0.75 for train service and 2 for bus service.

Accessibility Index

Weights

To calculate the final Accessibility Index (AI) value, a weighting is applied to each ASP to simulate the enhanced reliability and attractiveness of a route with a higher frequency over other ASPs. For each mode (e.g. bus, rail), the stop with the highest frequency is given a weighting of 1.0, with all other stops in that mode weighted at 0.5.

Finally, the EDF and the weighting are multiplied to produce an accessibility index for each route, and the accessibility indices for all routes are summed to produce an overall accessibility index for the POI.

Table 9 shows how the Public Transport Accessibility Level value is calculated, for the grid cell of ID 2300, it is served by 1 BRT services and 1 train station, note that the station Nijmegen has 6 routes.

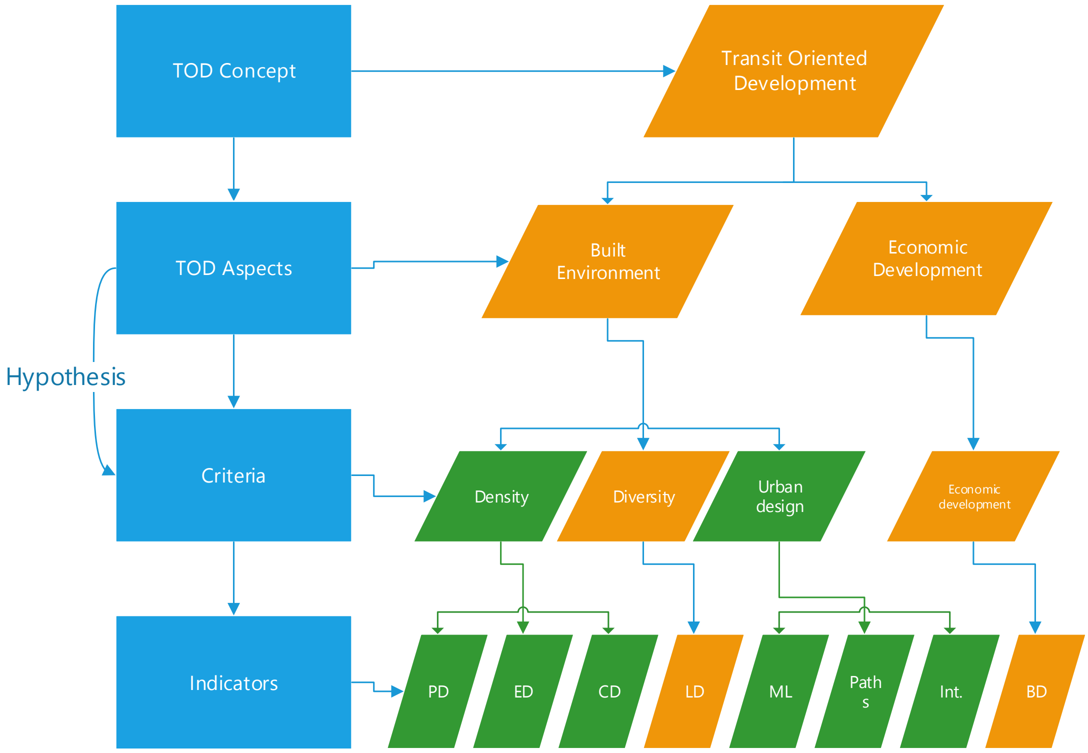
Table 9 Example of accessibility index calculation

Service	**Routes**	**Distance （Meters）**	**Walk time(Min)**	**Frequency**	**Weight**
BRT	Smetiusstraat	634.9	7.93	4	1
Train Nijmegen	Via Zutphen	714.7	8.93	2	0.5
	Via Zwolle	714.7	8.93	2	0.5
	Via Deurne	714.7	8.93	2	0.5
	Via Schiphol	714.7	8.93	2	0.5
	Via Den Helder	714.7	8.93	2	0.5
	Via Roermond	714.77153	8.934644	4	1
Routes	**SWT(Min)**	**Reliability**	**Access(Min)**	**EDF**	**Accessibility Index**
Smetiusstraat	7.5	2	10.32	1.72	1.72
Via Zutphen	15	0.75	24.68	1.21	0.61
Via Zwolle	15	0.75	24.68	1.21	0.61
Via Deurne	15	0.75	24.68	1.21	0.61
Via Schiphol	15	0.75	24.68	1.21	0.61
Via Den Helder	15	0.75	24.68	1.21	0.61
Via Roermond	7.5	0.75	17.18	1.74	1.74
All					6.51

5. RESULTS AND ANALYSIS

5.1 List of indicators

The following diagram illustrates the framework which the indicators in this research derived from.



The framework employed top down approach and the selection of indicators follows the steps: firstly, identified the main aspects of TOD regarding measurement of TOD all over the city region. Then formulated the criteria based on the aspects of TOD, and along with each criterion, the related hypothesis describes how the criteria affects and contribute to TOD level. Finally, based on each criterion and the selection principles discussed in previous section, the indicators used to measure TOD levels were selected from various literatures.

Based on all those selection methods and principles were discussed in chapter 3, Table 10 shows the result of modified list of indicators which are selected for measuring TOD index in this research. Overall, the criteria can represent the main aspects of TOD in terms of measurement for entire city region, and therefore meet the objective of this research. In addition, the indicators can efficiently measure the targeted criterion, and they all have significant impacts on TOD levels. Moreover, these indicators can be quantified based on available data.

However, due to data availability, some indicators could not be included, the list (Table 10) might looks not very balanced in this research since there is only one indicator represents economic development aspect of TOD, it would be better if the data for measuring indicators such as unemployment level and tax revenue are available as well.

Table 10 List of indicators in this study

Criteria	Indicators	Units
Level of density	Population density	Persons/Acre
	Commercial density	Commercial units/Cell
	Employment density	Jobs/Acre
Level of diversity	Diversity of land use	Entropy index value/Cell
Level of urban design	Level of mixed land use.	Mixedness index value/Cell
	Quantity accessible footpaths for walking and cycling	Total length (meters)/Cell
	Number of intersections or street crossings	Number of intersections/Cell
Level of economic development	Number of service/retail establishments	Business units/Cell

5.2 Computed indicators

The following maps show the results of each indicators. According to the concept of TOD, these indicators are related to the land use characteristics of this region, generally, it make sense that the high values of all these indicators are distributed in the urban core area as can be seen from the maps. The discussion of maps is following Table 11.

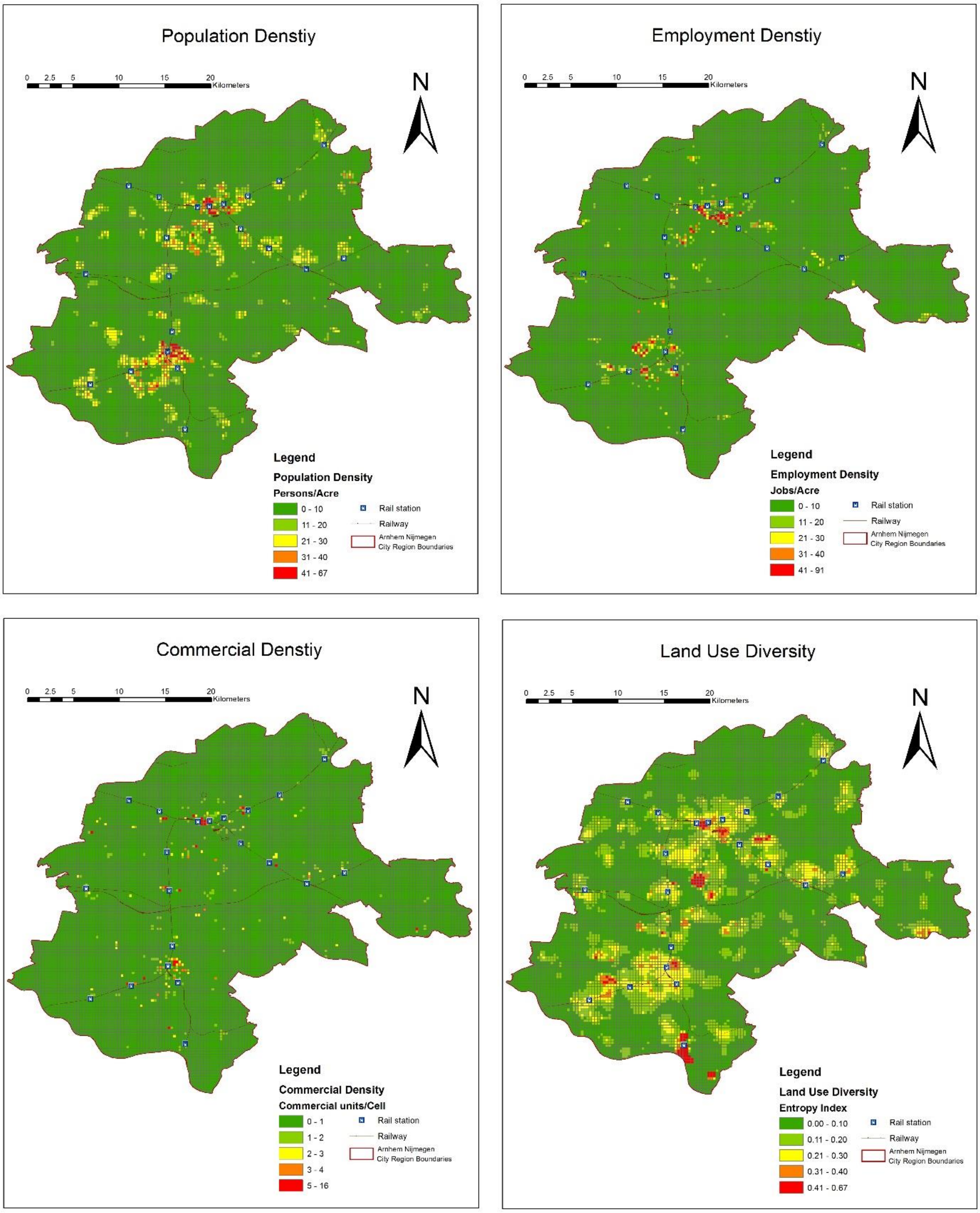


Figure 12 Maps of population, employment and commercial density and land use diversity indicators

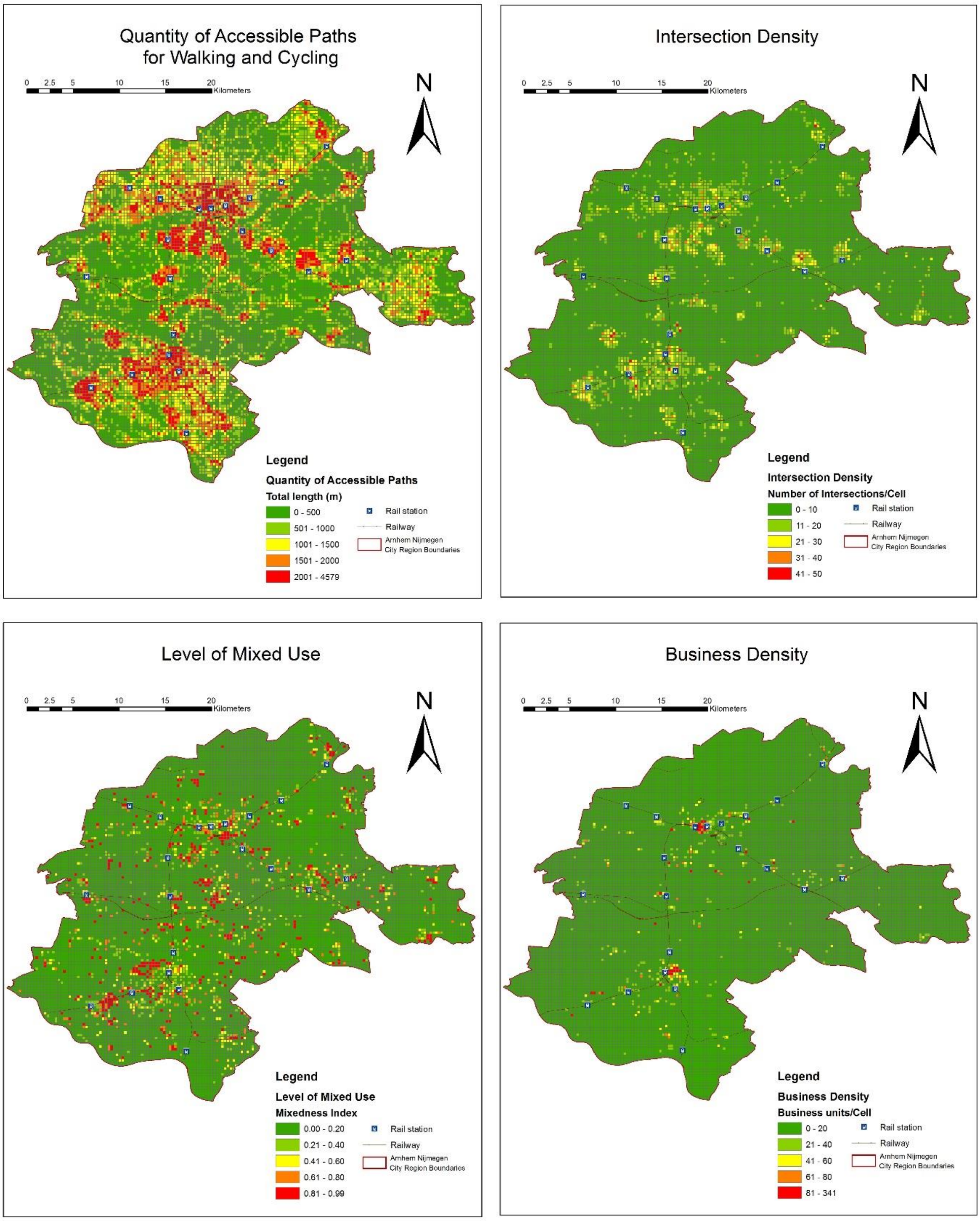


Figure 13 Maps of intersection density, quantity accessible paths for cycling and walking, level of mixed use and business density

Table 11 shows the descriptive statistics of each indicators, it can be clearly seen the mean values of each indicators are very low compared to the maximum values, this because the rural area and forest cover almost 70% of this whole region, and an amount of grid cells have value of zero for each indicators, the maps of indicators from Figure 12 and Figure 13 also reflect this effect.

Table 11 Descriptive statistics of the indicators

Indicators	Minimum	Maximum	Mean	Standard Deviation
Population density (persons/acre)	0	67.39	2.76	6.88
Employment density (Jobs/acre)	0	91.41	1.26	4.95
Commercial density (units/cell)	0	15.78	0.05	0.42
Land use diversity (Entropy index)	0	0.67	0.06	0.09
Quantity accessible paths (Meters/cell)	0	4579.27	782.80	726.88
Intersection density (No. of intersections)	0	50	4.03	6.37
Level of mixed use (Mixedness index)	0	0.99	0.08	0.21
Businesee density (units/cell)	0	340.87	2.27	10.31

High population density is essential to the benefit of TOD, it requires higher capacity and frequency, and then can increase transit ridership.

According to Pushkarev (1977)-a minimum density of 12 dwelling units/acre is necessary to support local bus service, assuming that 1 dwelling has average 3 people in Netherlands, this would be 36 persons/acre. Also, Calthorpe Associates and Development Department (1992) defined an average minimum density in TOD area should vary between 18 and 25 dwelling units/acre, it depends on proximity to transit service and the location within the urban area.

In the TOD guideline produced by Florida department of transport (FDOT), they recommend an area with at least 135 persons/acre is idea for an urban core region and a density between 100-145 persons/acre for general urban regions.

In this study area Arnhem and Nijmegen city region, the mean population density is 2.76 persons/acre which is far smaller than the range recommended by previous literatures, because in the whole region, the extensive agricultural, natural and forest area cover a huge portion of the region.

Look at the density in each grid cells (Figure 12), the highest density is 68 persons/acre, which is well beyond the minimum standard of TOD mentioned by Pushkarev (1977) and Calthorpe Associates and Development Department (1992), but still cannot reach the standards of general urban regions and urban core regions based on the TOD guideline by FDOT. Figure 12 shows the population density per grid cells in whole region, it can be seen that there are more regions of low density (green regions) than those of high density (red), these low density regions contribute too many to the mean.

Employment density is another density factor that can significantly influence transit ridership. TODs with jobs can serve to keep balance of utilization of transportation infrastructure, both highway and transit, and help to create an all-day environment(Pratt, 2007). According to Cervero et al. (2004), job density increasing from 5 jobs/acre to 60 jobs/acre can increase the rail commuting share up to 52.1%, and R. H. F. D. o. T. Ewing (1999) contends that job density of 25 jobs/acre will support frequent, high-quality of transit service, for light rail service, a density of 50 jobs/acre is favoured.

In the employment density map (Figure 12), it can be seen that the majority of the region is below 5 jobs/acre. This is caused by the large proportion of agriculture and forest in the region. But considering the urban core, the highest densities of grid cells are around the city Arnhem and Nijmegen which are more than 80 jobs/acre. The number of Jobs then have steadily dispersed from the urban core to the suburbs and rural areas.

Not only these two indicators, but the distribution all other indicator values are similar, seen Figure 12, high values are concentrated on the urban areas, and because of the larger proportion of agriculture, forest, and natural areas all over the region, the indicators values are generally low, the low values combined high frequency make the mean value of each indicators very low. It also can be seen from the Table 12.

5.3 SMCE model

In SMCE model, regarding the standardization methods, all indicators were used maximum functions and considered as benefit indicators. The weight of indicators were derived from the stakeholders of Arnhem Nijmegen city region based on a workshop in which they were asked to rank the criteria and indicators based on their importance in realization of TOD. This workshop was conducted by Singh (2013) for the same purpose as my research.

Table 12 shows the rank and weights of criteria and indicators. Surprisingly, the stakeholders put economic development at the first place, followed by are density, diversity and urban design. These weights are quite different from the various literatures discussed in section 2.3, many researches emphasized more in the built environment, however the stakeholders from the Arnhem and Nijmegen city region emphasized on the economic development, consequently, the indicators of business density takes weight of 0.4 which is much bigger than the weights of density, diversity and urban design indicators.

Table 12 Weights of criteria and indicators.（Rank order derived from the stakeholders）

Criteria	Indicators	Rank	Weights	Final weights
Level of density		**2**	**0.3**	
	Population density	1	0.5	**0.15**
	Employment density	2	0.33	**0.1**
	Commercial density	3	0.17	**0.05**
Level of diversity		**3**	**0.2**	
	Diversity of land use	1	1	**0.2**
Level of urban design		**4**	**0.1**	
	Quantity accessible paths	1	0.5	**0.05**
	Intersection density	2	0.33	**0.03**
	Level of mixed land use.	3	0.17	**0.02**
Level of economic development		**1**	**0.4**	
	Business density	1	1	**0.4**

5.4 Index value interpretation

Regarding the applied method in SMCE, the index value could be range from 0 to 1, however, in this research, to make it easily understand, the value range is changed to 0 to 100. So as seen in Figure 14, the computed TOD index value in the whole region of Arnhem Nijmegen are from 0 to 55. The higher value means the higher level of TOD and indicates that the urban development is oriented towards use of transit.

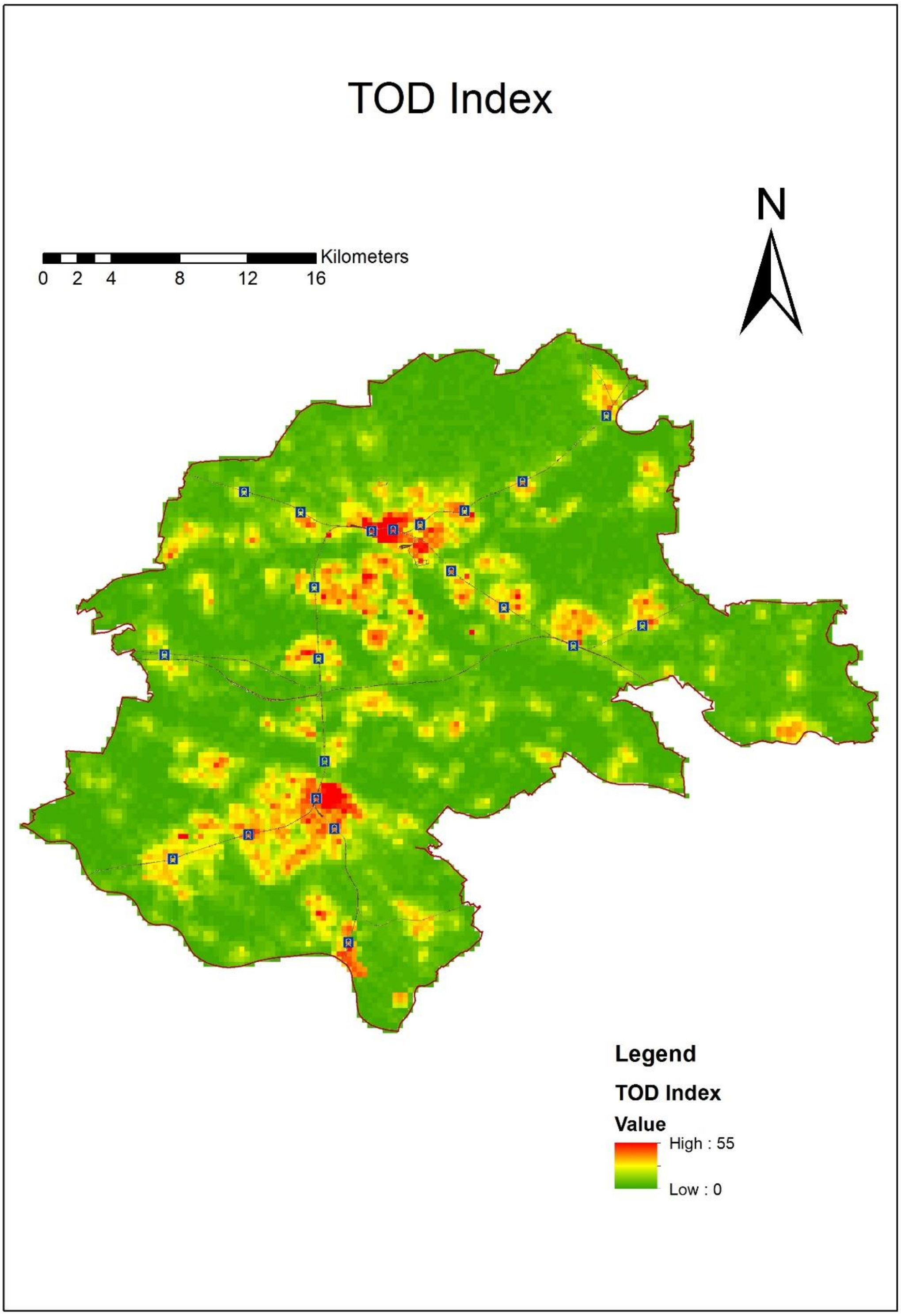


Figure 14 Map of TOD index

According to frequency statistics (Figure 15) of the TOD index for the study area, the values are not evenly distributed, the maximum TOD value is 55, and however the average value for entire region is 4.47. it can be seen (Table 15) nearly 70 percent of values are lower than 5, and only less than 1% of values are higher than 30.

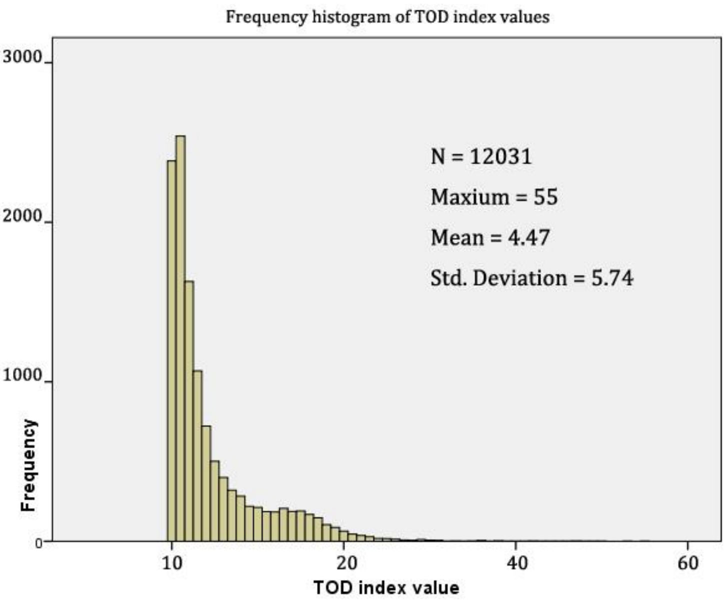


Figure 15 Frequency histogram of the TOD index

The value of 55 indicates that cell has the highest level of TOD compared to other cells in the entire Arnhem Nijmegen City Region based on the 8 indicators. The low average value of 4.47indicates there is a large proportion of low values contribute to the TOD index, since a large area in the whole city region is covered by forest and agriculture, the concept of TOD does not make sense in those locations and the value of indicators at those cells are very low or zero.

Compared to the result of Fard (2013), seen in Table 13, the highest TOD value in his research is 60, and the mean value is 16.69. The highest value is close but the mean value is bigger than that in this study. The results (Table 13) clearly show that values between 0-9 take a huge proportion which is much more than that in Fard's research, and higher values between 30-60 are much less than that in his research, so the mean value of TOD index in this research is low. This result was expected because of the following reasons.

In this study, when apportioning the indicators like population, commercial units, jobs and business, they were all based on the proportion of certain kinds of building footprints. However in his research, those methods were based on the area of land use. The area of building footprints are smaller than area of land use and cannot cover so many cells as area of land use, so the cells with zero value of those indicators are more than those in his research, which make the mean value of TOD value in this study is very low. In addition, there are 3 new indicators such as employment density, quantity accessible paths and number of intersections in this research can also make differences. Moreover, the results of weights of indicators are different, in this research they are based on the preferences of stakeholders', the economic development criterion takes the first place and has weight of 0.4, however in his research, it was the last one which only had weight of 0.1.

Table 13 Comparison of results between this research and (Fard, 2013)

Frequency statistics	Maximum	Mean	0-4 (%)	5-9 (%)	10-14 (%)	15-19 (%)	20-29 (%)	30-60 (%)
This research	55	4.47	10.01	10.95	19.61	31.76	13.94	13.73
Fard's research	60	16.69	69.4	14.3	8.1	5.8	2	0.4

Also from Figure 16, it shows the equal interval distribution of TOD index, higher values from 30 to 55 are colored by the yellow to red, and lower values are presented by green. As a general pattern, the high value cells are concentrated in the urban core, and as it can be seen they are close to the around train stations. The value of TOD index then have steadily dispersed from the urban core to the suburbs and rural areas. The distribution of TOD index value makes sense because all indicators used to measure TOD index are higher in populated and built up area.

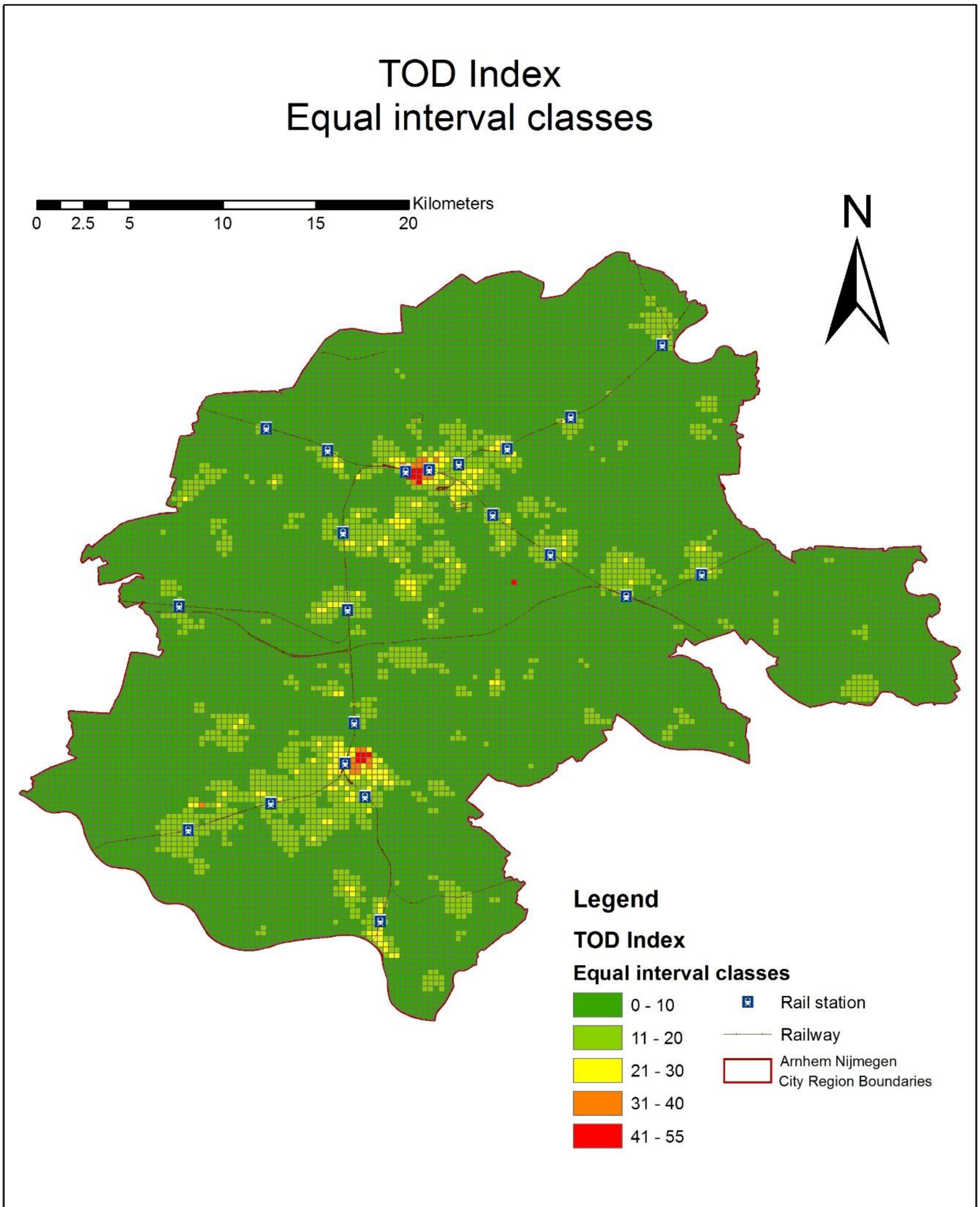


Figure 16 Map of TOD index based on equal interval

5.5 Sensitivity analysis

Testing the robustness of the results of the model in the presence of uncertainty, it was required to perform a sensitivity analysis by changing the both weights of criteria and indicators, it tested 16 times for indicators and 8 times for criteria, for each criteria and indicator increasing 10% and decreasing 10%.

When the certain criteria or indicator increased 10%, the rest of criteria or indicators would be decreased based on that 10%, and when the certain criteria or indicator decreased 10%, the rest of criteria or indicators would be increased based on that 10%.

Table 14 and 15 show the results of sensitivity analysis by changing the weights of indicators and criteria respectively.

Table 14 Frequency Statistic of sensitivity analysis results by changing weights of indicators

Sensitivity Analysis	Minimum	Maximum	Mean	Standard deviation	Number of cells between 40 and 50	Number of cells above 50
Base	0	55	4.47	5.74	12	3
Population+	0	56	4.48	5.71	11	4
Employment+	0	55	4.48	7.76	12	3
Commercial+	0	55	4.48	5.75	11	3
Diversity+	0	55	4.35	5.50	11	3
Paths+	0	55	4.40	5.70	12	3
Intersections+	0	55	4.45	5.72	12	3
Mixed use+	0	55	4.50	5.71	11	3
Business+	0	55	4.61	5.88	12	3
Population-	0	55	4.46	5.77	12	3
Employment-	0	55	4.50	5.71	12	3
Commercial-	0	55	4.45	5.72	12	3
Diversity-	0	55	4.58	5.86	13	4
Paths-	0	55	4.53	5.79	12	3
Intersections-	0	55	4.48	5.76	12	3
Mixed use-	0	55	4.48	5.76	12	3
Business-	0	55	4.32	5.59	10	4

Table 14 and 15 show the frequency statistic of all the sensitivity analysis results, as it can be seen, the maximum value of TOD index value are always 55, the average value of TOD index are in the range from 4.32 to 4.61. In addition, the number of high value cells have been counted, there are just 3 or 4 cells over 50, and 10 to 13 cells fall into the range of 40 to 50.

Table 15 Frequency Statistic of sensitivity analysis results by changing weights of criteria

Sensitivity Analysis	Minimum	Maximum	Mean	Standard deviation	Number of cells between 40 and 50	Number of cells above 50
Density+	0	56	4.52	5.75	13	3
Diversity+	0	55	4.35	5.60	11	3
Design+	0	55	4.39	5.68	12	3
Economic+	0	55	4.61	5.89	12	3
Density-	0	55	4.41	5.71	12	3
Diversity-	0	55	4.58	5.85	13	4
Design-	0	55	4.54	5.79	11	3
Economic-	0	55	4.32	5.60	10	4

Compared all the results of sensitivity analysis to the TOD index, they are all similar, changing the weight by 10% does not affect too much on the output, the small variances indicate the SMCE model was robust.

5.6 Spatial statistical analysis

As it was described in the previous chapter, in order to find the cluster of high TOD cells, some spatial statistical analysis were employed and the following results were achieved:

Globe Moran's I Statistic

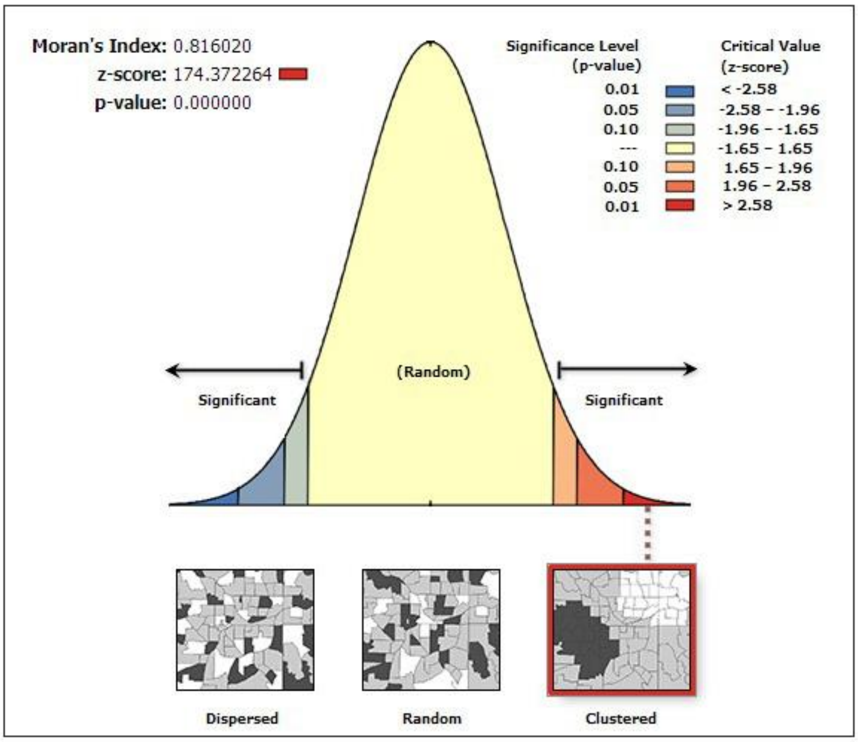


Figure 17 Spatial autocorrelation analysis result (Global Moran's I statistic from ArcGIS)

Figure 17 shows the results of spatial autocorrelation analysis, because the z-score value of 174.3 is high and p-value of 0 is highly significant, the null hypothesis which the TOD index values are distributed randomly and has no pattern in the study area can be rejected.

Given the z-score of 174.37, there is a less than 1% likelihood that this clustered pattern of TOD index values could be the result of random chance, so the confidence level of 99% the TOD index is clustered.

Getis-Ord and Anselin Local Moran's Statistical

Getis-Ord Gi* statistic identifies clustering of spatial distribution, however, it could not provide information about spatial dissimilarities, Anselin Local Moran's statistic can detect both features are among the homogeneous cluster and are dissimilar to the neighbouring features. So they both were used for accuracy.

Figure 18 shows the result of spatial clustering analysis, as it can be obviously observed in the two maps, there are quite a lot of areas are in yellow colour over all the study area, it means statistically significant clustering of TOD index values have not been found in those areas. This indicates those area have dispersed TOD values and the variation between those values are high. And another thing needs to be noticed is those two results did not detect the cold spots in the whole area and the cold spots that should be the low values cells are surrounded by low value cells. In this case, it could because the average level of TOD in the entire region is too low. Anyway, cold spots do not change the development planning directions and they are not suitable for any development.

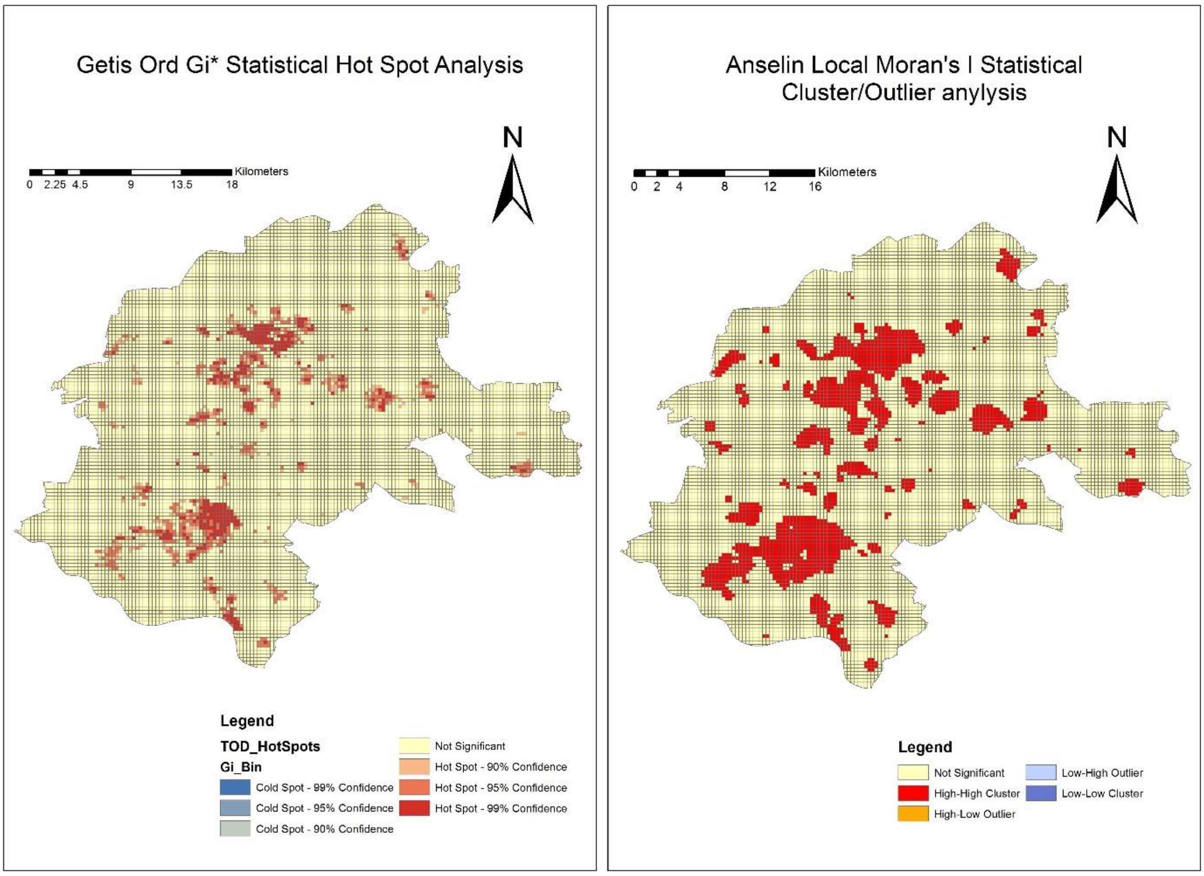


Figure 18 Maps of spatial clustering results based on Getis Ord statistic and Anselin Local Moran's I statistic

The red areas in the maps represent the hot spots of the TOD index, it means each cell in the red area has high TOD value and also is the part of high TOD cluster, those are the areas will be further analysed to increase the transport connectivity if that is poor currently.

Figure 19 shows the clusters of TOD index values which have been identified based on Getis-Ord and Anselin Local Moran's Statistical at the confidence level of 95% by overlaying those two maps. The latter method recognized more cells as hot spots, however, the red cells are identified by both of them were used for further analysis.

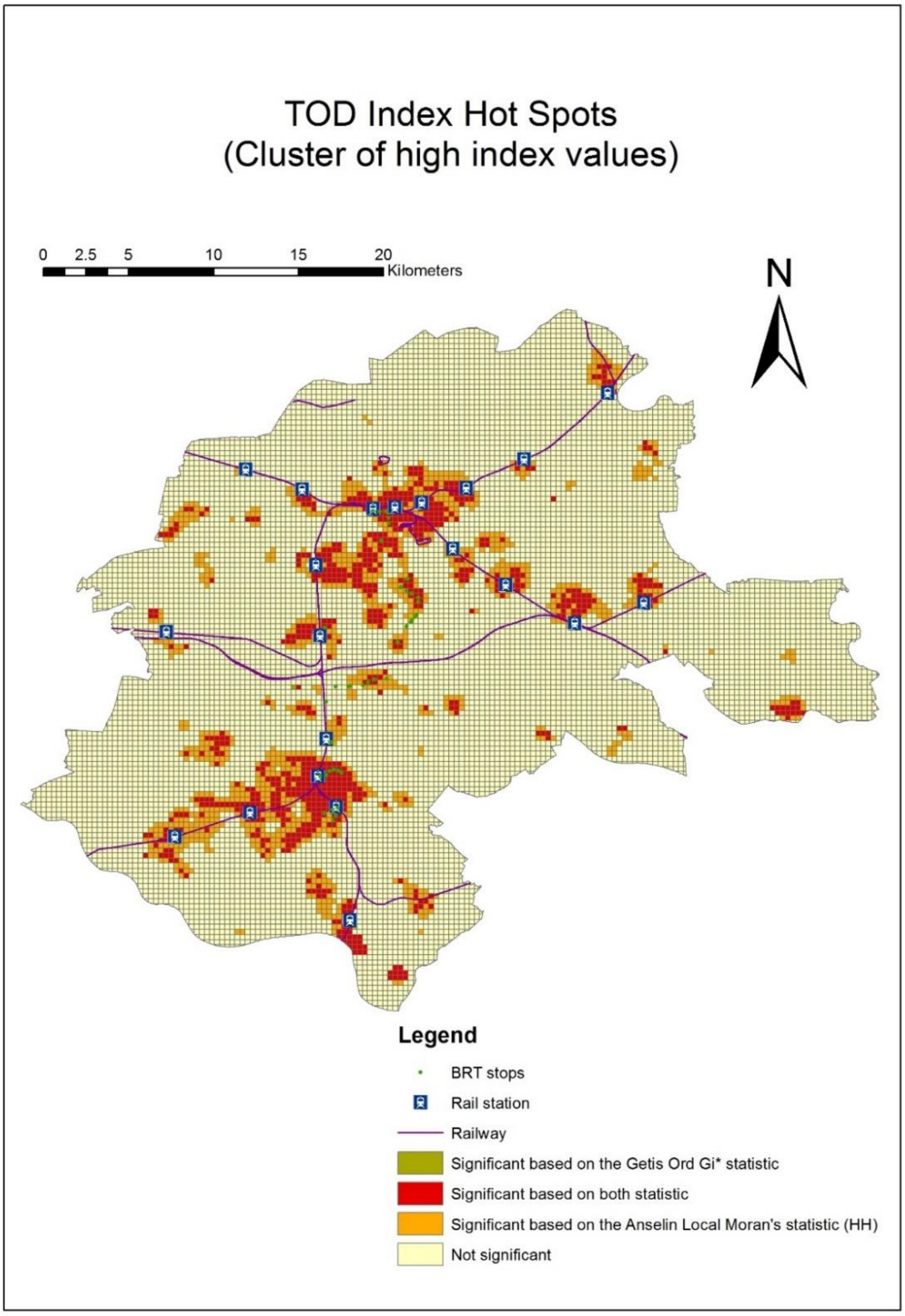


Figure 19 Map of statistic significant hot spots based on two methods.

5.7 Public Transport Accessibility Level

Figure 20 shows the map of public transport accessibility level, it measures the access to public transit (Train and BRT) for the entire city region.

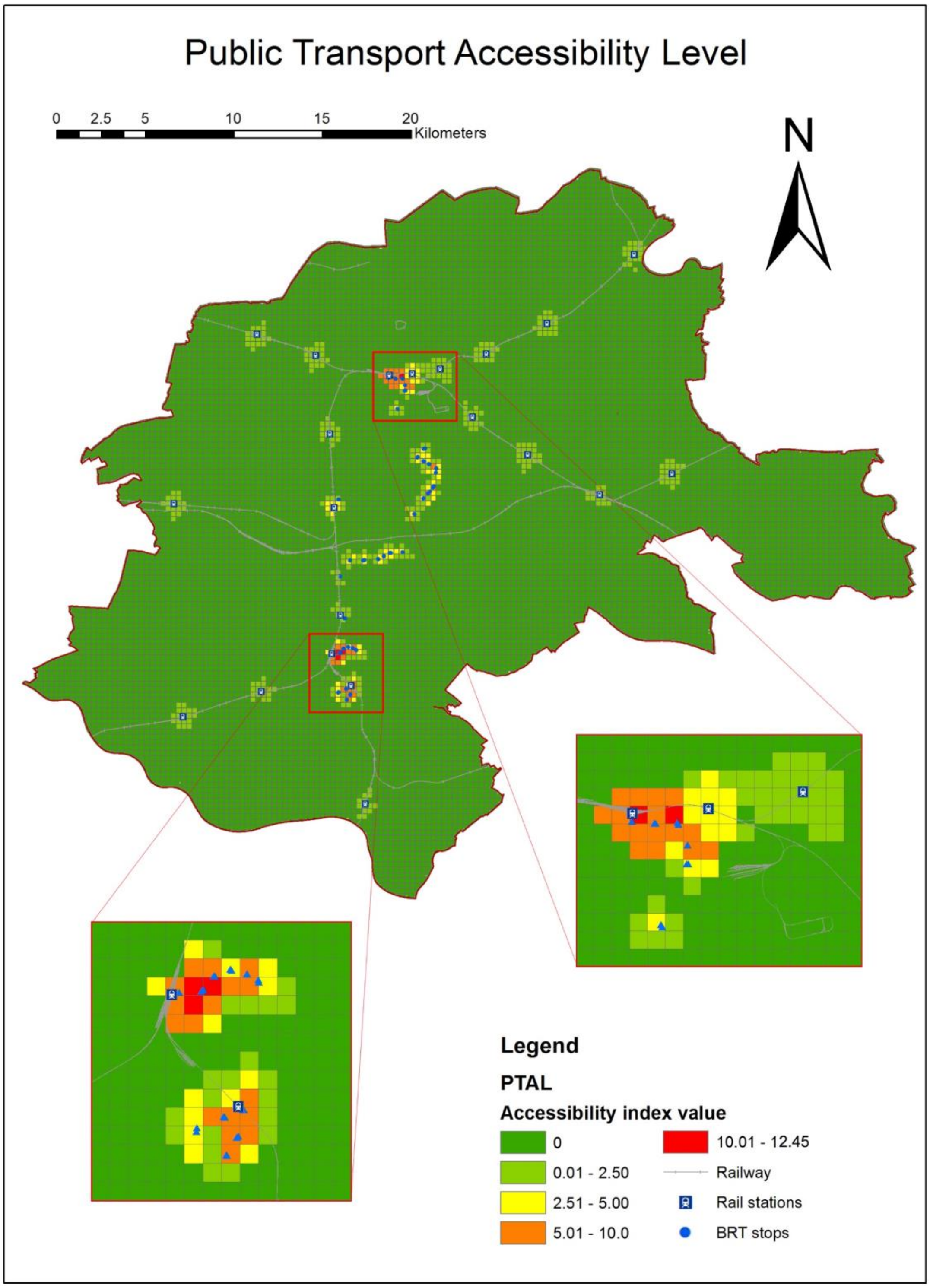


Figure 20 Map of public transport accessibility level in Arnhem Nijmegen region

The result shows the distribution of public transport accessibility index value, it can be seen there is a large proportion cells with zero value, because when measured the accessibility, it has been given a cut-off distance of 800 meters for the train stations and a cut-off distance of 640 meters for BRT stops. So overall, there are 472 cells (Table 16) are within the catchment area, the maximum accessibility index value is 12.45 and the minimum is 1.08, however the average index value is 2.43 which is very low.

Table 16 Frequency statistics of result of PTAL index values

Number	472
Minimal	1.08
Maximum	12.45
Mean	2.43
Std. Deviation	1.88

Value range	**Cumulative percent**
0—2.50	77.1%
2.51—5.00	91.3%
5.01—10.00	99.2%
10.01—15.00	100%

According to transport for London, having derived Accessibility Indices for a range of original points, the indices are then converted to a PTAL grade (1–6) through a banding system, and then defined in terms of Accessibility Levels (Table 17).

Table 17 Banding system of accessibility index (Transport for London, 2010).

PTAL	Range of Index	Description
1a (Low)	0.00—2.50	**Very poor**
1b	2.51—5.00	**Very poor**
2	5.01—10.00	**Poor**
3	10.01—15.00	**Moderate**
4	15.01—20.00	**Good**
5	20.01—25.00	**Very good**
6a	25.01—40.00	**Excellent**
6b (High)	40.01+	**Excellent**

It can be obviously observed that the accessibility values are very low in this study based on the Banding system of accessibility index by transport for London. Nearly 91% of the cells are having very poor accessibility and 99% of the cells have poor accessibility, also the highest value in this area is 12.45 which is just a moderate level. However, this results was expected because of the following reasons.

In this study, in terms of the public transit, it just considers the train and BRT services, the accessibility to regular buses which is supposed to have a significant impact could not contribute the values of index. In addition, the Arnhem and Nijmegen city region cannot reach the standards of London, since in metropolitan city like London, no matter the transport system, the infrastructure or the road network planning are all developed far better than those in this study area. So overall, the accessibility index values are lower in this research.

This objective of using PTAL is to identify the areas with poor accessibility, therefore those areas can be recommended for improvement. According to the Banding system of accessibility by transport for London (Table 17) as well as the arguments above for lower accessibility index values in this study, using value of 10 would cover almost all the cells in the city region, and therefore the impact of PTAL method would not be significant. So it is logical to take the lowest level of accessibility to be further analysed, which indicates values below 2.5 in this research are defined having the very poor accessibility.

5.8 Potential locations for transit nodes

Since this research is to identify the potential locations for transit connectivity, two main aspects needed to be considered as follow:

- Areas should have higher TOD levels.
- The access to current public stations should be poor.

As the map of hot spots (Figure 19) indicates the red areas are having higher levels of TOD, it means those areas developed well and oriented towards use of transit. To make all those areas more accessible and have a good transport connection, it was required to overlay the map with the map of public transport accessibility level (Figure 20) in which values below 2.5 are considered as very poor accessibility in this research. The output identifies the areas have higher level of TOD but have poor connections currently, so those areas should be recommended to improve the accessibility.

Once the areas were identified, it was required to assess them based on the size of TOD area. According the definition and scale of TOD have been discussed in section 2.1 and section 4.3, the common size of TOD area is a walkable area of radius of 250 meters to 800 meters around a station. Therefore, in this case, if the stations would be built in the centroid of the cells, a TOD area would at least be about 9 grid cells in a square format, so the clusters were identified and also have more than 9 cells would be the final recommendations.

The locations identified in the map below (Figure 21) are the result of the assessment based on all the criteria discussed before, the red cells are the locations should be taken into consideration to improve the access to transit. The results performed well in terms of TOD index and public transit accessibility, some of them are well located near the rail tracks and BRT bus line, and those areas (for example Location 1 in Figure 21) can be recommended to build new stations. However, some of them are located far from the existing rail tracks and BRT bus line, so it is required to build some new rail tracks and add new BRT lines (for example Location 2 in Figure 21), therefore, make those areas have good connections. Moreover, a large proportion of areas are located in the urban area of Arnhem and Nijmegen, those areas (for example Location 3, 4, 5 in Figure 21) are close to the existing train stations, it would be inappropriate to build new stations, and in this case it is suggested to improve the quality of transit service like the frequency of trains and BRTs, therefore improve the accessibility. Also in this city region, there is only one BRT line, so constructing more BRT lines among each cities in this region is an effective and necessary way to improve the accessibility level. This result then need to be recommended to the transit authorities and can be further put to analyse.

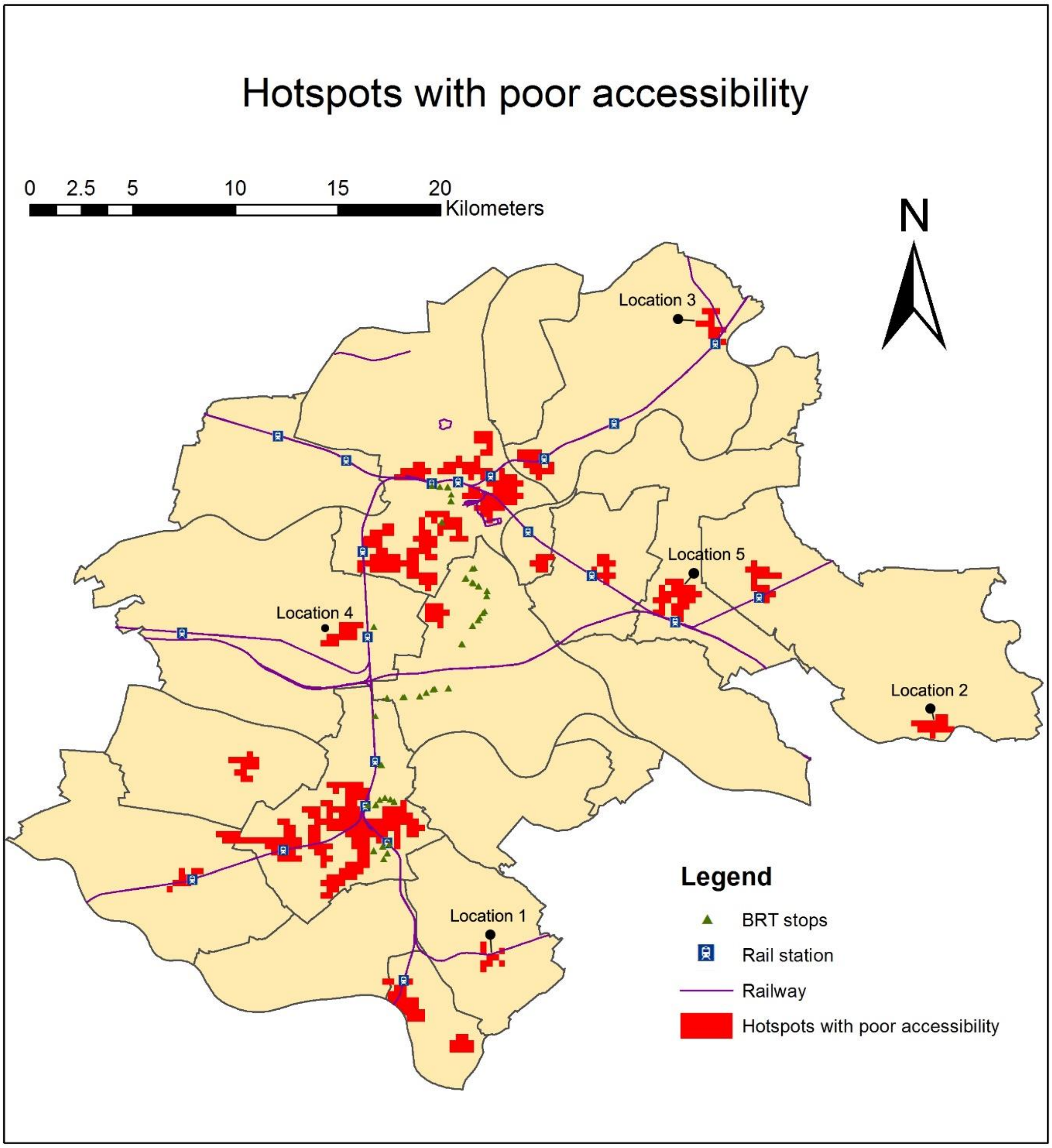


Figure 21 Hotspots with poor accessibility

Since TOD is defined as a compact, mixed use development near transit facilities with high-quality walking environments. The result of this research has been already assessed by the TOD index which has the characters like high density, high diversity and high-quality walking environment, if the access to transit can be improved, those areas would be qualified to be TOD areas based on all TOD requirements.

This result can be a guidance for the TOD planning, through a collaborative effort that local government as well as transit agencies are able to make targeted supportive infrastructure improvements to transit stations so as to make quite improvements on public transit connections. In addition it can be an effective way to improve the integration of land use and transportation planning, and bring various benefits to local government, transit agencies, private developers as well as the people who lives in such an environment.

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter gives the general conclusions of this research, also discusses the limitation of the study and offers recommendations for further research.

6.1 Conclusion

This research was conducted under the hypothesis that TOD can achieve sustainable development by integrate land use and transport planning. To plan TOD, it is required to measure the existing TOD level by developing a TOD index. The index helps to identify areas where urban development is oriented towards use of transit, but have poor access to transit.

To calculate the TOD index value, multiple spatial indicators specifically focusing on the built environment and economic development aspects of TOD were derived from the literatures and then measured over the context of Arnhem Nijmegen City Region. The calculation of indicators was based on developing several geoprocessing models to perform spatial analysis based on the vector based grid tessellation (300*300 meters) in ArcGIS.

In order to reflect the different stakeholders' preferences, and to obtain the composite index map, the SMCE (Spatial Multi-criteria Evaluation) model was developed, the weights are derived in a rank order from stakeholders in the city region, and all indicators were standardized based on the maximum function. Besides a sensitivity analysis was carried to test the robustness of SMCE model, it has been verified robust since the outputs change a little when modifying the weights of criteria and indicators.

To identify the hotspots and cluster of high TOD cells, a series of spatial statistical analyses were performed. At the same time, PTAL (Public Transport Accessibility Level) method was applied to calculate the accessibility index value to high quality of public transport service (Train and BTRs) for each cell.

Finally, overlaying the hotspots of TOD with the accessibility index identified the locations where urban development is oriented towards use of transit, but have poor access to transit. The results can then be recommended to the transit authorities and further put to analyse to build new transit stations.

6.2 Limitations

Regarding the spatial units of analysis in this research is grid tessellations of 300*300 meters, the methods used for disaggregating data into grid cells are based on assumptions that a building with a big footprint houses more people and have more employees which may not necessarily be true, because a high-rise building can live more people than low-rise building even though the latter one may have a big footprint. So this method can cause a certain level of error in calculation of indicators.

Moreover, not all useful indicators from the literatures could be included in this research, indicators such as mix of housing types, tax revenue and unemployment level were not selected and number of service/retail establishments was dropped and 'business density' was used due to the availability of data.

6.3 Recommendations

In terms of stakeholders' involvement, the research has already collected their views of weighting the different indicators, besides it would be better to hold another workshop to verify and analyse the result of alternative locations, to find out stakeholders' opinions and eventually to make right decisions on the future planning.

In addition, the further study can also use the TOD Index for evaluation of TOD projects, this may requires to collect some non-spatial data for indicators such as transit ridership and property values that play a crucial role in TOD, and access to transit could be an essential indicators as well.

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